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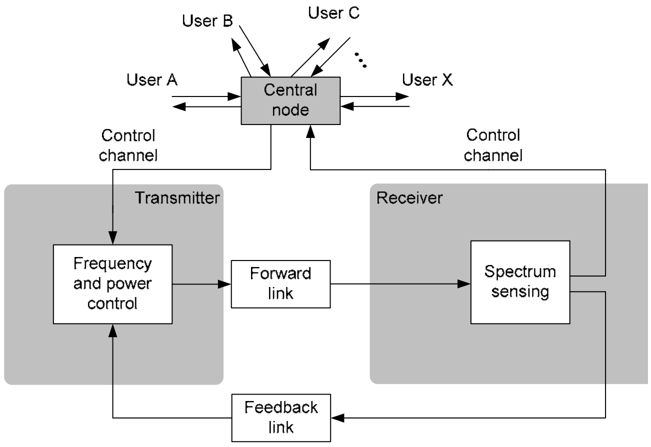

Channel state estimation and spectrum management for cognitive radios

Cognitive radio: An intelligent wireless communication system

Authors: Marja Matinmikko (editor), Marko Höyhtyä, Miia Mustonen, Heli Sarvanko, Atso Hekkala, Marcos Katz, Aarne Mämmelä, Markku Kiviranta, Aino Kautio

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Customer, contact person, address Tekes, Kari Markus Kyllikinportti 2, Länsi-Pasila, PL 69, 00101 Helsinki Steering group members: Nokia Siemens Networks: Kari Horneman Elektrobit: Jaakko Talvitie The Finnish Defence Forces: Heikki Rantanen Finnish Communications Regulatory Authority: Margit Huhtala (consultant member) VTT: Kyösti Rautiola, Aarne Mämmelä, Marcos Katz, Markku Kiviranta	Order reference 40453/05 CHESS 40315/06 CHESSEXT
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Summary

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The radio frequency spectrum is a scarce natural resource and its efficient use is of the utmost importance. The spectrum bands are usually licensed to certain services, such as mobile, fixed, broadcast, and satellite, to avoid harmful interference between different networks to affect users. Most spectrum bands are allocated to certain services but worldwide spectrum occupancy measurements show that only portions of the spectrum band are fully used. Moreover, there are large temporal and spatial variations in the spectrum occupancy. In the development of future wireless systems the spectrum utilization functionalities will play a key role due to the scarcity of unallocated spectrum. Moreover, the trend in wireless communication systems is going from fully centralized systems into the direction of self-organizing systems where individual nodes can instantaneously establish ad hoc networks whose structure is changing over time. Cognitive radios, with the capabilities to sense the operating environment, learn and adapt in real time according to environment creating a form of mesh network, are seen as a promising technology.

This report collects the research work carried out in the CHESS and CHESSEXT projects on cognitive radios and networks in 2006-2008. CHESSEXT project is the extension of CHESS project including one year research visit to Berkeley Wireless Research Center (BWRC) in Berkeley, California, which is a research center within University of California at Berkeley.

This report presents an overview of cognitive radios and cognitive radio networks. The report lists enabling techniques for cognitive radios and describes the state-of-the-art in cognitive radio standards, regulation, products and research. Cognitive radio tasks are reviewed with a more detailed discussion on spectrum sensing, and frequency and power management functionalities. Mesh networks are reviewed as their self-organizing structure is appealing for the use of cognitive radios. Some measurements on current spectrum occupancy are described indicating that even with low overall spectrum occupancy figures, the spectrum band usage can still frequent and the temporal characteristics need to be identified to find spectrum opportunities. In addition to the literature review of cognitive radios, the results of the project include link budget calculations, evaluation of the performance of an energy detection scheme with and without cooperation between the nodes, transmitter power control, and intelligent frequency selection. The results include both analysis and computer simulations using Matlab.

The availability of spectrum holes, i.e., frequency bands assigned to a primary user but that are vacant in a given place at a given time, can be estimated with spectrum sensing techniques, such as energy detection and feature detection. When little or no knowledge of the primary user signal is available, energy detection is useful while feature detection can exploit a priori information about the used waveforms. We have studied the performance of an energy detection scheme in terms of probability of detection and probability of false alarm without and with cooperation between the nodes. Cooperative detection by combining the observations of several cognitive radio nodes can be used to improve the performance of spectrum sensing. In addition to the estimation of the availability of spectrum holes, the predicted length of the spectrum holes is of interest in selecting suitable communication channels.

Frequency and power management selects suitable frequency bands and transmission power levels for the cognitive radio system. We have studied intelligent channel selection for transmission of data and control information based on the spectrum sensing information, which should minimize harmful interference to other users. Cognitive radio can learn temporal characteristic of channels over time which can be exploited in intelligent channel selection to improve the performance. Transmitter power control needs to assure reliable communication in the changing environment without causing harmful interference to other users. A good candidate for cognitive radios is the inverse power control technique that allocates lower transmission power levels to good channel realizations and higher power levels to deeper fading, aiming at minimizing the interference and to allow more secondary users to share the spectrum. Moreover, truncation, i.e., cutting off transmission in poor channel realizations, leads to performance benefits.

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Signatures	Signatures	Signatures
Written by Marja Matinmikko, research scientist	Reviewed by Aarne Mämmelä, research professor	Accepted by Jussi Paakkari, technology director

VTT's contact address

Kaitoväylä 1, PL 1100, FI-90571 Oulu, Finland

Distribution (customer and VTT)

Tekes/Kari Markus, Nokia Siemens Networks/Kari Horneman, Elektrobit/Jaakko Talvitie, The Finnish Defence Forces/Heikki Rantanen, Finnish Communications Regulatory Authority/Margit Huhtala and VTT.

Preface

This research report was made in the CHESS project at VTT in Oulu, Finland, in 2006-2008, and in the CHESSEXT project including a research visit to Berkeley Wireless Research Center (BWRC) in Berkeley, California, in 2007-2008. The report provides an overview of cognitive radios and summarizes our research efforts on spectrum sensing, frequency management and power control in a cognitive radio system.

This work was funded by Tekes and VTT whose support is gratefully acknowledged. The authors are grateful to the steering group for the valuable comments and guidance during the project: Kari Horneman (chairman of the steering group, Nokia Siemens Networks), Ilkka Keskitalo (former chairman of the steering group, Nokia), Jaakko Talvitie (Elektrobit), Kari Markus (Tekes), Heikki Rantanen (the Finnish Defence Forces), Margit Huhtala (Finnish Communications Regulatory Authority, consultant member), Kyösti Rautiola (VTT), Aarne Mämmelä (VTT), Marcos Katz (VTT), and Markku Kiviranta (secretary of the steering group, VTT).

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Marja Matinmikko
Marko Höyhtyä
Miia Mustonen
Heli Sarvanko
Atso Hekkala
Marcos Katz
Aarne Mämmelä
Markku Kiviranta
Aino Kautio

Abstract

The radio frequency spectrum is a scarce natural resource and its efficient use is of the utmost importance. The spectrum bands are usually licensed to certain services, such as mobile, fixed, broadcast, and satellite, to avoid harmful interference between different networks to affect users. Most spectrum bands are allocated to certain services but worldwide spectrum occupancy measurements show that only portions of the spectrum band are fully used. Moreover, there are large temporal and spatial variations in the spectrum occupancy. In the development of future wireless systems the spectrum utilization functionalities will play a key role due to the scarcity of unallocated spectrum. Moreover, the trend in wireless communication systems is going from fully centralized systems into the direction of self-organizing systems where individual nodes can instantaneously establish ad hoc networks whose structure is changing over time. Cognitive radios, with the capabilities to sense the operating environment, learn and adapt in real time according to environment creating a form of mesh network, are seen as a promising technology.

This report collects the research work carried out in the CHESS and CHESSEXT projects on cognitive radios and networks in 2006-2008. CHESSEXT project included a one year research visit to Berkeley Wireless Research Center (BWRC) in Berkeley, California, which is a research center belonging to the University of California at Berkeley. The report presents an overview of cognitive radios and cognitive radio networks. The report lists enabling techniques for cognitive radios and describes the state-of-the-art in cognitive radio standards, regulation, products and research. Cognitive radio tasks are reviewed with a more detailed discussion on spectrum sensing, and frequency and power management functionalities. Mesh networks are reviewed as their self-organizing structure is appealing for the use of cognitive radios. Some measurements on current spectrum occupancy are described indicating that even with low overall spectrum occupancy figures, the spectrum band usage can still frequent and the temporal characteristics need to be identified to find spectrum opportunities. In addition to the literature review of cognitive radios, the results of the project include link budget calculations, evaluation of the performance of an energy detection scheme with and without cooperation between the nodes, transmitter power control, and intelligent frequency selection. The results include both analysis and computer simulations using Matlab.

The availability of spectrum holes, i.e., frequency bands assigned to a primary user but that are vacant in a given place at a given time, can be estimated with spectrum sensing techniques, such as energy detection and feature detection. When little or no knowledge of the primary user signal is available, energy detection is useful while feature detection can exploit a priori information about the used waveforms. We have studied the performance of an energy detection scheme in terms of probability of detection and probability of false alarm without and with cooperation between the nodes. Cooperative detection by combining the observations of several cognitive radio nodes can be used to improve the performance of spectrum sensing. In addition to the estimation of the availability of spectrum holes, the predicted length of the spectrum holes is of interest in selecting suitable communication channels.

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realizations and higher power levels to deeper fading, aiming at minimizing the interference and to allow more secondary users to share the spectrum. Moreover, truncation, i.e., cutting off transmission in poor channel realizations, leads to performance benefits.

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List of abbreviations

3G	third generation
A/D	analog-to-digital
ADC	analog-to-digital converter
AM	amplitude modulation
AMTS	automated maritime telecommunications system
AP	access point
ASE	area spectral efficiency
ATIS	Alliance for Telecommunications Industry Solutions
AutoComm	autonomic communication
AWGN	additive white Gaussian noise
BER	bit error rate
BPF	bandpass filter
BPSK	binary phase shift keying
BS	base station
CBR	constant bit rate
CEPT	European Conference of Postal and Telecommunications Administrations
CFAR	constant false alarm rate
CHESS	Channel state estimation and spectrum management for cognitive radios
CLPC	closed loop power control
CNode	conscious node
CR	cognitive radio
CSFD	cyclo stationary feature detection
CSMA/CA	carrier sense multiple access with collision avoidance
DA	data aided
DAA	detect and avoid
DARPA	Defence Advanced Research Projects Agency
DCA	dynamic channel allocation
DECT	digital enhanced cordless telephone
DFS	dynamic frequency selection
DFT	discrete Fourier transform
DoD	Department of Defence (U.S.)
DSA	dynamic spectrum access
DSM	dynamic spectrum management
DTV	digital television
DySPAN	dynamic spectrum access networks
EC	European Commission
ECC	Electronic Communications Committee
EKF	extended Kalman filter
EMC	electromagnetic compatibility
ETSI	European Telecommunications Standards Insitute
EU	European Union
EWMA	exponential weighted moving average
FCC	Federal Communications Commission
FDMA	frequency division multiple access

FER	frame error rate
FFT	fast Fourier transform
FICORA	Finnish Communications Regulatory Authority
FRC	Federal Radio Commission
FSAPC	fixed step adjustment power control
FSK	frequency shift keying
FELMS	filtered error least mean square
FER	frame error rate
FTP	file transfer protocol
FxLMS	filtered-x least mean square
FxRLS	filtered-x recursive least squares
GloMo	global mobile information system
GPRS	general packet radio service
GPS	global positioning system
GSM	global system for mobile communications
HIPERLAN	high performance radio local area networks
HTTP	hypertext transfer protocol
IEEE	Institute of Electrical and Electronics Engineers
IEEE ComSoc	IEEE Communications Society
IEEE EMC	IEEE Electromagnetic Compatibility Society
IMT	International Mobile Telecommunications
IP	internet protocol
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radiocommunication sector
LA	local area
LMS	least mean square
LOS	line of sight
LS	least squares
MA	metropolitan area
MAC	medium access control
MANET	mobile ad hoc network
MC-CDMA	multicarrier code-division multiple access
MIMO	multiple input multiple output
MIT	Massachusetts Institute of Technology
ML	maximum likelihood
MMSE	minimum mean square error
MQAM	M-ary quadrature amplitude modulation
MRSS	multi-resolution spectrum sensing
MSK	minimum shift keying
MSPE	mean squared prediction error
MTU	maximum transfer unit
NPRM	notice of proposed rulemaking
NS2	Network Simulator 2, http://www.isi.edu/nsnam/ns/, (freely available open source simulation environment targeted at networking research)
NTIA	National Telecommunications and Information Administration
NTDR	near-term digital radio
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PN63	63-sample pseudo-random noise sequence
PRNET	packet radio network
PSD	power spectral density

PU	primary user
P2P	peer-to-peer
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
RF	radio frequency
RLS	recursive least squares
ROC	receiver operating characteristics
RSC	Radio Spectrum Committee
RSSI	radio signal strength indicator
RSPG	Radio Spectrum Policy Group
RX	receiver
SCC 41	Standards Coordinating Committee 41
SCF	spectral correlation function
SDR	software defined radio
SG	study group
SNR	signal-to-noise ratio
SPTF	Spectrum Policy Task Force
SSC	Shared Spectrum Company
SU	secondary user
SURAN	survivable adaptive radio networks
TDCS	transform-domain communication system
TDMA	time-division multiple access
TNC	terminal node control
TPC	transmitter power control
TV	television
TX	transmitter
UDP	user datagram protocol
UHF	ultra high frequency
U.S.	United States
UWB	ultra wideband
VHF	very high frequency
WGN	white Gaussian noise
WIFI	wireless fidelity
WINNER	Wireless World Initiative New Radio
WLAN	wireless local area network
WP	working party
WRC	World Radiocommunication Conference
WRAN	wireless regional area network
WWRF	Wireless World Research Forum
XG	next generation

1 Introduction

1.1 Current spectrum use

The radio frequency spectrum is a limited natural resource to enable wireless communication between transmitters and receivers. Licenses are usually required for operation on certain frequency bands. The use of radio spectrum in each country is nationally governed by the corresponding government agencies. In Finland, the decision-making body is the Finnish Communications Regulatory Authority (FICORA). In the United States (U.S.), the Federal Communications Commission (FCC) manages the non-federal use of spectrum while the National Telecommunications while the Information Administration (NTIA) governs the federal use.

The use of radio frequency spectrum is globally governed by the International Telecommunication Union (ITU). The Radiocommunication Sector of ITU, i.e., ITU-R, arranges World Radiocommunication Conference (WRC) every two to four years to review and revise the radio regulations, which are the international treaty governing the use of the radio spectrum and satellite orbits. The radio regulations represent the frequency allocations to different services and the rules of using the frequency bands. The agenda for a WRC is approved at the preceding WRC and the national organizations start the preparatory work for the next WRC right after the previous WRC. In Europe the European Conference of Postal and Telecommunications Administrations (CEPT) representing 46 national administrations is responsible for the preparatory work towards WRC. [FICORA 2007] For an overview of the spectrum regulatory framework, see [Takagi 2008].

In the European Union (EU) the Radio Spectrum Policy Group (RSPG) prepares opinions on issues related to radio spectrum. The EU Commission makes decisions on the use of radio spectrum that are mandatory for the EU member countries. The decisions are prepared in the Radio Spectrum Committee (RSC) of EU in co-operation with the national administrations. The EU Commission contracts out surveys to CEPT on technical and administrative issues on the use of radio spectrum in preparation for the decision making. [FICORA 2007]

The history of radio regulation in the U.S. dates back in 1912 when the principle that no one could use spectrum without a license and a series of spectrum policy principles that continue to the present were established [FCC 2002b]. In 1927 Federal Radio Commission (FRC) was established to control the regulations. Seven years later, in 1934, FCC replaced the FRC. This brought together the regulation of telephone, telegraph, and radio services within a single independent federal agency. No fundamental changes to the core principles were presented until 1993 when FCC was authorized to assign licenses through competitive bidding. In addition, certain amounts of spectrum were transferred from federal government use to commercial use. In 1997 "Congress expanded the Commission's auction authority, provided for the transfer of additional spectrum from federal government use and granted the Commission explicit authority to allocate electromagnetic spectrum so as to provide flexibility of use" [SPTF 2002]. From that point two key focus areas have emerged:

- promoting greater efficiency in spectrum use, and
- making more spectrum available.

In general, the frequency bands of the wireless communication spectrum are not currently used very efficiently, mainly due to the prevailing rigid frequency allocation policy. Present communication systems use an approach formulated in early 1920s in the United States largely as a consequence of the communication failures associated with the sinking of the Titanic in 1912 [FCC 2002b]. In that approach different frequency bands are assigned to different users and service providers, and licenses are required to operate within those bands. In technical point of view, this approach helps in system design since it is easier to make a system that operates in a dedicated band than a system that can use many different bands over a large frequency range. In addition, spectrum licensing offers an effective way to guarantee adequate quality of service (QoS) for license-holders.

Exclusivity leads to inefficient use of spectrum. FCC reported in [FCC 2002a] and [FCC 2002b] that while some bands are heavily used – such as those bands used by cellular base stations – many other bands are not in use or are used only part of the time. FCC's measurements in [FCC 2002a] in Atlanta, New Orleans, and San Diego in 2002 revealed that there are large variations in the intensity of spectrum use below 1 GHz. By observing two non-adjacent 7 MHz spectrum bands with a sliding 30-second window, the measurements showed that a fraction of 55-95 % of the observed frequencies were idle during the observation period on one band while on the other band the frequencies were almost fully idle.

Shared Spectrum Company conducted spectrum occupancy measurements on the bands between 30 MHz and 3 GHz at six locations in the U.S. in 2004 [SSC 2005]. The average occupancy over the locations was found to be only 5.2 % with the maximum occupancy 13.1 % in New York City and minimum occupancy 1 % in a rural area. The occupancy was defined as the fraction measured in time and frequency dimensions where the received signal strength exceeds a threshold.

Much greater spectral efficiency can be achieved with unlicensed spectrum usage [Satapathy 1996] in the bands that are not heavily used. Thus, there is an opportunity for systems that can dynamically exploit the available bands with suitable transmit power without interfering the present users who have higher priority or legacy rights (primary users). One drawback is that guaranteed QoS is not available in unlicensed spectrum. *Real-time secondary markets* allow license-holders lease rights to secondary users to use spectrum for the duration of license [Peha 2005]. With that approach, the quality of service requirements can be met for both primary and secondary users. However, opportunistic secondary systems that coexist with primary systems without cooperation with them are needed to really efficiently exploit the unused spectrum without the need to change existing primary systems.

The underutilization of some frequency bands opens up the opportunity to identify and exploit *spectrum holes*. A spectrum hole is defined as a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user [Haykin 2005]. If a secondary user can access a spectrum hole, the spectrum utilization is improved significantly. A promising mechanism to improve the spectrum utilization by exploiting the spectrum holes is based on the *cognitive radio* concept.

1.2 Cognitive radios and networks

Cognitive radio (CR) is an intelligent wireless communication system that is aware of its surrounding environment, learns from the environment and adapts its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters in real time [Haykin 2005]. The primary objectives of the cognitive radio are to provide highly reliable communications whenever and wherever needed and to utilize the radio spectrum efficiently. The key issues in the cognitive radio are awareness, intelligence, learning, adaptivity, reliability, and efficiency.

The term cognitive radio was first suggested by [Mitola 1999]. He defines the cognitive radio as a radio driven by a large store of a priori knowledge, searching out by reasoning ways to deliver the service the users want [Mitola 1999].The cognitive radio is reconfigurable and built on the software-defined radio (SDR).

The aim of the cognitive radio is to use the natural resources efficiently including frequency, time, and transmitted energy. Spectral efficiency is playing an increasingly important role as future wireless communication systems will accommodate more and more users and high performance (e.g. broadband) services. Cognitive radio technologies can be used in lower priority secondary systems that improve spectral efficiency by sensing the environment and then filling the discovered gaps of unused licensed spectrum with their own transmissions [Mitola 1999], [Haykin 2005]. Unused frequencies can be thought as a spectrum pool from which frequencies can be allocated to secondary users (SUs), for example, in a hotspot [Weiss 2004]. Spectrum pooling radio is a special case of a cognitive radio. Secondary users can also directly use frequencies discovered to be free without gathering these frequencies into a common pool. In addition, CR techniques can be used internally within a licensed network to improve the efficiency of spectrum use.

Transmission techniques for cognitive radio systems include overlay, underlay and interweave [Srinivasa 2007]. Underlay or interference avoidance model allows concurrent transmission of primary and secondary users in ultra wideband (UWB) fashion where the primary users are protected by enforcing spectral masks on the secondary signals so that the generated interference is below the noise floor for the primary user. However, underlay allows only short-range communication due to the power constraints. Overlay or known interference model also allows concurrent transmission of primary and secondary users. The secondary users use part of their transmission power for relaying the data of primary users and part of the power for their own secondary transmission. In the interweave model the cognitive radio monitors the radio spectrum periodically and opportunistically communicates over the spectrum holes. The focus in this report is in the interweave model. Note that the term overlay is used in many papers, such as [Čabrić 2006] to characterize the use of cognitive radios. However, we use the term interweave model to characterize the opportunistic spectrum use with cognitive radios.

The three major tasks of the cognitive radio include [Haykin 2005]:
(1) radio-scene analysis,
(2) channel identification, and
(3) dynamic spectrum management and transmit-power control.

The radio-scene analysis includes the detection of spectrum holes by for example sensing the radio frequency spectrum. The channel identification includes estimation of the channel state information which is needed at the receiver for coherent detection. The transmitter power control and dynamic spectrum management select the transmission power levels and frequency holes for transmission based on the results of radio scene analysis and channel identification. The first two tasks are carried out in the receiver (RX) while the third task is carried out in the transmitter (TX), which requires some form of feedback between RX and TX.

The cognitive radio is susceptible to emergent behaviour due to the time-varying nature of the operating environment. *Emergence* refers to the occurrence of properties at higher hierarchy levels of organization which are not predictable from properties found at lower levels. In CR systems the positive emergent property is the improved area spectral efficiency. Negative emergent properties include possibility to chaotic behaviour and traffic jams.

The cognitive radio approach can be extended to cognitive networks. A cognitive radio network is an intelligent multiuser wireless communication system that perceives the radio-scene, adapts to variations in the environment, facilitates communication between users by cooperation, and controls the communication through proper allocation of resources [Haykin 2007a], [Haykin 2007b]. The cognitive network encompasses a cognitive process that can perceive current network conditions, and then plan, decide, and act on those conditions [Thomas 2006]. The network can learn from adaptations and use them to make future decisions taking into account end-to-end goals. Cognitive networks require a software adaptable network to implement the actual network functionality and allow the cognitive process to adapt the network.

The most general theory in telecommunications is information theory which can be classified into syntactic, semantic, and pragmatic levels [Skyttner 2006]. *Syntactics* represents the lowest level which includes the study of relations of signs to other signs. Most of man-made theories are on this level including for example Shannon's statistical information theory. *Semantics* is the study of the relations of signs to what they represent. This level thus considers the meaning of the signs. *Pragmatics* represents the highest level which includes the study of the interpretation of signs to their users. This level considers the value and utility of the signs.

The term "cognition" refers to mental processes of perception (sensing), memory, judgment, and reasoning [Random House 1999]. Thus cognition includes sensoring, memory, processing and reasoning which are the tasks of the cognitive radio. The term "consciousness" refers to awareness of one's own existence, sensations, thoughts, surroundings, etc. [Random House 1999]. Consciousness includes emotions and free will. Thus, consciousness denotes a higher level of understanding than cognition which is not available in man-made machines. Consciousness denotes the ability to use one's senses and mental powers to understand what is happening. Consciousness indicates a state of awareness of self and environment [Columbia Encyclopedia 2001].

1.3 Purpose and content of the report

This report collects the work done in the CHESS and CHESSEXT projects in 2006-2008. The aim of the projects is a working cognitive radio concept that is demonstrated with MATLAB simulations. The concept aims to maximize spectral and energy efficiency based on power and frequency control and the use of network state information, which is partially given as external control information and partially estimated, reduced for transmission and combined.

The secondary system has to be spectrum aware in order to exploit the available spectrum efficiently. In this report, the three major tasks of cognitive radios from Section 1.2 are considered carefully. Different spectrum awareness techniques are classified. Advantages and challenges for each technique are presented. Cognitive radios aim to improve spectral efficiency by sensing the environment and then filling the gaps in licensed spectrum by their own transmissions. Spectrum sensing is a crucial task in a cognitive radio system. The transmission of licensed users has to be reliably detected and spectrum sensing should ensure adaptive transmission in wide bandwidths without causing interference to primary users. However, it is also very important to know how to exploit the sensed available spectrum efficiently. Transmission parameters have to be adapted based on the sensed spectrum and the channel estimation. To maximize the spectral and energy efficiency, power and frequency has to be jointly controlled. This is a challenging task. Investigation of efficient adaptive transmission strategies in cognitive radio network is one of the main tasks presented in this report. In addition, short overview of mesh networks as the architecture for cognitive radio networks is offered. The report works also as a definition document for a cognitive radio system. System model and relevant preliminary assumptions are presented in the report.

The basic research problems in the project include:
(1) how the cognitive radio is managed,
(2) how the change of the primary and a secondary user is made,
(3) how to minimize control information, and
(4) how to prevent unwanted interaction between the adaptive transmitter and receiver [Claasen 1985], traffic jams and chaotic behaviour [Haykin 2005].

The problems will be solved by reducing them into smaller subproblems, which are still essential for the whole aim, and examine one piece at a time. This makes it possible to keep the things simple and manageable. Simplifications and bottom-up approach is needed in the cognitive radio research. If the whole system is implemented straight away, nobody can tell how it works and what its performance is.

The results of the project include:
(1) a cognitive radio system concept,
(2) spectrum sensing algorithm for detecting spectrum holes,
(3) power control algorithm for cognitive radio,
(4) spectrum coordination algorithm, and
(5) demonstration of the system concept in MATLAB.

This report is organized as follows. In Chapter 2, the general framework for cognitive radios and cognitive radio networks is presented including the background and the tasks of the cognitive radios. In Chapter 3, wireless mesh networks, which are considered as a suitable system for the deployment of cognitive radios, are reviewed. Measurements on the current spectrum use and the channel models are presented in Chapter 4. Chapter 5 presents techniques for active spectrum sensing. Chapter 6 characterizes the power and frequency control algorithms for cognitive radio systems. Chapter 7 presents the developed cognitive radio system model. Chapter 8 presents the results from the project and finally, Chapter 9 draws conclusions.

2 Foundations and overview of cognitive tasks

The operation of the cognitive radio is based on the notion of spectrum holes, i.e., bands of frequencies assigned to a primary user, but, at a particular time and specific geographic location, they are not used by that user [Haykin 2005]. The objective of the cognitive radio is to identify the spectrum holes, and to provide the means for making the spectrum holes available for secondary users. This chapter discusses the foundations of cognitive radios and cognitive radio networks and provides an overview of the cognitive tasks.

2.1 Background

Currently, there is a lot of interest in the research and development of cognitive radios and cognitive radio networks worldwide. Haykin lists the following drivers for the development of cognitive radios in [Haykin 2007a]:

- improved spectrum utilization,
- regulators (e.g. FCC),
- US Department of Defense,
- international driver examples (e.g. New Zealand with no regulation),
- standardization bodies (e.g. Institute of Electrical and Electronics Engineers, IEEE) push for the development of new standards with cognitive radio capabilities, and
- research programs (e.g. Defense Advanced Research Projects Agency, DARPA).

According to [Haykin 2007a], future motivators for the development of cognitive radios include the following applications:

- collaborative networks,
- maintenance and fault detection networks,
- self organized networks, and
- cognitive multiple input multiple output (MIMO).

In addition, the cognitive radio approach can be useful in other applications such as home environment, utilization of vacant TV bands, messaging devices and other non-real time communication systems. The cognitive radio could improve communications in emergency situations when the traditional network becomes congested with calls for help due to the limited availability of spectrum bands.

Cognitive radio is inspired by cognitive science whose roots date back in 1956 with two scientific events [Haykin 2007b]:

- Symposium on Information Theory at Massachusetts Institute of Technology (MIT) in 1956. As a result, the language of information processing was started
- The Dartmouth Conference at Dartmouth College, New Hampshire 1956. The conference concentrated on intelligent machines and led to the development of neural networks.

In response to the scarcity of unallocated spectrum, the FCC has defined four different scenarios about how to improve spectrum access and efficiency of spectrum use by cognitive radio technologies [FCC 2003a]:

1. *A licensee can employ cognitive radio technologies internally within its own network to increase the efficiency of use.*

2. *Cognitive radio technologies can facilitate secondary markets in spectrum use, implemented by voluntary agreements between licensees and third parties. For instance, a licensee and third party could sign an agreement allowing secondary spectrum uses made possible only by deployment of cognitive radio technologies. Ultimately cognitive radio devices could be developed that "negotiate" with a licensee's system and use spectrum only if agreement is reached between a device and the system.*

3. *Cognitive radio technologies can facilitate automated frequency coordination among licensees of co-primary services. Such coordination could be done voluntarily by the licensees under more general coordination rules imposed by Commission rules, or the Commission could require the use of an automated coordination mechanism.*

4. *Cognitive radio technologies can be used to enable non-voluntary third party access to spectrum, for instance as an unlicensed device operating at times or in locations where licensed spectrum is not in use.*

The focus in this report is in the fourth scenario. In this scenario the radio can sense and be aware of its environment and can learn from its environment for the best spectrum and resources utilization. The radio can exploit today's situation so that existing systems remain unchangeable. Every cognitive system is adaptive but every adaptive system is not necessarily cognitive. Thus, cognition leads to adaptation but not necessarily vice versa.

2.2 Enabling techniques

Although the history of cognitive radios is rather short and the term "cognitive radio" first appeared only in [Mitola 1999], the technologies that enable the development of cognitive radios and cognitive radio networks have a long history. In essence, the development of the cognitive radio and cognitive radio networks is about exploiting the different technologies into a new system concept.

Haykin identifies the following enabling techniques for cognitive radios in [Haykin 2007a]:

- Bayesian signal processing (e.g. cognitive radar with the availability of a priori information),
- dynamic programming,
- learning machines with feedback (e.g. neural networks), and
- game-theoretic models.

In addition, also other enabling techniques can be identified:

- dynamic frequency management,
- software-defined radio (SDR), and
- cross-layer protocol design.

The enabling techniques that form the background of cognitive radios are described in the following sub-sections.

2.2.1 Bayesian signal processing

Bayesian signal processing is a method to estimate the real value of a random observed variable that evolves in time. Bayesian signal processing uses a priori information of the distribution of the random variables in deriving the estimates. For linear systems with Gaussian noise, Bayesian signal processing results in Kalman filtering while for non-linear systems, partical filters are used.

The Kalman filter is a recursive version of the minimum mean square error (MMSE) estimator introduced independently by Kalman in 1960 and Swerling in 1958. The Kalman filter is used to estimate the instantaneous state of a linear dynamic system perturbed by white Gaussian noise. The state of dynamic systems varies with time but the state is not typically directly measurable. Instead, the estimation is performed by using measurements which are linearly related to the state and corrupted by white Gaussian noise. Dynamic systems are characterized by the state-space model which consists of state evolution equation and a measurement equation. The Kalman filter is statistically optimal with respect to any quadratic function of estimation error. The mathematical model behind the Kalman filter is a reasonable presentation for many control problems and estimation problems. The Kalman filter is thoroughly studied in the book [Anderson 1979]. The historical development of Kalman filtering is studied in [Sorenson 1970] and a large survey of linear filtering theory with nearly 400 references is in [Kailath 1974].

In 1960, Kalman formulated a recursive solution to the optimum linear filtering problem using a state-space model for a dynamic system. The Kalman filter was defined for either stationary or nonstationary systems in either discrete time or continuous time with finite state dimension. Kalman introduced the state-space models for the signal and noise instead of the conventional method of specifying the signal and noise covariance functions. Swerling published in 1958 a memorandum which described a recursive procedure for orbit determination. This method was essentially the same as Kalman's method but the equation for updating the error covariance matrix had a different form [Sorenson 1970].

However, the Kalman filter theory has practical limitations. The Kalman filter theory is built on assumptions of system linearity and Gaussian distributions. The assumptions are often violated by the observation data encountered in practice. Extended Kalman filter (EKF) is not good enough for non-linear situations and therefore particle filters are needed.

Iterative processing using the turbo processing principle has been introduced in the Bayesian signal processing in the 1990s. The idea of passing probabilistic or soft information in decision making can yield significant performance improvements and is also appealing in the context of cognitive radios.

2.2.2 Dynamic programming

Dynamic programming refers to multi-stage decision processes [Bellman 1957]. The multi-stage decision processes correspond to situations where there is a physical system whose state at any time is specified by a vector and in the course of time, the system is subject to changes. Due to the changes, the variables describing the system undergo transformations. In a decision process, there is a choice of decisions or transformations that can be applied to the system at any time. In a single-stage process we have to make a single decision. If we make a sequence of decisions, the process is a multi-stage decision process. The multi-stage decision problems are exceedingly difficult. Dynamic programming suffers from the exponentially increasing demand on computation resources and size as the input-space dimensionality is increased linearly.

Algorithms are often tested with "toy problems" which do not present the actual operating environment of the algorithm [Haykin 2007a]. Large-scale upwards compatibility is a key issue in the algorithm development for cognitive radios.

2.2.3 Learning machines with feedback

A major task of the cognitive radio is to make decision on how to adapt the radio based on the information gathered from the environment. Techniques for improving the performance based on learning from the past history will be crucial in the development of cognitive networks. Generic learning-based cognitive radio with the capability to learn from the past in addition to simple reasoning is a relatively recent research area [Clancy 2007]. Various researchers have used, e.g., genetic algorithms or neural networks to fine tune radio parameters with the goal of optimizing the performance but the fundamental research on learning, reasoning and resulting intelligence in cognitive radio network operations remains rather uncharted.

2.2.4 Game theory

Game theory provides analytical tools to predict the outcome of complex interactions among rational entities. Game theory has been traditionally applied in economics, political science, biology, and sociology and also recently in telecommunication systems. A game has three basic components: players, a set of possible actions, and a set of utility functions. In a repeated game, players are assumed to be perfectly rational and to select their actions in a deterministic manner [Haykin 2005]. Thus, based on the past actions, each player can predict the moves of other players and select the best strategy to the problem. A *Nash equilibrium* is a stable operating point, in which no user has any incentive to change strategy. Power control games have been presented in [MacKenzie 2001] and also for cognitive radio in [Haykin 2005].

Potential game formulations for power control, call admission control and interference avoidance in cognitive radio networks are proposed in [Neel 2002]. Neel has also investigated the convergence conditions for various game models in cognitive radio networks in [Neel 2004]. Adaptive channel sharing etiquette for CR networks can be found in [Nie 2005]. An entirely cooperative game simplifies the problem to an optimal control-theoretic problem [Haykin 2005]. Cooperation is needed to optimally exploit the available spectral resources. The problem is that the amount of control information is bigger in a cooperative system.

2.2.5 Dynamic frequency management

Dynamic frequency management allows adaptive allocation of spectrum to various users in a multiuser environment as a function of spatiotemporally varying physical environment. Dynamic frequency management is the area that has been under intense investigation during the last two decades in the development of cellular telephony systems [Berggren 2004]. In these systems there is a single operator that controls all entities, i.e. base stations and mobile terminals in the system, inside a fixed allocated frequency band, well protected from “outside” interference.

Dynamic channel access (DCA) policies assign channels to different cells, so that every channel is available to every cell on a need basis, unless the channel is used in a nearby cell and the reuse constraint is violated [Singh 1997]. However, the situation changes if we have multiple heterogeneous entities using the same spectrum, each with their own objective. These problems can be stated as *non-cooperative resource management problems* [Berggren 2004]. Dynamic spectrum access (DSA)[1] and cognitive radios are proposed techniques to facilitate the flexible co-existence of different radio systems in a same frequency band. Digital enhanced cordless telecommunications (DECT) phones can be thought as simple pioneering cognitive radios [Walko 2005]. DECT phones select the frequency to use at a given time based on sensing of other users.

In physical carrier sensing the nodes in the wireless network wait until the total received power from ongoing transmissions is below a certain threshold before they start to transmit [Fuemmeler 2004]. The difference in CR system is that also the transmitting node has to sense if primary user starts to use the same frequency band. The primary users are privileged and thus do not need to know about the presence of the secondary users. SUs have to periodically monitor the presence of PUs [Weiss 2004]. Because a PU can tolerate interference maximally Δt seconds, monitoring has to be done at least every Δt seconds [Brodersen 2004]. During the detection period secondary users have to be silent [Weiss 2004]. In some special cases, continuous channel monitoring can be allowed [Öner 2004]. If the use is observed, the other frequency band from spectrum pool is chosen and transmission between SUs continues in that band.

2.2.6 Software-defined radio

The software-defined radio (SDR) denotes a class of reprogrammable or reconfigurable radios, meaning that the same piece of hardware can perform different functions at different times. In [Reed 2002] SDR is defined as a radio that is substantially defined in software and whose physical layer behavior can be significantly altered through changes to its software. Software-defined radios digitize the signal as early as possible in the receiver chain and convert the signal as late as possible to analog domain in the transmitter. The major driving forces for software-defined radio include multifunctionality, global mobility, compactness and power efficiency, ease of manufacture, and ease of upgrades [Reed 2002].

Software-defined radio allows flexibility to handle several standards since the radio functions can be changed by software. In application where access to multiple bands with multiple radio access modes is needed, the software-defined radio can reduce hardware size, weight and power through fewer radio units [Mitola 1995].

2.2.7 Cross-layer protocol design

Current wireless network protocol design is largely based on a layered approach where each layer is designed and operated independently. Such a *modular architecture* allows a design change to be made to one layer without requiring a change to other layers. In *cross-layer protocol design* adaptivity and optimization across multiple layers of the protocol stack are needed [Goldsmith 2002]. Each layer responds to variations local to that layer and information from other layers. The aim is to jointly optimize all protocol layers. However, cross-layer design should be approached holistically with some caution [Kawadia 2005a]. Modularity and layered architecture lead to longevity of the system and can be seen as a reasonable way to operate in wireless networks. Over a larger time horizon this can be regarded as performance optimization. As authors in [Kawadia 2005a] emphasize, *unbridled cross-layer design can lead to "spaghetti" design, which can stifle further innovations and be difficult to upkeep*. This architecture that is opposite of a modular one is known as an *integral architecture* [Ulrich 1995]. The performance of a system can be optimized by using more than one layer to implement needed function(s). However, modifications to any layer may require extensive redesign of the system. Modularity helps designers to understand the overall system and to focus their effort on a particular subsystem with the assurance that the entire system will interoperate. However, some integrality can be good to include to the system to achieve better performance. This increases the amount of control information.

2.3 State of the art in cognitive radios

Cognitive radios and cognitive radio networks are currently under a lot of investigation. This section provides a summary of selected research and standardization efforts related to cognitive radios and cognitive radio networks. Section 2.3.1 describes on-going standardization efforts and regulatory framework, Section 2.3.2 introduces some cognitive radio products, and Section 2.3.3 reviews the research efforts. Section 2.3.4 introduces some terms related to the cognitive radio research.

2.3.1 Cognitive radio standards and regulation

IEEE Standards Coordinating Committee 41 on dynamic spectrum access networks

Standardization work for cognitive radio networks has already been started. A major standardization effort related to cognitive radio networks is carried out in IEEE Standards Coordinating Committee 41 (SCC 41) on dynamic spectrum access networks, which is discussed next.

The IEEE initiated the 1900 Standards Committee on next generation radio and spectrum management [IEEE 1900]. The IEEE P1900 standards committee was founded in the first quarter of 2005 to develop standards for new technologies developed for next generation radio and advanced spectrum management. The standards committee was established jointly by the IEEE Communications Society (ComSoc) and the IEEE Electromagnetic Compatibility (EMC) Society.

On March 22, 2007 the IEEE Standards Board approved the reorganization of the IEEE 1900 effort as the IEEE Standards Coordinating Committee 41 (SCC 41), Dynamic Spectrum Access Networks (DySPAN), which is still sponsored by the IEEE ComSoc and EMC Societies [SCC41]. SCC 41 is a forum for information exchange in the area of dynamic spectrum access networks and a sponsor for related standards projects. An overview of the IEEE 1900 committee is given in [Hoffmeyer 2007]. As of September 2007, the SCC 41 consists of the following working groups [SCC41]:

- IEEE 1900.1 Working Group on Terminology and Concepts for Next Generation Radio Systems and Spectrum Management,
- IEEE 1900.2 Working Group on Recommended Practice for Interference and Coexistence Analysis,
- IEEE 1900.3 Working Group on Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules,
- IEEE 1900.4 Working Group on Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks, and
- IEEE 1900.A Working Group on Dependability and Evaluation of Regulatory Compliance for Radio Systems with Dynamic Spectrum Access.

The IEEE 1900.1 is developing a standard which will give technically precise definitions and explanations of key concepts related to spectrum management, policy defined radio, adaptive radio, software defined radio, and related technologies.

The IEEE 1900.2 is developing a standard on the analysis of coexistence and interference between various radio services. The standard will provide technical guidelines for analyzing the potential for coexistence or the interference between radio systems operating in the same frequency band or between different frequency bands.

The IEEE 1900.3 is developing a standard on technical guidelines for analyzing SDR software modules to ensure compliance with regulatory and operational requirements.

The IEEE 1900.4 is developing a standard to define the building blocks comprising network resource managers, device resource managers, and the information to be exchanged between the building blocks. This is done to enable coordinated network-device distributed decision making for improving the radio resource usage including spectrum access control.

The IEEE 1900.A is developing a standard that specifies test and analysis methods to be used when assessing whether the spectrum access behavior of a radio system with dynamic spectrum access capability complies with specified limits or rules.

Other relevant IEEE standardization activities on cognitive radios

Other relevant IEEE standardization activities related to cognitive radio networks include IEEE 802.22 standard on cognitive wireless regional area network (WRAN) which is a cognitive air interface for fixed, point-to-multipoint WRAN's that operate on unused channels in the VHF/UHF TV bands between 54 and 862 MHz [IEEE 802.22]. IEEE 802.11y working group is developing a standard for shared 802.11 operation with other users in 3650–3700 MHz band [IEEE 802.11y]. IEEE 802.11h standard amendment defines transmission power control and a dynamic frequency selection (DFS) algorithm for wireless local area networks (WLAN's) in 5 GHz band in Europe [IEEE 802.11h]. DFS selects the radio channel at the access point to minimize interference with other systems.

ITU-R standardization activities on cognitive radios

ITU-R is also conducting standardization activities related to cognitive radio networks. The current activities are more related to SDR but future activities will also consider cognitive radios. In particular, the next WRC in 2011 (WRC-11) will have an agenda item on SDR and cognitive radios:

"*to consider regulatory measures and their relevance, in order to enable the introduction of software-defined radio and cognitive radio systems, based on the results of ITU-R studies, in accordance with Resolution [COM6/18] (WRC-07).*

The standardization activities are mainly carried out in the Study Group 1 (SG 1) which is responsible for spectrum management and in the Study Group 5 (SG 5), which from October 2007 onwards is responsible for terrestrial services. The study groups are conducting studies in different working parties (WP). In SG 1 the work is done in WP 1B responsible for spectrum management methodologies and economic strategies. The studies on IMT systems will carried out in WP 5D of

SG 5 and other land mobile services excluding IMT in WP 5A of SG 5. The IEEE is a sector member of ITU-R and contributes to the standardization activities at ITU-R along with the other ITU members.

The ITU Radiocommunication Assembly in 2000/2003 sent out Question ITU-R 230-1/8 on software defined radios to find appropriate ITU definition, key technical characteristics, frequency bands, and interference considerations for SDR [ITU 2000]. The results of this joint question by ITU-R WP 8F and ITU-R WP 8A, the predecessors of WP 5D and WP 5A respectively, were collected in Report ITU-R M.2063 on software defined radio in IMT-2000 and IMT-Advanced [ITU 2005a] and Report ITU-R M.2064 on software defined radio in other land mobile services [ITU 2005b].

The ITU Radiocommunication Assembly in 2007 sent out Question ITU-R 241/8 on cognitive radio systems in the mobile service [ITU 2007a]. This work is currently at the beginnings. Question ITU-R 241/8 lists the following issues to be studied in ITU-R WP 5A:

1. What is the ITU definition of cognitive radio systems?
2. What are the closely related radio technologies (e.g. smart radio, reconfigurable radio, policy-defined adaptive radio and their associated control mechanisms) and their functionalities that may be a part of cognitive radio systems?
3. What key technical characteristics, requirements, performance and benefits are associated with the implementation of cognitive radio systems?
4. What are the potential applications of cognitive radio systems and their impact on spectrum management?
5. What are the operational implications (including privacy and authentication) of cognitive radio systems?
6. What are the cognitive capabilities that could facilitate coexistence with existing systems in the mobile service and in other radiocommunication services, such as broadcast, mobile satellite or fixed?
7. What spectrum-sharing techniques can be used to implement cognitive radio systems to ensure coexistence with other users?
8. How can cognitive radio systems promote the efficient use of radio resources?

The responses to the question will be collected in ITU-R Recommendations and/or Reports which will be completed by the year 2010.

The ITU Radiocommunication Assembly in 2007 also sent out another question related to cognitive radios, namely Question ITU-R 233/1 [ITU 2007b] on measurement of spectrum occupancy which is studied in ITU-R SG 1. Question ITU-R 233/1 lists the following issues to be studied SG 1:

1. What techniques could be used to perform frequency channel occupancy measurements, including processing and presentation methods?
2. What techniques could be used to perform frequency band occupancy measurements, including processing and presentation methods?
3. How can "occupancy" be defined for both, frequency channel as well as for frequency band measurements, also taking into account, the size of the used filter and the values measured in adjacent channels?
4. How can threshold levels be defined and applied in practical situations including dynamic threshold levels?

The results will be collected in ITU-R Recommendations that will be completed by the year 2009.

The spectrum bands currently used for TV present an interesting opportunity for the deployment of cognitive radio networks, as for example in the IEEE 802.22 WRAN standard. Therefore, the vacation of TV bands is discussed next.

Vacation of TV bands in the U.S.

TV broadcasting is currently in the transition phase from analogue to digital signals. Many countries currently broadcast both analog TV and digital TV (DTV) simultaneously. The existing analog services will be switched-off which will take place at different times in different countries. Some countries have already completed the switch-off while others plan to do it by 2015. For example, Finland completes the analog transmission on 1st September 2007. US will switch-off analog on 17th February 2009.

As the transition from analog to digital TV is completed, there will be vacant channels or white spaces in the TV bands. The FCC in U.S. adopted in 2004 a notice of proposed rulemaking (NPRM) proposing “to allow unlicensed radio transmitters to operate in the broadcast TV spectrum at locations where the spectrum is not being used” [FCC 2004]. The FCC has proposed to allow unlicensed operation in the following white spaces in the TV spectrum: 76-88 MHz, 174-216 MHz, 470-608 MHz, and 614-698 MHz. The FCC discussed three methods for operation on TV bands: control signals, position determination, and cognitive radio with dynamic frequency selection.

The key question in the deployment of cognitive radios on TV bands is whether the unlicensed devices with cognitive radio techniques can completely protect licensed broadcast TV services. The report [Sturza 2007] provides engineering support for application of cognitive radios on vacant TV bands. The report shows through analysis and simulation that an occupied DTV signal can be identified with practical certainty even if there is severe attenuation at the cognitive radio receiver compared to other receiving stations, which corresponds to the hidden terminal situation. In the hidden terminal problem, which is further explained in Section 2.6, the cognitive device does not detect the presence of the primary user due to blockage.

The report claims that an occupied DTV channel can be identified with practical certainty with less than one second observation time. The level of certainty is so high that the occurrence of electric power outages and natural disasters would be more likely cause of interruption of TV transmission than the unlicensed devices. The hidden terminal problem is taken into account by allowing a 37 dB additional attenuation for the DTV signal at the receiving cognitive radio device compared to rooftop antennas. According to the report, the probability that an unlicensed device located inside a building would see a DTV signal 37 dB below the rooftop level is negligible.

The approach for detecting the DTV signals in [Sturza 2007] takes advantage of the fact that the cognitive device must only detect the presence of a signal and does not need to demodulate it. Therefore, the detection of the presence of TV signal is possible at signal levels significantly lower than those required by the TV set. In addition, the cognitive device can take advantage of the known TV signal structure and its spectral features.

The spectrum of the DTV signal is flat over the channel bandwidth of 6 MHz, except for the pilot carrier located 0.31 MHz above the lower edge of the channel. The pilot carrier power is 11.3 dB lower than the total signal power and concentrated in a spectral line which is exploited in the signal detection. In the cognitive radio receiver [Sturza 2007] the pilot carrier is observed in a detection bandwidth centered on the pilot carriers. In addition to the pilot carrier, there is also thermal noise and main signal part present on the DTV band. The decision on the presence or absence of DTV signal is done based on hypothesis testing where the decision variable is a measurement of the pilot carrier power that is tested against a threshold.

The vacant TV bands after the transition from analog to digital TV are an appealing opportunity for the deployment of cognitive radios. However, as the transition phase takes places at different times in different countries, even inside the EU, there is not yet common incentive for the deployment of cognitive radios on these bands.

2.3.2 Cognitive radio products

The first commercial deployment of a cognitive radio network is still to be seen but there are already some cognitive radio products available which are discussed next.

Adapt4's XG1

First commercial CR product developed by Adapt4 is available in the market. Adapt4 introduced their cognitive radio XG1 in 2004 [Adapt4]. Adapt4's XG1 is an OFDM-based system that operates on licensed frequency bands in 217–220 MHz as a secondary user. The maximal data transmission rate of Adapt's XG1 is 192 kbit/s. The network supports mobile, point-to-multipoint and point-to-point with multi-hopping architectures. The network identifies unused frequencies, uses them for transmission and avoids those channels when other activity is detected.

The spectrum band 216-220 MHz is currently licensed to maritime mobile both in non-governmental and governmental use as shown in the FCC's spectrum inventory table [FCC DB]. The secondary users for the spectrum band 216-220 MHz in non-governmental use include:

- Aeronautical Mobile,
- Fixed, and
- Land Mobile.

The specific services among the secondary users in the non-governmental use include

- AMTS (Automated Maritime Telecommunications System): voice/data 2-way; 25 kHz; analog/digital,
- Amateur Radio: voice/data/image, 1 or 2-way, bandwidth base on need; analog/digital, and
- Private Land Mobile: voice/data 2-way 4 kHz channels; analog/digital.

The secondary users for the spectrum band 216-220 MHz in governmental use include:

- Aeronautical Mobile,
- Fixed,
- Land Mobile, and
- Radiolocation 627.

Adapt4 lists the following applications for cognitive radio [Adapt4]:

- critical infrastructure (e.g. power stations and transmission lines, water pump stations, and reservoirs),
- public safety (reduced vulnerability compared to traditional networks),
- homeland safety/disaster response (in emergency situations CR network can be built fast when the traditional network is broken),
- transportation (access to Internet and wide area coverage at lower frequency band), and

- military (undetectable and jam-resistant technology).

Adapt4's XG1 includes the following capabilities [Adapt4]:

- dynamic frequency selection,
- frequency hopping,
- dynamic power management,
- automatic configuration, and
- benefit from propagation conditions at lower frequency bands (low height antennas, better coverage, immunity to weather conditions).

The XG1 cognitive radio network monitors the activity of other users in the band and identifies unused bandwidth. The network generates a set of parallel sub-carriers and transmits on them while they are not in use. The network creates up to 45 sub-carriers, each of width 6.25 kHz, and rapidly hops among them using each narrowband channel for only about 10 ms. Therefore, the transmission is nearly visible and resistant to jamming. When another licensed user is sensed, the network stops using the carriers until they become vacant again.

The individual XG1 devices detect other users and relay this information to a central radio. The central radio processes this information to create a composite usage map covering the entire XG1 network whose radius can span over 80 km. The map is continuously updated and distributed throughout the network.

Interference avoidance is performed with two features: 1) a frequency-hopping technique is used to minimize the amount of time that any single frequency is utilized and 2) the radios' transmit power is dynamically regulated to minimize transmission power. Each remote radio in the network uses the minimum amount of transmission power needed to maintain reliable communications with the central radio. The central radio maintains an output power equal to that level demanded by the network link with the highest wattage requirement.

Cognichip

Cognichip is a low-cost radio device developed by France Telecom to operate on the ultra high frequency (UHF) spectrum 470-870 MHz as desribed in [Germain 2006]. Cognichip can detect spectrum opportunities and communicate using the white spaces in the TV spectrum. Cognichip uses a centralized architecture where the network consists of a base station and mobile terminals. The mobile terminals use the measure of radio signal strength indicator (RSSI) integrated in the transceiver chip for sensing the spectrum occupancy. The sensing of one channel is carried out in 24 ms while the sensing of all 504 channels takes 12 s. Therefore, it is not feasible to scan the entire spectrum but only selected parts. During spectrum sensing, the mobile terminal cannot receive data.

The base station collects the RSSI information from the mobile terminals and updates the channel occupation information in real time and makes decisions on the spectrum use. Switch in frequency in the reception mode takes 23.2 ms and in transmission mode 23.6 ms. The detection of a jammer and reconfiguration to a new frequency therefore takes approximately 50 ms at the base station.

Cognichip uses a centralized architecture and thus is not directly applicable to cognitive radio networks with ad hoc structure. However, Cognichip uses cooperative sensing for identification of spectrum opportunities and therefore is an interesting development stage on the way towards cognitive radio networks.

Rockwell's chip

The company Rockwell Collins has developed a broadband low power spectrum sensor for scanning the frequency band 30 MHz – 2.5 GHz [Newgard 2006]. The sensor can scan the spectrum at 18 GHz/s with 100 kHz resolution. With 25 kHz resolution bandwidth, the sensor can scan at 4.8 GHz/s. The scanning can also be done with resolution bandwidths up to 200 kHz to perform fast detection of large unused spectrum bands. The power consumption is below 2.5 W.

SDR platforms

Furthermore, advanced software defined radio platforms can be exploited in cognitive radio research and development. One example is SDR-3000 platform of Spectrum Signal Processing company [Spectrum]. It supports hundreds of simultaneous transmit and receive channels, each with independent air interface protocol. The system is flexible and scalable and can be customized as required, see [Spectrum] for details.

2.3.3 Cognitive radio research

Big companies have made major investments in the research of cognitive radios including for example Microsoft, Intel, Philips, and Google. New academic conferences have emerged that solely focus on cognitive radios and cognitive radio networks. Large research programmes have been established to study cognitive radios and cognitive radio networks. In the following, the major conferences and some of the major research efforts in the cognitive radio area are summarized.

Academic conferences

The major academic conferences in the field of cognitive radios are IEEE DySPAN and CrownCom. The IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (IEEE DySPAN), sponsored by the IEEE Communications Society, was held for the first time in 2005. IEEE DySPAN is a major academic conference in the field of dynamic spectrum access networks. The 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom) was held in 2006.

Defence Advanced Research Projects Agency (DARPA)

The Defense Advanced Research Projects Agency (DARPA) is the central research and development organization for the Department of Defense (DoD) in the U.S. [DARPA XG]. It is responsible for the development of new technology for military purposes. There is a public call for projects whose budgets are not defined in the call.

DARPA was founded in 1958. It is bridging the gap between near-term and long-term research. Most military funding is given for near-term research. DARPA (originally ARPA) started the funding of the Internet research in the 1960's (originally ARPANET). There are 500 programs going on of different sizes. New topics include networks, networked sensors, cognitive computing, automatic language translation, high productivity computing systems, air vehicles, high energy liquid laser area defense system, space3, low-cost titanium, bio warfare, and prosthetics. DARPATech 2007 was organized in August 7-9, 2007 in Anaheim, CA.

The spectrum access issues are unique in each country which is crucial in the development of military systems. The Next Generation (XG) program of DARPA develops enabling technologies and system concepts to dynamically redistribute allocated spectrum along with novel waveforms to provide improvements in assured military communications. The XG program develops theoretical underpinnings for dynamic control of the spectrum, the technologies and subsystems that enable reallocation of the spectrum, and the system prototypes to demonstrate applicability to legacy and future military radio frequency emitters. The goals are to develop, integrate, and evaluate the technology to enable equipment to automatically select spectrum and operating modes to both minimize disruption of existing users, and to ensure operation of systems.

Wireless World Research Forum (WWRF)

The WWRF consists of working groups (WG) and special interest groups (SIG). The WG 6 entitled "Cognitive wireless networks and systems" focuses on cognitive radio research. The objectives of WG 6 include the following [WWRF 2007]:

- definition of technical visions on all aspects of cognitive systems,
- facilitation of interactions with industry and academia on cognitive networking,
- preparation of white papers,
- dissemination of scientific results in the WWRF community,
- promotion of activities and results outside WWRF,
- establishment of liaison agreements with other organizations, and
- provision of forum for discussion and harmonization on standardization and regulation work.

WG 6 has identified the research area "Cognitive wireless networks" which focuses on the following aspects:

- Transition from reconfigurable networks towards networks with cognition capabilities
- Cognitive radio,
- Dynamic spectrum access in cognitive radio context,
- Radio resource management for cognitive wireless networks,
- Artificial intelligence,
- Machine learning techniques, and
- Network architectures supporting advanced spectrum and radio resource management schemes (mesh networks).

WG 6 has published white papers on the cognitive radio related topics. Scenarios, system requirements and roadmaps for reconfigurability are identified in [WWRF 2004]. Radio resource and spectrum management approaches in terms of cognitive radios together with spectrum regulatory perspectives are discussed [WWRF 2005].

2.3.4 Other terms related to cognitive radios

In addition to the term cognitive radio, there are a few other terms whose meaning is close to that. Authors in [Buddhikot 2005] use the term *Coordinated Dynamic Spectrum Access Networks* to describe the situation wherein the access to the spectrum in a region is controlled and coordinated by a centralized entity called *Spectrum Broker*. The term *spectrum agile radio* is used in [Mangold 2004] to describe a secondary user with cognitive capability. This term refers clearly to the ability of exploiting spectrum opportunities in space and time. Also *opportunistic radio* and *spectrum sensing radio* term are used in the literature to have the same meaning.

Detect and avoid (DAA) technology has been proposed to be used in ultra wideband (UWB) systems to minimize interference with fixed wireless equipment. DAA technologies are mitigation techniques to reduce interference to other services [Somayazulu 2006], [Lansford 2004]. DAA techniques can be used to a small portion of channels or to cover full bands. UWB device can employ narrowband detection to detect wireless signals and then automatically switch to another frequency to prevent any conflict [Wisair 2005].

Autonomic Communication (AutoComm) research studies the individual network element as it is affected by and affects other elements and the often numerous groups to which it belongs as well as network in general [Smirnov 2004]. AutoComm is a paradigm where the network itself grows out of the applications and the services end users wants. The network is autonomic and self-configurable. The goals of AutoComm are to understand how desired element's behaviors are learned, influenced or changed, and how, in turn, these affect other elements, groups and network. The self-organized networking structures will be able to sense their environment, detect and perceive changes and understand the meaning of these changes. That makes it possible to facilitate new ways of performing network control, management, middle box communication, service creation, etc.

The autonomous software defined radio receiver concept from [Hamkins 2006] is closely related to cognitive radios. The autonomous SDR receiver is developed for deep space applications to receive signals without much a priori knowledge about its characteristics. The autonomous SDR receiver can automatically recognize the attributes of an incoming signal without much a priori information and reconfigures itself to receive it. The receiver can autonomously recognize for example the angle of arrival, data rate, modulation index, modulation type, and signal-to-noise ratio (SNR). The techniques used in the autonomous SDR are closely related the techniques used for sensing the spectrum in cognitive radios to detect the presence of primary users.

2.4 Cognitive tasks

The major tasks of the cognitive radio can be characterized with the cognitive cycle which is discussed next.

2.4.1 Cognitive cycle

In general the cognitive cycle is a continuous process comprising of the following steps s) Sensing, b) Understanding, c) Deciding and d) Adapting, as described in Figure 2-1. Cognitive Radio exploits specifically this cycle in a manner that spectrum is the main figure to be sensed, and all the subsequent process focuses also on how to manage the spectrum based on the observations.

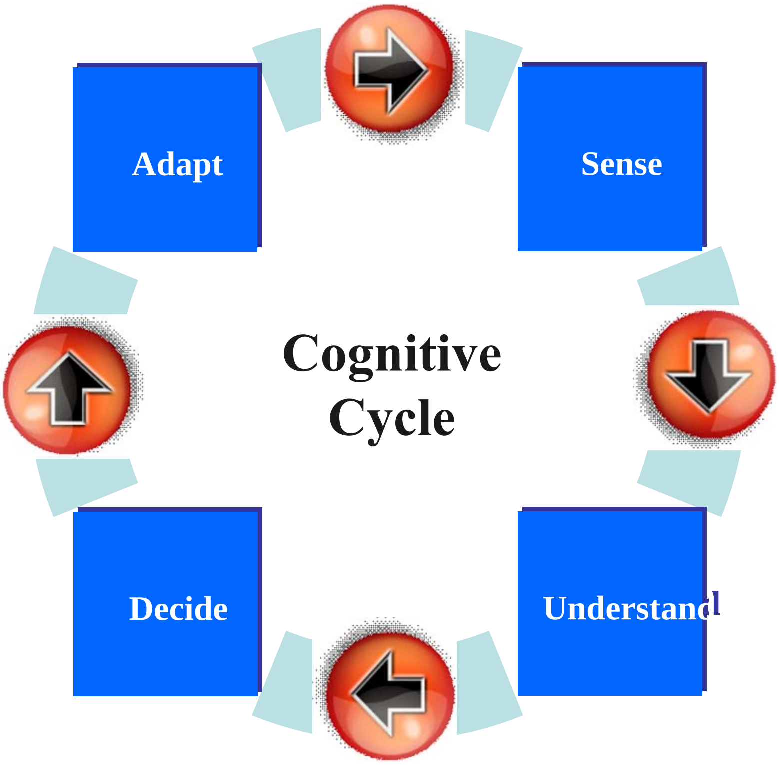


Figure 2-1. Generic cognitive cycle.

The major tasks of the cognitive radio include [Haykin 2005]:
1. radio-scene analysis,
2. channel identification, and
3. dynamic spectrum management and transmit-power control.

Radio-scene analysis performed in the receiver comprises the estimation of interference temperature of the surrounding radio environment of the receiver, detection of spectrum holes, and predictive modelling of the environment. Channel identification performed in the receiver is needed for coherent detection of the message signal as well as for improving the spectrum utilization. Finally, dynamic spectrum management and transmit-power control performed in the transmitter make decision on the transmission parameters based on the information provided by radio-scene analysis and channel identification.

The cognitive cycle comprising the cognitive tasks is presented in Figure 2-2. The feedback channel between the receiver and the transmitter is the facilitator for intelligence in the cognitive radio. The feedback channel is needed to transmit the following information [Haykin 2007a]:
- centre frequencies and bandwidths of the spectrum holes,
- combined variance of interference plus thermal noise in each spectrum hole,
- estimate of SNR for adaptive transmission.

Figure 2-2 presents a cognitive radio link where the transmitter and receiver are located in different cognitive radio devices. The cognitive radio devices are transceivers and therefore also the transmitter side includes a unit for radio scene analysis to sense the spectrum in the vicinity of the transmitter. However, this sensing unit belongs to a different link and therefore is not depicted in the figure. With cooperative detection, the spectrum sensing information from the receiver and the transmitter can be combined to provide more reliable information about the availability of spectrum holes. The cognitive tasks are further discussed in more detail in Sections 2.4.2 to 2.4.4.

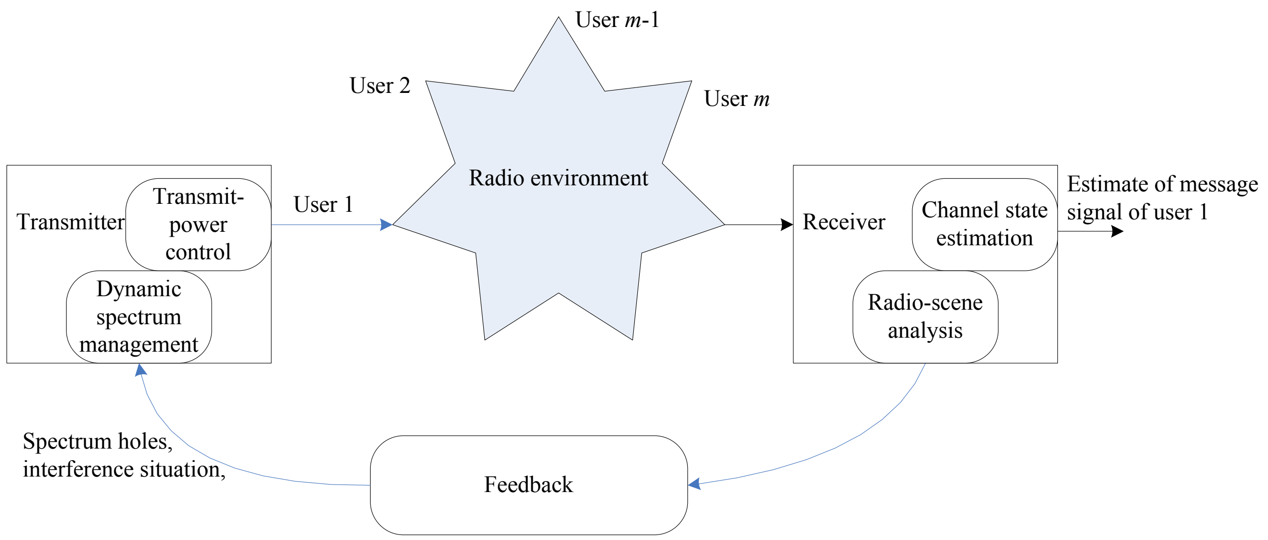


Figure 2-2. Cognitive cycle for cognitive radio link.

2.4.2 Radio-scene analysis

Radio-scene analysis encompasses spectrum awareness that can be classified into passive and active awareness as presented in Figure 2-3. The classification and the passive awareness presentation are taken from our article about spectrum awareness presented in book about cognitive and cooperative networks [Höyhtyä 2007]. In the passive awareness, the knowledge about electromagnetic environment, i.e. the spectrum use pattern, is received outside own secondary communication system. The knowledge about electromagnetic environment can be received from existing communication system, i.e., primary and secondary users negotiate for spectrum usage [Tonmukayakul 2004]. For example, the base station of the existing (primary) communication system like television broadcasts frequency environment to the CR terminals (SUs). The spectrum use pattern can be obtained also from a server [Raman 2005] or database [Brown 2005]. In addition, in a policy based approach, the primary system use is defined a priori [Mangold 2004]. This could lead to a rather static secondary usage without optimally exploiting spectrum holes (i.e., temporarily unused frequency band of primary user).

Another form of awareness is that secondary users actively sense the surrounding radio environment and adapt their transmissions based on the measurements. In non-cooperative situation nodes make their decisions independently based on the observations about the spectrum environment. In cooperative situation local measurements will be combined and signalled to all SU stations without using the frequencies occupied by the primary users (PUs) [Weiss 2004] before decisions about spectrum use are made. When the active method, also referred to as opportunistic spectrum use [DARPA XG] is used, the primary users do not need to know anything about SUs. CR systems may employ either or both forms of awareness, thus the discussed approaches should not be viewed as mutually exclusive. The reliable sensing of spectrum environment is perhaps the most important attribute of CR. It should ensure adaptive transmission in wide bandwidths without causing interference to primary users [Čabrić 2005]. The key challenge of spectrum sensing is the detection of weak signals in a noisy environment with a very small probability of miss detection. The same problem is present in radar systems [Skolnik 2002].

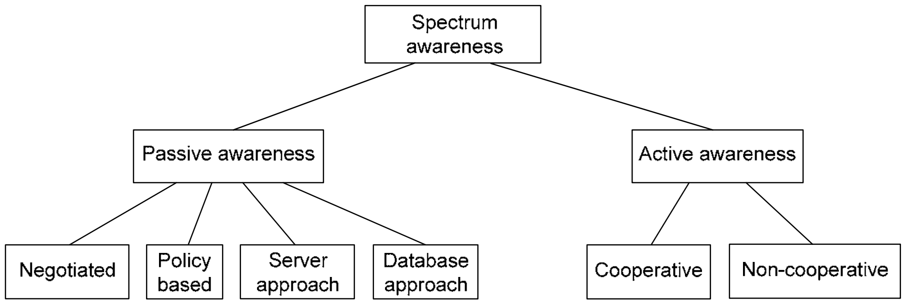


Figure 2-3. Spectrum sensing classification.

Passive awareness

In systems based on *negotiated spectrum use* the primary system explicitly announces secondary users about the allocated frequencies and the available spectrum opportunities. For example, the base station of existing (primary) communication system, such as television, broadcasts *beacons* that advertise the availability of licensed spectrum for secondary usage. A beacon can either grant permission to access the spectrum or deny access [Hulbert 2005]. Negotiation can include technical (transmit power, location, frequency, modulation *etc*.), financial (price, payment options *etc*.), and service quality (signal-to-noise ratio, interference protection *etc*.) parameters [Tonmukayakul 2004]. Parameters may be more or less specific depending on characteristics of services offered by the primary user and the secondary user. Guaranteed quality of service requirements can be met for both primary and secondary users only if primary users promise not to interfere. Most probably this is true only for a fee. *Real-time secondary markets* allow license-holders lease rights to secondary users to use the spectrum for the duration of license [Peha 2003]. Secondary users can make requests as needed and obtain the spectrum opportunities from licensees.

In the *policy based approach*, the radio regulation authority identifies a licensed band of the radio spectrum where use is low or the band is used with a deterministic pattern [Mangold 2004]. This band is then made available for secondary use. The authority assigns a set of policies that provide rules and constraints concerning how to use this available band. Policies can answer for example to questions such as [Marshall 2006]: *Am I allowed to use xyz MHz? How much power could I emit on frequency xyz? Could I double my bandwidth?* The set of policies are published in machine-understandable form for download from servers of the radio regulation authority [Mangold 2004], [DARPA XG]. Secondary devices repeatedly (e.g., once a day) seek for updates of policies that are relevant for their regulatory domain and update their information bases. After updating information, secondary users adapt their transmission parameters like frequency and power to meet policies. The fact that the use of primary system is defined a priori could lead to a rather static secondary use, without optimally exploiting spectrum holes (i.e., temporarily unused frequency band of primary user).

A primary system or the radio regulation authority can maintain a *table or database of frequency resources* in its server and both primary and secondary users can update this table. The database includes location information and an estimate of the interference range of the secondary user and it is most likely available over the Internet since it is pervasive, flexible, and low cost [Brown 2005]. Frequencies used by the licensed system can be seen and checked from this table. When a secondary user needs to transmit, it checks the table, chooses an available band and reserves it to its use. Other secondary users can then see that this particular band is occupied by a secondary user and can choose other resources for their use. When a primary or secondary user stops transmitting the associated band is released from the table and made available to other users. Secondary users have to check this table periodically to avoid interfering the primary system. The primary system can start using the band reserved by secondary user whenever there are no free bands left. If free bands exist, the primary system uses them instead of forcing a secondary user to stop using a band. In this way the spectrum can be used very efficiently. However, this approach may require an infrastructure to operate, e.g., a separate network for retrieving database information. The approach could be quite rigid and thus, not so suitable for fast, dynamic and highly efficient spectrum use.

Spectrum Server can be used to enable coexistence of radios in a shared environment in a centralized fashion [Raman 2005]. The centralized spectrum server obtains information about neighbourhood and interference through local measurements from different terminals and then offer suggestions to the efficient spectrum use. The spectrum information can be gathered from several separate secondary networks. Authors in [Buddhikot 2005] define the term *coordinated dynamic spectrum access networks* to describe situations wherein the access to the spectrum in a region is controlled and coordinated by a centralized entity called *Spectrum Broker*. This can be seen as a compromise between static allocations and the opportunistic spectrum use. Service providers and users of the networks do not a priori own any spectrum; instead they obtain time bound rights from a regional spectrum broker to a part of the spectrum and configure it to offer the network service. The requirement for this approach is that part of the spectrum is allocated by regulating authorities such as FCC for controlled dynamic access. In a certain region, spectrum broker owns that allocated spectrum and leases it to the requesters.

All these passive approaches are good in the sense that they can ensure interference-free communication to the primary system, since the spectrum use is defined a priori. The secondary system uses only frequencies accepted by the primary system or regulation authority. However, passive awareness increases the amount of needed control information in the system. Considerable signalling could be needed to disseminate frequency information. Furthermore, passive approaches are not compatible with existing licensed systems. They can still be very useful in the future. Note also that passive awareness approaches can be combined with opportunistic spectrum use. For example, policies can set some restrictions for the use of licensed spectrum.

Active awareness

Active awareness is a complementary method to passive awareness for achieving information on the current spectrum use in the surrounding environment. The idea of active awareness is to monitor spectrum by signal detection methods so that we can identify those frequency bands which other systems use. The method requires constant monitoring of the channel so that new primary users and possible vacant channels will be detected.

When using spectrum sensing, the hidden terminal problem might cause problems when there is an obstacle between the secondary system and the primary transmitter. In this kind of situation the secondary user might have good connection to primary receiver but it cannot necessarily detect the primary transmitter and its transmission. To overcome this kind of problem, we can use longer sensing period to increase the measurement accuracy but this reduces the available time for transmission. Another method to overcome hidden terminal problem is to use cooperation. When a device operates in a cooperative fashion, it shares the data, which it has collected from the spectrum environment, with other similar users. Hence, the secondary user can have information about the primary user even though it cannot see it.

Primary user detection can be accomplished by using, for example, matched filter, energy detection or cyclostationary feature detection. The advantage of energy detection is that we do not necessarily need much information about primary user and all secondary users can operate individually if necessary. On the other hand, feature detection, which utilizes a priori information on the primary users' signals, has better performance especially at low signal-to-noise ratios (SNR).

This report focuses on the active awareness as the method for radio-scene analysis. Techniques for active spectrum sensing are discussed in more detail in Chapter 5.

2.4.3 Channel identification

Knowledge of the channel state is required at the receiver for coherent reception. Thus, the channel state has to be estimated in the receiver. In addition, the computation of the channel capacity of a cognitive radio link and the power control algorithm in the transmitter require knowledge of channel-state information [Haykin 2005]. This implies that digital baseband algorithms for adaptive estimation of the state of a fast fading channel are also needed in CR system.

Channel identification algorithms can be classified into three categories: data-aided, non-data-aided and decision-directed methods. Data-aided channel estimation methods assume that the transmitted data is known and use this information in deriving the channel estimates. Non-data-aided channel estimation methods assume unknown transmitted data and remove the data by averaging. Decision-directed methods approximate the data-aided methods by detecting the data and using this data as a reference signal to the estimator.

A suitable method for channel state estimation in cognitive radio systems is to first use the acquisition mode to acquire an initial estimate of the channel state, and then switch to training mode to provide more accurate channel state estimates. In the acquisition mode a training sequence is used to acquire an estimate of the channel state. Also pilot symbols can be inserted between data symbols in order to update the channel state estimate, thus, an example of a possible signal model is illustrated in Figure 2-4.

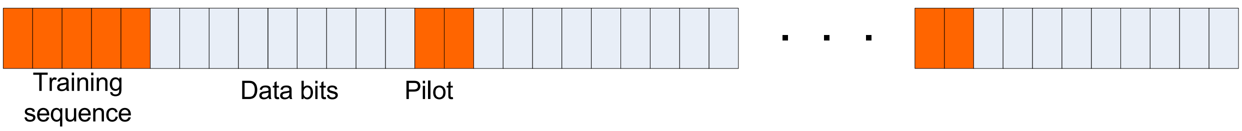


Figure 2-4. An example of the signal model.

In the acquisition mode, only a rough estimation of the channel state is required in order to initialize tracking. Therefore, open loop systems are adequate and often used for this purpose. A suitable channel estimator for acquisition of the channel state estimate is presented in Figure 2-5 [Levin 1960]. For a single tap channel equalization is simply normalization.

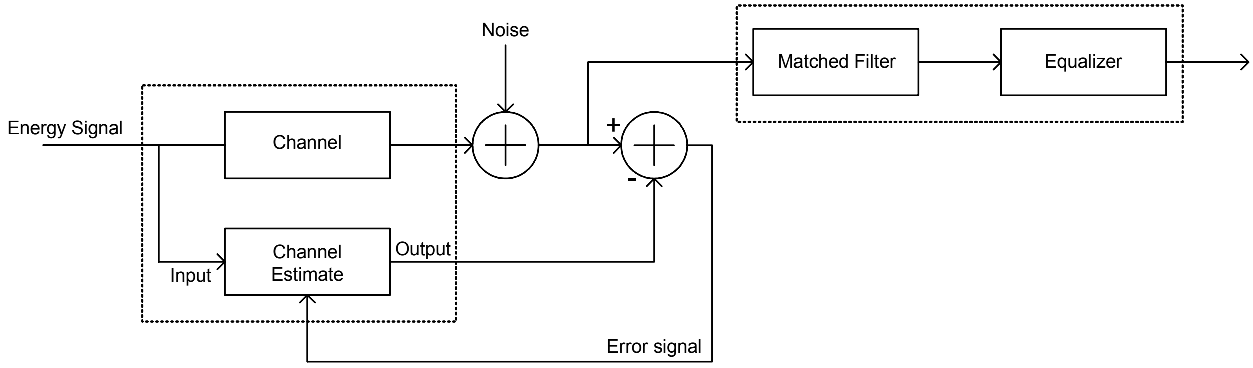


Figure 2-5. A channel estimator for acquisition.

When reliable estimate of the channel state is obtained, the training sequence is switched off, actual data transmission is initiated and the receiver is switched to the tracking mode. In the tracking mode, more accurate estimate is required and the ability to track changes in the channel state. Therefore, feedback loops are used which require a good initial estimate from acquisition to converge. For tracking the channel state a suitable estimator is a LMS/RLS estimator shown in Figure 2-6 [Magee 1973].

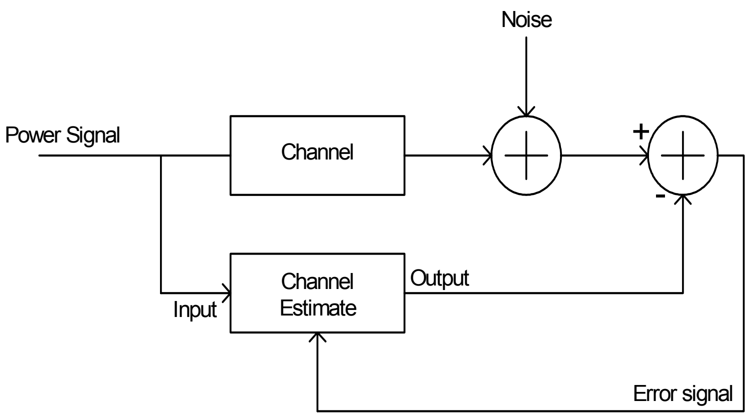


Figure 2-6. A channel estimator for tracking.

Challenges of the channel state estimation are caused by multipath fading, interference, noise uncertainty and nonstationary effects caused by e.g. shadowing. Also finite packet lengths might cause transients in the estimation in the beginning and at the end of the packets. If a wide bandwidth channel is considered, channel state might be dependent of the frequency.

2.4.4 Dynamic spectrum management and transmit-power control

After reliable identification of the available spectrum holes, the cognitive radio system needs to select the transmission parameters such as spectrum holes and power levels. Requirements for dynamic spectrum management require the following [Haykin 2007a]:

1. Secondary users of the unoccupied subbands must coexist with the primary users.
2. Interference temperature at the receiver input of each user in the network does not exceed a prescribed limit.

Power control, bit rate control, and dynamic spectrum management are the tasks in the transmitter side [Haykin 2005], [Hoven 2005]. The transmission techniques can be classified into three categories: overlay, underlay and interweave [Srinivasa 2007]. Underlay or interference avoidance model allows concurrent transmission of primary and secondary users in ultra wideband (UWB) fashion where the primary users are protected by enforcing spectral masks on the secondary signals so that the generated interference is below the noise floor for the primary user. However, underlay allows only short-range communication due to the power constraints technology [Zhou 2005]. Overlay or known interference model also allows concurrent transmission of primary and secondary users. The secondary users use part of their transmission power for relaying the data of primary users and part of the power for their own secondary transmission.

In the interweave model [Srinivasa 2007] the cognitive radio monitors the radio spectrum periodically and opportunistically communicates over the spectrum holes. Firstly, when primary users (PUs) communicate, the secondary users in the same frequency band are silent. If the transmission between SUs is on when PU starts to transmit in the same band, the SUs have to clear the frequencies in Δt seconds, where Δt is the maximal interference time that PU can tolerate [Brodersen 2004]. The transmitter power control must be adaptive and may be necessary to operate in distributed manner, and we need a feedback channel for transmission of control information [Haykin 2005]. In addition, a CR should know where it is and where the reachable CR terminals are [Jondral 2005]. Thus, it should include location sensors (e.g., Galileo or Global Positioning System (GPS)). The focus in this report is in the interweave model. Note that the term overlay is used in many papers, such as [Čabrić 2006], to characterize the use of cognitive radios, but we use the term interweave.

2.5 Towards cognitive radio networks

The notion of cognitive radios can be extended to cognitive radio networks. The cognitive radio network is an intelligent multiuser wireless communication system with the following abilities [Haykin 2007a], [Haykin 2007b]:

1. To perceive the radio environment (i.e., outside world) by empowering each user’s receiver to sense the surrounding environment continuously.
2. To learn from the environment and adapt to it in response to deviations in the environment.
3. To facilitate communication among multiple users through co-operation in a self-organized manner.
4. To control the communication resources among the multiple users through competition.
5. To create the experience of intention and self-awareness.

Cooperation is used to facilitate communications across the nodes in the network without any fixed infrastructure. Competition is used to provide control over the power transmitted from each node to maintain the interference temperature at a receiving node below a prescribed limit.

Two alternative approaches to build a cognitive radio network according to [Haykin 2007a] include the following:

1. Use an out-of-band licensed channel as the dedicated common channel available for all users. This approach has the disadvantage that the common channel occupies a role similar to base stations. Hence, it results in costly use of resources and presents a weak element in the system.
2. Exploit the principle of self-organized networks to build on ad hoc network (see [Haykin 1999]).

In the following, we briefly highlight the more generic concept of cognitive networks. In a cognitive network the same cognitive principles applied before are applied (see Figure 2-1), but not only to spectrum-related figures but to a large array of resources. We identify two types of resources, namely **radio resources** and **network resources**. The former include the fundamental resources used by any communication system, time, frequency (spectrum), space and energy (power). The latter resources encompass different types of resources available at the wireless network, including **built-in resources** (processing power of network devices, e.g., CPU, DSP, mass memory, battery, etc.), **user-interface resources** (sensors and other functionalities available on wireless terminals), as well as **social resources** (the user and users behind wireless devices). Figure 2-7 illustrates the discussed resources.

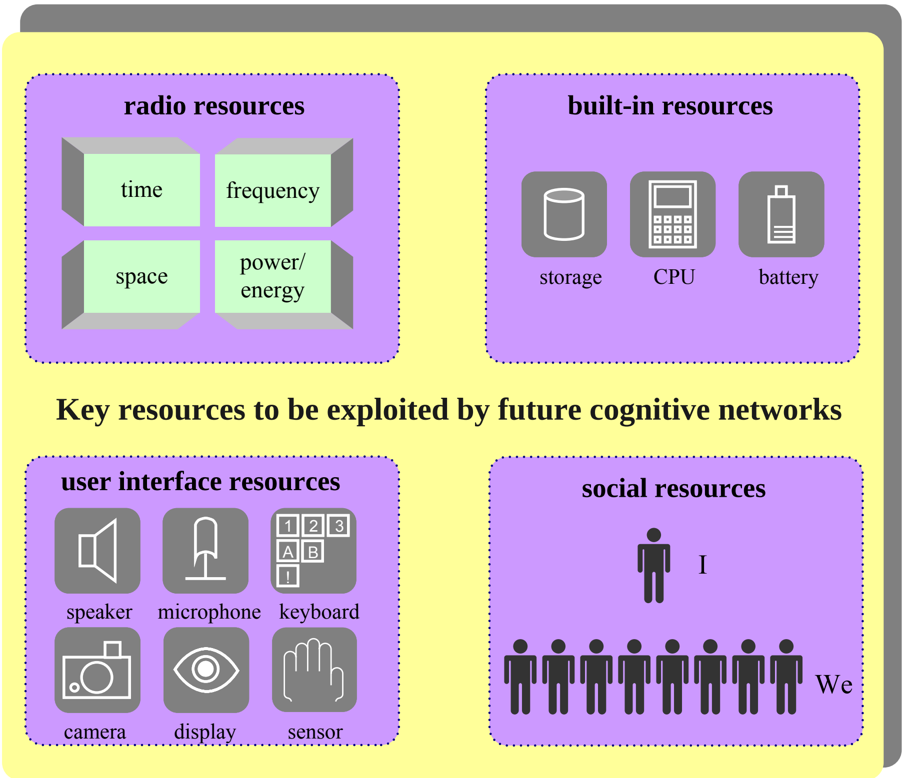


Figure 2-7. Radio resources and network resources.

Based on the above discussion, we can see that cognitive radio can be considered as a particular case of cognitive networks, where the main resource to be considered is spectrum. Figure 2-8 thus depicts cognitive radio in the context of cognitive networks.

The goal of fully cognitive networks will be two-fold, improve communicational capabilities of the wireless network, typically achievable throughput, QoS, etc, and, at the same time enhance the efficiency in the utilization of the mentioned large array of resources. Finally we foresee that social resources and their interaction with other (technical) resources of the wireless networks will become one of the most challenging and promising research areas of the future.

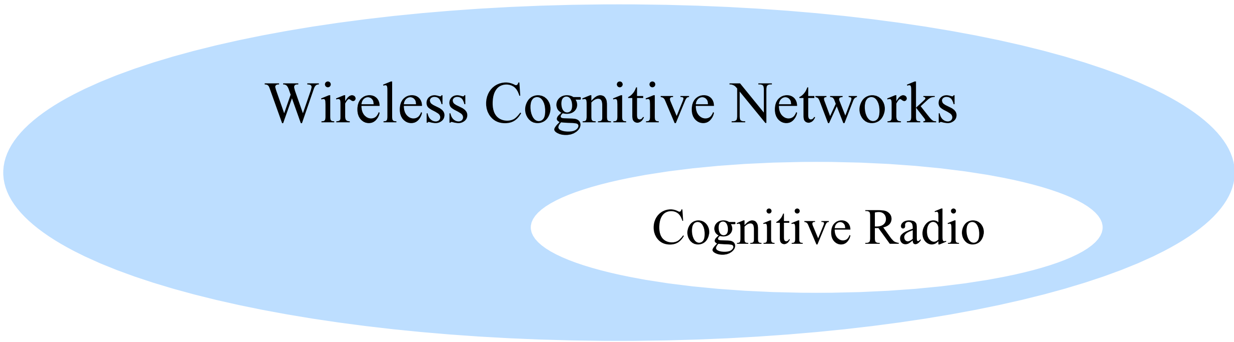


Figure 2-8. Cognitive radio as a particular instance of cognitive networks.

2.6 Challenges in cognitive radios and networks

The cognitive radio has no sense of sight which severely limits the ability to detect the environment. This can lead to the *hidden terminal problem* where the sensing secondary user is unaware of the presence of a primary user because it cannot reliably detect its presence. A PU terminal and a SU terminal can be separated by some physical obstacle opaque to radio signals. They can also be out-of-range of each other so that the reliable sensing of primary transmission becomes impossible. Two such terminals are said to be hidden from each other [Tobagi 1975].

One example of hidden terminal problem is a digital TV which lies at the cell edge where the power of received signal can be barely above the sensitivity of the receiver [Krenik 2005]. If the CR is not capable of detecting TV signal, it can start to use the spectrum and interfere with the signal the digital TV is trying to decode. This problem can be avoided if the sensitivity of CR outperforms primary user receiver by a large margin [Čabrić 2004], [Krenik 2005].

The hidden terminal problem is also present in WLAN systems which operate on open bands. In WLANs based on the IEEE 802.11 standard, the problem is tackled by using carrier sense multiple access with collision avoidance (CSMA/CA) scheme as the multiple access method. In CSMA/CA a station wishing to transmit first listens to the channel and only transmits if the channel is sensed “idle”. If the channel is sensed busy before transmission, the transmission is deferred for a random interval, which reduces the probability of collisions on the channel.

In a noncooperative game, the hidden terminal problem can cause unpredictable moves and thus lead to a bad situation. Cooperation and distributed methods help to avoid hidden terminal problem and thus reduce interference to the primary system. Access point (AP) is needed in an ad hoc wireless network to realize control-theoretic cooperation between secondary users. Spectrum sensing information of the nodes will be handled and combined in the access point [Weiss 2004]. Based on that information the occupancy vector is defined and distributed to the nodes in the network. Occupancy vector can be a simple binary vector in which 1 refers to the channel in use and 0 for a free channel. In a four-channel system where only the second channel is free, the occupancy vector is 1011.

It is not adequate to determine whether a band is free. The cognitive radio must also estimate the amount of interference and noise that would exist in the free subband to make sure that the transmission power of the cognitive radio does not violate the interference limit of the system.

The complexity of the cognitive radio is an important aspect. The benefits from the use of cognitive capability must exceed the cost of introducing the cognitiveness which inherently adds to the complexity of the system.

The cognitive radio must be capable of operating over wide bandwidths because the spectrum holes can be spread over large bandwidths. The cognitive radio must be able to sense wide bandwidths as well as transmit on wide range of bandwidth, which places challenges on the antenna design. In particular, the transmission may be spread to several narrow sub-bands and the emission to adjacent bands which are used by the primary users must be avoided.

In a cognitive network information is exchanged between the nodes. The amount of control information is an important issue since the transmission of the control information can become the bottleneck if the amount of control information is large. In an ad hoc network of cognitive radios, all control information is sent over the wireless links resulting in significant traffic amounts if not properly planned.

The emergent behaviour apparent in the cognitive network due to the adaptations in the time-varying operating environment is a key issue. When a set of adaptive equipment are connected, the uncontrolled adaptations can lead to fundamental problems. Emergent behaviour in cognitive radios can be classified into:

1. positive emergent behaviour, which is characterized by order, and
2. negative emergent behaviour, which is characterized by disorder (e.g. traffic jams and chaotic behaviour).

It is important to be able to detect negative emergent behaviour which is difficult. In positive emergent behaviour predictability is easier.

3 Mesh networks

Wireless networks can have different topologies. A network topology is a pattern of links connecting a pair of nodes of a network i.e., it defines the shape of the network. In centralized star topology all nodes in the network are connected to a central node (or a base station) that retransmits the transmissions of any peripheral node to the destination. The traditional mobile communication systems are centralized and base stations are used to route the calls resulting in large infrastructure costs. The general cognitive radio concept described in Chapter 2 does not fit well in this context even though the different cognitive radio functionalities can be applicable also to centralized architecture.

In an ad hoc wireless network the connection is established for the duration of one session and does not require established infrastructure [Goldsmith 2005]. Nodes discover others within a communication range to form a network. In addition, nodes that are out of range can be searched by forwarding messages over multiple nodes. This kind of network is called a multi-hop ad hoc network which is better suitable for cognitive radios compared to the centralized architecture. The deployment of cognitive radios in multi-hop ad hoc networks leads to self-organized networks which are built on co-operation to facilitate communication and competition to control the use of resources. The following sections describe the ad hoc network structure for cognitive radios.

3.1 Definitions and history

The word ‘ad hoc’ comes from Latin and its meaning freely translated corresponds to ‘for temporary purposes’. This denotes a wireless network that can be built in special purposes and is not bound to a certain time or place. One special property is the lack of fixed base stations (BS). This means that the nodes that form the network have to inform each other of their existence and also of the channel state. Because of the large measure of control needed in the network, ad hoc networks go through a constriction in capacity as the number of nodes increases.

Mesh network can be seen as a bunch of nodes which all communicate with each other creating a mesh. Every node can send and receive messages, but the nodes also function as routers to the data. Mesh networks are some kind of ‘key technology’ of the ad hoc networks [Akyildiz 2005]. Mesh networks consist of two types of nodes: mesh routers and mesh clients: Mesh routers exhibit minimal mobility while mesh clients can be mobile too. Mesh networks have multiple advantages: the capability of self-organization, reliability, exploitation of the existing technologies and thus the cheapness including low up-front costs [Akyildiz 2005]. The nodes can automatically establish and maintain mesh connectivity creating an ad hoc network. Basically the mesh network structure commits on routing issues in ad hoc networks but it can also be seen as a synonym to an ad hoc network.

Mesh networks can be divided into two class, *full mesh topology* and *partial mesh topology*. In a full mesh topology, also known as true mesh topology, all the nodes are connected directly to each of the other. This can be considered as the original definition of the mesh networks although they are really impractical and expensive on a large scale networks. Commonly, when talking about mesh networks, we mean a partial mesh topology. In partial mesh topology some nodes can be connected to all the others, but some nodes interact only with the nodes with which they exchange the data.

Ad hoc networks can be considered as a subset of wireless mesh networks [Akyildiz 2005]. Ad hoc networks history begins in the early 1970s. The packet radios can be seen as the first mobile ad hoc networks (MANET). In 1972 the Department of Defence (DoD) sponsored a Packet Radio Network (PRNET), which evolved into the Survivable Adaptive Radio Networks (SURAN) program in the early 1980s. The goal was to provide packet-switched networking to the mobile and hostile environment with no infrastructure. The nodes could be tanks, soldiers, aircrafts etc. [Ramanathan 2002].

Robert Kahn and Larry Roberts made also a lot of research related to the computers moving with a car and wirelessly connected to a bigger central computer, which they called a *packet radio network* [Kahn 1978]. This happened also in early 1970s.

Radio amateur activity started in the late 1970s. In 1978 first successful experiments using a terminal node controller (TNC) were done in Canada [Karn 1985]. The data, which was going to be sent, was first collected to the TNC and then sent as bursts or packets. Radio amateur activity extended fast to the U.S. and then all over the world.

For about two decades, packet radio was targeted mainly to the military purposes and to radio amateurs. In the early 1990s a new spate of development occurred [Ramanathan 2002]. Notebook computers and other viable communication equipment based on RF and infrared became popular. A commercial period had emerged and lots of applications were evolved. IEEE 802.11 subcommittee adopted the term *ad hoc networks*.

Meanwhile, the DoD continued funding programs like Global Mobile Information System (GloMo) and the Near-term Digital Radio (NTDR). GloMo was designed to provide office-environment Ethernet-type multimedia connectivity anywhere and anytime in handheld devices. The development has been fast until these days. A lot of ad hoc based standards have been emerged, such as HIPERLAN, Bluetooth, WiFi, ZigBee and many others.

3.2 Mesh network architecture

Wireless mesh networks are thought to be a key technology for next-generation wireless networking [Akyildiz 2005], [Jun 2003]. In a true mesh network, every node is connected to every other node [Centi 2004]. This fully connected approach is impractical and also expensive for large-scale networks. In general, partial mesh networks are implemented and definition for a mesh network usually means a partial one. Alliance for Telecommunications Industry Solutions (ATIS) telecom glossary defines mesh topology as *a network topology in which there are at least two nodes with two or more paths between them* [ATIS]. Mesh networks are built on a mix of fixed and mobile nodes interconnected via wireless links to form a multihop ad hoc network [Bruno 2005]. Wireless mesh networks are dynamically self-organized and self-configured [Akyildiz 2005]. The nodes of a network automatically establish an ad hoc network and maintain mesh connectivity.

The architecture of a mesh network can be classified into three types [Centi 2004], [Akyildiz 2005]. In *infrastructure meshing*, mesh routers form an infrastructure for clients i.e., terminals in the network. Mesh routers form a self-configuring mesh with self-healing links and can use gateway functionality to connect to the Internet. This infrastructure provides a backbone for conventional clients and enables integration with traditional wireless networks, through gateway/bridge functionalities in mesh routers. *Client meshing* provides peer-to-peer communications among clients, usually using one type of radios on devices. It is actually the same as a conventional ad hoc network. Mesh router is not required in client meshing. End user requirements in client meshing are harder since end users have to perform additional functions like routing and self-configuration.

These two architectures can be combined to form a *hybrid mesh network*. In a hybrid network, the clients can access the network through mesh routers as well as directly communicate with other clients. The hybrid architecture is the most versatile as it comprises all the advantages of mesh networks. Infrastructure provides connectivity to other networks, while routing ability of clients increases connectivity and coverage inside the network.

Mesh architecture provides some benefits over the traditional hierarchical architecture. The redundant routes enhance the reliability of transmission [Akyildiz 2005]. The same coverage can be achieved with lower transmission power through multi-hop communications. The throughput is also higher in long distance communications and the network can be easily expanded [Bruno 2005]. However, network performance is not scalable with either the number of nodes or the number of hops in the network [Akyildiz 2005]. New scalable medium access control (MAC), routing, and transport protocols are needed to achieve scalability. There are also security problems and the current capabilities of integrating heterogeneous networks are very limited.

The research on wireless mesh networks can be classified into two main areas. Firstly, development of protocols like routing, power control and higher layers like security issues [Akyildiz 2005], [Kawadia 2005b]. Secondly, establishment of the capacity of wireless networks (i.e., theoretical bounds on how much traffic they can support) is under heavy research [Gupta 2000], [Xie 2004], [Agarwal 2004], [Xue 2005], [Mergen 2005], [Cover 2006]. The network information theory basically gives the bounds for capacity also for a cognitive radio network.

Mesh networks cannot be spectrally very efficient. Reason for that is the amount of controlling information needed to maintain the topology of network. Both mobility and increasing network size increase the needed amount of control dramatically. On the other hand in a centralized cellular network the spectrum can be exploited quite efficiently. However, there are services rather than performance issues that are behind the mesh networking. Mesh networks can offer services that cellular systems are not capable to offer. They are networks that are established for a specific purpose and can be run down after a quite short use period. For example, in a big music festival in which 20 000 people participate, a specific communication network may be needed to fulfill the requirements during the event. Cognitive radio technology can increase the spectral efficiency in a mesh network. It also helps different mesh networks to share same spectral resources in a same local area.

Single-hop network: In a multi-hop ad hoc network, controlling the routing can help to avoid interference to primary users [Fujii 2005]. If the spectrum is monitored to be used by primary user in some area, the communication around the interference area is interrupted. Data packets are relayed through a redundant path to the destination. The single-hop ad hoc wireless networks represent the network used in hot-spot networks, smart rooms, emergency environments, and in-home networking [Shah 2005]. Since the area of these networks is small, all nodes can be within each other's transmission range. Thus the single-hop connection allows every node to communicate directly with any node in the network. The system can be delay limited, for example in voice applications, and throughput limited like in video streaming. The analytical models for delay and throughput in single-hop ad hoc network have been recently defined in [Alizadeh-Shabdiz 2006]. The relevant parameter values for an ad hoc network can be found in the literature. For example, Eshghi [Eshghi 2005] has investigated the performance of a multi-hop ad hoc network.

A major motivation for mesh networks is to extend the coverage of current and future wireless networks. Possible application areas for mesh networks include broadband home networking, community and neighborhood networking, enterprise networking, metropolitan area networks, transportation systems, building automation, health and medical systems, security surveillance systems, emergency networking, and peer-to-peer communications [Akyildiz 2005].

3.3 Traffic modeling

Data packet transmission on the source level in a network is commonly modelled by an ON/OFF source model [Willinger 1997] (also known as a packet train model) [Jain 1986]. The ON-period is the period in which a burst of data packets are sent and the OFF-period is the period in which no packets are sent. This model is basically controlled by two major sets of parameters: 1) distribution of the ON/OFF-periods and 2) distribution of packet arrivals within an ON-period. There exist many different traffic models that have their own pros and cons. Type of the network and offered services characterize the choice of the traffic model. In a wireless environment, two basic classes of traffic patterns exist [Haykin 2005]. 1) Deterministic patterns where during fixed time slot transmission is ON, then OFF. Pattern can follow some specific frame structure, in which case it is also periodic. 2) Stochastic patterns where traffic can be described only by statistical terms. Poisson and Pareto distributed traffics are examples of stochastic traffic.

Poisson model has traditionally been used for voice traffic modeling. It is analytically nice but does not fit well to actual bursty network traffic. Burstiness of traffic is taken into account for example in Markov-modulated Poisson and Packet train models. Markov models model the activity of traffic source with finite number of states: i.e., ON/OFF models. Self-similar models are needed for large-time scale analyses. Self-similar traffic seems the same regardless of the time scale it is observed. So it exhibits fractal properties and also calls attention to the chaos theory. Self-similar models include Fractional Brownian motion, Chaotic maps and PackMimeHTTP ns-2 traffic model that uses Weibull distribution to generate traffic. Also Pareto distribution has self-similar features and it generates real network type traffic. It is simpler than real self-similar models and it models well high speed networks.

In two-level Pareto-Poisson model the Pareto distribution is used to model distribution of the ON/OFF periods whereas Poisson is used for modelling the distribution of packet arrivals within an ON-period. The traditional view is that the Poisson distribution is very suitable for modelling the calls in the circuit switched network but is not so good for packet switched network. Pareto distribution instead characterizes well e.g. the operation of a router. However, it was noted in [Karagiannis 2004] that the current Internet traffic can be well represented by the Poisson model. In the Poisson model ON and OFF times are exponentially distributed.

We are more interested in ON/OFF-distribution than distribution of arrivals within an ON-period because for cognitive radio it is easier to exploit longer OFF-periods than very short periods between packets within ON-period. ON/OFF source model can be reliably used to model the wireless network traffic. File transfer protocol (FTP) and hypertext transfer protocol (HTTP) transmissions [Staehle 2000], video conferences and general packet radio service (GPRS) traffic [Lin 2003] are examples of that kind of traffics. Typical average ON-period time for a voice call is 3 min, for Internet dial up it is 20 min, and for packet data transmission it is in the range of 10 s. We assume exponentially distributed ON/OFF-periods for the transmission of primary user. The size of packets is limited to 1500 bytes in data transmission since this is the mostly used maximum transfer unit (MTU) [Staehle 2000]. To simplify situation, the packet and frame lengths are set to constant. When a cognitive radio detects the spectrum to be free (during OFF-period), it can start to exploit the free band until the next ON-period appears. The traffic from cognitive radio is constant bit rate user datagram protocol (UDP) traffic with constant packet and frame lengths.

3.4 Capacity of mesh networks

The performance evaluation of wireless networks is of great interest. In general, the performance of systems can be divided into three levels:

- information theoretic performance level,
- optimized performance level, and
- performance level of certain technology.

Information theory sets the upper limit for the system performance which can be approach with the optimized performance level. The optimized performance level is the upper bound for the given technology which is obtained by adjusting the system to obtain best possible performance for example by optimizing the node locations, transmission times etc. The performance level of a certain technology presents what can be achieved with the given technology on the average.

In the following sub-sections the capacity of wireless mesh networks is studied based on the paper [Gupta 2000].

3.4.1 Model for capacity

Commonly, capacity in a wireless network can be defined as a maximum number of users or maximum amount of data that can simultaneously be on the network [Skidmore 2005]. Thus capacity can bee seen as a quality of a network.

In [Gupta 2000], to investigate capacity of an ad hoc network, there are two important constructs. The first is a concept of throughput. It can be seen as a quality of a single user. It is usually defined as the time average of the number of bits per second that can be transmitted by every node to its destination, see Figure 3-1. This means that the throughput is the bit rate of the worst case between any two nodes in the network. There can be simultaneously transmitting nodes that cause interference and the route may not be the optimized one. We will use a symbol C to represent this throughput capacity.

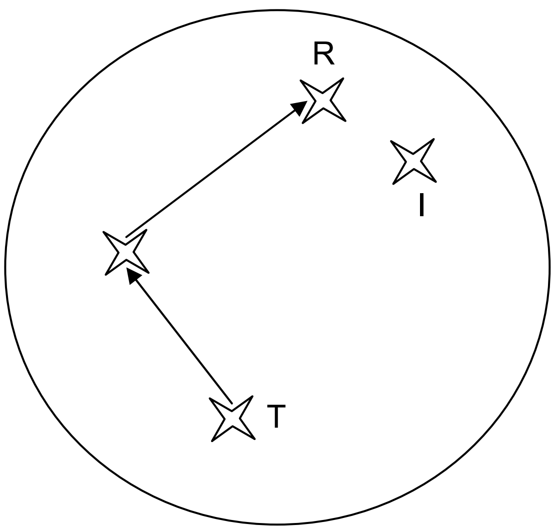


Figure 3-1. Throughput capacity.

Another way to inspect capacity is to talk about transport capacity C_T. It represents the bit-distance product that can be transported by the network per second and it is specified by the unit of bit-metres per second. It is a supremum of the distance weighted sum of rates that the network can deliver defined as $C_T = \sup_R \sum_{i,j} R_{ij}\rho_{ij}$, where R_{ij} is the feasible information rate vector and ρ_{ij} is the distance between node i and j [Xue 2005]. This is a quality of whole network. We assume that the route is optimal and the message goes over multiple hops. The interesting value is how many bits can be sent 1 meter towards its destination in one second. Figure 3-2 tries to clarify the idea.

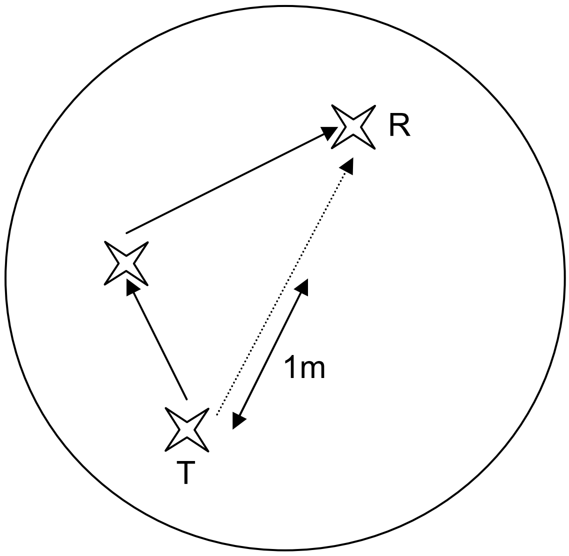


Figure 3-2. Transport capacity.

Originally transport capacity is a term related to the passenger traffic or transport traffic. It means "the number of persons, weight or volume of the load which can be carried by means of transport under given conditions" [Dictionary]. Number of persons (or weight or volume of the load) can be compared with bits. In passenger transport we talk about kilometres, while in data transmissions on an ad hoc network it is more natural to talk about meters. The given conditions mean basically time that is considered. In passenger transport it is commonly a year, while transmitting the data, we talk about seconds.

To proceed, it is good to consider the notations called *big-oh*, *big-theta* and *big-omega*. They are used to compare the order of some complex phenomena to some basic functions like x, x^2, $\log_x$ etc.

Big-oh's (O) definition

Let f(x) and g(x) be functions from the set of real numbers to a set of real numbers. Then f(x) is said to be O(g(x)) if and only if there are constants C and n_0 such that

$$|f(x)| < C|g(x)|, \qquad (3\text{-}1)$$

whenever $x > n_0$.

For example, $f(x) = 5x + 10$ is $O(x^2)$ because $5x + 10 < 5x^2 + 10x^2 = 15x^2$ for $x > 1$. Hence C=15, n_0=1. By this example, it is easy to understand that big-oh concerns with the "less than or equal to" relation between functions with large values of the variable.

Big-omega's (Ω) definition

Let f(x) and g(x) be functions from the set of real numbers to a set of real numbers. Then f(x) is said to be Ω (g(x)) if and only if there are constants C and n_0 such that

$$|f(x)| > C|g(x)|, \tag{3-2}$$

whenever $x>n_0$.

Notice that big-omega is the inverse of the big-oh notation. Thus it concerns with the "greater than or equal to" relation.

Big-theta's (Θ) definition

It is said that f(x) is Θ(g(x)) , meaning that it is not much worse but also not much better than g(x). The mathematical notation is

$$\begin{aligned} &f(x) = \Theta(g(x)) \\ &\Rightarrow f(x) = O(g(x)) \cap \Omega(g(x)). \end{aligned} \tag{3-3}$$

We usually say that f(x) is of order g(x), especially when $x \to \infty$.

We will need the following results from [Gupta 2000]:

Arbitrarily located node transmitting to an arbitrarily chosen destination:

1) The protocol model:

Suppose node X_i transmits to a node X_j over a subchannel. The transmission is successfully received by node X_j if

$$|X_k - X_j| \geq (1+\Delta)|X_i - X_j|. \tag{3-4}$$

Symbol X_k is any other node simultaneously transmitting over the same subchannel and Δ is the guard zone specified by the protocol, see Figure 3-3.

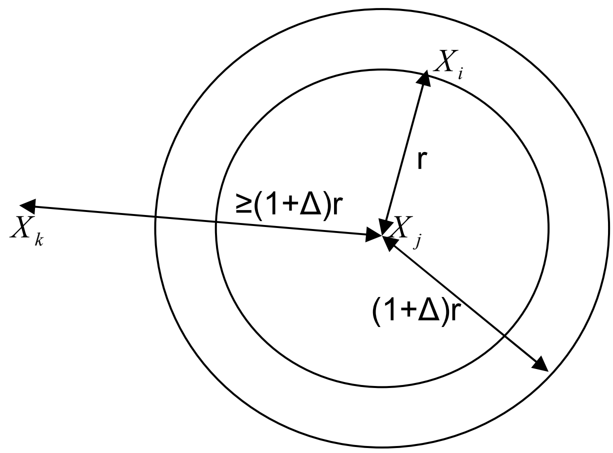


Figure 3-3. Successful transmission in an arbitrary network.

An upper bound on transport capacity:

$$C_{\mathrm{T}} = \lambda n \bar{L} \le \sqrt{\frac{8}{\pi}} \frac{W}{\Delta} \sqrt{n} \tag{3-5}$$

A constructive lower bound on transport capacity:

$$C_{\mathrm{T}} = \frac{W}{1+2\Delta} \frac{n}{\sqrt{n}+\sqrt{8\pi}}, \tag{3-6}$$

where W=fixed bit-rate/user
n=number of nodes (not mobile), multiple of four
λ=bits per second that every node wishes to send to its arbitrary destination
$\bar{L}$=the average distance between the source and the destination
Δ=guard zone

$$\Delta := \left(\frac{\beta P_{\min}}{P_{\max}}\right)^{\frac{1}{\alpha}} - 1, \tag{3-7}$$

where $\Delta>0$
β=signal to noise ratio (SNR) of a proper modulation method
α=path loss exponent (symbol n in [Rappaport 2002])

2) Optimal situation under the protocol model:

$$C = \Theta\left(\frac{W}{n^{\frac{1}{\alpha}}}\right) \tag{3-8}$$

$$C_{\mathrm{T}} = \Theta\left(W\sqrt{An}\right) \tag{3-9}$$

A=area of a disk

3) The physical model:

An upper bound on transport capacity:

$$C_{\mathrm{T}} = \lambda n \bar{L} \le \frac{1}{\sqrt{\pi}} \left(\frac{2\beta+2}{\beta}\right)^{\frac{1}{\alpha}} W n^{\frac{\alpha-1}{\alpha}} \tag{3-10}$$

A constructive lower bound on transport capacity:

$$C_{\mathrm{T}} = \frac{1}{\left(16\beta\left(2^{\frac{\alpha}{2}} + \frac{6^{\alpha-2}}{\alpha-2}\right)\right)^{\frac{1}{\alpha}}} \frac{Wn}{\sqrt{n}+\sqrt{8\pi}}, \tag{3-11}$$

where n=multiple of four

A transmission is successfully received if:

$$\text{SIR}=\frac{\dfrac{P_i}{\left|X_i-X_j\right|^{\alpha}}}{N+\sum\limits_{\substack{k\in T\\ k\neq i}}\dfrac{P_k}{\left|X_k-X_j\right|^{\alpha}}}\geq\beta \tag{3-12}$$

In (3-12) X_i is transmitting node and X_j is the destination. P_i is the power level chosen by X_i. X_k is another node simultaneously transmitting with a power level P_k, $k\in T$. N is the ambient noise power level and α is an attenuation parameter also known as path loss exponent [Rappaport 2002].

All the equations above assume that the nodes are immobile and their locations are known. If these assumptions can not be established, the capacity can only be even smaller with certain exceptions introduced in [Grossglauser 2002]. How ever, in this report, it is supposed that bringing in the CR handles these problems.

3.4.2 Recent progress

Although formulas introduced in Section 3.4.1 are still very significant in the field of wireless ad hoc network capacity analysis, a lot of complementary research has been made afterwards. Below are some notable results.

It is shown in [Grossglauser 2002] that mobility can also increase capacity. This is based on two main ideas: The first one is to use *multiuser diversity*, in which the common channel resources are allocated to the user that can best exploit it. Another way is to transmit only when the source and the destination are close together. Even if the increase in throughput capacity introduced in [Grossglauser 2002] is very significant, the assumptions are still too idealistic to be enforced in most applications.

It is shown in [Gupta 2003] that the transport capacity of Θ(n) is feasible in the certain family of networks while in [Gupta 2000] it was shown to be $\Theta(\sqrt{n})$. This difference occurs when there are $n/2$ source nodes close to each other and respectively $n/2$ destination nodes close to each other. This model is motivated by the multiple-input multiple-output (MIMO) architecture. Once again the assumptions are quite unrealistic: Because the source nodes and destination nodes are “close” to another, it is assumed that they are able to share all the information perfectly in a “short” time. Still, the authors bring out a good fact that by designing and employing more sophisticated multiuser coding schemes one may obtain sizable gains in at least some large wireless ad hoc networks.

3.5 Methods to improve the performance of mesh networks

Many methods that can improve energy efficiency and also spectral efficiency of an ad hoc network exist [Goldsmith 2002]. With channel coding desired BER can be achieved with lower transmitted energy and same holds for diversity combining. Capacity is increased using MIMO systems. In addition, beamforming can be used to reduce transmission power by focusing it to the desired direction. Beamforming reduces interference to other users and therefore the spectral efficiency is also better [Litva 1996]. Transmitter power control plays a key role in efficiency optimization [Kawadia 2005b]. Firstly, energy savings can be achieved by adjusting the power to the minimal level of connectivity that offers needed quality to the received signal. Secondly, the level of interference to other users can be kept low. However, algorithms that reduce the transmission power can be quite complex and therefore signal processing power is increased. The trade-off between them must be carefully considered. It is no use to include turbo coding, beamforming or very complex power control algorithm to the energy-constrained system if the total consumed energy increases.

Adaptive resource allocation means that the link transmission scheme is adapted to the varying channel, interference and data characteristics through variation of coding rate/scheme, constellation size, power level, symbol transmission rate, or any combination of these parameters [Goldsmith 2002]. Adaptation can remarkably improve the spectral efficiency. For example, in [Goldsmith 1997], the proposed variable-rate variable power MQAM technique can achieve a link spectral efficiency that beats the nonadaptive technique by a factor of five or more while maintaining the required link performance. Also optimization of frame length can significantly improve energy efficiency [Goldsmith 2002]. However, adaptation requires awareness and monitoring of the operating environment and information exchange between receiver and transmitter, which increases the system complexity and amount of controlling information.

Multi-antenna systems are needed to further increase capacity and mitigate the impairments by fading, delay-spread and co-channel interference [Akyildiz 2005], [Spyropoulos 2003]. It is clear that the system model becomes more complicated in a mesh network than that of a conventional multiple input multiple output (MIMO) system. Spectral reuse of wireless network can be increased with power control [Fuemmeler 2004]. In order to achieve much better spectrum utilization and management for wireless mesh networks, cognitive radios are needed [Stine 2005], [Akyildiz 2005]. When the mesh nodes are cognitive radio capable, they can efficiently exploit available spectral resources immediately after network is established. Cognitive radio networks have gained a lot of attention in different communities. In addition to the interest of government and regulatory, commercial, public safety and emergency response, and the military community have recognized the benefits that this new radio technology offers [Maldonado 2005].

The most promising mechanism to improve the performance of mesh networks seems to be cognitive radios. Other ideas to improve capacity include hierarchical user cooperation, spatial multiplexing, multipath routing, network coding, avoidance of interference, and interference cancellation.

Antenna arrays can be used for spatial multiplexing in addition to beamforming and spatial diversity [Bölcskei 2001]. Capacity is increased linearly in the number of antennas provided rich enough scattering is present. Spatial multiplexing works best with omnidirectional antennas, but the channel state must be known.

User cooperation can be done in different forms. If transmitters and receivers cooperate, we have a single-user channel. If only transmitters cooperate, we have a broadcast channel. If only receivers cooperate, we have a multiple-access channel. Duality of broadcast and multiple-access channels is considered in [Jindal 2004].

User cooperative diversity refers to cooperative use of antennas belonging to several nodes [Laneman 2004]. This is a form of spatial diversity and the system is sometimes called “a virtual array”. Mobile stations must detect signals from their partners. The user cooperation diversity is a form of relaying.

Hierarchical user cooperation achieves the optimal capacity scaling in ad hoc networks [Özgür 2007]. Cooperation includes local cooperation and intra-cluster cooperation. Clusters form distributed transmitter and receiver antenna arrays. MIMO antennas are used for spatial multiplexing. It has been found that for a fixed area the total throughput capacity scales linearly with n where n is the number of nodes in an ad hoc network. The fixed area networks are called "dense networks" and they are in general interference limited. If the density of nodes is fixed, scaling is from $n^{1/2}$ ($a > 3$) to n ($a = 2$, free space) depending on a in distance power loss r^{-a}. The fixed-density networks are called "extended networks" and they are in general coverage limited.

Network coordination is a form of coherent macrodiversity in cellular downlink using MIMO antennas [Karakayali 2006]. Information exchange is implemented through a high-speed backbone. Coordination is done by zero-forcing transmission or by dirty paper coding [Costa 1983]. If the interference is causally known, we can either try to cancel or subtract it or to precode the signal. The former method is suboptimal and leads to a power penalty. The latter method is optimal and no capacity loss is observed if the coding is properly done by using dirty paper coding. A simple example on dirty paper coding is presented in [Peel 2003]. A scheme for telecommunications proposed in [Erez 2005]. A practical alternative is interference avoidance [Pottie 1995]. Dirty paper coding and TDMA are compared in [Jindal 2005].

In superposition coding a linear combination of two signals is transmitted and decoded using successive interference cancellation [Cover 1975]. The method can be combined with dirty paper coding if the transmitter knows the channels to the users.

Multipath routing is used for load balancing and reliable data delivery [Gustaffsson 1997]. Load balancing is sometimes called traffic dispersion and reliable data delivery is using a form of space diversity. Multipath routing reduces congestion and improves throughput and reduces delays.

Network coding is a technique proposed to improve network capacity and reduce the number of transmissions in a wireless network [Ahswede00], [Koetter 2003], [Li 2003], [Ho 2005]. The term network coding refers to coding at a node in a network. An exclusive or (XOR) sum of two signals is broadcasted to save one transmission. One of the signals is assumed to be known by the receiver. Loss of one packet affects many packets and delays must be tolerated.

4 Channel measurements and models

The basic mechanisms by which the radio waves propagate are reflection, diffraction, and scattering. The temporal and spatial variations of the received signal in the wireless communication channel are divided into *path loss*, slow fading or *shadowing*, and fast fading or *multipath fading*. Path loss is the deterministic overall decrease in the signal strength with distance which is caused by the spreading of the electromagnetic wave radiating from the transmit antenna and the obstructive effects of objects surrounding the antenna. Shadowing is superimposed on the path loss. Shadowing causes slow random variations in the signal amplitude due to diffraction, scattering, and multiple reflections. Multipath fading causes fast random variations of the signal amplitude and phase due to mutual interference of the wave components of the multiray field. [Blaunstein 2002]

Measurements on the current spectrum use have identified that large portions of the frequency spectrum are allocated to different services are often unused. This chapter reviews some measurement activities on the current spectrum use and interprets their results by considering the applicability of cognitive radio techniques into real situations. Moreover, this chapter provides a short summary of channel modeling for path loss, shadowing and multipath fading.

4.1 Measurements on current spectrum use

Exclusivity leads to inefficient use of spectrum. FCC reported in [FCC 2002a] and [FCC 2002b] that while some bands are heavily used – such as those bands used by cellular base stations – many other bands are not in use or are used only part of the time. FCC's measurements in [FCC 2002a] in urban areas in the U.S., including Atlanta, New Orleans and San Diego, revealed in 2002 that there are large variations in the intensity of spectrum use below 1 GHz. The measurements were done on two non-adjacent 7 MHz spectrum bands with a sliding 30-second window. The measurements computed the fraction observed frequencies that were idle during each window with a granularity of 10 kHz. By observing the two non-adjacent 7 MHz spectrum bands, the measurements on one frequency band showed that a fraction of 55-95 % of the observed frequencies were idle during the observation period while on another frequency band the spectrum was almost completely idle. The FCC measurements are shown in Figure 4-1 and Figure 4-2.

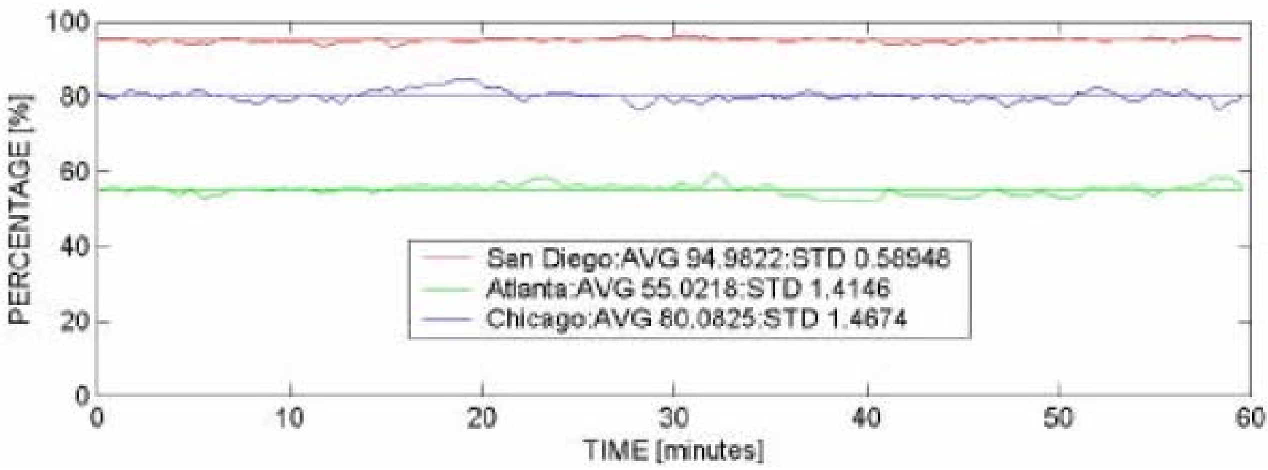


Figure 4-1. FCC measurement of idle spectrum on one 7 MHz band below 1 GHz.

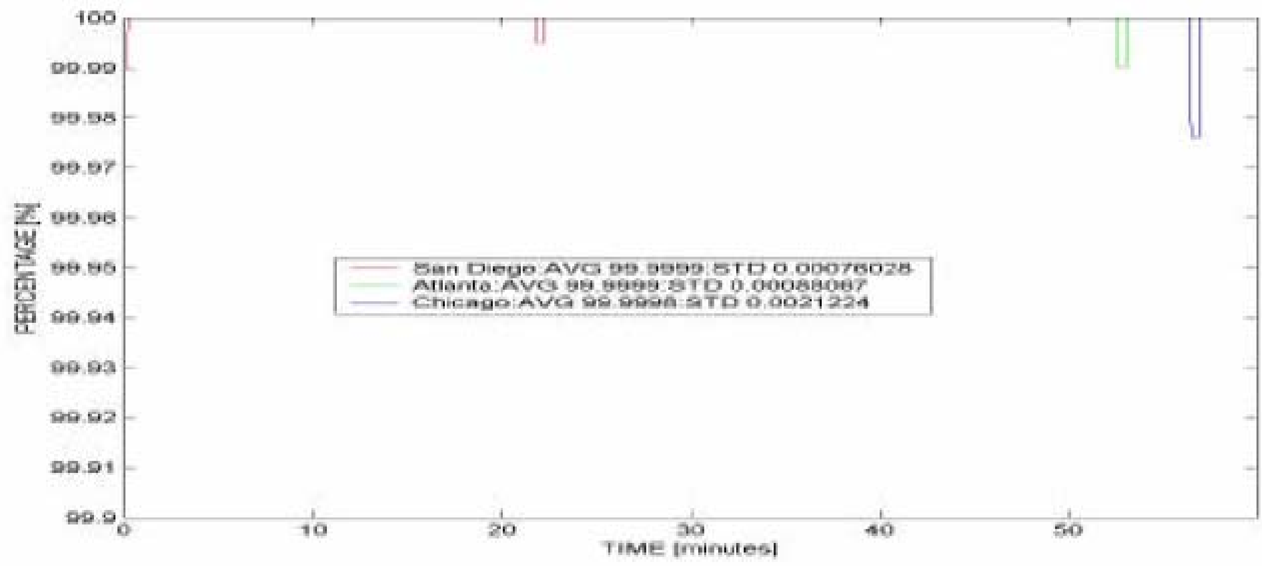


Figure 4-2. FCC measurement of idle spectrum on another 7 MHz band below 1 GHz.

Shared Spectrum Company (SSC) conducted spectrum occupancy measurements on the bands between 30 MHz and 3 GHz at six different locations in the U.S. in 2004 [SSC 2005]. The measurements in urban Chicago were published in [McHenry 2006]. The average occupancy over the six different locations was found to be only 5.2 % with the maximum occupancy 13.1 % in New York City and minimum occupancy 1 % in a rural area.

The occupancy was defined as the fraction measured in time and frequency dimensions where the received signal strength exceeds a threshold. Duty cycle was defined as the fraction of time the signal is "on" on the frequency. Occupied spectrum on a band was calculated as the product of the average duty cycle and the bandwidth. The overall occupancy was obtained by dividing the sum of occupied spectrum with the total spectrum in consideration.

The measurements were carried out over the bands between 30 MHz and 3 GHz and we have collected two measurement results from the roof of SSC's office in urban area in Vienna, Virginia, in December 2004 into Figure 4-3 and Figure 4-4 for illustration. The measurements in Figure 4-3 and Figure 4-4 were made on the frequency bands 108-138 MHz and 902-928 MHz, respectively.

The upper sub-plots in Figure 4-3 and Figure 4-4 show the maximum power value versus frequency measured during the measurement period. The middle sub-plots show the occupancy versus time and frequency where the spectrum band is occupied if the received signal power exceeds the threshold. The lower sub-plots show the duty cycle indicating the fraction of time the signal is above the threshold versus frequency.

Figure 4-3 shows the measurement results from the spectrum band 108-138 MHz which is used in the U.S. for air traffic control and aero navigation. The average occupancy was measured to be 10% which is a rather low value implying that there could be plenty of room for devices operating with the cognitive radio principle. However, when observing the middle sub-plot in Figure 4-3 it becomes evident that many of the sub-bands over this spectrum band are almost fully occupied and other sub-bands also include high occupancy. Therefore, even though the average occupancy is in the order of 10% according to this measurement, the spectrum band in fact is rather heavily used.

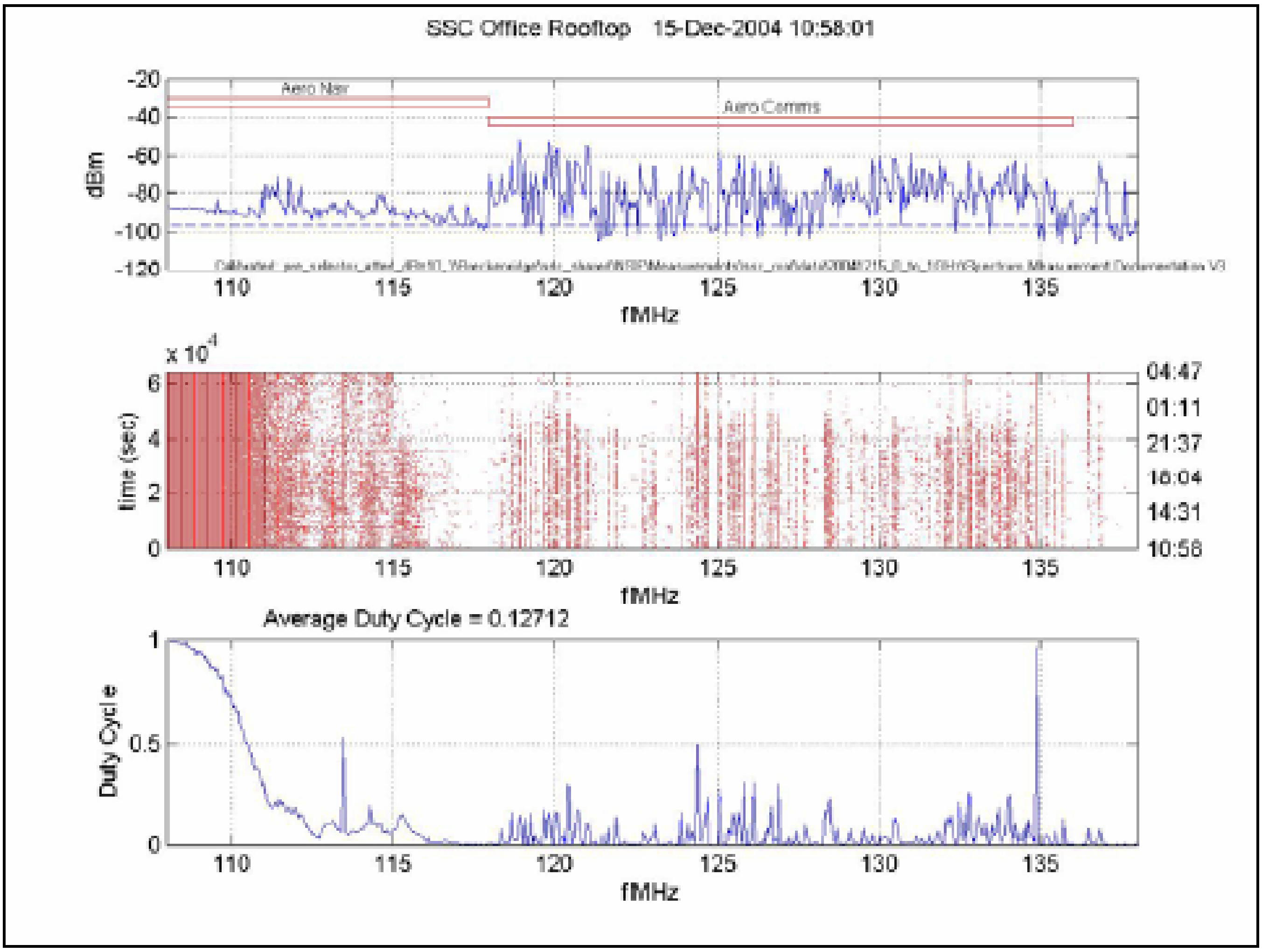


Figure 4-3. SSC measurement of spectrum occupancy on 108-138 MHz band in Vienna, Virginia.

Figure 4-4 shows the measurement results from the spectrum band 902-298 MHz which is used in the U.S. for radio location, location and monitoring service, amateur radio and unlicensed use. The average occupancy was measured to be only 1.1% which sounds like there is only very little usage and the band could be ideal for cognitive radio type of usage. However, when observing the middle sub-plot in Figure 4-4 it becomes evident that many of the sub-bands over this spectrum band are in fact used several times during the measurement period. The durations of the usage may be short but the cognitive radio must be able to reliably detect the transmissions of the primary users in order to be able to operate on the band which is challenging also in this situation.

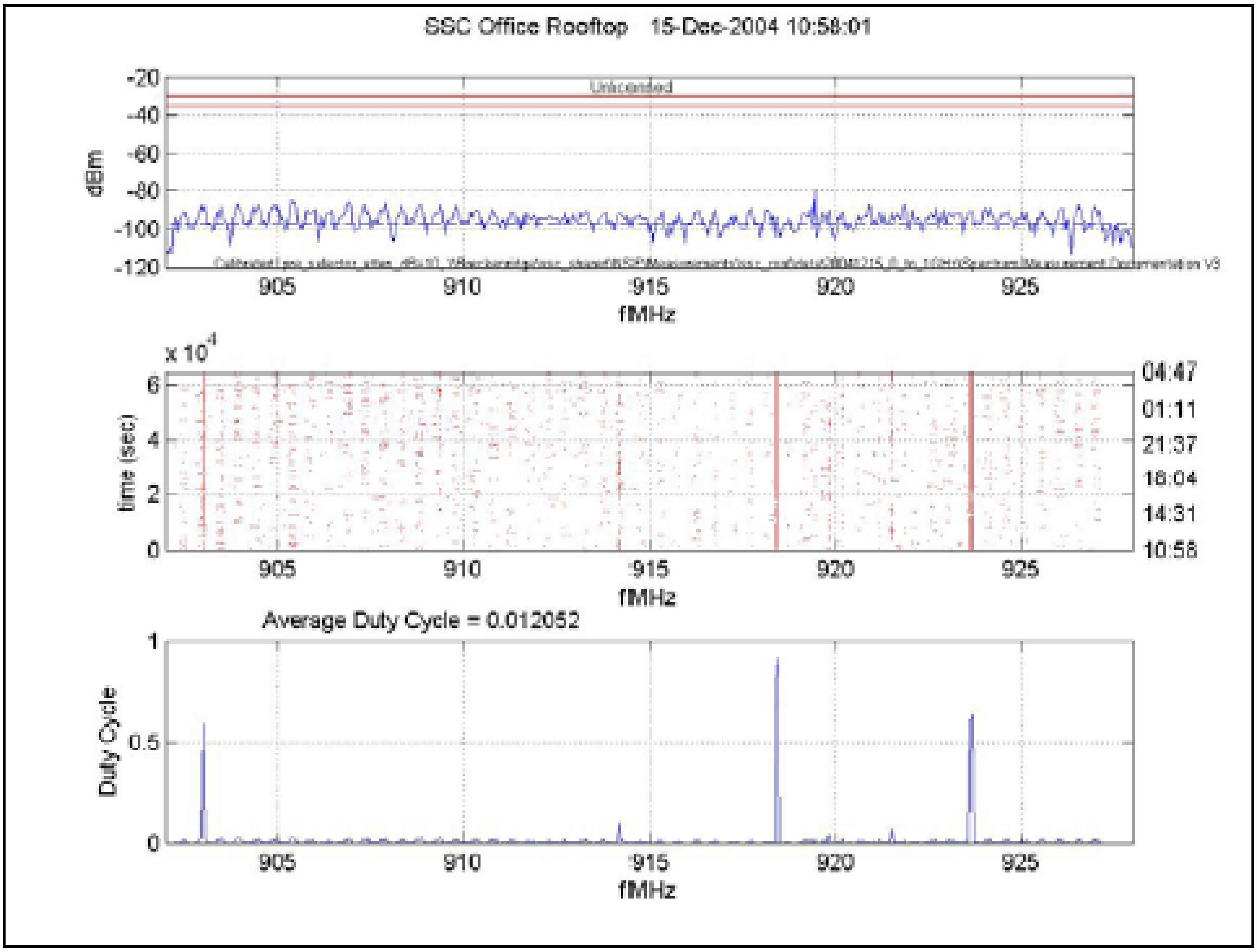


Figure 4-4. SSC measurement of spectrum occupancy on 902-928 MHz band in Vienna, Virginia.

4.2 Channel characterization

The propagation channel is usually characterized with the following three phenomena, namely path loss, shadowing and multipath fading, which are discussed next.

4.2.1 Path loss

The path loss between a transmitter (TX) and a receiver (RX) is defined as the transmitted power divided by the received power, typically expressed in decibels [Saunders 1999]. If the transmission medium is ideal with no absorption, the radiated power per unit surface area from a point source decreases as the square of the distance from the source. The *free space* propagation model is the simplest model to predict the received signal strength when a line-of-sight (LOS) path between TX and RX exists. The received power in free space propagation as a function of the distance *r* between transmitter and receiver is given by

$$P_R(r) = P_T G_T G_R \left(\frac{\lambda}{4\pi r} \right)^2 \qquad (4\text{-}1)$$

where P_T is the transmitted power, G_T and G_R are the TX and RX antenna gains, respectively, and λ is the wavelength [Rappaport 2002].

The path loss for the free space model, i.e., *free space loss*, is obtained in decibels from

$$L_{\mathrm{F(dB)}} = 10\log_{10}\left(P_\mathrm{T} / P_\mathrm{R}\right) = -10\log_{10}\left(\frac{G_\mathrm{T} G_\mathrm{R} \lambda^2}{(4\pi)^2 r^2}\right). \qquad (4\text{-}2)$$

The path loss gives the signal attenuation as a positive quantity in dB. The free space loss model is valid only for values of r which are in the far field of the transmit antenna. Typically, the free space loss is calculated using a reference distance r_0 which is in the far field of the antenna and is smaller than any practical distance for which the attenuation is calculated. Then, the received power in free space at a distance greater than r_0 is given by

$$P_\mathrm{R}(r) = P_\mathrm{R}(r_0)\left(r_0^2 / r^2\right). \qquad (4\text{-}3)$$

The average received signal power decreases logarithmically with distance. The *average path loss* as a function of r is expressed using a path loss exponent n according to [Rappaport 2002]

$$\overline{L}_{\mathrm{(dB)}}(r) = \overline{L}_{\mathrm{(dB)}}(r_0) + 10n\log_{10}\left(r/r_0\right) \qquad (4\text{-}4)$$

where $\overline{L}_{\mathrm{(dB)}}(r_0)$ is the average path loss at a reference distance r_0. The path loss exponent n depends on frequency, antenna heights, and propagation environment. It expresses how fast the path loss increases with distance. In free space n is equal to 2. The free space loss is a reference value for the loss because typically there are other sources of loss which are not included in the free space model. Therefore, the received power in outdoor environment will, in general, be considerably smaller than given by the free space loss and n is usually larger than 2 [Saunders 1999].

In the *plane earth loss* in the propagation takes place via a direct path and a reflection from the ground [Saunders 1999]. When the product of the height of the base station antenna h_b and the mobile station antenna h_m is much smaller than the distance r between the antennas, the received signal power can be approximated by

$$P_\mathrm{R}(r) = P_\mathrm{T} G_\mathrm{T} G_\mathrm{R} \left(\frac{h_\mathrm{b} h_\mathrm{m}}{r^2}\right)^2. \qquad (4\text{-}5)$$

When the antenna gains are excluded, the plane earth loss in decibels is

$$L_{\mathrm{P(dB)}} = 40\log_{10}(r) - 20\log_{10}(h_\mathrm{m}) - 20\log_{10}(h_\mathrm{b}). \qquad (4\text{-}6)$$

The *empirical* path loss models aim at predicting the signal strength at a particular receiver location and take into account the terrain profiles. An empirical model for *microcells* is the *dual-slope model* in which two separate path loss exponents are used to characterize the propagation [Saunders 1999]. The distance after which the propagation characterization changes from one exponent to the other is called the breakpoint distance which is usually 200-500 m. A typical value for the path loss exponent for distances below the breakpoint distance is 2 and for distance above the breakpoint distance it is 4 [Saunders 1999]. In order to smooth the transition from one exponent to the other, a method suggested in [Harley 1989] can be used.

4.2.2 Shadowing

The predicted path loss is a constant for a given base-to-mobile distance although in practice, the propagation conditions at a given distance are different for every path. This causes variations with respect to the nominal value of the path loss and is called *shadowing* or *slow fading*. Then, the total path loss becomes a random variable and the coverage radius of a cell is changed from a fixed predicted value into a statistical quantity [Saunders 1999]. Shadowing is caused by large terrain features, such as buildings and hills in macrocells and vehicles in microcells. According to measurements, the path loss expressed in absolute units at a particular location is a random variable which is *log-normally distributed* around the mean value which depends on the distance. The log-normal distribution is used both in macrocells and microcells to model the received signal power [Saunders 1999]. The measured signal levels expressed in dB at a given distance have a Gaussian distribution about the mean.

In shadowing, adjacent fading values are correlated. Gudmundson proposed a simple method to model the correlation properties of shadowing in suburban macrocells and urban microcells [Gudmundson 1991]. The autocorrelation function of the shadowing was approximated with an exponential function with good accuracy in macrocells. However, in microcells the correlation model gave less accurate results.

The conventional textbook explanation for the lognormality of shadow fading is a multiplicative model which assumes that there are several multiplicative random factors attenuating the received signal, and the logarithm of their product approaches the Gaussian distribution for sufficiently large number of such factors. Sum-of-products model where all the multipath components are separated and multiplied many times by independent attenuation factors thus generating lognormal distribution for the received separate multipath components is proposed in [Coulson 1998]. [Salo 2006] proposes an additive cluster-based model as a physical basis for local shadow fading. They assume that the received signal is a superposition from several scattering clusters (cluster is defined as a set of multipath components with 'similar' delays and arrival angles). They use central limit theorem to show that the shadow fading of the composite signal have approximately lognormal distribution. Authors present also some measurement results that support theoretical findings.

The state of the art assumption for the shadowing generation seems to be to first filter Gaussian noise and then use anti-log operation to generate lognormal fading [Gilhousen 1990], [Olmos 1999], [Gudmundsson 1991]. In [Goubran 1991] anti-log operation is used before filtering. Author is probably making a mistake since filtered lognormal signal cannot be lognormal since it tends to be Gaussian due to the central limit theorem.

4.2.3 Multipath fading

Multipath fading describes the rapid fluctuation in the amplitude of the received signal over a short period of time. When two or more replicas of the transmitted signal, i.e., multipath components, with different amplitudes and phases arrive at RX, the received signal consists of a sum of signal components. This causes random amplitude and phase variations in the received signal, i.e., signal fading. The most important physical factors affecting the multipath propagation are the reflecting objects in the channel, the speed of the mobile, the speed of the surrounding objects, and the bandwidth of the signal [Rappaport 2002]. When a large number of uncorrelated zero mean Gaussian random signal components arrive at the receiver, the magnitude of the received signal envelope follows the Rayleigh distribution and the channel is Rayleigh fading. If the received signal is made up of multiple reflective rays and a significant LOS component, the envelope follows the Ricean distribution and the channel is Ricean fading. If the amplitude of the LOS component approaches zero, the Ricean distribution becomes a Rayleigh distribution. In the early 1940s, Nakagami introduced the Nakagami-*m* distribution to describe the magnitude of the received signal. The Nakagami-*m* distribution gives good fit to empirical data from mobile radio channels. In addition, it includes the Rayleigh distribution as a special case and can approximate the Ricean distribution. [Saunders 1999], [Rappaport 2002]

A time-variant channel can be modelled using the Doppler power spectrum. This model is used in the power control studies presented in Section 8.3. Our channel is modelled with a flat Doppler power spectrum that corresponds to urban (where the transmitter is set above rooftop level) and indoor environments [Zhao 2003]. The rate of the channel variation can be characterized by Doppler frequency f_d. In Jakes' method sinusoids with different Doppler shifts are summed up [Jakes 1974]. Since a channel with a flat Doppler power spectrum is needed, N equal amplitude sinusoids are summed. The time-variant channel gain can be written as

$$h[k] = \sum_{i=1}^{N} a e^{j(2\pi f_i k + \phi_i)} \tag{4-7}$$

where N is the number of multipath components, a is the amplitude of every component, f_i is the Doppler shift of the ith component, ϕ_i is the random uniformly distributed phase shift of the ith component in range $[0, 2\pi[$ and k is time.

If the Doppler shifts of sinusoids are equally spaced between $[-f_d, f_d]$ the channel gain becomes periodic. Periodicity can be removed if the shifts are chosen so that the channel gain becomes quasi-periodic. The Doppler shift range is divided into N parts with equal size. The first component lies at frequency $-f_d$ but the frequencies of other components differ a random amount from the equal space solution. With these selections we obtain the whole spectrum range to use in every simulation. The spectrum is made symmetric over zero frequency, which makes the autocorrelation function of the channel real. In this way the simulations are made faster.

5 Active spectrum sensing techniques

To be capable to sense very weak signals, cognitive radios must have significantly better sensitivity than conventional radios [Čabrić 2004]. Requirements for radio frequency (RF) front-end and analog-to-digital converter (ADC) are very demanding. The requirements can be so tough that advanced techniques like beamforming are needed to make them feasible [Čabrić 2006a]. After reliable reception and sampling of a wideband signal, digital signal processing techniques are utilized to further increase radio sensitivity. Most of the recent spectrum sensing works focuses on primary transmitter detection based on local observations of secondary users.

In [Haykin 2005], the spectrum has been classified into three types by estimating the incoming RF stimuli, thus, black spaces, grey spaces and white spaces. Black spaces are occupied by high power local interferer some of the time and unlicensed users should avoid those spaces at those times. Grey spaces are partially occupied by low power interferers but they are still candidates for secondary use. White spaces are free RF interferers except for ambient noise made up of natural and artificial forms of noise e.g. thermal noise, transient reflections and impulsive noise. White spaces are obvious candidates for secondary use [Haykin 2005].

The goal of the spectrum sensing is to decide between the two hypotheses, namely

$$x(t)=\begin{cases} n(t) & H_0, \\ hs(t)+n(t) & H_1, \end{cases} \tag{5-1}$$

where $x(t)$ is the complex signal received by the cognitive radio, $s(t)$ is the transmitted signal of the primary user, $n(t)$ is the additive white Gaussian noise (AWGN) and h is the complex amplitude gain of the ideal channel [Ghasemi 2005]. The delay has not been taken into account. If the channel is not ideal, multiplication of h and $s(t)$ will change to convolution. H_0 is a null hypothesis, which states that no licensed user is present in a certain spectrum band. H_1 is the alternative hypothesis which indicates that some primary user signal exists.

Generally, spectrum sensing techniques can be classified into two main types, primary transmitter detection and interference temperature concept as shown in Figure 5-1. In addition, sensing techniques can be used both by cooperative and non-cooperative fashion. Techniques presented here are partly based on the book chapter [Höyhtyä 2007a].

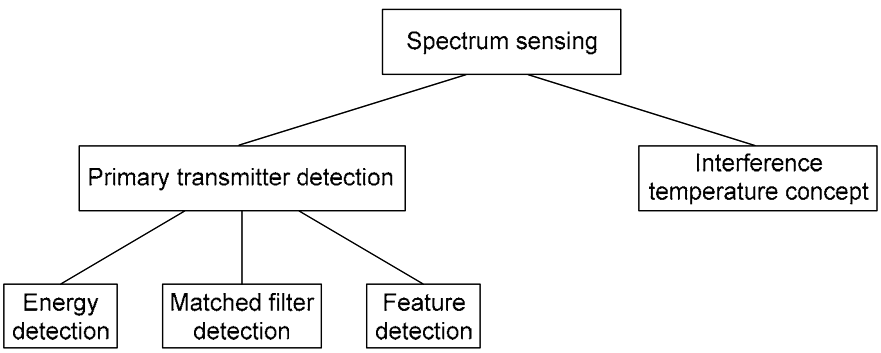


Figure 5-1. Spectrum sensing techniques.

5.1 Matched filter detection

The most important property of a matched filter is that if a signal $s(t)$ is corrupted by additive white Gaussian noise (AWGN), the filter with an impulse response matched to the signal $s(t)$ maximizes the output signal-to-noise ratio [Proakis 2001]. In the matched filter, the input $y(t)$ is correlated with a stored replica of the signal $s(t)$. The output is compared to a threshold in order to make a decision [van Trees 1968].

When secondary user has a priori knowledge of primary user signal at both physical and medium access control (MAC) layers, such as the pulse shape, modulation type and the packet format, the optimal signal detection method is a matched filter, since it maximizes received signal-to-noise ratio [Proakis 2001], [Čabrić 2004]. The main advantage is that matched filter needs less time to achieve high processing gain due to coherent detection [Sahai 2004]. For demodulation, cognitive radio has to perform timing and carrier synchronization, even channel equalization [Čabrić 2004]. When SU has no accurate information of the PU signal the matched filter works poorly. However, most licensed systems have pilots, preambles, synchronization words or spreading codes that can be used for coherent detection. A huge drawback in the use of matched filter is that it would require dedicated sensing receiver for every PU signal type. Digital television (DTV) band is an example where matched filter detection can be performed [Chang 2006]. A cognitive radio can detect 63-sample pseudo-random noise sequences referred to as PN63 sequences in DTV signal by a matched filter.

5.2 Energy detection

If the secondary receiver cannot gather sufficient information about the PU signal, the optimal detector is an energy detector, also called as a radiometer [Sahai 2004]. It is a common method for detection of unknown signals. It measures the energy in the received waveform over an observation time window [Urkowitz 1967]. The block diagram of the energy detector is shown in Figure 5-2 [Urkowitz 1967].

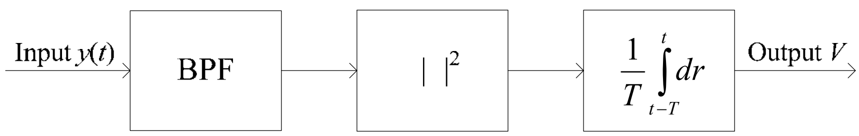


Figure5-2. Energy detection.

First, the input signal $y(t)$ is filtered with a bandpass filter (BPF) in order to limit the noise and to select the bandwidth of interest. The noise in the output of the filter has a band-limited, flat spectral density. Next, in the figure there is the energy detector consisting of a squaring device and a finite time integrator. The output signal V from the integrator is [Urkowitz 1967]

$$V = \frac{1}{T} \int_{t-T}^{t} |y(r)|^2 \, dr \, . \tag{5-2}$$

Finally, this output signal V is compared to the threshold η in order to decide whether a signal is present or not. The threshold η is set according to statistical properties of the output V when only noise is present. The energy detector is also often referred to as a quadratic detector. [Lehtomäki 2005] In the following Sections, two energy detection methods based on discrete Fourier transform (DFT) are introduced. First the basic idea of a periodogram is introduced and the problems related to it are clarified. Second, one type of the modified periodograms – Welch's periodogram – is presented. After that, drawbacks related to energy detection, independent of the used method, are clarified.

5.2.1 Periodogram

The periodogram method is a DFT based method to estimate power spectral density (PSD). The name of the periodogram comes from the fact that it was first used in determining possible hidden periodicities in time series. The periodogram spectral estimator can be given as [Stoica 1997]

$$\hat{\phi}_p(\omega) = \frac{1}{N}\left|\sum_{t=1}^{N} y(t)e^{-i\omega t}\right|^2 \qquad (5\text{-}3)$$

The analysis of statistical properties of the periodogram shows its poor quality as an estimator of the PSD. The bias and variance are often used as measures to characterize the performance of an estimator. The two effects caused by the bias of the estimate are *smearing* and *leakage*. The smearing of the estimated spectrum sets the spectral resolution limit of the method. The leakage, on the other hand, transfers power from the frequency bands that concentrate most of the power in the signal to bands that contain less or no power. The effect of smearing and leakage are particularly critical for spectra with large amplitude ranges. The bias, however, is not the main limitation of the spectral estimator. If that was the case the bias could be eliminated by increasing the length of processed sample N [Stoica 1997].

The main limitations of the periodogram method yield from the variance. The periodogram is an inconsistent spectral estimator which means that it continues to fluctuate around the true PSD with a nonzero variance. This effect cannot be eliminated even if the length of the processed sample N increases without a bound. Furthermore, the fact that the periodogram values are uncorrelated for large N values makes the periodogram exhibit an erratic behaviour. The Welch's method, described in the following Section, is one of the several modified periodogram-based methods which attempt to improve the statistical properties of the periodogram method. The Welch method as also the other modified methods decrease the variance of the estimated spectrum at expense of increasing the bias and, hence, decreasing resolution [Stoica 1997].

5.2.2 Welch's periodogram

The idea of the Welch's periodogram is to divide the data sequence into segments in order to reduce the large fluctuations of the periodogram. In the Welch's method these data segments are also allowed to overlap, which is a feature that distinguishes it from some other modified periodograms (such as Bartlett method or Blackman-Tukey method) [Stoica 1997].

The block diagram of the Welch's periodogram is shown in Figure 5-3. First, the input data sequence is filtered and A/D-converted. After that, the data sequence is partitioned into M segments. Averaging is done over the M segments. The length of each data segment is N_{DS} which corresponds to the length of the DFT (or FFT) if any zero padding is not used. If zero padding is used and zeros are inserted at the end of the segment for spectral interpolation, the length of the DFT is the length of the data segment N_{DS} added by the number of inserted zeros. The segments can be overlapping on each other by K samples. The FFT is performed for the segment and after that, the samples of the segment are squared. Averaging is done over all of the segments. Finally, the output values in the band of interest are compared to the threshold and the decision whether the signal is present or not is done.

In order to get a near maximum reduction of the variance with the fixed length of the input sequence, the recommended value for K is $N_{DS}/2$ [Welch 1967]. If the FFT size is increased, the frequency resolution improves, which helps narrowband signal detection. The bias of the estimate of the Welch's periodogram, as well as of the original periodogram, can be reduced by increasing the length of the input sequence [Stoica 1997]. Meanwhile, comparing to original periodogram, the use of Welch's periodogram reduces the variance of the estimate.

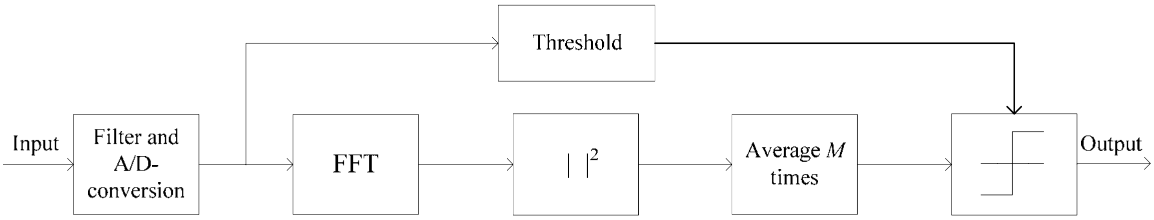


Figure 5-3. Implementation of an energy detector using Welch's periodogram.

5.2.3 Advantages and challenges

The implementation simplicity of the energy detector makes it favourable candidate for spectrum sensing task. However, the performance of the energy detector is highly susceptible to noise level uncertainty. Noise level uncertainty refers to a situation where the noise variance is only approximately known. Remarkable noise uncertainty can be arisen from e.g. thermal noise in components, nonlinearity of the components, inaccuracy of the noise estimator due to limited time of averaging or the channel may contain nonstationary noise and extraneous signal [Sonnenschein 1992]. The noise uncertainty causes problems especially in the case of a simple energy detector because it is difficult to set the threshold properly without the knowledge of the accurate noise level. A pilot tone from the primary transmitter can be used to alleviate this problem [Sahai 2004]. In addition, an energy detector cannot differentiate between modulated signals, noise, and interference. Thus, it cannot benefit from adaptive signal processing for cancelling the interferer and it is also prone to the false detection triggered by the unintended signals.

The performance of energy detector in shadowing/fading environments degrades clearly and secondary users may need to cooperate in order to detect the presence of primary users [Digham 2003], [Ghasemi 2005]. Figure 5-4 illustrates a situation where an obstacle prevents the secondary user from detecting the presence of the primary user and the secondary user starts to transmit. The secondary user's transmission causes interference to a primary user who is communicating with the hidden primary user that was not visible to the secondary user.

Another challenge when energy detector is used is to choose the right threshold for detection. The problem is presented in Figure 5-5 where the probability density functions of the received signal with and without primary signal can be seen. If we want to keep the probability of missed detections very low, the probability of false alarms increases and this would result in low spectrum utilization. On the other hand, a low probability of false alarms would result in high missed detection probability which increases the interference to the primary users. This trade-off has to be carefully considered. In most radar detectors, the threshold is set in order to achieve a constant level of false alarm [Skolnik 2002]. Threshold level is raised and lowered during detection to maintain a constant probability of false alarm. This approach is known as constant false alarm rate (CFAR) detection.

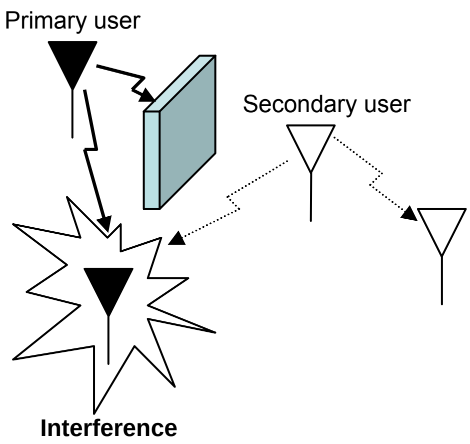


Figure 5-4. Interference caused by shadowing uncertainty.

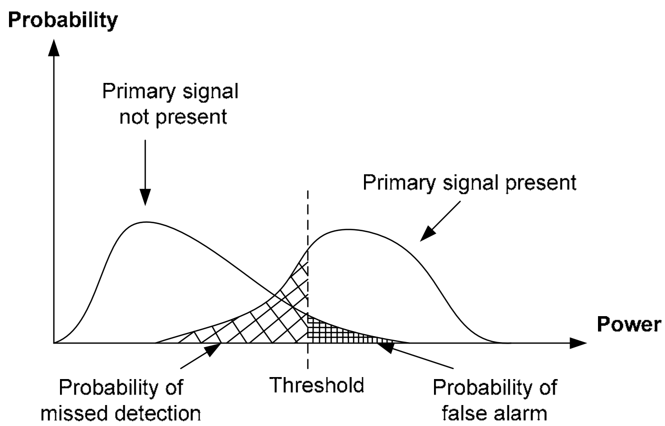


Figure 5-5. Trade-off between missed detections and false alarms.

A simple energy detector works poorly for frequency hopping spread spectrum signals. The channelized radiometer is a multichannel receiver that has several energy detectors that integrate energy in many frequency bands simultaneously [Miller 1993]. It is especially useful for detecting frequency hopping spread spectrum signals. An analysis of the effects of frequency sweeping on a channelized radiometer is presented in [Lehtomäki 2005]. It is assumed that the signal to be detected uses slow frequency hopping and that sweeping is faster than hop dwell time. In a practical signal detection system, the instantaneous bandwidth may be limited. In frequency sweeping, the center frequency is changed as a function of time to cover a wider bandwidth. Numerical examples in [Lehtomäki 2005] demonstrate that if the number of hops observed per decision is small, sweeping can be necessary to get the desired performance. When the channel is fading, the best performance is obtained using fast sweeping. The drawback of the channelized radiometer approach compared to a simple energy detector is the increased complexity.

5.2.4 Performance metric

The performance metric used for the simulations is receiver operating characteristics (ROC). It is completely specified by the values of probability of false alarm P_f and probability of detection P_d. In signal detection theory, ROC is used for measuring the performance as a trade off between selectivity and sensitivity. The probability of detection (or true positive) P_d is given as a function the probability of false alarm (or false positive) P_f. [van Trees 1968]

Probability of false alarm can be computed using central chi-square (or gamma) PDF with N degrees of freedom

$$P_f = P\{Y > \lambda \mid H_0\} = \frac{\Gamma\left(N/2, \frac{\lambda}{2\sigma^2}\right)}{\Gamma(N/2)} \tag{5-4}$$

where $\Gamma(.,.)$ and $\Gamma(.)$ are the incomplete and complete gamma function respectively, N is degrees of freedom, σ^2 is noise variance, Y is a decision statistic, λ is the decision threshold, and H_0 stand for the hypothese: no signal transmitted. On the other hand probability of detection can be computed using noncentral chi-square PDF with N degrees of freedom.

$$P_d = P\{Y > \lambda | H_1\} = Q_{N/2}(\sqrt{\frac{s^2}{\sigma^2}}, \sqrt{\frac{\lambda}{\sigma^2}} \tag{5-5}$$

where $Q_m(.,.)$ is Marcum Q-function, and H_1 stand for the hypothese: signal transmitted. The parameter $s^2 = \sum_{i=0}^{N/2} A_i^2$ is called the noncentrality parameter of the distribution and A_i is signal amplitude. Above equations are valid for simply energy detector. [Proakis 2001]

In Figure 5-6, an example of a ROC curve is given. It can be seen from the figure that by increasing the distance between the means of the two densities d the performance improves. If the threshold $\lambda = 0$, the hypothesis H_1 is always selected, thus, the probabilities $P_d = P_f = 1$. As the threshold λ increases, P_d and P_f decrease. When the threshold $\lambda = \infty$, the hypothesis H_0 is always selected and therefore $P_d = P_f = 0$. The operating point and, thus, the probability of false alarm can be adjusted according to the application. [van Trees 1968]

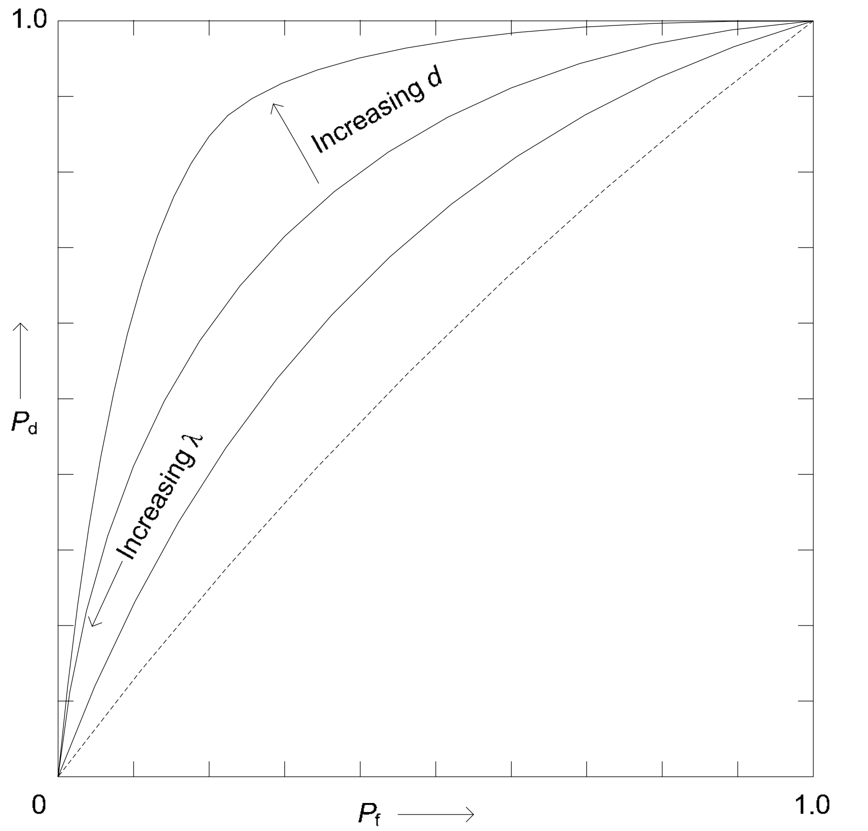


Figure 5-6. An example of receiver operating characteristic (ROC) curve.

The theoretical power density spectrum curve of linear digital modulated signal [Proakis 2001], when the sequence of information symbols is uncorrelated, is

$$\Phi(f) = \sigma_i^2 A^2 T \mathrm{sinc}^2(\pi f T) + A^2 \mu_i^2 \delta(f) \qquad (5\text{-}6)$$

where f denotes frequency bins, σ_i^2 is variance of information symbol, μ_i is information symbols mean, δ is Dirac's delta function and T is symbol length. In this case $T = 20$ which corresponds to over sampling ratio. Equation (5-6) consists of two terms which emphasize the two different types of spectral components. The first term is the continuous spectrum, and its shape depends only on the spectral characteristic of the signal pulse $g(t)$. The second term consists of discrete frequency component at zero frequency in QPSK and QAM signal cases. When the information symbols have zero mean, i.e., $\mu_i = 0$ the discrete frequency components vanish. This condition is usually desirable for the digital modulation techniques under consideration, and it is satisfied when the information symbols are equally likely and symmetrically positioned in the complex plane as in QPSK signal case. [Proakis 2001]

In order to apply the calculations of P_d and P_f of chi-square distribution, we assume that the noncentrality parameter s^2 is a constant. In reality, it is a random variable, but if the number of segments is large, s^2 approaches a constant value. For that reason, the analysis is valid only asymptotically. For simplifying the analysis, we do not take into account an aliasing phenomenon and neither the possible overlapping in Welch's periodogram.

In the Welch's periodogram, we assume that (5-4) and (5-5) are valid for all frequency bins separately. From (5-6) we obtain the energy of the signal for all frequency bins. In the center frequency, the energy is A^2T. Thus, measuring the energy of the center frequency we can use the noncentrality parameter $s^2 = MA^2T$, where M is the number of segments. If we want, for averaging purposes, measure also the energy of the other frequency bins, we need to take into account the frequency dependence of (5-6). Thus, the noncentrality parameter becomes

$$s^2 = M \sum_{l=-L/2}^{L/2} A_l T \left(\mathrm{sinc}(\pi f_l T)\right)^2 \qquad (5\text{-}7)$$

where L is the number of frequency bins to be averaged around the zero frequency and $f_l = l/(T*N_{\mathrm{FFT}})$ are the corresponding frequencies. If L is small enough compared to total number of frequency bins, i.e. $|f_l|<<1/T$, we can note that sinc^2-function remains almost a constant, i.e. one. Thus (5-7) reduces to $s^2 \approx LMA^2T$. Equations (5-4) and (5-5) can be now rewritten as

$$P_f = P\{Y > \lambda \mid H_0\} = \frac{\Gamma\left(LM, \frac{\lambda}{2\sigma^2}\right)}{\Gamma(LM)} \qquad (5\text{-}8)$$

and

$$P_d = P\{Y > \lambda | H_1\} = Q_m\left(\sqrt{\frac{LMA^2T}{\sigma^2}}, \sqrt{\frac{\lambda}{\sigma^2}}\right) \qquad (5\text{-}9)$$

where the product LM corresponds to $N/2$.

5.3 Feature detection

It is commonly recognized that radiometric methods are inherently susceptible to unknown or changing background noise and interference levels. In the radiometric approaches the signal of interest is modelled as a stationary random process. However, in most of the modern communication systems and for the purpose of signal interception, the signal of interest can be modelled as a cyclostationary random process instead [Gardner 1988]. Cyclostationary processes are random processes for which the signal characteristics are periodically time-variant. This means that statistical properties such as the mean and autocorrelation change periodically as functions of time. Many of the signals used in wireless communication and radar systems possess this property. The idea of the cyclostationary feature detection is to utilize the built-in periodicity of the modulated signal [Čabrić 2004], [Shankar 2005]. Cyclostationary signals exhibit correlation between widely separated spectral components due to spectral redundancy caused by periodicity. Cyclostationarity may be caused by modulation or coding, or it may be also intentionally produced in order to aid channel estimation synchronization. In wireless communication systems we typically have some knowledge on the waveforms and structural or statistical properties of the signals that the primary user of the spectrum is using. Cyclostationary signals typically do not exhibit spectral lines because the spectral lines of the unmodulated carriers or pulse trains are spread out over relatively broad bands by the stationary random modulation. An illustration of a cyclostationary feature detector is presented in Figure 5-7. Parameter α is the cycle frequency. It describes the frequency separation of the correlated spectral components [Gardner 1992].

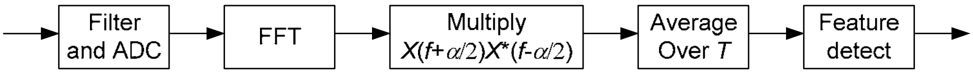


Figure 5-7. Implementation of a cyclostationary feature detector.

A process is cyclostationary in the wide sense if its mean and autocorrelation are periodic or sum of periodic functions of time. If there is more than one source of periodicity and the periods are not all commensurate, then the process is called almost cyclostationary since its parametrs are almost periodic functions of time. An important characteristic property of a cyclostationary random process is that it exhibits spectral correlation, i.e., the complex envelopes of some pairs of frequency components have nonzero temporal correlation. This contrasts sharply with stationary processes, in which no pairs of distinct frequency components are correlated. It is the exploitation of this spectral correlation property of the signal of interest that leads to devices with superior tolerance to noise and interference as compared to radiometric devices.

The autocorrelation function

$$R_x(t+\tau/2, t-\tau/2) = E\{x(t+\tau/2)x(t-\tau/2)\} \quad (5\text{-}10)$$

for the signal $x(t)$, by the virtue the almost cyclostationarity of $x(t)$, will be an almost periodic function of the variable t, and will therefore admit the Fourier series representation

$$R_X(t+\frac{\tau}{2}, t-\frac{\tau}{2}) = \sum_{\alpha} R_X^{\alpha}(\tau) e^{j2\pi\alpha t} \quad (5\text{-}11)$$

where the sum is over integer multiples of fundamental frequencies, such as carrier frequency, baud rate, chip rate, hop rate, and their sums and differences. The Fourier coefficients $R_X^{\alpha}(\tau)$, which depend on the lag parameter τ, are given by the equation

$$R_X^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} R_X(t+\frac{\tau}{2}, t-\frac{\tau}{2}) e^{-j2\pi\alpha t} dt \quad (5\text{-}12)$$

and α is called the cyclic frequency. The function $R_X^{\alpha}(\tau)$ is called the cyclic autocorrelation function. For $\alpha = 0$, it reduces to the conventional autocorrelation function $R_X^{0}(\tau)$. If the process has zero mean, then this is also the cyclic autocovariance function. When the autocorrelation function has exactly one period T_0, we have the set of cyclic frequencies

$$A = \{\alpha = k/T, k \geq 1\} \quad (5\text{-}13)$$

The cyclic frequencies are harmonics of the fundamental frequency. If $x(t)$ is a cycloergodic process, then the expectation operator in (5-10) can be omitted to obtain

$$R_X^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t+\frac{\tau}{2}) x(t-\frac{\tau}{2}) e^{j2\pi\alpha t} dt \quad (5\text{-}14)$$

The process $x(t)$ is almost cyclostationary in the wide sense and the set of cyclic frequencies A is comprised of a countable number of frequencies that do not need to be harmonics of the fundamental frequency. In general, the process is said to be cyclostationary if there is $\alpha \neq 0$ such that $R_X^{\alpha}(\tau) \neq 0$ for some value of τ. Typically cyclic frequencies are assumed to be known or may be estimated reliably. The Fourier transform

$$S_X^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) e^{-j2\pi f\tau} d\tau \quad (5\text{-}15)$$

is called the cyclic spectral density function or spectral correlation function (SCF) [Gardner 1988]. The features are detected by analyzing a spectral correlation function. For $\alpha = 0$, it reduces to the conventional power spectral density function, that is, the spectral density of time-averaged power. $S_X^{\alpha}(f)$ can be interpreted as a spectral correlation function via the following characterization

$$S_x^{\alpha}(f) = \lim_{T\to\infty} \lim_{\Delta t\to\infty} \frac{1}{T\Delta t} \int X_T(t, f+\alpha/2) X_T^*(t, f-\alpha/2) dt \quad (5\text{-}16)$$

The set $\{\alpha: R_X^{\alpha}(\tau) \neq 0\}$ is called the set of cycle frequencies. The spectral correlation function which is also known as the cyclic spectral density function could be measured by the normalized correlation between two spectral components of $x(t)$ at frequencies $(f+\alpha/2)$ and $(f-\alpha/2)$ over an interval of length Δt, i.e.,

$$S_{xT}^{\alpha}(f)_{\Delta t} = \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} \frac{1}{\sqrt{T}} X_T(t, f+\alpha/2) \cdot \frac{1}{\sqrt{T}} X_T{}^*(t, f-\alpha/2) dt \quad (5\text{-}17)$$

The spectra of x(t) over the time interval [t-T/2, t+T/2] is defined by

$$X_T(t, v) = \int_{t-T/2}^{t+T/2} x(u) e^{-j2\pi vu} du \quad (5\text{-}18)$$

The ideal measurement of the SCF for the received signal $x(t)$ is given by

$$S_x^{\alpha}(f) = \lim_{T\to\infty} \lim_{\Delta t\to\infty} S_{xT}^{\alpha}(f)_{\Delta t} \quad (5\text{-}19)$$

For weak Gaussian signals in WGN, the maximum likelihood (ML) signal detection criterion leads to the approximate sufficient statistic

$$y_{ml}(t) \approx \int_{t-T/2}^{t+T/2} \int_{t-T/2}^{t+T/2} R_s(u, v) x(u) x^*(v) du dv. \quad (5\text{-}20)$$

It can be shown that this quadratic form is asymptotically optimal even when the weak signal of interest is not Gaussian [Gardner 1992] [Middleton 1966]. Thus, for weak-signal detection, the optimum detector implements a quadratic transformation of the received data and compares the resultant statistic to a threshold.

The actual device specified by (5-20) depends on the particular signal model employed. If the signal is modelled as almost cyclostaionary, then the autocorrelation is given by (5-11) and resulting device can be expressed as a multicycle detector [Gardner 1988]

$$y_{\mathrm{mc}}(t) = \sum_{\alpha} \int_{-\infty}^{\infty} S_s^{\alpha}(f)^* S_{X_T}^{\alpha}(t,f)df \qquad (5\text{-}21)$$

where the sum is over all α for which the SCF $S_s^{\alpha}(f)$ is not identically zero. The function

$$S_{X_T}^{\alpha}(t,f) = \frac{1}{T} X_T(t, f+\alpha/2) X_T^*(t, f-\alpha/2) \qquad (5\text{-}22)$$

where $X_T(t,v)$ is defined in (5-18), is called the cyclic periodogram.

If the signal is modeled as stationary, then only the term $\alpha = 0$ in (5-21) is nonzero and we obtain the optimum radiometer

$$y_r(t) = \int_{-\infty}^{\infty} S_s^{0}(f)^* S_{X_T}^{0}(t,f)df \qquad (5\text{-}23)$$

Various arguments can be constructed for using the magnitude of only one term $\alpha \neq 0$ in (5-23)

$$y_{\mathrm{sc}}(t) = \int_{-\infty}^{\infty} S_s^{\alpha}(f)^* S_{X_T}^{\alpha}(t,f)df \qquad (5\text{-}24)$$

The device that compares the magnitude of the statistic (5-24) to a threshold is referred to as a single-cycle detector or just cycle detector. By way of interpretation, the cycle detector output $y_{\mathrm{sc}}(t)$ is a measure of the amount of spectral correlation present in the received waveform whereas the radiometer output $y_{\mathrm{r}}(t)$ is a measure of the amount of energy present in the received waveform. Single-cycle detector (5-24) generates from the received signal $x(t) = s(t) + n(t)$ a spectral line at frequency α with maximum power level, subject to a constraint on the output noise spectral density level at frequency α [Gardner 1988].

In [Öner 2004] a cyclostationary-based method is proposed to continuously detect the signal of the PU in a cognitive radio system. In their demonstration, a GSM network is a PU and an OFDM based WLAN is a SU. Since the cyclic features of the WLAN and GSM signals are different enough, they can monitor the channel continuously i.e. the SU can transmit/receive data and sense the spectrum even at the same time. In conventional sensing approach, the reaction speed of the existence of the PU is poorer, since no detection is possible between two sensing period. In addition, the throughput of the SU network is increased because of any silent period is not needed.

In [Fehske 2005], cyclic spectral analysis, dealing with second order transformations of a function and its spectral representation, was conducted for binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), frequency shift keying (FSK), minimum shift keying (MSK), and amplitude modulation (AM) signal types. This analysis was combined with pattern recognition based on neural networks in attempt to provide more efficient and reliable performance. The use of a neural network for classification was found to be a highly flexible method easing the retraining of the network for new signal types.

5.4 Combined energy detection and feature detection

5.4.1 Drawbacks and advantages of Radiometry

The radiometer output contains a spectral line at $\alpha = 0$ regardless of whether or not the signal is present whereas the cycle detector contains a spectral line at $\alpha \neq 0$ only if the signal is present. Thus, the radiometer must distinguish between the strength of the spectral line at $\alpha = 0$ due to signal plus noise or interference, and the spectral line at $\alpha = 0$ due only to noise or interference whereas the cycle detector need only distinguish between the presence and absence of a spectral line at $\alpha \neq 0$ [Gardner 1988].

Dense communication bands create a severe environment for distinguishing signals of interest from background noise and interfering signals since the signals of interest can be buried beneath much stronger groupings of interfering signals. The modulation format of the signal of interest can make it indistinguishable from the noise background, for example, if the signal is direct-sequence spread-spectrum modulated with no easily identifiable spectral features to distinguish it from other signals. The presence of several identically distributed spectrally superimposed signals will confuse most energy detection schemes, preventing the interceptor from determining anything more than the knowledge that signals are present in the environment. Another significant drawback is that energy detection cannot distinguish among different types of transmissions or interference from signals or primary and secondary users of the spectrum. Controlling the false alarm rates and the decision threshold in mobile applications is difficult because signal-to-noise ratios may be time-varying. Energy detection schemes are inherently unable to measure or exploit timing or phasing properties (carrier phase, chip, or baud timing) of the signals of interest or interferences because these energy detectors usually cannot exploit the cyclostationary or periodically time-variant signal characteristics [Gardner 1988].

When little or no knowledge of the signal structure is available to the interceptor, one is driven to using the radiometer. Even when the signal structure is partially known, a radiometer may be chosen for the simplicity of its hardware and the robustness of its performance in the face of changing signal characteristics. [Sonnenschein 1992]

5.4.2 Drawbacks and Advantages of Cyclic-Feature Detection

The main advantage of the feature detection is that it discriminates the noise energy from modulated signal energy. This is due to that noise has no spectral correlation while modulated signals are cyclostationary with spectral correlation due to embedded redundancy of signal periodicities. Cyclic-feature detection techniques have the ability to perform signal timing measurement, discriminate against signals not of interest using sufficiently long collects, and reduce sensitivity to unknown and changing background noise level and interference activity. Also information such as the carrier frequency and chip rate could be calculated according to the cyclic frequencies [Gardner 1992]. Another reason why procedures based on cyclostationarity are attractive in the area of signal detection is that they are robust against random noise and interference and thus have particularly good performance at the low SNR regime. However, computational complexity of feature detection methods is higher in comparison with energy detection methods. Cycle detection methods do require that the signal of interest exhibit cyclostationarity, and the single-cycle detectors also require knowledge of the value of a cycle frequency. Thus, modifications of the modulation schemes that destroy, substantially weaken, or vary the cyclostationarity of the signal are needed to prevent interception by cycle detection. Cyclostationary detectors require also longer observation times than energy detectors. Therefore spectral holes that are short in time cannot be exploited so efficiently than with sensing methods that require less sensing time. However, as was highlighted in [FCC 2003a], feature detectors can achieve a huge processing gain over a radiometric detector. A feature detector can be capable of receiving signals more than 30 dB below the noise floor. The hidden node problem that might result in missing the presence of a signal becomes much less likely than with radiometric detectors.

5.4.3 Combined detection

Figure 5-8 represent sensing system which is comprised of a wideband antenna, a wideband RF front-end for down converting received signal, energy detection for determine candidate channels and feature detection for identifying the type of incoming signal and detecting low power signals [Benko 2006]. The unoccupied channel selection is done by a two step approach to meet the time and sensitivity requirement from the MAC. First, multiple unoccupied channel candidates are determined by energy detection method. The threshold can be set by the cognitive radio node. The swapping time is more important than the sensing sensitivity at this stage. This information is sent to the MAC for selecting one candidate channel for communication. Then feature sensing is performed for the selected channel for identifying the type of incoming signal. Also at this stage, very low power narrowband signal can be detected. If any signal is detected at the given channel, then MAC will select another candidate channel for feature detection.

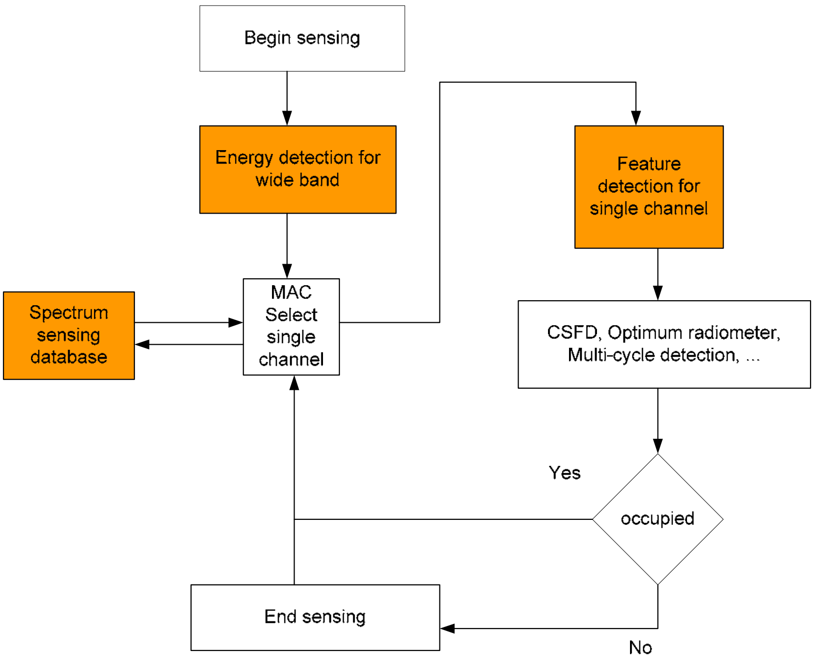


Figure 5-8. Combined energy and feature detection.

In Figure 5-9 a system level architecture for spectrum sensing is presented [Zhang 2006]. On the system level, energy detection can be implemented as an FFT algorithm, which has a computational complexity of $O((N/2)\log_2 N)$ where N is the size of FFT. Cyclostationary feature detection is a combination of an FFT and spectral correlation, which has a computational complexity of $O(N^2 + N/2\log_2 N)$. When large N is used, the processing of cyclostationary feature detection can be prohibitive in terms of performance and computational power. It means that building a dedicated cyclostationary feature detector is simply too expensive. Therefore cyclostationary feature detection is a complimentary option when energy detection fails. Energy detection can be switched to cyclostationary feature detection by turning on the spectrum correlation function module. This option can be supported by a reconfigurable platform where the processing elements for spectral correlation can be switched on or off.

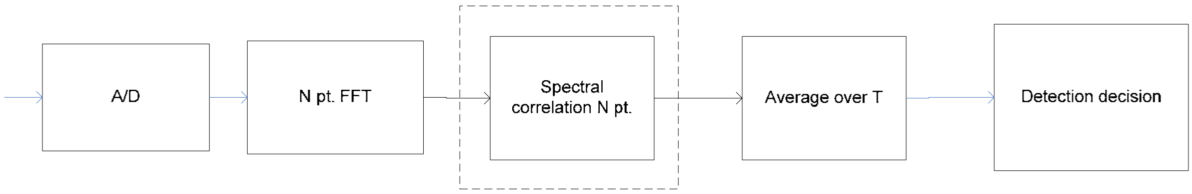


Figure 5-9. Combined energy and feature detector.

5.5 Interference temperature concept

Simple energy detection is not adequate for radio scene analysis because the cognitive radio must also consider the interference situation. The interference in the environment and the interference caused by the cognitive radio device must not exceed the limit of the primary system which is discussed in this section.

Interference is conventionally regulated in a transmitter-centric way. The idea is that interference can be controlled at the transmitter through the radiated power, location of individual transmitters and the out-of-band emissions [Akyildiz 2006]. However, interference actually takes place at the receivers as in the case presented in Figure 5-4. PU terminal and SU terminal are separated by physical obstacle opaque to radio signals. Two such terminals are said to be hidden from each other [Tobagi 1975]. One good example of hidden terminal problem is also a digital TV which lies at the cell edge; the power of received signal can be barely above the sensitivity of the receiver [Krenik 2005]. If the CR is not capable of detecting TV signal, it can start to use the spectrum and interfere with the signal the digital TV is trying to decode. This problem can be avoided if the sensitivity of CR outperforms primary user receiver by a large margin [Čabrić 2004], [Krenik 2005].

A new model for measuring interference and referred as interference temperature has been introduced by Federal Communications Commission [FCC 2003b]. As opposed to current transmitter-centric approach, this model attempts to regulate interference at the receivers, where it is distinctly harmful. The interference temperature T_I is a measure of the power and bandwidth occupied by interference [Clancy 2006]. It is specified in Kelvins and is defined as

$$T_I = P_I / kB \qquad (5\text{-}25)$$

where P_I is the interference power in watts over bandwidth B measured in hertz, and k is Bolzmann's constant ($1.38 \cdot 10^{-23}$ J/K). The idea is that interference and noise can be characterized with a single number taking just a single measurement by the CR. To be more exact, the interference temperature equals the constant noise temperature plus interference term caused by interference environment [Clancy 2006 pp.15–17].

The interference temperature limit T_L characterizes the maximum amount of tolerable interference for a given frequency band in a particular location where the receiver can operate satisfactorily. The idea behind using this limit is to regulate received power rather than transmitted power [Clancy 2006]. However, received power is still regulated by adjusting the transmitted power. CR terminals operating in licensed frequency bands have to measure the current interference temperature and adjust their transmission in a way that they avoid raising the interference temperature over the limit. Thus, real-time interactions between transmitter and receiver in an adaptive manner are needed [Haykin 2005]. The following must hold at all licensed receivers:

$$T_I + P_S / kB \leq T_L \qquad (5\text{-}26)$$

Thus, for each transmission T_I is measured and suitable transmitted power and bandwidth B are computed to meet QoS requirements without violating T_L. Symbol P_S is the received power of the transmitted secondary signal at the primary receiver. Attenuation is assumed to be known. Note that interference temperature limit multiplied by Bolzmann's constant yields the corresponding upper limit on permissible power spectral density in a frequency band of interest [Haykin 2005]. That density is measured in joules per second or, equivalently, watts per hertz.

Due to interrelations between interference temperature and bandwidth, measuring of the interference temperature may be necessary done with an iterative algorithm like hill climbing or fixed point iteration [Clancy 2006]. The fundamental problem in the interference temperature model is that a cognitive radio user can only be aware of its precise location with the help of positioning system. Since primary receivers are usually passive devices, a secondary user cannot be aware of their precise locations [Akyildiz 2006]. In addition, if the effects of cognitive radio transmissions cannot be measured on all possible receivers, interference temperature measurement may not be feasible.

5.6 Spectrum sensing challenges

Sensing ability: Cognitive radios are in a way blind and they cannot see other radios. They have only "hearing". This makes cognitive operation very demanding. Imagine that a blind man arrives to a crossing and tries to conclude whether the road is free or not to go based only on his hearing. Several challenges for the spectrum sensing exist that need to be investigated. Many open questions are related to sensing ability in wide bandwidths, interference temperature measurement, spectrum sensing in multi-user environments, and cooperative detection techniques. The main requirement for detection is a reliable, accurate, and fast detection of primary users. Advanced techniques are needed to sense very wide bandwidths rapidly and reliably.

Narrow band sensing: In [Sahin 2006] authors recommend to use limited target spectrum for spectrum sensing instead of very wide band detection. By using limited sensing bandwidth, sampling at or above Nyquist rate is possible even with current technology. Computational burden can be restricted to a reasonable level and the rather high cost analog front-end (including a wideband antenna, wideband amplifiers and mixers) required for a very wide spectrum scan can be avoided. Furthermore, it can be prevented that a single type of cognitive radio occupies the majority of spectrum opportunities. Authors propose that regulatory agencies should allocate spectrum bands for different types of cognitive radios depending on the intended range and the throughput requirements.

Dual-stage sensing: In papers [Hur 2006] and [Park 2006], a cognitive radio system with a dual-stage spectrum sensing is proposed. This approach combines coarse and fine sensing to meet the sensing speed and accuracy requirements of a cognitive radio system. Firstly, a wavelet transform-based Multi-Resolution Spectrum Sensing (MRSS) energy detection method takes a snapshot of the current spectrum use pattern over the whole band of interest and identifies the occupancy of each spectrum segment. Secondly, a more sensitive time-domain feature detection method scrutinizes candidate spectrum segments determined free in MRSS stage. MRSS processing is performed in the analog domain which makes low-power and real-time operations realizable.

Interference measurement: Interference temperature concept is also a promising approach for spectrum use. As long as cognitive radios do not exceed the interference temperature limit by their transmissions, they can use the band. Two primary challenges in interference temperature concept are [Kolodzy 2006]: "(1) the determination of the background interference environment as a function of spatial location and frequency; and (2) the in situ measurement of the interference temperature to determine optimal radio transmission parameters." The latter refers to the fundamental problem that cognitive radios cannot be aware of the precise locations of primary receivers and they cannot measure the effects of their transmissions on all possible receivers.

One possible approach for *in situ* monitoring is to use measurements from many fixed and mobile sites and integrate the data to create an overall power flux density map across a large area [Kolodzy 2006]. The problem is that the spatial sampling is insufficient to accurately map multipath fading. In [Shankar 2005], a separate sensor network based sensing architecture is proposed to effectively address the interference temperature model. This model offers diversity to cope with multipath fading. In addition, continuous low power communication is possible by separating the sensing and operational functions. However, this approach requires fixed infrastructure to be made for sensing and limits therefore the possibilities to use the cognitive radio system everywhere. In [Hulbert 2005] a beacon approach was proposed to alleviate *in situ* problem. Primary receivers send beacons to inform SUs about frequencies they use. Beacons are transmitted always at the same power level. Thus, a SU can choose its operating frequency based on the lowest beacon power. In addition, assuming the channel to be reciprocal (i.e. fading is same in both directions), the SU can estimate the effect of its transmission quite accurately in the location of PU receiver and calculate its transmission power to meet interference temperature constraint. However, this approach requires the changes to be done to the primary system.

Spectrum sensing in multi-user networks: Environment in which cognitive radios operate consists usually of multiple secondary users and primary users [Akyildiz 2006]. In addition, the cognitive radio networks can be co-located with other secondary networks competing for the same spectral resources. Secondary users can interfere each other in spectrum sensing which makes it more difficult to detect primary users reliably. In such a multi-user environment, cooperation is needed to exploit spatial diversity. The need for cooperation creates challenges to the spectrum sensing information distribution. Delays in cooperation have to be very short and the signalling overhead caused by sensing information distribution must be kept low. Otherwise there would be very few temporal resources that can be used for cognitive radio transmission. To overcome these problems, fast physical layer signalling, boosting protocol, was proposed in [Weiss 2003] for centralized spectrum pooling systems. However, there are several open research challenges in multi-user network operation. To mention a few: What kind of cooperation is really needed to efficiently exploit the spatial diversity? In addition to the spectrum holes, what information should be distributed (location, transmitted power and frequency of different users)? How to cooperate with other secondary networks? Do we need to cooperate with primary networks too?

5.7 Cooperative detection

Advantages and challenges: Considering spectrum sensing performed by a single radio, sensing requirements are set by the worst case channel conditions introduced by multipath, shadowing and local interference. By allowing multiple radios to share their sensing measurements it is possible to improve the overall probability of detection through exploiting the inherent variability of the channel. Several cognitive radios in various locations will not experience the worst channel conditions; therefore, the one with good channel conditions can provide reliable sensing information for the whole network. [Čabrić 2007] In order to improve the performance of the spectrum sensing, several authors have proposed cooperation among SUs [Čabrić 2004, Hillenbrand 2005, Ghasemi 2005]. In the cooperative sensing, all the SUs send their knowledge about the channel state to an access point [Weiss 2003], [Weiss 2004] or a "master" node [Visotsky 2005]. The node collects the channel state information and makes the final decisions whether PU is present or not.

It is clear that the interference to the PU is decreased due the cooperation. The cost for that is the increased complexity. The bandwidth of the control channel should be increased due to increased control traffic between the nodes. The delays of the combining and relaying processes reduce the time of the data transmission. In addition, independence and trust issues can affect to the performance improvement of the cooperation. [Mishra 2006] Shadowing correlation occurs when two radios are blocked by the same obstacle [Liberti 1992] and it degrades the performance of the co-operative sensing when SUs are close to each other. Shadowing correlation becomes less significant as the distance between two users increases. [Ghasemi 2005] This was also shown in an experimental study performed in the Berkeley Wireless Research Centre [Čabrić 2006b]. In the study, it was shown that the probability of detection monotonically increases as the separation between two cooperating radio increases. It is possible that the SU network has one or more malfunctioning nodes e.g., node/nodes that always report false alarms when doing spectrum sensing. Dealing with this kind of nodes is possible when the behaviour and the amount of malfunctioning nodes can be predicted. In that case, the effect can be compensated by increasing the amount of nodes. However, malicious users and the users that fail unpredictably set the upper bound on the performance of a cognitive radio. [Mishra 2006]

Boosting protocol: Different approaches have been suggested for collecting and sharing the information in cooperative spectrum sensing. A boosting protocol for spectrum pooling system is suggested in [Weiss 2003]. The boosting protocol consists of two different phases. In the first phase, the subbands that are accessed since the last detection cycle are indicated. In the second phase, the subbands that have become idle since last detection system are signalled. The basic idea is that the information will be sent by transmitting complex symbols at maximum power level on the OFDM symbols that want to be pointed out and on the remaining OFDM symbols zeros will be transmitted. This information will be gathered by an access point (AP) and the information about actual pool allocation will be distributed among all associated mobile terminals and those who want to get associated.

Hard and soft information combining: In [Visotsky 2005], the difference between hard and soft information combining strategy was investigated. Using a hard information combining strategy each sensing node performs local hypothesis test and reports a binary value to the "master" node indicating whether it believes that channel is occupied or not. "Master" node decides that the channel is free only if all of the nodes agree that it is free. In the soft information combining, each node sends the full observation to the "master" node which then uses a likelihood ratio test to make the decision whether the channel is occupied or not. From the results obtained in [Visotsky 2005] it can be concluded that soft combining clearly outperforms hard combining in terms of probability of missed opportunity. Another conclusion from [Visotsky 2005] is that by increasing the number of co-operative nodes the performance of the network can only be increased until a certain limit due to the fact that the performance is fundamentally limited due to the increasing amount of correlated observations between neighbouring nodes. The experimental study using hard decision combining [Čabrić 2006b] concluded that the biggest cooperation gain is observed when moving from single radio to two cooperating radios.

The difference in performance of soft and hard information combining was also investigated in [Mishra 2006]. In this paper, the results were given as sensitivity in [dBm], thus, the power ratio in decibel (dB) of the measured power referenced to one milliwatt (mW). The results indicated that the difference between the two combining methods is small. The difference compared to the results in [Visotsky 2005] is due to the fact that in [Visotsky 2005] the radios are assumed to be tightly synchronized and therefore they can collectively overcome the lower bound on the SNR below which detection is not reliable. Which of the assumptions is more practical depends on the considered network topology. In order to assume tightly synchronised radios, a central controller e.g. a base station is required. Thus, it is not a reasonable assumption for ad hoc networks.

Network topology: It was stated in [Haykin 2007b] that cognitive radio networks it is desirable to be decentralized – configured in a self-organized manner. Therefore, adoption of ad hoc networks was suggested as a basis for cognitive radio networks. Self-organization builds on cooperation and competition which complement each others. Cooperation facilitates communication across the nodes of the decentralized network and competition provides control over the power transmitted from individual nodes of the decentralized network in a way that interference temperature limit is not exceeded. [Haykin 2007b]

One approach for self-organizing network adopting ultra wide-band (UWB) radio on the physical layer is presented in [di Benedetto 2006]. In their approach, one node is elected to be an observer: evaluating and selecting the strategy of operation based on its perception of the environment. Other nodes adjust their rules of operation according the strategy. [di Benedetto 2006] Another approach was introduced in [Shankar 2005]. In their approach, the attempt was to take advantage of both centralized and decentralized networks by separating the sensing and operational functions. In their paper, they introduced a spectrum-aware sensor network comprising of a set of sensors deployed in a certain area sensing the spectrum and reporting the sensing results to the "master" node. The "master" node may further process the collected data and makes it available to all operational networks. Operational networks – with centralized architecture – are responsible for data transmission and opportunistic use of the spectrum. Introducing the sensor network provides diversity, removes lost opportunity costs caused by the sensing time, and brings power advantages. [Shankar 2005]

5.8 Estimation/prediction of primary user traffic

The goal of traffic prediction is to forecast future traffic rate variations as precisely as possible, based on the measurement history [Sang 2002]. In cognitive radio context the prediction aims to determine idle times in PU traffic to be utilized by secondary transmissions. First thing to detect from traffic before making actual predictions is the type of the traffic.

There are different types of traffic to which prediction can be used:

1) periodic traffic with fixed ON+OFF time, ON and OFF time can vary
2) fixed OFF times, random ON times
3) fixed ON times, random OFF times
4) both ON and OFF times are random

Sensing of primary channels is a sampling process to determine the state (ON or OFF) of the channels at every sampling instant. The outcome of sensing is a binary sequence for each channel. This sequence tells us about traffic that is ongoing. It can show the periodicity, distribution of idle and busy times and utilization percentage of channel. Because the traffic in different channels can be anything from 4 types mentioned above, it would be desirable if cognitive radio could identify the type of traffic after a short learning period from the binary sequences gathered during period.

ON and OFF times can be assumed to be random in each channel before learning period is over. Classification can be made as presented in Figure 5-10.

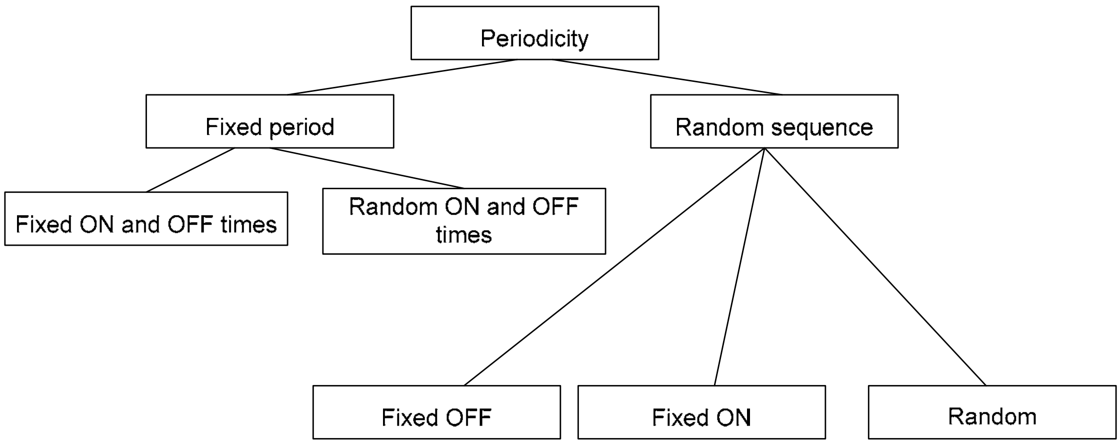


Figure 5-10. Classification of primary user traffic patterns.

First, periodicity is searched from the binary sequence. Authors in [Clancy 2006] proposed that global maximum of autocorrelation function is to be used for detection of period length. Actually this doesn't work if period length is fixed and ON and OFF times are not as we will show later. Autocorrelation function can be estimated from samples as follows

$$R_{xx}[m] = \sum_{n=0}^{N-m-1}(x[n]x[n+m]) \tag{5-27}$$

Autocorrelation function over many periods gives several peak values, one example for type 1) patterns both with fixed (first row) and random ON and OFF times is shown below.

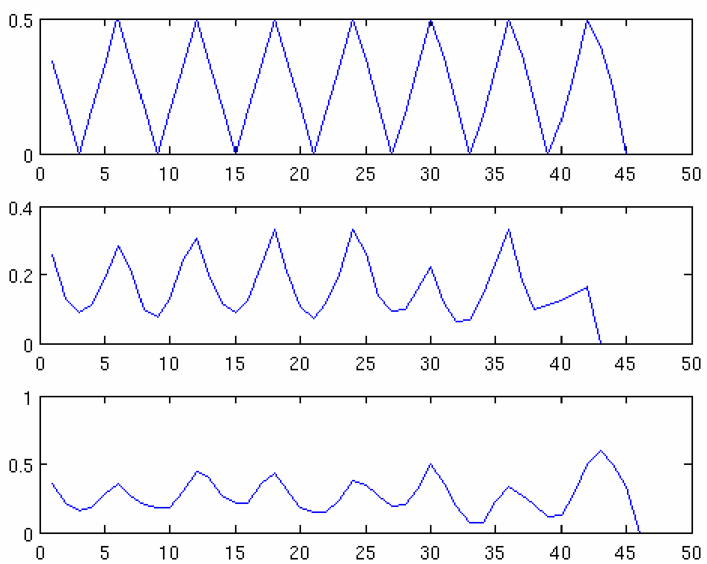


Figure 5-11. Autocorrelation plots for three periodic binary sequences.

The first row represents autocorrelation for the sequence that repeats exactly same in every period. Other two are sequences where period length of ON+OFF time is fixed but in different periods the length of ON (and naturally OFF) time changes. Only in first case the maximum of autocorrelation can tell the period length ($\tau = 6$ that is same for all 3 rows). However, one can use local maximums when calculating the period length. Following pseudocode can be used to check if the binary sequence is periodic or not:

```
Compute autocorrelation Rxx of the input sequence
Search global (tau_max) and local maximums of Rxx
Calculate average separation between consecutive local max values, tau_ave
Calculate standard deviation of separations, std

if tau = = max_tau,
        Period length  is max_tau,
        Sequence is periodic = TRUE
elseif std is smaller than limit value            % deviation small enough
  tau = round(tau_ave)                      % tau rounded to nearest integer
        sequence is periodic = TRUE
else
        sequence is stochastic
```

Autocorrelation function is sensitive to sampling rate and therefore the sensing period restricts the ability to detect very short periods. Traffic patterns can change over time and thus, we have to limit the timescale to be looked for by some kind of moving time-window in collecting samples and making estimations.

When the classification is done from the sequence it is then easier to select appropriate model for prediction. In addition to periodicity, CR should gather statistic about idle (OFF) and busy (ON) times in different channels and also measure the utilization percentage. Even though the traffic is divided into two classes, fixed or random ON and OFF times, random can actually mean that instead of fixed time there can be real random process or only a few possible choices for length of ON and/or OFF times. For example, there can be L different packet lengths that determine the length of ON period in the primary transmission.

Future idle times

Statistics about the length of ON and OFF periods give valuable information about how channel has been utilized in the past. This information helps us to predict future idle times at least with probabilistic means. Let's look at five classes shown in Figure 5-10. In fixed period case, it is possible that ON and OFF periods are fixed or random. In first case, we can make exact predictions about future and fully utilize all available resources for secondary transmission. In latter case, after channel becomes idle at time t_o, we know exactly how long it will be available before PU appears again. The starting point in first case for idle period (T_s) in M consecutive periods and the length of period (T_l) is given below:

$$T_s = t_n + T_{ON}\,,\ n = 1,\ldots,M \qquad (5\text{-}28)$$

$$T_l = T_{OFF} = \tau - T_{ON}\,. \qquad (5\text{-}29)$$

Beginning time of period n with length τ is t_n, T_{ON} and T_{OFF} are lengths of ON and OFF periods. In latter case when ON and OFF times are random,

$$T_{idle} = \tau - (t_o - t_n)\,,\ n = 1,\ldots,M. \qquad (5\text{-}30)$$

When period length is not fixed, we have to make our decisions based on the statistics gathered. In case of fixed OFF period, we know the remaining idle time (T_{OFF}) after channel becomes available at time t_o.

When ON time is fixed and OFF time random, we can calculate the starting time of idle period after ON period starts but the length can be only estimated with probabilistic way. When both times are random, we can calculate the probability of remaining idle period after we detect the channel to become idle. When ON and OFF times are assumed to be exponentially distributed and channel is sensed to be currently idle, one can calculate the probability of channel being idle during next time slot Δt using renewal theory [Kim 2007] as

$$P_{idle}(\Delta t) = (1-u) + u \cdot e^{-(\lambda_{OFF}+\lambda_{ON})\Delta t}, \quad (5\text{-}31)$$

where u is the utilization percentage of channel i.e., the fraction of ON time over observation window. Parameters λ_{OFF} and λ_{ON} are reverses of mean times of ON and OFF periods, $1/\lambda_{OFF} = E[T_{OFF}]$. However, this works only for this special case. To be used with wide variety of traffic patterns, probability prediction should be more general. In next chapters, we will propose a simple histogram-based method for prediction in case of random ON and OFF periods.

Method for random traffic

Cognitive radio can store measurements of idle and busy times to the database and construct a histogram of them. Time-windowing can be used to adapt to possible changes in ON/OFF patterns on different channels and to avoid calculations with too many values. Mean availability times of channels can be calculated and kept up-to date with exponential weighted moving average (EWMA) method without looking into database using

$$T_{n+1} = \alpha \cdot t_n + (1-\alpha)T_n, \quad (5\text{-}32)$$

where

T_{n+1} = new estimated availability time
T_n = last estimated availability time
t_n = latest real availability time
α = constant attenuation factor between 0 and 1

Time-window for estimation is selected with suitable selection of α. EWMA has been proposed for prediction in [Hwang 2000] and [Sharma 2007], the latter in cognitive radio context. However, this value tells not enough about the use of channel. One good thing to look is the utilization percentage from all values over the time window. Utilization percentage can show us how heavily the channel is used on average. However, to know more exactly what kind of traffic is going on, one should look at the distribution of idle and busy times. From database, probabilities for different channels to be available at least X amount of time can then be calculated as

$$P(t \geq X) = \frac{\textit{amount of idle time values} \geq X}{\textit{amount of all idle time values}} \quad (5\text{-}33)$$

Using the database, CR could also estimate the time to transmit under interference constraint (i.e., W% guarantee not to interfere with PU). This means that it would transmit continuously without sensing certain amount of time and trust in distribution → choose transmit time Z so that

$$P(t \leq Z) = 1 - W\ . \tag{5-34}$$

This way CR can loose its sensing period requirements. However, using so the sampling process slows down and in future database cannot give as accurate information.

Analytical way of estimation that can be done with exponentially distributed ON and OFF times is faster than database search but cannot be used with any kind of traffic. With limited time scale, histogram based method works reasonably well.

6 Frequency and power management

Available spectrum holes can be spread over a wide frequency range with variable bandwidths and band separations [Čabrić 2005]. The states of the free bands or channels have to be estimated to optimally exploit spectrum and transmitted power. In addition, efficient link maintenance mechanisms are needed to assure the quality of the secondary communication in the cognitive radio environment [Willkomm 2005].

6.1 Dynamic spectrum management

Dynamic spectrum management (DSM) is closely related to the transmitter power control [Haykin 2005]. The DSM algorithm selects, based on the detected spectrum holes and the level of transmitted power, a modulation strategy that is appropriate to the surrounding radio environment. The algorithm will adapt to the time-varying conditions [Chakravarthy 2005]. The aim is to efficiently exploit the radio frequency (RF) spectrum and to assure reliable communication over a wireless channel. A signal-to-noise ratio (SNR) gap (gap between the performance of a practical coding-modulation scheme and the theoretical value of channel capacity) can be included in calculating the transmission rate [Haykin 2005]. The gap is selected to be large enough for reliable communication. This means that the value of the gap is added to the theoretical value to mitigate nonidealities.

Spectral route management: The spectrum will be continuously and periodically monitored during the operation of the SUs. The spectrum holes that are now available are not necessarily free in the future [Haykin 2005]. Thus, spectrum management algorithm has to know an alternative spectral route if the primary user needs the particular spectrum hole for its own use. Cooperation between nodes is needed to assure fairness in spectrum sharing [Nie 2005]. The spectrum management algorithm can improve the frame error rate (FER) with two possible actions in a situation where the prescribed FER cannot be achieved: (1) selects a more spectrally efficient modulation strategy or (2) starts to use another available spectrum hole [Haykin 2005]. When the first approach is used, the computational complexity of algorithm is increased. The latter approach increases the needed bandwidth for communication. However, we have no justifications for (1) approach so it should be considered with caution.

Channel sharing mechanisms: The simplest channel sharing method between two different users is time sharing. In a cognitive network time sharing means that primary and secondary users use same frequency and SU fills time holes in that band by its own transmission. It was pointed in [Devroye 2006] that by employing a§ scheme other than time sharing, better rates can be achieved by both users. When frequency sharing is used in addition to time sharing, the capacity of cognitive radio system is increased.

Utilization of temporal variations in primary channels by secondary users: Cognitive radio should be more than only adaptive opportunistic radio. In order to be called intelligent, it should have ability to learn from the experiences, which is a very conventional ability in artificial intelligence systems. However, learning-based cognitive radio is a relatively unchartered research area [Clancy 2007].

A huge majority of cognitive radio research is focused on methods that use only instantaneous information about environment as a basis for dynamic operation. Available channels can be assumed to be equally good [Kanodia 2004], [Nie 2005], and [Zheng 2005] or characterized based on interference level [Jing 2005] or bandwidth [Clancy 2006]. In addition, proposed systems work usually reactively. Secondary users sense their environment and react to detected changes in spectrum availability. Such approach can result in bad selection of channels for secondary operation since the system randomly selects channels that may be heavily utilized by primary user almost all the time. This may cause frequent service disruptions for secondary user and result in interference to primary users. In addition, every channel switch causes non-negligible delay for transmission. If a single channel can be used over a long period, such delays can be avoided and capacity is improved.

There are many reasons that encourage us to utilize temporal characteristics of channels in a CR network in operation. These reasons include following:

- A CR system can abandon some channels after some investigation time if it seems that the band is used almost all the time. It is not reasonable to waste resources to these bands that cannot offer communication possibilities. Energy efficiency is better if system concentrates only on channels that seem to be potential for secondary transmission.
- Knowledge about how channels have been used in the past can offer valuable information about how it is occupied in the future. This helps to find robust channel for controlling.
- In addition to control channel selection, temporal information helps to choose best channels for data transmission. Transmission should concentrate on channels which offer enough time for data delivery. If a channel comes unavailable before data is fully delivered, packets in the link will be dropped and lost.
- Prediction can help cognitive radio to operate proactively rather than reactively. If reliable prediction is possible, operating frequency can be changed before PU appears in a same band. This reduces interference to PUs and service disruptions to secondary user.
- Every channel switch causes delays for the transmission. According to [Merritt 2005], every switch takes several milliseconds with today's equipment. If a single channel can be used for transmission, such delays can be avoided.
- In multi-hop network, every frequency change causes need for routing table update. If this happens very frequently, large amount of energy and bandwidth resources is consumed to keep tables up-to-date and capacity of system decreases.

Shortly said, utilization of temporal information helps to choose best channels for controlling and data transmission, helps to avoid wasting of resources, decreases delays and improves capacity. We propose here a distributed MAC protocol to be used in cognitive ad hoc networks. The protocol utilizes temporal information so that things mentioned above are taken into account.

How problem has been solved so far

The problem hasn't been explored much in the literature. However, there are couple papers that present some possible solutions to the problem. The seminal paper of [Haykin 2005] emphasized that dynamic spectrum management algorithm should include information about a traffic pattern of primary user occupying the channel. In a wireless environment, two basic classes of traffic patterns exist [Haykin 2005]. 1) Deterministic patterns where during fixed time slot transmission is ON, then OFF. Pattern can follow some specific frame structure, in which case it is also periodic. 2) Stochastic patterns where traffic can be described only by statistical terms. Poisson distributed traffic is one example of stochastic traffic.

In order to plan better the secondary use of spectrum without cooperation with primary user, some authors have proposed predictive models to be used in spectrum sharing [Clancy 2006], [Acharya

2006], [Yang 2007]. Primary traffic pattern is assumed to be representable by cyclostationary random process in [Clancy 2006]. From the history data of the channel, algorithm searches for a period length that maximizes the autocorrelation function. The period length is assumed to be same all the time. When channel becomes idle, expected availability length can then be calculated.

In [Acharya 2006], authors propose proactive access method to utilize TV-broadcast characteristics. The aim is to maximize throughput by intelligently choosing channels with largest availability values. Availability is estimated with average duration of channel availability and frequency of primary occurrences over specified time interval. Three-tier model that includes availability statistics from three types of observation windows, immediate, short-term and long-term, is then used to calculate the usability of channel. Three-tier model is used with exponential weighted moving average method. Authors also combine the method with distributed MAC protocol.

The main goal of paper [Yang 2007] is to minimize interference to primary users by predicting the future idle times and changing to better channels before primary user appears to channel used currently. Authors investigate specifically the usability of prediction under exponential ON-OFF model, and also periodic-exponential model where either duration of ON or OFF times is fixed and only another period is exponentially distributed. Aim is to estimate the probability that channel will be idle in the next time slot and jump to channel with high probability. With periodic model, proactive method outperforms clearly reactive method. Also with memoryless exponential model, performance is slightly improved.

Problems and limitations with channel selection methods

Presented papers just assume controlling to work perfectly and selection of control channel is not considered at all. However, it is a large challenge in a cognitive network to find a best possible channel for controlling. Another thing is that the selected method should not be restricted only to one possible traffic model. It should work with a variety of traffic classes and thus, a general model would be needed. Basically CR should characterize whether the traffic is deterministic or stochastic and based on that it should use different method for selecting the channel. Therefore, the method should include a method for availability time prediction, rules for intelligent channel selections for data transmission and controlling, and a distributed MAC approach to utilize temporal information in a CR network.

Approach for spectrum sharing

Perfect knowledge about traffic patterns in different primary channels would make spectrum sharing easy. We could then plan our spectrum usage including routing and frequency switches in a non-interfering manner. Capacity could be maximized and controlling would be extremely robust. However, we can’t know exactly what is going on around us and especially hard is to know how things will be in future. In the following sections, we will describe an approach for spectrum sharing utilizing temporal characteristics of channels. We will also discuss methods that could help in gathering information.

Basic steps for spectrum sharing can be described as (modified slightly from [Ma 2005]): 1) *Sensing*. In order to transmit, a CR node has to know how spectrum is utilized around its vicinity. It forms spectrum use pattern over the bandwidth of interest using two-stage sensing method combining energy and feature detection. 2) *Channel selections*. At first, selection of three operational bands, control channel, backup channel, and data channel is done randomly. Cognitive radio will learn temporal characteristics of channels over the time as presented in Section 5.8 and will use this information when selecting channels. 3) *Transmitter-receiver handshake*. Transmitter sends request over control channel to the intended receiver to be communicated with. The request includes possible channels for communication. Receiver picks up a channel that is available also for it and responses with message that includes band selection. 4) *Data transmission* over negotiated channel.

In a multi-user CR network, the role of control channel is important. It is used to coordinate nodes in different frequency bands, for changing spectrum sensing information in cooperative sensing system, to control simultaneous quiet periods and sensing, to negotiate for spectrum, and so on. Because of the importance of this channel and the nature of communication over channels whose availability changes over time, it is a good idea to select the best channel among available ones to be control channel for cognitive network.

Given that primary users can appear at any time, backup channel for controlling is proposed in [Cordeiro 2007] to make controlling extremely robust. Backup channel should be the second best channel. Best one is the low interference level channel with deterministic traffic or if no available ones, stochastic one with longest predicted availability time. When PU appears in the control band, controlling is immediately changed to the backup channel and new backup channel is selected. Other available channels can be used for data transmission[1]. For example, bands F_1 and F_2 in Figure 1 are good candidates for controlling because of predictable deterministic pattern. When neither of them is available, band F_5 seems to be most promising since it offers more availability time than other bands.

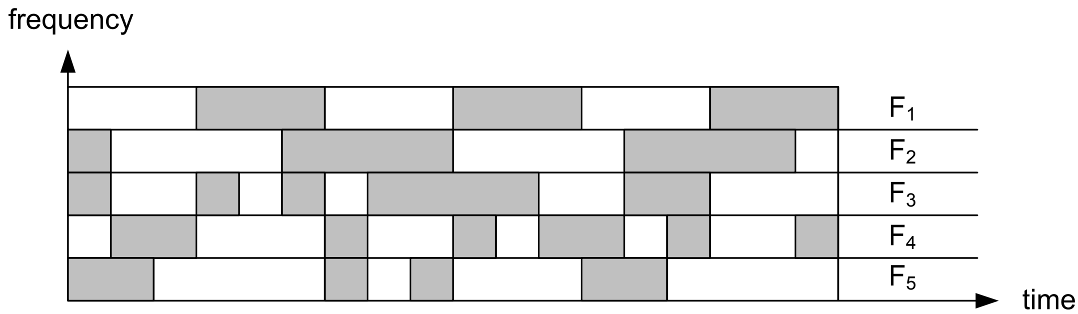


Figure 6-1. Example traffic patterns of different channels. White spaces describe time instants without traffic.

When control channel is robust, coordination of multi-user operation without interfering with PUs is much easier. It also helps to maintain data flows between different users that have to change their operating frequencies often because of PU appearance in a band. In addition, good controlling helps to avoid collisions inside own network.

Availability time prediction described in Section 5.8 helps to choose the best channels into use. In addition, temporal history information gives valuable information to the sensing process. A CR system can abandon some channels after some investigation time if it seems that the band is used almost all the time. It is not reasonable to waste resources to these bands that cannot offer communication possibilities. Energy efficiency is better if system concentrates only on channels that seem to be potential.

Intelligent channel switching:

[1] Backup channel could also be used for data transmission but must be vacated immediately when control channel switch is needed.

Secondary users utilize past observations of channels to build predictive models of spectrum availability, and schedule their spectrum use in order to maximize spectrum utilization while minimizing the disruption rate to primary users. To do that, SUs have to select the channel to switch to in intelligent way. We propose here couple of criteria to channel selection.

Intelligent channel selection 1:
A user switches to available channel *j* with largest expected remaining idle period T_j, chosen as

$$\arg\max_j T_j . \tag{6-1}$$

Where T_j is the calculated remaining idle time in the case of periodic signal

$$T_j = \tau_j - T_{ON}^j - T_{cons}^j \tag{6-2}$$

or the remaining idle time with at least probability of 0.5 in case of stochastic signal, i.e. median value of idle times

$$T_j = T_{50}^j - T_{cons}^j . \tag{6-3}$$

This means that from the predicted idle time for the channel, the consumed idle time is subtracted (i.e., time when CR was operating in different channel) and channel with longest idle time is selected. In case of stochastic traffic, the predicted idle time is the median value of all idle times. To avoid time-consuming search, also mean time of idle times could be used.

Intelligent channel selection 2:
A user prefers periodic channels with longest remaining idle periods because of the accurate prediction. If periodic channels are not available, then select stochastic with longest expected remaining idle period. CR can switch proactively to new channel before PU appears. It changes channel when *Tj* is over, don't wait until PU appears.

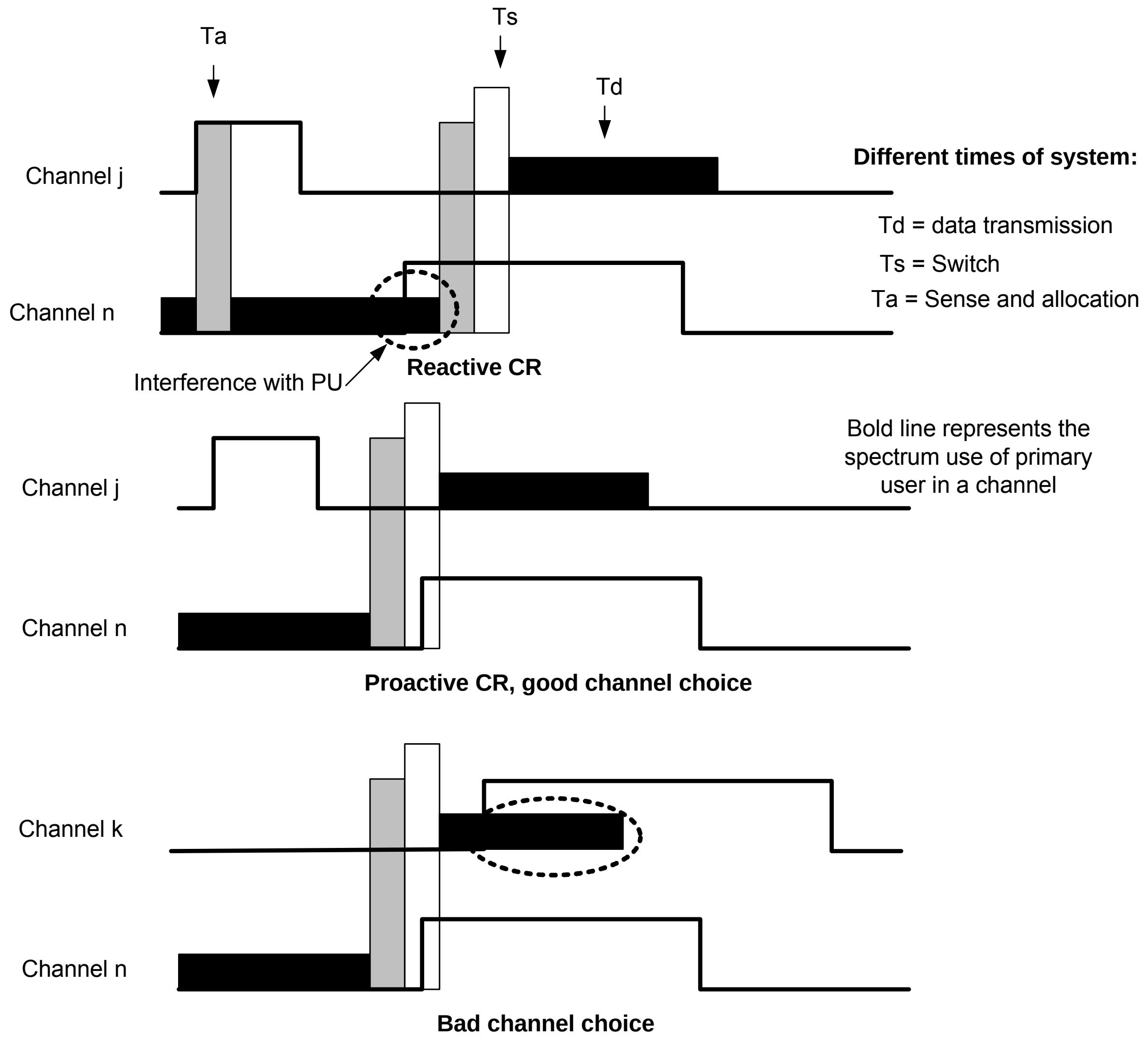


Figure 6-2. Different channel selections.

Figure 6-2 shows different channel selection possibilities. CR can select next channel reactively or proactively. Reactive method switches to different channel after PU sensed to appear in the same channel. Proactive method changes channel before collision, it predicts that PU will appear soon and switches to channel *j*. Next channel should also be selected based on predicted value: channel *j* is much better choice than channel *k* because it offers longer time to CR operation. However, the effectiveness of predictive approach depends heavily on the predictability of traffic.

6.2 Transmitter power control

The radio waves are distributed to all directions from the omnidirectional transmitter antenna. In addition, in the signal path there can be obstacles where the signal is further attenuated. The total attenuation includes a mean, called path loss, and random changes called shadowing [Rappaport 2002]. A typical model for shadowing is lognormal. The effects of path loss and shadowing to the signal are multiplicative as presented in Figure 6-3. [Mämmelä 2006]. Shadowing is assumed to be same for all multipath components. In mobile wireless systems the power of the received signal varies significantly even every half a carrier wavelength especially when no direct path between a transmitter and receiver exists. This phenomenon is called multipath fading, and it degrades greatly the performance of the system. The signal is also corrupted by additive noise and interference.

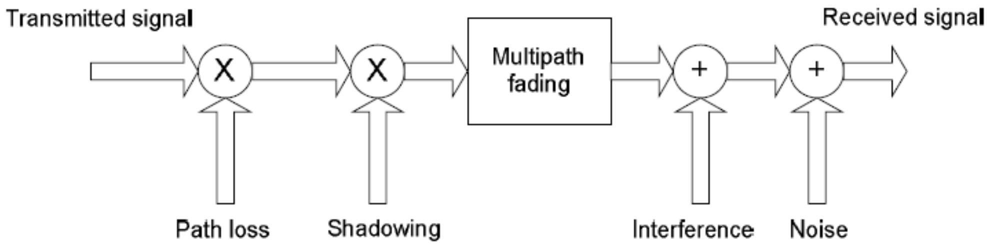


Figure 6-3. Several parts of channel model.

If the secondary users know each others location in the network, path loss between nodes can be computed based on location information. Transmitted power is usually adjusted based on the instantaneous channel state [Goldsmith 2005]. From the viewpoint of power control algorithm, path loss is considered as an attenuating factor. The effect of shadowing is also multiplicative.

Transmitter power control in an ad hoc network assures the data transmission at the minimum power level to maintain links, and adapts to changes in transmission environment [Kawadia 2005b], [Bambos 1998]. Transmitter power level along with the attenuation of channel determines the quality of the received signal, the range of the transmission and the interference level it creates to the other receivers in the network. The first property has an impact to the physical layer, the other affects to routing and thus to the network layer, and because of interference congestions can occur which has influence to the transport layer. Thus, as [Goldsmith 2002] states, transmitter power control plays a key role in the cross-layer design and is particularly important under energy constraints, since energy across the entire protocol stack must be minimized. In multi-hop environment power level affects end-to-end delay because it has an impact to the number of hops and congestion. It also affects throughput capacity of the network [Gupta 2000].

Task of power control: In a multiuser cognitive radio environment two tight limits affect the transmitter power control: (1) *Interference temperature limit* and (2) the limited number of spectrum holes [Haykin 2005]. Because of interference, the cognitive radios have to adjust their power levels according to their proximity to a primary receiver [Hoven 2005]. Shadowing effects can be compensated by means of high sensitivity. The aim of the transmitter power control of SUs is to maximize the capacity of the network while taking energy efficiency into account. However, the aim can be different in different situations. In [FCC 2005] the task of power control is presented as: “to permit transmission at full power limits when necessary, but constrain the transmitter power to a lower level to allow greater sharing of spectrum when higher power operation is not necessary”.

Inverse control is a good choice for a cognitive radio network. Inverse power control allocates lower transmission power levels for good channel realizations and higher power levels for deeper fading. By using the minimum amount of transmission power needed to achieve prescribed requirements the cognitive radio minimizes the interference it creates to licensed users and allows more secondary users to share the spectrum. A practical closed loop inverse control method is fixed step adjustment power control (FSAPC), known also as conventional closed loop power control (CLPC) [Salmasi 1991]. When this method is used, transmission power is adjusted up- or downwards by a fixed amount (typically 1 dB/ms) depending on whether the received power has been over or below a threshold value. The FSAPC method is simple but not fast enough to compensate deep fades in the channel. In the literature adaptive step size and also predictive power control methods are used to improve the performance of the conventional FSAPC algorithm [Höyhtyä 2007b]. Filtered-x LMS (FxLMS) algorithm is a variable step algorithm that adjusts the step size in a nearly optimal way.

The system model for power control is presented in Figure 6-4. Input data $x[k]$ are sent from transmitter to receiver. The data are assumed to be known in the receiver, and thus the system is data-aided (DA). The complex fading gain of the channel is $h[k] = \alpha[k]e^{j\theta[k]}$ as described in section 4.2.3 and $n[k]$ is additive white Gaussian noise (AWGN) at time k. The amplitude of the fading gain is $\alpha[k]$ and $\theta[k]$ is the phase shift. The data are transmitted through the channel and the instantaneous transmit power $P[k]$ is allocated based on the channel gain estimate $\hat{h}[k]$ sent by the receiver. Direct LS estimation of $h[k]$ is made online.

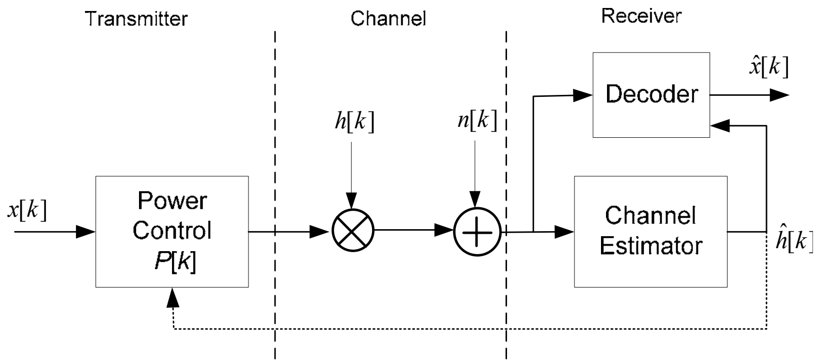


Figure 6-4. System model for power control

Conventional power control: The structure of the FSAPC control [Salmasi 1991] is presented in Figure 6-5. The power of the received signal averaged over three (m = 3) symbols is compared to the reference power level P_{ref} in the receiver. If the error signal ε_k is positive, power is adjusted upwards while negative error causes downward adjustment. The power control algorithm can be written as

$$P_k = P_{k-1} + C_k \Delta P \text{ [dB]} \quad (6\text{-}2)$$

where the power control command is $C_k = \begin{cases} +1, & \varepsilon_k \geq 0 \\ -1, & \varepsilon_k < 0 \end{cases}$. The typical step size ΔP is 1 dB. If the step size is smaller, the control is slower, but it can be more accurate. With a larger step size the control is faster but it cannot achieve good accuracy. The power level is adjusted for example once in a millisecond.

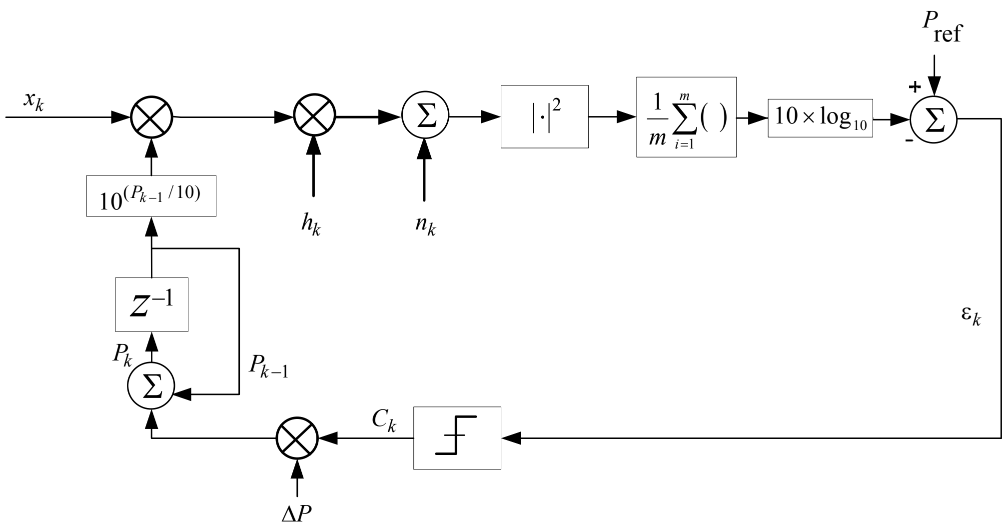


Figure 6-5. FSAPC and VSAPC control structure

The FSAPC method approximates the channel inversion. The weakness of this method is that closed loop control is too slow. The fading can typically be tens of dB even every half a carrier wavelength. If the mobile device moves fast (e.g. in a car), the controlling rate 1 dB/ms is not fast enough to compensate fading. Larger steps or diversity is required in such situations.

The control structure presented in Figure 6-5 can be used also in the variable step adjustment power control (VSAPC) [Yang 1999]. The idea is that when the power of the received signal is far from the desired, the control step is increased to reach the desired level faster. When the error signal is small, the transmitted power is kept in the same level. The power control command for VSAPC is

$$C_k = \begin{cases} 3, & \text{when } P_{\mathrm{err}} < -5\kappa \\ 2, & -5\kappa \le P_{\mathrm{err}} < -3\kappa \\ 1, & -3\kappa \le P_{\mathrm{err}} < -\kappa \\ 0, & -\kappa \le P_{\mathrm{err}} < \kappa \\ -1, & \kappa \le P_{\mathrm{err}} < 3\kappa \\ -2, & P_{\mathrm{err}} \ge 3\kappa \end{cases} \quad (6\text{-}3)$$

where P_{err} is the power of error signal in dB and $\kappa = 0.5\Delta P$.

FxLMS power control: The power control structure based on the FxLMS algorithm is introduced in Figure 6-6. It also approximates the channel inversion. The algorithm updates the coefficient $c[k]$ of a one-tap filter. The algorithm can be written as

$$c_k = c_{k-1} + \mu x_k^{'} \varepsilon_k \quad (6\text{-}4)$$

where μ is the adaptation step size of the algorithm, the filtered input signal is $x_k^{'} = |x_k \hat{h}_k|$ and ε_k is the error signal to be minimized. If the variation of channel is slow enough, the algorithm can track the changes and invert the channel.

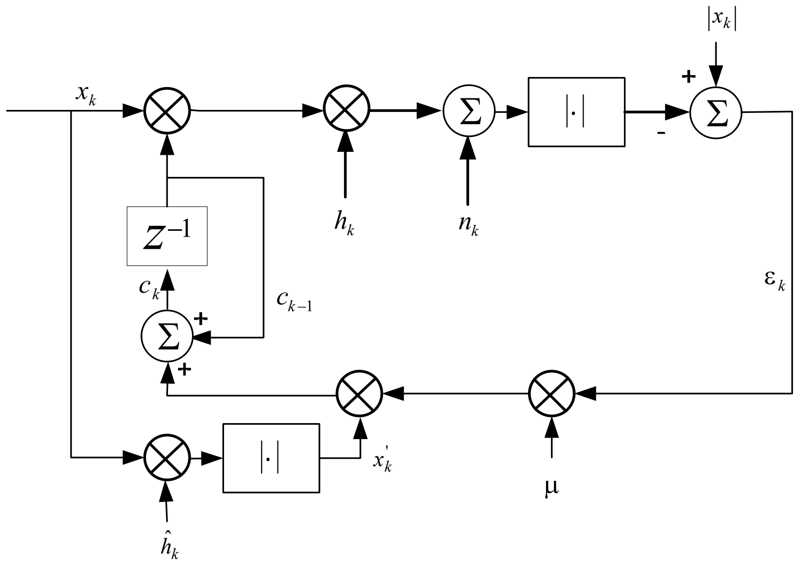


Figure 6-6. FxLMS power control

The choice of initial conditions for the FxLMS algorithm is not critical [Widrow 1996]. The algorithm is stable if μ is small enough, and transients die out just as with the conventional LMS algorithm. In a slowly fading channel h_k can be assumed constant over the memory of the LMS algorithm and the amplitude of the data is constant. Thus the stability condition to the structure when noise is neglected and the channel state is known is

$$0 < \mu < 2/(|x_k|^2 |h_k|^2) . \qquad (6\text{-}5)$$

An optimal step size can be found for each different h_k. The optimum value for the adaptation step size is in the middle of the defined range [Kuo 1996]. Therefore the optimum adaptation step size should be time variant. The optimum step size in a known channel can be defined as

$$\mu_{\text{opt}} = 1/(|x_k|^2 |h_k|^2) . \qquad (6\text{-}6)$$

When the channel gain is estimated, the system becomes unstable if this step size is used. To stabilize the control the optimum step size is given by

$$\mu_{\text{opt}} = \frac{1}{(|x_k|^2 |\hat{h}_k|^2) + c_{\text{term}}} \qquad (6\text{-}7)$$

where c_{term} is a small number that prevents the adaptation step size to grow to infinity when the estimated received power is very small [Kuo 2003].

Usually the adaptation step size of the FxLMS algorithm is not time-variant. However, the algorithm with a fixed adaptation step size corresponds to a first-order system. It cannot track the fastest changes in time-variant channel without lag error that can be quite large. The best performance is achieved by optimizing the adaptation step size with the instantaneous power of the input signal. It means that the FxLMS algorithm with a fixed step size is changed to the normalized version of it. The normalized version of the FxLMS algorithm corresponds to the filtered-x recursive-least-squares (FxRLS) algorithm [Kuo 1996] that can also be used in power control.

FELMS power control: Nonlinear control is needed to keep the amount of control information low and still obtain fast control. One possible algorithm for that is Filtered-error LMS (FELMS) algorithm [Widrow 1996]. When that algorithm is used, the error signal is filtered instead of input signal. FELMS structure is presented in Figure 6-7. However, some modifications will be done to that to make it working in the logarithmic scale.

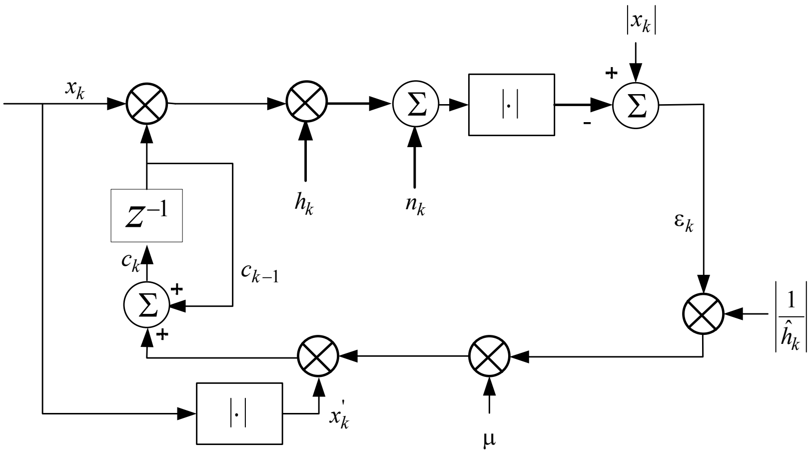


Figure 6-7. FELMS control structure

Truncated power control: A large part of the transmission power in continuous inverse control solutions is used to compensate the deepest fades. The performance of the FxLMS method can be further improved by using a cutoff that interrupts the transmission if the channel state deteriorates to bad enough. This kind of method is used in the well known truncated channel inversion [Goldsmith 1997]. Delay-tolerant applications require full-inversion method to be used in power control. However, in an opportunistic cognitive radio network it may be impossible to avoid delays. Such a network is not good for real-time communication. Therefore, power control does not need to assure delayless communication. To be very energy or power efficient, threshold policies have to be used [Kabamba 2005]. Transmission is interrupted when the channel gain deteriorates under certain cutoff value. The idea is presented in Figure 6-8.

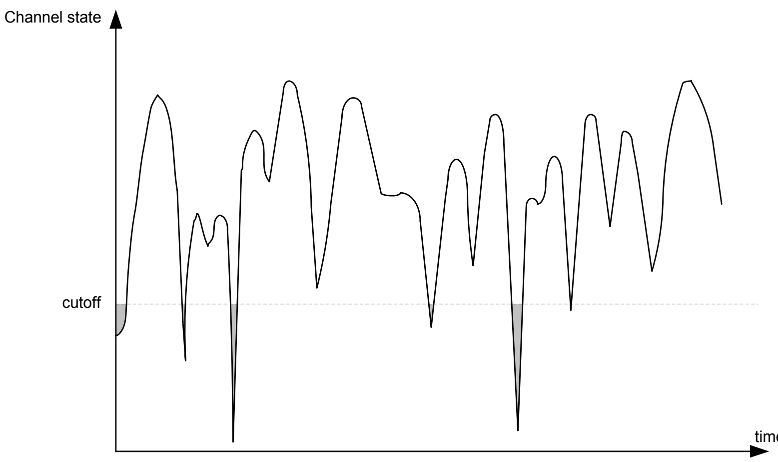


Figure 6-8. Threshold policy in communication.

Data is transmitted only when channel gain is above threshold. Transmission power is zero when gain is below the cutoff value. The basic idea is that transmission power is not wasted to deep fades. Instead, it is saved to better time instants for more aggressive transmission. It has been recently proven in [Kabamba 2005] that regardless of modulation and demodulation methods and taken general assumptions in wireless channel model into account the optimal power control method is based on threshold policy. Power efficiency and throughput can be clearly improved when compared to continuous transmission schemes.

Truncated channel inversion (TCI) compensates fading above a cutoff while meeting power constraint [Goldsmith 1997]. The received SNR is kept in the level $\sigma_0 = 1/[1/\gamma]_{\gamma_0}$ where $[1/\gamma]_{\gamma_0} = \int_{\gamma_0}^{\infty} \frac{1}{\gamma} p(\gamma) d\gamma$ and cutoff value γ_0 is chosen to maximize capacity $\frac{C_{\text{tci}}}{B} = \log_2\left(1 + \frac{\bar{\gamma}}{E_1(\gamma_0/\bar{\gamma})}\right) e^{-\gamma_0/\bar{\gamma}}$. FxLMS power control structure can be modified to meet same constraint. Modified structure is presented in Figure 6-9.

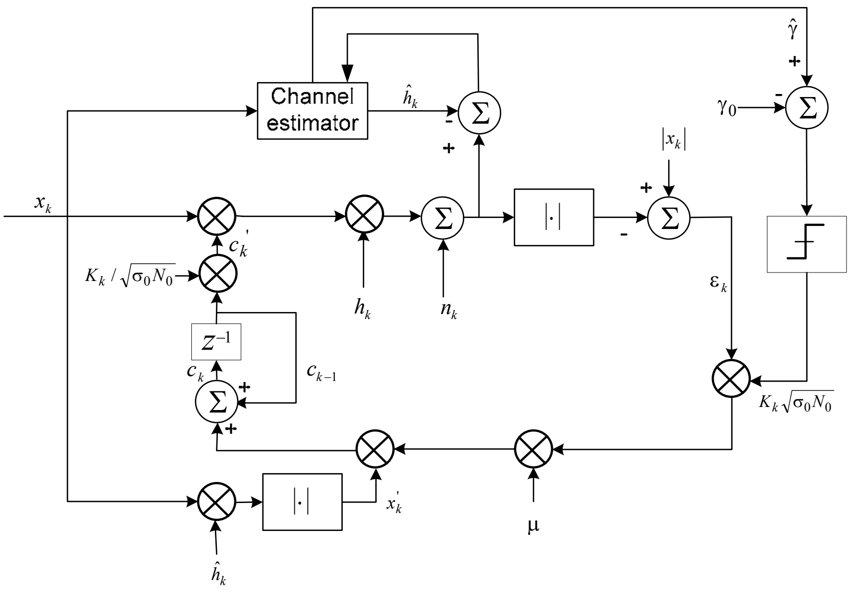


Figure 6-9. Truncated FxLMS power control.

The algorithm can now be presented with following equations:

$$\varepsilon_k = |x_k| - \left| x_k c_{k-1} K_k / \sqrt{\sigma_0 N_0} h_k + n_k \right| \tag{6-8}$$

$$c_k = c_{k-1} + K_k \sqrt{\sigma_0 N_0} \varepsilon_k \mu |x_k h_k| . \tag{6-9}$$

The parameter K_k in equations is a factor that defines when the transmission is interrupted,

$$K_k = \begin{cases} 1, & \text{when } \hat{\gamma} \geq \gamma_0 \\ 0, & \hat{\gamma} < \gamma_0 \end{cases} . \tag{6-10}$$

Channel state estimate that is compared to cutoff value is $\hat{\gamma} = P_{\text{avg}} \cdot (|\hat{h}_k|^2 / N_0)$.

If the data rate is kept constant during transmission above threshold and the aim is to keep overall data rate in the same level R than in continuous transmission scheme, it has to be normalized with inverse of probability of outage P_{out}. Thus, the data rate will be

$$R_t = R/(1 - P_{\text{out}}). \qquad (6\text{-}11)$$

Probability of outage is the cutoff time when transmission is off, i.e., channel gain is below the threshold. Additional outage time in CR system comes from the fact that transmission has to be off during spectrum sensing to obtain reliable results about spectrum use. In addition, some time is needed also for spectrum allocation between users and also for time needed to reconfigure the transmitter after frequency shift.

6.3 Adaptive bit and power loading

The discrete Fourier transform (DFT) –based schemes are natural choices for cognitive radio system [Chakravarthy 2005]. The DFT operation is needed anyway for the analysis of the spectral activity of the primary users [Weiss 2004]. Therefore, it comes at no extra cost. Orthogonal frequency division multiplexing (OFDM) is a good candidate because of its flexibility and computational efficiency [Haykin 2005], [Weiss 2004]. It enables to leave a set of sub-carriers unused providing an adaptive transmit filter. However, conventional OFDM is not suitable because of spectral leakage which produces interference to the adjacent channels [Čabrić 2005]. Spectral shaping is needed to improve the spectral leakage. That can be efficiently done by controlling independently the power of each sub-carrier. The other proposed candidates in [Chakravarthy 2005] are transform-domain communication system (TDCS) and multicarrier code-division multiple access (MC-CDMA). The spectrum scavenging property of TDCS, and the flexibility and frequency domain design of MC-CDMA and OFDM make these three technologies intrinsic candidates for CR system.

OFDM power loading: Channel characteristics have to be taken account to optimally use transmission resources in multi-carrier transmission. By varying the assignment of the transmission power and data rates among subchannels, it is possible to avoid, or use to a lesser extent, severe distorted spectrum parts. The optimal power and bits allocation is found by use of loading algorithms [Starr 1999]. Overall bit rate maximization can be achieved by using water filling algorithm [Bingham 1990]. However, in practice there is no desire to reach the channel capacity, but to transmit with desired data rate at lowest error rate possible while taking power constraint into account. There exist two different power loading problems [Starr 1999]. The first one is *bit rate maximization problem* where we have a fixed amount of energy and the goal is to distribute it among the subchannels such that the overall bit rate is maximized. The other is *margin maximization problem* in which we have to transmit a fixed number of bits per symbol and the goal is to determine the bit allocation that requires the least amount of energy.

In a cognitive radio transmission adaptive bit loading based on SNR onto OFDM carriers in which primary user is not active can be used [Kolodzy 2005]. Performance can be improved by adaptively loading the different subcarriers depending on their SNR. When a licensed user is detected on a carrier band, this carrier will be switched off and zero bits will be loaded to that carrier. Because one aim of a CR is to minimize the interference range, margin maximization problem based power loading scheme could be very suitable solution. A bit and power allocation method that minimizes the transmitter power for a fixed information rate was provided in

[Czylwik 1996]. Also a Fischer-Huber algorithm which tries to guarantee that all subcarriers have the same SNR is a very practical solution [Fischer 1996]. The main idea in that algorithm is to distribute data and power in order to minimize the error probability.

7 System model

This chapter presents the cognitive radio system model considered in the project. Instead of a large multi-hop mesh network it is first reasonable to simplify situation to a single-hop wireless network and concentrate mainly to the cognitive radio concept. First, we define the performance metrics in Section 7.1. Section 7.2 presents the system model used in the simulations in Chapter 8 together with power limit considerations.

7.1 Performance metrics

A *performance requirement* is a requirement that any proposed solution must fulfil (Bock uses the concept *performance criterion* in his book [Bock 2001]). The performance requirements for cognitive radio system are: reliable spectrum hole and primary user detection, accurate link estimation between nodes, fast and accurate frequency control and power control method that assures reliable communication between CR terminals and non-interference to primary users. A *performance metric* is a postulate that transforms the results of the task into measures of performance for drawing conclusions about the task objective [Bock 2001]. By these metrics the success or failure of tasks is evaluated.

Performance value or performance is a numerical value of the performance metric, to be compared with the performance requirement. Performance metrics can be examined by the means of QoS parameters like reliability, mean throughput, peak throughput, precedence, and delay as defined in European Telecommunications Standards Institute (ETSI) specifications [ETSI 2001]. In a cognitive radio, adaptations to the physical layer will ensure a communication channel with certain guarantees for bandwidth use and data throughput [Ball 2005], [Rieser 2004]. To know the performance of our whole system as well as the performance of parts of it we need to measure these QoS values and compare them to the performance of existing systems. Below are the metrics for our system. They are slightly modified from ETSI definitions [ETSI 2001].

The major performance metric used in our studies is the receiver operating characteristics (ROC) used in the performance evaluation of spectrum sensing. ROC is explained in more detail in Section 5.2.4. In addition, other performance metrics are relevant in the study of cognitive radios and cognitive radio networks, as discussed in the following. However, the simulations in Chapter 8 do not include results for these other performance metrics.

Other performance metrics:

1. Throughput:

   Throughput is normally defined as time average of the number of bits per second that can be transmitted by every node to its destination. It depends for example on the spectral (bandwidth) efficiency in a given bandwidth and how efficiently the interference is avoided or suppressed, and is thus related to the use of bandwidth and transmitted energy. *Area spectral efficiency* (ASE) is the total data rate of users per unit bandwidth per unit area (bits/s/Hz/m^2) for a specified BER [Alouni 1999]. The measure was initially defined by Hatfield [Hatfield 1977], Alouini and Goldsmith were the first to consider the ASE with adaptive transmission [Matinmikko 2002]. ITU has proposed measures *traffic/cell* (Mbits/s/cell) and *system capability* (Mbits/s/MHz/cell) in spectrum requirement calculations for the third generation (3G) systems [ITU 1999]. The latter is basically the same as ASE. The capacity of the network is traditionally defined as throughput capacity.

Another good metric is *transport capacity* C_T that is a distance weighted sum of rates that the network can deliver, bit-meters per second [Gupta 2000]. One bit-meter means that one bit has been transported a distance of one meter toward its destination. Transport capacity is defined as $C_T = \sup_R \sum_{i,j} R_{ij}\rho_{ij}$, where R_{ij} is the feasible rate vector for the *i,j* source-destination pairs and ρ_{ij} is the distance between them. It is a natural measure of the distance hauling capacity of wireless networks and is thus a useful quantity for designers to keep in mind [Xie 2004]. Whenever a rate vector is feasible, and is such that its distance weighted sum is close to the transport capacity, then designer can assure that the network is being operated close to the maximal capacity.

2. Delay

The delay attribute indicates the acceptable transfer time of a packet from source to its destination. Mean delay is the average end-to-end delay of packets transmitted and 95-percentile delay is the time within 95 percent of packets have reached the destination. Delay is caused by network congestion and transmission problems that cause errors, as well as hardware and software inefficiencies [Sheldon 2001]. Based on this encyclopedia [Sheldon 2001], delay may be caused by following:

- *Network congestion* caused by excessive traffic.
- *Processing delays* caused by inefficient hardware.
- *Queuing delays* occur when buffers in network devices become flooded.
- *Propagation delay* is related how long it takes a signal to travel across a physical medium.

In addition, the selected transmission method influences the delay. For example suspension of transmission during bad channel realizations causes random delays.

3. Reliability

The reliability attribute indicates the tolerance for *error rates* and the needed *amount of control information* which is the amount of information needed to create and maintain network connectivity, including the information of spectrum holes and the network state information. It can be alternatively stated as the amount of information needed among users to implement an order optimal policy [Berry 2004]. In 3G systems, reliability is defined in terms of the residual error rates for the following cases: loss probability, duplication probability, mis-sequencing probability and corruption probability [ETSI 2001]. Error rate is the rate of incorrectly received bits, blocks or data elements to the total number of bits, blocks or data elements sent during a specified time interval. Most commonly used metric is bit error rate (BER), but also frame error rate (FER) is used. Error rate depends on energy efficiency and is usually stated relative to the SNR values. Thus, *transmitted energy per bit* is an important metric. When transmitted energy is normalized by the receiver noise spectral density, the result is transmitted SNR per bit [Mämmelä 2005]. Transmitted energy is a basic system resource. In a mobile system it is taken from the battery of the transmitter and is therefore limited.

4. Precedence

The precedence indicates the relative importance of maintaining the service commitments under abnormal conditions. Three values of precedence are 1 (high priority), 2 (normal priority), and 3 (low priority). In cognitive radio system primary users have higher priority than secondary users and they are privileged to the spectrum usage. Also fairness between secondary users in a network can be thought to belong to this class. Resources in the network should be fairly divided to users, see for example [Chaudet 2005].

ASE and transmitted energy per bit can be modified somehow to include the transport capacity definition (bit-meters).

7.2 System model for cognitive radio network

In the cognitive radio system model the primary users do not need to know anything about CR devices, and there is no need to modify existing systems, which is thought to be a basic prerequisite to a CR system. It is important that the legacy PUs can still operate in the conventional way even in the presence of the CR system. One solution to provide high data rates over short distances is UWB but higher transmission powers and narrower bandwidths are needed to obtain larger coverage. Therefore, in our system, SUs are silent when a PU transmits and UWB technology is not used.

7.2.1 Cognitive radio system model

The general cognitive radio system model for our studies is presented in Figure 7-1. The cognitive radio system model includes primary users and secondary users and one secondary user is selected as the conscious node (CNode) that plays the role of spectrum coordination in the network [Di Benedetto 2006]. The dimensions of the systems and the numbers and locations of the users are for illustration only. At the beginning of network operation, the first node is elected to CNode and it remains same until it disconnects the network. A scenario for the cognitive radio system is introduced in Figure 7-2 where the locations of PUs and SUs are chosen randomly in the network area using uniform distribution. The gray color in the figure describes the area where SU and PU interfere with each other. It is also the area where it is possible for SU to detect the presence of PU.

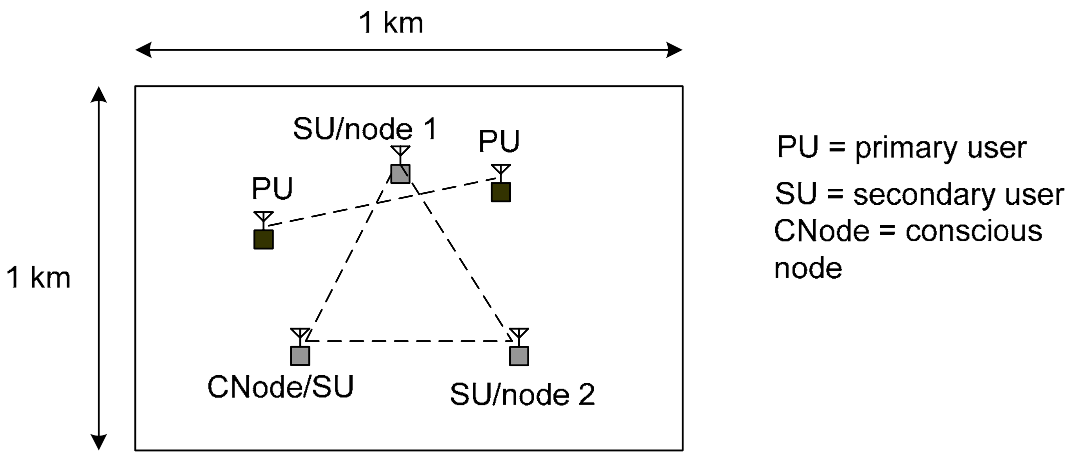


Figure 7-1. CR system model.

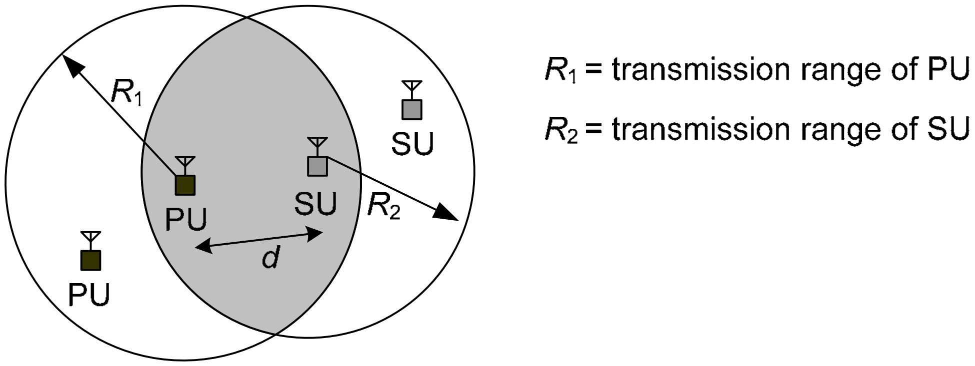


Figure 7-2. One possible simulation scenario.

The block diagram for the cognitive radio node in our system model is presented in Figure 7-3. The tasks of the cognitive radio node include spectrum sensing at the receiver for identification of spectrum holes, transmission of the sensing information to the transmitter side of the link via the feedback link and to the CNode via the control channel, and frequency and power control at the transmitter based on the feedback information from receiver and control information from the CNode.

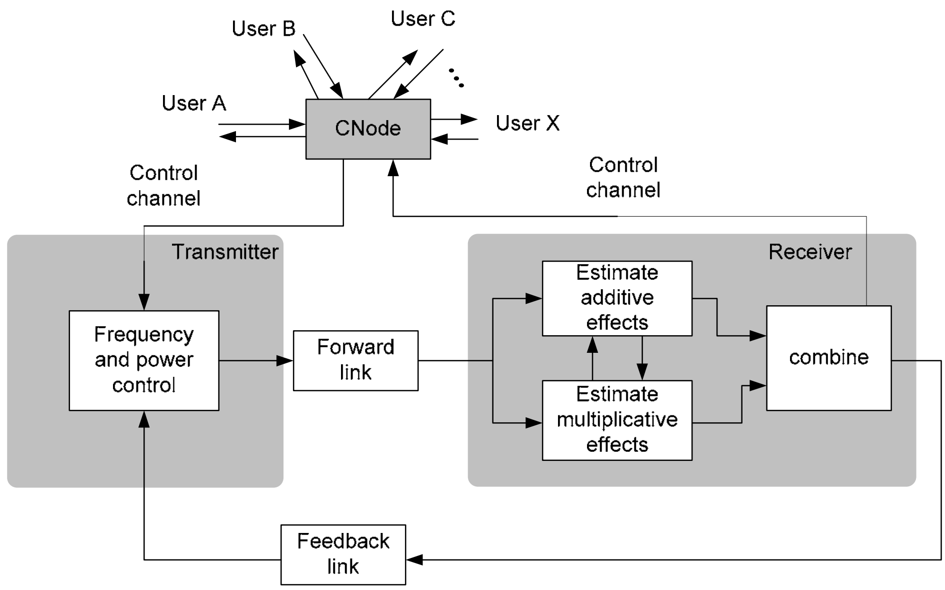


Figure 7-3. Block diagram of cognitive radio node.

The CNode starts by sending a beacon signal in a common control channel to inform other nodes the possibility to join the network. The role of CNode differs from conventional access point because it has now cognitive capability and the communication between nodes is peer-to-peer (P2P) type communication. The locally sensed spectrum information of nodes will be sent to a common control channel, combined in the CNode, and then broadcasted to the CR terminals in the network. In essence, communication between two CR terminals can be divided into the following steps:

1. Spectrum sensing in each node and sensing information transmission to the common control channel.

2. Combining of sensing information in the CNode and broadcasting the combined information to all CR terminals including the permission to the willing nodes to communicate.
3. Starting the transmission between two terminals, for example by training sequence first and then channel estimation is in the tracking mode and actual data transmission is on.
4. Periodical spectrum sensing is done every Δt seconds; data transmission is interrupted during sensing → back to the point 1.

Spectrum sensing is done in our system model using the Welch periodogram energy detection scheme presented in Section 5.2 in an AWGN channel. The more detailed spectrum sensing simulation model is presented in (Figure 8-1) in Section 8.2 together with the obtained results which include receiver operating characteristics as defined in Section 5.2.4. Simple models for cooperative spectrum sensing are used in Section 8.2 as described in Section 5.7 by combining the spectrum sensing information from two or three cooperating radios in AWGN channel with Welch periodogram.

The power control technique in our system model uses the model presented in Figure 6-4. Power control studies are done with conventional and truncated power control algorithms as presented in Section 6.2 and the results are shown in Section 8.3.1 and 8.3.2, respectively. The frequency management studies presented in Section 8.3.3 are done with the channel selection techniques from Section 6.1 using the primary user traffic prediction method described in Section 5.8.

7.2.2 Power limit considerations

Instead of interference temperature concept discussed in Section 5.5, 1 dB coexistence criterion is used in calculations in Chapter 8 to provide actual interference ranges with different receiver sensitivities. In [IEEE 2004], the fundamental criterion for coexistence in terms of acceptable interference in the victim receiver is defined as the interference level that causes 1 dB degradation in receiver sensitivity. This means that the interference power has to be 6 dB below receiver thermal noise. The interference range for secondary transmission can be defined as a range in which coexistence criterion stated above is not met. Interference range can also be seen as a sensing range for a cognitive radio device. To be more exact, sensing range r_s should be as much as the transmission range of primary transmitter r_{pu} plus interference range of secondary transmitter r_{int} to avoid interfering with primary user in the case the primary receiver is located in the edge of the transmission range. So the spectrum sensor should be highly sensitive. The scenario is shown in Figure 7-4. Transmission range of the cognitive radio is r_{cr}.

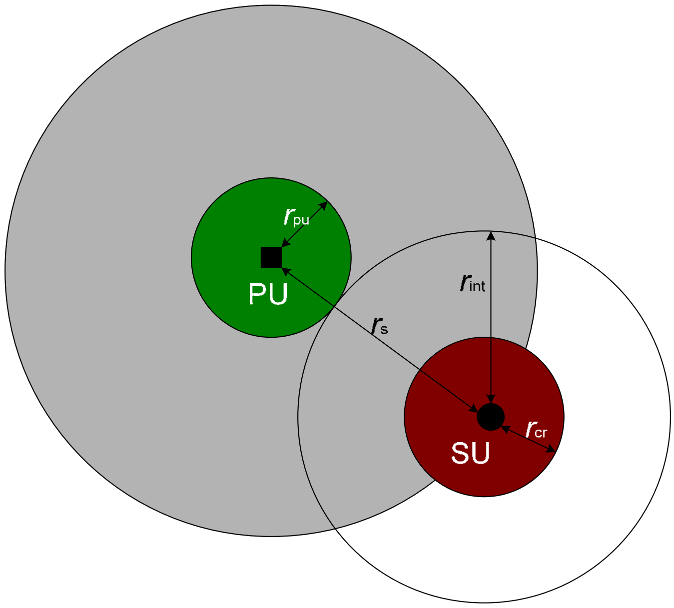


Figure 7-4. Transmission, sensing, and interference ranges.

So what is the rule for transmission power limit calculation? While it could be very helpful to know the location of PU receivers and the estimate of the power loss gain of channel between them and secondary transmitters, neither of this information may be available in real systems. If the locations of primary receivers are available, e.g., in some database, this information should of course be used. But assuming fully active CR system we don't get information from primary users during operation. However, we could know something about primary users when we manufacture our cognitive radios. The receiver decoding sensitivity of the PU and the noise figure are the key issues to know. Knowing the decoding sensitivity of PU receiver and the spectrum sensing sensitivity of the cognitive radio we can calculate how much further a CR can detect the primary transmission than a primary receiver. Using worst case budgeting, i.e., assuming only the free space path loss between CR transmitter and PU receiver and large fading in a secondary link, and using 1 dB coexistence criterion, we can calculate how much power we can transmit and what could be the transmission range of the CR system.

Receiver sensitivity defines the minimum radio frequency (RF) signal power level required at the input of a receiver for a certain BER performance. This is a decoding sensitivity of receiver. It is defined as

$$S = N + N_F + \gamma \text{ [dB]}, \qquad (7\text{-}1)$$

Where $N = kTB$ is the noise floor level in a band of interest, $k = 1.38 \cdot 10^{-23} J/K$ is the Bolzmann's constant, T is the temperature in degrees Kelvin and B is the bandwidth. The symbol N_F is the noise figure and γ represents instantaneous received SNR value. The decoding sensitivity and the spectrum sensing sensitivity are different things. While decoding sensitivity tells how much power is needed to decode the signal correctly, the sensing sensitivity defines the power level that can be detected. If the PU decoding sensitivity and noise figure are not known, they should be assumed to be as good as possible. Rule above is for a single sensing device. More reliable sensing results can be achieved with collaboration and then worst case budgeting is not needed.

8 Results

This chapter presents the analytical and simulation results produced in the project based on the literature presented in Chapters 2 to 6 and the system model defined in Chapter 7. The results include link budget calculations, analysis and simulations of the performance of adaptive spectrum sensing with and without cooperation, as well as frequency and power management. The results from our studies are also briefly summarized in [Matinmikko 2008] together with a motivating overview of cognitive radios and the regulatory framework.

Link budget calculations are presented in Section 8.1 to find out maximal transmission power levels. Adaptive spectrum sensing studies in Section 8.2 concentrate on the energy detection with the Welch periodogram method and determine the performance of spectrum sensing functionality in terms of receiver operating characteristics. In addition, cooperative sensing is studied to find out what kind of performance improvements can be achieved. The results from the performance evalution of Welch's periodogram are also summarized in [Sarvanko 2008].

The frequency and power management studies in Section 8.3 consist of transmitter power control investigations with different algorithms and selection of transmission frequencies based on traffic prediction methods. In particular, the suitability of an adaptive transmitter power control algorithm presented in [Höyhtyä 2005], [Höyhtyä 2007b] to the cognitive radio system is investigated and an intelligent channel selection scheme [Höyhtyä 2008] is presented.

8.1 Link budget calculation

The link budget calculations use the system model presented in Figure 7-2 where node 1 and node 2 lie in distance d from each other. The parameter values used in the link budget calculations are shown in Table 8-1.

TABLE 8-1. PARAMETERS USED IN LINK BUDGET CALCULATIONS

Communication range	200 m
Transmitter power	25 mW (max)
Path loss exponents	$a = 2$, $b = 4$
Standard deviation of shadowing	8 dB
Fading margin	10 dB
Desired SNR at receiver	10 dB
Noise figure	5 dB
Carrier frequency	2 GHz
Channel bandwidth	1 MHz
Transmitter antenna height	2 m
Receiver antenna height	2 m

We assume that signal propagates in LOS environment characterized by the two-slope path loss model [Harley 1989], [Alouini 1999] such that average received signal power $\overline{P}_{\mathrm{rx}}$ [W] is

$$\overline{P}_{\mathrm{rx}} = \frac{K}{d^{a}(1 + d/g)^{b}} P_{\mathrm{tx}}, \qquad (8\text{-}1)$$

where K is a constant, a (usually two) is a basic path loss exponent for short distances, b (between two and six) is an additional path loss exponent, and P_{tx} [W] is the transmitted signal power. The parameter g [m] is the break point of path loss curve and is given by $g = 4h_{tx}h_{rx}/\lambda_c$ where h_{tx} [m] is the transmitter antenna height h_{rx} [m] is the receiver antenna height and λ_c [m] is the wavelength of the carrier frequency. We use antenna heights $h_{tx} = h_{rx} = 2$ m, which are typical for mobile user [Alouini 1999]. When the carrier frequency f_c is 2 GHz, we obtain break point at 106.67 m. In 5 GHz system the break point is 266.67 m.

The parameter K in equation (8-1) depends on the used transmitter. The type of the antenna, usage of beamforming etc. affect the constant value. [Alouini 1999] and [Alasalmi 2002] have used value $K = 1$ in their simulations. This choice can be good with comparative studies but when we want to calculate link budget we have to know value that have connection to the real world. When isotropical antenna is used, the free space path loss can be calculated as [Saunders 1999]

$$L_F = \left(\frac{4\pi d f_c}{c}\right)^2, \qquad (8\text{-}2)$$

where c is the speed of the light. Now, we can find the K by setting the path loss exponents $a = 2$ and $b = 0$ so that

$$L_F = \left(\frac{4\pi d f_c}{c}\right)^2 = \frac{d^a(1+d/g)^b}{K} = \frac{d^2}{K} \Leftrightarrow K = \frac{1}{\left(\frac{4\pi f_c}{c}\right)^2}. \qquad (8\text{-}3)$$

To find the maximal needed transmitted power we have to calculate the path loss with the distance $d = 200$ m, which is thought to be the maximal range for a cognitive link. With 2 GHz system the break point distance is 106.67 m. Let the path loss exponents to be $a = 2$ and $b = 4$. Now

$$L_F = 10\log\left(\frac{d^a(1+d/g)^b}{K}\right) = 10\log\left(\frac{200^2(1+200/106.67)^4}{\frac{1}{\left(\frac{4\pi\cdot 2\cdot 10^9}{3\cdot 10^8}\right)^2}}\right) = 102.8 \text{ dB}. \qquad (8\text{-}4)$$

Noise power in 1 MHz band is $N = kTB = 1.38\cdot 10^{-23}$ J/K $\cdot$ 290 K $\cdot 1\cdot 10^6$ Hz $= 4.002\cdot 10^{-15}$ W . In decibels it is 10 lg(kTB) = -144 dBW. When we add noise figure 5 dB [ETSI 1998] and the fading margin 10 dB [Saunders 1999] and take into account that desired SNR in the receiver is 10 dB we obtain that needed received signal power is (-144 + 5 + 10 + 10) dBW = -119 dBW. Thus, the maximal needed transmitter power when the is

$$P_{tx} = P_{rx,desired} + L_F = -119 \text{ dBW} + 102.8 \text{ dB} = -16.2 \text{ dBW} = 24.0 \text{ mW}. \qquad (8\text{-}5)$$

However, these calculations do not take transmitter power control into account. We have shown in [Mämmelä 2006] that power control can improve or deteriorate the link budget depending what kind of power control method is used. Bit error rate depends both on the link budget and the distribution of the received signal. Therefore the link budget can be worse with inverse power control than without because the distribution is better.

Fade margin is calculated so that the probability of the value of shadowing does not exceed the fade margin for 90% of locations at the maximal range (200 m from transmitter). When the receiver is nearer the value of the total path loss is less. Thus a greater percentage of locations will have acceptable coverage. Shadowing component L_s in decibels is a zero-mean Gaussian random variable with standard deviation σ_L. To find L_s that provide 90% successful communications at the fringe of coverage we take the argument of $Q(.)$ function, $z = L_s/\sigma_L$ for which the path loss is less than the maximum acceptable value for at least 90 % of locations [Saunders 1999]. $Q(.)$ function is the cumulative normal distribution. Now $Q(z)$ should be 10 % = 0.1 which corresponds to the value $z = 1.25 \rightarrow L_s = z\sigma_L = 1.25*8$ dB = 10 dB. If we want to take multipath fading into account in link budget calculations, the fade margin should be larger maybe in the range of 30 dB.

8.2 Spectrum sensing

In this section, the results concerning spectrum sensing are shown. In Section 8.2.1, the simulation model is explained and the spectrum of the signal in different phases of the simulation is analyzed. The results presenting the performance of the spectrum sensing with Welch periodogram in terms of receiver operating characteristic (ROC) are presented in Section 8.2.2.

8.2.1 The simulation model

The simulation model is presented in Figure 8-1. The primary user sends quadrature phase shift keying (QPSK) symbols on a 1 MHz frequency channel with the carrier frequency of 4 MHz over a complex additive white Gaussian noise (AWGN) channel. Symbols are sent at the symbol rate of R_S = 500 ksymbols/s. First, the noise has been added to the RF input signal. Then received signal has been downconverted to baseband. The used detection method is Welch periodogram which was explained more detailed in Section 5.2.2. the Welch's periodogram alerts when received signal energy exceeds the detection threshold. The number of frequency bins to be averaged around the zero frequency is denoted by L. The input signal is segmented in time domain and the number of segments is denoted by M. In order to illustrate the function of the Welch periodogram, the power spectral density (PSD) of the signal at numbered points 1)-5) is shown in following five pictures both in the case of primary user sending the signal and in the case where only noise is present.

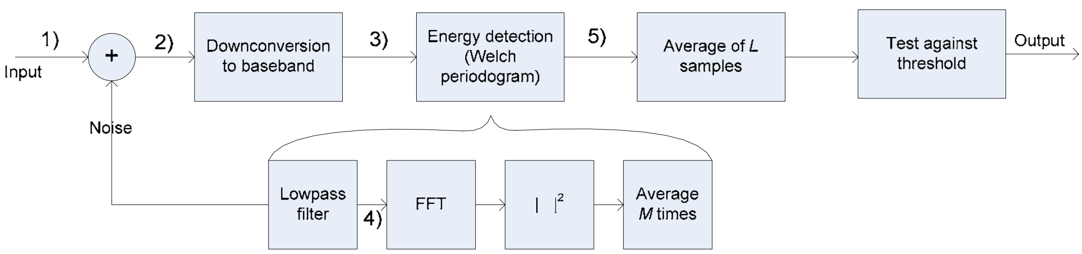
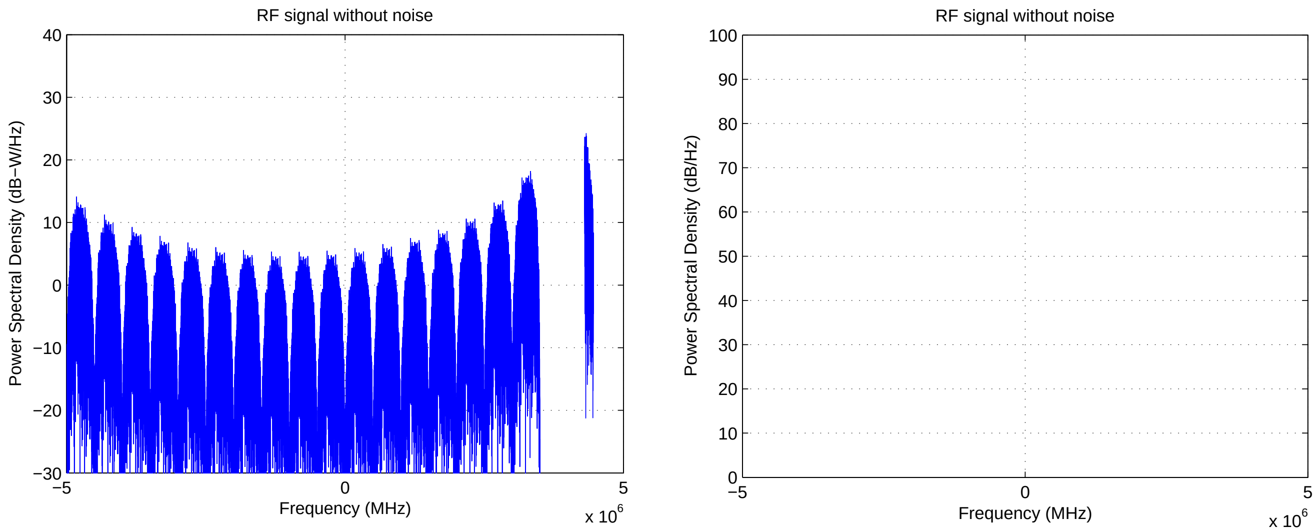


Figure 8-1. Simulation model.

The PSD of the input signal is illustrated in Figure 8-2 a). The power of the signal is $P_S = \gamma(0) = E(S_t S_t^*) = 10$ defined for the B = 10 MHz bandwidth. [Proakis 1988] In Figure 8-2 b), the primary user is not sending information.



a) b)

Figure 8-2. The input signal when a) primary user is sending information and b) when only noise is present.

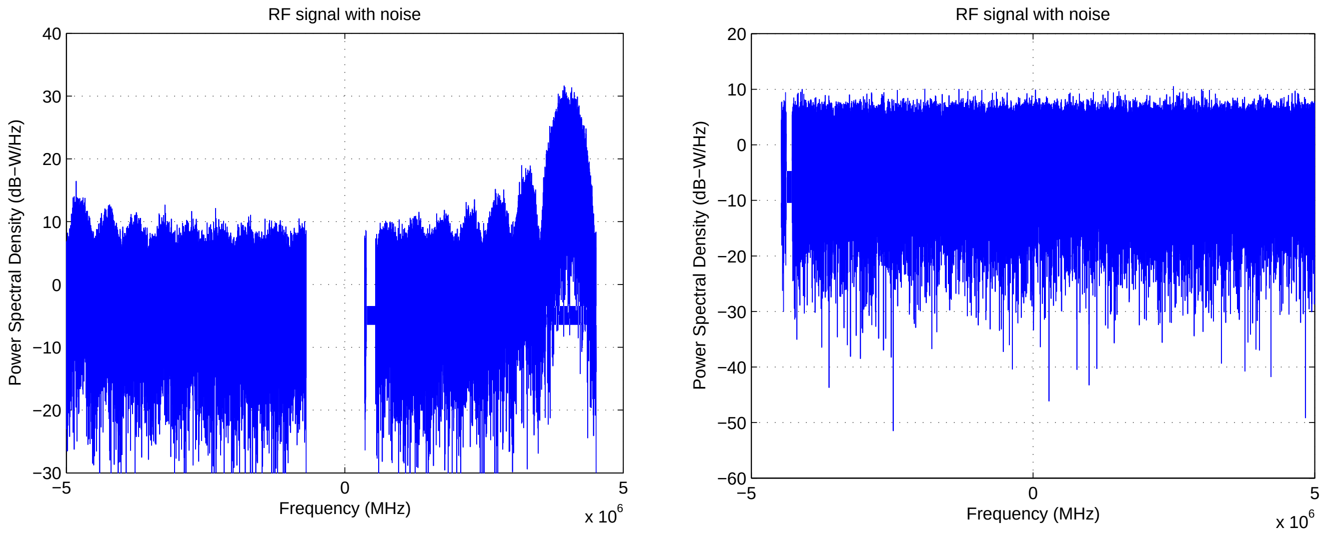
After the white Gaussian noise has been added the spectrum of the signal is presented in Figure 8-3 a) when primary user signal is present and b) when only noise is present. Using the same definition as for the signal power [Proakis 1988], the noise power P_N = 1. Thus, signal-to noise ratio measured for the bandwidth B is S/N = 10 dB. Signal-to-noise ratio measured for the symbol bandwidth can therefore be calculated as

$$\mathrm{E/N_0} = (B/R_\mathrm{S}) * (\mathrm{S/N}) = 200 \sim 23\,\mathrm{dB}. \quad (8\text{-}6)$$

This value corresponds to the average value of the PSD on the 1 MHz band with center frequency of 4 MHz. This is not clearly visible from Figure 8-3 a) due to high fluctuations of the PSD estimate. However, the accuracy of the value was confirmed using the Parseval’s relation

$$\frac{1}{N}\sum_{k=0}^{N-1}\left|x[n]\right|^2 = \frac{1}{N}\sum_{k=0}^{N-1}\left|X[k]\right|^2 \text{ when}$$
$$X[k] = \sum_{n=0}^{N-1} x[n]\exp(-j2\pi(k/N)n), k = 0,1,...,N-1. \quad (8\text{-}7)$$

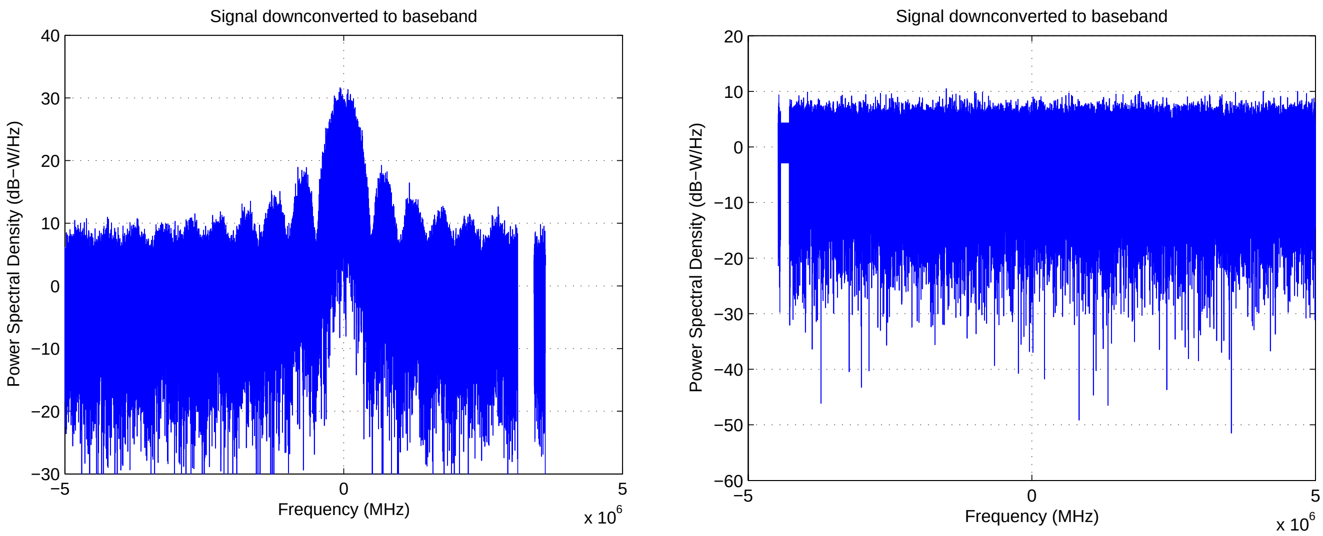
It should be noted that definition of DFT equals to the one used by Matlab and also in [Kay 2006]. In some literature (e.g. [Oppenheim 1999]), scaling factor $1/N$ exists in the definition of DFT therefore also Parseval's Relation is defined differently.



a) b)

Figure 8-3. Input signal with noise when a) primary user is sending information and b) when only noise is present.

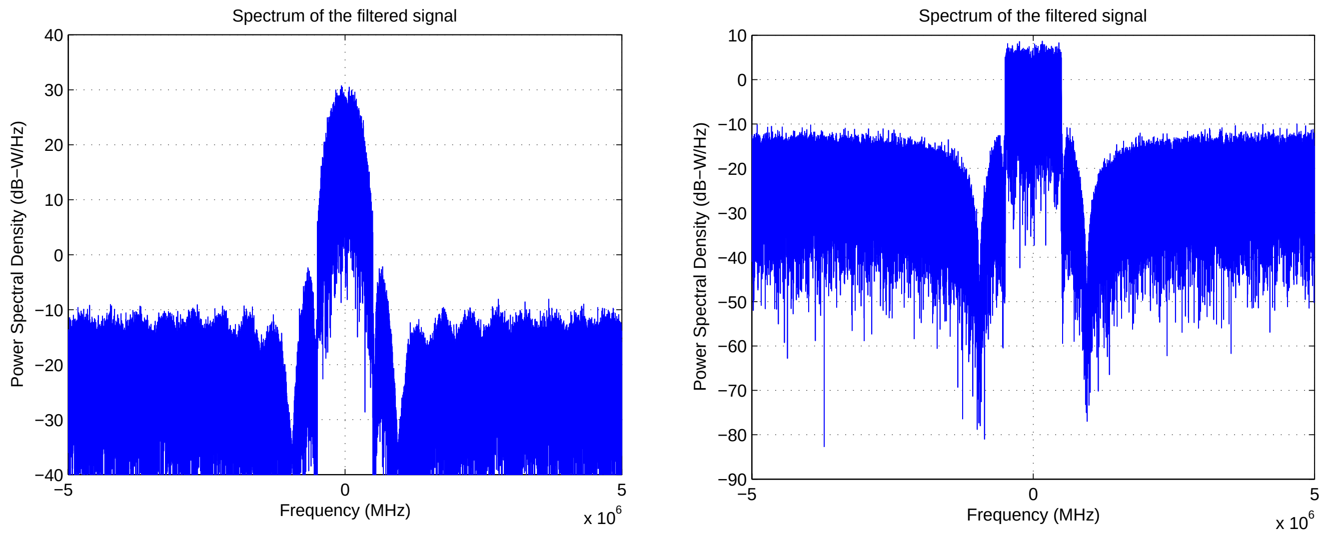
The input signal with noise is downconverted to baseband. The resulting signal is shown in Figure 8-4 a) when primary user is present and in Figure 8-4 b) when only noise is present.



a) b)

Figure 8-4. Downconverted signal when a) primary user is sending information and b) when only noise is present.

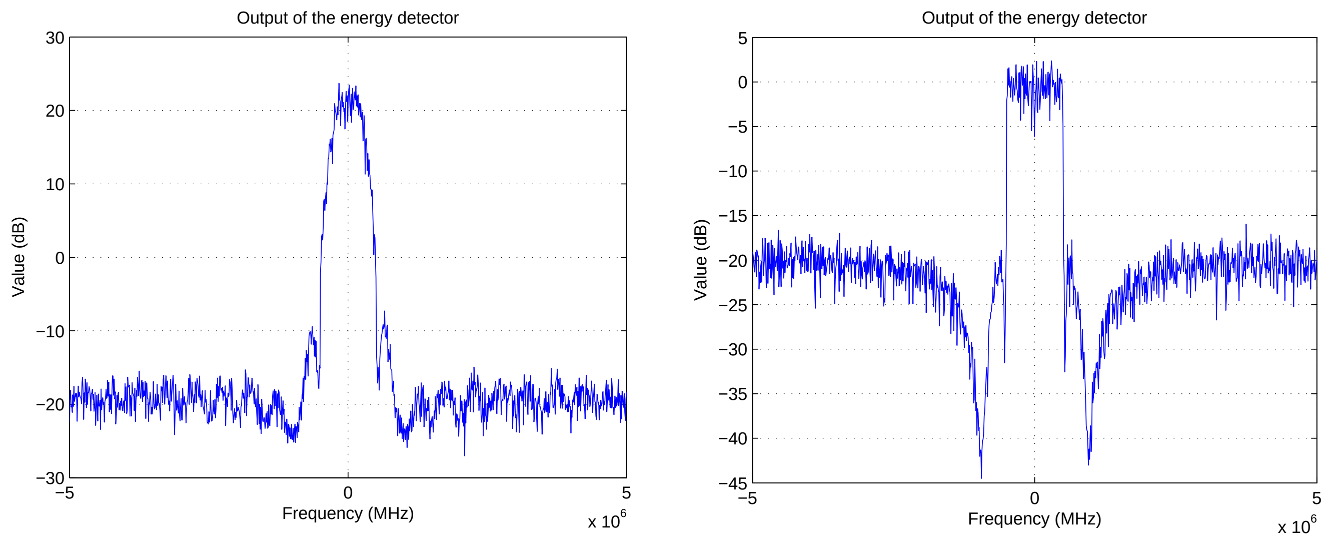
After the downconversion, the signal is fed to the energy detector, thus, Welch's periodogram. In the first phase of the periodogram, signal is lowpass filtered. The used filter is an 8th order digital elliptic filter with 1 dB peak-to-peak ripple, 20 dB minimum stopband attenuation and 1 MHz corner frequency. The spectrum of the filtered signal is given in Figure 8-5 when a) primary user signal is present and b) when signal is not present.



a) b)

Figure 8-5. Filtered signal when a) primary user is sending information and b) when only noise is present.

After the filtering, FFT is performed and signal is squared. The length of the FFT is 1024. The input sequence is divided into 8 segments and averaging is done over those segments. Windowing is done using a rectangular window. The windows can be overlapping as explained in Section 5.2.2. However, no overlapping was used when plotting the signals in Figure 8-6 a) when primary user is sending information and Figure 8-6 b) when only noise is present. The output signal from the energy detector is then compared to the threshold in order to determine whether a signal is present or not. The comparison is done with the mean value obtained from the width of a 1 MHz channel.



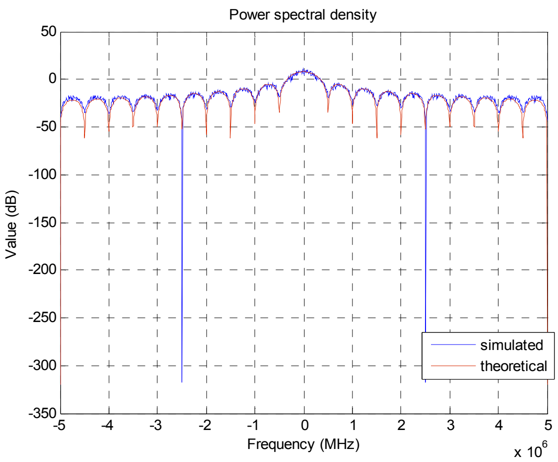
a) b)

Figure 8-6. The output of the detector when a) primary user is sending information and b) when only noise is present.

The theoretical power spectrum density is illustrated in Figure 8-7 for signal and signal + noise. Simulated power spectrum density curve has been measured using Welch periodogram. Now one can see that spectrum peak corresponds to energy of QPSK pulse. Spectrum shape is $sinc^2$ and this results from use of rectangular pulse.

At high frequencies one can notice spectrum aliasing when comparing theoretical and simulated curves. Simulated curve is higher. Aliasing results from the fact that signal in simulations is discrete time signal and spectrum is periodic but in Proakis' analysis signal is continuous time signal and spectrum is nonperiodic. Aliasing can not be removed totally by using windowing function since aliasing results from the rectangular symbol waveform. By changing pulse shape the aliasing will decrease.

Simulated spectrum has always noise. This noise is due to the Welch periodogram method since signal is random and randomness is a consequence of the spectrum estimate. Randomness can be reduced by increasing number of segments. Noisiness is due to the following reasons: 1) starting point of FFT-window is random compared to the symbol starting point and 2) symbol sequence in the FFT window is random. Variance decreases when the number of segments = K increases. Segment's overlapping decreases variance but analysis is more difficult since noise samples are partially the same in different segments causing that noise samples correlate in different segments.



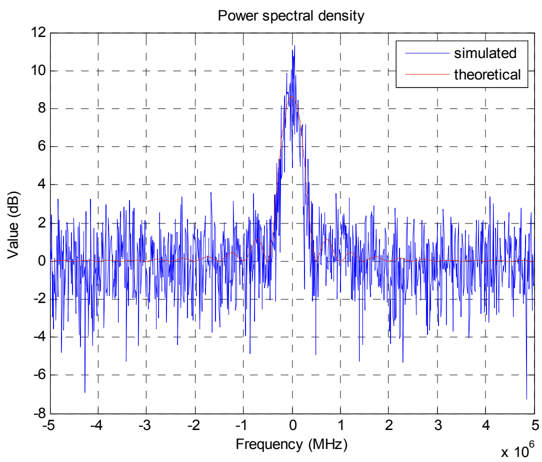


Figure 8-7. Power spectrum density for signal and signal + noise

8.2.2 Simulation results

In the Monte Carlo computer simulations, the Welch periodogram has been studied in the frequency domain. Each simulation scenario is repeated 10^5 times. A complex AWGN channel and one QPSK signal are used in the simulations. The SNR = E/N_0 values were -7, -2 and 3 dB. Used FFT length N_{FFT}, which corresponds to the segment length and rectangular window, are 512 or 1024. When we do not use overlapping, block lengths N_b are 205 and 410 symbols for FFT sizes 512 and 1024, respectively. And correspondingly when using overlapping N_b is 116 or 231. In the analysis and simulations we use T = 20. Figures 8-8 – 8-14 present theoretical and simulated receiver operating characteristic curves for the Welch periodogram. The theoretical ROC curve is obtained using equation (5-8) and (5-9). In Figure 8-8, there are theoretical and simulated ROC-curves for one segment and eight segments when detecting one QPSK-signal. The signal-to-noise ratio is -7 dB. N_{FFT} is 1024. In this case the number of frequency bins to be averaged around the zero frequency L is 10. We compare two cases. In the first case we use only one segment which corresponds to periodogram. In the second case we use 8 non-overlapping segments. It can be seen that the performance is better when using 8 non-overlapping segments. In Figure 8-9 is also one QPSK signal detection situation when SNR is -7 dB and N_{FFT} is 1024. In this case the number of frequency bins to be averaged around the zero frequency L is 1. Now we can see that performance is worse compared to case when L = 10. In Fig 8-10 case we have used FFT length 512.

Comparing Figures 8-8 and 8-10 we can notice that the length of FFT has no effect on the performance.

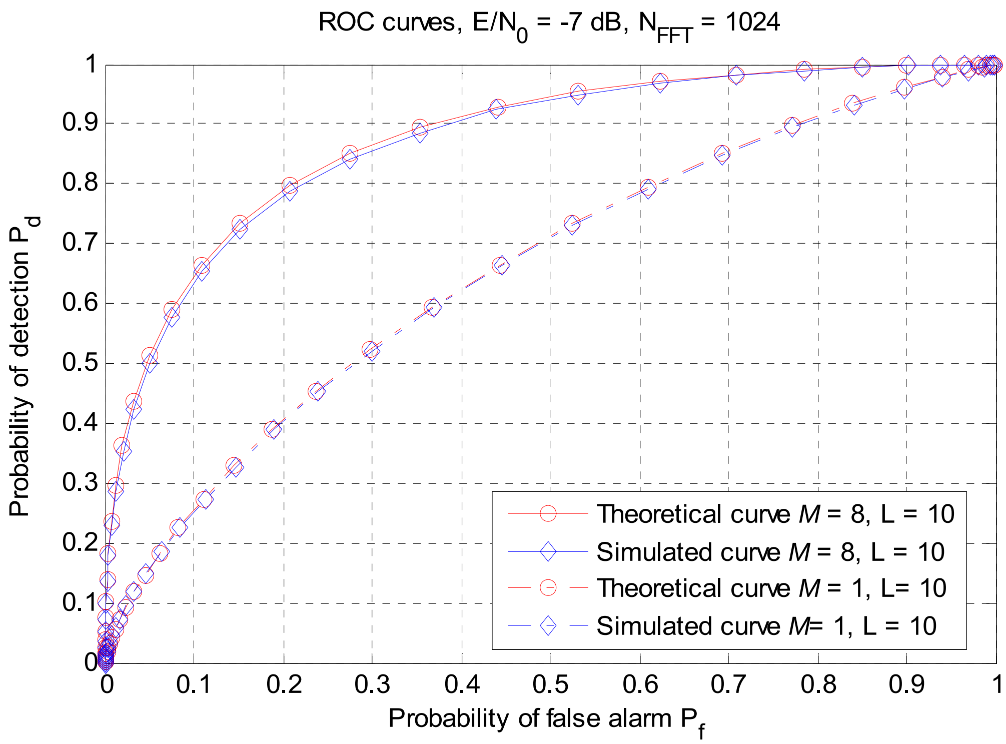


Figure 8-8. Receiver operating characteristic. FFT = 1024, SNR = -7 dB

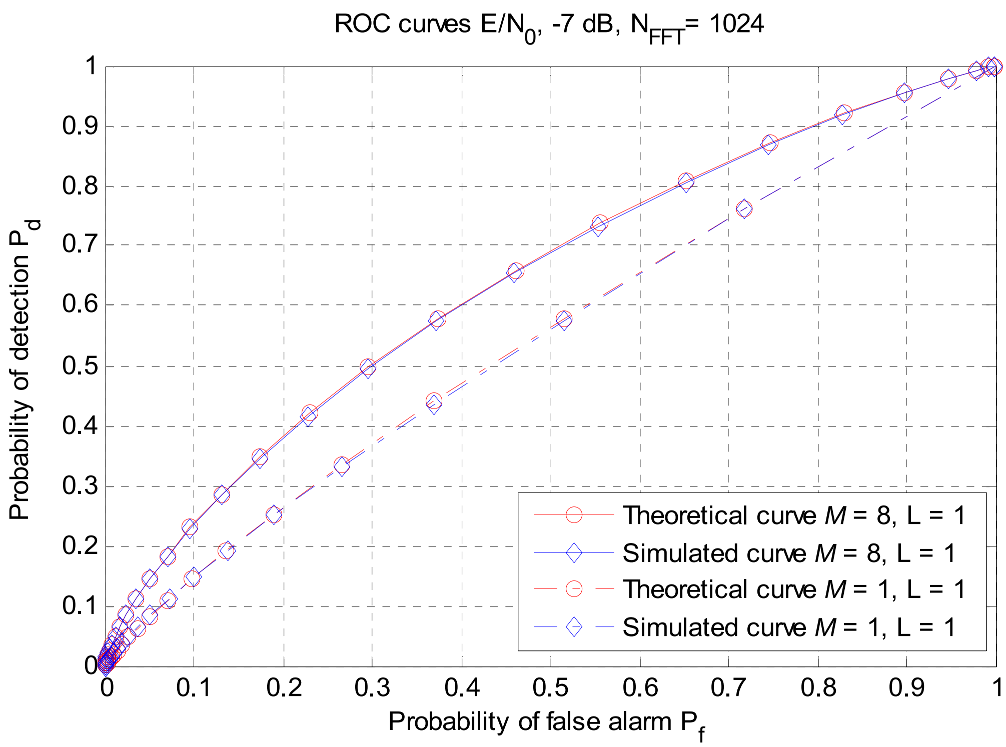


Figure 8-9. Receiver operating characteristic. FFT = 1024, SNR = -7 dB

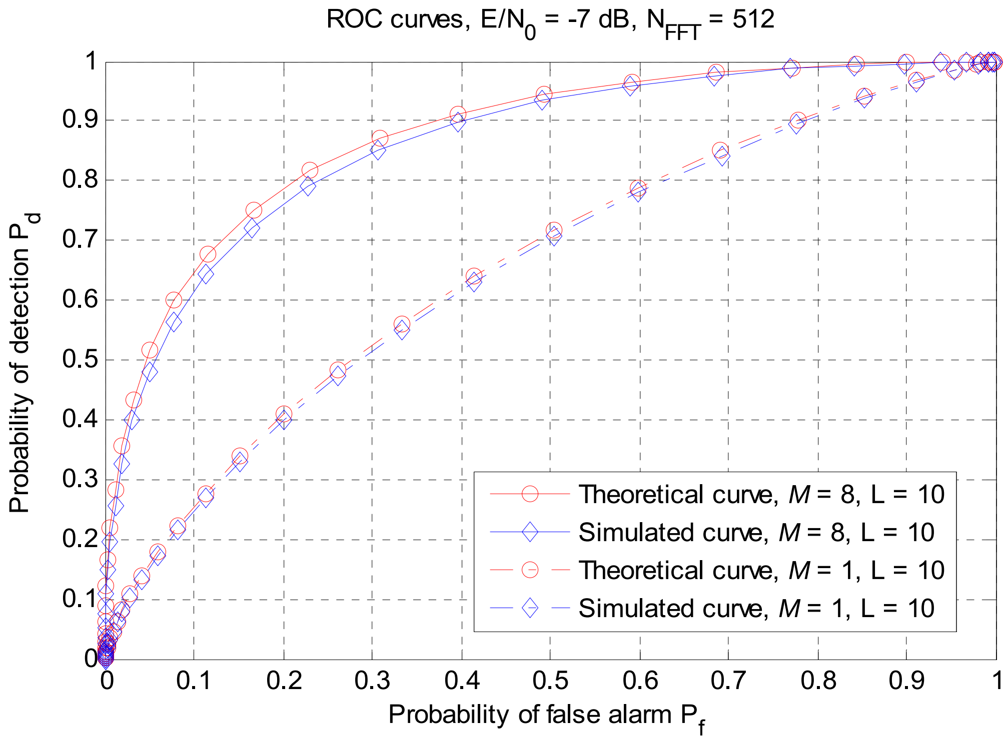


Figure 8-10. Receiver operating characteristic. FFT = 512, SNR = -7 dB

In Figure 8-11 also overlapping case is presented for eight segments and the packet length N_p is now 231 samples. In non-overlapping case N_p is 410 samples. the segments are overlapping on each other by half of the N_{FFT} samples. We can notice that when using overlapping the performance is almost the same as without overlapping but now the length of the packet can be much smaller.

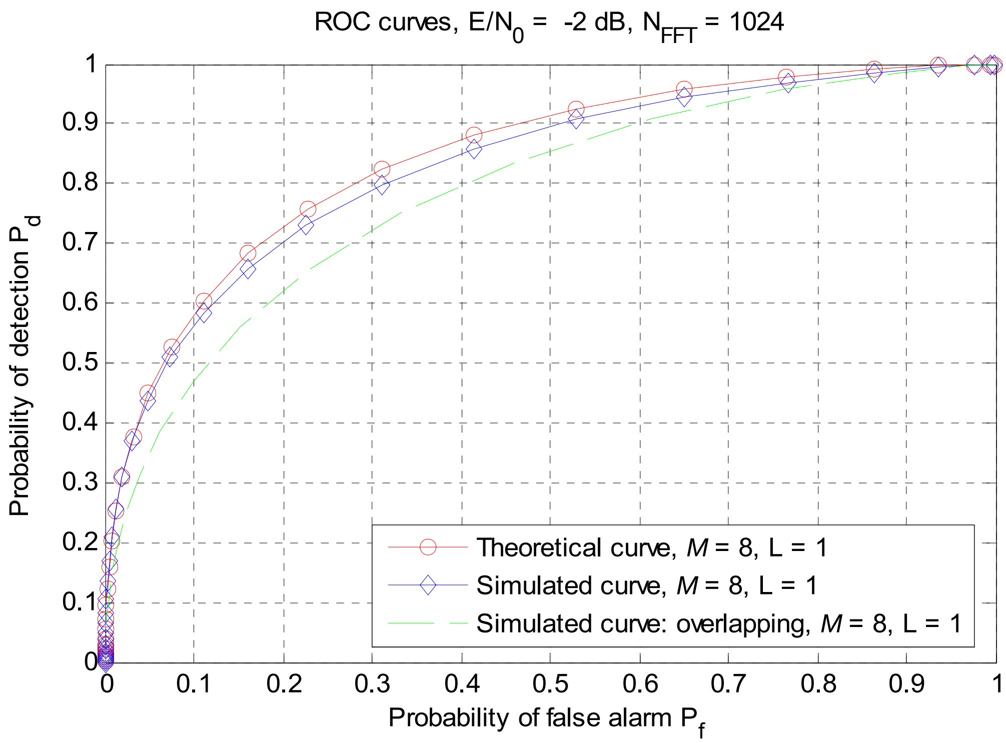


Figure 8-11. Receiver operating characteristic. FFT = 1024, SNR = -2 dB

Fig. 8-14 shows ROC-curves when N_{FFT} = 1024, SNR = 3 dB, L = 1 or 10, and in overlapping case M = 8 or 15 We have also simulated case where M = 15 and N_p = 205, i.e. the packet length corresponds to case when we do not use overlapping. We clearly see performance improvement when we compare overlapping case with 15 segments to non-overlapping case with eight segments. Figs. 8-12 and 8-13 present overlapping and non-overlapping cases when N_{FFT} = 512, SNR = -7 dB, L = 1 or 10, and in overlapping case M = 8 or 15. When using L =1, we can see that performance is worse compared to the case when L = 10. In addition, simulations show that we can achieve small gain using overlapping compared to the non-overlapping case. However, even with the averaging and overlapping the probability of detection is low with low probabilities of false alarm.

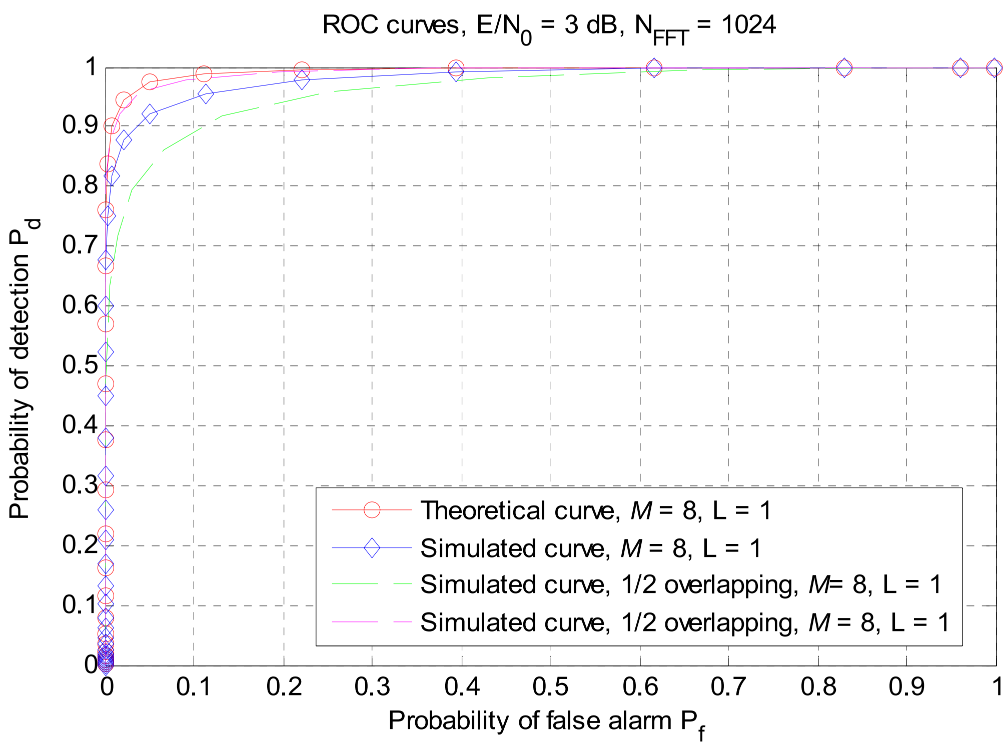


Figure 8-12. Receiver operating characteristic. FFT = 1024, SNR = 3 dB

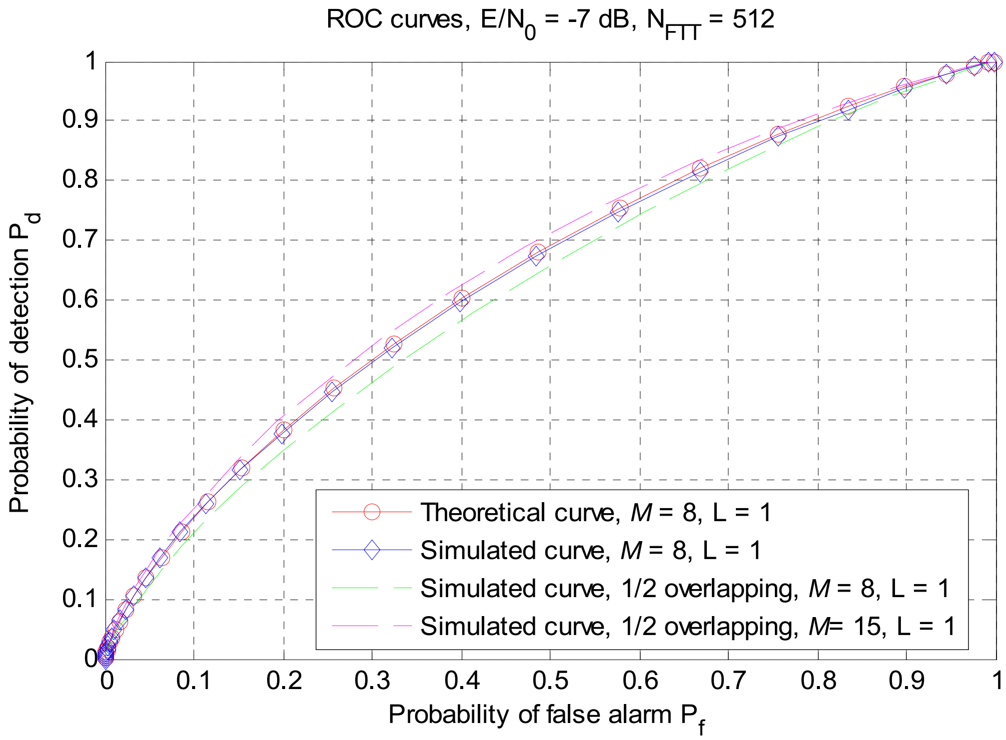


Figure 8-13. Receiver operating characteristic. FFT = 512, SNR = -7 dB

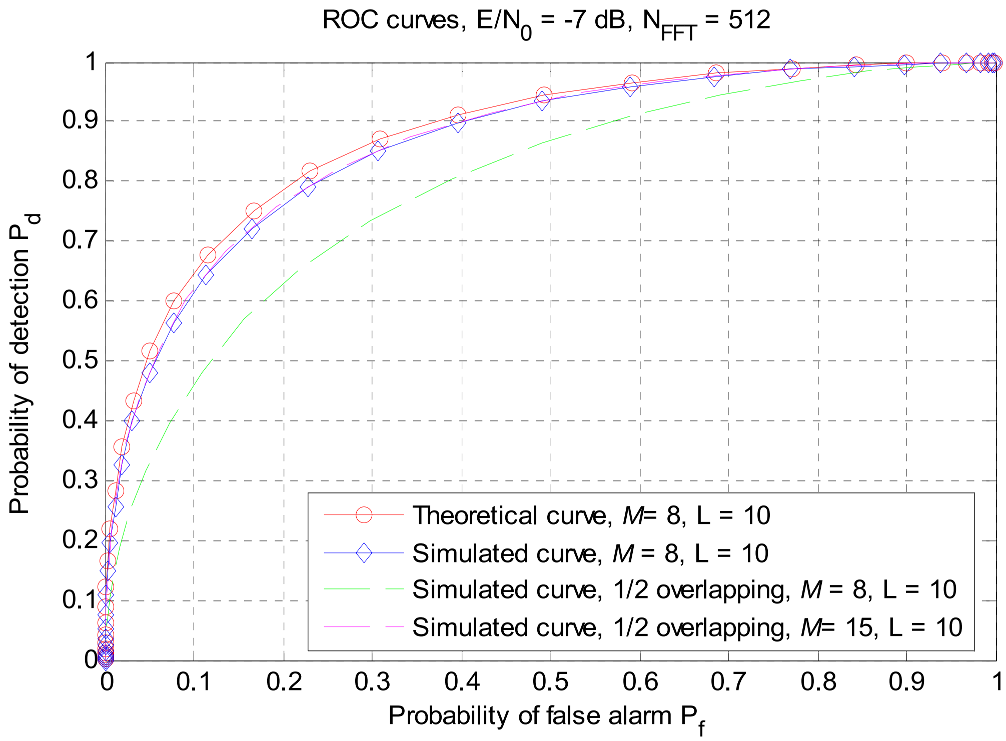


Figure 8-14. Receiver operating characteristic. FFT = 512, SNR = -7 dB

In the following, the results for cooperative sensing are presented in the case of AWGN channel. The probabilities of false alarm and detection are simulated when the number of cooperating cognitive radios n_{CR} is two and three. The case of single cognitive radio is also shown for comparison. In Figure 8-15, an example of the network layout is shown. Fifteen nodes with random x- and y-coordinates are placed in one square kilometer area. Their 200 meter transmission ranges are marked with circles. One node (marked red in the figure) is randomly selected for sensing. The selection is done among the nodes that have at least n_{CR}-1 nodes within their transmission range. The potential nodes for cooperation, thus, the nodes within transmission range from the sensing node are marked green in the figure.

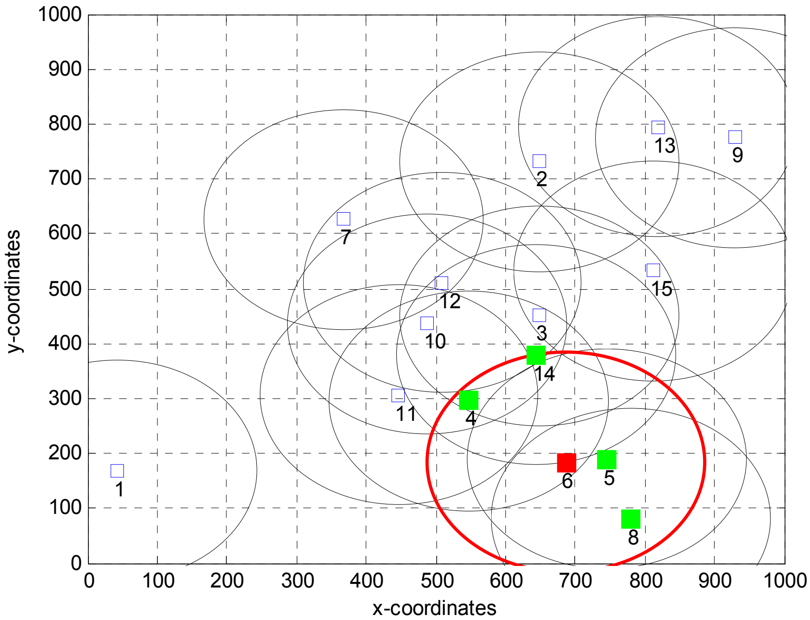


Figure 8-15. The sensing node and potential nodes for cooperation.

In the example, cooperation of three cognitive radios is assumed (n_{CR}=3). The sensing node selects randomly two nodes within its transmission range for cooperation as shown in Figure 8-16. Interesting topic for future research would be to investigate different policies for selection of cooperating nodes in an environment with multipath fading and shadowing.

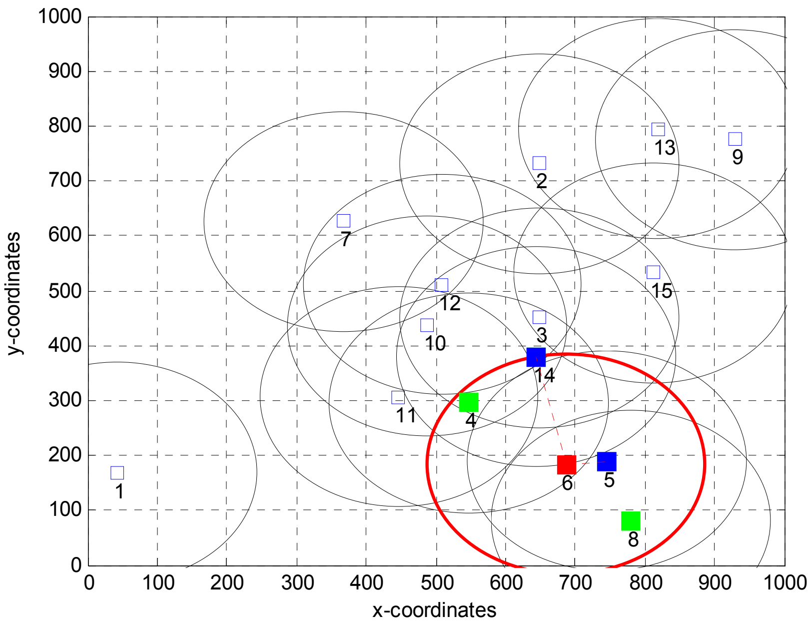


Figure 8-16. Nodes selected for cooperation.

Each radio detects the presence of the primary user signal using the model presented in Figure 8-1. As stated in Section 5.7, for a system without central controller the gain achieved using soft decisions instead of hard decisions is small. For that reason and also due to its simplicity, hard decision combining is the method of choice for the simulations. The nodes selected for cooperation perform local hypothesis test and send binary value to sensing node indicating whether they believe that the channel is occupied or not. The sensing node combines decisions from cooperating radios using simple or-rule: if one of the cooperating radios detects a primary user, the decision is made that primary user is present. The joint probability for detection Q_d and false alarm Q_f can therefore be given as

$$Q_\mathrm{d} = 1-(1-P_\mathrm{d})^{n_\mathrm{RC}} \text{ and}$$
$$Q_\mathrm{f} = 1-(1-P_\mathrm{f})^{n_\mathrm{RC}}, \qquad (8\text{-}8)$$

where P_d and P_f are probabilities of detection and false alarm from a single user, calculated using (5-9) and (5-8), respectively. Signal-to-noise ratio E/N_0 = -7 dB and QPSK signal is assumed. The segment length in all cases corresponds to the length of FFT, N_FFT, and averaging is done over ten middle FFT samples (L = 10). The average is compared to a decision threshold, which is changed so that the whole range from 0-100% probabilities of false alarm and detection are obtained. The minimum and maximum values for the threshold are selected separately for each simulation and probabilities of false alarm and detection for 50 equally spaced threshold values between the minimum and the maximum are investigated. In Figure 8-17, the probabilities of false alarm P_f and detection P_d are shown for the periodogram with one segment (M = 1) of length N_FFT = 512. When only one segment is considered, the block length equals to the segment length. It can be seen from the figure that by increasing the number of cooperating radios, both the probability of false alarm and the probability of detection are increased.

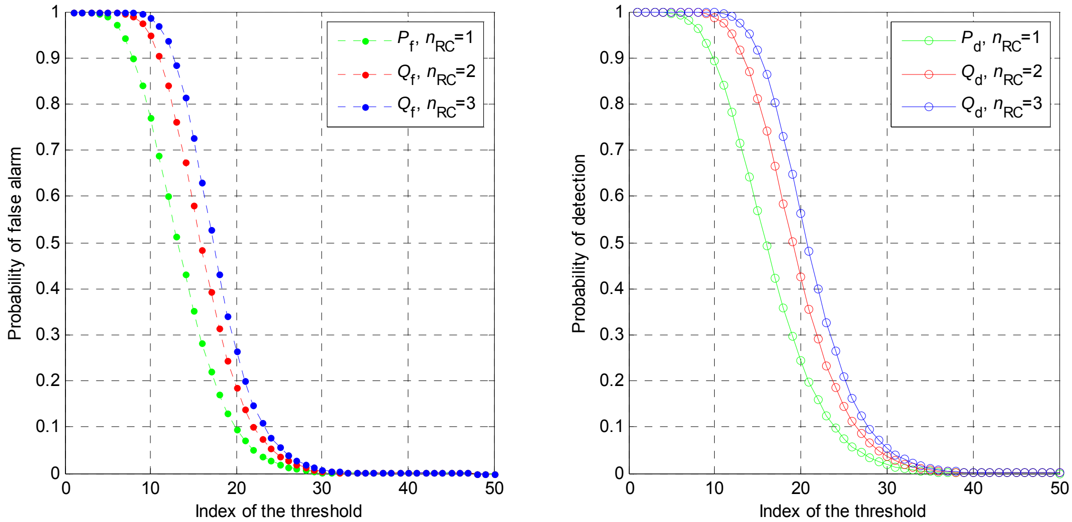


Figure 8-17. Probabilities of false alarm and detection for one segment of length N_FFT = 512.

The corresponding receiver operating characteristics (ROC) curves for one segment periodogram are shown in Figure 8-18. The theoretical curves, calculated with Equations (5-8), (5-9), and (8-8), are shown for comparison. In the figure, approximately 1 percentage unit difference can be seen between the theoretical and the simulated curves. This can be explained by the fact that the theory assumes that the noncentrality parameter is constant, whereas in the simulations the noncentrality parameter is a random variable. It converges to a constant value when the number of segments approaches infinity. Thus, the accuracy of the theory improves asymptotically. The theory also neglects the effect of aliasing. From the figure we can see that with 20% probability of false alarm the increase in probability of detection P_d is 5 and 8 percentage units for two and three cooperating radios, respectively.

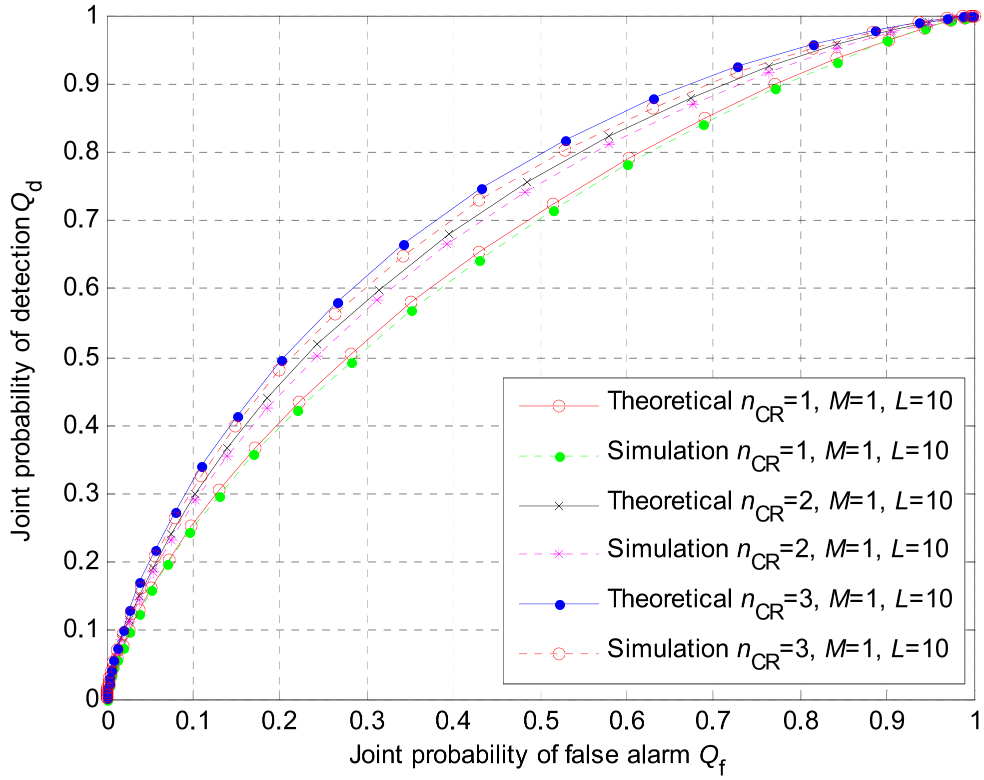


Figure 8-18. Theoretical and simulated ROC curves for one segment of length N_{FFT} = 512.

In Figure 8-19, simulated and theoretical ROC curves are shown for eight (M = 8) non-overlapping segments of length N_{FFT} = 512, thus, the block length is $M*N_{FFT}$. From the figure it can be noted that the cooperation gain becomes more significant than in the one segment periodogram. With 20% probability of false alarm the increase in probability of detection P_d is 10 and 13 percentage units for two and three cooperating radios, respectively. This supports the result from the experimental study in [Čabrić 2006b] indicating that the largest increase in the probability of detection is observed when moving from single radio to two cooperating radios. The difference between theory and simulation in this case is approximately 3 percentage units.

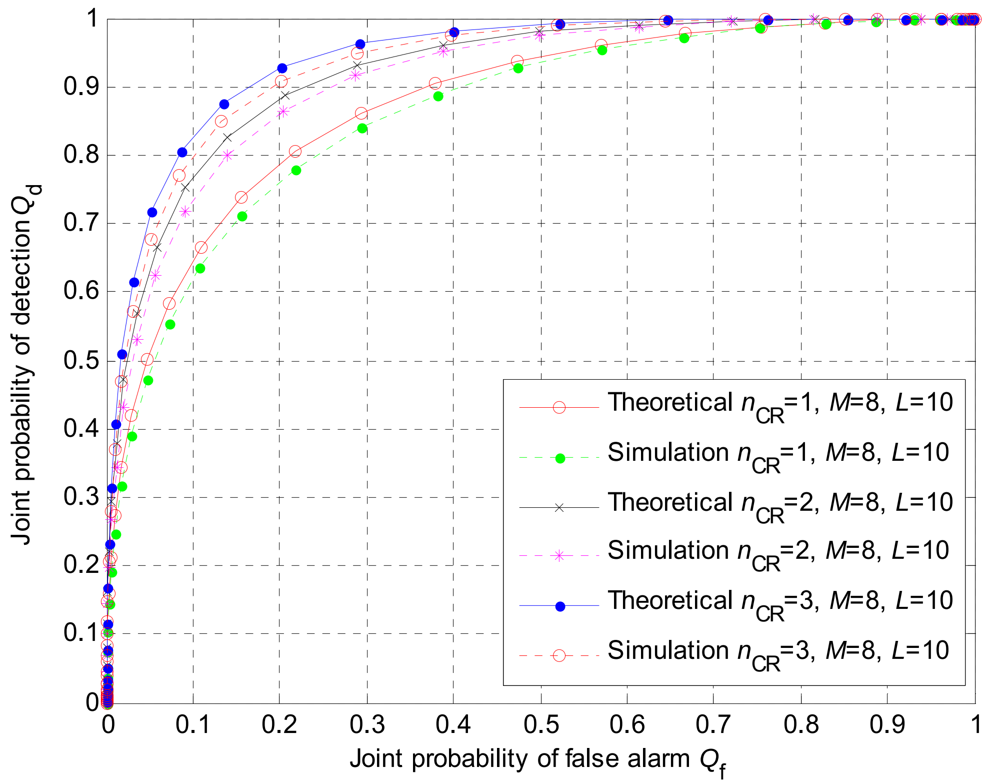


Figure 8-19. Theoretical and simulated ROC curves for eight non-overlapping segments of length $N_{FFT} = 512$.

In Figure 8-20 an investigation on the effect of overlapping segments was conducted. The non-overlapping case with eight segments is shown as a reference. The ROC curves show that equal performance is obtained with eight non-overlapping segments than with 15 segments with the overlapping of half segment length. This is intuitively understandable since the block lengths are equal in these two cases 8* (N_{FFT}) whereas in the case of eight overlapping segments the block length is reduced to almost half of the size (4.5* N_{FFT}). With 20% probability of false alarm the decrease in probability of detection P_d is approximately 13 percentage units compared to the case of non-overlapping segments. The decrease is equal in the cases of one, two and three cognitive radios. Comparing the case of eight non-overlapping segments and fifteen segments with overlapping of half segment size it can be noted that the expected gain achieved due to reduced variance of the estimate for overlapping segments is not visible from ROC curves. However, in the simulations an average of ten middle FFT samples (L = 10) was taken which reduces the impact of the variance of the estimate.

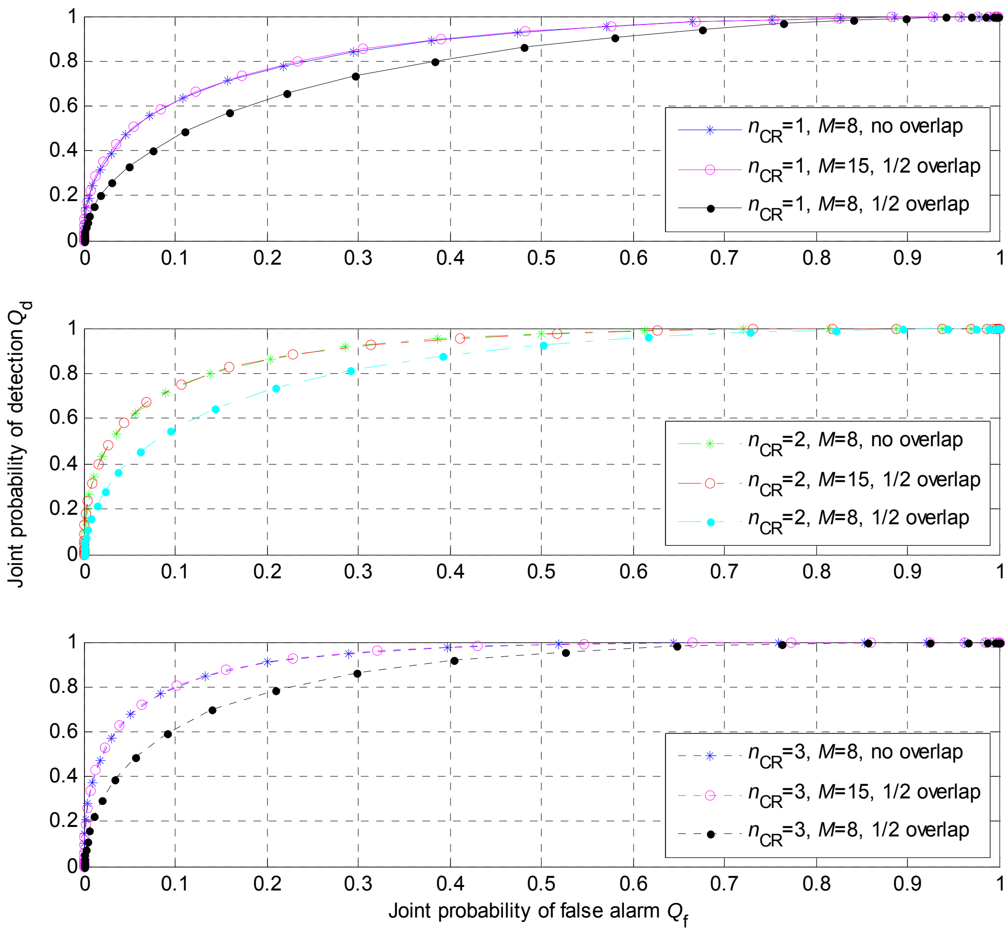


Figure 8-20. ROC curves without overlapping for $M = 8$ and with overlapping for $M = 8$ and $M = 15$ segments, segment length $N_{FFT} = 512$.

Further investigation on ROC curves shown above leads to examination of probabilities of detection and false alarm separately in Figure 8-21 and Figure 8-22, respectively. From Figure 8-21. it is visible that for the case of eight overlapping segments the probability of detection is approximately 10 percentage units lower than for the case of eight non-overlapping segments. On the other hand, from Figure 8-22. it can be noted that the difference between these two in the probability of false alarm is much smaller, approximately 5 percentage units. It can be concluded that the decrease of the performance is more due to the decrease in probability of detection than on the increase of probability of false alarm. There is not a significant difference between of one, two and three cognitive radios.

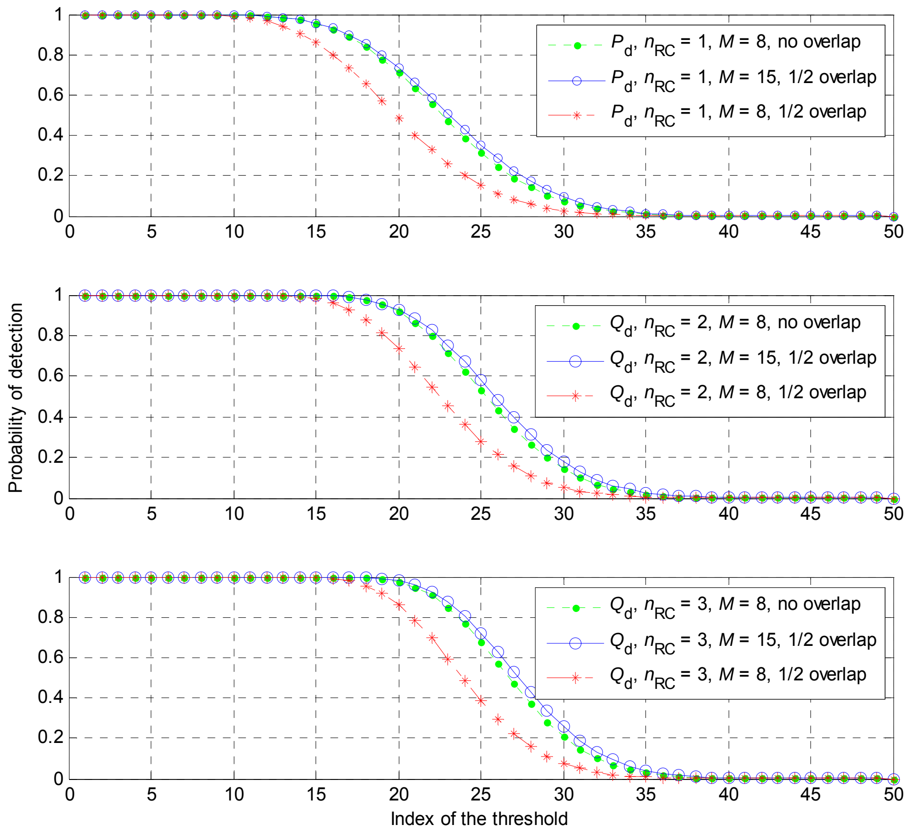


Figure 8-21. Probabilities of detection without overlapping for $M = 8$ and with overlapping for $M = 8$ and $M = 15$ segments, segment length $N_{FFT} = 512$.

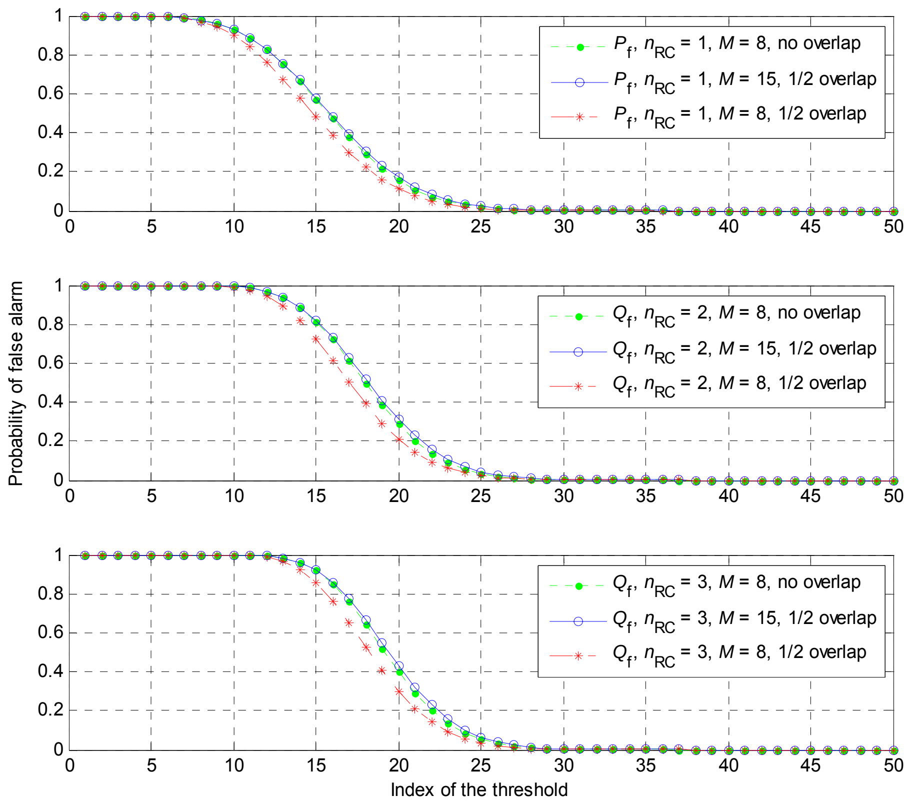


Figure 8-22. Probabilities of false alarm without overlapping for $M = 8$ and with overlapping for $M = 8$ and $M = 15$ segments, segment length $N_{FFT} = 512$.

In Figure 8-23, the simulation results for one segment periodogram are shown with the segment length of N_{FFT}=1024. The cooperation gain in this case is an increase of 6 and 9 percentage units in probability of detection P_d with 20% probability of false alarm for two and three cooperating radios, respectively. Comparing the results to the case of segment length N_{FFT}=512 (shown in Figure 8-16) it can be seen that increasing the segment length does not increase the probability of detection. However, the difference between theoretical and simulated results is smaller with the increased segment length.

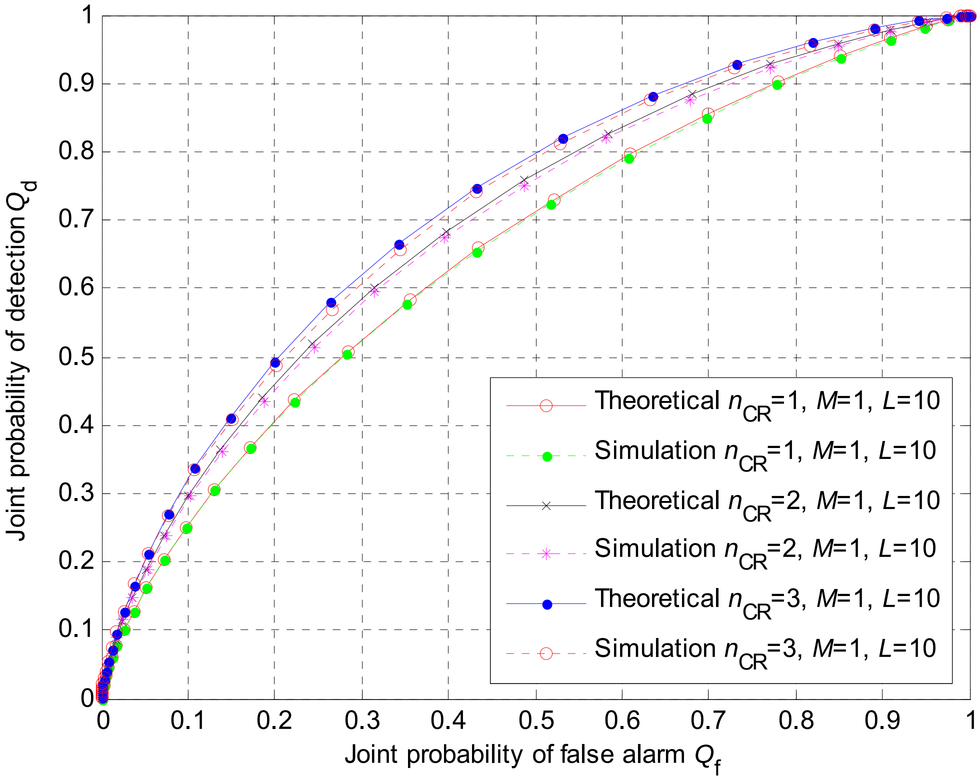


Figure 8-23. Theoretical and simulated ROC curves for one segment of length N_{FFT} = 1024.

Figure 8-24 shows the ROC curves for eight non-overlapping segments with segment length of N_{FFT} = 1024. With 20% probability of false alarm the increase in probability of detection P_d is 10 and 13 percentage units for two and three cooperating radios, respectively. The same result was obtained for the case of segment length N_{FFT} = 512 in Figure 8-19. Similarly to the case of one segment: no additional increase in detection is achieved by increasing the segment length but the simulation results follow better the theoretical ones than the ones with shorter segment length. From the figures presented on the cooperative sensing it can be concluded that the highest increase in probability of detection is observed when moving from single cognitive radio to two cooperating radios and it is also simplest form of cooperation, requiring least signaling. However, it should be noted that simulation model does not take into account shadowing or multipath fading. It does not model hidden terminal problem either. Adding these phenomena to the simulation model would add the unreliability of the sensing information and could therefore lead into results favoring more extensive cooperation between users.

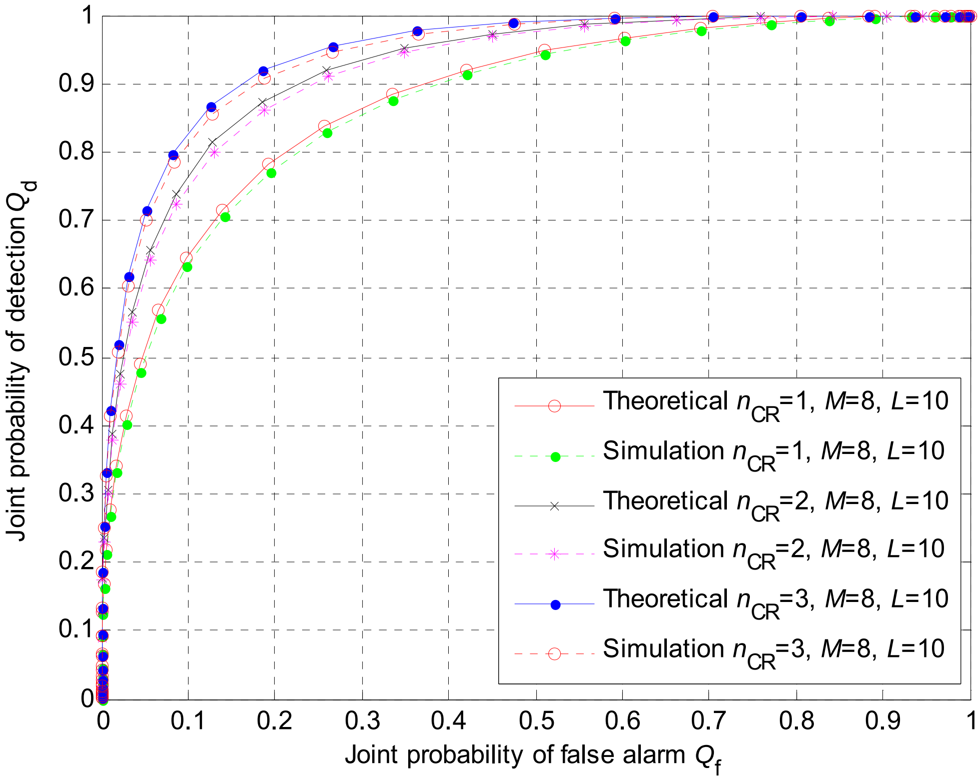


Figure 8-24. Theoretical and simulated ROC curves for eight non-overlapping segments of length $N_{FFT} = 1024$.

8.2.3 Conclusions from spectrum sensing

We have studied Welch's periodogram from a spectrum sensing and cognitive radio perspective. We generalized and applied the previous theoretical analysis of the energy detection to the Welch's periodogram. Furthermore, we extended our study to cooperative spectrum sensing. The simulations show that Welch's periodogram signal detection method operates well for narrowband signals. Simulations confirm that Welch's periodogram enhances the performance of the periodogram method. The main limitations of the periodogram method yield from the variance. The periodogram is an inconsistent spectral estimator which means that it continues to fluctuate around the true PSD with a nonzero variance. This effect cannot be eliminated even if the length of the processed sample increases without a bound. Furthermore, the fact that the periodogram values are uncorrelated for large number of the processed samples makes the periodogram exhibit an erratic behavior.

From the results on cooperative sensing presented here it can be concluded that the highest increase in probability of detection is observed when moving from single cognitive radio to two cooperating radios, however, adding phenomena such as shadowing, multipath fading, or hidden terminal problem to the simulation model would add the unreliability of the sensing information and could therefore lead into results favoring more extensive cooperation between users. This would lead to a trade-off between reliable sensing information and the costs caused by more extensive cooperation - such as complexity and increased signaling. Adding shadowing would bring up another trade-off on the distance between the cooperating radios. Decreasing the distance would lead to lower delays; however, correlation of shadowing - caused by two radios being blocked by the same object - would degrade the performance of cooperative sensing when radios are close to each other. This would lead to the development of algorithms for finding the optimal radios for cooperation from the candidates. Before mentioned problems are not covered here, however, they are interesting topics and subjects for future research.

8.3 Frequency and power management

First simulations in the frequency and power management studies have been conventional power control simulations in the link level with different power control structures which are presented in Sections 8.3.1 and 8.3.2. We have simulated well known algorithms from literature and proposed our own algorithms to inverse power control task, see Section 6.2. We have done simulations with conventional FSAPC algorithm, variable step adjustment power control (VSAPC), and FxLMS algorithm based power control. The transmission data are BPSK modulated with a rate of 10 kilobits per second. Frequency management studies in Section 8.3.3 include prediction of idle and busy periods of traffic in the channels and selection of the transmission channels.

8.3.1 Power control in time-variant channel

It is very interesting to know how good the well-known FSAPC method presented in Section 8.2 performs in the channel defined in the system model. In this system f_d is chosen to be 10 Hz and the normalized Doppler frequency is 0.001, which corresponds to a slowly fading channel. The number of multipath components, N, is chosen to be 12. The channel gain is presented in Figure 8-25.

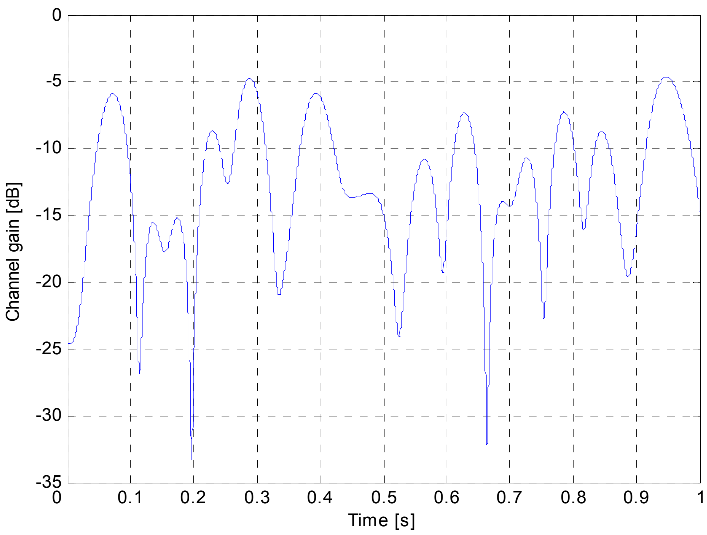
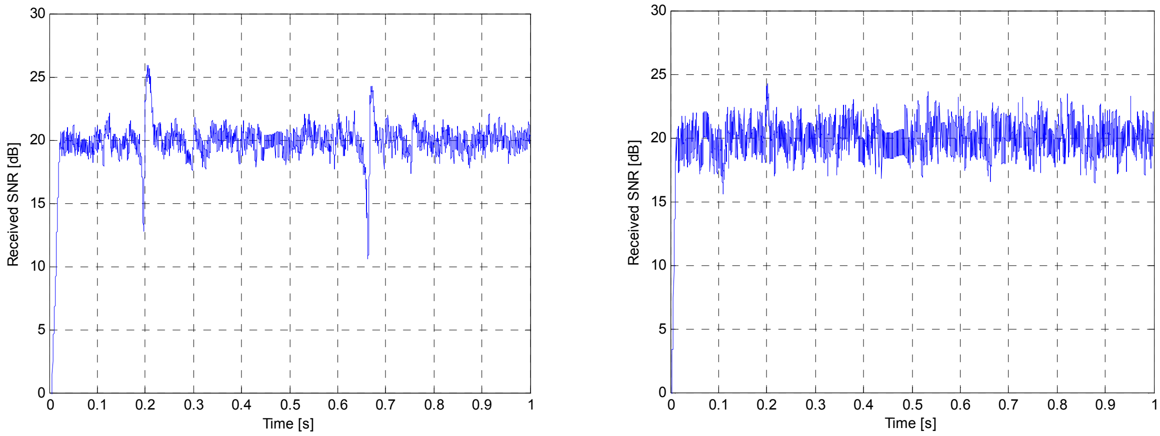


Figure 8-25. Channel gain, peak normalization used

The variance of n_k is chosen so that the average received SNR is 20 dB. The performance with the step size of 1 dB is shown in Figure 8-26 a). The standard deviation of received SNR is now 1.24 dB. The control cannot compensate deep fades well. The received SNR is too low during a deep fade. Then the transmission power is adjusted upwards and because of lag error it is too high for a while after the fade. Clearly we need a faster power control method.



a) 1 dB step b) 2 dB step

Figure 8-26. The received SNR with FSAPC power control

When the step size is doubled to 2 dB the tracking ability is improved and the method can compensate the deep fades in the channel quite well. The large deterioration following this selection is that the best achievable accuracy of control suffers significantly. It can be seen in Figure 8-26 b) that the level of received SNR fluctuates significantly all the time. As expected, the standard deviation is bigger with 2 dB step size than with 1 dB step size. The dB-scale value for it is 1.37 dB. This means that more accurate control is achieved with 1 dB step size. The main reason for that is that the received signal is kept in desired power level more accurately most of the time even though the performance during deep fades is worse.

The performance of VSAPC method presented in Section 6.2 is shown in Figure 8-27. Clear improvement can be noticed when compared to the performance of FSAPC method. Deep fades can now be compensated and also between the deep fades the received signal is kept in the desired level quite accurately. The value of standard deviation is 0.78 dB.

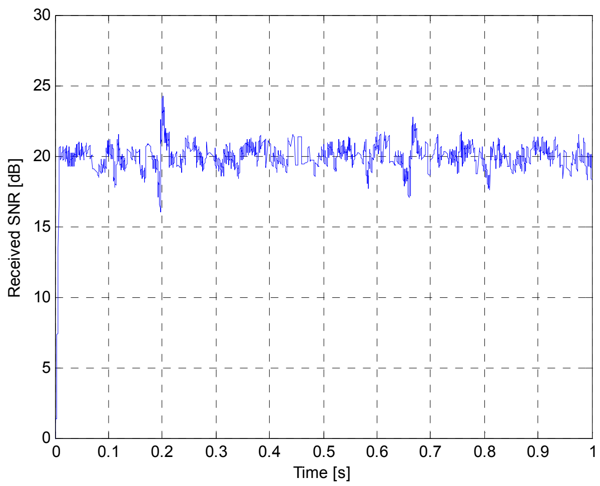


Figure 8-27. The received SNR with VSAPC power control.

When the normalized FxLMS algorithm presented in Section 6.2 is used in power control, the performance of the system is further improved. The power level is adjusted once in a millisecond as in the FSAPC and VSAPC methods. The value of c_{term} was chosen to be 2/SNR, where SNR is the transmitted SNR [Mämmelä 2006]. The bigger SNR is used the more stable the control is and smaller correction term is needed. It can be seen from Figure 8-28 that with FxLMS power control the level of received SNR can be held in the desired level with good accuracy.

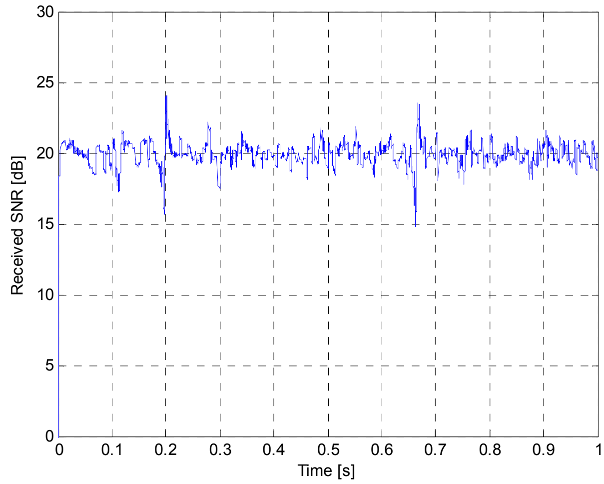


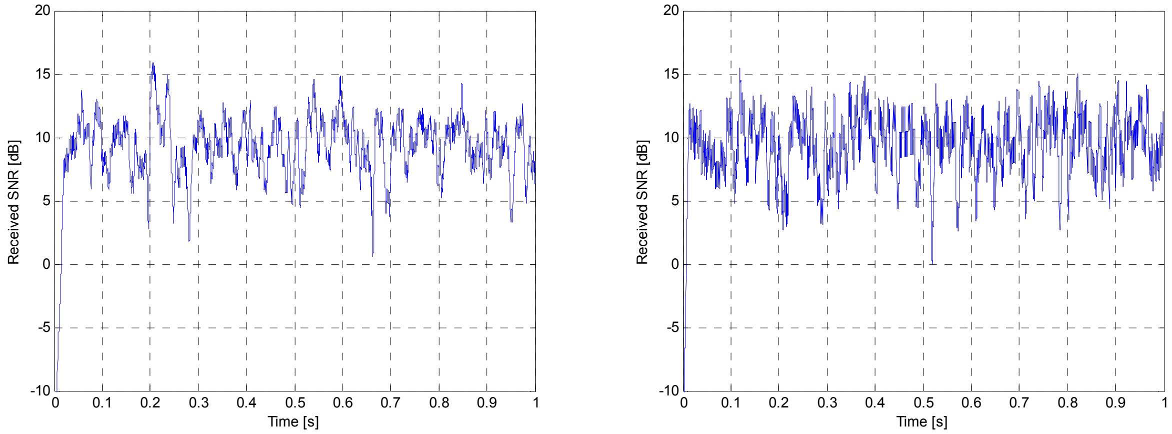
Figure 8-28. The received SNR with FxLMS power control.

During a deep fade in the channel the signal is a little bit weaker than it should be and after the fade the transmission power is too large for a while. When the results are compared to the results shown in Figure 8-26 and Figure 8-27, it can be seen that the system with FxLMS power control clearly outperforms the reference systems. The received SNR is held in the desired level with a better accuracy all the time. The value of standard deviation is 0.76 dB. Standard deviations for different SNRs are presented in Table 8-2. We can see that the accuracy of FxLMS power control is the best among the methods compared. Performance is only slightly deteriorated with an estimated channel where data aided least squares (LS) estimation is used.

TABLE 8-2. STANDARD DEVIATIONS OF DIFFERENT RECEIVED SNR VALUES (IN DECIBELS)

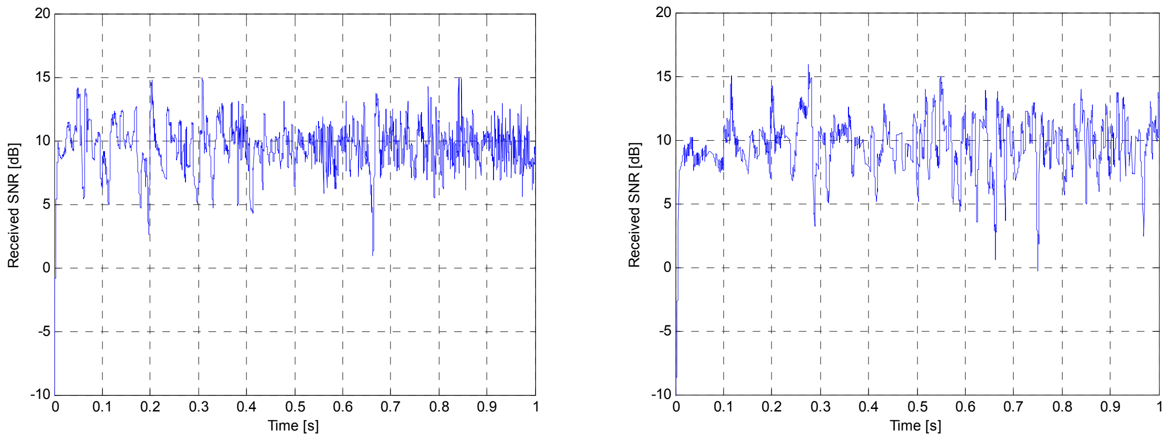
Average received SNR	**FSAPC (step size = 1 dB)**	**FSAPC (step size = 2 dB)**	**VSAPC**	**FxLMS, estimated channel**	**FxLMS, known channel**
5 dB	3.49	4.35	3.44	3.03	2.93
10 dB	2.02	2.29	1.95	1.92	1.90
15 dB	1.44	1.58	1.18	1.22	1.12
20 dB	1.24	1.37	0.78	0.76	0.68
25 dB	1.13	1.25	0.60	0.51	0.48
30 dB	1.11	1.22	0.51	0.39	0.37

When we compare the results received with average received SNR being 10 dB, the differences between methods are not so clear. Results presented in the Table 8-2 are achieved by averaging over many simulations. If we plot individual simulations, it is hard to see what the good methods are when noise power is increased. Simulation results are presented in Figure 8-29 and Figure 8-30. However, the FxLMS method works well with all SNR values.



a) 1 dB step b) 2 dB step

Figure 8-29. The received SNR with FSAPC power control



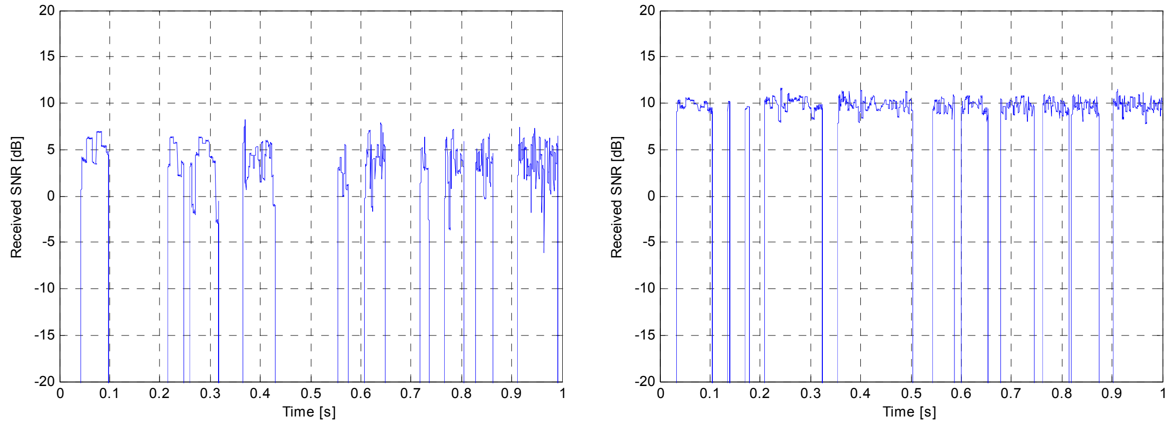
a) FxLMS b) VSAPC

Figure 8-30. The received SNR with FxLMS and VSAPC power control

The reason that makes the FSAPC control attractive in practical systems is that power control command is only one bit. Therefore the transmission rate of the feedback channel can be kept low. VSAPC and FxLMS algorithms need a higher bit rate in the feedback channel to achieve accurate control. But accuracy and fast control are required in many systems. Consequently, the methods with variable step size like the FxLMS power control are important to investigate. FxLMS algorithm performance was tested with quantized steps. With 3 bit quantization (8 possible step sizes) the algorithm is still better than fixed step adjustment power control (FSAPC). But VSAPC is slightly better than quantized FxLMS power control. When average received SNR is 20 dB the standard deviation is 0.78 dB for VSAPC and 0.80 dB for FxLMS.

8.3.2 Truncated power control

This section provides results for truncated FxLMS power control presented in Section 6.2 in a flat fading multipath channel that is modeled as shown in Section 4.2.3. Received SNR values with different average transmitted SNR values are presented in Figure 8-31.



a) average transmitted SNR = 10 dB b) average transmitted SNR = 20 dB

Figure 8-31. The received SNR with truncated FxLMS power control

When the average transmitted SNR was set to be 10 dB, the channel gain was more than a half time worse than the cutoff value. The probability of outage was 55%. When average transmitted SNR was set to 20 dB, the received SNR was 9.9 dB and the probability of outage reduced to 27%. What is interesting to note is that with full inversion FxLMS method approximately 27 dB average transmitted SNR was required to achieve 10 dB average received SNR. The difference to truncated scheme is approximately 7 dB. Thus, the truncated scheme is clearly much more energy efficient. However, to achieve the same average throughput, data rate during the transmission has to be higher and this reduces the actual SNR difference.

More detailed information is presented in Figure 8-32. The needed transmitted SNR to achieve received target SNR is clearly smaller with truncation. However, when the target SNR is increased, the lines get closer. When the difference is almost 9 dB with 6 dB target SNR, it is almost 3 dB smaller with 12 dB target. The reason for that is that more transmitted energy is allocated to deeper fades. This can be seen also from outage percentage. Probability of outage for three cases presented are 0.47/6 dB, 0.31/9 dB and 0.21/12 dB.

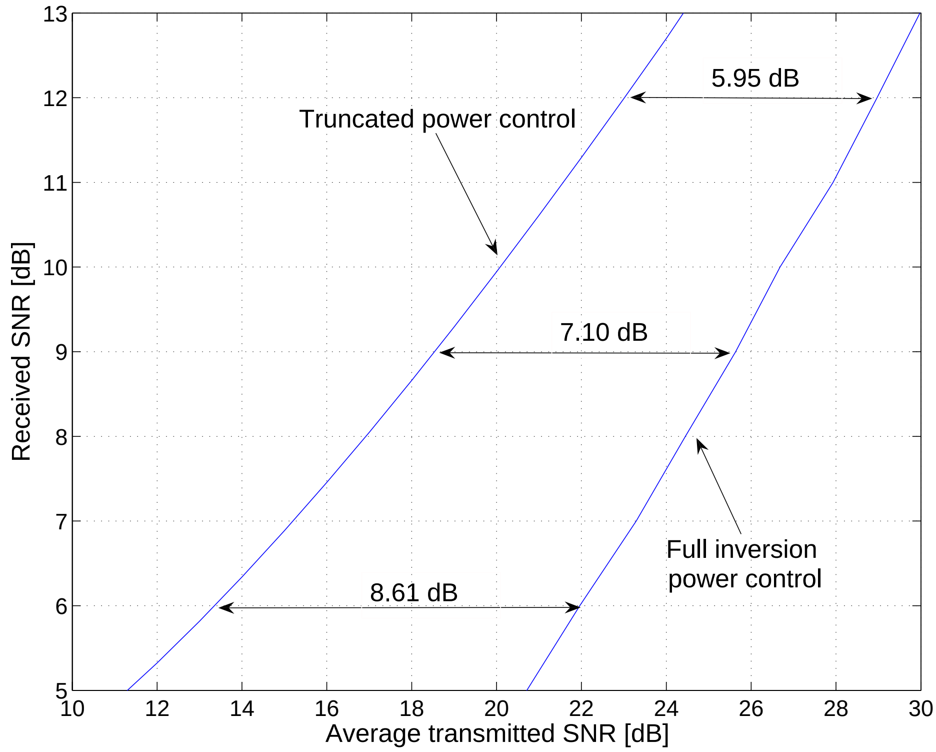


Figure 8-32. Transmitted SNR versus received SNR curves for truncated and full inversion power control.

To obtain results about interference range and more fair comparisons about transmitted SNR requirements that take data rate variation into account, we made link budget calculations. Noise power in 10 kHz band is $N = kTB = 1.38 \cdot 10^{-23} J / K \cdot 290\, K \cdot 1 \cdot 10^{4} = 4.002 \cdot 10^{-17}$ W. In decibels it is 10 lg(kTB) = -164 dBW. Based on (6-11) and outage information we can compute data rate requirements and actual SNR differences between full and truncated inversion methods. Results are shown in Table 8-3.

TABLE 8-3. DATA RATES AND ACTUAL SNR DIFFERENCES BETWEEN FULL INVERSION AND TRUNCATED SCHEME

Received target SNR	R_t	Noise floor level N, $B = R_t$	Actual SNR difference
6 dB	18.87 kbps	-161.22 dB	8.61-(164-161.22)=5.83 dB
9 dB	14.49 kbps	-162.37 dB	5.47 dB
12 dB	12.66 kbps	-162.95 dB	4.90 dB

Because of higher data rate, the noise floor changes and this reduces the actual SNR difference between truncated and full inversion power control schemes. However, it remains remarkable.

Interference range

To obtain numerical results about the interference range variations, we made some calculations with a simple model. Node 1 and node 2 lie at the distance of *d* from each other. We assume that signal propagates in line-of-sight (LOS) environment characterized by the two-slope path loss model described in Section 8.1.

When we assume noise figure of 5 dB and take into account that desired SNR in the receiver is 9 dB to achieve BER of 10^{-5} we obtain that receiver sensitivity is (-134 + 5 + 9) dBm = -120 dBm. In Rayleigh fading channel, the probability of fade depth to be less than F is simply $p = \exp(-1/F)$. Thus, for 99% coverage, fade margin of 20 dB is needed. The maximal needed transmitter power with the fading margin of 20 dB and shadowing margin of 10 dB which provides 90% successful communications at the fringe of coverage with 8 dB standard deviation is $P_{tx} = P_{rx,\ desired} + L_F$ = -150 dBW + 20 dB + 10 dB + 102.8 dB = -17.2 dBW = 19 mW.

Note that shadowing does not exceed the fade margin for 90% of locations at the maximal range (200 m from transmitter). When the receiver is nearer the value of the total path loss is less. Thus, clearly more than 90 percent of locations will have acceptable coverage. With truncation and with target SNR of 9 dB, the needed transmitted SNR is 5.47 dB smaller. We can calculate that maximal needed transmitter power is then only 5.4 mW. With 1 dB coexistence criterion and assuming that the required SNR for link we are interfering is 9 dB the interfering signal has to be 15 dB below the receiver sensitivity not to interfere. For example, with -85 dBm receiver sensitivity, the signal has to be below -100 dBm at this receiver.

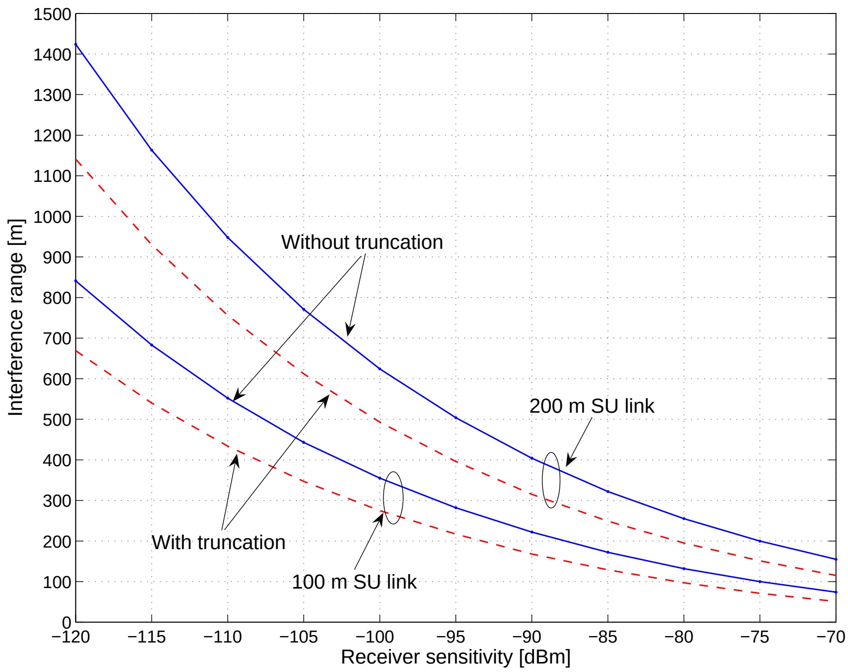


Figure 8-33. Interference range with different receiver sensitivities for 100 m and 200 m SU links.

To see the interference range in the highly improbable worst case situation, when 30 dB fading exists in SU link that uses maximum distance of 100 or 200 meters, and no fading at all exists between SU transmitter and PU receiver, we made calculations with different receiver sensitivities. We assumed that signal propagates according to (8-1). Results are shown in Figure 8-33. With 200 m link and sensitivity of -70 dBm, the range is 155 m with full inversion and 115 m with truncation. Thus, the interference area that is a circle with radius of interference range is reduced to the 55 % of the original. When sensitivity is -95 dB, ranges are 396 m and 504 m with interference area ratio of 61.7 %. If the system we are interfering with is equally sensitive cognitive radio system with -120 dBm sensitivity, the ranges are 1424 m and 1141 m with interference area ratio of 64.2 %. Thus, the gain of using truncated power control scheme is that interference area is reduced almost to the half from original. If path loss exponents would be smaller, the difference would be even larger. With 100 m SU link, 12.88 dB less power is needed and consequently the interference ranges are smaller as can be seen in Figure 8-33. The interference area ratios with shorter link are even better because the attenuation mainly happens before the break point in the path loss curve. Thus, truncation improves the performance of low power transmitter even more. In addition to the interference reduction to the primary users, truncation improves the spectrum efficiency by allowing more secondary users to access the spectrum at the same time.

Capacity. How much better capacity can we achieve with same energy consumption? Since the difference in transmitted SNR is 7.10 dB when BER target is 10^{-5}, we can raise the data rate with truncated scheme so that noise power becomes 7.10 dB higher. This happens with 51 kHz band which corresponds to (51 kbps · (1-0.31)) = 35.2 kbps average data rate. Thus, compared to full inversion scheme, we can achieve 3.5 times the throughput with the same energy consumption. If we are not allowed to raise our bandwidth, one option is to change the modulation to more efficient one. QPSK offers same BER performance than BPSK. If 16-QAM is selected, 3 dB larger SNR is needed to achieve same BER with double throughput. This is less than the difference achieved with truncation. To achieve same throughput with full inversion, data rate during transmission should be 1.449 times higher. By changing the modulation we can double the data rate and still get clearly smaller interference range.

Coexistence scenario

Assuming 1 Mbps QPSK transmission in 500 kHz band, 5 dB N_F and 9 dB SNR to achieve required BER, the sensitivity of the receiver is S = -103 dBm. With 200 m link and 30 dB fading, transmitter power should be 29.8 dBm. If PU sensitivity is a realistic -90 dBm, interference ranges are approximately 845 m/670 m for full inversion/truncation. With 100 m link, transmission power should be 17 dBm and interference ranges are 490 m/383 m. Assuming PU link to be 200 m, spectrum sensor should sense signals 200 m farther than interference ranges mentioned above. With 30 dB fading, attenuations for cases mentioned are 170.2 dB/165.7 dB for 200 m link and 160.2 dB/157.0 dB for 100 m link.

When PU transmitter uses 40 dBm transmitted power, sensitivity of spectrum sensor should be -130.2 dBm/-125.7 dBm for 200 m link and -120.2 dBm/-117.0 dBm for 100 m link. Can we detect any of these signals when the noise floor is -117 dBm? Uncertainties in the noise and interference levels and the coherence time induce limits on how weak signals individual sensors can detect [Tandra 2005], [Tandra 2007]. The minimum power level is called SNR wall and cannot be overcome by increasing the sensing time. SNR wall with 1 dB noise uncertainty for energy detector is 3 dB below noise floor and can be further reduced by 20 dB by using feature detection. So the achievable sensing values are -120 dBm and -140 dBm for 500 kHz band. Only 100 m link with truncation can be used with energy detectors. All scenarios are achievable with feature detection. Assuming 10 dB gain for cooperative detection, also 200 m link with truncation can be used with simple energy detectors. Because the signal levels for detection with truncation are higher, faster sensing times and more efficient spectrum utilization can be achieved.

These calculations show that we can use highly sensitive cognitive radio system with relatively long transmission links inside the primary system even under worst case conditions. Interference can be controlled with transmitter power control together with reliable spectrum awareness method. However, if much higher data rate is needed, multi-carrier transmission over multiple spectral holes could be used. The other option is to cope multipath fading with diversity and use power control to mitigate the effects of path loss and shadowing. This would allow even better spectrum sharing and interference range reduction. Truncation offers much better energy efficiency also in shadowing channel [Kim 2000].

8.3.3 Frequency management

EWMA prediction. Frequency management approach described in Section 6.1 is based on the prediction methods from Section 5.8. The efficiency of the approach depends on the reliability of prediction. EWMA method (Equation 5-32) has been shown to be very good choice for prediction purposes in business and economic time series [Makridakis 2000]. Major conclusion based on huge amount of tests, over 20 prediction methods compared with 3003 different real world data sets, is that sophisticated or complex statistical prediction methods doesn't provide more accurate forecasts than simpler ones. In CR environment, it is shown to be useful in TV transmission prediction [Acharya 2006]. We have investigated the usability of EWMA with a couple of examples. If the OFF period is fixed, EWMA works perfectly but with more random traffic, there are problems. We have measured ON and OFF periods of IEEE 802.11 traffic to find out if we can use EWMA prediction to foresee the future values.

The 802.11 traffic was measured from one channel, where over 27000 samples of idle and busy times were measured and analyzed. Mean idle time was 0.0056 s, and the values were between [2.07*10^-7, 0.0976] s. Most idle times were very short. Idle time distribution can be seen in Figure 8-34.

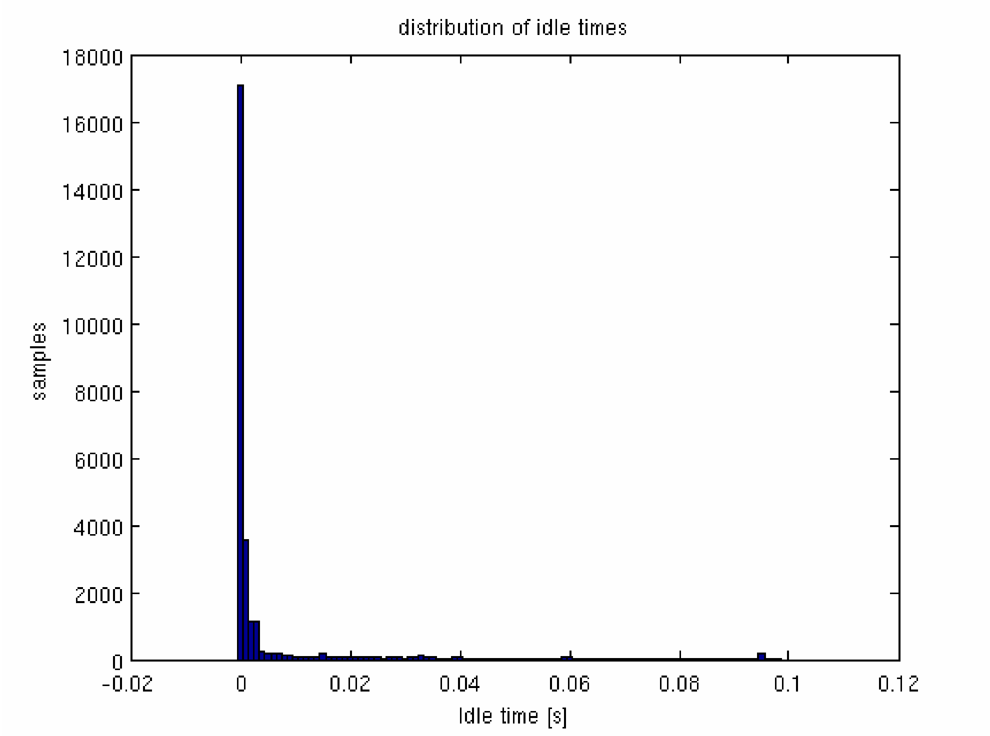


Figure 8-34. Idle time distribution of 802.11 traffic

EWMA method was tested with different α values to see if we can predict next idle times based on the history. Large α means that recent values are heavily weighted, while a small value indicates that past values affect more. Faster response is achieved with larger α. The results from the EWMA traffic prediction studies are shown in Figure 8-35.

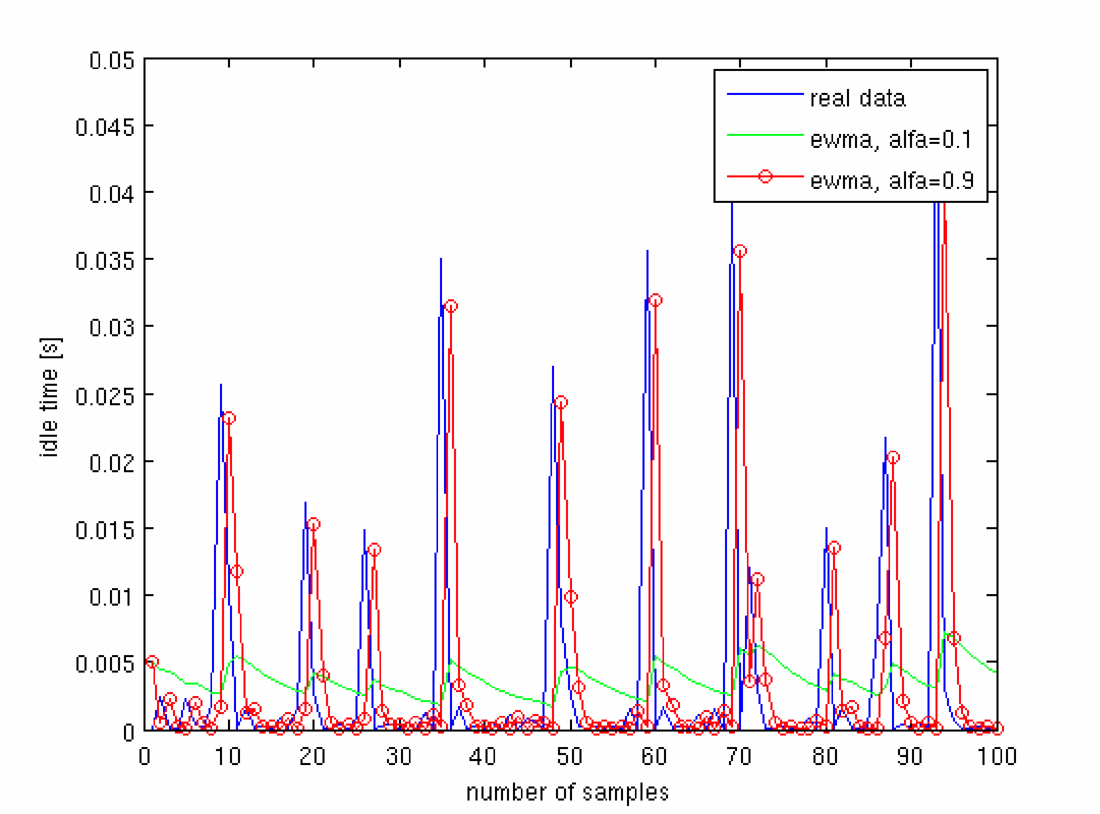


Figure 8-35. EWMA prediction of idle times.

Prediction was made over 27000 samples and accuracy was measured with mean squared prediction error (MSPE)

$$MSPE = E\left[\sum_{i=1}^{n}(I_i - \hat{I}_i)^2\right], \tag{8-9}$$

where I_i is the real idle time and $\hat{I}_i$ the predicted idle time. Based on the Figure 8-35, one could think that larger α is better because of better tracking ability. However, as can be seen from Table 8-4, small values of α give the best performance. Actually the best “prediction” was achieved with real average over all values (MSPE = 2.37*10^-4).

TABLE 8-4. MEAN SQUARED PREDICTION ERRORS WITH DIFFERENT VALUES OF α

α value	0.1	0.3	0.5	0.7	0.9	1.0
MSPE *10^-4	2.48	2.92	3.40	3.93	4.58	5.00

Based on the test made with real IEEE 802.11 traffic, only probabilistic values are important with random traffic, i.e., distributions and mean values of idle times. In addition, availability times should rather be longer than in millisecond scale to be reasonable for CR operation. In reality, we don’t know exact lengths of idle times as we are sensing every X seconds for Y seconds to get reliable results which limits our ability to measure and detect short times. In addition, according to

[Merritt 2005], every channel switch takes several milliseconds with today's equipment. Thus, CR should concentrate on channels that offer longer idle times.

Multi-channel prediction and dynamic frequency management. In order to see how well proposed intelligent channel selection approach presented in Section 6.1 works when compared to random opportunistic channel selection we made experiments with periodical and stochastic traffic patterns. Simulation parameters for experiment were as shown in Table 8-5.

TABLE 8-5. SIMULATION PARAMETERS

Parameter	**Value**
Transmission period	90 ms
Sensing period	10 ms
Switching delay	10 ms
Number of channels	8
Primary user traffic models	Stochastic channels with exponentially distributed ON and OFF times Periodic channels with fixed ON and OFF periods
Utilization, mean idle times, and period lengths of primary traffic	Almost uniformly distributed utilization [0.1, 0.9], mean idle times between [1s, 14s], period lengths [2s, 20s]
Simulation time	10 000 s
Channel selection methods	Intelligent channel selection I, random selection

We examined the number of switches over simulation time when either random or intelligent channel selection method was used. For simplicity, the classification was assumed to work perfectly. Intelligent selection procedure then took the exact traffic type into account. From the results shown in Table 8-6, we can see that learning always improves the efficiency of the system. When stochastic traffic with exponentially distributed idle and busy times was used, the number of switches with intelligent method was 17% smaller than with random selection. With periodic traffic the difference was 43%. When both periodic channels and stochastic channels were used, improvement was around 20%.

TABLE 8-6. NUMBER OF SWITCHES WITH DIFFERENT SELECTION METHODS AND TRAFFICS

Method	**Primary traffic**	**Switches**
Random	Stochastic, mean idle [1s, 10s]	2153
Intelligent	Same	1796
Random	Periodic	2112
Intelligent	Same	1215
Random	Combined, 4 stochastic, 4 periodic channels	1431
Intelligent	Same	1157

We investigated also utilization based selection. Next channel to be selected was the one with lowest utilization. Quite interestingly, random channel selection worked more efficiently in case of stochastic traffic. In case of periodic traffic, result was vice versa. The main reason for this is that utilization alone doesn't tell us enough about spectrum availability. It is important to check the distribution of idle times and look at the expected *remaining idle period*.

We tested the classification method with stochastic and periodic traffic with parameter values mentioned in Table 8-5. Stochastic pattern was always classified right. With the periodic traffic where the amount of possible ON times was limited as is the case of packet-based network, the classification made right decision in 80 % of tests.

We made simulations with different channel selection methods to see how the number of channels affects the performance. The number of channels varied from 5–20. Both exponential and periodic traffic patterns were examined. Since the search of the median time for stochastic traffic can be time-consuming, we tried also a method were the expected time is the mean idle time of the channel. Results for exponential traffic are shown in Figure 8-36.

With 5 channels the methods are almost equally good since there are not many channels to choose from. When the amount of primary channels is increased, the difference between intelligent and random selection increases. The intelligent method can concentrate on the best channels. Quite interestingly, the mean idle time based selection outperformed slightly the median based selection in every case. Reason for this is the fact that median time is smaller than mean time in exponential traffic and the subtraction of T_{CONS} affects more to the median based selection. This means more conservative approach and probable abandoning of good channels. The result is good since it shows significant gains for relatively simple prediction method. The gain in channel switches ranges from 6% with 5 channels to 39% with 20 channels while the average number of available channels increases approximately linearly as [2.2 4.7 7.4 9.4]. The mean average idle times for channels were [3.5 3.2 3.5 3.6] s. Random selection follows approximately the average idle time distribution with more switches with lower average idle times whereas the intelligent method takes advantage of the increasing number of good channels.

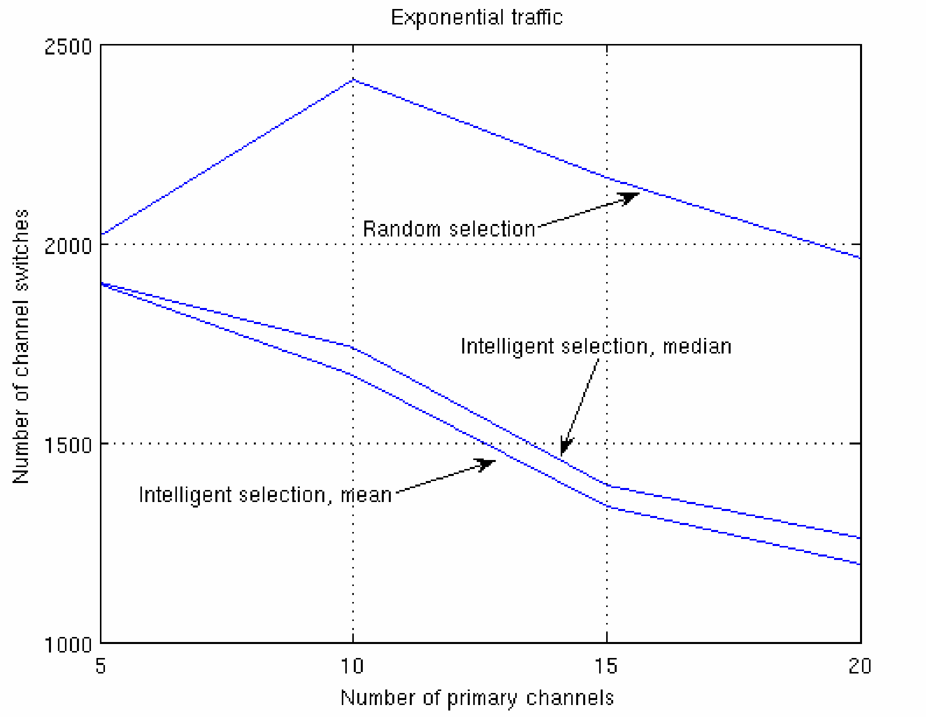


Figure 8-36. Amount of channel switches with stochastic traffic.

The performance with periodic traffic patterns is shown in Figure 8-37. The intelligent selection method can predict the idle times almost perfectly and can select the best channels very well. The gain compared to the random method is large all the time. With 15 and 20 channels, the amount of switches with intelligent selection is 55% lower than with random selection. The average mean idle times for channels are now [7.0 6.1 6.6 6.5] s. Again, the performance of random selection depends on the average values of channels whereas the intelligent selection method concentrates to good channels and can take advantage of an increasing number of them.

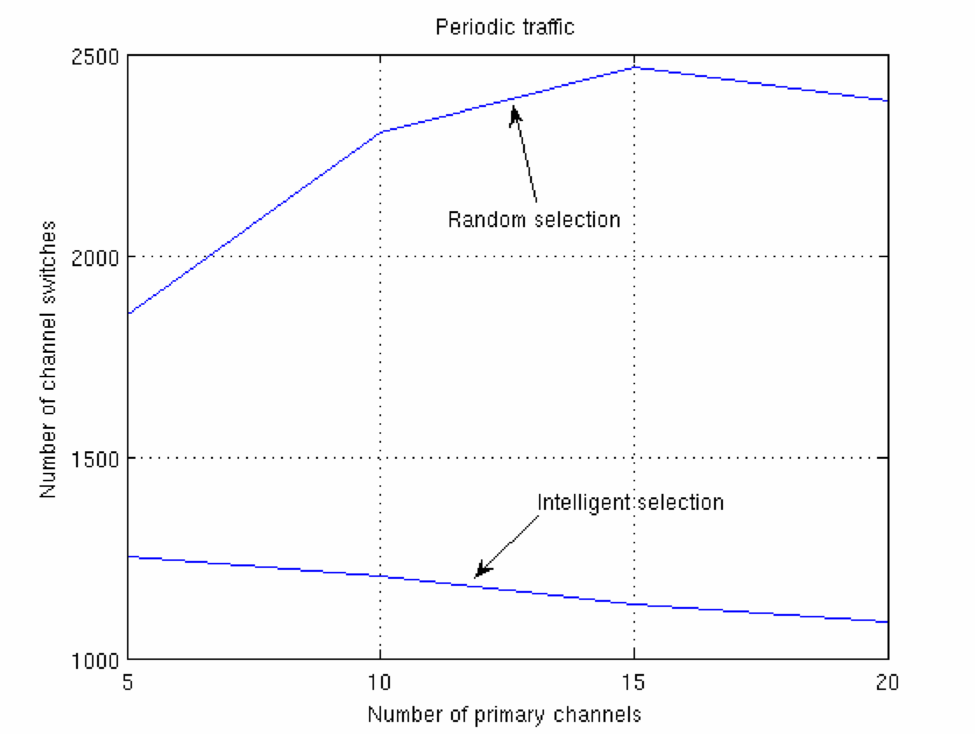


Figure 8-37. Amount of channel switches with periodic traffic.

A reactive CR switches to different channel after a PU is sensed to appear in the same channel. To reduce the interference with PUs, a CR could switch proactively to a new channel before the PU appears in the current band. It can change the channel when the predicted T_j is over, and it does not wait until the PU appears. Especially with deterministic traffic this proactive method is preferred.

In some cases the prediction of busy times in addition to idle times could make sense. Depending on the application used and its QoS requirements, this allows estimating if we could stay and wait for the channel to become idle instead of frequency hopping. Multi-hop ad hoc networks are possible target systems for this kind of operation. In multi-hop networks, every frequency change causes a need for an update of the routing table. If this happens very frequently, a large amount of energy and bandwidth resources are consumed to keep those tables up-to-date and as a result, the capacity of the system decreases.

8.3.4 Conclusions for power and frequency management

Cognitive radio should minimize interference it creates to licensed users. This can be done by using minimum amount of transmitter power. In an active cognitive radio system, spectrum sensing sensitivity together with worst case link budgeting tells how much transmission power is allowed to use in order to avoid interfering with primary receivers. In a cognitive radio network using active awareness principles, delays cannot be avoided because of periodical sensing. Such a network is not good for real-time communication. Thus, power control method does not need to assure delayless communication.

A large part of the transmission power in continuous inverse control solutions is used to compensate the deepest fades in a fading channel. Truncation in power control reduces the energy consumption and transmission power. Thus, interference to primary users is reduced and more secondary users are allowed to share the spectrum. Both energy and spectrum efficiency are improved. In addition, sensing requirements can be relaxed because of shorter interference range. This means faster sensing times and better spectrum utilization. Drawback is that no data are transmitted below threshold which causes random delays to transmission. However, we can achieve much better average throughput with same interference range when compared to conventional full inversion scheme.

Truncation is a good choice for transmission in a CR system. When channel becomes bad enough, the secondary transmitter should stop transmitting and continue again when situation is better. Another option is to change frequency. Further work is still needed to investigate how the multipath fading affects the operation of a cognitive radio and what are the best methods to mitigate these effects. For example, an interesting research topic could be to investigate the effects of diversity and beamforming to the transmitter power needs and to the interference range. Intuitively, the combination of directional antennas, good diversity method and truncated power control method could offer very efficient spectrum sharing solution. However, the total energy consumption in transmitter and receiver side should be taken into account. In addition, experiments with multiple secondary users causing aggregate interference could be done.

Intelligent channel selection helps to select the best channels for control and data transmission. Even with totally random exponential traffic patterns the amount of switches reduces clearly when using intelligence which improves the efficiency of the spectrum use. Cognitive radios should have learning abilities to be able to intelligently select channels for secondary use in a way that minimizes delays and maximizes throughput.

However, more work is needed in this area. Interesting things to look at are the use of intelligent selection models with a wide variety of primary traffic patterns and the reliability of the classification method. Also we can test the approach with real measured network traffic. We should also investigate the effect of proactive channel selection on the amount of switches, delays and throughput. In addition, the case with multiple secondary users sharing the spectrum would be interesting to look at since a channel may now become busy also by CR activity. These things will be investigated in future.

9 Conclusions

This report provides an up-to-date summary of cognitive radio research. The concept of cognitive radio is a promising technique to efficiently use the frequency spectrum. The introduction of cognition into telecommunication in the form of cognitive radios with the emphasis on learning opens up the more general notation of *cognitive dynamic systems* that can also be applied to other disciplines. In the future the principles of cognitive radio will be extended to cover other resources available in the network, leading to the emergence of a more generic type of approach, namely cognitive networks.

The future systems will be intelligent in terms of spectrum utilization but the legacy systems cannot be changed. Therefore, the introduction of cognitive radio capabilities in the future wireless networks should have no impact on the existing networks. There is a constant need for radio regulation, especially as the operation environment is changing toward cognition, but the forms of regulation and the spectrum access mechanisms may be different in the future. The next WRC-11 will consider the introduction of SDR and cognitive radio systems into the international regulatory framework of ITU-R and therefore the research efforts on cognitive radios assisting the preparatory work toward WRC-11 are important and urgent.

Spectrum sensing is a crucial task in the cognitive radio system to identify vacant frequency bands to enable opportunistic spectrum access. In particular, reliable detection of the presence of primary users is of uttermost importance since the cognitive radio operating as a secondary system is not allowed to cause harmful interference to the primary user. Thus, the performance evaluation of spectrum sensing schemes is important. We have evaluated the performance of Welch's periodogram method in terms of the probabilities of detection and false alarm using analysis and simulations. Since the different spectrum sensing schemes are associated with different advantages and limitations, a combined detector that consists of an energy detector for coarse sensing of spectrum and a feature detector for more detailed sensing of selected frequency bands could be a useful solution. We have also considered a cooperative model for cognitive radios to improve the performance of spectrum sensing by using the sensing information obtained from several nodes. Due to the limited awareness of a single cognitive radio node, cooperative sensing will be important in practical cognitive systems. This would lead to a trade-off between reliable sensing information and the costs caused by more extensive cooperation - such as complexity and increased signaling.

Selection of transmission frequencies using learning from the past is a promising area for applying the cognitive radio's learning capabilities, which is a relatively unexplored area. Prediction of future available times of different channels based on history information of the channel use help the cognitive radio to select the best channels for control and data transmission. Learning based intelligent channel selection using knowledge of the past channel usage is useful in the selection the best channels for control and data transmission leading to performance improvements. A cognitive radio can learn the patterns in different channels over time. However, this is possible only in certain types of channel usage as, in general, it is impossible to predict the future behavior of other users. The situation becomes even more complicated in the presence of several cognitive radios or systems that try to access the same spectrum.

Power control is an important part of the cognitive radio system as the cognitive radio system is not allowed to cause harmful interference to licensed users. Therefore, minimum amount of transmitter power should be used. Truncated power control where the transmission is stopped during bad channel realizations is a good candidate for transmission in a CR system in order to minimize the interference to other users. We have studied inverse power control that allocates lower transmission power levels to good channel realizations and higher power levels to deeper fading, aiming at minimizing the interference and allowing more secondary users to share the spectrum. Alternative approaches such as waterfilling using higher transmission powers in better channel realizations would also be interesting to study in the cognitive radio context where opportunistic use exploiting the available resources is in the focus.

The cognitive radio approaches have also some limitations. In particular, the key question in the evolution of cognitive radios into future cognitive networks is how to arrange control signaling between neighboring nodes in a rapid, robust and efficient way. Rapidity is a consequence of the limited time period when the spectrum holes are vacant. Robustness is due to the requirements of real life environment where reliable communication is needed. Efficiency aims at minimizing the use of resources such as energy and computations. The following questions will be relevant for future studies on cognitive radios and cognitive radio networks:

- How to acquire reliable information on the current spectrum use in the surrounding wireless ecosystem?
- Do we need to define new cognitive radio-specific figures to assess performance in such wireless networks?
- How to create and maintain the control and signaling structure?
- What are the most suitable architectures for a cognitive radio system?
- How to arrange cognitive radio network system?
- How to design of a low-rate feedback channel that is distributed across the cognitive radio network?
- What is the bandwidth required for signaling versus the obtained benefit in spectrum use?
- How to vacate the radio resources in existing systems so that cognitive radio type of communication can be achieved between users?
- How to development of predictive models to address the duration of spectrum holes?
- How to deal with exploitation and malicious behaviour in cognitive radio networks?
- How cognitive radio will evolve into cognitive networks?

10 References

[Acharya 2006] P. A. K. Acharya, S. Singh, and H. Zheng, "Reliable open spectrum communications through proactive spectrum access," in *Proc. of TAPAS*, August 2006.

[Adapt4] Adapt 4. http://www.adapt4.com/adapt4-products.php

[Agarwal 2004] A. Agarwal and P. R. Kumar, "Capacity bounds for ad hoc and hybrid wireless networks," *ACM SIGCOMM Computer Communications Review*, Vol. 34, pp. 71–82, July 2004.

[Ahlswede 2000] R. Ahlswede et al., "Network information flow," IEEE Transactions on Information Theory, vol. 46, pp. 1204-1216, July 2000.

[Akyildiz 2005] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Elsevier Computer Networks*, vol. 47, pp. 445–487, March 2005.

[Akyildiz 2006] I. F. Akyildiz *et al.*, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Elsevier Computer Networks*, vol. 50, pp. 2127-2159, September 2006.

[Alasalmi 2002] J. Alasalmi, "Area Spectral Efficiency of Cellular Mobile Radio Systems," Technical report, VTT Electronics, 43 pp, 2002.

[Alizadeh-Shabdiz 2006] F. Alizadeh-Shabdiz and S. Subramaniam, "Analytical models for single-hop and multi-hop ad hoc networks," *Mobile Networks and Applications*, Vol. 11, pp. 75–90, February 2006.

[Alouini 1999] M.-S. Alouini and A. J. Goldsmith, "Area spectral efficiency of cellular mobile radio systems," *IEEE Transactions on Vehicular Technology*, vol. 48, pp. 1047–1066, July 1999.

[Anderson 1979] B. D. O. Anderson and J. B. Moore, "Optimal Filtering," Prentice Hall, Englewood Cliffs, New Jersey, 357 pp, 1979.

[ATIS] ATIS, Alliance for Telecommunications Industry solutions, Telecom glossary. [Online]. http://www.atis.org/tg2k/

[Ball 2005] S. Ball *et al.*, "Consumer applications of cognitive radio defined networks," in *Proceedings of DySPAN 2005*, pp. 518–525, November 2005.

[Bambos 1998] N. Bambos, "Toward power-sensitive network architectures in wireless communications: Concepts, issues, and design aspects," *IEEE Personal Communications*, Vol. 5, pp. 50–59, June 1998.

[Bellman 1957] R. Bellman, "Dynamic Programming", Princeton University Press, Princeton, NJ, 1957.

[Benko 2006] J. Benko, "A PHY/MAC Proposal for IEEE 802.22 WRAN Systems, Part 1: The PHY," IEEE 802.22-06/0004r1, Feb. 2006.

[Berggren 2004] F. Berggren *et al.*, "Dynamic spectrum access–Phase 1: Scenarios and research challenges; *TRITA-S3-RST-0407*," Technical report, September 2004. [Online]. Available: http://www.wireless.kth.se/projects/DSA/DSA_report_phase1.pdf

[Berry 2004] R. A. Berry and E. M. Yeh, "Cross-layer wireless resource allocation," *IEEE Signal Processing Magazine*, vol. 21, pp. 59–68, September 2004.

[Bingham 1990] J. A. C. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Communications Magazine*, vol. 28, pp. 5–14, May 1990.

[Blaunstein 2002] N. Blaunstein and J.B. Andersen, *Multipath Phenomena in Cellular Networks*. Boston, Artech House. 296 pp, 2002.

[Bock 2001] P. Bock, *Getting It Right: R&D Methods for Science and Engineering*, Academic Press, 2001.

[Brodersen 2004] R. W. Brodersen *et al.*, "CORVUS: A cognitive radio approach for usage of virtual unlicensed spectrum," *White paper,* July 2004. [Online]. Available: http://bwrc.eecs.berkeley.edu/Research/MCMA/CR_White_paper_final1.pdf

[Brown 2005] T. X. Brown, "An analysis of unlicensed device operation in licensed broadcast service bands," in *Proceedings of DySPAN 2005*, pp. 11–29, November 2005.

[Buddhikot 2005] M. M. Buddhikot *et al.*, "DIMSUMNet: New Directions in Wireless Networking Using Coordinated Dynamic Spectrum Access," in *Proceedings of WoWMoM 2005*, pp. 78–85, June 2005.

[Bölcskein 2001] H. Bölcskei et al., "Fixed broadband wireless access: State of the art, challenges, and future directions," IEEE Communications Magazine, pp. 100-108, Jan. 2001.

[Čabrić 2004] D. Čabrić, S. M. Mishra, and R. W. Brodersen, " Implementation issues in spectrum sensing for cognitive radios," in *Proceedings of Asilomar Conference 2004*, pp. 772–776, November 2004.

[Čabrić 2005] D. Čabrić and R. W. Brodersen, "Physical layer design issues unique to cognitive radio systems," in *Proceedings of PIMRC 2005*, September 2005.

[Čabrić 2006a] D. Čabrić *et al.*, "Spectrum sharing radios," *IEEE Circuits and Systems Magazine*, vol.6, pp. 30–45, 2006.

[Čabrić 2006b] D. Čabrić, A. Tkachenko and R.W. Brodersen "Experimental study of spectrum sensing based on energy detection and network cooperation", in *First International Workshop on Technology and Policy for Accessing Spectrum*, August 2006.

[Čabrić 2007] D. Čabrić and R. W. Brodersen, "Robust Spectrum Sensing Techniques for Cognitive Radio Networks," in *Towards Cognitive and Cooperative Wireless Networking:*

Techniques, Methodologies and Prospects edited by F. Fitzek and M. Katz, pp. 373-394, Springer, 2007.

[Centi 2004] J. Centi, “Wireless mesh: the evolution of wireless network,” *Bechtel Telecommunications Technical Journal*, vol. 2, pp. 53–63, January 2004.

[Chakravarthy 2005] V. Chakravarthy *et al*., “TDCS, OFDM and MC-CDMA: A brief tutorial,” *IEEE Radio Communications*, vol. 43, pp. S11–S16, September 2005.

[Chang 2006] S.-Y. Chang, “Analysis of proposed sensing schemes for IEEE802.22 WRAN,” IEEE 802.22-06/0032r1 document, March 2006.

[Chaudet 2005] C. Chaudet *et al*., “Performance issues with IEEE 802.11 in ad hoc networking,” *IEEE Communications Magazine*, vol. 43, pp. 110–116, July 2005.

[Claasen 1985] T. A. C. M. Claasen and W. F. G. Mecklenbräuker, “Adaptive techniques for signal processing in communications,” *IEEE Communications Magazine*, vol. 23, pp. 8–19, Nov. 1985.

[Clancy 2006] T. C. Clancy, *Dynamic spectrum access in cognitive radio networks*, Ph. D. dissertation, University of Maryland, 2006.

[Clancy 2007] C. Clancy, J. Hecker, E. Stuntebeck & T. O’Shea, “Applications of machine learning to cognitive radio networks”, *IEEE Wireless Communications*, August 2007.

[Columbia Encyclopedia 2001] The Columbia Encyclopedia, 6th ed. New York: Columbia University Press, 2001–04. www.bartleby.com/65/.

[Cordeiro 2007] C. Cordeiro and K. Challapali, “C-MAC: A cognitive MAC protocol for multi-channel wireless networks,” in *Proc. of CrownCom conference*, August 2007.

[Costa 1983] M. Costa, “Writing on dirty paper,” *IEEE Transactions on Information Theory*, vol. 29, pp. 439-441, May 1983.

[Coulson 1998] A. J. Coulson *et al.*, “A statistical basis for lognormal shadowing effects in multipath fading channels,” *IEEE Transactions on Communications*, vol. 46, pp. 494–502, April 1998.

[Cover 1975] T. Cover, “An achievable rate region for the broadcast channel,” *IEEE Transactions on Information Theory*, vol. 21, pp. 399 – 404, July 1975

[Cover 2006] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, John Wiley & Sons, 2006.

[Czylwik 1996] A. Czylwik, “Adaptive OFDM for wideband radio channels,” in *Proc. of IEEE GLOBECOM 1996*, pp. 713–718, November 1996.

[DARPA XG] DARPA XG, “DARPA neXt Generation (XG) Program,” [Online]. http://www.darpa.mil/ato/programs/XG/index.htm.

[Devroye 2006] N. Devroye, P. Mitran, and V. Tarokh, “Limits on communications in a cognitive radio channel,” *IEEE Communications Magazine*, vol. 44, pp. 44–49, June 2006.

[Di Benedetto 2006] M.-G. Di Benedetto, G. Giancola, and M. D. Di Benedetto, “Introducing consciousness in UWB networks by hybrid modelling of admission control,” *Springer Journal on Mobile Networks and Applications*, vol. 11, pp. 521-534, August 2006.

[Dictionary] The Free Dictionary by Farlex. http://www.thefreedictionary.com/transport+capacity

[Digham 2003] F. F. Digham, M.-S. Alouini and M. K. Simon, “On the energy detection of unknown signals over fading channels,” in Proc. of IEEE International Conference on Communications (ICC’03), pp. 3575-3579, May. 2003.

[Erez 2005] U. Erez and S. ten Brink, “A close-to-capacity dirty paper coding scheme,” *IEEE Transactions on Information Theory*, vol. 51, pp. 3417-3432, Oct. 2005.

[Eshghi 2005] K. Eshghi *et al.*, “Performance evaluation of multihop ad hoc WLANs,” *IEEE Communications Magazine*, vol. 43, pp. 107–115, March 2005.

[ETSI 1998] ETSI: Universal Mobile Telecommunication System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS (UMTS 30.03 version 3.20), April 1998.

[ETSI 2001] ETSI: Digital cellular telecommunications system (Phase 2+) (GSM); General Packet Radio Service (GPRS); Service description; Stage 2, 3GPP TS 03.60 version 7.5.0, Release 1998, January 2001.

[FCC 2002a] FCC Spectrum Policy Task Force (SPTF), “Report of the Spectrum Efficiency Working Group,” November 2002.

[FCC 2002b] FCC Spectrum Policy Task Force (SPTF), *FCC Spectrum Policy Task Force report*, ET Docket No. 02-135, November 2002.

[FCC 2003a] FCC (Federal Communications Commission), “Notice of proposed rulemaking and order,” Report ET Docket no. 03-322, December 2003.

[FCC 2003b] FCC (Federal Communications Commission), “Notice of inquiry and proposed rulemaking,” ET Docket no. 03-289, November 2003.

[FCC 2004] FCC, “Notice of Proposed Rule Making in the matter of Unlicensed operation in the TV broadcast bands,” ET Docket no. 04-186, FCC 04-113, May 2004.

[FCC 2005] FCC, “Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies,” ET Docket no. 03-108, March 2005.

[FCC DB] FCC, Frequency Assignment Data Bases: “Spectrum inventory table 137 MHz to 100 GHz”. http://www.fcc.gov/oet/info/database/spectrum/

[Fehske 2005] A. Fehske, J. Gaeddert and J. H. Reed, “A new approach to signal classification using spectral correlation and neural networks”, in *Proceedings DySPAN 2005*, pp. 144-150, November 2005.

[FICORA 2007] “Radiotaajuuksien kysyntä tulevaisuudessa”. Finnish Communication Regulatory Authority, report in Finnish, 2007.

[Fischer 1996] R. F. Fischer and J. B. Huber, “A new loading algorithm for discrete multitone transmission,” in *Proc. of GLOBECOM 1996*, pp. 724–728, November 1996.

[Fuemmeler 2004] J. A. Fuemmeler, N. H.Vaidya, and V. V. Veeravalli, “Selecting transmit powers and carrier sense thresholds for CSMA protocols,” University of Illinois at Urbana-Champaign, *Technical Report*, October 2004.

[Fujii 2005] T. Fujii and Y. Suzuki, “Ad-hoc cognitive radio –Development to frequency sharing systems by using multi-hop network,” in *Proceedings of DySPAN 2005*, pp. 589–592, November 2005.

[Fundenberg 1998] D. Fundenberg and D. K. Levine “The theory of learning in games,” MIT Press, Cambridge, 276 p, 1998.

[Gardner 1988] W. A. Gardner, “Signal interception: A unifying theoretical framework for feature detection,” *IEEE Transactions on Communications*, vol. 36, pp. 897–906, August 1988.

[Gardner 1992] W. A. Gardner and C. M. Spooner, “Signal interception: Performance advantages of cyclic-feature detectors,” *IEEE Transactions on Communications*, vol. 40, pp. 149–159, January 1992.

[Germain 2006] F. Germain, M. Ghozzi, J-P. Laval, O. Lobry, T. Jarboui and F. Marx, “The Cognichip: a flexible, lightweight spectrum monitor,” Cognitive Systems with Interactive Sensors 2006, COGIS 2006, Paris, France, March 15 - 17, 2006.

[Ghasemi 2005] A. Ghasemi and E. S. Sousa, “Collaborative spectrum sensing for opportunistic access in fading environments,” in *Proceedings of DySPAN 2005*, pp. 131–136. November 2005.

[Gilhousen 1990] K. S. Gilhousen *et al.*, ”Increased capacity using CDMA for mobile satellite communication,” *IEEE Journal on Selected Areas in Communications*, vol. 8, pp. 503–514, May 1990.

[Glossglauser 2002] M. Grossglauser and David N.C. Tse, “Mobility increases the capacity of ad hoc wireless networks,” *IEEE/ACM Transactions on networking*, vol. 10, no. 4, 477-486 August 2002

[Goldsmith 1997] A. J. Goldsmith and S.-G. Chua, “Variable-rate variable-power MQAM for fading channels,” *IEEE Transactions on Communications*, vol. 45, pp. 1218–1230, October 1997.

[Goldsmith 2002] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *IEEE Wireless Communications*, vol. 9, pp. 8–27, August 2002.

[Goldsmith 2005] A. J. Goldsmith, *Wireless communications*, Cambridge University Press, 2005.

[Goubran 1991] R. A. Goubran, H. M. Hafez, and A. U. H. Sheikh, "Implementation of a real-time mobile channel simulator using a DSP chip," *IEEE Transaction on Instrumentation and Measurement*, vol. 40, pp. 709–714, August 1991.

[Grossglauser 2002] M. Grossglauser and David N.C. Tse, "Mobility increases the capacity of ad hoc wireless networks," *IEEE/ACM Transactions on networking*, vol. 10, no. 4, 477-486 August 2002

[Gudmundson 1991] M. Gudmundson, "Correlation model for shadow fading in mobile radio systems," *Electronic Letters*, vol. 27, pp. 2145–2146, Nov. 1991.

[Gupta 2000] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on information Theory*, vol. 46, pp. 388–404, March 2000.

[Gupta 2003] P. Gupta and P. R. Kumar, "Towards an information theory of large networks: An achievable rate region," IEEE Transactions on information theory, vol. 49, no. 8, August 2003.

[Gustafsson 1997] E. Gustafsson and G. Karlsson, "A literature survey on traffic dispersion," *IEEE Network*, vol. 11, March-April 1997, pp. 28 – 36.

[Hamkins 2006] J. Hamkins and M. K. Simon (ed.), *Autonomous software-defined radio receivers for deep space applications*, John Wiley & Sons, 2006.

[Harley 1989] P. Harley, "Short distance attenuation measurements at 900 MHz and 1.8 GHz using low antenna heights for microcells," *IEEE Journal on Selected Areas in Communications*, vol. 7, no. 1, pp. 5-11, 1989.

[Hatfield 1977] D. N. Hatfield, "Measures of spectral efficiency in land mobile radio," IEEE *Transactions on Electromagnetic Computing*, vol. EMC-19, pp. 266–268, Aug.1977.

[Haykin 1999] S. M. Haykin, "Neural networks: A comprehensive foundation," (2nd ed.) Prentice Hall, Upper Saddle River, NJ, 1999.

[Haykin 2005] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 25, pp. 201–220, February 2005.

[Haykin 2007a] S. M. Haykin, Cognitive radio and radio networks. INFWEST seminar in Helsinki, 27-28 June 2007.

[Haykin 2007b] S. M. Haykin, "Fundamental issues in cognitive radio," In: B. Bhargava and E. Hussain (ed.) Cognitive radio networks, Springer-Verlag, 2007.

[Hillenbrand 2005] J. Hillenbrand, T. Weiss, and F. Jondral, “Calculation of detection and false alarm probabilities in spectrum pooling systems,” *IEEE Communications Letters*, vol. 9, pp. 349–351, April 2005.

[Ho 2005] T. Ho, M. Médard, and R. Koetter, “An information-theoretic view of network management,” *IEEE Transactions on Information Theory*, vol. 51, pp. 1295–1312, April 2005.

[Hoffmeyer 2007] J. Hoffmeyer, “IEEE 1900 Committee: Next generation radio and spectrum management,” IEEE 1900 project overview presentation, http://grouper.ieee.org/groups/emc/emc/1900/files/1900_Committee_Overview.ppt

[Hoven 2005] N. Hoven and A. Sahai, “Power scaling for cognitive radio,” in *Proceedings of WirelessCom 2005*, pp. 250–255, June 2005.

[Hulbert 2005] A. P. Hulbert “Spectrum sharing through beacons”, in *Proceedings of PIMRC 2005*, pp. 989–993, September 2005.

[Hur 2006] Y. Hur *et al.*, “A wideband analog multi-resolution spectrum sensing (MRSS) technique for cognitive radio (CR) systems,” in *Proceedings of ISCAS 2006*, pp. 4090–4093, May 2006.

[Hwang 2000] C.-H. Hwang and A. C.-H. Wu, “A predictive system shutdown method for energy saving of event-driven computation,” ACM Transactions on Design Automation of Electronic Systems, pp. 226-241, April 2000.

[Höyhtyä 2005] M. Höyhtyä, Adaptive power control as inverse control in multipath fading channel (in Finnish), master’s thesis, University of Oulu, 2005.

[Höyhtyä 2007a] M. Höyhtyä, A. Hekkala, and A. Mämmelä, ”Spectrum awareness: techniques and challenges for active spectrum sensing,” in *Towards Cognitive and Cooperative Wireless Networking: Techniques, Methodologies and Prospects* edited by F. Fitzek and M. Katz, pp. 353-372, Springer, 2007.

[Höyhtyä 2007b] M. Höyhtyä and A. Mämmelä. Adaptive Inverse Power Control Using an FxLMS Algorithm. IEEE 65th Vehicular Technology Conference 2007 (VTC2007-Spring), Dublin, Ireland, 22-25 April 2007, pp. 3021-3025.

[Höyhtyä 2008] M. Höyhtyä, S. Pollin and A. Mämmelä, “Performance improvement with predictive channel selection for cognitive radios,” in *Proceedings of First IEEE International Workshop on Cognitive Radios and Advanced Spectrum Management (IEEE CogART’08)*, February 2008.

[IEEE 1900] IEEE 1900, IEEE standard series on next generation radio and spectrum management, [Online]. http://grouper.ieee.org/groups/emc/emc/ieee_emcs_-_sdcom/P1900-X_Stds/ieee_emcs_-_p1900-x_main.htm

[IEEE 802.11h] IEEE 802.11h, Amendment 5: Spectrum and transmit power management extensions in the 5 GHz band in Europe, [Online]. http://standards.ieee.org/getieee802/download/802.11h-2003.pdf

[IEEE 802.11y] IEEE 802.11y, Contention Based Protocol standard for the IEEE 802.11 family of standards, [Online]. http://grouper.ieee.org/groups/802/11/Reports/tgy_update.htm

[IEEE 802.22] IEEE 802.22, Working group on wireless regional area networks (WRAN), [Online]. http://www.ieee802.org/22/

[IEEE 2004] "IEEE Recommended practice for local and metropolitan area networks coexistence of fixed broadband wireless access systems", IEEE 802.16.2^{TM} -2004 working group, March 2004.

[ITU 1999] Recommendation ITU-R M.1390. Methodology for the calculation of IMT-2000 terrestrial spectrum requirements, 24 pp, 1999.

[ITU 2000] Question ITU-R 230-1/8. Software defined radios. http://www.itu.int/pub/R-QUE-SG08.230/en

[ITU 2007a] Question ITU-R 241/8. Cognitive radio systems in the mobile service. http://www.itu.int/pub/R-QUE-SG08.241/en

[ITU 2007b] Question ITU-R 233/1. Measurement of spectrum occupancy. http://www.itu.int/publ/R-QUE-SG01.233/en

[ITU 2005a] Report ITU-R M.2063. Software defined radio in IMT-2000, the future development of IMT-2000 and systems beyond IMT-2000, 2005.

[ITU 2005b] Report ITU-R M.2064. Software-defined radio in the land mobile services, 2005.

[Jain 1986] R. Jain and S. A. Routhier, "Packet trains - Measurements and a new model for computer network traffic," *IEEE Journal on Selected Areas in Communications*, vol. SAC-4, pp. 986–995, September 1986.

[Jakes 1974] W. C. Jakes, *Microwave Mobile Communications*, New York: Wiley, 1974.

[Jindal 2004] N. Jindal et al., "On the duality of Gaussian multiple-access and broadcast channels," *IEEE Transactions on Information Theory*, vol. 50, pp. 768-783, May 2004.

[Jindal 2005] N. Jindal and A. Goldsmith, "Dirty-paper coding versus TDMA for MIMO broadcast channels," *IEEE Transactions on Information Theory*, vol. 51, pp. 1783-1794, May 2005.

[Jing 2005] X. Jing, S.-C. Mau, D. Raychaudri and R. Matyas, "Reactive cognitive radio algorithms for coexistence between 802.11b and 802.16a networks," *in Proceedings of GLOBECOM*, pp. 2465-2469, November/December 2005.

[Jondral 2005] F. K. Jondral, "Software-defined radio–Basics and evolution to cognitive radio," *EURASIP Journal of Wireless Communications and Networking*, 2005:3, pp. 275–283, August 2005.

[Jun 2003] J. Jun and M. L. Sichitiu, “The nominal capacity of wireless mesh networks,” *IEEE Wireless Communications*, vol. 10, pp. 8–14, October 2003.

[Kabamba 2005] P. T. Kabamba, S. M. Meerkov, and C. Y. Tang, “Optimal, suboptimal, and adaptive threshold policies for power efficiency of wireless networks,” *IEEE Transactions on Information Theory*, vol. 51, pp. 1359–1376, April 2005.

[Kahn 1978] R. E. Kahn and S. A. Gronemeyer, “Advances in packet radio technology,” *Proceedings of the IEEE*, vol. 66, pp. 1468-1496, November 1978.

[Kailath 1974] T. Kailath, “A View of Three Decades of Linear Filtering Theory,” *IEEE Transactions on Information Theory*, vol. 20, no. 2, pp. 146-181, 1974.

[Kanodia 2004] V. Kanodia, A. Sabharwal and E. Knightly, “MOAR: A multi-channel opportunistic auto-rate media access protocol for ad hoc networks,” in *Proc. of BROADNETS*, pp. 600–610, October 2004.

[Karagiannis 2004] T. Karagiannis *et al*., A nonstationary Poisson view of Internet traffic,” in *Proceedings of INFOCOM 2004*, vol. 3 pp. 1558–1569, March 2004.

[Karakayali 2006] M. K. Karakayali et al., “Network coordination for spectrally efficient communications in cellular systems,” *IEEE Wireless Communications*, vol.13, pp. 56-61, August 2006.

[Karn 1985] P. Karn, H. Price and R. Diersing, “Packet radio in the amateur service,” *IEEE Journal on Selected Areas in Communications*, vol. 3, pp. 431-439, May 1985.

[Kawadia 2005a] V. Kawadia and P. R. Kumar, (2005a), “A cautionary perspective on cross-layer design,” *IEEE Wireless Communications*, vol. 12, pp.3–11, February 2005.

[Kay 2006] S. Kay “*Intuitive Probability and Random Processes using Matlab*,” Springer, 2006.

[Kim 2000] S. W. Kim and A. J. Goldsmith, “Truncated power control in code-division multiple access communications,” *IEEE Transactions on Vehicular Technology*, vol. 49, pp. 965–972, May 2000.

[Kim 2007] H. Kim and K. G. Shin, “Efficient discovery of spectrum opportunities with MAC-layer sensing in cognitive radio networks,” *IEEE Transactions on Mobile Computing, 2007* (accepted for future publication).

[Koetter 2003] R. Koetter and M. Médard, “An algebraic approach to network coding,” *IEEE/ACM Transactions on Networking*, vol. 11, pp. 782–795, October 2003.

[Kolodzy 2005] P. J. Kolodzy, “Cognitive radio fundamentals,” in *34th SDR Forum meeting*, April 2005.

[Kolodzy 2006] P. J. Kolodzy, “Interference temperature: a metric for dynamic spectrum utilization,” *International Journal of Network Management*, vol. 16, pp. 103–113, March-April 2006.

[Krenik 2005] W. Krenik and A. Batra, “Cognitive radio techniques for wide area networks,” in *Proceedings of ACM IEEE Design Automation Conference 2005*, pp. 409–412, June 2005.

[Kuo 1996] S. M. Kuo and D. R. Morgan, *Active Noise Control Systems: Algorithms and DSP Implementations*, New York: Wiley, 1996.

[Kuo 2003] S. M. Kuo, X. Kong, and W. S. Gan, “Applications of adaptive feedback active noise control system,” *IEEE Transactions on Control Systems Technology*, vol. 11, pp. 216-220, March 2003.

[Laneman 2004] J. Laneman et al., Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Transactions on Information Theory*, vol. 50, pp. 3062-3080, Dec. 2004.

[Lansford 2004] J. Lansford, “UWB coexistence and cognitive radio,” Proceedings of the International Workshop on Ultra Wideband Systems joint with Conference on Ultrawideband Systems and Technologies (Joint UWBST & IWUWBS 2004) pp. 35-39, 18-21 May 2004.

[Lehtomäki 2005] J. Lehtomäki, Analysis of Energy Based Signal Detection, Ph. D. dissertation, University of Oulu, 2005.

[Levin 1960] M.J. Levin "Optimum Estimation of Impulse Response in the Presence of Noise", *IRE Transactions on Circuit Theory*, vol. 7, pp. 50- 56, March 1960.

[Li 2003] S.-Y. R. Li, R. W. Yeung, and N. Cai, “Linear network coding,” *IEEE Transactions on Information Theory*, vol. 49, pp.371–381, February 2003.

[Li 2007] Z. Li and K. J. Ray Liu, “Dynamic spectrum sharing: A game theoretical overview,” *IEEE Communications Magazine* vol. 45, no. 5, pp. 88-94, May 2007.

[Liberti 1992] J.C. Liberti & T.S. Rappaport “Statistics of shadowing in indoor radio channels at 900 and 1900 MHz”, in *Proceedings of Military Communications Conference,* October 1992.

[Lin 2003] Y.-B. Lin and S.-R. Yang, “A mobility management strategy for GPRS,” *IEEE Transactions on Wireless Communications*, vol. 2, pp. 1178-1188, November 2003.

[Litva 1996] J. Litva and T. K.-Y. Lo, *Digital Beamforming in Wireless Communications*, Artech House, 1996.

[Ma 2005] L. Ma, X. Han, and C.-C. Shen, “Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks,” in *Proc. of DySPAN*, pp. 203–213, November 2005.

[MacKenzie 2001] A .B. MacKenzie and S. B. Wicker, “Game theory in communications: Motivation, explanation, and application to power control,” in *Proceedings of Globecom 2001*, pp. 821–826, November 2001.

[Magee 1973] F. Magee and J. Proakis "Adaptive maximum-likelihood sequence estimation for digital signaling in the presence of intersymbol interference," *IEEE Transactions on Information Theory*, vol. 19, pp. 120- 124, January 1973.

[Makridakis 2000] S. Makridakis and M. Hibon, "The M3-competition: results, conclusions, and implications," *International Journal of Forecasting* 16, pp. 451-476, 2000.

[Maldonado 2005] D. Maldonado *et al*., "Cognitive radio applications to dynamic spectrum allocation," in *Proceedings of DySPAN 2005*, pp. 597–600, November 2005.

[Mangold 2004] S. Mangold *et al.*, "Spectrum agile radios: Radio resource measurements for opportunistic spectrum usage," in *Proceedings of GLOBECOM 2004*, pp. 3467–3471, November-December 2004.

[Marshall 2006] P. Marshall, "Policy languages, and specifically, How can we standardize the basis for extensible cognitive radio tools?" *SDR Forum Workshop on Cognitive Radio*, April 10, 2006.

[Matinmikko 2002] M. Matinmikko, "Measures of spectral and power efficiency of cellular mobile radio systems," Technical report, VTT Electronics, 52 pp, 2002.

[Matinmikko 2008] M. Matinmikko, M. Mustonen, H. Sarvanko, M. Höyhtyä, A. Hekkala, A. Mämmelä, M. Katz and M. Kiviranta, "A motivating overview of cognitive radio: Foundations, regulatory issues and key concepts," in *Proceedings of First IEEE International Workshop on Cognitive Radios and Advanced Spectrum Management (IEEE CogART'08)*, February 2008.

[McHenry 2006] M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson and C. S. Hood, "Chicago spectrum occupancy measurements & analysis and a long-term studies proposal", *First International Workshop on Technology and Policy for Accessing Spectrum (TAPAS'06)*, Boston, MA, United States, August 5, 2006. URL: http://portal.acm.org/citation.cfm?id=1234389

[Mergen 2005] G. Mergen and L. Tong, "Stability and capacity of regular wireless networks," *IEEE Transactions on Information Theory*, vol. 51, pp. 1938–1953, June 2005.

[Merritt 2005] R. Merritt, "Mesh casts wider network", *EE Times*, March 2005.

[Middleton] D. Middleton, "Canonically optimum threshold detection," *IEEE Transactions on Information Theory*, vol. 12, no. 2, 230-243, April 1966.

[Miller 1993] L. E. Miller, J. S. Lee, and D. J. Torrieri, "Frequency-hopping signal detection using partial band coverage," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 29, pp. 540–553, April 1993.

[Mishra 2006] S. M. Mishra, A. Sahai and R. W. Brodersen, "Cooperative sensing among cognitive radios," in *Proceedings of ICC 2006*, June 2006.

[Mitola 1995] J. Mitola, "The software radio architecture," *IEEE Communications Magazine*, pp. 26-38, May 1995.

[Mitola 1999] J. Mitola III and G. Q. Maguire, Jr., “Cognitive radio: Making software radios more personal,” *IEEE Personal Communications*, vol. 6, pp. 13–18, Aug. 1999.

[Mitola 2006] J. Mitola, *Aware, adaptive and cognitive radio: The engineering foundations of radio XML*, Wiley, 2006.

[Mämmelä 2005] A. Mämmelä, I. Saarinen and D. P. Taylor, ”Transmitted energy as a basic system resource”, in *Proc. GLOBECOM’05,* 2005.

[Mämmelä 2006] A. Mämmelä and R. Wichman, “Cellular Communication Channels,” in: *The Wiley Encyclopedia of Telecommunications and Signal Processing,* vol. II, part 3, 2006.

[Neel 2002] J. Neel, J. H. Reed, and R. P. Gilles, “The role of game theory in the analysis of software radio networks,” in *Proceedings of SDR Forum Technical Conference*, November 2002.

[Neel 2004] J. Neel, J. H. Reed, and R. P. Gilles, “Convergence of cognitive radio networks,” in *Proceedings of WCNC 2004*, pp. 2250–2255, March 2004.

[Newgard 2006] R. Newgard, C. Conway, T. Journot and J. Jiacinto, “Broadband spectral sensing for dynamic spectrum allocation”, in Proceedings of the International Symposium on Advanced Radio Technologies, pp. 137-140, 7-9 March 2006.

[Nie 2005] N. Nie and C. Comaniciu, “Adaptive channel allocation spectrum etiquette for cognitive radio networks,” in *Proceedings of DySPAN 2005*, pp. 269–278, November 2005.

[Olmos 1999] J. J. Olmos *et al.*, ” Design and implementation of a wide-band real-time mobile channel emulator,” *IEEE Transactions on Vehicular technology*, vol. 48, pp. 746–764, May 1999.

[Oppenheim 1999] A. V. Oppenheim, R. W. Schafer, and J. R. Buck, “*Discrete-Time Signal Processing*,” 2nd ed. Prentice-Hall, 1999.

[Park 2006] J. Park *et al.*, “Implementation issues of a wideband multi-resolution spectrum sensing (MRSS) technique for cognitive radio (CR) systems,” in *Proceedings of CrownCom 2006*, June 2006.

[Peel 2003] C. B. Peel, “On ‘dirty-paper coding’,” *IEEE Signal Processing Magazine*, pp. 112-113, May 2003.

[Peha 2005] J. M. Peha, “Approaches to spectrum sharing,” *IEEE Communications Magazine*, vol. 43, pp. 10–12, February 2005.

[Pottie 1995] G. J. Pottie, “System design choices in personal communications,” *IEEE Personal Communications*, vol. 2, pp. 50-67, Oct. 1995.

[Proakis 1988] J. G. Proakis and D. G. Manolakis, “*Introduction to Signal Processing*,” Macmillan, 1988.

[Proakis 2001] J. G. Proakis, "Digital communications" (4th ed.) McGraw-Hill, Boston, 1002 pp, 2001.

[Raman 2005] C. Raman, R. D. Yates, and N. B. Mandayam, "Scheduling variable rate links via a spectrum server," in *Proceedings of DySPAN 2005*, pp. 110–118, November 2005.

[Ramanathan 2002] R. Ramanathan and J. Redi, "A brief overview of ad hoc networks: challenges and directions," *IEEE Communication Magazine*, vol. 40, pp. 20-22, May 2002.

[Random House 1999] Random House Webster's Concise College Dictionary. Random House, 1999.

[Rappaport 2002] T. S. Rappaport, "*Wireless Communications: Principles and Practice,*" (2nd ed.) Prentice-Hall, 736 pp, 2002.

[Reed 2002] J. H. Reed, "*Software radio: A modern approach to radio engineering*," Prentice Hall, 567 pp, 2002.

[Rieser 2004] C. J. Rieser *et al.*, "Cognitive radio testbed: Further details and testing of a distributed genetic algorithm based cognitive engine for programmable radios," in *Proceedings of MILCOM 2004*, pp. 1437–1443, October–November 2004.

[Robert 1997] C. P. Robert, "The Bayesian Choice: A decision-theoretic motivation," Springer Verlag, 436 pp, 1997.

[Sahai 2004] A. Sahai, N. Hoven, and R. Tandra, "Some fundamental limits on cognitive radio," in *Proceedings of Allerton Conference*, September–October 2004.

[Sahin 2006] M. E. Sahin and H. Arslan, "System design for cognitive radio communications," in *Proceedings of CrownCom 2006*, June 2006.

[Salmasi 1991] A. Salmasi and K. S. Gilhousen, "On the system design aspects of code division multiple access (CDMA) applied to digital cellular and personal communication networks," in *Proceedings of IEEE Vehicular Technology Conference*, pp. 57-62, May 1991.

[Salo 2006] J. Salo, *Statistical Analysis of the Wireless Propagation Channel and its Mutual Information*, Ph. D. dissertation, Helsinki University of Technology, 2006.

[Sang 2002] A. Sang and S. Li, "A predictability analysis of network traffic," *Elsevier Computer Networks*, vol. 39, pp. 329–345, January 2002.

[Sarvanko 2008] H. Sarvanko, M. Mustonen, A. Hekkala, A. Mämmelä, M. Matinmikko and M. Katz, "Cooperative and noncooperative spectrum sensing techniques using Welch's periodogram in cognitive radios," in *Proceedings of First IEEE International Workshop on Cognitive Radios and Advanced Spectrum Management (IEEE CogART'08)*, February 2008.

[Satapathy 1996] D. P. Satapathy and J. M. Peha, "Spectrum sharing without licenses: Opprtunities and dangers," in *Proceedings of TPRC '96*, October 1996.

[Saunders 1999] S. R. Saunders, *Antennas and Propagation for Wireless Communication Systems*, John Wiley & Sons, 409 pp, 1999.

[SCC41] IEEE Standards Coordinating Committee 41 (SCC 41), Dynamic Spectrum Access Networks (DySPAN). http://www.scc41.org/

[Shah 2005] S. H. Shah, K. Chen, and K. Nahrstedt, “Dynamic bandwidth management in single-hop ad hoc wireless networks,” *Mobile Networks and Applications*, Vol. 10, pp.199–217, February 2005.

[Shankar 2005] N. Sai Shankar, C. Cordeiro and K. Challapali, “Spectrum agile radios: Utilization and sensing architectures,” in *Proceedings of DySPAN 2005*, pp. 160-169. November 2005.

[Sharma 2007] M. Sharma, A. Sahoo and K. D. Nayak, “Channel selection under interference temperature model in multi-hop cognitive mesh networks,” in *Proceedings of DySPAN 2007*, April 2007.

[Sheldon 2001] T. Sheldon, *McGraw-Hill Encyclopedia of networking & telecommunications*, 2001.

[Singh 1997] S. P. Singh and D. Bertsekas, “Reinforcement learning for dynamic channel allocation in cellular telephone systems,” *Advances in Neural Information Processing Systems 9*, pp. 974–980. MIT Press, 1997.

[Skidmore 2005] R. Skidmore, “Designing for coverage, capacity and voice quality,” January 2005. URL: http://www.phoneplusmag.com/articles/5a1special02.html

[Skolnik 2002] M. I. Skolnik, *Introduction to radar systems*, McGraw-Hill, 2002.

[Skyttner 2006] L. Skyttner, “General systems theory: Perspectives, Problems, Practice”, 2nd ed. World Scientific Publishing Company, 2006.

[Smirnov 2004] M. Smirnov, “Autonomic Communication,” *White paper*, November 2004. [Online]. Available: http://www.autonomic-communication.org/publications/doc/WP_v02.pdf

[Somayazulu 2006] V.S. Somayazulu, J.R. Foerster, and R.D. Roberts, “Detect and avoid (DAA) mechanism for UWB interference mitigation,” *Proceedings of the IEEE 2006 International Conference on Ultra-Wideband*, pp. 513-518, Waltham, MA, Sept. 2006.

[Sonnenschein 1992] A. Sonnenschein and P. M. Fishman, “Radiometric detection of spread-spectrum signals in noise of uncertain power,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. 28, pp. 654-660, July 1992.

[Sorenson 1970] H. W. Sorenson, “Least-squares estimation: from Gauss to Kalman,” IEEE Spectrum vol. 7, no. 7, pp. 63-68, 1970.

[Spectrum] Spectrum, Spectrum Signal Processing company, SDR-3000 platform, [Online]. http://www.spectrumsignal.com/products/sdr/sdr_3000.asp

[Spyropoulos 2003] A. Spyropoulos and C. S. Raghavendra, “Capacity bounds for ad-hoc networks using directional antennas,” in *Proc. of ICC 2003*, Vol. 1, pp. 348–352, May 2003.

[Srinivasa 2007] S. Srinivasa and S. A. Jafar, ”The throughput potential of cognitive radio: A theoretical perspective,” *IEEE Communications Magazine* vol. 45, no. 5, pp. 73-79, May 2007.

[SSC 2005] Shared Spectrum Company. “Spectrum Occupancy Measurements”, 2005. http://www.sharedspectrum.com/measurements/

[Staehle 2000] D. Staehle, K. Leibnitz, and P. Tran-Gia, “Source traffic modeling of wireless applications,” University of Würzburg, *Technical Report No. 261*, 2000.

[Starr 1999] T. Starr, J. M. Cioffi, and P. Silverman, *Understanding Digital Subscriber Line Technology*, New Jersey, Prentice Hall 1999.

[Stine 2005] J. A. Stine, “Spectrum management: The killer application of ad hoc and mesh networking,” in *Proceedings of DySPAN 2005*, pp. 184–193, November 2005.

[Stoica 1997] P. Stoica and R. L. Moses, *Introduction to Spectral Analysis*, New Jersey, Prentice Hall, 1997.

[Sturza 2007] M. A. Sturza and F. Ghazvinian, ”White spaces engineering study: Can cognitive radio technology operating in the TV white spaces completely protect licensed TV broadcasting?,” New America Foundation: Wireless Future Program: Working paper #16, Jan. 2007.

[Sydor 2004] J. Sydor, “True broadband for the countryside,” *IEE Communications Engineer*, vol. 2, pp. 32–36, April–May 2004.

[Takagi 2008] H. Takagi and B. H. Walke (Eds.), *Spectrum requirement planning in wireless communications: Model and methodology for IMT-Advanced*, John Wiley & Sons, 2008 (in press).

[Tandra 2005] R. Tandra and A. Sahai, “Fundamental limits on detection in low SNR under noise uncertainty,” In *Proc. of WirelessCom 2005*, pp. 464-469, June 2005.

[Tandra 2007] R. Tandra and A. Sahai, “Fundamental limits on feature detection,” In *Proc. of DySPAN*, April 2007 (in press).

[Thomas 2006] R. W. Thomas, D. H. Friend, L. A. DaSilva, and A. B. MacKenzie, “Cognitive networks: Adaptation and learning to achieve end-to-end performance objectives,” *IEEE Communications Magazine*, pp. 51-57, December 2006.

[Tobagi 1975] F. A. Tobagi and L. Kleinrock, “Packet Switching in Radio Channels: Part II-The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution,” *IEEE Transactions on Communications*, vol. com-23, pp. 1417–1433, December 1975.

[Tonmukayakul 2004] A. Tonmukayakul and M. B. H. Weiss, “Secondary use of radio spectrum: A feasibility analysis,” in *Proceedings of TPRC ’04*, October 2004.

[Ulrich 1995] K. T. Ulrich and S. D. Eppinger, *Product design and development*, McGraw-Hill, 1995.

[Urkowitz 1967] H. Urkowitz, “Energy detection of unknown deterministic signals,” Proceedings of IEEE, vol. 55, pp. 523-531, April 1967.

[van Trees 1968] H. L. van Trees, *Detection Estimation, and Modulation Theory*, John Wiley & Sons, 1968.

[Visotsky 2005] E. Visotsky, S. Kuffner and R. Peterson, “On collaborative detection of TV transmissions in support of dynamic spectrum sharing,” in *Proceedings of DySPAN 2005*, pp. 338-345. November 2005.

[Walko 2005] J. Walko, ”Cognitive radio,” *IEE Review*, vol. 51, pp. 34–37, May 2005.

[Weiss 2003] T. Weiss, J. Hillenbrand, A. Krohn and F. K. Jondral, “Efficient signalling of spectral resources in spectrum pooling systems”, in Proceedings of *10th Symposium on Communications and Vehicular Technology in the Benelux*, November 2003.

[Weiss 2004] T. A. Weiss and F. K. Jondral, “Spectrum pooling: An innovative strategy for the enhancement of spectrum efficiency,” *IEEE Communications Magazine*, vol. 42, pp. S8–S14, March 2004.

[Welch 1967] P. D. Welch, “The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms,” *IEEE Transactions on Audio and Electroacoustics*, vol. au-23, pp. 70-73, June 1967.

[Widrow 1996] B. Widrow and E. Walach, *Adaptive Inverse Control*, Upper Saddle River, NJ: Prentice-Hall, 1996.

[Willinger 1997] W. Willinger *et al.*, “Self-similarity through high-variability: Statistical analysis of Ethernet LAN traffic at the source level,” *IEEE/ACM Transactions on Networking*, vol. 5, pp. 71–86, February 1997.

[Wisair] Wisair, “Detect and avoid technology for ultra wideband (UWB) spectrum usage,” *White paper*, 2005, [Online]. http://www.wisair.com/wp-content/DAA_WP.pdf

[Willkomm 2005] D. Willkomm, J. Gross, and A. Wolisz, “Reliable link maintenance in cognitive radio systems,” in *Proceedings of DySPAN 2005*, pp.371–378, November 2005.

[WWRF 2004] Wireless World Research Forum, “Scenarios, system requirements and roadmaps for reconfigurability”, WWRF Working Group 6 White Paper, 2004.

[WWRF 2005] Wireless World Research Forum, “Cognitive radio and management of spectrum and radio resources in reconfigurable networks”, WWRF Working Group 6 White Paper, 2005.

[WWRF 2007] Wireless World Research Forum, “WWRF WG6 Cognitive Wireless Networks and Systems: Charter”, http://www.wireless-world-research.org/fileadmin/sites/default/files/about_the_forum/WG/WG6/Charter/wg6_charter_20070430.pdf

[Xie 2004] L-L. Xie and P. R. Kumar, “A network information theory for wireless communication: scaling laws and optimal operation,” *IEEE Transactions on Information Theory*, vol. 50, pp. 748–767, May 2004.

[Xue 2005] F. Xue, L.-L. Xie, and P.R. Kumar, “The transport capacity of wireless networks over fading channels,” *IEEE Transactions on information theory*, vol. 51, no.3, pp. 834-847, March 2005

[Yang 1999] Y.-J. Yang and J.-F. Chang, “A strength-and-SIR-combined adaptive power control for CDMA mobile radio channels,” *IEEE Transactions on Vehicular Technology*, vol. 48, pp. 1996–2004, November 1999.

[Yang 2007] L. Yang, L. Cao, and H. Zheng, “Proactive channel access in dynamic spectrum networks,” in *Proc. of CrownCom*, August 2007.

[Zhang 2006] Q. Zhang, A. B. J. Kokkeler and G. J. M. Smit, “A reconfigurable radio architecture for cognitive radio in emergency networks,” The 9th European Conference on Wireless Technology 2006, Manchester, UK, pp. 35-38, 10-12 Sept 2006,

[Zhao 2003] X. Zhao, J. Kivinen, P. Vainikainen, and K. Skog, “Characterization of Doppler spectra for mobile communications at 5.3 GHz,” *IEEE Transactions on Vehicular Technology*, vol. 52, pp. 14-23, January 2003.

[Zheng 2005] H. Zheng and L. Cao, “Device-centric spectrum management,” in *Proc. of DySPAN*, pp. 56–65, November 2005.

[Zhou 2005] X. Zhou *et al.*, “Cognospectrum: Spectrum adaptation and evolution in cognitive ultra-wideband radio,” in *Proceedings of International Conference of Ultra-Wideband 2005*, pp. 713–718, September 2005.

[Öner 2004] M. Öner and F. Jondral, “Cyclostationary-based methods for the extraction of the channel allocation information in a spectrum pooling system,” in *Proceedings of IEEE Radio and Wireless Conference 2004*, pp. 279–282, September 2004.

[Özgur 2007] A. Özgür et al., “Hierarchical cooperation achieves optimal capacity scaling in ad hoc networks,” IEEE Transaction on Information Theory, vol. 53, Dec. 2007, to be published (http://arxiv.org/PS_cache/cs/pdf/0611/0611070v4.pdf).

Annex 1 Remarkable cognitive radio research groups

Cognitive radio research is a hot topic in wireless communications. In addition to Mitola's work on cognitive radios [Mitola 1999], [Mitola 2006], the following remarkable groups exist in the area.

1. **Cognitive wireless technology, Virginia Polytechnic Institute and State University, Blacksburg, Virginia**
   People: Charles W. Bostian, Tom Rondeau *et al*.
   Topics: cognitive engine that uses genetic algorithms is a software package that can make any electronically agile radio platform cognitive
   - aware of itself, its user, and its environment
   - capable of experimenting and learning
   - capable of configuring itself to achieve a wide variety of goals
   - aim is a huge mesh network (over 1000 nodes) with cognitive engine in every node, largest and most intelligent wireless network test bed ever build

   Papers: [Rieser 2004], [Ball 2005]

2. **Berkeley Wireless Research Center, University of California at Berkeley**
   People: Robert W. Broderson, Danijela Čabrić *et al*.
   Topics: Physical layer design issues
   - spectrum sensing: energy detection and cyclostationary feature detection
   - wideband transmission: power control and spectrum shaping
   - CORVUS: vision of cognitive radio that uses allocated spectrum in a opportunistic manner to create "virtual unlicensed bands" i. e. bands that are shared with the primary users on a non-interfering basis.

   Papers: [Brodersen 2004], [Čabrić 2004], [Čabrić 2005], [Čabrić 2006a], [Čabrić 2006b]

3. **Electrical Engineering and Computer Science, University of California at Berkeley**
   People: Anant Sahai, Niels Hoven *et al*.
   Topics: Limits on cognitive radio, sensing, power control
   - opportunistic and cooperative sensing
   - limits on detection
   - constraints on transmit power

   Papers: [Sahai 2004], [Hoven 2005], [Mishra 2006]

4. **Communications Research Centre, an Agency of Industry Canada, Ottawa**
   People: John Sydor *et al*.
   Topics: Spectrum mining, efficient scalable wireless network technology
   - cognitive algorithms and radio system control software to detect interference and optimize the use of frequency spectrum
   - MILTON: microwave radio system that uses low power signals to relay Internet data bi-directionally between users and a hub antenna located within 1-2 kilometers in 5 GHz bands. The network monitors the radio environment and has the ability to configure itself in a manner that mitigates interference to its users.
   - aim is to provide a bridge to broadband wireless Internet

   Papers: [Sydor 2004]

5. Telecommunication Network Group, Technical University of Berlin
People: Adam Wolisz, Daniel Willkomm *et al*.
Topics: spectrum management and cognitive radio technologies
- reliable link maintenance
- in conjunction with BWRC, design of CORVUS system

Papers: [Willkomm 2005]

6. Institut für Nachrichtentechnik, Universität Karlsruhe
People: Friedrich K. Jondral, Timo Weiss *et al*.
Topics: Spectrum pooling cognitive radios
- common spectrum pool from where the spectral resources can be rent
- etiquette, fairness
- MAC and physical layer issues

Papers: [Jondral 2005], [Weiss 2003], [Weiss 2004]

7. Information Connectivity Branch, Air Force Research Laboratory, Rome, New York
People: Vasu Chakravarthy, James P. Stephens *et al*.
Topics: Cognitive radios, spectrum management
- TDCS, OFDM, and MC-CDMA
- Adaptive waveform technique which adapts to the changing electromagnetic environment and synthesizes waveform features in the frequency domain
- Adaptive waveform communication system is also referred as Tranform Domain Communication System (TDCS)

Papers: [Chakravarthy 2005]

8. Adaptive Systems Laboratory, McMaster University, Hamilton, Canada
People: Simon Haykin *et al*.
Topics: Cognitive radios, mesh networks
- channel estimation
- spectrum sensing
- power control
- intelligent mesh routing

Papers: [Haykin 2005], [Haykin 2007a], [Haykin 2007b]

9. Advanced Technology Office, DARPA
People: Preston Marshall *et al*.
Topics: The Next Generation (XG) Program
- automatic frequency selection and operating modes to both minimize disruption of existing users, and to ensure operation of U.S. systems
- aim is to develop and demonstrate a set of standard dynamic spectrum adaptation technologies for legacy and future emitter systems for joint service utility

Papers: [Marshall 2006]

10. Swisscom innovations, Bern
People: Stefan Mangold *et al*.
Topics: Cognitive radios, spectrum agile radios
- spectrum etiquette
- game theory
- opportunistic spectrum use

Papers: [Mangold 2004]

11. Carnegie Mellon University, Pittsburgh
People: Jon M. Peha *et al*.
Topics: secondary markets, opportunistic access
- spectrum sharing models
- regulatory and policy issues
- spectrum management techniques

Papers: [Satapathy 1996], [Peha 2003], [Peha 2005]

12. Broadband and Wireless Networking Laboratory, Georgia Institute of Technology, Atlanta
People: Ian F. Akyildiz *et al*.
Topics: OFDM-based cognitive radio networks
- cross-layer operations
- scenarios over the heterogeneous xG network environment

Papers: [Akyildiz 2006]

13. Wireless Communications & Signal Processing Group, University of South Florida, Florida
People: Huseyin Arslan *et al*.
Topics: Cognitive radio algorithms
- cross-layer adaptation
- distributed cognition
- Spectrum sensing and shaping

Papers: [Sahin 2006]

14. Wireless Information Network Laboratory, Rutgers University, New Jersey
People: Narayan Mandayam *et al*.
Topics: Cognitive radio network
- spectrum servers
- network architectures
- cooperative coding
- spectrum sensing and sharing strategies

Papers: [Raman 2005]

15. Division of Engineering and Applied Sciences, Harvard University, Cambridge
People: Vahid Tarokh, Natasha Devroye *et al*.
Topics: Cognitive radio channels, information theory
- cognitive radio channel capacity
- cognitive decomposition of wireless networks

Papers: [Devroye 2006]

16. INFO-COM Department, University of Rome La Sapienza, Italy
People: Maria-Gabriella Di Benedetto *et al*.
Topics: Cognitive radio and cognitive UWB
Papers: [Di Benedetto 2006]