Department of Communications and Networking

Secondary spectrum usage in TV white space

Kalle Ruttik

Aalto University

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Aalto University
School of Electrical Engineering
Department of Communications and Networking

Supervisor
Prof. Riku Jäntti

Preliminary examiners
Prof. Markku Juntti, University of Oulu
Prof. Markku Renfors, Tampere University of Technology

Opponent
Prof. Petri Mähönen, RWTH Aachen University

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Abstract

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Abstract

Currently, the use of TV frequencies is exclusively license based with the area not covered by licensed TV transmitters being known as TV white space. In TV white space, the spectrum can be reused by a secondary user. This thesis studies how the TV white space can be used by a cellular system. The study addresses the problems of how the access to the spectrum is arranged, how the spectrum usage is constrained and how much capacity a secondary system will have.

The access to TV white space can be arranged by using spectrum sensing or a geolocation database. This spectrum sensing relies on the performance of the signal detection algorithm. The detector has to operate in a fading environment where it should identify very low signal levels. In this thesis, the detector performance in a slow and fast fading environment is modeled. The model indicates that for a sufficiently long measurement time the impact of the fast fading can be averaged out. Unfortunately, simple single antenna-based detectors are not able to operate at a low enough signal-to-noise level. We propose a novel multi antenna-based detection algorithm that is specially designed to operate in a fading environment.

TV white space is characterized by the amount of spectrum available for secondary usage. Because of the signal detection errors, a system using the sensing-based access is not able to use the entire available spectrum. This dissertation provides a method for estimating the spectrum utilization efficiency. The method illustrates how the detection error level affects the amount of available spectrum.

One of the central questions studied in this thesis is how to describe the interference generated by the secondary transmitters. In the conventional model, the interference is computed as the sum of the interfering powers from individual transmitters. An alternative approach, pursued here, is to characterize the transmitter by its transmission power density per area. With such a model, the interference computation is done by integrating over the secondary system deployment area. The proposed method simplifies the interference estimation process.

In data communication systems the spectrum attractiveness depends on the data rate the system can provide. Within the scope of this work, the achievable data rate is computed for a cellular system. Such computation is described as an optimization problem. The solution to this problem is found by searching for the optimal power allocation among the cochannels and the adjacent channels of a nearby TV transmitter.

Keywords TV white space, cellular, spectrum sensing, capacity, interference

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Tiivistelmä

Tämä väitöskirja käsittelee TV-lähetystaajuuksien uudelleenkäyttöä. Tällä hetkellä TV-taajuuksien käyttäminen on lisenssipohjaista. Lisenssi myönnetään tietylle palvelun peittoalueelle. Suunniteltujen peittoalueiden ulkopuolella voidaan TV-spektriä allokoida toissijaisille radiojärjestelmille. Yksi tämän työn tarkoituksista oli tutkia, kuinka hyvin TV:n lähetystaajuudet soveltuvat solupohjaiseen datalähetykseen TV-lähetysten rinnalla. Työssä tarkastellaan, kuinka pääsy voidaan järjestää, kuinka suurta järjestelmien välistä interferenssiä havaitaan ja millaisen tehokkuustason toissijainen verkko voi saavuttaa.

Pääsy TV-kaistalle voidaan järjestää käyttämällä ns. spektrihaistelua tai keskitettyä tietokantaa. Spektrinhaistelussa toissijainen käyttäjä tarvitse detektorin, mikä pystyy ilmaisemaan erittäin heikkoja signaaleja myös häipyvässä kanavassa. Tässä työssä on kuvailtu detektorin, eli ilmaisimen suorituskykyä ympäristössä, missä esiintyy niin hidasta kuin nopeaa häipymistä. Analyysi osoittaa, että yksittäinen ilmaisin pystyy poistamaan nopean häipymisen vaikutuksen. Valitettavasti vain yhtä antennia käytettäessä yksinkertainen ilmaisin ei pysty tarjoamaan spektrinhaistelussa riittävää suorituskykyä. Tässä työssä ehdotetaan moniantenni-detektointimenetelmää, joka on suunniteltu toimimaan häipyvässä radiokanavassa.

Käytettävissä olevan spektrin määrä on yksi TV-tutkimuksen kriittisistä kysymyksistä. Toissijaisen spektrin käyttöä voidaan hallinnoida paikallisella spektrihaistelulla. Tässä työssä on osoitettu, kuinka detektointimenetelmän epätäydellisyydet vähentävät spektrikäytön alueellista tehokkuutta.

Toissijaista spektrin käyttöä rajoittaa tarve kontrolloida siitä TV-vastaanottimille aiheutuvia häiriöitä. Kokonaishäiriö lasketaan kaikilta lähettimiltä vastaanotettujen häiriötehojen summana. Tässä työssä esitetään yksi menetelmä kokonaisinterferenssin arviointiin. Lähettimiä kuvataan niiden käyttämällä tehotiheydellä neliömetriä kohti. Interferenssi lasketaan integroimalla yli toissijaisen verkon palvelualueen.

Radiotaajuuksien hyödyllisyys matkaviestijärjestelmille riippuu saavutettavissa olevasta tietoliikennenopeudesta kyseisellä kaistalla. Työssä ehdotetaan algoritmia, joka mahdollistaa optimaalisen spektrikäytön tarkastelun soluverkossa, kun TV-vastaanottimien suojausehto on annettu. Ehdotettu algoritmi antaa toissijaisille lähettimille optimaalisen tehoallokoinnin käytettävissä oleville taajuuksille.

Avainsanat Toissijainen spektrin käyttö, solukkoverkko, spektrihaistelu, kapasiteetti, interferenssi.

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Preface

The research work for this thesis has been carried out at the Department of Communications and Networking of Aalto University during 2008 – 2011. The main body of this work was done in the scope of the EU QUASAR project.

First, I would like to thank Prof. Riku Jäntti under whose supervision this work has been completed. Further, I would like to thank the coworkers in the QUASAR project, Konstantinos Koufos and Jussi Kerttula for the efficient and fruitful cooperation.

During the years of working in the ComNet and its predecessor Laboratory of Communications I have had an opportunity to work in multiple research teams. It has been a unique chance to experience different research styles. For that chance, I would like to express my gratitude to Prof. Sven-Gustav Häggman, Prof. Olav Tirkkonen and late Prof. Seppo J. Halme.

ComNet has been a very pleasant place to work. For that, I have to thank the ComNet personnel who have helped with all possible practical work related matters. Particularly, without the help of Mr. Mika Nupponen, Mr. Viktor Nässi, Mr. Seppo Saastamoinen many practical problems would have taken much longer to be solved. I would also like to thank Mr. William Martin whose final proofreading greatly improved the language of the manuscript.

Over the years I have had a privilege to get to know numerous extraordinary people. I thank them all for providing the warm, enjoyable and creative work environment.

Helsinki, November 7, 2011,

Kalle Ruttik

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I K. Ruttik, K. Koufos, R. Jäntti. Spectrum reuse at the border of a primary user cell. *IEEE Transactions on Communications*, Volume 57, no. 12, pp. 3836 – 3846, December 2009.

II K. Ruttik, K. Koufos, R. Jäntti. Computation of aggregate interference from multiple secondary transmitters. *IEEE Communications Letters*, Volume 15, no. 4, pp. 237 – 439, April 2011.

III K. Ruttik, K. Koufos, R. Jäntti. Model for computing aggregate interference from secondary cellular network in presence of correlated shadow fading. *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2011*, pp. 433 – 437, September 2011.

IV K. Ruttik, K. Koufos, R. Jäntti. Modeling of the secondary system's generated interference and studying of its impact on the secondary system design. *Radioengineering*, Volume 19, no. 4, December 2010.

V K. Ruttik, K. Koufos, R. Jäntti. Detection of unknown signals in a fading environment. *IEEE Communications Letters*, Volume 13, no. 7, pp. 498 – 500, July 2009.

VI K. Ruttik, K. Koufos, R. Jäntti. Spectrum sensing with multiple antennas. In *IEEE Proceedings of International conference on Systems, Man and Cybernetics 2009, SMC 2009*, pp. 2281 – 2286, December 2009.

VII R. Jäntti, J. Kerttula, K. Koufos, K. Ruttik. Aggregate interference with FCC and ECC white space usage rules: case study in Finland. In *IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2011*, pp. 599 – 622, April 2010.

Author's Contribution

Publication I: "Spectrum reuse at the border of a primary user cell"

The author proposed the method for estimating the spectrum efficiency near the primary cell border. The author developed the model that describes the signal power distribution as observed at the cell border and used this model for improving the performance of the detection algorithm. In cooperation with Mr. Konstantinos Koufos, the author evaluated the performance of the proposed algorithm numerically. Prof. Riku Jäntti supervised the work.

Publication II: "Computation of aggregate interference from multiple secondary transmitters"

The author developed the model that describes the aggregate interference and proposed an efficient algorithm for computing the interference level. The author made the simulations of the system. The other authors participated in the validation of the results.

Publication III: "Model for computing aggregate interference from secondary cellular network in presence of correlated shadow fading"

The author proposed the integration-based model to describe interference from a cellular system. Together with Mr. Konstantinos Koufos, the author simulated and validated the suitability of the proposed model to approximate the brute force computation of the interference. In this publication, Mr. Konstantinos Koufos included in the interference model a correlation of the fading. Prof. Riku Jäntti supervised the work.

Publication IV: “Modeling of the secondary system’s generated interference and studying of its impact on the secondary system design”

The author was the main contributor in this publication. The author defined the secondary system power allocation as an optimization problem. He derived the required constraints and proposed a solution to the problem. The simulation code for the model analysis was created by the author. The other authors participated in the validation of the results.

Publication V: “Detection of unknown signals in a fading environment”

The author made the analytical derivation of the model. He proposed the analytical approach and derived the final results. The author simulated the detector performance in a fading environment. The other authors participated in the validation of the results.

Publication VI: “Spectrum sensing with multiple antennas”

The author proposed the detection method. He derived the detection algorithm and described the performance of the detector by an analytical model. The other authors participated in the validation of the results.

Publication VII: “Aggregate interference with FCC and ECC white space usage rules: case study in Finland”

The author devised the approach to describe the achievable cellular system data rate in TV white space. The approach also allowed the investigation of the impact of various spectrum allocation rules on the TV receivers. The author also participated in the development of the computational algorithm.

List of Abbreviations

ALOHA	ALOHA random access
BC	Broadcast channel
BEM	Block edge mask
CDMA	Code division multiple access
CRS	Cognitive radio system
CS	Carrier sense
DPC	Dirty paper coding
ECC	Electronic Communications Committee
EIRP	Equivalent isotropically radiated power
FCC	Federal Communications Commission
FDMA	Frequency division multiple access
FWS	Fixed wireless system
ITU	International Telecommunication Union
MAC	Medium access control
MBOA	Multiband OFDM alliance
MGF	Moment generating function
MI	Multiple access interference margin
OFDMA	Orthogonal frequency division multiple access
PFD	Power flux density
P-MP	Point to multi-point
PPP	Poisson point process
PSD	Power spectral density
PU	Primary user
QoS	Quality of service
ROC	Receiver operating characteristic
RRM	Radio resource management
SDR	Software defined radio
SEM	Spectrum emission mask

SINR	Signal-to-interference-plus-noise ratio
SIR	Signal-to-interference ratio
SM	Safety margin
SNR	Signal-to-noise ratio
SU	Secondary user
TDMA	Time division multiple access
TV	Television
TVWS	TV white space
UEF	Utilization efficiency
UTF	Utilization factor
UWB	Ultra wideband
Wi-Fi	Wi-Fi alliance

List of Symbols

a	index of location
A	network service area
A_f	transmitters' footprint
A_s	area outside of TV coverage and protection area
A_{TV}	TV coverage area
A_Δ	TV protection area
$A(\Omega)$	channel availability for scenario Ω
B	bandwidth
C	constant
$C(\cdot)$	channel capacity
C_{MM}	cell capacity with round max-min scheduling
C_p	primary link capacity
C_{RR}	cell capacity with round robin scheduling
C_s	secondary link capacity
$d(\alpha)$	power of the cyclostationary component α
$E\{\cdot\}$	expectation operation
f	frequency
f_s	sampling frequency
FM	fading marging
$F_{TW2}(\cdot)$	Tracy-Widom distribution of order 2
g	attenuation
$g_{j,i}$	attenuation from transmitter j to receiver i
h_n	channel gain
H_0	hypothesis 0
H_1	hypothesis 1
I_C	interference from a cellular system
I_j	interference power from transmitter j
$\hat{I}_{j,a}$	estimated interference power at location a generated by transmitter j

I_P	interference from a PPP
$K_{\frac{P_{line}}{P_{Rayl}}}$	non-centrality parameter
L	decision variable
M	useful effect obtained with the aid of the communication system
	number of antennas, and also used as an index
MI	interference margin
n	noise sample
N	number of collected samples
N_0	noise power spectral density
O_a	outage probability at the location a
$\hat{O}_a$	estimated outage probability at the location a
$p_A(\cdot)$	location probability density
$p_{fast,Rayl}(\cdot)$	power distribution of amplitude having Rayleigh distribution
$p_{fast,Rice}(\cdot)$	power distribution of amplitude having Rice distribution
$p_{fast,NakM}(\cdot)$	power distribution of amplitude having Nakagami M distribution
$p_{slow,G}(\cdot)$	power distribution of amplitude having gamma distribution
$p_{slow,\mathrm{lg}}(\cdot)$	power distribution of amplitude having log-normal distribution
$p(\cdot\|\cdot)$	conditional probability
P	power
P_d	power density
P_D	detection probability
P_f	false alarm probability
P_{line}	power of the line-of-sight signal component
P_m	probability of missing detection
P_n	noise power
$\hat{P}_{n,a}$	estimated noise power at location a
P_p	primary transmitter power
P_r	received signal power
$\hat{P}_{r,a}$	estimated received signal power at location a
P_s	secondary transmitter power
P_{Rayl}	power of the Rayleigh signal component
Pr_{H_0}	prior probability of hypothesis H_0
Pr_{H_1}	prior probability of hypothesis H_1
Pr_s	prior probability of the secondary user to be located in a secondary service area
Pr_{Δ_2}	prior probability that secondary user can transmit in a protection area
q	confidence factor
$Q(\cdot)$	Q function
$Q_N(\cdot)$	Marcum Q function

r	distance
r_{mm}, r_{nm}	elements of an autocorrelation matrix
R	data rate
$R(a)$	data rate at location a
R_p	data rate at the primary receiver
R_s	data rate at the secondary receiver
$\mathbf{R}_y$	autocorrelation matrix
s	transmitted signal
s_n, s_i, s_j	transmitted signal sample
S	space
SM	safety margin
$S_x^\omega(\cdot), S_y^\omega(\cdot)$	spectral correlation function
T	time
T_{coh}	coherence time
T_s	sampling interval
w_0, w_1, w_2, w_p, w_s	messages
x	random variable
y	received signal
y_i	signal received by receiver i
$\mathbf{y}_n$	vector of samples from multiple antenna
y_n	received signal sample n
$\mathbf{Y}$	matrix of received samples
z	random variable

α	fraction
α_I	intercell interference
α_{sf}	shape parameter of a gamma distribution
α_γ	shape parameter of a gamma distribution describing slow fast fading
β	path loss exponent
β_{sf}	scale parameter of a gamma distribution
β_γ	scale parameter of a gamma distribution describing slow fast fading
$\delta(\cdot)$	Dirac delta function
Δ	scaling factor
γ	SINR
$\bar{\gamma}$	average SINR
γ_a	SINR at location a
$\gamma_{D\|U}$	protection ration
γ_i	SINR at receiver i

γ_p	SINR at primary receiver
γ_t	SINR target
$\Gamma(\cdot,\cdot)$	incomplete gamma function
$\Gamma(\cdot)$	gamma function
η	decision threshold
Θ	fraction of the transmission power allocated for pilots
λ	eigenvalue
μ	mean path loss
μ_G	mean path loss of a secondary signal
μ_{NM}	mean of the maximal eigenvalue of the autocorrelation matrix
μ_{TV}	mean path loss of a TV signal
ν_j	transmission activity factor
σ_{NM}	standard deviation of maximal eigenvalue of the autocorrelation matrix
σ_{SU}	standard deviation of a secondary signal
σ_{TV}	standard deviation of TV signal
Ω	scenario
Ω_p	set of primary system technical parameters
Ω_s	set of secondary system transmitter parameters
Ω_Θ	set of the physical environment parameters

1. Introduction

1.1 Motivation for the thesis

Our dalliance with Internet generates so much traffic that it cannot be served solely by the radio spectrum allocated for data transmission. In the search for additional bandwidth, we examined closely the spectrum currently used by other services. Simple measurements gave an impression that large parts of the spectrum are actually underused [1]. Such measurements ignited the idea of secondary spectrum usage. A secondary user (SU) will use the spectrum left free by the current license owners, spectrum primary user (PUs).

A closer look reveals that the spectrum is actually relatively densely populated. The seemingly free spectrum is in guard space or guard bands reserved for protecting the systems from intersystem interference. Uncontrolled transmission in guard areas would therefore break the fragile interference balance in the current systems.

Broadcast systems are characterized by large guard areas and low spatial spectrum utilization. In such sparsely allocated systems, the spectrum utilization can be improved by allowing transmission in the guard areas between the systems. In order to permit such transmission, the following problem must be addressed: "How to design a spectrum reusing system that improves the spectrum utilization and at the same time retains the service quality of existing spectrum users?". Essentially, the coexistence of the current television (TV) systems and new spectrum reusing systems requires efficient interference control.

Interference minimization has been a topic of study already for over a hundred year. In the early stages of radio communications, it was recognized that simultaneously transmitted radio signals are interfering with each other. An easy way to reduce the level of interference is by keeping different transmitted signals apart. This can be done either by using orthogonal signaling or by taking advantage of the attenuation of the channel.

In practice, the separation methods of the signals are limited by the technology we have at our disposal. Early wireless communication systems did not have any complex signal processing abilities, the only practical option for separating different users being the use of linear filtering. Linear filtering is an easy way to remove the impact of signals transmitted in different frequencies. Such a simple separation possibility made it natural to start isolating the radio systems by allocating different frequency bands to them.

The long tradition of international frequency agreements started with the first International Radiotelegraph Convention in 1906 [2]. The first agreement allocated frequencies between 500 and 1000 kHz for maritime services and reserved the band 188 - 500 kHz for military communication. A broader allocation of frequencies took place in 1927 in the International Radiotelegraph Conference. In that conference, the frequencies from 10 kHz to 60 MHz were allocated. Today the regulation of the frequency usage is made by the International Telecommunication Union (ITU) established on 15^{th} November 1947. In about 100 years the frequencies spanning from tens of kHz till hundreds of GHz have been reserved [3].

Historically, systems providing different services were allocated to separate frequencies. Such separation was made because the services were provided by using different technical solutions. Development of communication methods and the availability of cheap computing power has lead to the convergence of technologies and services. Differences between services have become blurred, various technologies provide the same service, or alternatively one technology can be used to offer multiple services [4]. One manifestation of this convergence is the development of software defined radio [5]. A software defined radio (SDR) is able to change radio parameters by using software [6]. It needs only a simple radio frequency front-end which can easily be tuned to different spectrum areas. By using software defined radio, flexible spectrum usage is no more limited by transceiver implementation issues but rather with a need for spectrum usage control architectures and protocols.

A software defined radio could communicate at any available frequency. The possibilities brought by flexible radios have lured economists to propose new spectrum usage strategies [7] [8] [9]. By putting the spectrum on the market, it is easier to find somebody who could use it. Unfortunately most of the proposed strategies assume a replacement of current network infrastructure, a slow and expensive process. A short term, and cheaper, solution would be to leave the current network infrastructure intact and to realize better spectrum utilization by only allowing secondary spectrum usage. Secondary spectrum users would require a new network in any case.

The new secondary spectrum users have to guarantee the connection quality of current spectrum using services. How to guarantee that is currently an open question. Possible options are to arrange the secondary transmission as underlay, overlay, or interweave [10]. The choice of these arrangements has to be based on the spectrum utilization benefits they provide. The spectrum utilization, however, is not the only metrics needing to be considered. While designing the new system we also need to know what kind of capacity a secondary system can expect.

1.2 Scope and content of the thesis

While investigating the secondary systems we have to answer the following questions: For what purpose is the secondary spectrum used? How should the secondary access be arranged? How much capacity can the secondary system have? How well should the primary system be protected?

The utilization of spectrum depends on how well the spectrum using systems complement each other. This thesis is about the usage of TV frequencies for data transmission. The combination of TV and wireless data systems is very attractive since the TV transmitters are remotely located. The areas where the TV frequencies are unused can be populated with low power transmitters. The case where these low power transmitters belong to a cellular system is studied in this thesis.

The TV transmission uses a large chunk of spectrum under 1 GHz. In Finland, the frequencies allocated to TV transmissions are $470 - 862$ MHz. Due to the nature of TV system planning, the TV coverage areas are separated by large areas where the TV frequency is not used. The area outside the coverage area of TV transmitters that can be used for secondary transmission is called TV white space (TVWS). Chapter 2 defines this white space and describes what is meant by the term TV spectrum availability.

There is no shortage of proposals for organizing secondary spectrum usage [11]. Chapter 3 describes three main paradigms for arranging the secondary spectrum access.

The secondary spectrum access is expected to be controlled by using a spectrum sensing or a geolocation database assisted access. Chapter 4 gives an overview of the most common detection methods and describes the methods that Publication VI improves upon. Spectrum sensing is a simple decentralized spectrum access method. In a sensing method, the most critical issue is how well the sensing is able to detect signals with very low levels. Such low detection level is especially important in a fading environment. Subsection 4.2 describes the algorithms and models used for computing the detection performance in various fading environments. A model that allows studying the detection performance if both fast and slow fading are present is derived in Publication V.

A centralized database can have much more precise information about the radio environment than can be acquired by spectrum sensing. In the near future, database-based spectrum access is considered as the only practical spectrum access option. In Europe ECC and in the US FCC are considering slightly different proposals for database functionalities. These two approaches are compared in Chapter 5. In Publication IV we investigate the performance of a cellular system deployed according to the FCC requirements.

Chapter 6 provides an overview of the current state of the interference modeling research as well as giving background information for Publication II and Publication III. Secondary transmission generates interference to the TV receivers and to the other secondary receivers. Most of the current interference models, however only describe interference inside a single system. Only a few known models are tailored particularly for describing aggregate interference from a secondary system. The interference inside the single system limits the capacity of the system. An overview of the common wireless data network capacity models is given in Chapter 7. In Publication IV, we use a simple model for assessing the secondary network capacity in TVWS.

An important secondary spectrum usage study area is the estimation of the amount of available spectrum. Chapter 8 illustrates how much secondary spectrum could be made available in Finland and what data rate a secondary cellular system can provide by using this spectrum. Chapter 8 is mainly based on the results derived in Publication VII.

1.3 Contribution of the thesis

The TVWS usage research field is particularly vibrant with many new results appearing literally every day. During the research for this thesis, we constantly monitored the state-of-the-art and positioned our work to solve the issues needed for making the secondary spectrum access possible.

1. In Publication I, we proposed a method for estimating the spectrum utilization efficiency as a function of TV signal detector decision parameters. Near the TV cell border the spectrum can be used even in the presence of a TV signal. In Publication I we designed a signal model that can be used for describing the TV signal at the TV coverage area border. The proposed model is used for improving the detector performance and as a result we can achieve better spectrum utilization.

2. A secondary spectrum allocation is limited by the aggregate interference from all the secondary transmitters. In Publication II, we propose a method for a quick estimation of the aggregate interference from a large secondary network. Instead of summing up the interfering powers from individual transmitters, the method integrates over the average power density in the secondary network. The method also incorporates the impact of fading in the aggregate interference and expresses the moments of the aggregate interference. The suitability of the integration model for describing the aggregate interference is described in Publication III. In Publication III we also extend the aggregate interference model to incorporate correlated fading.

3. In Publication IV, we propose a method for optimizing the power allocation among the secondary systems using cochannel and adjacent channel. We describe the power allocation as an optimization problem. The proposed method allows us to investigate the power allocation trade-offs in secondary systems.

4. In Publication V, we describe a power detector performance in a shadow and fast fading environment. The proposed model is parametrized by the fading characteristics. The model allows us to study the performance of detectors in various fading environments.

5. In Publication VI, we propose a multiple antenna-based signal detection algorithm. The method is applicable even if the signals from the antennas have different front-end amplifications or the antennas measure independent fading. The method groups the subsets of the measured samples and averages out the implementation or environment related differences in different antennas.

6. In Publication VII, we compute how much TVWS spectrum is available in Finland. In this publication we compare the achievable capacity while following spectrum usage rules by FCC and ECC. Particularly, we investigate how those rules protect the incumbent TV receivers.

2. Spectrum allocation

Radio spectrum is a range of electromagnetic frequencies that are used for wireless communication. The spectrum is treated as a resource that is distributed among different communication systems.

Traditionally, the officials have taken a simple approach and licensed the spectrum exclusively to one system only. The spectrum license allows the system to use the given bandwidth in given space and time. The officials protect the license holders by banning the other nearby transmitters from using the same or neighboring frequencies.

Since there is very high demand for the spectrum this scarce resource has to be used as efficiently as possible. In its recommendation ITU-R 1046 [12], the ITU recommends to measure the spectrum usage by a spectrum utilization factor (UTF)

$$U = B \cdot S \cdot T \tag{2.1}$$

where B is used frequency bandwidth, S is utilized geometric space, T is utilized time. The T is the time the spectrum is denied from other users. The recommendation ITU-R 1046 clarifies that *the geometric space of interest may also be a volume, a line (e.g. the geostationary orbit), or an angular sector around a point* [12].

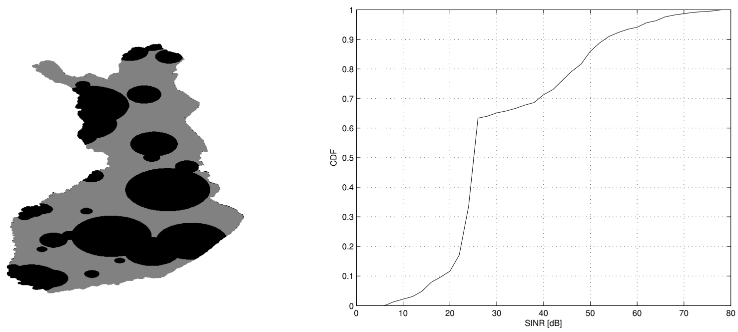
How well a particular system utilizes the spectrum allocated to it can be expressed as spectrum utilization efficiency (SUE) [12]

$$SUE = \frac{M}{U} \tag{2.2}$$

where M is defined as the useful effect obtained with the aid of the communication system in question. For instance, M can be the number of calls the system can support (in Erlangs) or the data rate the system can transmit.

2.1 TV white space

Traditionally, a TV cell is covered by a signal from a single high power transmitter. Such a transmitter can serve a large cell but it also generates interference into a very large area. In order to avoid interference the cochannel TV cells are located far apart. An example of the use of TV channel 30 in Finland is illustrated in Fig. 2.1. Between the cochannel TV cells there are substantial areas where the frequency is not used. We could increase the SUE by allowing some low power transmitters in this unused space. Such spectrum using system would contain secondary spectrum user (SUs) who could use the spectrum as long as the receivers in TV coverage area are not disturbed.



(a) Coverage **(b)** SINR

Figure 2.1. TV channel 30 use in Finland a) coverage area (black) b) SINR distribution at the cell borders.

The TV service coverage is designed to sustain some interference from cochannel transmitters. The quality of a received signal is expressed by its signal-to-interference-plus-noise ratio (SINR) [13]

$$\gamma = \frac{P_r}{\sum_j I_j + P_n} \tag{2.3}$$

where P_r is the received signal power, I_j is the interfering power from transmitter j and P_n is the noise power. The interference is computed as the aggregate interference from all the active transmitters. It contains power received from other broadcasting stations and from the secondary transmitters. The acceptable TV reception is possible as long as the received SINR exceeds some target value, $\gamma \geq \gamma_t$.

In this thesis, we investigate the channel availability in the TV white space:

Definition 1. *TV white space (TVWS) is defined as the area outside of TV coverage areas where the TV frequencies can be used such that the TV reception quality is better than or equal to the minimum required reception quality level.*

The TV reception quality is defined by the target SINR level γ_t and the target outage probability O_t. In a fading environment, the SINR is described by its distribution. The situation where the instantaneous SINR is below the target SINR is called signal outage. The primary system allows certain outage $O_a \leq O_t$, where O_a is the outage probability at the location a. The chance of the outage can be computed from the SINR distribution

$$O_a = \Pr\left(\gamma_a \leq \gamma_t\right) \quad (2.4)$$

where γ_a is SINR at the location a.

The received TV signal level varies in time and in space. The spatial changes are the result of user movements, fast fading, and large objects, shadow fading. The temporal changes are due to the changes in atmosphere since the signal propagation depends on weather conditions. With those two random processes, the TV reception quality is expressed as a function $F(X, Y)$ that describes the field strength that is exceeded in $X\%$ of locations at $Y\%$ of time [14].

The spatial and temporal variations are due to the different independent factors. The variations contribute to the channel model as two random variables that are summed together [15]. This sum can be replaced by a new random variable in what case the total fading is described by a single distribution and the outage is expresses as in Eq. (2.4).

The system transmitting in TVWS is called a secondary spectrum user. For identifying whether we have a TVWS or not, we locate the secondary transmitters in the candidate area. We have TVWS if we find these secondary transmission powers that the target outage probability for receivers located in the TV coverage area is not violated.

In practice we test the reception quality in the TV coverage area by selecting test points and evaluating the outage probability at these points. The secondary transmission increases the interference level and by doing that it reduces the SINR value. The TV reception can sustain additional interference only if at any of the test points the outage constraint is not violated.

Whether we have a possibility for secondary transmission or not depends on the current SINR level at the TV coverage area border. A current SINR levels on TV cell borders is illustrated in Fig. 2.1b which describes the SINR on the test points in TV cells using channel 30 in Finland.

In Finland, the TV transmission in channel 30 uses 64 QAM with coding rate $2/3$ and in a Rician fading environment it requires SINR $\gamma_t = 17.3$ dB [16]. As we can see, at some test positions the SINR is well above this target. Near to these locations there is a potential for secondary transmissions.

The current recommendations consider three possible secondary spectrum access methods [17] [18]: the access to the spectrum is controlled by a database, the access decision is based on the measurements in the given spectrum area, or the pilot signals are introduced that will be detected by secondary users. Compared with its complexity the pilot-based systems do not provide sufficient primary system protection. Therefore, only sensing and database-based access are considered as viable options for arranging the secondary access [19].

2.2 Spectrum allocation in network planning

The concept of secondary spectrum usage is supported by the experience gained from planning of cellular wireless systems. In first generation wireless cellular systems, frequency allocation was done during the network planning process [20]. At that time, the technology for dynamic frequency change was not available and the transmitters had to be equipped with frequency specific hardware. Nowadays the circuit design allows us to design transceivers with relatively simple and quick frequency tuning circuits. Therefore, the emerging wireless systems contain real time frequency allocation that is done as a part of the radio resource management (RRM) operation [21]. Cellular networks have been good testbeds for real time spectrum usage optimization. The secondary frequency allocation process can learn from the experiences gained in cellular systems.

The common cellular network planning steps are illustrated in Fig. 2.2 [22] [23]. A process with similar steps can be identified also for a TV network [24].

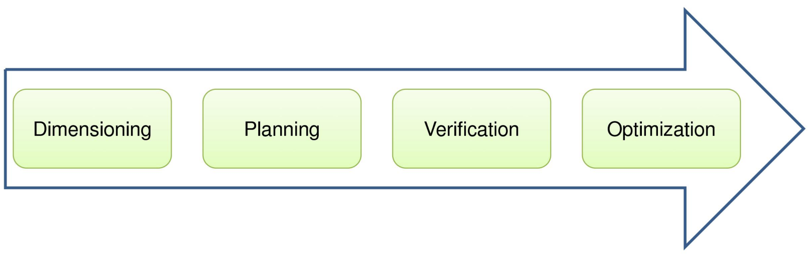


Figure 2.2. Network planning process steps.

The dimensioning stage is used for predicting the network cost. At that stage, the available frequency spectrum is considered and the system designed to serve the subscriber density with a given traffic and service mix. That design produces the initial estimate of the amount of hardware needed to satisfy the QoS requirements.

The dimensioning stage produces only the site density information. In the planning stage, we make the initial site allocation and use network planning tools that contain propagation condition information. During planning the actual site coverages, capacities and service qualities are all computed.

The initial network plan is the input to the site survey and acquisition. The site acquisition is accompanied with the frequency planning among the sites and with the interference analysis.

Before launching the network, the planned network quality is verified. At this verification stage, prelaunch optimization and parameters tuning is also done. The initial network tuning is based on the drive tests.

An operating network undergoes continuous optimization. The basis for which optimization is the constant monitoring of network traffic and quality parameters which gives the feedback that is used for the fine tuning of the network operational parameters.

2.2.1 Secondary network access as a network planning problem

Secondary spectrum usage is closely related to network planning. The network planning methods can be used while performing the dynamic spectrum allocation to the secondary system.

Before the spectrum will be opened up for secondary usage it is necessary to first assess whether the white space is economically attractive or not. Such an assessment contains an estimation of the amount of available spectrum and the cost of providing services in that spectrum area. This estimation is supported by planning tools, that can help us to predict the cost of the secondary networks' deployment and the possible available data rates.

The dynamic spectrum control benefits from the experiences acquired while operating RRM in cellular networks. The RRM provides the practical examples of frequency allocations. Based on these examples, we know what kind of computing power and signaling speed a realistic frequency allocation requires. We can treat the cellular system as a testbed that illustrates the technical difficulties a secondary spectrum allocation architecture has to face.

To be applicable to the secondary system design the conventional network planning methods have to be adapted to the new dynamic environment. For instance, the planning of a classical cellular network is not tailored to cope with an uncertain amount of available bandwidth or with the limitations on intersystem interference.

Usually, radio systems planners know the amount of available spectrum. The spectrum available to a secondary system, however, is not known beforehand. The amount of the spectrum depends on the activity of primary spectrum users. Such uncertainty makes the planning of an expensive network infrastructure very challenging. The problem can be avoided, fortunately, by using a special exclusive secondary license or by deploying infrastructure free, ad hoc type, networks.

In Publication IV, we make the initial estimate of the capacity of a secondary cellular network, the approach used being similar to the cellular system dimensioning stage. We extended the conventional dimensioning with constraints on intersystem interference and the limitation on the available transmission power. The proposed approach can be incorporated into industrial level network planning tools.

The uncertainty related to the spectrum availability favors solutions with low infrastructure cost; for instance, suitable networks would use femtocells or Wi-Fi. The design of such networks is relatively straight forward, requiring only a minimal amount of planning. However, we still need to estimate the business value of those networks. The business value estimation process still needs supporting data from a network planning tool, the development of which is not within the scope of this thesis.

The secondary spectrum allocation process is a similar operation to radio resource management (RRM) done inside the system. Inside the network, the RRM manager controls the transmitters' access to the spectrum. A similar control process can be observed in the secondary spectrum allocation process. Achieving a balance between these two spectrum controls is an important study issue that provides directions for future research in this field of study.

3. Spectrum sharing paradigms

It is common to model a communication link as a scaled transmitted signal in additive white Gaussian noise (AWGN) [13]

$$y = \sqrt{Pg} \cdot s + n \tag{3.1}$$

where $P \in \mathbb{R}^+$ is the transmitted power, $g \in \mathbb{R}^+$ describes the attenuation on the channel, $s \in \mathbb{C}$ is the complex baseband equivalent of the transmitted signal, and $n \in \mathbb{C}$ is the complex additive circular Gaussian noise. The additive noise n has a mean $E\{n\} = 0$ and variance $E\{|n|^2\} = \frac{N_0}{2}$, where N_0 is the one-sided power spectral density of noise.

It is common to express the attenuation g as the combination of the path loss and the impact of fading

$$g = 10^{\mu/10} x \tag{3.2}$$

where μ is the mean path loss in dB and x is a random variable describing the fading process. Slow fading is most commonly described by deriving x from a log-normal or a gamma distribution and fast fading by deriving x from an exponential or a gamma distribution.

The mean path loss is conventionally described by a simple power law model

$$\mu = 10 \log C r^{\beta} = 10 \log C + 10 \beta \log r \tag{3.3}$$

where r is the distance from the transmitter to the receiver, β is the path loss exponent, and C is a correction term. The correction term C reflects the impact due to the antenna height and due to the terrain on the transmission path. The power law model is a basis for a commonly used Okumura-Hata channel model [25].

An alternative to the power law model is a table-based path loss model which is described in ITU-R recommendation P.1546 [14]. This recommendation contains tables of measured path loss values for different frequencies, terrain models and antenna heights. The path loss at non tabulated distance is computed by interpolating from the given values.

The maximum amount of information that we can convey from the transmitter to the receiver is called the channel capacity. In an AWGN channel, the channel capacity can be achieved with a circular-Gaussian distributed signal x [26]

$$C(\gamma) = B \log_2 (1 + \gamma) \tag{3.4}$$

where $\gamma = \frac{Pg}{BN_0} = \frac{Pg}{P_n}$ is the signal-to-noise ratio (SNR) and B is the signal bandwidth. Eq. (3.4) describes the maximum amount of bits per second (bit/s) one can transmit in an AWGN channel for the given SNR. Sometimes the links are described also by their spectral efficiency (bit/s/Hz).

A general wireless network contains multiple transmitters and receivers. At any moment, the network can have multiple active links. The received signal on an individual wireless link can be modeled by augmenting Eq. (3.1) with signals from other active transmitters. The received signal at the receiver i is

$$y_i = \sqrt{P_i g_{i,i}} \cdot s_i + \sum_j \sqrt{P_j g_{j,i}} \cdot s_j + n_i \tag{3.5}$$

where index j stands for other transmitters and $g_{j,i}$ describes the channel between the transmitter j and the receiver i.

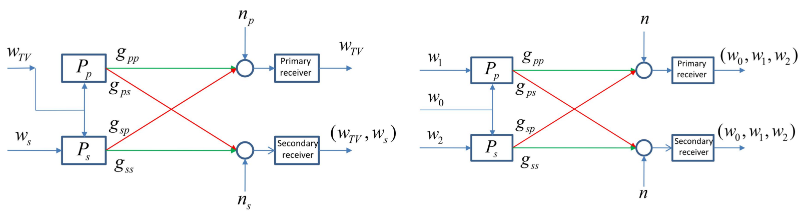
In a wireless channel, the transmissions in concurrent links disturb each other's reception. An increase in power at one link also increases interference experienced at other links. Given the power of each transmitter and the path loss in each link, we can compute SINR of each user. The vector of the SINR values can be converted to a vector of data rates that each link can support, each user can achieve. By changing the transmission powers, we can change the vector of achievable data rates. The capacity of the whole system is described as the closure of the achievable data rate combinations over all the links [27] [28].

The Shannon capacity (3.4) describes only a single link. What would be a corresponding equation for a spatially distributed system is unknown. The capacity can be computed only for a particular system configuration. For instance, for a multiple access channel or for a broadcasting channel [29].

Our application, TVWS, is a special type of a wireless network. The secondary transmission has to be arranged such that the TV receivers can operate without any change. Arranging the secondary transmission can be investigated by using a simple two transmitter two receiver (2×2) network. In Fig. 3.1a one link would correspond to the TV transmission and the other to the secondary transmission. The received signals in a 2×2 system are expressed as

$$\begin{aligned} y_p &= \sqrt{P_p g_{pp}} s_p + \sqrt{P_s g_{sp}} s_s + n_p \\ y_s &= \sqrt{P_s g_{ss}} s_s + \sqrt{P_p g_{ps}} s_p + n_s \end{aligned} \tag{3.6}$$

where index p and s describe the primary and the secondary transmitters, P_p, P_s are the power of the transmitters, g_{pp}, g_{sp}, g_{ps}, g_{ss} are the corresponding attenuations and n_p n_s describe noise in the secondary and primary receivers.



(a) 2 × 2 MAC channel **(b)** 2 × 2 general interference channel

Figure 3.1. Two transmitter two receiver system as a system containing primary and secondary transmitters and receivers.

The capacity of a 2 × 2 system is defined as the set of achievable data rates at both receivers. The system can also be interpreted as two multiple access channels, one for each receiver. The capacity of such channel is derived in [30] and [27].

If a 2×2 system is interpreted as two MAC channels, both the transmitted messages are independent and the transmitters do not share any common information. The system can be described also as two transmitters having common and independent parts of the messages (Fig. 3.1b) [28]. The set up used in [28] was modified for the primary and secondary transmission environment in [31].

The model in Fig. 3.1b provides multiple alternatives for arranging the secondary access. The interference to the primary system can be avoided by using one of the following approaches [10]:

1. Secondary system transmission does not influence the primary connections at all. That situation can occur if, for instance, the primary and the secondary transmissions are orthogonal to each other.
2. There is positive margin between the current primary system connection quality and the target quality. Introduction of secondary transmissions will reduce the current primary connection quality but will not violate the primary target quality value.
3. The secondary system cooperates with the primary system and improves the primary connection quality. The secondary signal can then bring this improved quality down to the minimum required connection quality, the primary connection's minimum target value.

These approaches lead to different spectrum access schemes: *underlay*, *overlay*, *interweave*. The transmission schemes differ by the amount of information and the type of information the secondary system uses. In general, the implementation of the methods assumes that the secondary system is able to collect information about the PU transmission. Such educated transmission is also called the cognitive channel [31] [32] [11]. A device that takes advantage of the collected knowledge is called cognitive radio. The cognitive radio is interpreted as the equipment that not only recognizes the channel state but also adapts its transmission to this state [33]. ITU [6] defines the cognitive radio system (CRS) as:

Definition 2. *A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.*

3.1 Underlay spectrum sharing

The underlay spectrum usage is the simplest secondary spectrum sharing approach. To protect the primary receivers, the secondary transmitter does not need to know the primary signal or primary transmission patterns. The coexistence of different systems is based on appropriate selection of secondary transmission power.

The underlay approach is closely related to the interference temperature concept [34] [35]. The interference temperature was defined by FCC as the interfering signal temperature at the primary receiver. In order to comply with the interference temperature requirement, the secondary system has to know the attenuation in the channel and to limit its maximum transmission power. Current FCC TVWS usage proposals are not based on the interference temperature [18]. However, the specification proposed in Europe by ECC has some similarities to this concept [17].

An underlay secondary transmitter selects its transmission power such that the SINR target, γ_t, at any primary receiver is not violated. The SINR condition can be expressed for a two transmitter case as

$$\gamma_p = \frac{P_p g_{pp}}{P_s g_{sp} + P_n} \geq \gamma_t. \tag{3.7}$$

There are two ways for limiting the SINR. First, if the secondary transmitter knowns the attenuations, the primary system received power $P_p g_{pp}$ and attenuation g_{sp}, it can select its power P_s such that Eq. (3.7) is satisfied. Alternatively, if the received powers and attenuations are not known the interference can be limited by using signals that have very low power spectral density, like ,for example, ultra wideband signals.

A wideband transmission simplifies the coexistence of the primary and secondary systems. The systems do not need to know anything about each other. They are decoupled by limiting the amount of power the secondary system can emit in the bandwidth allocated to the primary system.

A wideband signal can be created by using signaling with a short pulse or a sequence of short pulses. The latter one is known as a spreading operation [36]. Since the spread signal has the same power as the initial signal, the power spectral density is reduced. The power density of the spread signal in the information rate bandwidth, R, is decreased by the spreading factor $\frac{B}{R}$, where B is the spread signal bandwidth. By selecting the spreading factor and the transmission power, we can make the spread signal nearly invisible to the narrowband spectrum users. Conversely, the spread signal is relatively immune to the narrowband interference [37].

Wideband signaling is proposed as a signaling scheme for various specifications. The proposed implementations contain the usage of short pulses [38] or the creation of wideband spectrum by using OFDM-based modulation [39].

In theory, wideband signaling offers a possibility to transmit with a very high data rate [40]. Unfortunately, in a multipath environment, the wideband transmission is plagued with implementation-related issues. For instance, it is extremely challenging to estimate the channel and to synchronize the signals. Also, the implementations have been very power consuming and unsuitable for practical applications.

If the attenuations on the channels are known, the transmitter could directly limit its transmission power to meet the SINR requirement (3.7). Unfortunately, in the TV coverage area, we could have thousands of receivers, with it being nearly impossible to know the exact received signal level at each of them. The way around this problem has been to guarantee the target SINR level at the TV coverage area border. In this simplified situation, the secondary transmitter does not need to know attenuations at particular receivers but just the attenuation at the border of the coverage area (see Fig. 3.2).

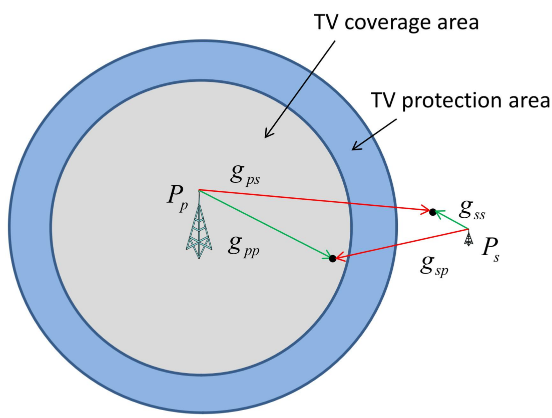


Figure 3.2. TVWS access with protection area.

The distance to the cell border can be identified by using simple signal level detection [34]. The attenuation is related to the distance and therefore we can map the measured signal level directly to the distance from the TV transmitter. Unfortunately, in a fading channel the signal level is not a good approximation of the distance. For guaranteeing the primary signal protection in a fading channel the detection level has to be set very low [18]. Currently, the detection-based admission control is still under study and no good solution is known for it.

3.2 Interweave spectrum sharing

The need for data transmission usually arises in bursts. A sequence of transmission bursts can be described by an ON-OFF model [41] [32]. The underlay spectrum sharing approach tacitly assumes that, compared to the detection and secondary transmission times, the durations of being in the ON and OFF states are very long. If that is not the case, we can determine not only the signal level but also the ON-OFF pattern of the primary activity. Such activity information is used in interweave spectrum sharing.

The idea of interweave spectrum usage was born together with the of the cognitive radio system concept [42]. The spectrum measurements indicated that licensed transmitters use the spectrum only some of the time [1]. A cognitive radio was envisioned as a piece of equipment that is able to interweave with the primary transmission.

Since the primary and secondary transmissions are separated in time they are orthogonal. The interweave spectrum usage resembles the classical time sharing system. In the limiting case the secondary system is capable of filling all the free time frequency space. The capacity of such a ideal time-sharing system is expressed as

$$\begin{aligned} R_P &\leq \alpha C\left(\frac{P_p g_{pp}}{P_n}\right) \\ R_S &\leq (1-\alpha)\, C\left(\frac{P_s g_{ss}}{P_n}\right) \end{aligned} \tag{3.8}$$

where R_P and R_S are the data rates achievable by the primary and secondary systems and α is the fraction of time the primary system uses the spectrum.

The full spectrum utilization depends on how well the secondary transmitter can detect and fill the time gaps left by the primary systems. How easy it is to detect a gap depends on the primary system ON-OFF pattern, the primary signal level at the detector and the deployed detection method. The capacity in Eq. (3.8) is achieved only if the secondary system is able to detect and to fill all the spectrum gaps.

The spectrum gaps could last only a few milliseconds or be as long as a few hours. In an extreme case, the secondary transmitter attempts to interweave into time gaps occurring between transmitted packets. In order to identify the packet intervals the secondary system needs to measure the channel with very high frequency. The collected samples could fall into a border between an ON-OFF transition and even with a high rate of measurements it is not guaranteed that the change of state will be detected. The need for measurements can be reduced if the SU constructs a model of the state dwelling times [43] [44].

The interweave operation resembles the functionality of a scheduler. The scheduler with knowledge of global transmission needs can be interpreted as a genie-based interweave system. The performance of a genie-based system can be achieved by an ideal spectrum detector. An alternative approach would be to avoid the detection and to communicate the locations of the spectrum holes to the secondary system in some other way. The cooperation between the primary and secondary system can also create spectrum holes. The primary system can free some time slots for secondary transmission (as can be done in the DVB-T2 system [45]).

Like the overlay, also the interweave could be used for arranging spectrum access outside of the TV coverage area. Outside of the TV coverage area the signals are interweaved not only in time but also in space.

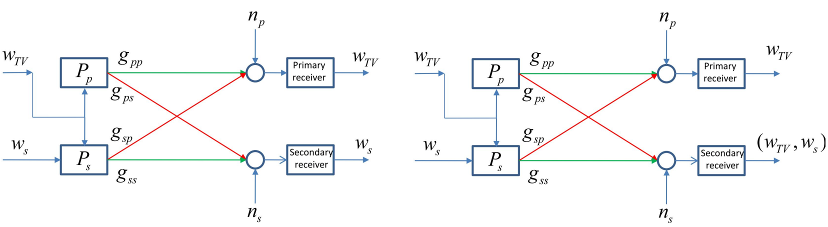
3.3 Overlay spectrum sharing

In interweave spectrum access, the secondary system utilizes only the knowledge about the primary system transmission pattern. For the overlay spectrum access, the secondary system needs to know not only the transmission pattern but the whole primary signal. The secondary system combines its own data with the primary message and transmits this combined message synchronously with primary transmission. The new message is constructed such that both the primary and secondary system's signal quality will be satisfied.

The overlay spectrum sharing requires that the secondary system knows the primary signal. Such knowledge can be expressed as an information exchange between transmitters or as a common message known to both transmitters (Fig. 3.1b). The capacity of a 2×2 system having a common message is analyzed in [28]. The analysis of the channel with information exchange is adopted for the cognitive radio context by [31] and [46].

The model in [28] splits the transmitted signals into three groups as presented in Fig. 3.1b. Data to be transmitted to both receivers, w_0, and the receiver's specific messages w_1, w_2. In the general case, both receivers decode all of the messages. The sub case would be if a receiver decodes only a part of the messages [46]. For example, the primary receiver decodes messages w_0 and w_1 and the secondary receiver messages w_0 and w_2.

In [46], the interference channel model is adopted for cognitive radio in the TVWS context. In TVWS overlay access, we can set $w_1 = 0$ and the common signal is the TV signal $w_0 = w_{TV}$ (Fig. 3.3a). The secondary system knows both messages. It combines them into the transmitted message such that the secondary receivers can decode w_s. The common signal has to be decoded only by the primary receiver. The TV signal rate cannot be changed and the capacity of the 2×2 overlay system is described as the maximum data rate the secondary system can transmit.



(a) Simple decoding and decoding with DPC **(b)** Decoding with multiuser detection

Figure 3.3. Overlay information channel model for the TVWS usage.

The secondary overlay transmitter allocates a fraction, αP_s, of its transmission power for retransmitting the TV signal and a fraction, $(1-\alpha)P_s$, for transmitting its own signal. The retransmitted TV signal boosts the signal level at the TV receivers and the SINR is increased. The secondary signal is perceived by the TV signals as noise and the SINR is decreased. The fraction, α, is selected such that the SINR target, γ_t, at the TV receivers will not be violated.

The overlay system is often studied by assuming that the channel gains are known [47] [46]. In known channels, the transmitted signals can be precoded such, that at the receiver the main TV signal and retransmitted signal sum in phase. In the TVWS set up, the large number of receivers makes it impossible to be aware of all the channels. In unknown Rayleigh fading channels the signals are combined not in phase but as their powers. The data rate in such random channel can be limited as [48]

$$C_p = \log_2 \left(1 + \frac{P_p g_{pp} + \alpha P_s g_{sp}}{P_n + (1-\alpha) P_s g_{sp}} \right). \tag{3.9}$$

In practice we can assume that the primary system data rate is fixed, $R_p \leq C_p$. In the system design, we select α such that it maximizes the secondary system data rate given the constraints of the TV system data rate. If no interference compensation method is used, the secondary receiver treats the interference as noise and the achievable capacity in the secondary link is

$$C_s = \log_2 \left(1 + \frac{(1-\alpha) P_s g_{ss}}{P_n + P_p g_{ps} + \alpha P_s g_{ss}} \right) \tag{3.10}$$

The interference can be removed by using complex signal processing methods. Such signal processing methods are encoding on the transmitter side, by using dirty paper coding (DPC) [49], or using multiuser detection on the receiver side [50]. After interference compensation, the capacity of the secondary link is as if the interference would not be present at all. Both of the interference compensation methods allow us to construct systems that have the same achievable secondary link capacity. In a Gaussian noise environment, this capacity is the same as the single link Shannon capacity.

The DPC and multiuser detection provide guidelines how to construct the system that achieves the promised capacity limits. The promised capacity is achievable only in the ideal system that has exact channel knowledge. In a DPC case, the channel has to be known at the transmitter while in multiuser case detection is at the receiver. Unfortunately, in the presence of channel estimation errors, the promised capacity cannot be reached.

Overlay with dirty paper coding

DPC is an effective way to simplify the reception by using the processing power at the transmitter. The transmitter uses a code that contains the knowledge about the interference. The channel combines the actual interference and the encoded messages. The code is selected such that the interference becomes invisible to the receiver. By using the DPC the achievable capacity in the link is the same as if the interference would not be present at all [49].

DPC encoding presumes that the transmitter knows the interfering signal and the channel gains g_{ps}, g_{ss}. If channel gains are not known, the method cannot be applied and the capacity is characterized by (3.10). Given the channel knowledge, the secondary system capacity is

$$C_s = \log_2\left(1 + \frac{(1-\alpha)\,P_s g_{ss}}{P_n}\right). \tag{3.11}$$

Overlay with iterative decoding

The DPC relies on the transmitter-side interference compensation. Alternatively, the multiuser detection relies on the receiver-side compensation. The decoder first decodes the primary signal and then the secondary signal. The multiuser decoding can reach the channel capacity only if both messages are decoded error free (Fig. 3.3b). For successful decoding the achievable data rates have to satisfy the following equations

$$C_{p,s} \leq \log_2\left(1+\frac{P_P g_{pp}+\alpha P_s g_{sp}}{P_n+(1-\alpha)\,P_s g_{ss}}\right) \tag{3.12}$$

$$C_s \leq \log_2\left(1+\frac{(1-\alpha)\,P_s g_{ss}}{P_n}\right) \tag{3.13}$$

$$C_{p,s}+C_s \leq \log_2\left(1+\frac{P_p g_{ps}+P_s g_{ss}}{P_n}\right) \tag{3.14}$$

where $C_{p,s}$ is the maximum data rate at which the primary signal can be error free when decoded at the secondary receiver. The capacity region bounded by (3.14), (3.13) and (3.12) is a subset of capacity region of the two user Gaussian multiple access channel. The equations here consider that the primary system data rate is fixed and the iterative decoder first decodes the primary user signal. In this case, (3.14) follows directly as a sum of (3.13) and (3.12).

The secondary receiver first decodes the primary signal. It is able to do it if the TV data rate is less or equal to the constraint (3.12). Together Eq. (3.9) and (3.12) create the set of constraints the TV data rate has to satisfy. Both of the constraints depend on the fraction α. Since the TV data rate is fixed we have to set the α such that both of the capacities C_p, $C_{p,s}$ are greater than the TV data rate

$$R_{TV} \leq \min_{\alpha}\left\{C_p(\alpha), C_{p,s}(\alpha)\right\}. \tag{3.15}$$

The capacities depend on the attenuations in the channels. If the channels are known, we can select α appropriately, on the other hand, if the channels are not known, the data rates are difficult to guarantee.

In a special case, when the TV transmitter is switched off, the TV receiver reception quality is guaranteed only by the secondary retransmitted signal. In this case, the fraction of power allocated to the primary signal is such that [48]

$$SINR_{TV} \leq \frac{\alpha}{1-\alpha}. \tag{3.16}$$

The overlay approach allows us to use secondary transmission also inside the TV coverage area, TV *black space* [31] [48]. Since most of the users are currently located inside the TV coverage area, such TV black space usage is very attractive from the business point of view.

4. Detection-based spectrum access

Before the secondary system can transmit it has to identify whether the primary system is using the spectrum or not. Such identification can be done by detecting the presence or absence of the primary system signal. This spectrum access method is known as the detection-based spectrum access or spectrum sensing-based access.

The simplest detection-based method assumes that the detector does not have any information about the locations of TV transmitters' and their transmission powers. All the parameters needed for protecting the TV receivers have to be estimated from the measurements. In spectrum sensing-based medium access, the user replaces all the required estimations with TV signal level detection. If the signal level is detected to be low enough, the spectrum is assumed to be free and can be used for transmission.

Spectrum sensing can be used to enable the underlay or interweave spectrum access. In interweave settings, the secondary user has to identify spatially or temporarily unused spectrum areas.

In TVWS, a secondary user should identify whether at the measured location the spectrum is spatially unused. The TV transmitter stays in the ON or OFF state for a relatively long time. For example, in Finland most of the TV transmitters transmit continuously and there is no OFF state. We can assume that mostly the secondary user has to determine whether it is placed inside or outside of a TV coverage area and therefore decides only whether the spectrum is spatially unused or not.

The continuous transmission assumption does not hold in the case of wireless microphones. The wireless microphones are relative low power transmitters that occupy certain TV bands. In these bands, the secondary spectrum user has to identify the ON-OFF state of the microphone. In order to avoid the disturbance, the secondary user has to make periodic measurements as was described earlier in Section 3.2. This thesis, however, considers only the methods for identifying primary signal level. The issues related to periodic measurements are well beyond the scope of this thesis.

The secondary transmitter has to control the interference it generates to the TV receivers. Such control requires the knowledge of the radio channel from the location of the secondary transmitter to the TV coverage area border. The detection-based spectrum access avoids the estimation of the channel. The method just attempts to guarantee that the transmitter is far enough from the TV coverage area. To guarantee that, the method uses the signal level as proxy for the distance. It is possible to do that since the attenuation is the function of the distance and therefore also the signal level reflects the distance to the transmitter. If the measured signal level falls below the detection threshold, we can assume that the measurement is taken at certain distance from the transmitter. With the appropriately selected detection threshold, it can be assumed that the secondary user will transmit far enough from the TV coverage area border.

Due to its simplicity, the detection-based spectrum access is a very attractive access method for independent ad hoc type networks. Each transmitter could measure the spectrum and make the access decision independently. Morevover, such a simple access rule does not require any complex infrastructure.

Detection-based spectrum access also has some drawbacks. In a fading environment, the signal level is only loosely related to the distance. In order not to miss the signal in deep fades, the detector should be able to identify very low signal levels. Outside of the TV coverage area the required signal level could be well under the noise level. The current agreement is that a secondary equipment should be able to detect a TV signal as low as -114 dBm [18]. Such a low detection level means that in most cases the spectrum can be used only at a significant distance from a TV cell border.

We can avoid the impact of fading by averaging the measurements made by multiple users [51]. Such cooperative signal level detection allows us to reduce fading margin and the spectrum can be used nearer to the TV coverage borders. The cooperative sensors have to meet the regulatory requirements. It is, however, difficult to specify and control the performance of a distributed sensor network. Therefore, currently the officials cannot make the type approvals of systems using distributed measurements.

4.1 Signal detection

A detector measures the spectrum and based on the measurements has to separate between two conditions: the primary signal is present or the signal is absent. The detector does not know which one of these two cases is present but we can construct hypotheses about them [52]; The hypothesis H_0 corresponds to the situation when we measure only noise, and alternatively the hypothesis H_1 assumes that the measured samples contain a signal and noise.

Which hypothesis is present is decided by comparing a statistics L with a threshold η. The statistics L is computed from the measured samples

$$L = \lg\left(p(y_n|H_0)\mathrm{Pr}_{H_0}\right) - \lg\left(p(y_n|H_1)\mathrm{Pr}_{H_1}\right) \underset{H_1}{\overset{H_0}{\gtrless}} \eta \tag{4.1}$$

where $p(y_n|H_0)$ and $p(y_n|H_1)$ are the probability distributions of the described signals under the corresponding hypotheses; Pr_{H_0} and Pr_{H_1} are prior probabilities of the occurrence of the hypotheses.

The decision rule (4.1) instructs us to prefer hypothesis H_0 if $L > \eta$ and hypothesis H_1 otherwise. The detection is described by one of the four possible courses of action:

- $p(H_0|H_0)\,\mathrm{Pr}_{H_0}$ the signal is not present and we make correct decision.
- $P_f = p(H_1|H_0)\,\mathrm{Pr}_{H_0}$ the signal is not present but we decide otherwise. This situation is known as the false alarm.
- $P_m = p(H_0|H_1)\,\mathrm{Pr}_{H_1}$ the signal is present but the detector miss detects its absence. This situation is known as the miss detection probability.
- $P_D = p(H_1|H_1)\,\mathrm{Pr}_{H_1}$ detection probability, the signal is present and we detect it correctly.

If the prior probabilities Pr_{H_0} and Pr_{H_1} are equal we can ignore them in these equations.

The detector could have two erroneous courses of action, miss detection or false alarm. The design of a detector is about of how to minimize these errors. By setting the decision threshold, we can vary these errors. Unfortunately, the minimization of them contains two contradictory requirements, by reducing one error we will increase the other. The dependency between these two errors is illustrated graphically by a receiver operating characteristics (ROC) curve. A ROC curve is a graphical representation of the dependency between P_m and P_f as a function of the detection threshold, η [52].

In many cases, the prior probabilities are not available. This problem can be bypassed by simply limiting the false alarm probability $P_f \leq \alpha$ and maximizing the detection probability. A test designed following such criteria is called the Neyman-Pearson test. We can redesign the test (4.1) by rearranging the decision procedure

$$\lg\left(p(y_n|H_0)\right) - \lg\left(p(y_n|H_1)\right) \underset{H_1}{\overset{H_0}{\gtrless}} \eta - \lg\left(\frac{\mathrm{Pr}_{H_0}}{\mathrm{Pr}_{H_1}}\right) = \eta'. \tag{4.2}$$

In the test (4.2) the unknown prior probabilities are incorporated into the decision threshold η'. The threshold is treated just as a level. The threshold is set such that the detection probability P_D is maximized under the constraint $P_f \leq \alpha$. By treating the threshold as a level identified through the optimization process we can ignore the actual values of the prior probabilities.

The detection process grants the spectrum access if the decision variable is less than the decision threshold, $L < \eta'$. This kind of event can occur not only when the signal is not present but also when we miss detect the signal presence. Therefore, the probability of miss detection describes the probability that the secondary transmitter transmits while the primary signal is present. Such disturbance from the secondary system can be limited by constraining the miss probability, $P_m < O_a$ or $(1 - P_D) < O_a$. The test is designed by minimizing the P_m under the constraint $(1 - P_D) < O_a$.

The Neyman-Pearson test does not incorporate the prior probabilities of the hypotheses. In a TVWS usage context, the prior probabilities describe the chance that a randomly located secondary user finds the spectrum free or occupied. Such prior probabilities can be computed in case of hypothesis H_0 as the ratio of the area where the spectrum can be used to the total area and in the case of H_1 it is $1 - \mathrm{Pr}_{H_0}$. We can incorporate prior information into the decision by designing the test according to a Bayesian approach [52]. The Bayesian test is designed by using the prior probabilities in the η computation in (4.2).

In Publication I we used prior probabilities to describe the efficiency of the ideal detection algorithm. The ideal spectrum allocation algorithm is able to identify all the locations where the spectrum can be used. For such an algorithm the detection errors do not exist, $P_m = 0$ and $P_f = 0$. In Publication I we investigated how a detection algorithm with certain P_m and P_f values has an impact on spectrum utilization efficiency.

In a tightly planned network, the TV signal is always present and at each location the measurements contain signals from at least one of the TV transmitters. In this type of network network, $\mathrm{Pr}_{H_0} = 0$ and P_m are sufficient to describe the secondary spectrum usage. The spectrum will be used if the computed statistic is less than η. A higher level of η means that the spectrum will be used closer to the coverage area, while a lower η allows the spectrum usage only further away. Currently, it is agreed that the decision level $\eta = -114$ dB provides a sufficiently large protection distance to the TV receivers [18]. In 8 MHz TV bandwidth, it means that the threshold is about 10 dB under the noise power level.

Reviews of the most common detection methods can be found in [53] [54] and [55]. These reviews explain the properties of typical detectors such as matched filter detectors, cyclostationarity-based detectors and energy detectors. In [53] a detector using wavelets is described also. The reviews in [54] and [55] contain the description of correlation based detectors and eigenvalue-based detectors. At this time , the research of the detectors is very active and many different detection approaches are continuously emerging. In the literature, we can find proposals for more exotic detectors not described in the above referred reviews. For instance, in [56] a nonparametric detection method is described.

The results in Publication V and Publication VI are related to power detectors and correlation-based detection. In the following section, we describe the basic working principles and performance of these types of detectors. For comparison, we also describe the most common detectors like matched filters, feature detectors and eigenvalue based detectors.

Matched filters A matched filter (MF) is the optimal detector of a known signal in Gaussian noise. The matched filter correlates the known signal with the collected samples [13]

$$L = \frac{1}{N} \sum_{n=1}^{N} s_n^* y_n \tag{4.3}$$

where s_n^* is the complex conjugate of the known signal at the receiver and y_n stands for the collected samples.

The performance of the MF is superior to the methods that do not use the knowledge of the signal structure. The information flow in a TV signal is random and only the pilot symbols are known exactly. The MF can be applied on those known symbols [57]. The performance of the filter can be expressed as

$$\begin{aligned} P_f &= Q\left(\frac{\eta}{\sqrt{\frac{N_0}{2}N}}\right) \\ P_m &= Q\left(\frac{\eta - \sqrt{\Theta P_r}}{\sqrt{\frac{N_0}{2}N}}\right) \end{aligned} \tag{4.4}$$

where P_r is the received signal power and $\sqrt{\Theta}$ is the fraction of the symbols reserved for pilot symbols.

Cyclostationary detectors A cyclostationary detector searches for a periodic structure present in most of the signals created by humans. A stationary white noise does not have any periodicity. Therefore the presence of a periodic component in the received samples is a clear sign of the existence of communication signals.

The simplest single cycle detector computes the spectral correlation function $\hat{S}_y^{\omega}(f)$ of the received signal y_n and matches it with the complex conjugate of the spectral correlation function $S_s^\omega(f)^*$ of the signal s_n that is searched for

$$L = \int_{-f_s/2}^{f_s/2} \hat{S}_y^\omega(f) S_s^\omega(f)^* df \tag{4.5}$$

where f_s is the sampling frequency.

The spectral correlation function is computed from the localized Fourier transforms of the continuous received signal $y(t)$

$$Y_T(n,f) = \int_{nT_s-T/2}^{nT_s-T/2} y(t)e^{-i2\pi ft}dt \tag{4.6}$$

where T_s is the sampling interval, n is the index of sample and T is the FFT window size. The spectral correlation function is

$$\hat{S}_y^\omega(f) = \frac{1}{NT}\sum_{n=0}^{N} Y_T\left(n, f+\frac{\omega}{2}\right) Y_T^*\left(n, f-\frac{\omega}{2}\right). \tag{4.7}$$

In the case of hypothesis H_0 (pure noise), the decision variable can be modeled by a zero mean Gaussian distribution [58]. The performance of a cyclostationary detector can be computed like the performance of an MF but now we have to consider not the signal power but the cyclostationary component power P_c

$$\begin{aligned} P_f &= Q\left(\frac{\eta}{\sqrt{\frac{N_0}{2}N}}\right) \\ P_m &= Q\left(\frac{\eta-\sqrt{P_c}}{\sqrt{\frac{N_0}{2}N}}\right) \end{aligned} \tag{4.8}$$

where $P_c = d^2(\omega)P_r$ with P_r standing for the received signal power and $d^2(\omega)$ is the power of the searched periodic component ω [59]

$$d^2(\omega) = \sqrt{N}\int_{-\infty}^{\infty} |S_s^\omega(f)|^2 df. \tag{4.9}$$

The cyclostationarity depends on the channel, and on the particular periodicity of the generated signal [58]. The method is computationally complex and sensitive to the accuracy of the sampling time instant [60].

Energy detector The energy detector, or radiometer, computes the decision statistics by summing up the powers of the measured samples [61]

$$L = \sum_n |y_n|^2. \tag{4.10}$$

If the signal is absent, the computed statistic contains only the noise power, otherwise the measured samples contain noise and signal power. The detector does not need to know the signal structure.

In the absence of the signal, the measured samples have a gamma distribution. The power of the signal plus noise sample is described by a non-central gamma distribution. The performance of the detector can be computed from the corresponding cumulative distribution function (CDF) [61] [62]

$$\begin{aligned} P_f &= \Gamma\left(N, \frac{\eta}{N_0}\right) \Big/ \Gamma\left(N\right) \\ P_m &= 1 - Q_N\left(\sqrt{N\gamma}, \sqrt{\frac{2\eta}{N_0}}\right) \end{aligned} \tag{4.11}$$

where N_0 is the noise power spectral density, N is the number of samples collected, $\Gamma(\cdot,\cdot)$ is the incomplete gamma function and $Q_N(\cdot,\cdot)$ is the Marcum Q-function [13]. These functions are defined as

$$\Gamma(\kappa,\eta) = \int_{\eta}^{\infty} x^{\kappa-1} e^{-x} dt \tag{4.12}$$

$$Q_N(\kappa,\eta) = \frac{1}{\kappa^{N-1}} \int_{\eta}^{\infty} x^N e^{-(x^2+\kappa^2)/2} I_{N-1}(\kappa x) \tag{4.13}$$

where $I_N(\cdot)$ is the modified Bessel function of the first kind.

The energy detector is an optimal detector for detecting an unknown signal in Gaussian noise. As we can see, the detection performance depends on the knowledge of the noise power. The knowledge of the power level is especially important in detecting very low signal levels. If the uncertainty of the noise power level is in the order of the signal power, the energy detector becomes unusable [58].

Correlation properties-based detectors The autocorrelation detection searches for the correlation in the received samples. It constructs an autocorrelation matrix and determines whether it is an identity matrix or not. In a multipath channel, a detector receives multiple delayed copies of the signal. The correlation matrix of a signal with delayed copies has non zero off diagonal elements. White Gaussian noise does not have such correlation and its correlation matrix is the identity matrix [63].

The detector creates from the received samples the following $M \times (N-M)$ matrix

$$\mathbf{Y} = \begin{bmatrix} y_0 & y_1 & \cdots & y_N & 0 & \cdots & 0 \\ 0 & y_0 & \cdots & y_{N-1} & y_N & \cdots & 0 \\ \vdots & \vdots & \ddots & & & \ddots & \\ 0 & 0 & \cdots & y_0 & y_1 & \cdots & y_N \end{bmatrix} \tag{4.14}$$

and computes the autocorrelation matrix $\mathbf{R}_y = \mathbf{Y}\mathbf{Y}^*$. As we see M defines the size of the correlation matrix.

In the reference [63] we can find two detection algorithms. Both of them are using the covariance properties of the received signal. The simplest detector computes the mean over the main diagonal elements of $\mathbf{R}_y$ and compares it with the mean over the off diagonal elements

$$L = \frac{\frac{1}{M}\sum_{m} |r_{mm}|}{\frac{1}{M(M-1)}\sum_{n \neq m} |r_{nm}|} \tag{4.15}$$

where r_{mm} and r_{nm} are the main diagonal and the off diagonal elements of the correlation matrix $\mathbf{R}_y$.

The false alarm probability of such detector is [63]

$$P_f \approx 1 - Q\left(\frac{\frac{1}{\eta}\left(1 + (M-1)\sqrt{\frac{2}{N\pi}}\right) - 1}{\sqrt{2/N}}\right) \tag{4.16}$$

As we can see, the autocorrelation detector performance does not depend on the noise power level. As such it avoids the noise uncertainty problem that affected the energy detector.

4.1.1 Detectors using multiple antennas

Multiple antennas allow us to make parallel measurements of the environment. The detection algorithms using multiple antennas can be distinguished based on the measurement combination methods. The simplest approach is to treat each antenna as a separate detector and simply sum up the detection results. More advanced methods treat the measurements from multiple antennas together. The common approach is to compute the correlation matrix which eigenvalues or off diagonal elements indicate the presence of the signal.

Treating antennas as independent detectors By treating the antennas as independent sensors, we can apply in each of them any of the single detector algorithms. How to combine the statistics from multiple sensors, antennas, is a classical fusion problem. The fusion could take place before or after the initial decision.

If fusion takes place before the decision, usually all the antennas are assumed to measure a similar source. The sources have the same signal distribution and the same true hypothesis. This assumption allows us to apply single antenna-based detection algorithms by creating a vector of all the samples from all the antennas.

If the analog front-ends for different antennas are not calibrated, the assumption that the signals from different antennas come from similar sources does not hold.

In this case, the samples can be combined by using the well-known maximum ratio or equal gain combining algorithms [64]. By using these combining algorithms, it is possible to construct a detector which combines the detection results at individual antennas. In the literature, one could find the performance analysis of a multi-antenna detector with energy detectors in individual antennas [65], or with cyclostationary detectors in individual antennas [66].

The algorithms at the individual antennas still suffer from the problems we outlined above for the single antenna detectors. The approach does not utilize the diversity the multiple-antenna system provides.

Eigenvalue detectors An eigenvalue detector tests whether the largest eigenvalue of the covariance matrix among the signals from different antennas contains only pure noise or a signal plus noise.

The received signal from different antennas can be expressed in vector form as

$$\mathbf{y}_n = [y_{1n}, y_{2n}, \ldots, y_{mn}, \ldots, y_{Mn}]^T \tag{4.17}$$

where the sample y_{mn} is defined as the n-th received signal sample from antenna m. We can compute the correlation matrix

$$\mathbf{R}_y = E\left\{\mathbf{y}\mathbf{y}^T\right\}. \tag{4.18}$$

In eigenvalue detectors, the noise is usually assumed to be independent and spatially white. All the eigenvalues of the correlation matrix of the noise have about the same value. The eigenvalue detectors assume that if one of the subspaces contains also the signal the corresponding eigenvalue will contain signal plus noise power. That eigenvalue will be higher than the rest of the eigenvalues [67].

In order to remove the noise level uncertainty, we normalize the highest eigenvalue with the estimate of the noise level. The estimate is computed by averaging over the other eigenvalues. Using such an estimate is justified if it is assumed that the signal is present only in one eigenvalue and the rest of the eigenvalues contain only noise. The decision variable is computed as

$$L = \frac{\lambda_i}{\sum_{i=2}^{M} \lambda_i} \tag{4.19}$$

where λ_i are the eigenvalues of the matrix $\mathbf{R}_y$.

The performance of the detector is computed only for a high number of antennas [67]

$$P_f = 1 - F_{TW2}\left(\frac{\eta - \mu_{NM}}{\sigma_{NM}}\right)$$
$$P_m = 1 - Q\left(\frac{\eta\sqrt{N}(M-1)\left(1 - \frac{1+\gamma}{N\gamma}\right)}{1+\gamma} - \frac{\sqrt{N}}{1+\frac{M-1}{N\gamma}}\right) \tag{4.20}$$

where F_{TW2} is Tracy-Widom distribution of order 2 and

$$\mu_{NM} = \left(1 + \sqrt{\frac{M}{N}}\right)$$
$$\sigma_{NM} = \frac{1}{\sqrt{N}}\left(1 + \sqrt{\frac{M}{N}}\right)\left(\frac{1}{\sqrt{N}} + \frac{1}{\sqrt{M}}\right)^{1/3}. \tag{4.21}$$

Correlation-based multiantenna detector When antennas are treated as independent sensors, we do not utilize the full diversity provided by multiple antennas. The eigenvalue detector does not suffer from that problem. However, they are designed with the assumption that the signal is in one subspace only, i.e. the signal is arriving from one direction. Also, the performance characteristics in (4.20) are derived only for a high number of antennas.

The correlation matrix-based detection that is described above for a single receiver can be extended to cover multiple-antenna systems [68]. The correlation-based detection algorithm assumes that the signal, if present, generates correlation between the antenna elements. Such correlation generates the correlation matrix with nonzero off diagonal elements in comparison with the zero off diagonal elements of a spatially white noise.

The elements of the correlation matrix estimate are computed as the multiplication of long vectors. Because the central limit theorem the distribution of the elements is well approximated by a Gaussian distribution. In [68] the decision variable is computed as a sum of the correlation matrix elements. The decision variable distribution is described by its first two moments and P_f P_m are computed from the $Q(\cdot)$ function.

In multiple-antenna systems, the signals from different antennas could change differently, changes which could occur due to the independent fast fading in different antennas or due to the clock difference in the front-ends of antennas. If the fading in antenna elements is independent, the computed covariance matrix becomes a diagonal matrix. In this case, we are not able to apply either the eigenvalue detectors or correlation-based detectors. This problem occurs especially when the correlation matrix estimate is computed from a large sample sequence where the channel amplitude and phase changes during the sequence. Fortunately, we can compute the correlation matrix estimate from a short sequence where the channel change is not significant. In Publication VI we used such insight and proposed a detection algorithm that can operate in cases where the signals in different antennas have different changes but in a short time interval the signals do not change significantly.

The algorithm proposed in Publication VI splits the measurements into subsets and computes correlation matrices for each subset. The final correlation matrix estimate is computed by averaging the correlation matrices of the subsets. The detection is made by using the computed correlation matrix estimate as input to the correlation detector [69]. The number of samples in the subset is selected such that the changes during this samples collection time is insignificant. In Publication VI, we described the P_m and P_f probabilities of the proposed detector. As seen in Fig. 4.1, the simulations and predictions from the analytical model are very close. The details of the algorithm used for generating Fig. 4.1 can be found in Publication VI.

In a fading channel the proposed algorithm has a superior performance compared with the simple correlation-based algorithm described in [68] and depicted in Fig. 4.2. In that comparison both detectors have 4 and 2 antennas and each antenna element observes independent fading. The fading is generated using a Jakes channel model [70]. The fading is computed for a user speed of 20 m/s and carrier frequency of 500 MHz. The decision is made based on 10^6 samples collected during 100 ms.

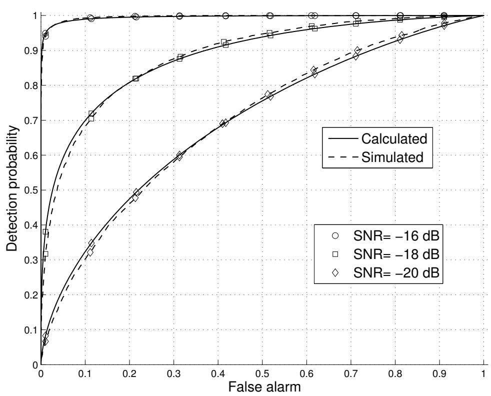


Figure 4.1. Comparison of computed and simulated ROC curves of the proposed detector. The simulations are made for a 4 antenna detector with 10^5 samples and block size 100.

4.2 Detection in fading environment

In this section, we describe the computation of the detector performance in fading environments. The detector performance is computed as follows

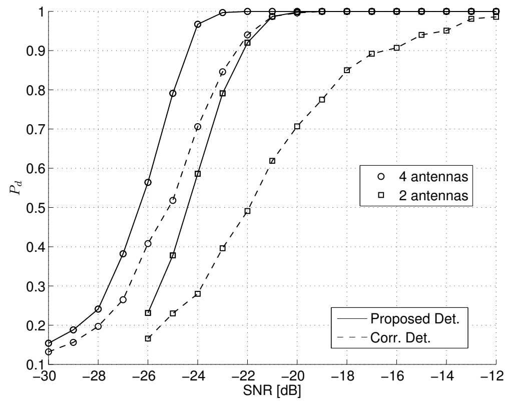


Figure 4.2. Performance of the correlation based multiantenna detector proposed in [68] and the detector proposed in Publication VI. The detectors have 4 and 2 received antenna and the probability of false alarm is fixed to $P_f = 0.1$. The performance in evaluated in a fading environment with a user speed of 20 m/s and carrier frequency of 500 MHz. The fading is generated by using a Jakes model from [70]. The detection is made based on 10^6 samples collected in 100 ms.

1. Compute the mean path loss by using the signal propagation model.
2. Use the fading model and scale the mean path loss with the random fading amplitude.
3. Compute the detection probability by using the faded signal amplitude distribution.

In numerical simulations, these three steps are usually separated. If they are separated, we can compute in the first two steps the mean signal level and in the last step to use the detector performance expression in an AWGN channel. However, we can simplify the computation by combining the last two steps. This can be done by expressing the detector performance directly in the fading environment.

There are two ways to compute the detection probability in a fading environment. First we can compute the miss detection probability P_m as a function of SINR. This instantaneous $P_m(\gamma)$ will be averaged over the fading distribution

$$P_m = \int_0^\infty P_m(\gamma)p(\gamma)d\gamma \tag{4.22}$$

where $p(\gamma)$ is the distribution of SINR in the fading channel.

An alternative method would be first to evaluate the distribution of the decision variable by averaging over the fading and then to compute the cumulative distribution of the decision variable

$$P_m = \int_{-\infty}^{\eta} \int_0^\infty p(L \mid \gamma)p(\gamma)d\gamma dL \tag{4.23}$$

where $p(L \mid \gamma)$ is the decision variable distribution in an AWGN channel. As one can see, the second approach also computes the distribution of the decision variable. This intermediate result is useful for analyzing the performance of cooperative detectors. For instance, cooperative detectors could improve the detection performance by summing up the statistics computed in individual detectors. The distribution of this sum is a convolution of the distributions of the individual summed terms.

Computation of $p(\gamma)$ requires knowledge of the slow and fast fading distributions.

4.2.1 Fast fading models

Fast fading is observed if the channel use time is longer than the channel coherence time. Fast fading is characterized by the quick changes of the channel. These kinds of changes occur due to the scattering of the signal while it is propagating from transmitter to receiver.

Rayleigh distribution In a Rayleigh fading environment, the received signal is a sum of multiple reflected signal components [71]. If there is no dominant component, the amplitudes of all components are of the same order. The Sum of many random components approaches a central complex Gaussian distribution. In polar coordinates, a central complex Gaussian distribution has a Rayleigh distributed amplitude and the phase that is uniformly distributed in the interval $[0 \ldots 2\pi]$. The signal power and SNR have an exponential distribution

$$p_{fast,Rayl}(\gamma) = \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} \tag{4.24}$$

where γ is the instantaneous SNR and $\bar{\gamma}$ is the mean SNR.

Rician distribution In the existence of the line of sight between the transmitter and the receiver, the direct signal component is much stronger than other signal reflections. Multiple reflected components still are summing up to a Gaussian distribution but now the line-of-sight component creates a noncentral mean. The amplitude of this signal is described by a Rician distribution [71]. The SNR of the noncentral Gaussian signal is described by the noncentral chi-square distribution

$$p_{fast,Rice}(\gamma) = \frac{K_c + 1}{K_m} e^{-K_c + \frac{(K_c+1)\gamma}{K_m}} I_0 \left(2\sqrt{\frac{K_c(K_c+1)\gamma}{K_m}} \right) \tag{4.25}$$

where $K_c = \frac{P_{line}}{P_{Rayl}}$ is the noncentrality parameter and $K_m = P_{line} + P_{Rayl}$ is the average power envelope, P_{line} is the power of the line of sight component and P_{Rayl} is the power of the Rayleigh component.

Nakagami-M distribution Signal amplitude is described by a Nakagami-M distribution if the SNR of the signal has a central gamma distribution [71]

$$p_{fast,NakM}(\gamma) = \frac{1}{\Gamma(m)} \left(\frac{m}{\bar{\gamma}}\right) \gamma^{m-1} e^{-\frac{m}{\bar{\gamma}}\gamma}. \tag{4.26}$$

With two degrees of freedom, $m = 2$, the gamma distribution is the exponential distribution. A gamma distribution with higher degrees models a signal that is created by summing up the powers of the multiple arriving components. A signal with a strong line of sight component can be modeled by a non-central gamma distribution.

4.2.2 Shadowing models

Slow or shadow fading arises when the phase change in the channel is relatively constant over the channel usage time. A slow channel change usually occurs due to large objects on the signal path. The parameters of the slow fading are usually computed by averaging the received signal field over an area of size 10-40 wavelengths. In a wide range of environments, the shadow fading can be approximated by a log-normal distribution. Nevertheless, there is no good physical explanation why this distribution arises. Some alternative distributions, such as the Nakagami M and the Gaussian distributions, also turn out to be good approximations for shadowing [72].

Log-normal distribution A log-normal model of the slow fading is justified by the "multiplicative interpretation" of the channel [72]. The CDF of the log-normal distribution plotted in logarithmic arguments gives a straight line. The straight line is easy to fit the measurement data. That simplicity has been one of the reasons for the wide adoption of the log-normal model. The PDF of the log-normal distribution is

$$p_{slow,lg}(\bar{\gamma}) = \frac{10/\lg(10)}{\gamma\sqrt{2\pi\sigma_{dB}^2}} e^{-\frac{(10\lg(\bar{\gamma})-\mu)^2}{2\sigma_{dB}^2}} \tag{4.27}$$

where μ is the mean of the shadow fading and σ_{dB} is the standard deviation of the fading. Both of these parameters are given in dB. The shadow fading standard deviation is usually measured to be in the range of $3 - 8$ dB [73].

Gamma distribution In some cases, the gamma distribution gives a better fit to the measured data. The reason why the slow fading is well approximated by gamma distribution can be explained by the scattering. A sum of scattered signals from random rough surfaces approaches a gamma distribution [74]. While the log-normal distribution is a relatively simple model, it often does not allow an analytical treatment. On the other hand, the gamma distribution often offers us a simple analytical treatment.

The gamma and log-normal distributions can be approximated by each other by matching their moments. The gamma distribution parameters expressed as the functions of corresponding log-normal distribution are $a_{sf} = \left(e^{\sigma_{dB}^2} - 1\right)^{-1}$ and $\beta_{sf} = e^{\frac{\mu+\sigma_{dB}^2}{2}} \left(e^{\sigma_{dB}^2} - 1\right)^{-1}$ [75]

$$p_{slow,g}(\bar{\gamma}) = \frac{1}{\Gamma(\alpha_{sf})\beta_{sf}^{\alpha_{sf}}} \left(\bar{\gamma}\right)^{\alpha_{sf}-1} e^{-\frac{\bar{\gamma}}{\beta_{sf}}}. \quad (4.28)$$

4.2.3 Hybrid models of fast fading and shadowing

The separation of the slow and fast fading is somewhat artificial. It is more common that the radio channel contains both: slow and quick amplitude changes. The model describing the signal SNR in both shadowing and fast fading can be found by averaging the fast fading over the slow fading

$$p\left(\gamma\right) = \int_0^\infty p_{fast}(\gamma|\bar{\gamma}) p_{slow}(\bar{\gamma}) d\bar{\gamma} \quad (4.29)$$

where $\bar{\gamma}$ can be interpreted as the mean around which the fast fading process occurs.

Suzuki distribution The model describing the signal power of the mixture of the Rayleigh fading and the log-normal shadowing is called Suzuki distribution [76]:

$$p\left(\gamma\right) = \int_0^\infty \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} \frac{10/\lg(10)}{\gamma\sqrt{2\pi\sigma_{dB}^2}} e^{-\frac{(10\lg(\bar{\gamma})-\mu)^2}{2\sigma_{dB}^2}} d\bar{\gamma}. \quad (4.30)$$

Unfortunately, this integral does not have a closed form solution and has to be evaluated numerically.

Generalized Gamma distribution A general distribution that encompasses both slow and fast fading is proposed in [77]. A normalized form of it is a generalized gamma distribution. The distribution is

$$p\left(\gamma, \alpha, \beta, c\right) = \frac{c\left(\bar{\gamma}\right)^{\alpha-1}}{\beta^{c\alpha}} \frac{e^{-\left(\frac{\bar{\gamma}}{\beta}\right)^c}}{\Gamma\left(\alpha\right)} \quad (4.31)$$

where the lower tail of this distribution is controlled by parameter α, the upper tail by c and β is the normalization constant. This distribution captures the properties of the fast and shadow fading in a very simple form. The lower tail of the distribution corresponds to the fast fading, the upper tail to the shadow fading distribution. A study of matching this distribution to the measurement data is given in [78].

Gamma distribution In Publication V, we describe the combination of the slow and fast fading environment by appropriately parameterizing a gamma distribution. The benefit of this model is that the fast and slow fading parameters are clearly separated. At the same time, the model of the gamma distribution often allows for a simple analytical treatment.

The model is derived by describing both slow and fast fading with gamma distributions. These two distributions are combined and approximated by the new gamma distribution. The final approximation is done by matching the moments (see Publication V for details).

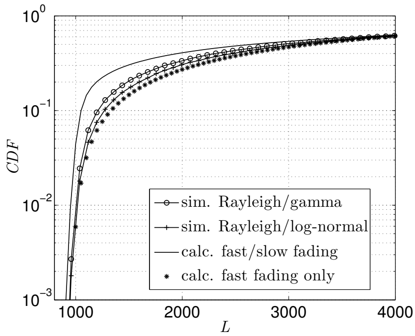
$$p\left(\gamma, \alpha_\gamma, \beta_\gamma\right) = \frac{(\gamma)^{\alpha_\gamma - 1}}{\beta_\gamma^{\alpha_\gamma}} \frac{e^{-\frac{\gamma}{\beta_\gamma}}}{\Gamma\left(\alpha_\gamma\right)}. \tag{4.32}$$

The matched moments are $\alpha_\gamma = \frac{\alpha_{sf} n/2}{1+\alpha_{sf}+n/2}$ and $\beta_{sf} = 1 + \alpha_{sf} + n/2$, where α_{sf} and β_{sf} are slow fading parameters that can be computed if the log-normal parameters are known, n is the number of independent fast fading blocks. The independent fast fading blocks describe the situation where the channel coherence time T_{coh} is less than the measurement time NT_s, where N is the number of samples and T_s is the sampling interval. During the measurements, we observe $n = \frac{NT_s}{T_{coh}}$ independent signal levels.

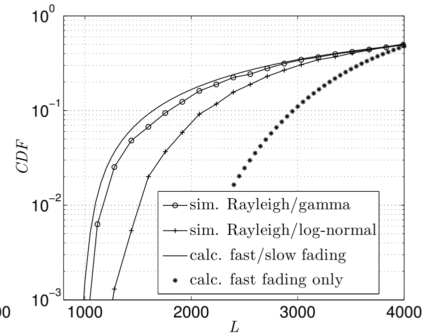
Fig. 4.3 presents the detector performance as a function of the number of received samples and the number of fast fading blocks. Details of the computations of the results in Fig. 4.3 are given in Publication V. In general, we can claim that the quickly changed fast fading can be compensated by collecting samples over a sufficiently long time. However, after averaging out the fast fading the detector performance is dominated by the slow fading.

4.3 Spectrum utilization efficiency with detection methods

In Publication I, we look at the detection-based spectrum access from the spectrum utilization point of view. The spatial spectrum utilization is expressed as the area where the spectrum is used normalized to the total area. The protection area near the cell border reduces the spectrum spatial utilization efficiency. The situation is illustrated in Fig. 4.4. With TV coverage area A_{TV} and protection area A_Δ, a secondary user can use the spectrum only if it is located in the area A_s. For a uniform user dis-



(a) One fast fading block



(b) 20 fast fading blocks

Figure 4.3. Comparison of the detector performance by using (4.32) and simulated results in Rayleigh/log-normal fading and Rayleigh/gamma fading. Two different fast block fading channels a) samples collected from one fast fading block, b) samples collected from 20 fast fading blocks.

tribution, the user will be in this area with probability $\Pr_s$. The total spatial spectrum utilization will be

$$U = \frac{A_{TV} + A_s}{A_{TV} + A_\Delta + A_s} = \frac{A_{TV}}{A_{TV} + A_\Delta + A_s} + \Pr{}_s. \tag{4.33}$$

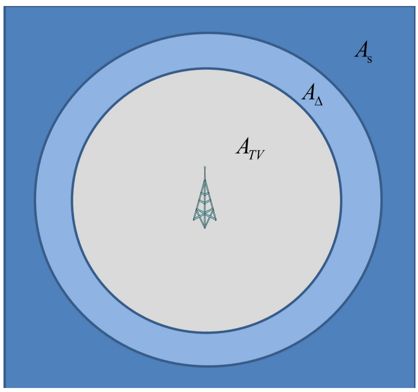


Figure 4.4. Visualization of different types of spectrum access areas: A_{TV} is TV coverage area, A_Δ is TV protection area, A_s is secondary user service area.

Spectrum utilization is improved if the spectrum can be used as close to the TV coverage area as possible. Such usage requires signal detection close to the TV cell border. Near the TV cell border the decision problem is no longer identification whether the TV transmitter is active or not but identification of the distance to the coverage area border [79]. Detection close to the cell border has two specific features. First, for protecting the primary users, the detection threshold has to be selected relatively low. Second, the detector does not identify the presence or absence of the signal but rather attempts to identify what is the particular signal level.

Close to the TV cell border the signal is always present and the detection has to identify only the signal level. This means that hypothesis H_0 does not contain only noise but it also contains the TV signal that has propagated outside of the TV coverage area. In Publication I, we propose to incorporate the signal presence probability into the detection algorithm. The signal level outside the coverage area is modeled by the uniform distribution. The validity of the proposed approximation is studied also in [80].

The detection error means that the transmitter will not use the spectrum even if the spectrum usage is allowed. This kind of error reduces the spectrum utilization further. With detection error, the spectrum utilization becomes

$$U = \frac{A_{TV}}{A_{TV} + A_{\Delta} + A_s} + (1 - P_f) \cdot \mathrm{Pr}_s. \tag{4.34}$$

Sometimes the spectrum can be used also in the protection area, A_{Δ}. For example, if the secondary transmitter is inside a building or it is located in a valley, the transmitted signal towards the TV coverage attenuates enough and does not disturb the TV reception. Assume the amount of locations in A_{Δ} where the spectrum can be used is Pr_{Δ_2}. In the absence of detection and estimation errors, all the available spectrum can be used and the spectrum utilization is

$$U = \frac{A_{TV}}{A_{TV} + A_{\Delta} + A_s} + Pr_{\Delta_2} Pr_{\Delta} + \mathrm{Pr}_s. \tag{4.35}$$

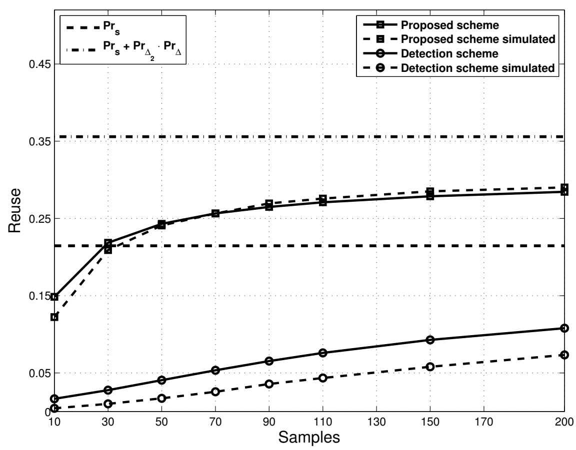


Figure 4.5. Reuse comparison for proposed and detection-based decision scheme for different numbers of measurement samples. The values used in the computations are $\mathrm{Pr}_s = 0.21$, $\mathrm{Pr}_{\Delta} = 0.29$ and $\mathrm{Pr}_{\Delta_2} = 0.5$.

The spectrum can be reused in the area A_s and in some location in area A_{Δ}. In the area A_{Δ} the secondary user has to make an additional environment analysis and based on that analysis decides whether the spectrum will be used. With the detection and estimation errors, a secondary user can recover only a part of the available spectrum.

Comparison of spectrum utilization with ideal detectors using Eq. (4.35) and with actual detection is illustrated in Fig. 4.5. The details of the equations used for the numerical evaluation are given in Publication I.

4.4 Discussion

In this chapter, a review of the detection methods used for identifying the existence of a primary user signal is given. First, the most commonly used detection methods are described, then it is portrayed how to compute the detector performance in a fading environment, and, finally, it is illustrated how to estimate the spectrum utilization given that the secondary system uses a detection-based spectrum access.

The detectors are used for identifying the presence or absence of a primary system signal. Most common detector types are matched filters, energy detectors and feature detectors. In the presence of the known signal the matched filters have superior performance compared to the two other types of detectors. Unfortunately, for its operation a matched filter needs the knowledge of the signal structure. In the presence of multiple types of primary systems it has to test the existence of signals from all of them. For a large number of primary systems, such testing becomes very complex.

Energy detection is a simple option for detecting unknown signals. Since an energy detector does not need to know the signal structure, it is not able to distinguish among different primary signals. Such indifference becomes a limiting factor if the secondary system wants to estimated the distances to multiple primary systems. Moreover, for good performance at low SINR levels the energy detector requires the exact knowledge of the noise power level. In practice the precise noise power level is not available and therefore at low SINR levels the energy detector cannot, in fact, be used [58].

Feature detectors utilize the signal features that do not exist in the white Gaussian noise. The feature detectors can operate without the knowledge of the noise power level. Also they can distinguish between signals with different features. However, the feature detectors are relatively complex to implement and they are sensitive to the carrier frequency offsets and sampling clock errors [60].

Some of the problems appearing in detectors with a single antenna can be avoided by using detectors with multiple antennas. The antennas can be treated as independent single antenna detectors whose outputs are fused together or the signals from different antennas can be processed together.

One of the detection methods that treats the antennas together is the eigenvalue detection. The eigenvalue detector does not need to know the noise power density level. It is also able to operate at very low SINR levels and is not very complex.

The signals in different antennas can undergo independent fading. In Publication VI we proposed a new correlation-based detection algorithm that is insensitive to the fading difference in different antennas. How the proposed method performs if the noise power level is different at different antenna front-ends remains still to be studied.

In the context of TVWS usage, the detector has to identify not only the existence of the primary signal but also the distance to the TV coverage area border. Sufficient distance to the primary system is guaranteed by setting sufficiently low detection levels. In a fading environment detection level can be computed by conditioning the detection probability with the fading distribution and averaging over all the fading levels. In the academic literature, most studies of the detection methods consider only slow or fast fading. In Publication V we describe how to derive the detection level in the presence of both slow and fast fading. The proposed method can consider the diversity in a block fading channel. The method is suitable for estimating the performance of any detector whose miss and false alarm probabilities are described by the Gamma distributions.

In a fading environment, a single detector can guarantee the protection of the primary receivers only by having a very low detection level. We can overcome this problem by using multiple cooperating detectors. The cooperation methods are subject to practical limitations. Currently, in academic the community there is active ongoing research into identifying the methods for optimal combinations of the measurements from different detectors (see for instance review in [81]). The questions to be answered are: How should the measurements be present? How should the measurements be combined? How should the data exchange protocols be designed? How should the distance among the detectors be described? How should the correlation in the measurements be addressed?

The last section in this chapter describes the method for estimating the spectrum utilization efficiency of a secondary system using spectrum sensing. The ideal spectrum using method discovers all the locations where the secondary spectrum usage is possible. In Publication I we describe how the detection errors affects the spectrum utilization. Because of the errors, the detection-based spectrum access is not able to use the entire available spectrum.

The geolocation database controlled spectrum access can be assumed to operate without detection errors. When estimating the amount of available secondary spectrum in Finland, we assumed that the spectrum access is controlled by the geolocation database. The spectrum access with geolocation database is described in the next chapter.

5. Geolocation database assisted spectrum access

A detection-based access method estimates the distance to the TV coverage area by measuring the TV signal level. In a fading environment, the signal level and the distance are very loosely related. The protection of primary receivers can be guaranteed only by using very conservative decision levels. Such conservative levels account for a severe fading and in most cases the detection level significantly overestimates the actual distance to the primary receivers.

An ideal spectrum allocation algorithm would know the locations of users and path losses between all primary and secondary users. Such ideal conditions can be approached by using a centralized controller, a geolocational database. The database will have a global view of transmitters' locations and coverage areas. Such global knowledge allows the database to make a very tight spatial spectrum allocation.

What exact operations the database has to carry out and what information it will provide to spectrum users is currently still under study. Some testbeds have emerged [82] and even some servers running the spectrum availability database have been implemented [83]. A set of functions the database could provide are reported by the ECC working group for spectrum engineering, SE43, in ECC report 159 [17].

According to the ECC proposal, the secondary user measures its location and initiates a query to the database. The database responds with the information about the available spectrum. The ECC report specifies what parameters the secondary user should send to the database and what information the database will provide back to the user. It leaves open how the database decides and allocates the spectrum. The user applies to the database by providing the following information:

- Location
- Location accuracy
- Device type
- Device ID/model
- Expected area of operation (optional).

The database will respond with parameters:

- Available frequencies
- Maximum transmit power
- The appropriate national/regional database to consult (optional)
- Time validity of the information provided
- If sensing is required (optional).

The allocation engine is illustrated in Fig. 5.1. The database is a central computing unit that utilizes the primary user information, environment information, and the predefined frequency allocation rules. The allocated frequency resources are stored and stamped accordingly to the location and time.

We can say that the geolocation database tracks the location of the primary spectrum users and admits the secondary users based on the interference estimation. The database can know the locations and relevant path loss information of all the transmitters. The interference can be computed as aggregate interference from all the transmitters. In Publication II, we propose an algorithm that simplifies aggregate interference computation from a large number of transmitters.

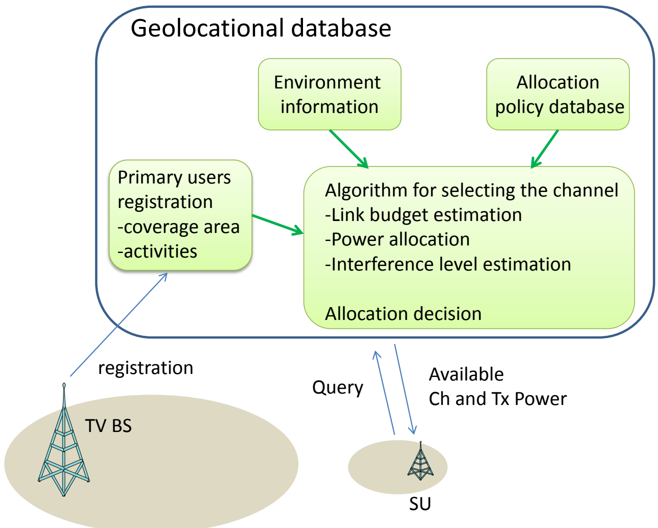


Figure 5.1. Functionality of a geolocation database.

The spectrum allocation is relatively easy for a single secondary user operating independently from other secondary users. In this case, the database needs only to compute the path loss, use it in the SINR estimation, and allocate power such that the interference constraint is satisfied. Since the location of any user is known, the database computes the path loss by using the channel model and the terrain data.

The allocation of spectrum to a secondary system is much more complex than allocation to a single user. Radio systems usually contain their own resource control, radio resource management (RRM). RRM has an impact on the interference generated from the system and the intersystem interference model has to contain such impact. The RRM partly duplicates the functionality of the spectrum allocation database. Both of them control the access to the spectrum, transmission moments and the emitted powers. The interference control has to be shared between the database and the RRM. How to do it efficiently is currently an open study issue.

The power allocation does not depend only on the user location but also on the locations and transmission powers of other users. The power allocation should satisfy the target SINR at primary receivers given the aggregate interference from all the secondary transmitters. For computing such SINR, the database needs an aggregate interference computation algorithm. An overview of interference modeling approaches is presented in the next chapter. In Publication II, we propose a model that allows us to quickly compute the interference from a cellular network where all BSs use the same transmission powers.

The same aggregate interference level can be met with different power allocation rules. However, different allocation rules provide different secondary system capacity. In Europe ECC and in US FCC have adopted slightly different approaches for the power allocation. Below we outline the main characteristics of these power allocation rules.

Compared to the detection-based methods, a geolocation database-based frequency allocation allows us to achieve tighter spatial frequency utilization. As such, the database-based allocation provides a reasonable estimate of how much spectrum can theoretically be used. In Publication IV and Publication VII, we estimated the capacity of a cellular network operating in TVWS. In Publication IV, we used the approach proposed by the FCC. In Publication VII we compared the efficiency of the power allocation rules of the FCC and ECC.

5.1 White space usage with FCC rules

The FCC describes the secondary spectrum usage rules in its recommendation 174 (FCC 174) [18]. The FCC rules allow a fixed and portable secondary spectrum usage. The portable users are assumed to be mobile terminals. A mobile user's antenna height is assumed to be about few meters and the maximum transmission power is limited to 100 mW. The fixed transmitters are allowed to transmit 4 W of equivalent isotropically radiated power (EIRP).

FCC 174 protects the TV receivers from fixed transmitters interference by reserving

Table 5.1. Protection areas defined by FCC [18].

Antenna height	Required distance from the TV coverage contour	
	co-channel	adjacent
< 3 m	6.0 km	0.1 km
$3 < 10$ m	8.0 km	0.1 km
$10 - 30$ m	14.4 km	0.74 km

a no transmission area (protection area) around the TV coverage area. The protection area is defined as the nearest distance to the TV coverage area border where a secondary system can use the spectrum. The protection area is defined for both the co-channel and two adjacent channels.

The fixed transmitters are classified based on their antenna height. Attenuation from lower positioned antennas is less than from those positioned higher. Therefore, the class of transmitters with lower antenna height needs a smaller protection area. The protection areas required for co-channel transmission for different transmitters classes are given at Table 5.1, the table is being adapted from [18].

The spectrum allocation rules proposed by FCC do not explicitly consider the impact from multiple secondary transmitters. The spectrum allocation is done only for a single user based on its location. The allocation does not need any information about other users. It is assumed that the specified protection distances are sufficient for keeping the aggregate interference under control.

5.2 White space usage with ECC rules

The ECC rules allow us to adapt the transmission powers based on the user location. The co-channel spectrum can be used everywhere outside of the TV coverage area but the transmission power has to satisfy an SIR requirement [17]:

$$P_s = \mu_{TV} - \mu_G - \gamma_{D|U} + q\sqrt{\sigma_{TV}^2 + \sigma_{SU}^2} - MI - SM - FM \qquad (5.1)$$

where μ_{TV}, σ_{TV} are the mean and standard deviation of the TV signal, μ_G is the mean path loss of the secondary signal, $\gamma_{D|U}$ is the protection ratio in dB due to the frequency offset between the TV receiver and the secondary device, $q = Q^{-1}(1-O_n)$ is the Gaussian confidence factor and Q^{-1} is the inverse Q-function, MI, SM, and FM are protection margins.

The ECC rules protect the TV receiver form interference generated by multiple secondary transmitters by using appropriate interference margins, MI. The current proposal contains three different margin values $MI = 3, 5, 6$ dB for $2, 3$ and 4 secondary interferers respectively. For more interferers, we can use the additional safety margin SM. The fading margin FM incorporates various protections, for example protection from fading [17].

Compared to the FCC rules, the ECC rules allow more flexible frequency use. The power is allocation based on the actual interference level the user will generate. The co-channel can be used everywhere, outside of the TV coverage area, as long as (5.1) is satisfied. The adjacent channel can even be used inside the coverage area. For finding the allowed power for an adjacent channel we have to change the protection ratio, $\gamma_{D|U}$, to correspond to the interference level from the considered adjacent channel. The TV reception sustainability to adjacent channel interference can be set based on measurements, for instance the ones reported in [84].

5.3 Discussion

Since the geolocation database knows the location of all the transmitters it can estimate the generated interference. Such estimation can be used for controlling the transmission powers and therefore the system is able to guarantee the primary system connection quality.

The database-based access is particularly attractive for controlling white space usage. The TV broadcasting uses few high power transmitters. It is easy to construct a database of their coverage areas. The database can predict the interference the secondary transmission generates and control the interference level. In the near future, the geolocation database-based control is considered as the only option for TVWS access.

The current recommendations contain only a very simple aggregate interference control method. The recommendations are continuously updated and new approaches are considered. Based on our work in Publication II, we have submitted to the ECC a proposal for a new interference control method [19].

The proposed concept treats the interference that a secondary system can generate as a resource which is distributed among the secondary transmitters. Each transmitter can generate only a fraction of the total interference. The transmission power of a single transmitter is constrained by this fraction.

In the report [19], the power allocation concept is illustrated only with a simple channel model. The model still needs to be adjusted for a realistic radio environment [85]. Also, the current model is not suitable for controlling the interference from a cellular network with large cells (Publication III).

In Publication IV we described the power allocation algorithm as a constrained optimization problem. A geolocation database can use the proposed algorithm for controlling and allocating the transmission powers of secondary transmitters'.

6. Interference modeling

A secondary network designer has to answer two questions, how the new network affects the TV receivers and how well the network can serve its users. Answer to the first of these questions requires an intersystem interference model. Answer to the second question requires the model that allows us to compute the capacity of the network given the intersystem interference constraint. This chapter describes the aggregate interference generated from cellular and ad hoc networks while the next chapter contains the models used for evaluating the capacity of these networks.

The secondary spectrum usage creates a need to model the interference between different types of systems. In the last few decades, interference modeling has been mainly focused on a single system. Inside a single system, the interference models can take advantage of the known transmitter and receiver characteristics. Also, often the system can sway significant control over the spectrum usage patterns of transmitters. In order to be applicable in the primary secondary system set up, the single system interference models have to be modified for the intersystem context. The main difference between the single system interference and multi-system interference is that the transmitters in different systems are usually much more loosely coupled.

6.1 Interference models for spectrum licensing

One area, where intersystem interference control has had pivotal importance has been spectrum licensing. During the licensing process, the officials have to predict whether the existing license holders will be protected. The protection is done by posing constraints on the design of the new spectrum using system. The posed constraints depend on how the officials model the system in the interference analysis. Historically, the spectrum usage license is issued for a particular service that is provided by using a specific technology. A new trend is to issue technology neutral licenses which only protect other spectrum users and do not favor any specific technology. Anybody can use the spectrum as long as others are not disturbed. The existing models used for spectrum allocation are classified in [86] as

- Spectrum emission mask
- Block edge mask
- Power flux density
- Power spectral density
- Combined models

Spectrum emission mask (SEM) model is used in traditional spectrum sharing analysis. The system can use transmitters and receivers with technical characteristics specified in the license. Those characteristics contain, for instance, the spectrum mask the transmitted signal should fit to, the definition of the type and height of the antennas the transmitter can use. At the receiver side, the license specifies requirements for sensitivity, selectivity etc. The target characteristics are enforced by requiring the type approval of equipment.

The SEM specifications pose requirements on a single transmitter and receiver. The interference among the systems is estimated by modeling the network populated with users with specified characteristics. In the ITU recommendations, we can find the basic criteria for the coexistence of various systems: criteria for the coexistence of multiple fixed wireless systems are specified in ITU-R F.1706 [87], and criteria for the coexistence of fixed wireless and other systems are described in ITU-R F.758 [88], criteria for the coexistence of a fixed system and wireless mobile systems are in ITU-R F.1334 [89]. The ECC has recommendations for the coexistence of a TV system and fixed wireless links [90].

Block edge mask (BEM) is an attempt to use technology independent requirements. Compared to SEM, BEM model allows more flexibility for selecting the transmission reception technology. The spectrum license is issued by specifying how much power the transmitter could emit in a certain spectrum area (spectrum block). That is done by giving the spectrum mask the transmitted signal should fit to.

The BEM supposes to contain the minimum set of requirements needed for the peaceful coexistence of different spectrum using systems. The license holder could deploy any technology that meets the BEM requirements. However, after the technology (a particular system) is selected, the interference analysis is still done for this particular system with the system specific parameters.

The BEM model is used in ECC Rec.(04)05 to regulate the coexistence of a point to multi-point (P-MP) and fixed wireless systems (FWS) in the 3.4-3.8 GHz band.

The BEM is a transmitter-specific requirement as it limits the power spectral mask of an individual transmitter. The limitation can be imposed on the transmitted power or on the equivalent isotropically radiated power (EIRP). The constraint using EIRP is more restrictive since it limits the gains provided by directional antennas.

Power flux density (PFD) model describes the aggregate interference from all the transmitters. It is defined as the level of the aggregate interference the system can generate at a certain point. Usually, this point is selected to be at the location of the protected receiver. The SEM and the BEM are constraints imposed on the individual transmitters. The control of each individual transmitter separately is not sufficient if one wants to guarantee some target aggregate interference level.

The PFD is commonly used to protect the radio systems close to countries' borders. In this case, it is defined as the level of the power flux that cannot be exceeded at the border of the neighboring country. A computer tool estimating the power flux over the country borders is described in [91]. The PFD is also used while enforcing the radio silence zone, and radio quiet zones for radio astronomy observation [92].

Aggregate power spectral density (PSD) model describes the allowed aggregate transmitted power. It is measured as the sum over the transmission powers of the transmitters in a given area.

The PFD specifies the interference levels at the receivers, however, these levels are difficult to control. It is easier to control the total emitted power from all the transmitters in a certain area. The control of power density in the area makes the transmitters powers dependent on the powers of the other transmitters.

The PSD model limits the power at the transmitters before the antenna. Since the antenna gain can vary, also the interference level can vary. For guaranteeing the interference levels, the PSD model should be used not only setting the limits on transmission powers but also making assumptions about the types of used antennas.

Hybrid approach is a combination of the various constraints described above. For instance, we could limit the PFD at a certain location but at the same time we could also limit the maximum transmission power of any of the individual transmitters (BEM constraint).

6.2 Interference from wireless data networks

The aggregate interference I is affected by different system layers [93]. In a wireless system, we can identify the following interference impacting factors:

- *Attenuation in the radio channel.* The radio channel is modeled by the mean path loss and fading. The slow and fast fading are usually described separately but both of them can be modeled by random variables.

- *Location of the interfering transmitters*. Different types of networks have different transmitters location patterns. For instance, in a cellular network downlink the base station (BSs) can be assumed to have a regular location pattern and the locations of the BS can even be assumed to be known. This assumption does not hold in an ad hoc network, where the arbitrary locations of transmitters create the additional source of randomness.

- *Activity factor of transmitters*. As all the transmitters are not active at the same time, the level of interference can be controlled by scheduling the access to the spectrum. This control is in the domain of RRM and medium access control (MAC).

These factors are usually considered independent and therefore modeled separately. The uncertainties they generate are specified by distributions and the aggregate interference is described by a random variable

$$I = \sum_j I_j = \sum_j \nu_j P_j g_{ja} \tag{6.1}$$

where we have separated three sources of randomness: ν contains the impact of the transmitters' activity factor and medium access control, P_j stands for the transmission power that might affect a power control, g_{ja} is the attenuation from transmitter j to the location a and it contains both fading and path loss from an unknown transmitter's location.

In a simple case, the activity of the transmitters is assumed to be $\nu = 1$ and power control is absent, $P_j = const$. In this situation, we can assume the only source of the randomness is the radio channel. A direct evaluation of (6.1) can be done by computing the attenuation from each transmitter, scaling the transmission powers and summing all those interfering signals. The single interfering term I_j is modeled by a distribution, since the channel model contains mean path loss and random fading terms. Summation of random variables is a convolution of their distributions. Usually, such convolution does not have a closed form expression and for the most common fading distributions, approximations have been proposed.

In Publication II we computed the aggregate interference in a shadow fading channel. It is conventional to replace the sum of log-normally distributed shadowed interferers' with a new log-normal random variable

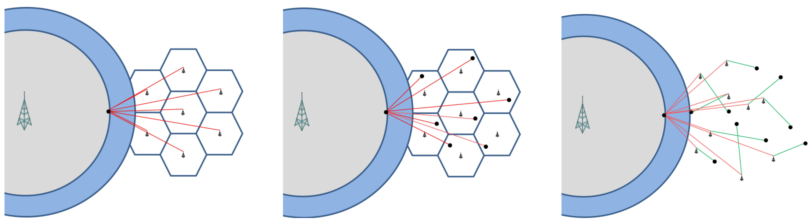
$$\sum_j P_j 10^{0.1(\mu + x_j)} \Rightarrow 10^{0.1(\mu_s + z)} \tag{6.2}$$

where the left side contains the channel model from (3.2), μ_s is the aggregate mean interference and z is the new Gaussian distributed random variable with mean zero and variance selected to match the moments of the distribution of the sum in the right side.

Currently, the exact distribution of the sum of the log-normally distributed random variables is unknown. The two most common methods for finding approximation to this sum are the Schwartz-Yeh method [94] and the Fenton-Wilkinson method [95]. In contrast, the Schwartz-Yeh method computes the approximation in the log domain by summing up the elements one by one. The Fenton-Wilkinson method selects the random variables, μ_s and z, on the left side of (6.2) to have the mean and variance the same as the mean and variance of the actual sum on the right.

The sum in (6.2) can be approximated also for other fading environments when the fading variable x has different distributions. For instance, in [96] are given models for Rayleigh, Rician, Suzuki, Log-normal and Nakagami-M channels. A study of interferers with gamma distribution is made in [97].

The two most common network structures for providing wireless data connections are cellular and ad hoc networks. The main difference between these two networks is that a cellular network can be modeled with regular layout of transmitter while in an ad hoc network the transmitters are located randomly. Based on these differences, we can distinct among three different cases: cellular system downlink, cellular system uplink, ad hoc system. These systems are illustrated in Fig. 6.1.



(a) Cellular DL **(b)** Cellular UL **(c)** Ad hoc

Figure 6.1. Interference from wireless networks a) cellular downlink, b) cellular uplink, c) ad hoc network.

A downlink of a cellular network is served by a BS. Usually, the BS transmitter is located in the center (or corner) of the cell and the antenna is relatively high. In the uplink of a cellular system, the transmitters are the cellular users. The users could be located anywhere in the cell. In an ad hoc network, the locations of transmitters are modeled to be fully random. These three different distributions of transmitters result in different intersystem interference models.

6.2.1 Cellular system downlink

A model for a cellular system downlink was initially devised for broadcasting systems. In broadcasting systems, we have a high power TV tower surrounded by the service coverage area. In early TV networks, the frequency reuse was very sparse and the coverage area was evaluated solely based on the signal-to-noise ratio at the cell border. When the TV frequency reuse became denser, a cellular approach was proposed. In a cellular approach each TV coverage area is modeled as a cell with a transmitter located at the center (or at the border) of the cell. At the end of the 1970's, the cellular approach was adopted to describe cellular mobile networks [98] [20].

In the context of a cellular network, the initial interference studies were concerned about guaranteeing a sufficiently good SINR for the users at the cell border [20]. In early cellular networks the interference at the cell border was controlled by selecting an appropriate frequency reuse factor. The reuse factor is selected by computing the interference for various frequency reuse patterns and selecting the smallest reuse that still satisfies the SINR constraint at the cell border. Searching for the frequency reuse can be described as a graph coloring problem [99]. The network is described as a graph where vertexes represent the cells and edges connect the cochannel cells and the coloring describes the frequency allocation.

Most modern cellular systems use in each cell the same frequency. In reuse *one* networks the interference is controlled dynamically. The frequency allocation is decided based on the instantaneous interference condition in the network. In a cellular downlink the interference condition is computed from Eq. (6.1) by evaluating the attenuation from each BS transmitter, scaling the transmitted powers and summing over all the received interfering signals. Since the computation procedure is relatively simple, the studies have extended the interference modeling to include more advanced system properties. For instance, in [100] the interference model also contains power control. Some of the downlink interference models also incorporate the activity of transmitters by estimating the average transmission power from a state model describing the transmission activity of the transmitter [101] or by simply scaling the interference with the user activity factor [102].

6.2.2 Cellular system uplink

In a cellular system uplink, the transmissions come from the users located anywhere inside the cell. Since these locations are not known, the model has to incorporate a method of describing the distribution of interfering transmitters. Usually, the interference is modeled as average interference. CDMA and ALOHA multiple access schemes do averaging implicitly. Both of these access methods permit multiple active transmitters in a cell. The transmitters' transmission activity and locations can be assumed to be independent and random. Interference from such independently located transmitters can be modeled by a Poisson point process (PPP) [103]. By using the PPP model, we can easily describe the moment generating function (MGF) of the interference distribution (such computation is described also below in Section 6.3.1).

In a cellular uplink, the PPP model can be extended to incorporate the power control and handoff [104]. In [104], the interference is described by computing the mean and variance of the SINR. Due to the model complexity, in this publication the suitability of the model is illustrated by evaluating the moments numerically and comparing them with the ones acquired from simulations. In [105], the PPP model is used to compute the single user outage probability as a function of the number of active users in a CDMA network. The results in [105] are mainly illustrated by using numerical evaluation but it provides also a Chernoff bound for the outage.

6.2.3 Ad hoc networks

An ad hoc network is defined as an infrastructureless wireless network. It can be modeled as randomly located pairs of transmitters and receivers. The interference modeling problem in ad hoc networks is usually related to the need to find the SINR at an arbitrarily located receiver. Good overviews of interference modeling methods in ad hoc networks can be found in [106] [107] and [108].

The interference modeling in ad hoc networks is dominated by two approaches, protocol models and physical models [109].

The protocol model is a suitable approach if the interference is dominated by a single neighbor. According to this model, we do not evaluate the interference directly. The model replaces the interference computation by enforcing exclusion areas. The receiver is surrounded by a protection zone (circle) where the interfering transmitters cannot transmit. Because of the simplicity of the model, it is commonly used in the studies of higher layer protocols.

The protection zone conditions can be described as the requirement that the distance to any interfering transmitter r_{ji} is more than a scaled distance of the communication link r_{ii}.

$$r_{ji} \geq (1 + \Delta) r_{ii} \tag{6.3}$$

where Δ is the scaling factor selected such that the SIR requirement will be satisfied.

The protocol model does not consider the aggregate interference and therefore it is suitable only for studying a sparse network. The aggregate interference is incorporated into a more complex physical model [109] which describes the SINR of each user. The physical model does not require exclusive spectrum usage area and it can take into account the capture property. The model allows a gradual increase of the interference and therefore the interference can be generated as long as the reception is possible.

The protocol and physical models have many similarities [110]. In the protocol model, the exclusion area defines the density of active transmitters. In [110], it is shown that the density of the active transmitters in the protocol model can be selected to be the same as the density of the users in physical model. Such a relation allows us to connect the protocol model with the generated aggregate interference and to use this connection for guaranteeing a certain SINR level.

The physical model describes the interference as a function of transmitter spatial distributions. If the transmitters are located independently and uniformly, the interference can be computed from the PPP model. The PPP model is also modified for a non-uniform (clustered) distribution of transmitters [111]. It turns out that compared with the clustered interferers' model, considered in [111], the uniform PPP model provides a lower bound to the interference. An overview of various PPP-based derivation of spatial interference models can be found in [108].

A PPP model is suitable for characterizing an ALOHA type medium access scheme where each transmitter could transmit independently. Usually, the medium access scheme does not allow an arbitrary transmission. For instance, a CSMA/CS protocol reserves a protection area. The transmitters is surrounded by the area where no other transmitter will be active. This kind of reservation is modeled by a Matern process [112]. Differently from PPP, the Matern process is not analytically tractable. When using the Matern model, the moments of the interference distribution have to be evaluated numerically.

6.3 Modeling of the aggregate interference from a secondary system

The current secondary spectrum usage rules by the FCC [18] and the ECC [17] administer mainly a single secondary transmitter. Interference from a single transmitter is much easier to control than that from multiple transmitters. An economically viable secondary data transmission system would contain multiple transmitters. Most of the models that are describing the secondary system aggregate interference have evolved from the need to describe the internal interference of some radio system. We can find models that compute the sum of powers from discrete transmitters and we can also find modified PPP-based models.

A straightforward approach to aggregate interference modeling is summing up all the interfering powers. In [113], such a sum is found for a cellular secondary network surrounding the TV coverage area. The source [113] finds how many cells are surrounding the TV coverage area and then computes the interference from this number of cells.

It is difficult to compute the interference from a large number of secondary transmitters. We can simplify the computation by clumping the transmitters together. After clumping, the interference is not treated as from discretely located transmitters but as coming from a "sea" of transmitters which is described by the power density emitted from a unit area [114], $P_d = \frac{P_s}{A_f}$, where P_s is the secondary transmitter transmission power and A_f is the "footprint" of the transmitter. The footprint describes the area allocated for one transmitter. The footprint can be interpreted as the area of the network divided by the number of cochannel transmitters in the network. In a cellular network, the footprint contains the cell area and the co-channel protection area surrounding it.

The "sea" model allows us to compute the aggregate interference by integrating the transmission area. In general, such an integral is not analytically solvable. A closed-form solution, describing interference from a half plain is given in [114] where the interference model is derived for the case when the secondary transmitters cover an area that is bordered with a straight line. The border line is touching the TV protection area border. The line splits the area into two parts, the TV coverage area is on one side of the line and the secondary transmitters are on the other side of the line. The integral is evaluated over the half plain that is covered with the "sea" of transmitters. It is interesting to note that the interference from this half plain can be expressed as an increase of the path loss exponent $I \approx P_d r^{\beta+2}$, where r is the distance to the protection area border. The results of [114] are also validated in [115].

An alternative treatment of interference is based on the usage of the PPP model. Unlike traditional PPP models, the secondary system transmitters are located outside of the TV protection area. Like the "sea" model, also the PPP approach derives the interference parameters by integrating the whole secondary system deployment area. The closed-form solution of the PPP-based interference model can be found in [116]. In [116], the moments of the interference distribution are found by integrating from the protection area border to infinity. The PPP model indicates that for certain cases the interference distribution resembles a Gaussian distribution. The Gaussian approximation is suitable for a relatively high density of secondary transmitters [117].

In the next section, we compare the moments of the interference computed by using PPP and the "sea" models.

6.3.1 Aggregate interference from a Poisson Point Process

The interfering signal from location a is expressed as $I_{1,a}(P_s, x) = P_s g(r_{ai})x$ where r_{ai} is the distance from location a to the point i where the interference is computed, $g(r_{ai})$ is the corresponding average path loss, P_s is the transmission power, and x is the random variable describing the fading. The distribution of this signal can be constructed by combining the distributions of the transmission power, fading and probability that the transmitter is located at a,

$$p(I_{1,a}) = p_P(P_s)p_X(x)p_A(a) \tag{6.4}$$

where $p_X(x)$ is the fading distribution and $p_A(a)$ is the probability density at location a (the location probability of the user). Without power control, the power is constant $p(P_s) = \delta(P_s)$ where $\delta(\cdot)$ is the Dirac delta function. Assume that the user can be located anywhere in the secondary system coverage area A. The interference $I_1(x)$ from such a single user is described by averaging the interferences from the possible user locations

$$I_1(x) = P_s x E\{g(r_{ai})\} = P_s x \int\limits_A g(r_{ai})p_A(a)\,da. \tag{6.5}$$

For uniformly distributed users $p_A(a) = \frac{1}{A}$. The moment generating function of the interference distribution is

$$M_1(s) = \int\limits_x p_X(x) \int\limits_A e^{sxP_s g(r_{ai})} \frac{1}{A} dadx. \tag{6.6}$$

As the PPP model says, the probability of having k users in an area is given by the Poisson distribution

$$\Pr(k) = N^k \frac{e^N}{k!} \tag{6.7}$$

where N is the average number of users in the area A and it is computed as $N = \lambda A$ where λ is the node density per unit area.

The average moments over the amount of users are given as

$$F(s) = \sum_{k=0}^{\infty} E\{M(s)|k\} \Pr(k). \tag{6.8}$$

The conditional moments of interference from k independent transmitters are

$$E\{M(s)|k\} = M_1(s)^k. \tag{6.9}$$

By using (6.7) and (6.9) in (6.8) we get the moment generating function for the aggregate interference distribution [118]

$$F_P(s) = \sum_{k=0}^{\infty} E\{M(s)|k\} \frac{N^k e^{-N}}{k!} = e^{N(M(s)-1)}. \tag{6.10}$$

We compare the interference moments of the PPP with the moments of the interference from a cellular system by using the same power density in both systems

$$P_d = \frac{P_s}{A_f} \tag{6.11}$$

where $A_f = \frac{A}{N}$ and A_f is the footprint of one transmitter.

The mean and the variance of the aggregate interference can be computed from the first two derivatives of (6.10). In this computation, we use (6.11) and get

$$E\{I_P\} = F'(s)\big|_{s=0} = P_d E\{x\} \int_A g(r_{ai}) da \tag{6.12}$$

$$\begin{aligned} E\left\{I_P^2\right\} &= F''(s)\big|_{s=0} \\ &= P_d^2 A_f E\left\{x^2\right\} \int_A g^2(r_{ai}) da + P_d^2 \left(E\{x\} \int_A g(r_{ai}) da \right)^2 \end{aligned} \tag{6.13}$$

where I_P stands for the aggregate interference from the PPP.

6.3.2 Aggregate interference from a cellular system

Assume a cellular system deployed in the area A with one cell footprint A_f. In the center of each cell is a BS using transmission power P_s. The interference from such a system can be directly computed by summing the interference from each individual transmitter j.

$$I_C = \sum_j^N P_s x_j g(r_{ji}) \tag{6.14}$$

where $N = \frac{A}{A_f}$ is the number of cells in the area, x_j is the fading from the BS j, i describes the location where the interference is evaluated. Again we assume no power control and describe the fading by the distribution $p_X(x)$.

The first moment of the interference is

$$E\{I_C\} = P_s E\{x\} \sum_j^N g(r_{ji}) \tag{6.15}$$

where $g(r_{ji})$ is the average path loss from transmitter j to location i, and in each path the mean path loss is the same, $E\{x\} = E\{x_j\}\ \forall j$.

The second moment of the interference from a cellular system is

$$E\left\{I_C^2\right\} = P_s^2 \sum_n \sum_m g(r_{ni}) g(r_{mi}) E\{x_n x_m\} \tag{6.16}$$

$$\begin{aligned} &\approx P_s^2 E\left\{x_n^2\right\} \sum_{n=m} g(r_{ni}) g(r_{mj}) \\ &\quad + P_s^2 E\{x_n x_m\} \sum_{m \neq n} g(r_{ni}) g(r_{mi}). \end{aligned} \tag{6.17}$$

We assume an independent fading with the same mean at all the locations. In this case, the cross terms can be assumed to be equal to the power of the mean $E\{x_n x_m\} = E^2\{x\}$ and we get

$$\begin{aligned} E\left\{I_C^2\right\} &= P_s^2\left(E\left\{x_n^2\right\} - E^2\{x\}\right)\sum_{n=m} g(r_{ni})g(r_{mj}) \\ &\quad + P_s^2 E^2\{x\}\sum_{n,m} g(r_{ni})g(r_{mi}) \qquad (6.18) \\ &\approx P_d^2\left(E\left\{x_n^2\right\} - E^2\{x\}\right) A_f \int_A g(r_{ai})^2 da \\ &\quad + P_d^2 E^2\{x\}\left(\int_A g(r_{ai}) da\right)^2 \qquad (6.19) \end{aligned}$$

where in (6.19) we replace P_s with power density and approximate the sums with integrals

$$\begin{aligned} \frac{1}{A_f}\sum_n g(r_{ni})^2 A_f &\approx \frac{1}{A_f}\int_A g(r_{ai})^2 da \\ \frac{1}{A_f^2}\sum_n\sum_m g(r_{ni})g(r_{mi})A_f^2 &\approx \left(\frac{1}{A_f}\int_A g(r_{ai}) da\right)^2. \end{aligned}$$

Comparison of the interference from a cellular system and from a PPP

In Publication II, we derived the equation describing the aggregate interference from a cellular system in a shadow fading environment. We noticed that the moment matching method by Fenton-Wilkinson allows us to derive easily the first and second moments of the aggregate interference (Eq. (6.15) and (6.17)). The Fenton-Wilkinson approximation replaces the sum of log-normal distributed random variables with a new log-normal random variable that has the same mean and variance. This replacement is illustrated in Eq. (6.2) above. Such an approximation allows us to bring the fading mean and variance in front of the summations in Eq. (6.15) and (6.17). This is similar to the operation done in Eq. (6.5).

Interestingly, the cellular and point process have the same mean interference (the first moment is the same). The difference is in the second moment. We see that the variance of the interference from the PPP is higher than the variance from a regular cellular system. The non-central moments are

$$\begin{aligned} E\left\{I_C^2\right\} &\approx P_d^2 E\left\{(x - E\left\{x\right\})^2\right\} A_f \int_A g(r_{ai})^2 d_a \\ &+ P_d^2 E^2\left\{x\right\} \left(\int_A g(r_{ai}) d_a\right)^2 \end{aligned} \tag{6.20}$$

$$\begin{aligned} E\left\{I_P^2\right\} &\approx P_d^2 E\left\{x^2\right\} A_f \int_A g(r_{ai})^2 d_a \\ &+ P_d^2 E^2\left\{x\right\} \left(\int_A g(r_{ai}) d_a\right)^2 . \end{aligned} \tag{6.21}$$

These two second moments are related as

$$E\left\{I_C^2\right\} + P_d^2 E^2\left\{x\right\} A_f \int_A g(r_{ai})^2 da = E\left\{I_P^2\right\}. \tag{6.22}$$

A can be seen in Fig. 6.2, the contribution of the first parts of the sums in (6.20) and (6.21) is small. Therefore, both variances are very close to each other and we can approximate the variances as

$$E\left\{I_C^2\right\} \approx E\left\{I_P^2\right\} \approx P_d^2 E^2\left\{x\right\} \left(\int_A g(r_{ai}) d_a\right)^2 . \tag{6.23}$$

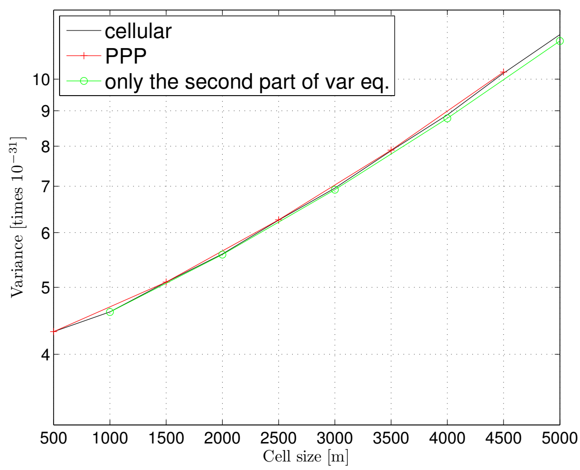


Figure 6.2. Variance of the aggregate interference computed for cellular and PPP models evaluated as a function of the cell footprint A_f. For comparison is also provided the value of the common term in the interference Eq. (6.23).

In Publication II, we extend the aggregate interference computation model proposed in [114] to also contain shadow fading. This publication also describes the algorithm that simplifies the numerical evaluation of the aggregate interference. The proposed quick evaluation method allows us to study the interference from a large area. By using this algorithm, we are able to describe how the size of the secondary network affects the interference level. In Fig. 6.3, it is illustrated how the interference will change if the area from where the interference is calculated is increased. (The details of the computation used for generating Fig. 6.3 are given in Publication II).

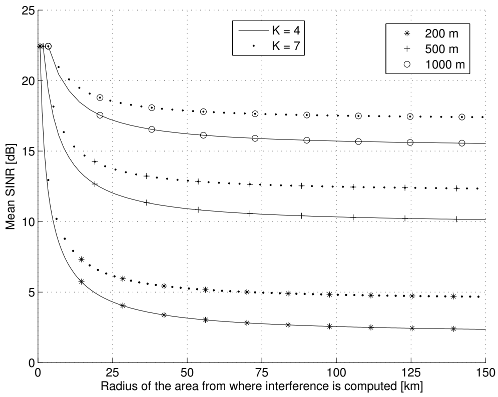
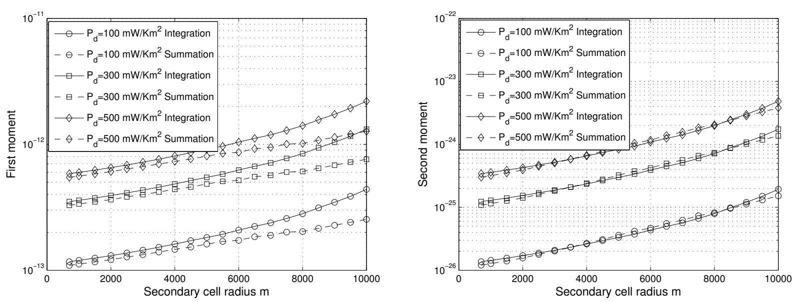


Figure 6.3. SINR if the area from where the interference is computed is changed. K describes frequency reuse in the cellular system. A different set of curves correspond to different cell sizes, $200, 500, 100$ m.

The applicability of the "sea" model depends on how well the approximation in (6.20) holds. In Publication III, the model is tested by evaluating the interference directly and comparing it with the results from the "sea" model. The model turns out to be suitable even when the radius of the cells is as large as 4 km (see Fig. 6.4, the details of the computation are described in Publication III).



(a) mean **(b)** variance

Figure 6.4. Comparison of the aggregate interference computed as an integral over power density and as a sum over interference from individual transmitters in a cellular network.

6.4 Discussion

The intersystem interference modeling has its roots in system licensing. Traditionally, the spectrum usage license is issued for a certain system with predefined transmitter receiver characteristics. Such licenses limit the spectrum users' freedom to select among competing technologies. A new trend in the spectrum licensing is not to define the system that can use the spectrum but only to pose constraints on the interference the spectrum user is able to generate for other users. The license owner is free to select any technology as long as the selected technology meets the constraints described in the license.

After selecting the technology, the technology independent license owner still has to estimate the interference the particular selected system will generate. Such computation can be done by general interference estimation models. The suitable models are categorized as direct sum-based models or statistical models.

The direct sum-based model estimates the generated interference by summing up the interfering power from each transmitter. Such a model requires information about the transmission powers, the locations of transmitters, and attenuations on the channels. For a large number of transmitters, the direct sum computation becomes time-consuming.

A statistical model does not consider the particular location of each transmitter. It describes the system by corresponding distributions: distribution of locations, distribution of transmission powers, distribution of attenuations in the channel. The models expresses the disturbance at the receiver as the distribution of interfering power.

The most commonly used statistical model is the PPP model. The PPP model assumes that each transmitter is arbitrarily located in the service coverage area. According to PPP model each transmitter can transmit independently, therefore the suitability of PPP model to describe a wireless system with scheduling protocols has been questioned. A scheduling can be modeled as no transmission area around the transmitter. In order to describe the scheduling process the PPP model has been modified, for instance, by introducing an exclusion area around each located transmitter as is done in the model with the Matern process [112].

In Publication II and Publication III we studied the interference generated by a cellular system. In the considered system, each cell has one active transmitter. In Publication II the interference distribution from such a cellular network is derived. In this chapter, we illustrate that for the same power density the interference distributions from a cellular system and from a PPP process are very similar. The mean interference levels of those models are the same and the difference in the second moment is relatively small.

7. Wireless network capacity

Whether the white space will be opened for secondary use or not depends on how attractive it is economically. While analyzing the TVWS, we are not only interested in how much spectrum is available but what data rate density we can support in the available spectrum. Wireless data transmission systems are compared based on the data rate density per area [bit/s/Hz/km^2] they can offer. Since the capacity of a wireless network is not known we can express only the achievable data rate for a particular network implementation. This is not the capacity in a Shannon sense since it is not proved to be the maximum achievable data rate in the system. However, because it describes the achievable data rate for a particular network implementation it is often known as the wireless network capacity. In this chapter we use the *capacity* term as it is used in the context of the wireless networks.

In this Chapter we consider again the ad hoc and the cellular networks (See Fig. 7.1). The cellular system capacity is an important parameter used in the network planning and therefore it is extensively studied and modeled. However, in the planning process, the technology the planned system will use is known. In TVWS study, we have to describe the capacity of a hypothetical system. We do not have equations describing the capacity of a general wireless network. While estimating the capacity of a cellular system in the TVWS, we considered the simplest cellular system model. We wished to disengage our model from any specific technical solutions. The derived results describe the capacity in the worst case situation when the cellular system does not use any advanced capacity enhancement methods. Such capacity description can be the basis for the initial spectrum value estimation. After all, the white space will be used by some new emerging technologies and in the future the system capacity still has to be re-evaluated for particular yet unknown methods.

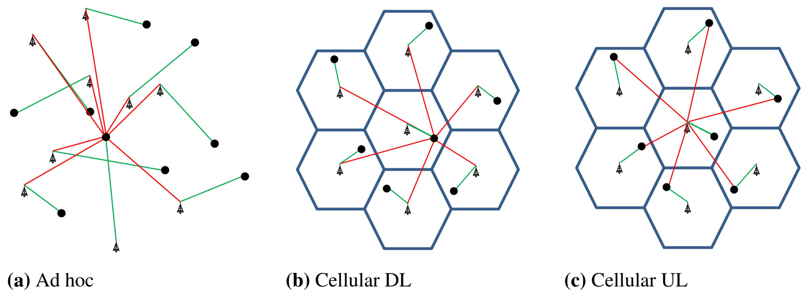


Figure 7.1. Network models a) ad hoc network, b) cellular down link, c) cellular uplink.

7.1 Ad hoc network capacity

If in an ad hoc network the transmitter directly communicates with the receiver, we have a single hop network. If this is not possible, intermediate transmitters have to forward the message and the network is called a multihop network.

The ad hoc network capacity can be described as *transport capacity* or *transmission capacity*. The *transport capacity* is defined as the end-to-end throughput scaled with the end-to-end distance [109]. The throughput of the network is limited by the interference level. In ad hoc networks, the interference is a random variable that depends on the locations and the density of transmitters. The *transport capacity* is usually expressed and studied as a function of the user density per area [109].

The *transport capacity* is not a good measure for characterizing single hop networks which are better described by the achievable rates on the links, the *transmission capacity* [119]. The *transmission capacity* is defined as the number of successful transmissions in the unit area normalized by the transmission attempts in that area. Like the *transport capacity*, also the *transmission capacity* depends on the density of transmitters. In the literature, we can find models that compute the *transmission capacity* in the case of nonuniform distribution of nodes [120] or in the case of transmitters using space time multiple access [121].

The *transport* and *transmission capacities* can be evaluated analytically only for very simple systems. Usually, the analysis contains the assumptions that the network covers an infinite area and the noise level is uniform over the whole area. The resulting closed-form equations are not directly applicable to describe realistic network configurations. For instance, in TVWS the interference level in the secondary network is affected by interference from TV transmitters. Such additional interference is nonuniform and currently we do not have a model accounting for its impact on ad hoc network capacity.

7.2 Cellular network capacity

A cellular network is an infrastructure-based system that covers the service area with a cellular structure. A classical cellular system has cell sizes from a few hundred meters to tens of kilometers. With the advent of femtocells, the difference between single hop ad hoc and cellular system models has become somewhat vague. The femtocells are small cells that are allocated relatively randomly. A network with such cells resembles more an ad hoc network than a traditional cellular system. In our studies, we used only a classical interpretation of cellular systems.

A cellular system serves multiple users in a cell. As explained in Chapter 3 the capacity of a system with multiple users is described as the closure of tuples of achievable data rates of individual users. The achievable data rates depend on the radio technology used in the system, instantaneous attenuations in the channels between the users, and the scheduling technology used in the system.

A particular system operates at the certain point of the capacity region, it selects one tuple of user data rates. The capacity of a system can be described by the sum of the data rates in the selected tuple (one number only). For one cell, this number describes the cell capacity, i.e. cell throughput.

In the publications, we described the achievable capacity of a secondary cellular system. This is achieved by computing the throughput in individual cells. In general, this description requires that we specify the physical layer technology of the cellular system. We have to decide whether we describe the capacity in uplink of downlink, what kind of advanced technologies the system uses, and what kind of scheduling method is applied.

A cell has a very particular communication structure. The transmission from the BS to users is a communication from one to many. It is called downlink and often described as a broadcast channel (BC), see Fig. 7.1b. The transmission from the users to the BS, uplink, is a communication from many to one and described also as a multiple access channel (Fig. 7.1c).

Uplink and downlink operate in different interference conditions. The capacity achievable in uplink is usually less than in downlink [73]. However, most of the Internet services generate more traffic in downlink. Because of this unbalanced traffic, the service quality is considered to be limited by the downlink capacity. The downlink is also more critical in the aggregate interference analysis. As shown in [122], more than sixty uplink transmitters are required to produce aggregate interference equal to the interference generated by one BS in downlink.

It is relatively easy to compute the capacity of a single cell. In that case, the intercell interference does not exist and the sum capacity depends only on the location of the users in the cell. The equation describing the cell throughput with proportionally fair scheduling can be found in [123] or in [124]. The analysis in [124] also contains the capacity model that contains the impact of a fading channel. The impact of the scheduling on the cell capacity is elaborated later in this section.

The single cell capacity approximates reasonably well the capacity of the cells in a network with high frequency reuse. If the nearby cells use the same frequency, we will not be able to ignore the intercell interference and therefore the single cell capacity differs significantly from the actual network capacity. The classical approach to incorporate the impact of neighboring cells is to describe the intercell interference as the fraction of the own cell interfering power α_I [125].

$$\gamma_i = \frac{P_i g_{ji}}{(1+\alpha)\sum_{j\neq i} P_j g_{ji} + P_n} \tag{7.1}$$

where γ_i is the SINR at receiver i, $P_i g_{ii}$ is the useful signal power and the corresponding attenuation, $\sum_j P_j g_{ji}$ is the interfering power from all the transmitters simultaneously active in the cell and α is the scaling factor that considers the neighboring cell interference. The model (7.1) stems from CDMA networks where the interference is dominated by interference from other users in the same cell. Howerver, the use of the model is not limited to CDMA networks. It has been successfully applied to approximate SINR in TDMA based networks [126] [127].

Planners compute the network capacity for the particular system they are about to roll out. The system uses a specific multiple access scheme which is used in the capacity computation. To describe the capacity of a general cellular system, it is necessary to decide how to consider the impact of the multiple access.

The multiple access scheme which provides the highest network capacity has been long debated. Initially, it was assumed that CDMA offers higher capacity than TDMA or FDMA [102]. In those initial studies, the CDMA system contained advanced capacity enhancing methods such as, power control and voice activity factors. It turned out that with rate adaptation and advanced scheduling, the capacities of TDMA and FDMA systems are nearly the same as the capacity of CDMA-based systems [128] [125].

The network capacity is highly dependent on the system ability to use the spatial dimension. We can find capacity studies investigating the impact of MIMO [129] [130] [131] [132], directed antennas [133] [134] [135] [136], advanced frequency allocation methods [137] [138] [139] [140], and cooperative transmission between the users [141] [142] [143]. These advanced methods use sophisticated signal processing and their performance is implementation dependent. Most of these methods make the network capacity computation to be relatively complex. In describing available capacity in TVWS we prefer a simple model that can quickly be evaluated in a country-wide network. By omitting these complex methods, it is possible to obtain a lower bound for the available data rate.

In early versions of GSM the cell capacity was limited by the data rate guaranteed to the user at the cell border. At that time, the technology was not able to take advantage of SINR differences inside the cell and all the users had to be served with the same data rate. In order to guarantee the connection quality to all users in the cell the data rate in the cell was bound by the SINR at the cell border.

The SINR conditions at the cell border can be improved by using different frequencies in adjacent cells. The frequency band is divided into K sub-bands, where K is the frequency reuse factor. The frequencies are allocated with such reuse pattern that the distance between cells using cochannel bands is maximized [20]. The frequency reuse improves the SINR at the cell border but at the same time it reduces the bandwidth allocated to the cell. The reduction of bandwidth is usually compensated by using complicated frequency allocation algorithms [137] [138] [139]. However, simulations indicate that by using the whole bandwidth in all the cells offers about the same capacity as can be achieved with higher frequency reuse factors that are combined with complex frequency allocation algorithms [140].

Which tuple of possible achievable user data rates is selected depends on how the system schedules the users, i.e. how the system shares the available resources. In general, the scheduling algorithm strives for the fair allocation of resources [144]. However, the definition of what is fair is up to the system designer. Two common scheduling algorithms are Max-Min fair and round robin scheduling. The former attempts to equalize the data rate of all users and the latter equalizes the time share allocated to the users [145].

In a cellular system, the SINR depends on the user location in the cell. Near to the BS the SINR is higher than at the cell border. In time division multiplexing the system selects a user and schedules its transmission. The achievable data rate for this user depends on its SINR and how long it can transmit. The capacity of a cell with adaptive modulation and coding can be computed by evaluating the data rate at each location in the cell and using a weighted average over those data rates. The weighting function is selected to reflect the time share each user will use for its transmission.

The interference situation in the cellular downlink is illustrated in Fig. 7.1b. For a particular location a the SINR is

$$\gamma_a = \frac{P_i g_{ia}}{\sum\limits_{j \neq i} P_j g_{ja} + P_n} \tag{7.2}$$

where P_i is the transmission power from the BS in the cell and P_j are the powers of neighboring cells, g_{ia} and g_{ja} are attenuations from the corresponding BS to the location a. The corresponding data rate at location a is $R(a) \leq C(\gamma_a)$.

The round robin scheduler allocates the equal time share to each user. As a result, all data rates are used equally. With uniform user density in the cell, the capacity can be expressed as the average of data rates $R(a)$ in the cell

$$C_{RR} = \int_A R(a)da \tag{7.3}$$

where the integral is over the cell area A.

Notice that with the round robin scheduling the users near the BS will have higher data rates than the ones at the cell border. As the name indicates, the Max-Min fair scheduling attempts to maximize the minimum data rate [145]. It does it by allocating less time share for users having higher data rate and more time share to the users having lower data rate. If the allocated time shares are selected as $t(a) = \frac{1}{R(a)}$, all users will be served with the same data rate

$$C_{MM} = \frac{1}{\int_A \frac{1}{R(a)}da}. \tag{7.4}$$

The capacity C_{MM} also describes the average service rate in the cell.

In a practical system, (7.3) and (7.4) have to be evaluated numerically. The TVWS covers the whole country. In such a large area, the numerical evaluation of (7.3) and (7.4) is time-consuming. Therefore, in our analysis in Publication IV, the cell capacity by the throughput at the cell border is described. The cell border throughput describes the worst SINR in the cell and provides the lower bound for the cell capacity.

The results are computed for a system where the TV coverage area is surrounded with no transmission area. The cellular system covers the space outside of the no transmission area (the set up is illustated in Fig. 3.2). The x describes the size of the no transmission area.

In Publication IV, we study the achievable capacity of a secondary cellular system. We describe an algorithm that helps to find the capacity maximizing power allocation among cochannel and adjacent channel transmitters. In one channel, cochannel or adjacent channel, all the transmitters use the same transmission power level. The optimization algorithm searches for power levels such that the total capacity over the cochannel and adjacent channel is maximized. The power level is computed by estimating the maximum power density that still meets the interference constraint on the TV receivers. The interference level is computed by assuming a TV coverage area that is surrounded by a no transmission area with size Δ. The setup is illustrated in Fig. 3.2. The found capacity at the cell border is illustrated in Fig. 7.2. (The details of the computation process are provided in Publication IV.)

It is interesting to note that for all selected cell sizes the adjacent channel has enough power to drive the cells to operate in a power-limited range. In that range, the cell border capacity is limited by the interference from other cells and for all cell

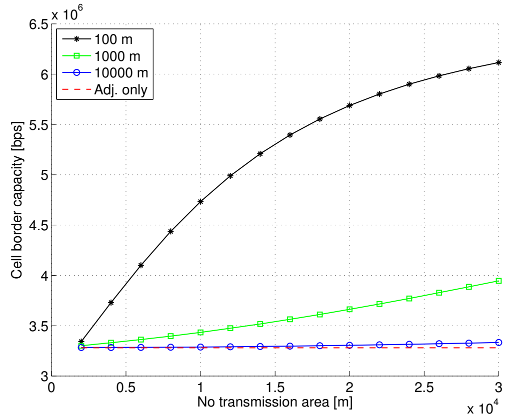


Figure 7.2. Capacity of the secondary cellular system as a function of the no-transmission area (x axis) surrounding a TV coverage area (see system model in Fig. 3.2). The capacity is expressed as the sum of the capacities on cochannel and adjacent channel. The capacity is computed as the minimum capacity observed at any of the secondary cell borders. The minimum capacity is maximized by finding the power allocation for the cochannel and adjacent channel such that the SINR target at the TV cell border is satisfied. The secondary system has hexagonal cells and covers the whole area available for it. The computations are made for networks with cell radiuses $100, 1000, 10000$ m. The TV system parameters are: transmission power 200 kW, TV cell size 140 km, TV target SINR 15.4 dB, and path loss exponent 3.2.

sizes the cell border capacity is about the same. In cochannel, the allocated power is not sufficient to drive the large cells into a power-limited range. The noise level still has significant impact on the SINR level and therefore the capacities of the networks with different cell sizes vary significantly.

7.3 Discussion

In this chapter, we describe the capacity of a wireless network. Such a description is needed for assessing the achievable data rate of a secondary system.

Currently, the capacity of a general wireless network is not known. For practical purposes, the capacity is defined as the achievable capacity of the particular network implementation. The achievable data rate is described as the closure of the vectors of the achievable data rates of all users. Which point in the closure is selected depends on how the system schedules the users.

The achievable data rate depends on the physical layer implementation. For instance, the network capacity can be improved by employing MIMO, directed antennas, only using cooperative transmission, etc. How to quantify the impact of the combinations of those methods is still not well understood. While assessing the value of TVWS we assumed the simplest wireless system. The results describe the lower bound of the capacity since they do not consider the impact of any of the advanced methods.

In this chapter we described the system capacity with Max-Min and round robin scheduling. The capacity evaluation contains integration over the cell coverage area. Such integration has to be evaluated numerically and for a large network it is time consuming. The capacities of the systems using these scheduling methods are lower bounded by the data rate of the user with worst SINR. In a cellular setup the user with the worst SINR is located at the cell border.

We use the data rate of the user at the cell border to describe the achievable data rate of the cell. The data rate of the cellular system is evaluated by computing the capacity of each cell. This simple description makes the least assumption about the technology the secondary system deploys.

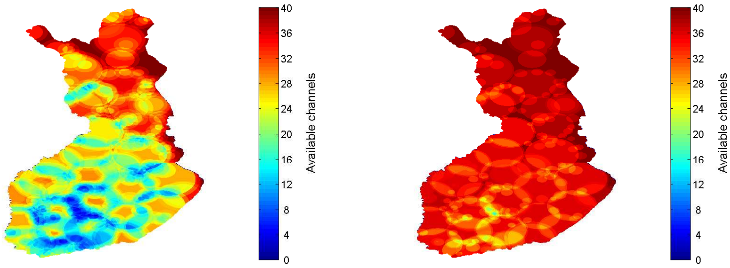
8. Amount of available white space in Finland

At the current stage of the TVWS studies, there is a need to estimate the amount of available spectrum and to estimate the business value of the spectrum. On the one hand, the secondary system has to satisfy the constraints posed by primary connections. On the other hand, the secondary system has to meet its users' demands. In order to meet these constraints, the spectrum allocation can be done through an iterative allocation process.

A secondary system with fixed cells can use only certain transmission power levels. If the available levels area not sufficient to meet the expected users demand, it is necessary to change the secondary system configuration and to evaluate the new set of available transmission power levels. We continue with such iterations till a satisfactory configuration is found. If there is no configuration that satisfies the constraints, we can claim that there are not enough resources available, i.e. there is no spectrum opportunity.

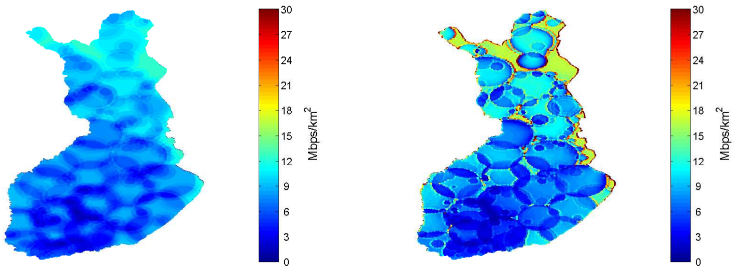
After the FCC fixed the spectrum usage rules, it became possible to compute the amount of available spectrum. The most extensive country-wide estimation of the amount of available spectrum has been made in [146]. In Publication VII we followed the approach used in [146] and the TVWS estimation for both FCC and ECC spectrum usage rules. Additionally, we studied how those rules protect the TV receivers if the secondary system is a country-wide cellular network. By using a cellular network as the secondary system, we were able to estimate the secondary system capacity. The computed amount of available spectrum and the achievable data rate are described in Fig. 8.1 and 8.2 respectively. Capacity per area in Finland is expressed also by its cumulative distribution function (CDF) in Fig. 8.3.

The cellular network approach used in Publication VII provides a realistic estimation of the density of the secondary transmitters. This density is used for computing the aggregate interference in Fig. 8.4. As can be observed, the current rules are not able to fully protect the TV receivers. It turns out that the ECC rules actually provide better capacity and better protection for TV receivers.



(a) FCC **(b)** ECC

Figure 8.1. The number of available channels in Finland calculated based on (a) FCC rules (b) ECC rules. The computation with FCC rules is done with protection distances $r_p = 14.4$ km for the cochannel and $r_p = 0.74$ km for the adjacent channel.



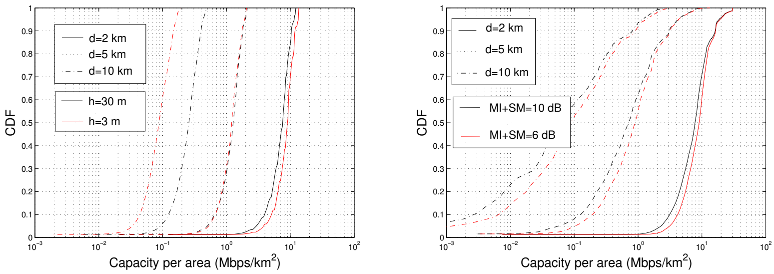
(a) FCC **(b)** ECC

Figure 8.2. Capacity per area calculated based on (a) FCC rules, (b) ECC rules. The computation with FCC rules is done with protection distances $r_p = 14.4$ km for the cochannel and $r_p = 0.74$ km for the adjacent channel. The computation with ECC rules is done with safety margin $SM = 10$ dB. In both systems, the capacity is computed for the secondary cell size $d = 2$ km and antenna height $h = 30$ m.

8.1 Discussion

In this chapter, we evaluated the achievable data rate of a cellular system deployed in the TVWS in Finland. The value of TVWS is not described only by the amount of available spectrum but also by the data rate the secondary system can offer. The achievable data rate was computed by maximizing the achievable capacity given the interference constraint of the primary system.

The white space studies found in the literature either measure the available spectrum or compute the available spectrum. The measurements usually do not indicate the transmission power levels the secondary system can use [1]. The computations of the white space evaluate the amount of spectrum available at certain locations given the coverage area of the TV cells [146]. Such numerical studies are missing the ex-



(a) FCC **(b)** ECC

Figure 8.3. Distribution of the capacity per area calculated based on (a) FCC rules, (b)ECC rules. The computation with FCC rules is done with protection distances $r_p = 14.4$ km for the cochannel and $r_p = 0.74$ km for the adjacent channel. The capacity for FCC based system is evaluated with two different antenna heights h. The computation with ECC rules is done with the antenna height $h = 30$ m and different margins $MI + SM$. The capacities are evaluated for different secondary cell sizes d.

tensive analysis of the secondary system, what transmission powers it can use, and what data rates it provides. For instance, in [146] the secondary system analysis contains intersystem interference but does not evaluate the secondary system aggregate interference at TV receivers.

In Publication VII we outlined the method for computing the capacity of the cellular secondary system operating TVWS. The proposed methodology not only describes the amount of available white space spectrum but also identifies the usefulness of that spectrum.

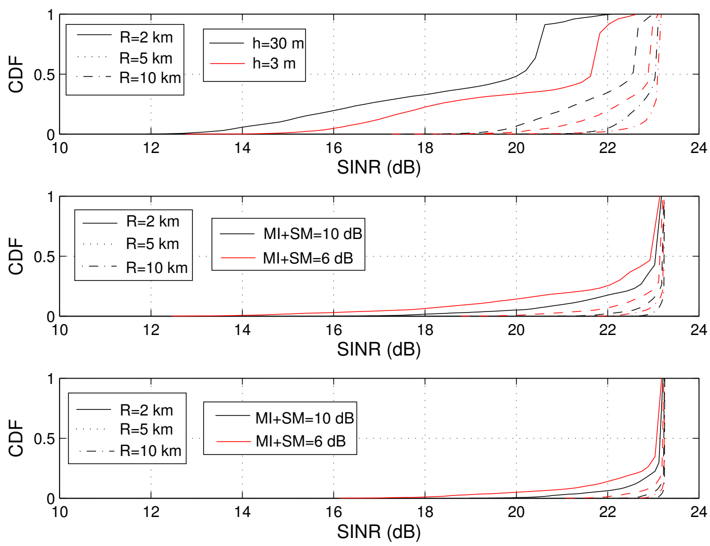


Figure 8.4. Distribution of the SINR at the TV cell borders in the presence of interference from the secondary cellular system. The calculations are made for the systems based on (a) FCC rules, (b) ECC rules with antenna height $h = 30$ m. (c) ECC rules with antenna height $h = 1.5$ m. The computation with FCC rules is done with protection distances $r_p = 14.4$ km for the cochannel and $r_p = 0.74$ km for the adjacent channel. The FCC rules based system is evaluated with two different antenna heights h. The computations for the system with ECC rules are done for two different margins levels $MI + SM$. The SINR is computed by considering the aggregate interference from all the secondary transmitters. The distributions are evaluated for different secondary cell sizes d.

9. Summary

In this thesis, the author analyzes methods that enable TVWS usage for data transmission. The studied questions are related to how to discover the free spectrum, how the secondary transmitters will affect the primary receivers and what data rates a secondary system can provide.

The secondary spectrum access is arranged either by using spectrum sensing or database-based access control.

The sensing-based spectrum access relies on the detection of the primary signal level. A suitable detector should be able to discover primary signals with very low power level. The conventional detectors who use only a single measuring antenna are either very complex or incapable of detecting low signal levels. Such problems can be avoided by using multiple antennas. Detectors using multiple antennas can be made very simple but still provide good performance at low signal levels.

In a fading environment, the different antennas observe different channel changes. The conventional detection algorithms will not operate well if such changes are large. In this thesis, the author proposes a detection algorithm that copes with the independent signal variations in antennas. The algorithm is a modification of the correlation-based detection algorithm. The detector performance is described by deriving the false alarm and miss probabilities of the algorithm.

The secondary system should be able to detect a primary signal in a fading environment. In this thesis, the author proposes a model that describes a detector performance in the presence of slow and fast fading. The model illustrates how a single detector is able to average over the variations due to the fast fading. Such averaging is not possible for the slow fading. Therefore a single detector does not have a good method for combating slow fading. Currently, in a slow fading environment the single detector can guarantee the protection of the primary receivers only by using very low detection thresholds.

In order to achieve a tight spectrum reuse, the primary signal level detection-based spectrum access has to allow spectrum usage also near to the TV cell border. Close to the TV cell border, the detection does not identify the existence or absence of the TV signal, but rather the secondary transmitter's distance to the TV coverage area border. In a fading environment, the signal level detection is a non efficient method for such distance estimation. A low detection level means that the TV cell border will be surrounded by an area where the spectrum will not be used. That is because, in most of the locations in this area the TV signal is not in the fade and therefore exceeds the detection threshold and therefore can not be used.

The impact of fading can be removed by using multiple collaborating detectors, i.e. cooperative sensing. The cooperative sensing can improve the spectrum usage efficiency. However, the cooperative sensing has its own challenges [81]. Whether the cooperative sensing can become a viable option for the spectrum access remains to be seen.

Because of its poor performance, currently, the sensing-based access is not considered as an option for secondary spectrum access. The spectrum access is arranged only by using a geolocation database. The geolocation database assisted spectrum access can use relatively precise location knowledge. The problems of the database-based access are how to control the interference the secondary system generates at the TV receivers and how much capacity a secondary system will have. In this thesis, the author proposes the model for computing the secondary system generated interference and the method for evaluating the secondary cellular system capacity.

The aggregate interference is the interference generated from all the transmitters. In this thesis a model is put forward that estimates the aggregate interference as an integral over the secondary network coverage area. The interference level is expressed as the function of the network emitted power density. The proposed model demonstrates a good match to the conventional interference estimation based on the sum of powers received from each secondary transmitter.

The interference is not generated only from the co-channel but also from the adjacent channel. The author considers the power allocation process among the co-channel and adjacent channel as an optimization problem. The solution to this problem indicates that high power transmitters are only permitted to use adjacent channels. Since at least in central Europe, all the adjacent channels are co-channels to some other TV station, it becomes questionable if high power secondary transmitters could be used at all. Our initial results indicate that in Finland, in certain situations, the secondary cellular BS could use relatively high transmission powers. The allocated power depends on the power used by other nearby secondary transmitters. The high power can be used if there are not many nearby secondary users, i.e. the secondary network is sparse.

By selecting the secondary system to be a cellular network, we are able to de-

scribe the achievable capacity of the secondary system. In this thesis, such capacity is computed in the TVWS of Finland. The results are presented as the function of the secondary cell size. With given parameters, it turns out that in Finland there is a considerable TV spectrum resource available.

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Errata

Publication VI

The legend in Figure 1 should be read in the reverse order:

○ SINR= -16 dB

□ SINR= -18 dB

◇ SINR= -20 dB

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The aim of this dissertation is to identify how the spectrum currently allocated for TV broadcasting can be reused by some other communication systems. The spectrum reuse is allowed only if the current TV users are not disturbed. The study addresses the problems of how the secondary access to the spectrum is arranged, how the interference is controlled and how much capacity a secondary system will have. The outcomes of the thesis contain a TV signal detection algorithms, a method for estimating and controlling the aggregate interference from multiple transmitters and the estimate of the capacity of a secondary cellular system.

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