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M.Sc. Thesis

Cognitive Radio Design: An SDR Approach

Rahman Doost-Mohammady

Abstract

Cognitive Radios are currently a big challenge for the telecommunications industry. Many efforts are in progress to make communication radio systems as adaptive as possible such that they are aware of their environment and they are self configurable. An ultimate adaptive radio with the specified features is used to be called a Cognitive Radio. A cognitive radio can sense its operating environment's conditions and it is able to reconfigure itself and to communicate with other counterparts based on the status of the environment and also the requirements of the user to meet the optimal communication conditions and to keep quality of service (QoS) as high as possible. In this research a design of a stand-alone (non-centralized) cognitive radio system will be approached. The heart of the cognitive radio is the cognitive engine. The problem of having a cognitive engine to start a non-cooperative communication with other cognitive radios within its range and meeting the QoS requirements imposed by the application, is addressed in this thesis and it is discussed how, by using spectrum holes and adjusting the radio parameters accordingly, this goal is reached. More specifically, a bootstrapping protocol is proposed for the initiation of communication among cognitive radios in the network after which both transmitter and the receiver are configured on the same frequency and tune on the same settings e.g., modulation and coding. The other modules discussed in the cognitive radio design are the policy engine, the spectrum sensor and the SDR transceiver. These modules are not part of this research, however, they are included in the design.

Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology

Cognitive Radio Design: An SDR Approach

Thesis

submitted in partial fulfillment of the
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Master of Science

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by

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Abstract

Cognitive Radios are currently a big challenge for the telecommunications industry. Many efforts are in progress to make communication radio systems as adaptive as possible such that they are aware of their environment and they are self configurable. An ultimate adaptive radio with the specified features is used to be called a Cognitive Radio. A cognitive radio can sense its operating environment's conditions and it is able to reconfigure itself and to communicate with other counterparts based on the status of the environment and also the requirements of the user to meet the optimal communication conditions and to keep quality of service (QoS) as high as possible. In this research a design of a stand-alone (non-centralized) cognitive radio system will be approached. The heart of the cognitive radio is the cognitive engine. The problem of having a cognitive engine to start a non-cooperative communication with other cognitive radios within its range and meeting the QoS requirements imposed by the application, is addressed in this thesis and it is discussed how, by using spectrum holes and adjusting the radio parameters accordingly, this goal is reached. More specifically, a bootstrapping protocol is proposed for the initiation of communication among cognitive radios in the network after which both transmitter and the receiver are configured on the same frequency and tune on the same settings e.g., modulation and coding. The other modules discussed in the cognitive radio design are the policy engine, the spectrum sensor and the SDR transceiver. These modules are not part of this research, however, they are included in the design.

Acknowledgments

Although my name appears as the sole author of the thesis, in reality a number of people are responsible for the work. First and foremost, I would like to thank my thesis advisors, Dr. Gerard Janssen and Dr. Przemysław Pawełczak. I must thank Gerard, for his great efforts in making my reports and my thesis readable, and teaching me the process of good scientific writing. Przemysław introduced me to the topic of cognitive radio and he steered my research efforts to attack interesting and potentially solvable problems. I must also thank Hans Segers, my superviosr at TNO ICT who introduced me to the most recent software defined radio technology and also helped me a lot in the way of progressing my research work. I must thank all three of them for their positive attitude and also for helping me to improve my writing. Working with them has been very inspiring: their energy, dedication and excellent organization. I acknowledge Prof. Ignas Niemegeers and Dr. Arjan van Genederen for their participation in my MSc thesis committee. I could not have wished for better collaborators and coaches. Their contributions, detailed comments and insights have been of great value for me. I am also grateful for the opportunity to work at TNO ICT. My warmest thanks go to all my friends, especially Sina Maleki, Arash Vafanejad, Adeola Adejuwon and Mani Zandifar for offering their tremendous support and friendship during these times. Finally, and most importantly, I would like to express my gratitude and humility to my parents, my brothers and my only sister. Even thousands of kilometers apart, they have been present through every step of my life, providing support in difficult times. They have been a constant source of inspiration, and this thesis is dedicated to them.

Rahman Doost-Mohammady
Delft, The Netherlands
June 29 2009

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List of Abbreviations

FCC	**F**ederal **C**ommunication **C**ommision
CR	**C**ognitive **R**adio
SDR	**S**oftware **D**efined **R**adio
OOK	**O**n-**O**ff **K**eying
SNR	**S**ignal to **N**oise **R**atio
BER	**B**it **E**rror **R**ate
QoS	**Q**uality **O**f **S**ervice
I	**I**n-phase
Q	**Q**uadrature

List of Symbols

$\frac{E_b}{N_0}$	bit-energy to noise-power spectral density
$\frac{k}{n}$	Channel Coding Rate
M	MPSK Modulation Level
T_{sens}	Sensing Time
L_1	Number OOK Periods during the Calling phase
L_2	Number OOK Periods during the Acknowledgment phase
P_{fa}	Flase Alarm probability in Spectrum Sensing
P_d	Detection probability in Spectrum Sensing

Introduction 1

In this thesis, we discuss an SDR-oriented design for cognitive radio. The purpose of this chapter is to introduce the problems addressed in this thesis, motivate the need for our approach, and describe the main contributions and the organization of this thesis.

1.1 Motivation

The Federal Communications Commission reported (FCC) in 2002 [7] that there is widespread belief that radio spectrum use in the US is either crowded or becoming very crowded. There is some evidence indicating that the shortage of spectrum is often a spectrum access problem. That is, the spectrum is available, but its use is compartmented by traditional policies based on traditional technologies. The National Telecommunication and Information Administration's (NTIA) chart of spectrum frequency allocations in Figure 1.1, shows that within the current spectrum regulatory framework, all of the frequency bands are exclusively allocated to specific services and according to the FCC regulations no violation from unlicensed users is allowed. On the other hand, there are vast temporal and geographical variations in the usage of allocated spectrum with utilization ranging from 15% to 85% in the bands below 3 GHz [4]. Figure 1.2 shows the spectrum utilization in the frequency range 0. . . 6 GHz measured by the Berkeley Wireless Research Center (BWRC) at downtown Berkeley. We can see in the chart that for the frequency ranges 2. . . 3 GHz and 5. . . 6 GHz, the spectrum utilization is less than 10%, while for 3. . . 5 Ghz, it is even worse and is less than 1%. The results of these measurements, seriously question the suitability of the current regulatory regime and possibly provide the opportunity to solve the spectrum scarcity problem. A solution to this problem is to make spectrum available on an unlicensed basis. This brings up the concept of spectrum sharing which allows spectrum use by secondary users under the requirement that they limit their interference to pre-existing primary users [4]. Cognitive Radio is a promising technology to solve the spectrum sharing problem and let secondary users use the spectrum on an unlincensed basis, but it is currently a big challenge for the telecommunications industry. The reason for that is the need for self-adaptivity of the cognitive radio. By adapting the transmission to the environment, a cognitive radio is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user. One major application of cognitive radio is the ability to adapt one's radio's physical layer (PHY) properties to optimize overall system performance. This may include changing center frequency, bandwidth, modulation type, coding parameters, or one of many other different components that define how radios communicate [6].
Cognitive Radio was initially thouhgt as an extension to Software-Defined Radio. Software-Defined Radio (SDR) is a term first coined by Joseph Mitola in 1991. The

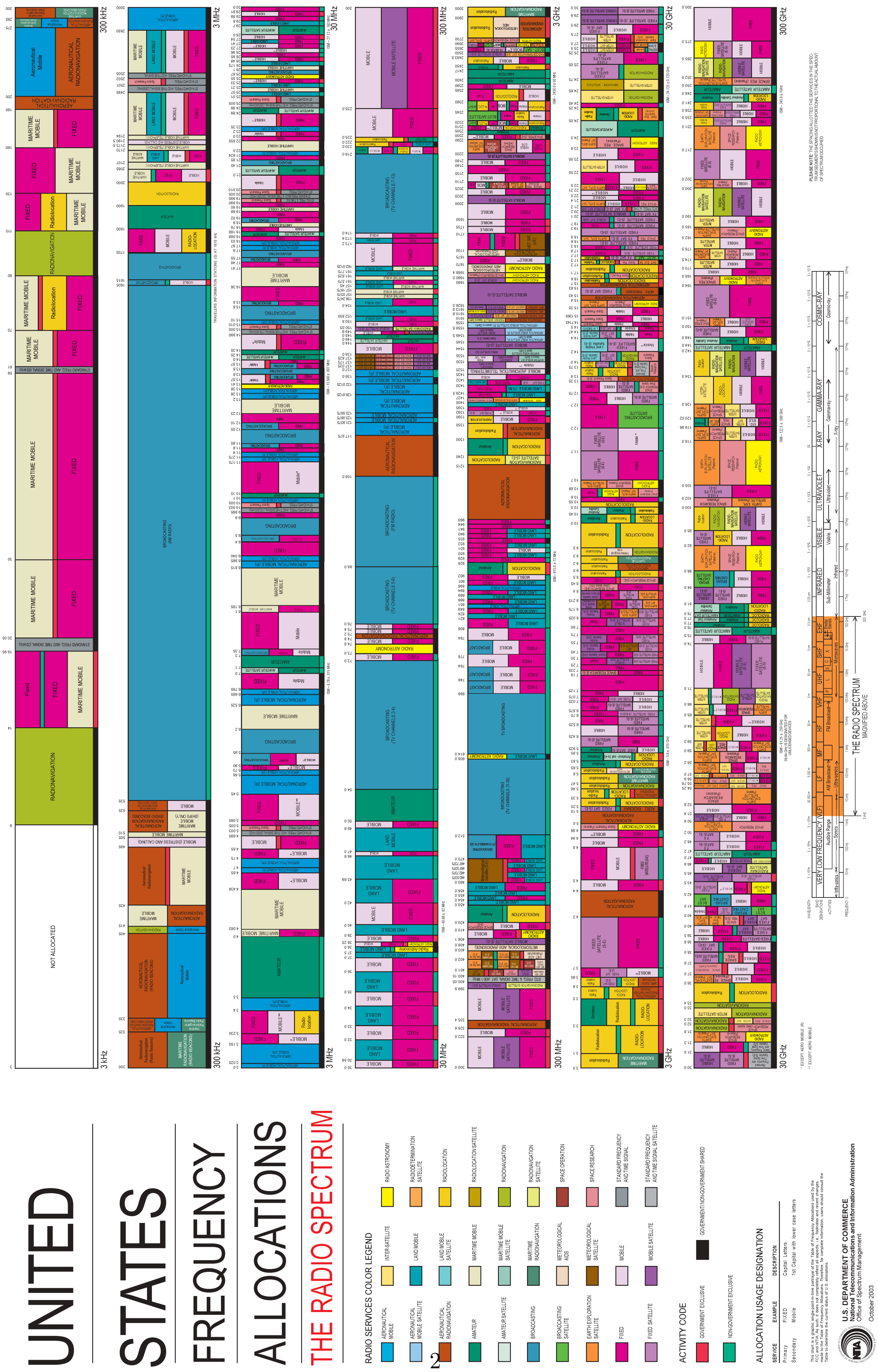


Figure 1.1: The NTIA's Frequency Allocation Chart [7].

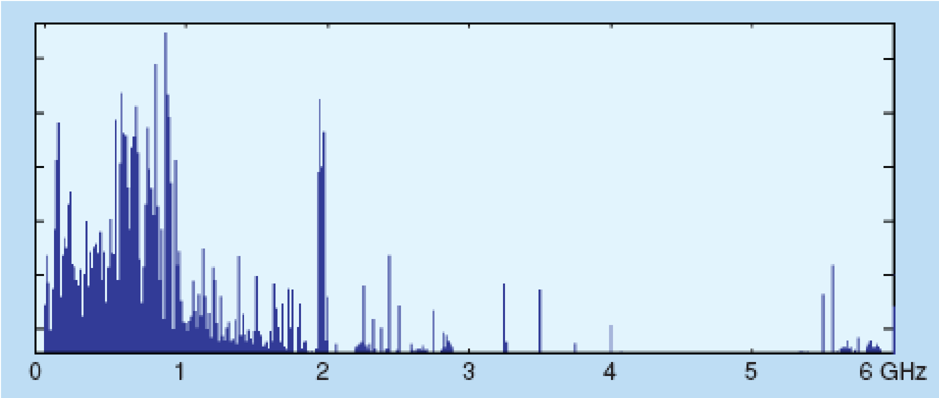


Figure 1.2: Spectrum utilization measurement in 0-6 GHz band [3].

purpose of SDR is to shift the inflexible hardware components of the radio systems to the software. In other words, SDR is a radio that can operate a significant range of RF bands and air interface modes through software [26]. The more of the functionality of the radio is implemented in software, the more flexible the SDR will be. More specifically, SDR is a transceiver whose communication functions are realized as programs running on a suitable processor. An SDR transceiver comprises of all the layers of a communication system from the PHY layer to Application layer [34]. The current effort in the SDR community is to develop more and more communication software components to be deployed on SDR development platforms to build more capable communication systems. The SDR is able to deploy and switch among these available components on the fly according to the environment condition and user demands. For this to come true, a cognitive layer is required to make the decisions on how to change these components based on the observed environment and user interface commands. If the cognitive layer is available, the SDR, which is a flexible radio, turns into a cognitive radio which is able to intelligently adapt itself to the outside world. The way this cognitive layer behaves is one of topics of this thesis.
We mentioned that an SDR platform needs to be as flexible as possible in order to accommodate a wide variety of communication options. This creates a radio which is able to work in different situations or networks. When using a legacy waveform, an SDR can communicate with other legacy radios. But consider the case where an SDR is controlled by a cognitive layer and a network needs to be setup on the fly with no information about the functions of other radios in the network. This justifies the need for protocols to enable the communication among the radios that are not necessarily using the same communication parameters and are not tuned to the same frequency. Such a protocol is also proposed in this thesis based on a particular cognitive radio architecture.

1.2 CR and SDR: Past and Present

Since when the SDR and Cognitive Radio concepts were proposed by Mitola in 1991 and 1999, there has been a huge trend toward bringing such concepts to reality. The first initiation began by the US army and US Department of Defense in 1992 when they decided to use programmable processing to emulate more than 10 existing military radios, operating frequency bands between 2 and 2000 MHz [20]. This was the first phase of the project. But in the second phase which was launched in 1995, the goal was to get a more quickly reconfigurable architecture with bridging capability with different radio protocols. The other major effort for the expansion of SDRs was the creation of the Joint Tactical Radio System (JTRS) [12] program by the US military in 1997 to develop an open architecture of cutting edge radio waveform technology that allows multiple radio types (e.g., , handheld, aircraft, maritime) to communicate with each other. Apart form the US, there has also been research and industry initiations for SDR in Europe, Japan and other parts of the world, examples of which can be found in [37]. In the current decade with the introduction of cognitive radios and the emergence of new shortages on Spectrum as reflected in FFC Spectrum Task Force report [7], new efforts were kicked off to design more intelligent and universal radios to the spectrum scarcity problem. At a particular instance, the US Department of Defense's Defense Advanced Research Projects Agency (DARPA) launched the Next Generation (XG) program [35] with the goal to develop both the enabling technologies and system concepts to dynamically redistribute allocated spectrum along with novel waveforms in order to provide improvements in assured military communications in support of a full range of worldwide deployments. U.S. Forces face unique spectrum access issues in each country in which they operate, due to competing civilian or government users of national spectrum. In August 2006, the Shared Spectrum Company (SSC) and DARPA demonstrated, for the first time, a six node network of XG radios capable of using spectrum over a wide range of frequencies, i.e. 225-600 MHz, on a secondary basis [32]. Also the Software Defined Radio Forum (SDRF) is formed as a non-profit organization comprising of approximately 100 corporations around the globe dedicated to promoting the development, deployment and use of software defined radio technologies for advanced wireless systems. This forum holds annual technical conferences and exhibitions of the most recent advances in the SDR technology to be demonstrated. Apart from these industrial efforts, there has also been a big research movement in the communication area toward SDR and CR. A dedicated conference is held since 2005 by IEEE called Dynamic Spectrum Access Network (DySpan) in which the most recent research results in different aspects, e.g. spectrum sensing, spectrum sharing and spectrum management, are presented. Demonstration sessions are also held during the conference wherein the industry and academia present their cognitive radio demonstrations. The most recent conference was held in October 2008 in Chicago, USA. The demos represented at this conference are listed in Figure 1.3 with detailed specifications.

1.3 Outline and Contributions

In this thesis we try to elaborate on the design of a simple cognitive radio by leveraging on a software defined transceiver and a military legacy waveform. The design includes the hardware architecture required for a software-defined operation. We also use flexible legacy military waveform software of the so-called STANAG4285 as an en-

Project Name	Company / University	Platform	Waveform/Sub-carriers	Frequency Range	Spectrum Sensing	Transmit/ Receive	Application	Centralization	Coordination	Team Members	Where/When
A dynamic spectrum access system employing adaptive carrier selection and intelligent spectrum sensing techniques on multiple platforms.	Delft University of Technology	USRP - P25M	OFDM	ISM	Energy Detection			None		5	Dyspan-2008
TV white space demonstation system	Adaptrum, USA	Dedicated Hardware	OFDM	400-1000 MHz	Energy Detection	Tx and Rx	?	None	Wireless uPhone Beacon Generation and Detection	?	Dyspan-2008
Band-width Adaptive waveforms for DySpans	University of Dublin, Trinity College	CTVR IRIS SDR (Intel GPP)	OFDM / 64	?	?	Tx and Rx	Video	None	Cyclostationary Signatures	?	Dyspan-2008
Spectrum Sensing to achieve Frequency Rendezvous using Xilinx FPGAs	University of Dublin, Trinity College	IRIS SDR - XUP - USRP	DQPSK	?	Energy Detection	Tx and Rx	Video	None	None	6	Dyspan-2008
A Heterogeneous cognitive radio network enabling dissimilar cooperative spectrum sensing , dynamic spectrum access, and	Virginia Tech	USRP - Gnuradio - Lyrtech SFF SDR board	Single-Carrier	ISM and 482-500 MHz	Cooperative Sensing (energy sensing)	Tx and Rx	Audio/Video	None	Control Channel	16	Dyspan-2008
TV white-space device prototype using covariance-based signal detection	Institute for Infocomm Research, Singapore	Dedicated Hardware including FPGA and DSP	None	470-860 Mhz	Covariance-based Signal Detection	None	None	None	None	5	DySpan-2008
TV White Space Cognitive Radio Demonstration	Motorola	Dedicated Hardware	UHF non-proprietary 802.11 MAC/PHY	UHF	Energy Detection	Rx and Tx	Video	Yes	CE-CE Protocol via control ch	?	DySpan-2008
Large Scale Cognitive Wireless Networks	OMESH Networks Inc., Canada	?	Zigbee (IEEE 802.15.4)	ISM	?	Rx and Tx	Voice/Video	Yes	?	1	Dyspan-2008
A Cognitive Radio Prototype Operating in UHF TV bands	Philips Research, NY, USA	WiFi Cards - Dedicated Hardware	?	UHF	Energy Detection and Feature detection	Rx and Tx	Video	None	MAC protocol	4	Dyspan-2008
Demonstration of Spectral Sensing and Signal Classification	Rockwell Collins Inc, USA	Rockwell Collins XG spectral sensor	None	30-3000 MHz	Feature Detection	None	None	None	None	4	Dyspan-2008
A Policy-based multi-band radio	Shared Spectrum Co., USA	DSA1000	IEEE 802.16d	TV White Space	?	Tx and Rx	Video/Data	?	?	?	Dyspan-2008
Signal Identification for Cognitive Radio	University of South Florida, USA	None	None	?	Power Spectral Detection	None	None	None	None	3	Dyspan-2008
Reliable detection of white space spectrum	University of Utah	Lyrtech SDR	Single-Carrier	?	Filterbank Sensing	Tx and Rx	Voice	?	?	5	Dyspan-2008

Figure 1.3: Cognitive Radio Demonstrations in DySpan 2008.

abling proof-of-concept for cognitive radio design. As a major contribution, a spectrum sharing protocol is discussed to network different radios using the given software and hardware architecture.

Chapter 2: Cognitive Radio's Architectural Design

In chapter 2, an architectural design of a SDR transceiver is given. This SDR transceiver is able to do arbitrary IQ modulation and demodulation of baseband signals generated by software and translated to a wide range of IF frequencies. Also a multi-mode waveform of the so-called STANAG4285 including different modulation and coding modes and its functional blocks are explained. At the end of this chapter, algorithms for the operation of a cognitive engine (cognitive layer structure) is proposed which tunes the radio to the optimal communication parameters according to the application demands and channel condition (e.g., SNR and primary users' presence).

Chapter 3: Spectrum Sharing Protocol

In this chapter, a spectrum sharing protocol is proposed for the communication setup among cognitive radio nodes of chapter 2. This protocol enables the radios to setup a communication without the exchange of any control data including the tuning frequency, modulation scheme or coding scheme. As a matter fact these communication settings are estimated at the receiver without any prior information from the transmitter.

Chapter 4: Parameter Estimation and Power Control

In chapter 4, algorithms for the estimation of communication parameters i.e., modulation level, coding rate and SNR is illustrated.

Chapter 5: Performance Analysis Results

In this chapter, a performance analysis of the protocol presented in chapter 3 is given. Performance measures include energy consumption, connection timing and also probability of successful connection between two nodes. Also the scenarios in which the protocol fails to connect two nodes are discussed in this chapter.

Chapter 6: Conclusions and Furture Work

This chapter summarizes the main ideas of the thesis and gives suggestions for further research in this area.

System Design 2

It is not a trivial task to set optimal radio parameters on a cognitive radio. The "Optimal" parameters for such a system are the ones that get maximum throughput and cause minimum interference to the primary users. The purpose of this chapter is to design an algorithm for our cognitive engine to find opportunities from the spectrum sensing data based on the detected energy in each spectrum channel. Based on the existing opportunities and other environment variables e.g., time, location and etc, Cognitive Engine algorithms should find optimal communication parameters like transmission power level, modulation and coding scheme after confirming with the Policy Conformance module.

2.1 SCA-based System Architecture

The Software Communication Architecture (SCA) is published by the Joint Program Executive Office (JPEO) of the Joint Tactical Radio System (JTRS). This architecture was developed to assist in the development of software defined radio communication systems, capturing the benefits of recent technology advances which are expected to greatly enhance interoperability of communication systems and reduce development and deployment costs. The SCA establishes an implementation-independent framework with baseline requirements for the development of software for software defined radios [13].

SCA defines a set of interfaces that isolate the system applications from the underlying hardware. This set of interfaces is referred to as the system Core Framework. It also provides the infrastructure and support elements needed to ensure that once software components are deployed in a system, they are able to execute and communicate with the other hardware and software elements present in the system. These software components are categorized as follows:

Device: The software that provides the capabilities for waveforms to execute and access the system hardware.

Resource: Applications (Waveforms) consist of one or more resources. The resource interface provides a common SCA API for the control and configuration of software components.

Service: Non-hardware (software-only) resources provided by the system for use by applications are generally referred to as services.

With the above introduction on the new methodology toward SDR implementa-

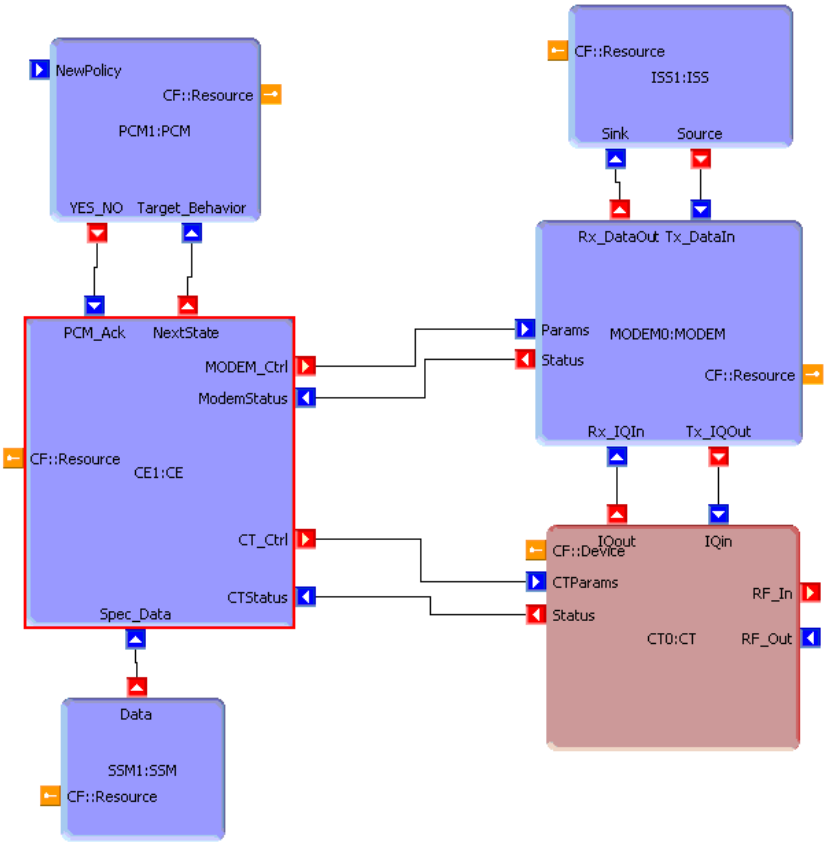


Figure 2.1: A SCA-based Architecture for a Policy-based Cognitive Radio.

tion, we proceed with an architectural overview of a SCA-based cognitive radio.

In Figure 2.1, an overview of the architecture for our cognitive radio system is sketched and the flow of data among different blocks is shown with connecting lines.
Spectrum Sensing Module (SSM): This module is a Resource and provides data on the amount of interference detected in each frequency band. We do not focus on the details of this block and the underlying algortihms and processes in this thesis, but we assume that we deal with an energy detecting spectrum sensing.
Policy Conformance Module (PCM): This module is a Resource. The target settings that the system wants to switch to is fed to this module and it decides, based on the existing policies and waveforms and their characteristics, a Yes or No response. The system settings in question are: center frequency, frequency bandwidth, power level, modulation scheme and coding ccheme. We do not also focus on this module in detail. A thorough investigation on the functionality and theories behind such module is done in a parallel MSc work by Ms. Adeola Adejuwon.
Cognitive Transceiver (CT): This module is a Device and plays the role as the outer block for transmission and reception of the signals in the environment. The transceiver settings like IF frequency and transmission power are adjusted by the software on this module. This transceiver receives IQ samples and modulates them

with any Center frequency that has been set by the cognitive layer. A Cognitive Transceiver architecture is given in the next section of this chapter. This architecture is implemented at TNO ICT.
MODEM: Modulator-Demodulator Module is a Resource and is the baseband processing software running on top of the cognitive transceiver device. This block is able to create digital symbols out of the application data bits. These symbols are fed to the tranceiver as it is observed in Figure 2.1 which are further modulated and processed for transmission. Communication settings like modulation and coding scheme is applied in this block. An example of this block is explained in Section 2.3.
Cognitive Engine (CE): This is a Resource that provides the Modem and CT with control signals to adapt themselves to the new situations by changing its frequency, tranmission power, modulation and etc. This is actually a decision making module which decides to change the system configuration based on the data coming from the SSM (and even other modules like GPS, clock, etc.) and inquiring the PCM.
Information Sink and Source (ISS): This module is a Resource. This is where the data of whatever type (e.g., Voice, Video) originates and goes into.

In the next section of this chapter, we review the SDR transceiver design which is developed as part of WINTSEC[1] project at TNO ICT[2]. This transceiver is placed at our Cognitive Transceiver module (see Figure 2.1) as the base of the rest of our cognitive radio design and all other components will be built on top it. In section 3-3, we review an implementation of a military HF waveform, namely STANAG 4285, to be deployed in our MODEM module explained in the above architecture. Also an analysis of a software implementation of this waveform in FGAN[3] is given in this section. STANAG 4285 is a waveform with multiple communication modes including different modulation and coding schemes which makes it a good candidate for cognitive radio implementation. Based on the above transceiver and waveform, an algorithm is designed for a cognitive engine to control other blocks of the cognitive radio.

2.2 SDR Transceiver Specification

A general model [25] of the transceiver to be used for the development of a cognitive radio, is given in figure 2.2. Since the ideal Software-Defined Radio aims to shift the AD and DA converter as close as possible to the antenna, in this transceiver model digitization has been at the IF. The part which contains the fast digital signal processing is performing the translation from the complex baseband signals to digital IF and vice versa.

The following processing steps are typically found in the receive path of the digital IF transceiver model:

[1]Wireless INTeroperability for SECurity project started in 2006 for finding wireless interoperability solutions for European security agencies.

[2]TNO is the Netherlands organization for applied research. TNO ICT in the information and communication technology branch of TNO located in Delft, the Netherlands

[3]The Forschungsgesellschaft fr Angewandte Naturwissenschaften (FGAN Research Establishment for Applied Science) is located in Wachtberg, Germany

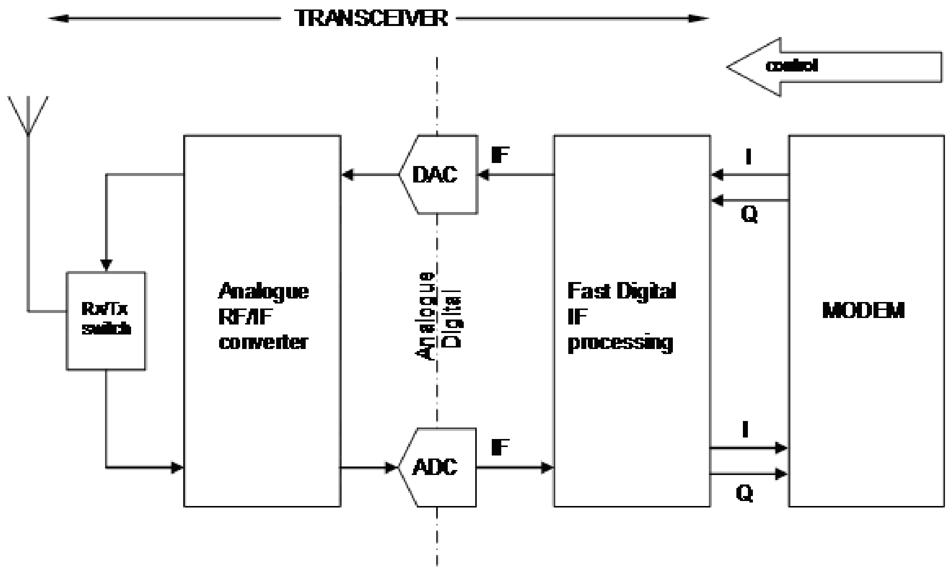


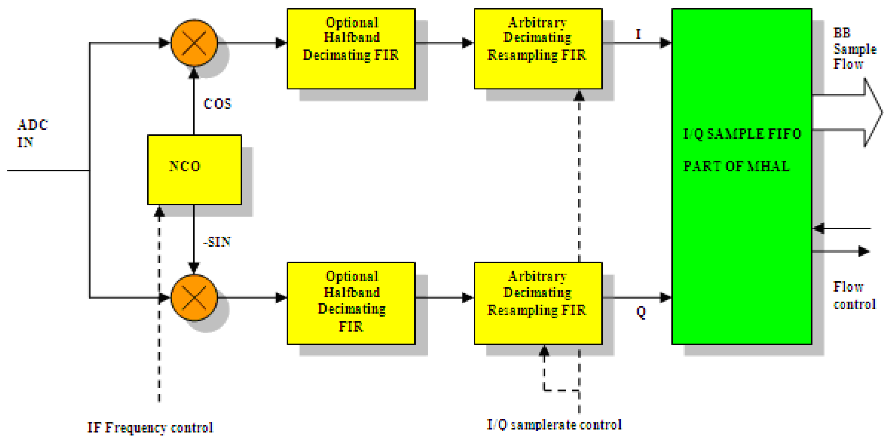
Figure 2.2: Transceiver model with digitization at IF.

1. Digital Down Conversion
2. Sample rate conversion/decimation
3. Adaptive channel equalization
4. Symbol timing recovery
5. Carrier tracking / synchronization
6. Pulse shaping / channel filtering

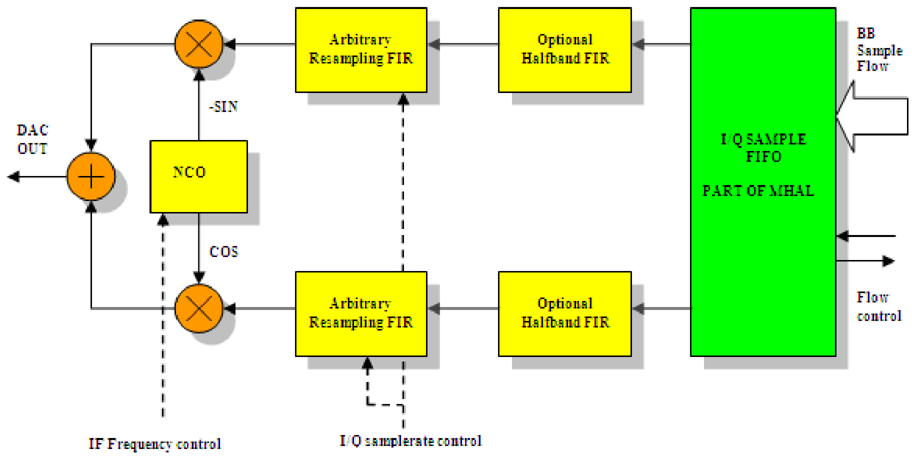
The Fast Digital IF Processing block shifts the IF centered input spectrum to baseband I and Q streams. The real valued input spectrum from the A/D converter is multiplied with the sine and cosine outputs of a numerical controlled oscillator in order to obtain in-phase and quadrature-phase values. This will compose the Digital down Conversion step. The bandwidth of the I and Q baseband streams, which result from the down conversion process, is in general small compared to the ADC sample rate and therefore need to be limited. Band limiting and lowering the sample rate can be accomplished by means of a programmable decimating filter. This will also compose the Sample rate Conversion and Decimation step for the above transceiver. From the above blocks, 3, 4, 5 and 6 can be developed in software.

The following processing steps are typically found in the transmit path of the digital IF transceiver model:

1. Pulse shaping / channel filtering
2. Interpolation
3. Digital Up Conversion



(a)



(b)

Figure 2.3: Transceiver Block diagram: (a) RX path signal processing, and (b) TX path signal processing.

The first operation is supposed to be different based on the SDR requirements and filter impulse response and can be changed depending on the system needs. So it is left to be developed in the software. Before the baseband I and Q streams can be modulated on an IF carrier the sample rate of the shaped symbols need to be increased in order to match the processing rate of the digital up-convertor block. A programmable interpolating re-sampling filter provides this functionality. This block serves two purposes; bandwidth limitation and arbitrary re-sampling of the input signal to a fixed output sample rate. After interpolation the complex baseband signal is translated to the final digital IF frequency. This can be accomplished in a similar manner as being performed in the analog domain with the aid of a numerically controlled oscillator (NCO), two multipliers and an output adder. At this stage the signal is ready for sending to the output of the D/A converter.

2.3 Waveform Specification

2.3.1 General description of STANAG 4285

STANAG 4285 is the NATO standard for HF communication. Its center frequency is set to 1800Hz and cannot be changed. It consists of several data rate modes (75-2400 bps) and two different interleaving options (short and long). The STANAG 4285 used modulation types are (BPSK, QPSK OR 8-PSK). If the 8-PSK modulation used, the rate is set to 2400 baud. If QPSK modulation is used, the 1200 baud is set. If BPSK modulation is used, the 600 or in case of using channel coding with 1/2, 1/4 or 1/8 the 300, 150 or 75 baud is used.

2.3.2 STANAG 4285 Waveform Code Analysis

In this section, the structure of the C code that generates IF samples based on STANAG 4285 legacy military waveform is elaborated. This code is developed by the FGAN Company based in Germany. The objective of this section is to have an abstract idea from this code about how our final transceiver should look like and what are the building blocks and their specifications. The codes are divided in 2 parts. The first part is the transmitter and the second part is the receiver. In the following, both parts are explained.

2.3.2.1 Transmitter

The transmitter code is mainly broken into 2 major blocks; Encoder, and Modulator.

- *Encoder:* This Forward Error Correcting module is basically working based on three parameters:

    1. The Symbol Mapping Scheme e.g. BPSK, QPSK, 8-PSK
    2. The Coded Rate e.g. 2400 bps, 1200 bps, 300bps, 150 bps
    3. The Interleaving Type e.g. long or short.

    The whole encoding process has 3 stages; Initialization, Encoding and Interleaving. The Encoding stage starts with taking a frame of 256 bytes and ends up with frames of 4 bytes.

- *Modulator:* This module is working based on the Symbol Mapper Input Scheme which can be BPSK, QPSK or 8-PSK. This module is also capable of oversampling the signal by a user defined factor. This block takes a frame of 128 symbols in its input and generates IQ samples at the output. In the beginning of transmission, it automatically generates preamble signals. Also AGC and probe sequences are generated before the transmission. After symbol mapping, IQ data is passed through a Root Raised Cosine FIR filter. This module also does the final up-conversion by multiplying the IQ samples by Sine and Cosine waves. The main

function makes use of these blocks with the following approach:
For the whole transmitter, the base data rate is considered as 600 bps. But as the modulation scheme changes, this data rate is multiplied by a factor imposed by the number of modulation points. In the first transmission burst, the AGC prefix and probe sequence are sent and from the second burst on, data symbols are encapsulated in the frame. In case no coding is applied, the number of data bytes per frame is determined by the symbol mapping scheme which is shown in the following table:

PSK	Number of data bytes per frame
BPSK	16
QPSK	32
8PSK	48

Table 2.1: STANAG4285 Databytes per frame when no coding is used.

In case coding is applied, the number of data bytes per frame is determined by both the PSK scheme and the coding rate. The following shows this relation:

PSK/Coded Rate (bps)	2400/1200/600	300	150	75
BPSK	8	4	2	1
QPSK	16	8	4	2
8PSK	32	16	8	4

Table 2.2: STANAG4285 Databytes per frame in different coding scenarios.

2.3.2.2 Receiver

The receiver code has mainly 5 parts; Preamble Search, Doppler Multiplier, Doppler Synchronization Tracking, Demodulator, and Decoder.
The Preamble Search block is actually looking for the beginning of meaningful data including a frame pattern in the received IQ Samples. Function *PreamSearch* gets 2 arrays of data containing real and imaginary data samples and the number of samples in each array and returns the number of meaningful samples from the start the frame it finds in the arrays. If the return value is zero, no frame has been found in the data and if the return value is more than zero, a frame has been found from some point in the input data arrays.
The next action taken is Phase Correction of the received signal with the aid of Doppler tracking or in other words with the amount of Doppler frequency that has been estimated and fed back from the Doppler Synchronization Tracking module. Because of this feed back, in the first round of operation, a Doppler frequency 0 is used by the Doppler Multiplication module. The next stage is demodulation. Several operations are accomplished in the demodulation module. The first operation is channel estimation. In the designed receiver, the maximum length for the channel is determined as 32. Within the function *acq_PN*, based on the probe sequence part of the input signal inserted during the transmission as the training sequence, channel taps are actually

estimated to equalize the data signal values from the channel convolution. In a function called *decision* based on the PSK scheme and number of bits per symbol, bits are decided depending on the received IF data. For instance, if 8-PSK is used, 3 bits are extracted from each pair of I and Q samples. This module returns a chunk of 128 data symbols. The mapping scheme determines the number of bits in each data symbol. In addition to the data symbols, in this module 3 other outputs are generated which are the real and imaginary parts of the channel's coefficients, projected SNR, and phase error. These outputs are actually fed to another module called Doppler Synchronization Track to estimate the Doppler frequency. Doppler Synchronization Track calculates Doppler Frequency and SyncSampleFlag. SyncSampleFlag takes -1, 0 and +1 values and it actually represents the number of shifts required to perform on the input frame. By -1, the index of the last frame is pulled in to the current frame. By +1, the first index of the current frame is discarded. By 0, no pointer is replaced. The last major part of the receiver is the Decoder. This module is basically taking soft extracted bits from the modulator output and retrieves hard data bits. In more detail, first deinterleaving is done on the soft bits and the final decoding process is done to get the actual data bits.

2.4 Cognitive Engine Design

The aim of a cognitive engine is to actually enable radio self-configuration based on demands imposed by the environment or the radio user. There are two events which enforce the radio to change its settings and still stay operational. The first one is the detection of a primary user on the operating frequency of the radio. And the second one is the change of the application demanded by the user. For instance, when the user demands to send data instead of audio signal, the radio should adjust itself to meet the new requirements of that application. In other words, each application has its own QoS requirements which should be met when using a transmission system. A number of QoS objectives or requirements for a radio are listed below [15].

1. **Rate (R):** This parameter depends on the needs of the application (from any type e.g., Data, Audio, Video) served by the radio. After getting a request for an amount of bandwidth from the application, the radio should look for a new frequency band in the spectrum sensing results in case it can not serve this request by keeping the same settings like the bandwidth, modulation scheme (increasing the number of modulation symbols) or other possibilities of the radio.

2. **Bit Error Rate (BER):** This parameter also depends on the type of application. For instance, it might be 10^{-9} for data, 10^{-5} for audio and 10^{-10} for video. The radio should try to guarantee such error rates by applying proper coding methods or increasing the power depending on the amount of SNR the receiver experiences or increasing the bandwidth if it is not sufficient for the current application.

3. **SNIR:** This parameter is unaffected by any system design choices, such as modulation and coding. But it can be increased by the amount of transmission power in many scenarios. It can be assumed that the receiver exchanges data on the

amount of measured SNR to adjust settings at the transmitter side in such a way that the SNR reaches an acceptable threshold.

4. **Interference (I):** Amount of interference to the primary users depends on the specific frequency band on which the radio operates. Therefore, this value should be looked up by the Policy Engine. There's another aspect of the interference, namely the amount of unwanted interference signal from other signal sources working in the same frequency band. In both cases this amount should be minimized. But from the latter perspective it's up to the cognitive engine to choose a band in which the radio experiences the least amount of interference on average.

5. **Spectral Efficiency (η):** it is an indicator of how efficiently the assigned bandwidth is used. This term is actually the ratio of actual (source) data rate (b/s) over the utilized bandwidth (Hz).

Moreover, there are a number of adjustable settings on the radio with which the cognitive engine can control the above QoS requirements:

1. **Coding Rate ($\frac{k}{n}$):** This parameter determines the rate of data after being encoded using a convolutional encoder in proportion to the input source data rate.

2. **Modulation Level (M):** the schemes included in the systems could be BPSK, QPSK, 8-PSK (M=2, 4, 8) or more sophisticated ones. An increase in the value of M has a direct impact on the bandwidth efficiency.

3. **Carrier Frequency (f_c):** Carrier frequency should be chosen in such a way that it doesn't exceed the half of sampling frequency of the up-sampled signal.

4. **Transmission Power (P_{tx}):** Power should be used optimally in order to just reach the required BER at the receiver.

5. **Bandwidth (W):** Enough bandwidth must be assigned to afford the coded and modulated data rate needed by the application.

Therefore the role of the cognitive engine would be to use radio resources (spectrum and power) in order to achieve the required QoS parameters.

2.4.1 Relations among QoS parameters and radio settings

Among the radio settings mentioned in the previous section, the received SNR is only controlled by Bandwidth and Transmission Power level. The relation would be as the following [9]:

$$\frac{C}{N} = \frac{P_{tx} G_{AT} G_{FS} G_{AR}}{\kappa T_{sys} B} \tag{2.1}$$

or,

$$\left(\frac{C}{N}\right)_{dB} = (P_{tx})_{dBw} + (G_{AT})_{dB} - (L_{FS})_{dB} + \left(\frac{G_{AR}}{T_{sys}}\right)_{dB} - \kappa_{dB} - B_{dB} \tag{2.2}$$

where P_{tx} is the transmission power level, G_{AT}, G_{FS} and G_{rx} are transmitter antenna gain, free space signal attenuation and receiver antenna gain respectively. Moreover, κ is the Boltzmann constant; T_{sys} is the system noise temperature in Kelvin, and B is the transmission bandwidth in Hertz. Therefore Transmission power is an option to increase SNR at the receiver. With MPSK modulation where $m = \log_2 M$ and also coding rate $\frac{k}{n}$ where k is the number of information bits and n is the number of coded bits, the required bandwidth W is

$$W = \frac{n}{km} R \tag{2.3}$$

The selection of the coding rate depends on the BER required by the application. For MPSK modulation without coding the symbol error probability in AWGN channel is [33]

$$P_E = 2Q\left(\sqrt{\frac{2E_s}{N_0}} \sin\frac{\pi}{M}\right), \tag{2.4}$$

where $\frac{E_s}{N_0}$ is symbol-energy to noise-power spectral density, $Q(x)$ is the complementary error function and is defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{\infty}^{x} exp\left(-\frac{u^2}{2}\right) du, \tag{2.5}$$

Also $\frac{E_s}{N_0}$ is related to $\frac{E_b}{N_0}$ (bit-energy to noise-power spectral density) and $\frac{E_c}{N_0}$ (channel-bit energy to noise-power spectral density), via the following relation:

$$(\log_2 M)\left(\frac{k}{n}\right)\left(\frac{E_b}{N_0}\right) = (\log_2 M)\left(\frac{E_c}{N_0}\right) = \left(\frac{E_s}{N_0}\right) \tag{2.6}$$

Furthermore, $\frac{E_b}{N_0}$ is function of SNR and rate R:

$$\left(\frac{E_b}{N_0}\right)_{dB} = \left(\frac{S}{N_0}\right)_{dB-Hz} - R_{dB-\frac{bit}{sec}} \tag{2.7}$$

The symbol error probability given in 2.4 holds only when no coding is applied. When no coding is used, the $\frac{E_s}{N_0}$ in 2.4 can be replaced with $(\log_2 M)\left(\frac{E_b}{N_0}\right)$. However, using coding means less required energy per bit or $\frac{E_b}{N_0}$ for a fixed BER. The difference between $\frac{E_b}{N_0}$ when coding is used and the $\frac{E_b}{N_0}$ when no coding is used to reach the same amount of BER is called coding gain:

$$G(dB) = \left(\frac{E_b}{N_0}\right)_{uncoded}(dB) - \left(\frac{E_b}{N_0}\right)_{coded}(dB) \tag{2.8}$$

By knowing the coding gain, in case of using coding, a new $\frac{E_b}{N_0}$ is obtained which can be used in 2.4 for the coded BER. Although not mathematically simple for all types of coding schemes, the coding gain can be calculated for each coding scheme separately. Examples of coding gain for the BCH coding scheme with different sizes are given in

n	k	Coding Gain G (dB), MPSK $BER = 10^9$
31	26	2.0
63	57	2.2
63	51	3.1
127	120	2.2
127	113	3.3
127	106	3.9

Table 2.3: Bandwidth-compatible BCH codes [33].

Table 2.3.

To reach the required BER, the above symbol error probability can be used to acquire a minimum $\frac{E_s}{N_0}$ which is equivalent to $(\log_2 M)\frac{E_b}{N_0}$. If this value of $\frac{E_b}{N_0}$ is already equal to or less than SNR then, no coding is required to meet BER requirement. Otherwise coding should be used to compensate $\frac{E_b}{N_0}$. In the list of available coding schemes in the system, the one that has a gain that make $\frac{E_b}{N_0}$ just less than what is required for the BER could be chosen for the operation.

2.4.2 Cognitive Engine's Algorithm

In this section, an exhaustive algorithm for determination of communication parameters for the cognitive engine is given. We assume that the Signal-to-Noise-Ratio is estimated at the receiver with known SNR estimation techniques and returned to the transmitter. Therefore, every optimization problem is treated such that the transmitter knows the SNR. Then we can start with finding a good combination of settings on the parameters to reach the QoS objectives:
First we start inquiring the SNR from the receiver (note that the cognitive engine can be at the receiver side.) and then we derive $\frac{E_b}{N_0}$ with having the rate R requested by the application. Then from the list of available channels specified by the spectrum sensing module, we need to determine some bandwidth nominees. They include the ones with special length varying from a minimum to a maximum. The maximum bandwidth for communication is required for the situation where coding rate $\frac{k}{n}$ is minimal and $m = \log_2 M$ is also minimal, in the set of available modulation and coding schemes in the cognitive radio.

$$BW_{max} = R\left(\frac{n}{k}\right)_{max} / m_{min} \tag{2.9}$$

The opposite situation holds for the minimum bandwidth where

$$BW_{min} = R\left(\frac{n}{k}\right)_{min} / m_{max} \tag{2.10}$$

As an example, for a system including BPSK, QPSK and 8-PSK modulation schemes and coding rates 2/3, 1/2 and 1/3, the maximum bandwidth is $3R$ and the minimum is $R/2$. Thus we need to look for the bandwidth fit for such rates in the spectrum sensing result vector. In the next step, we look for the combination of modulation and coding rate in the given list from the previous step which gives a BER below the requested amount. For the start we check from the highest m because highest m means higher bandwidth efficiency. Also as m increases, higher $\frac{E_b}{N_0}$ is needed for a certain BER. In other words, higher m equals higher BER. All those m values that result in a sufficient BER for the system are kept in a new list plus the ones that can be potentially suitable if combined with coding. In other words, the search process also includes those modulations whose corresponding $\frac{E_b}{N_0}$ (with respect to the required BER) can be compensated by coding.

If the gain for the available coding schemes are available to the cognitive engine then it is easy to search for the suitable candidate combinations of modulation and coding schemes. At the end of this step a list of possible combinations for modulation and coding schemes is obtained in which some of the cases may require special coding and some may not. In this list, all options now satisfy the required R and BER conditions.

In the next step the problem must be optimized in favor of other QoS objectives i.e., Spectral Efficiency and the average interference on the selected bands. It should be noted that in the first iteration of the algorithm, all the calculations are done with having the minimum transmit power in the system. Once the iteration is done for all QoS objectives referred to above and we don't have any candidate on the list, then we need to increase the power with a known amount depending on the power control module of the transceiver in order to reach a higher SNR at the receiver and do another iteration of the specified algorithm. Figure 2.4 is a graphical representation of the above algorithm.

In the flowchart of Figure 2.4, there are a number of ambiguities of various types, i.e., implementation, conceptual and also system-related; those must be solved. The way the algorithm is interfaced to the user, policy engine and also spectrum sensor is the implementation ambiguity. We mentioned above that if at the end of the iteration of the exhasutive search for finding the optimal transmission settings no optimal set is found, the transmission power must be increased. The amount of increase in transmit power in each iteration is a system-related ambiguity. And finally it should be conceptually resolved that how the SNR is estimated and how transmitter and receiver are synchronized. We try to resolve the latter issue in the next chapter of the thesis.

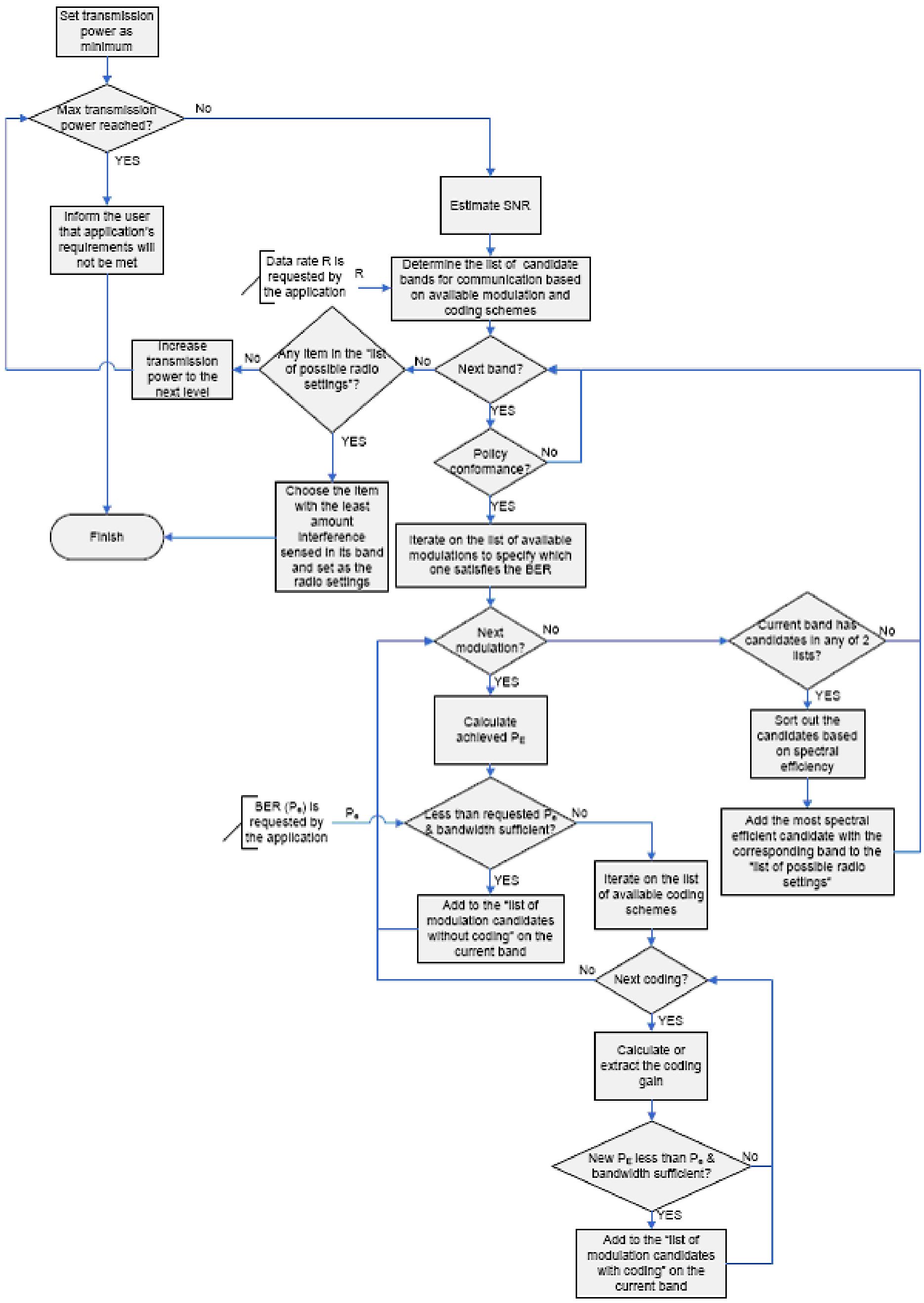


Figure 2.4: A flowchart of an exhaustive algorithm for the cognitive engine.

Spectrum Sharing Protocol 3

In this chapter of the thesis, we discuss a protocol with which the cognitive radios, whose architecture was illustrated in the previous chapter, can communicate with each other.

3.1 Background Discussion

One major application of cognitive radio is the ability to adapt one's radio physical layer (PHY) properties to optimize the overall system performance. This may include changing center frequency, bandwidth, modulation type and coding parameters [6]. In [30,31], genetic algorithms are proposed to optimize the above components in a joint manner to reach the optimum system performance. But no systematic protocol for these algorithms to work in a network of nodes is available. Many MAC protocols have been proposed to enable spectrum sharing among cognitive radios. A survey of MAC protocols for opportunistic spectrum access is given in [28]. For instance, Liangping et al. [23] have proposed the DOSS non-centralized spectrum sharing protocol to enable secondary users to communicate with each other when no primary user is present. But their protocol works with multiple radio transceivers and is based on the setup of a control channel to exchange communication parameters they want to use. Other MAC protocols like C-MAC [8] are also based on the concept of a dynamic control channel which changes over time. In [17, 18], a protocol for link rendezvous is proposed. Link rendezvous [29] is the process for CR network nodes to rendezvous with each other based on the sensed spectral environment. The protocol in [17, 18] is based on sending analog attention signals for the connection setup and signal feature detection at the receivers which is more complex than energy detection. In this chapter we propose a PHY signaling (link rendezvous) protocol that enables secondary users to rendezvous through digital signaling with the use of energy detection spectrum sensing. This protocol enables each cognitive radio to discover the communication parameters by itself without the need to setup any redundant MAC control channel. Also it finds the optimum transmission power for the signal to guarantee the required bit error rate.

3.2 System Model

In the previous chapter, we discussed the cognitive engine design and how to deploy an algorithm in it to optimize communication parameters based on the data Rate and BER requirements and also the channel condition. In this chapter, a signaling protocol for non-cooperative communication between two or more cognitive radios, capable of using multiple waveforms, is elaborated. The word "non-cooperative" refers to the fact that the radio which receives the call (callee) from the calling radio (caller) is not aware of the waveform of the signal. For the communication to be carried out, the callee must recognize the waveform by analysing the received signals and respond to the caller. In our model, each radio is equipped with a spectrum sensing module and a policy database engine. The radio continuously scans a predefined spectrum range (e.g., the HF band). The following table represents an example of some radio settings used in the STANAG4285. In Table 3.1, moving to the lower options (waveforms) means lower

Rate(bps)	Modulation	Coding Rate
2400	8-PSK	-
1200	QPSK	-
600	BPSK	-
300	BPSK	1/2
150	BPSK	1/4
75	BPSK	1/8

Table 3.1: Cognitive Radio settings.

BER and also lower bit-rate and vice versa. In contrast to bit-rates which are exactly defined in the Table 3.1, the range for the BER could be different depending on the SNR or more precisely $\frac{E_b}{N_0}$. As discussed in the previous chapter, the only setting on the radio that impacts the SNR is the transmission power. So in order to reach the required BER, power must be adjusted on the radio. In Chapter 2 we presented a joint optimizing algorithm for the cognitive engine to achieve QoS requirement. That optimizing algorithm outputs all the radio settings i.e., modulation, coding, etc for the given QoS requirements. But redefining the problem in this chapter and restricting the rate options to certain modulation and coding sets, eases the problem and diminishes it to a power control problem. In other words, according to what is requested by the application for the data rate, a pair of modulation and coding from the above table is chosen. But for the BER requirement of the application, only transmission power must be adjusted. We assume that the maximum adjustable power on each frequency channel is posed by the policy engine to the radio to limit interference to the primary users. Also the minimum power on the channel is a function of SNR and the required BER. Thus a protocol is required for the transmitter to estimate the SNR at the receiver and also to help to synchronize both radios on the same frequency channel. This protocol is called bootstrapping [28] as the initiation of cognitive radio operation. For the start of the dynamic spectrum access communication, not only the caller but also the callee will sense the spectrum in order to recognize each other on a specific channel with some specific detected energy pattern which is explained in the next section. We propose a signaling protocol for dynamic access to a static set of contigous frequency channels. An assumption is made for designing such a protocol: the sensing time for all the radios in the network is the same. The term sensing time is the time that it takes to scan the whole working band of each radio. The cognitive radio is assumed to be in one of the four states at each time shown in Figure 3.1. The above state machine can be adopted for any radio either at the caller side or the callee side.

Idle (sensing): While not communicating, the radio is in the idle state and will

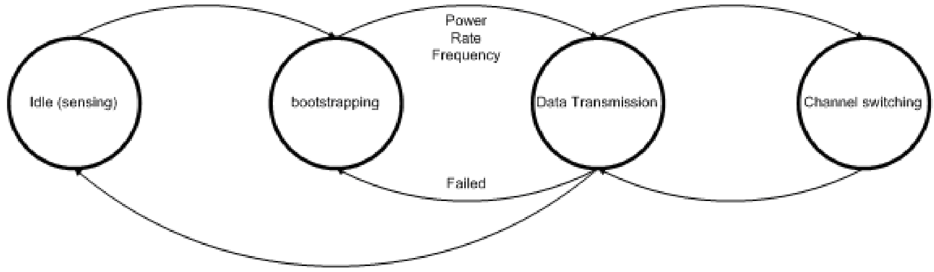
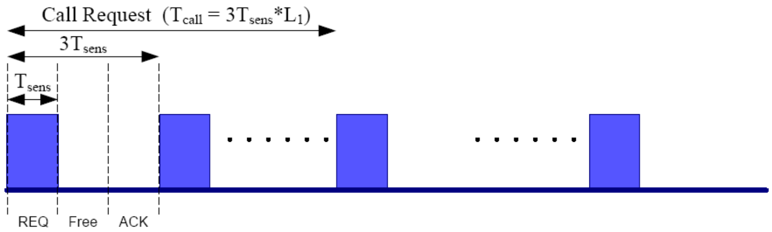


Figure 3.1: Cognitive radio state machine.

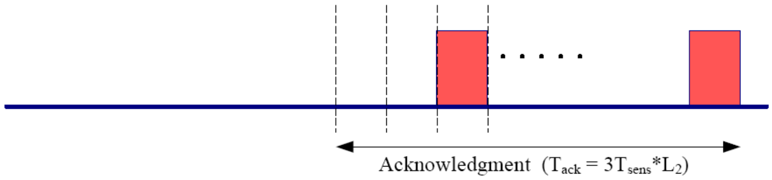
continuously sense the channels repeatedly by means of energy detection. The time taken to sense all the channels is considered at T_{sens} and is assumed to be fixed for all the radios. Needless to say that T_{sens} depends on the complexity of the sensing algorithm, working bandwidth and the agility of the sensing hardware. T_{sens} can be lowered with the advance of technology.
Bootstrapping: The proposed bootstrapping consists of eight phases run jointly by the caller and the callee. It starts with channel and data rate selection and call request signaling by the caller. Then the callee goes through call detection, SNR estimation, modulation recognition, and acknowledgment signaling. In the sequel, the caller will accomplish the bootstrapping by SNR estimation and power adjustment.

Channel & Rate Selection: Assuming perfect spectrum sensing, the caller picks a channel where no primary user is active. Also the application running on the radio may require a minimum data rate R and a maximum BER. For the rate R, the caller picks the closest rate in the Table 3.1. Obviously, each rate profile corresponds to a modulation and coding pair for the radio operation. Also for the chosen M and AWGN channel, the BER is a function of SNR [33]. The selected coding scheme also has an effect on the BER. In Section 2.4.1, relations for the calculation of BER for a pair of PSK modulation and coding are given. The other parameter necessary for determining the BER is SNR. It was already mentioned that the only setting on the radio that impacts the sensed SNR at the receiver is the transmission power. Thus, in order to reach the required BER, the caller must somehow measure the SNR at the callee side where we assume that it is the same as the caller side.

Call Request Signaling: Tuning the RF front-end to the selected channel and the chosen rate and using maximum allowable transmission power, the cognitive radio starts transmitting preamble data over the channel to the target radio with on-off keying signaling. The preamble in the signal contains the address of the target radio. In Figure 3.2, the pattern used for such on-off keying is shown. The OOK period is $3T_{sens}$. Each period is divided to 3 slots: *REQ*, *Free* and *ACK*. During Call Request, the signal is ON in *REQ* slot and it is OFF in *Free* and *ACK*. The signal lasts T_{sens} because at the receiver, the spectrum sensing will definitely sense a track of the signal on the transmitting channel. In other words, if the spectrum sensing takes T_{sens} in iteration of all the channels and on one of the channels, there is an incoming signal



(a)



(b)

Figure 3.2: Bootstrapping process with on-off keying signaling: (a) Call Request signaling vs. Time at the caller side, (b) Acknowledgment signaling vs. Time at the callee side.

lasting for T_{sens} this signal will be surely detected (in case spectrum sensing is perfect). This holds also for OFF periods when no signal is transmitted and the spectrum sensing will sense no signal on the transmitting channel.

Call Detection: Those radios in the network which are in reach of the signal and are not involved in any other communication, including the target callee, periodically sense the band and keep a history of specific length L_1 of the detected energy in each channel and also the decision they have made about the existence of a signal in that channel. The value of L_1 should not be too small such that the OOK pattern is mistaken by a primary user nor it should be too large that it overloads the network and makes the bootstrapping too long. An analysis on the amount of L_1 is given in Chapter 5. Once an OOK pattern of Fig. 3.2(a) is observed by spectrum sensing, a call is presumed to be taken place from a node.

SNR Estimation at the Callee Side: Considering AWGN channel, what is received at the callee RF front-end during the OFF period is only Gaussian noise and during the ON period it would be signal plus Gaussian noise. Therefore by averaging over the available power samples in the OFF periods, an approximation of noise power is obtained. Equivalently an average of the signal power samples during the ON periods approximates signal-plus-noise power from which the noise power is subtracted and pure signal power is obtained.

Modulation and Coding Recognition: Since the communication is supposed to be non-cooperative, the callee has no information about the MPSK modulation used in the IF signal nor about the coding scheme. To be able to demodulate the symbols out of the signal, the callee must know the modulation. If the modulation is BPSK, a cycle for extracting the coding scheme will also be considered. This process will also be explained in Chapter 4.

Acknowledgment Signaling: After identification of the modulation and coding, the receiving radios are able to demodulate the signal and take the preamble out. Then the radios other than the target callee will discard the communication and the callee start acknowledging to the caller by on-off keying after tuning on the new frequency channel, modulation and coding and using maximum allowable transmission power for L_2 periods. The pattern used for acknowledgment signaling is shown in Figure 3.2(b) against the Call Request signaling. It can be seen that the acknowledgment signal is transmitted in the ACK slot as it is reserved in Figure 3.2(b). Since a radio with one RF Front-End is not able to transmit and receive at the same time, either the caller or the callee can hear each other during their off period. As can be seen in Figure 3.2, the callee senses an on-off keying pattern with duty cycle 50% during its off period and the same for the caller when the reply is received.

Noise Estimation at the Caller Side: At the caller, the on-off keying acknowledgment is received for L_2 periods. Then, the caller radio starts estimating the noise from the incoming on-off keying specifically during the Free Slot.

Power Adjustment: Assuming that the noise experienced at the caller side is equal to the noise at the callee side, the caller can adjust its signal power to meet the required BER by the application based on probability of error for the received symbol given in 2.4.

Data transmission: In this state, the radio works in frames. A small fraction of each frame will be assigned to spectrum sensing in order to make sure that no primary user is present yet. Such frame partitioning methods are discussed in the literature in the spectrum sharing topic. One instance of such method is given in [8].

Channel Switching: When a primary user enters and starts using the licensed spectrum during the data transmission of our radio, a channel switching procedure must be performed. As a backup channel is always considered during handshaking (bootstrapping), both the caller and the callee can move to the new frequency channel and continue the communication. The main characteristic of the proposed protocol is its ability to make handshaking possible without any exchange of radio configuration data or setting up a control channel. At any point during the bootstrapping the communication might fail. These failing scenarios are discussed in the Chapter 5.

4 Parameter Estimation

4.1 SNR Estimation

4.1.1 Background Discussion

Signal-to-noise ratio (SNR) is defined as a measure of signal strength relative to background noise [40] and it is an important measure for the channel quality and QoS measurements is fully dependent on this parameter. In practice, the SNR is unknown to the transmitter and must be estimated by the receiver [27]. Hence, most of the proposed SNR estimation techniques are based on the assumption of known modulation of the received signal. For instance in [1], 4 estimate measures of SNR are compared for QPSK modulated signals. Furthermore, SNR estimators are categorized as data-aided (DA), which assume the knowledge of the transmitted symbols, and non-data-aided (NDA) estimators, which do not [14]. Of course, because of the higher flexibility and less use of resources during the communication, NDA methods are of higher interest. Recently, with the emergence of Software-Defined Radios, the trend has moved to the design of methods that are unaware of the signal's modulation and more specifically estimation of the SNR from the IF samples. One such estimator is the so-called generalized split-symbol moments estimator (SSME) [16]. The conventional version of this estimator forms its SNR estimation statistic from the sum and difference of information extracted from the first and second halves of each received data symbol. But the generalized version reconfigures the conventional version with partitioning the symbol interval into a larger number of subdivisions than the two that characterize the conventional SSME. It is also shown that this method works for all M-PSK modulations and can be extended to two dimensional modulations (polar space), e.g. QAM, as well. It is also shows a better performance than the conventional SSME. In [40], a blind SNR estimation algorithm is presented based on Eigen value decomposition of the correlation matrix of the received signals and the principle of combined information criterion. This method has also no need to prior information of the modulation or any thing else and only treats received digitized signal samples. It is also shown that this method works with the same performance for different modulation schemes including MPSK, QAM, FSK and etc. While the maximum-likelihood (ML) approach to the problem will result in the highest quality estimator, as is typically the case with this approach, it results in a structure that is quite complex unless the receiver is provided with some knowledge of the data symbols typically obtained from data estimates made at the receiver [16]. Having prior information about the signal helps to have more accurate SNR estimation but it is not always applicable. However, in the proposed protocol in Chapter 3, a signal pattern is proposed to be sent for call request to help the receiver to estimate the SNR based on the ON or OFF signal states. This is fully explained in the next subsection.

4.1.2 SNR Estimation in the Spectrum Sharing Protocol

In the previous chapter, we described a non-centralized signaling protocol for bootstrapping to initiate a communication between nodes in a dynamic spectrum access network. One phase of this bootstrapping is SNR estimation to determine how much power is needed to meet the BER requirements in the data transmission phase. Considering an AWGN channel, what is received at the callee RF front-end during the OFF period is only Gaussian noise and during the ON period it would be signal plus Gaussian noise. Therefore, by averaging over the available power samples in the off periods, an approximation of the noise power is obtained. Equivalently an average of the signal power samples during the on periods approximate signal-plus-noise power from which the noise power should be subtracted and pure signal power is obtained. The only thing that should be known to the cognitive engine is the on and off times which are based on the reports of the spectrum sensing. Spectrum sensing supplies the detected power in each frequency band and also the decision made about the presence or absence of a signal in each band to the cognitive engine. More specifically, there are two hypotheses as follows:

$$\mathcal{H}_0 : Y[s] = W[s], \quad s = 1, \ldots, S \tag{4.1}$$

$$\mathcal{H}_1 : Y[s] = X[s] + W[s], \; s = 1, \ldots, S. \tag{4.2}$$

Here the $X[s]$, $W[s]$ and $Y[s]$ values are signal, noise and observed power samples respectively. All samples are assumed to be iid. S is the number of times the channel is sensed which is equal to $3L_1$ (see Figure 3.2(a)). The spectrum sensor decides on one of the two hypotheses and reports the $Y[s]$ value and its decision to the cognitive engine. From the observed power samples, approximations of signal power A and noise power N will be obtained

$$A = \left(\frac{1}{K} \sum_{\mathcal{H}[s]=\mathcal{H}_1} Y[s] \right) - \left(\frac{1}{S-K} \sum_{\mathcal{H}[s]=\mathcal{H}_0} Y[s] \right) \tag{4.3}$$

$$N = \frac{1}{S-K} \sum_{\mathcal{H}[s]=\mathcal{H}_0} Y[s] \tag{4.4}$$

where K is the number of signal samples and will be equal to L_1 for the proposed signaling. Having A and N, an estimation of SNR is obtained

$$SNR = 10 \log_{10} \frac{A}{N}. \tag{4.5}$$

It should be mentioned again that this estimation method totally relies on the fact that spectrum sensing will make the right decision on the presence or absence of the signal. This method might not be feasible in general cases where there is no information about when the signal is present and when it is not. But for the proposed protocol, this is the least complex and most accurate method that can be adopted.

4.2 Modulation Recognition

4.2.1 Background Discussion

Modulation recognition is a topic with a long history in communication research. It has lots of applications in the military field when exposed to enemy's unknown signals. But with the emergence of Software-Defined and Cognitive Radios, a need for such technique has emerged since any cognitive radio may want to non-cooperatively communicate with other radios in the environment. Noise addition to the modulated signal is an irreversible mapping. If the signal modulation is not known at the receiver and the channel through which the signal is transmitted is noise-free, the modulation scheme of the signal can be easily estimated and the symbols can be extracted. But otherwise when noise, which is a random signal, is added to the signal, then identification of the signal will become challenging. The aim of the modulation recognition process is to actually estimate the modulation used in the noisy signal. With decreasing SNR, it becomes more difficult to figure out the modulation type. The robustness of modulation recognition methods are measured with their performance in low SNRs. A complete survey of modulation recognition methods of both types referred to above, are given in [11]. Generally, there are two modulation estimation techniques. They are linear and non-linear modulation feature estimation. The first one minimizes the errors between IF features (such as amplitude, phase, and frequency) and their matching templates. The non-linear modulation feature estimation involves non-linear transforms (such as power-law and moments) [36]. The above methods do not assume any prior information about the signal and they just use pattern recognition methods or template comparison methods to identify the modulation. But with the presence of prior information, one could improve the accuracy of modulation recognition. For instance, SNR information or the amount of noise in the signal can outstandingly improve the modulation recognition. In [16], an optimum (maximum likelihood) and a suboptimum classifier are presented with formulations based on known SNR and carrier frequency and symbol duration. The suboptimum classifier is much less complex with very low degradation in performance with respect to the optimum one. The proposed schemes are given for PSK modulation and AWGN channel. Among the modulation recognition methods specifically for SDRs, [38] has proposed a scheme for distinction among BPSK, QPSK, 8-PSK and 16QAM. The method is based on a phase difference distribution among received symbols and also flat fading channel. Because of no prior information about the signal, this method lacks performance while even for SNR values more than 20 dB, the modulation recognition is not 100% correct. Also [41] has proposed a suboptimal method for recognition of PSK modulation schemes based on the known SNR. This method is explained in detail in the next subsection.

4.2.2 Modulation Recognition in the Spectrum Sharing Protocol

For PSK schemes the phase of the signal and its distribution is the decisive factor. A suboptimal but computationally simple algorithm is proposed in [41] based on the phase distribution. In [2], the Tikhonov function is given as the phase pdf of a received

CW signal buried in AWGN:

$$p(\psi) = \frac{exp(2\gamma \cos(\psi)}{2\pi I_0[2\gamma]} \tag{4.6}$$

where $I_0[.]$ is the modified Bessel function of zero order and first kind, and γ is the signal-to-noise ratio. Combining the above expression with BPSK, QPSK and 8-PSK constellation distribution, leads to the below pdfs for noisy BPSK, QPSK and 8-PSK signals

$$p(\psi; BPSK) = \frac{1}{2\pi I_0[2\gamma]} \cosh[2\gamma \sin(\psi)], \tag{4.7}$$

$$p(\psi; QPSK) = \frac{1}{2\pi I_0[2\gamma]} \cosh[\sqrt{2}\gamma \cos(\psi)] \cosh[\sqrt{2}\gamma \sin(\psi)] \tag{4.8}$$

$$\begin{aligned} p(\psi; 8PSK) = \frac{1}{4\pi I_0[2\gamma]} \{&\cosh\left[2\gamma \cos(\psi)\cos(\frac{\pi}{8})\right] \cosh\left[2\gamma \sin(\psi)\sin(\frac{\pi}{8})\right] \\ &+ \cosh\left[2\gamma \cos(\psi)\sin(\frac{\pi}{8})\right] \cosh\left[2\gamma \sin(\psi)\cos(\frac{\pi}{8})\right]\}. \end{aligned} \tag{4.9}$$

For each PSK scheme a measure is derived based on a multivariate maximum a posteriori (MAP) decision function $p(\psi_L|H_\alpha)$ where α is 1, 2 or 3 for each of BPSK, QPSK and 8-PSK modulations. Also we assume L received samples of the signal which are iid. Thus, the joint probability density $p(\psi_L|H_\alpha)$ is

$$p(\psi_L|H_\alpha) = \prod_{L}^{i=1} p(\psi(i)|H_\alpha) \tag{4.10}$$

Based on the MAP function, the scheme that has the highest $p(\psi_L|H_\alpha)$ is chosen as the estimated modulation for the signal. More precisely, the likelihood measures for BPSK, QPSK and 8-PSK correspond to l_{bpsk}, l_{qpsk} and l_{8psk} respectively.

$$l_{bpsk} = \sum_{i=1}^{L} \ln\left(\cosh[2\gamma\alpha(i)]\right), \tag{4.11}$$

$$l_{qpsk} = \sum_{i=1}^{L} \ln\left\{\cosh[\sqrt{2}\gamma\alpha(i)] \cosh[\sqrt{2}\gamma\beta(i)]\right\}, \tag{4.12}$$

$$\begin{aligned} l_{8psk} = \sum_{i=1}^{L} \ln \frac{1}{2} \{&\cosh[2\gamma\alpha(i)\alpha_c] \cosh[2\gamma\beta(i)\beta_c] \\ &+ \cosh[2\gamma\alpha(i)\beta_c] \cosh[2\gamma\beta(i)\alpha_c]\}. \end{aligned} \tag{4.13}$$

The above measures are extendable to higher order PSK constellations like 16-PSK, etc. But they are not used in practice.
It is worth mentioning that we tried to justify our own modulation recognition method

based on the distribution of I and Q samples. But at the end it could not outperform the method proposed in [41]. Anyhow, we present our efforts below and compare its results with the ones in [41] in Chapter 5. First we derived the pdf for both I and Q samples of the received signal for the AWGN channel. The AWGN channel is supposed to add Gaussian noise with mean 0 and variance σ^2. For each PSK constellation, a zero carrier phase was assumed as is shown in the figure below.

In the original (zero carrier phase) BPSK constellation, the I component is either 1 or -1 while the Q component is 0. Therefore, in the noisy constellation each component has the following pdf

$$p(I;2) = \frac{1}{2}\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(I-1)^2}{2\sigma^2}} + \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(I+1)^2}{2\sigma^2}}\right) \tag{4.14}$$

$$p(Q;2) = \frac{1}{2}\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{Q^2}{2\sigma^2}}\right) \tag{4.15}$$

For a QPSK constellation with 4 constellation points, each of the I and Q components have values 0 in two points and 1 in one point and -1 in one point. For each of them the following pdfs can be imagined

$$p(I;4) = \frac{1}{4}\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(I-1)^2}{2\sigma^2}} + \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(I+1)^2}{2\sigma^2}} + \frac{2}{\sigma\sqrt{2\pi}}e^{-\frac{I^2}{2\sigma^2}}\right) \tag{4.16}$$

$$p(Q;4) = \frac{1}{4}\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(Q-1)^2}{2\sigma^2}} + \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(Q+1)^2}{2\sigma^2}} + \frac{2}{\sigma\sqrt{2\pi}}e^{-\frac{Q^2}{2\sigma^2}}\right) \tag{4.17}$$

Finally for 8-PSK, I and Q components can have values -1 (one point), $-\frac{\sqrt{2}}{2}$ (two points), 0 (two points), $\frac{\sqrt{2}}{2}$ (two points) and 1 (one point). Then the pdf for each component is

$$\begin{aligned} p(I;8) = \frac{1}{8}(&\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(I-1)^2}{2\sigma^2}} + \frac{2}{\sigma\sqrt{2\pi}}e^{-\frac{(I-\frac{\sqrt(2)}{2})^2}{2\sigma^2}} + \frac{2}{\sigma\sqrt{2\pi}}e^{-\frac{I^2}{2\sigma^2}} \\ &+ \frac{2}{\sigma\sqrt{2\pi}}e^{-\frac{(I+\frac{\sqrt(2)}{2})^2}{2\sigma^2}} + \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(I+1)^2}{2\sigma^2}} \end{aligned} \tag{4.18}$$

$$\begin{aligned} p(Q;8) = \frac{1}{8}(&\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(Q-1)^2}{2\sigma^2}} + \frac{2}{\sigma\sqrt{2\pi}}e^{-\frac{(Q-\frac{\sqrt(2)}{2})^2}{2\sigma^2}} + \frac{2}{\sigma\sqrt{2\pi}}e^{-\frac{Q^2}{2\sigma^2}} \\ &+ \frac{2}{\sigma\sqrt{2\pi}}e^{-\frac{(Q+\frac{\sqrt(2)}{2})^2}{2\sigma^2}} + \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(Q+1)^2}{2\sigma^2}} \end{aligned} \tag{4.19}$$

Of course if other constellation schemes (e.g., with some carrier phase) is used for modulations, the above distributions will be different and will not be very difficult to derive. But we carry on our calculation with no carrier phase as above. We used the same criterion as proposed in [41] to derive mathematical expressions for each PSK scheme. The criterion was maximum a posteriori for a random vector of L signal samples $p(I_L + Q_L|H_\alpha)$. With further calculations the following measures l_{bpsk}, l_{qpsk} and l_{8psk} for each of the BPSK, QPSK and 8-PSK schemes were derived

$$l_{bpsk} = \sum_{i=1}^{L} \left[\ln \left\{ 2\cosh \left[\frac{A(i)}{\sigma^2} \right] \right\} - \frac{A(i)^2 + 1}{2\sigma^2} \right] - L \ln 2 \tag{4.20}$$

$$l_{qpsk} = \sum_{i=1}^{L} \left\{ \ln \left[6 + e^{\frac{4A(i)-4}{2\sigma^2}} + e^{\frac{-4A(i)-4}{2\sigma^2}} + 4e^{\frac{2A(i)-1}{2\sigma^2}} + 4e^{\frac{-2A(i)-1}{2\sigma^2}} \right] - \frac{A(i)^2}{2\sigma^2} \right\} - L \ln 16 \tag{4.21}$$

$$\begin{aligned} l_{8psk} = \sum_{i=1}^{L} \Big\{ \ln \Big[& 14 + e^{\frac{4A(i)-4}{2\sigma^2}} + e^{\frac{-4A(i)-4}{2\sigma^2}} + 4e^{\frac{2A(i)-1}{2\sigma^2}} + 4e^{\frac{-2A(i)-1}{2\sigma^2}} \\ & + 4e^{\frac{2\sqrt{2}A(i)-2}{2\sigma^2}} + 4e^{\frac{-2\sqrt{2}A(i)-2}{2\sigma^2}} + 8e^{\frac{\sqrt{2}A(i)-0.5}{2\sigma^2}} + 8e^{\frac{-\sqrt{2}A(i)-0.5}{2\sigma^2}} \\ & + 4e^{\frac{(-2-\sqrt{2})A(i)-(1.5+sqrt2)}{2\sigma^2}} + 4e^{\frac{(2+\sqrt{2})A(i)-(1.5+sqrt2)}{2\sigma^2}} + 4e^{\frac{(-2+\sqrt{2})A(i)-(1.5-\sqrt{2})}{2\sigma^2}} \\ & + 4e^{\frac{(2-\sqrt{2})A(i)-(1.5-\sqrt{2})}{2\sigma^2}} \Big] - \frac{A(i)^2}{2\sigma^2} \Big\} - L \ln 64 \end{aligned} \tag{4.22}$$

where $A(i) = I(i) + Q(i)$, the sum of I and Q components for the sample i. As mentioned earlier, the above expressions could not outperform the method in [41] in PSK modulation recognition. Thus, we decided to adopt the former method in the system.

4.3 Channel Encoding Recognition

In Chapter 3, convolutional codes with three different coding rates $\frac{1}{2}$, $\frac{1}{4}$ and $\frac{1}{8}$ were used along with three MPSK modulation levels in order to have multiple levels of BER available for the system. In the previous section, a method was adopted for signal modulation recognition. In this section, a method for channel coding recognition will be discussed.

For decoding the convolutional coded data, the Viterbi algorithm is proposed. The Viterbi decoding algorithm for convolutional codes can be easiest described using the trellis representation [39]. Since coding with different rates is applied to the data in different BER conditions, the proper trellis structure used for these coding rates is different. The channel encoding recognition module for our cognitive radio should be able to identify the coding rate. Then the cognitive radio will use the corresponding trellis to decode the data. Methods for adaptive channel coding are proposed using supplementary information for the receiver or feedback to the transmitter [21] [22]. But these methods are not of interest for non-cooperative communication as required by a cognitive radio.

To the best of our knowledge, little research effort has been done on channel coding recognition. A method for adaptive channel coding using a finite state machine is proposed in [19]. In contrast to the adopted modulation recognition method in the previous section, where we had 100% probability of correct recognition for SNRs more than a specific value, in [19] even for very high SNR values, we still have a small chance of wrong code detection. Anyway, channel coding recognition can be a topic for further research.

Performance Analysis Results 5

In this chapter, a performance evaluation of the signaling protocol proposed in Chapter 3, is presented. We consider three measures of performance. Those are the connection (bootstrapping) time, probability of a successful connection and energy efficiency.

5.1 Probability of a Successful Connection

Other than T_{sens}, the connection time (T_{boot}) also depends on the number of on-off periods $(L_1 + L_2)$ for the whole bootstrapping phases to be completed and is as follows (see Figure 3.2)

$$T_{boot} = 3\,(L_1 + L_2)\,T_{sens} \tag{5.1}$$

Due to the dynamic access nature of the protocol, some scenarios might happen during T_{boot} that fails the bootstrapping and they are given as follows:

5.1.1 Primary users presence

Activation of primary users are the main reason for the caller and the callee to vacate the channel. Since we assume radios with only one RF Front-End, either the caller or the callee are not able to transmit and receive at the same time. More specifically, the Caller transmits during the REQ slot and starts sensing during *Free* and ACK slots. Furthermore, when Acknowledgment starts, the callee transmits the acknowledgment during the ACK and senses during the REQ and *Free*. According to Figure 3.2, presence of any signal during the *Free* and ACK slots of the Call Request phase the caller terminate the bootstrapping. Also if any signal is detected during the *Free* slot of the Acknowledgment by either the caller or the callee, they will stop the communication.

5.1.2 No Acknowledgment

There are situations that no acknowledgment is received by the caller. One could be failed modulation recognition by the callee and consequently failure in extracting the preamble. Also the target might be in a deep fade and can not detect the Call Request.

5.1.3 Interference From Other Nodes

During the Call Request phase of the caller, there's a possibility that another node finds the channel as unused during *Free* and ACK slots and starts another bootstrapping process. In such a case the caller would immediately terminate its transmission and vacate the channel to avoid any hypothetical interference to the primary users, because it can not tell if the intefrering source is the primary user or is another secondary user. Also those radios which were involved in another communication during the Call Request phase and are released during the Acknowledgment phase, might need to start a new communication and sense the channel during the *Free* slot as unused and start bootstrapping. In this scenario the original bootstrapping will fail too. To give a mathematical interpretation of such scenarios we use α as the average percentage of the time that primary users are present in the whole band, n as total number of channels and λ as the average traffic rate of the cognitive network (number of bootstrapping attempts per second). Assuming a Poisson distribution for the incoming bootstrapping attempts and regarding the average traffic rate for a single channel which is $\frac{\lambda}{(1-\alpha)n}$, the probability of bootstrapping without collision is

$$P_{nocol} = P_{req}P_{ack} = \left(e^{\frac{-2\lambda T_{sens}}{(1-\alpha)n}}\right)^{L_1} \left(e^{\frac{-\lambda T_{sens}}{(1-\alpha)n}}\right)^{L_2} \tag{5.2}$$

where P_{req} and P_{ack} are the probabilities of no collsion at Call Request and Acknowledgment phases respectively.

5.1.4 False detection of On-Off Keying Pattern

If the spectrum sensors at either sides fail to detect the signal in any of the *REQ* and *ACK* slots or mistakenly announce the presence of the signal in the *Free* slot, Call Request and Acknowlegment patterns will not be correctly recognized and consequently the bootstrapping process will fail. With any energy detection sensing algorithm there is a P_{fa} and a P_d value which are false alarm and detection probabilities, respectively [5]. More specifically, P_{fa} is the probability that no signal is present in the channel but spectrum sensing mistakenly senses a signal. Also P_d is the probability that a signal is present in the channel and correctly detected by spectrum sensing. Considering sensing time as fixed means that the observed number of samples are also fixed. This means that P_{fa} and P_d are functions of SNR. Therefore, the minimum of these two parameters for the lowest operable SNR conditions of the radio are considered here as fixed values. Based on these values guaranteed by the sensing algorithm, the probability of a correctly received OOK pattern in both Call Request and Acknowledgment phase is given by

$$P_{OOK} = P_{CRP}P_{AP} = {P_d}^{L_1+L_2} \left(1 - P_{fa}\right)^{2L_1+L_2}. \tag{5.3}$$

where P_{OOK}, P_{CRP} and P_{AP} are the probabilities of full correct received OOK during bootstrapping, Call Request phase and Acknowledgment phase.

Due to the independence of sensing and collision events, P_{ook} and P_{nocol} can be multiplied to derive the total probability of successful bootstrapping.

$$P_{success} = {P_d}^{L_1+L_2} \left\{\left(1 - P_{fa}\right) \left(e^{\frac{-\lambda T_{sens}}{(1-\alpha)n}}\right)\right\}^{2L_1+L_2} \tag{5.4}$$

5.2 Energy Consumption

The proposed bootstrapping process is designed to work with the maximum allowable transmission power P_{max}. However when bootstrapping ends, the optimum power is adjusted on both communicating nodes and the actual data transmission is done with the minimum required power P_{opt} in the present SNIR condition. Therefore, the total consumed energy during the bootstrapping is

$$E_{boot} = (L_1 + 2L_2)\, T_{sens} P_{max} \tag{5.5}$$

Consider T_{TR} as the time required for the actual data transmission with the requested data rate, then the energy efficiency of the protocol is as follows:

$$\gamma_1 = \frac{P_{opt} T_{TR}}{P_{opt} T_{TR} + E_{boot}} \tag{5.6}$$

In contrast to our protocol, a hypothetical protocol without bootstrapping can be considered which is not power-optimized and uses power P where $P_{opt} \leq P \leq P_{max}$. The energy efficiency for such a hypothetical protocol is

$$\gamma_2 = \frac{P_{opt}}{P} \tag{5.7}$$

Assuming L_1 and L_2 as equal, a constraning relation on the value of L_1 to outperform the hypothetical protocol with respect to the consumed energy is obtained

$$L_1 \leq \frac{T_{TR}\,(P - P_{opt})}{3T_{sens} P_{max}} \tag{5.8}$$

5.3 Numerical Results

SNR estimation accuracy is important since the power adjustment phase is based on its result. The accuracy of the algorithm is evaluated with $L_1 = 50$. A hundred baseband random bits are mapped with QPSK symbols and modulated with signal carrier frequency of 8 Hz and oversampling ratio of 20. The noise standard deviation (square root of power) in the signal is varied from 0 to 10. Figure 5.1 shows the accuracy of estimated SNR versus the real SNR within the range [-25,20] dB. It is shown that the estimation is almost accurate down to SNR of -10 dB. The accuracy of the SNR estimation for a different number of on-off periods (L_1) is also evaluated for SNR -3 dB. It is observed from Figure 5.2 that the estimation accuracy is steady for L_1 values beyond 100.

Figure 5.3 shows the simulation results of the modulation detection algorithm. For each MPSK, the performance is measured once with the estimated SNR and once with the real SNR. The range for actaul carrier-to-noise-ratio (CNR) is -15 to 15 dB and 100 baseband bits with oversampling ratio 4 and $L_1 = 25$ are used. Figure 5.3 shows that BPSK is totally identified for the signals with SNR as low as -15 dB. For QPSK and 8-PSK signal, the performance of the algorithm degrades and the reliable recognition starts from -3 and 2 dB respectively. Interestingly, it is observed that estimation error in low SNRs has no obvious impact on the modulation recognition. To perfectly check the effect of relaible SNR estimation on the modulation recognition performance,

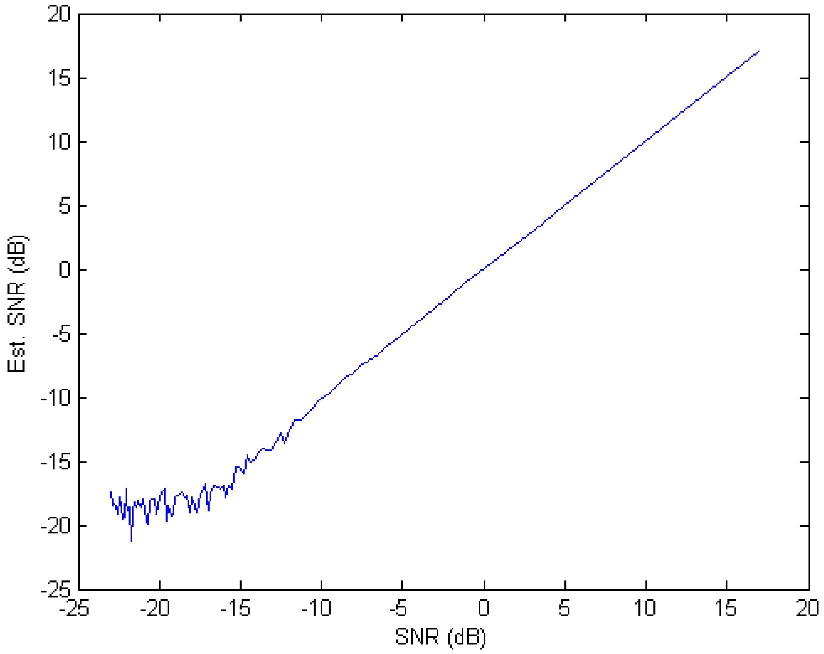


Figure 5.1: Comparison of Estimated SNR with Real SNR.

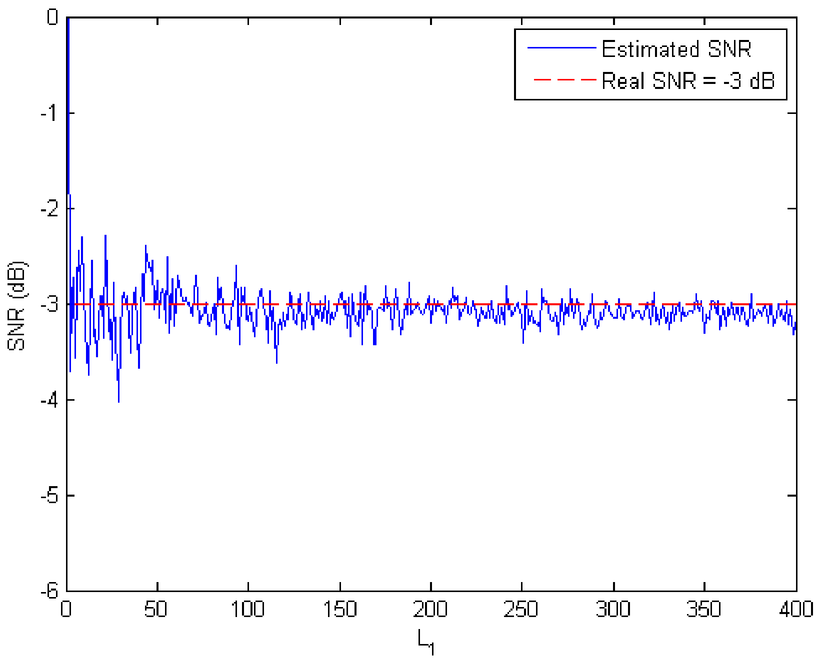


Figure 5.2: Comparison of Estimated SNR with Real SNR: Estimation vs. number of OOK periods (L_1) at SNR=-3dB.

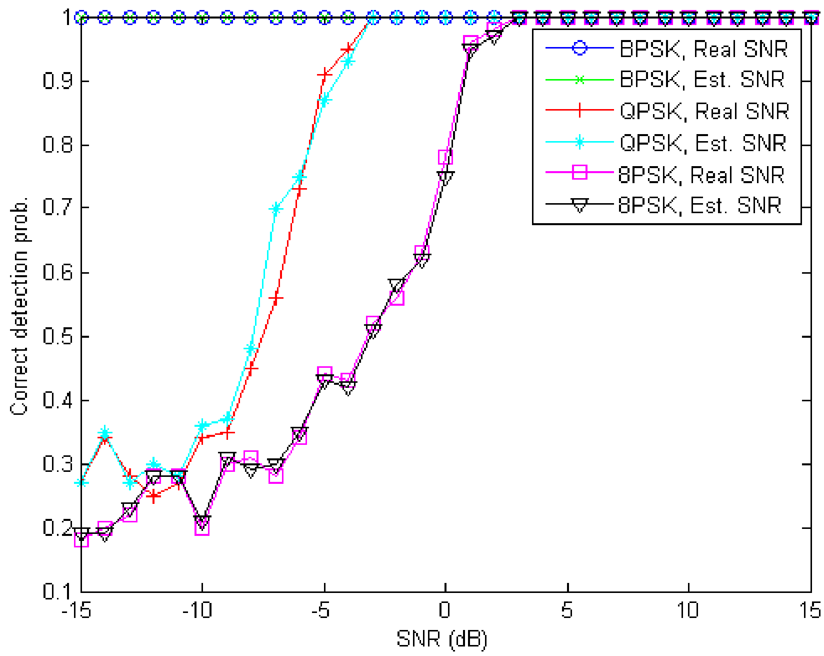


Figure 5.3: Modulation Recognition Performance vs. SNR for 3 differently modulated signalings.

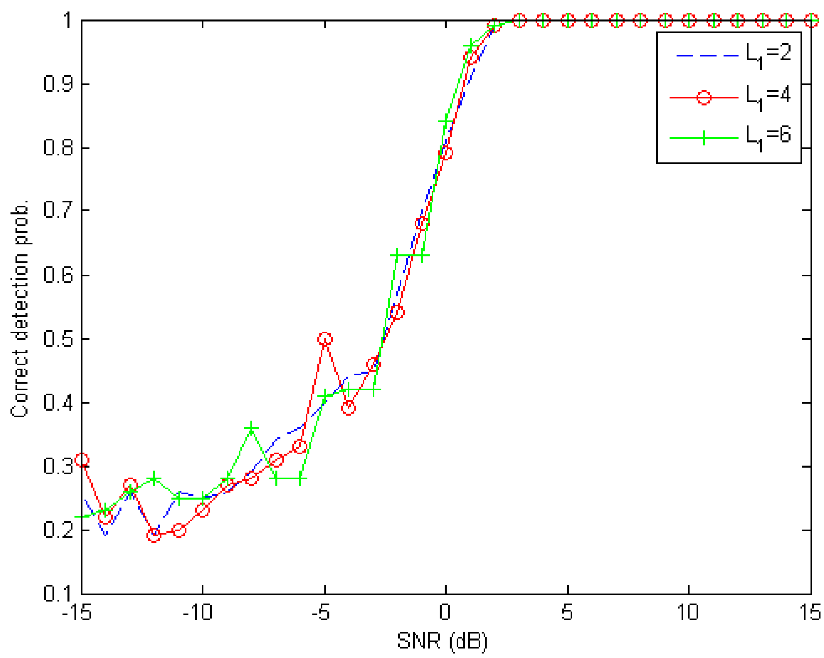


Figure 5.4: 8-PSK Recognition Performance vs. estimated SNR with different number of OOK periods L_1.

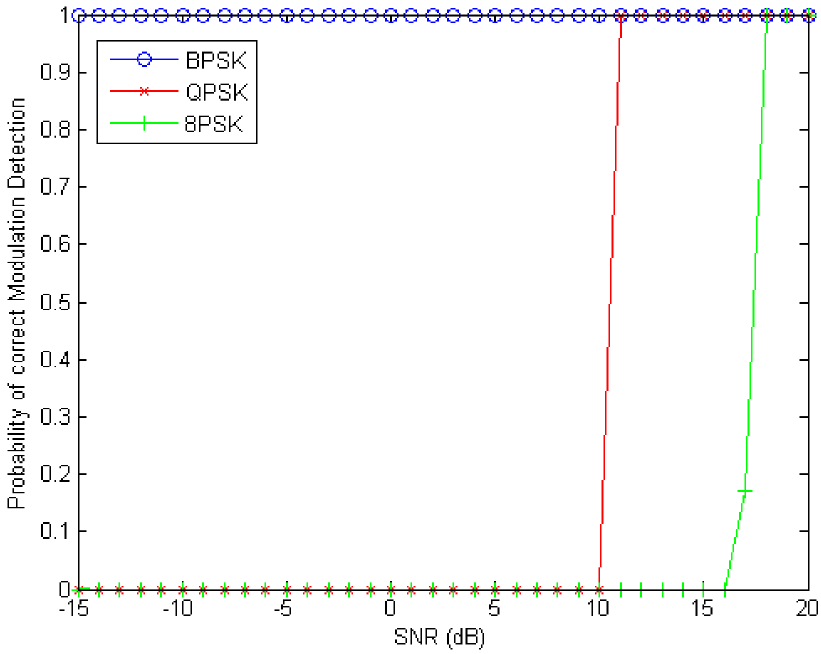


Figure 5.5: Modulation Recognition Performance vs. estimated SNR based on 4.20, 4.21 and 4.22.

we simulated the same experiment for three L_1 values 2, 4 and 6 which is shown in Figure 5.4 and obviously the performance is the same for different values of L_1.
In Section 4.2, we gave likelihood measures 4.20, 4.21 and 4.22 for three PSK modulation schemes which we mentioned could not outperform the method in [41]. The result of these measures are given for comparsion in a range of SNR -15 dB to 20 dB in Figure 5.5.

Also the maximum value for L_1 and L_2 to assure a certain probability of successful bootstrapping based on 5.4 in different traffic rate situations is simulated in Figure 5.6. For simplicity, L_1 and L_2 are taken as equal and T_{sens} is fixed as 1 ms. Also $P_{fa} = 0.01$ and $P_d = 0.95$. The curves belong to 3 different probabilities of successful bootstrapping, 0.9, 0.75 and 0.5. The steps on each curve are because L_1 and L_2 are integers. The above curves heavily depend on the false alarm and detection probabiliy of spectrum sensing. Therefore to be confident about the performance of the protocol, we need to have reliable spectrum sensing. Although we have used more idealistic values for P_{fa} and P_d in our simulations, but these two can be minimized and maximized respectively, if the sensing time is increased [5]. For instance, in the Berkeley Emulation Engine 2 [5] which is an spectrum sensing platform, 0.1 and 0.9 are reached for P_{fa} and P_d respectively. On the other hand, increasing the sensing time will lead to more probability of interruption by other secondary users of the network during bootstrapping as discussed in Section 5.1. This shows a trade-off between having lower error in sensing (lower false alarm and higher detection probabilities) and higher connection success. The value of L_1 also depends on how high the probability of successful connection should be in a

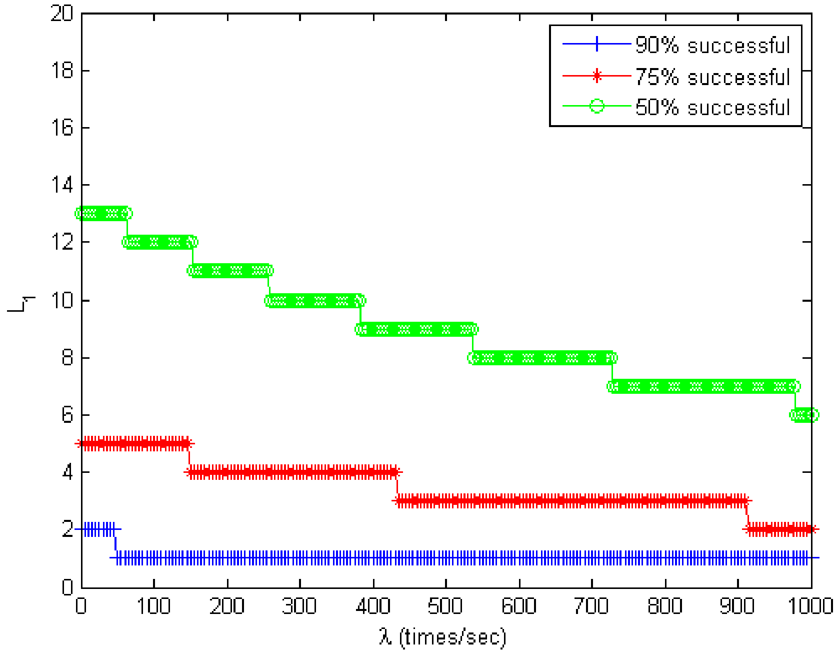


Figure 5.6: The maximum number of OOK periods for 90%, 75% and 50% successful bootstrapping in different traffic rates.

network. It is seen that for 90% successful bootstrapping the maximum L_1 is 2 for low traffic rates.

6 Conclusions and Future Works

In this chapter we summarize the work done in the thesis, draw final conclusions, and suggest directions for further research.

6.1 Conclusions

In this thesis, we elaborate on a design path for a Cognitive Radio. An SDR transceiver design is explained which is able to produce an IF signal on an arbitrary upsampling frequency from the base-band signal. This baseband signal is assumed to be encoded and modulated with an IQ modulator in software. By software, we mean that part of the processing before the IF-processing is done on a general purpose processor, based on the SDR concept. The IF-processing part, which translates the baseband signal to the IF on a higher carrier frequencies, is performed on faster devices like an FPGA. On the other hand, the receiving path is also explained with more or less the same architecure as the transmit path. The received IF-signal from the AD converters on any arbitrary carrier is transformed to baseband, demodulated, decoded and further processed in software. For the software part, we use a multimode legacy military waveform which is able to change its mode to different PSK modulation levels and coding rates (convolutional coding). With the given flexible transceiver and waveform, a design for a cognitive engine is given. The cognitive engine will change the settings of the radio e.g., carrier frequency, modulation and coding optimally in order to respond to the application demands e.g., data Rate, BER and also adapt the radio in terms of transmit power, frequency, modulation and coding to the channel conditions. Transmit power is adapted based on the BER requirement from the application and SNR experienced at the receiver. The frequency on which the radio operates will change according to the bandwidth requirement from the application and also the presence of primary users. The spectrum sensing will determine the available channels to be used by the cognitive radio by means of energy detection on each channel. Modulation and coding are jointly selected based on the application data rate and also BER. Although giving the optimum radio settings, the cognitive engine algorithm is an exhaustive one and has a high complexity. To reduce the complexity, some of these settings must be eased to and combined in order to reach a less complex algorithms. The proposed algorithm does not search the whole transmit power range but it searches the optimum one in steps.

A signaling protocol is proposed for bootstrapping in a cognitive radio network based on the specificition of the radio presented in Chapter 2. The bootstrapping is a process for the initiation of communication among radios in a cognitive network during which the involved radios agree on using a specific waveform, frequency channel, transmission power and all other required communication parameters. One important feature of the proposed bootstrapping process is that it tries to establish non-cooperative communication between the radios such that no control channel for the exchange of the mentioned communication parameters is required. For this, the caller transmits OOK signaling patterns with a pre-defined period. The receipient of the communication detects this pattern by means of energy detection spectrum sensing and estimates the waveform used by the caller. One advantage of the protocol is that a minimal transmission power is estimated by the caller to be used in the actual data transmission after the bootstrapping is completed. Also because of no need for a control channel, the network can be setup autonomously without manual intervention. Although the protocol is proposed for statically allocated spectrum access and yet to be generalized to dynamically allocated spectrum access. The bootstrapping is performed jointly by the caller and the callee radios. This process consists of 8 phases including: Channel and Rate Selection, Call Request Signaling, Call Detection, Callee-side SNR estimation, Modulation and Coding Recognition, Acknowledgment Signaling, Caller-side Noise Estimation and Power Adjustment. For the protocol to work properly, a highly reliable spectrum sensing is required.

Estimation of the communication parameters from the received signal at the callee is described. These parameters include received SNR, PSK modulation, and the coding. The SNR is estimated by measuring the signal and noise power during the ON and OFF times of the OOK signal. Also PSK modulation level of the signal is estimated by using some likelihood measures derived from the phase distribution of the signal samples. Also some likelihood measures from the I and Q samples of the signal are derived. The coding recognition is a hardship of the whole protocol. No contribution in this area is made in this thesis, but only a reference is given.

Failure scenarios of the protocol are discussed. Also mathematical expressions for the reliability and efficiency of the protocol are derived. The reliability of the protocol is measured with the probability of successful connection. This probability is shown to be a function of traffic in the network and also the accuracy or reliability of spectrum sensing. It is shown that higher reliability in spectrum sensing leads to the proper detection of OOK at the receiver. Also less traffic rate increases the probability of having successful bootstrapping. It is shown that SNR estimation mechanism in the proposed protocol works reliably even in very low SNRs. Modulation recognition has lower performance than the SNR estimator. More specifically, it is observed that correct modulation recognition takes place in higher SNR than the bound for correct SNR estimation. But the performance of the modulation recognition is still good enough for the reliability of the protocol. Furthermore, it is shown that non-accurate SNR estimation does not affect the modulation recognition that much. It is also shown that the probability of successful bootstrapping heavily depends on the accuracy of spectrum sensing and to some extent on the traffic rate. When a high probability of successful bootstrapping is desired, more accurate spectrum sensing is required, otherwise the number of OOK periods for the protocol becomes too low and might not be suitable for the reliability of the protocol. In all, the accuracy of spectrum sensing and the number of OOK periods have contradicting impact on the reliability of the protocol.

6.2 Future Work

- **Generalized Modulation Recognition**
  The protocol is proposed only for MPSK modulation recognition. But it can be extended to other modulation schemes as well such as QAM. This needs more likelihood tests to be done in the modulation recognition phase of the protocol and increase its complexity.

- **Channel Coding Recognition**
  Channel coding is an important part of wireless communication. To complete the chain of non-cooperative bootstrapping, a reliable recognition method must be investigated. Although a method is suggested to be used from the literature, it is not a reliable one since the probability of successful recognition does not reach to 1 even in high SNRs.

- **Fading Channels**
  In this theis, we only consider AWGN among the radios in the network. As a future work, it is worth investigating how the protocol performance is affected by fading. Does it affect the SNR estimation accuracy and subsequenctly the modulation recognition? How is the power adjustment phase of the protocol affected?

- **Sensing Time Jitter**
  Consider the channel which is being sensed at the receiver exactly when the bootstrapping starts. We name this channel and its neighboring channels as boundary channels of the bootstrapping. If the sensing time has jitter, the protocol might experience a failure in case the signaling takes place in the boundary channels. Mathematical analysis for such failure can be suggested as a future research.

Implementation

A

Implementation of the system we have proposed in this thesis was not possible because of the limitation in time and facilities. But still there was an opportunity to simulate this system in MATLAB Simulink. Simulink is an environment for multi-domain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing [24].

A.1 STANAG4285 Transceiver in Simulink

Fortunately, we were able to access a Simulink model of STANAG 4285 waveform which was developed in German FGAN Co. by Stefan Couturier. This model was developed in an effort for SCA implementation of STANAG4285 for later adoption of it on a real hardware platform. The model includes so many customized blocks and user-defined blocks that simulate a STANAG4285 transmitter and receiver. User-defined blocks are C code pieces in a Simulink customized format of so-called S-functions. In Simulink, each block has its own inputs and outputs ports. The blocks can be connected to each other in a sequential form to convert or transfer a source signal to signal sink. Each block can also have several sub-blocks, all included or so-called "masked" inside the main block. In Figure A.1, an abstract Simulink model of the complete transmission network for STANAG4285 is sketched. The above model has a data source which feeds characters in bits to the transmitter. The transmitter encodes and modulates these

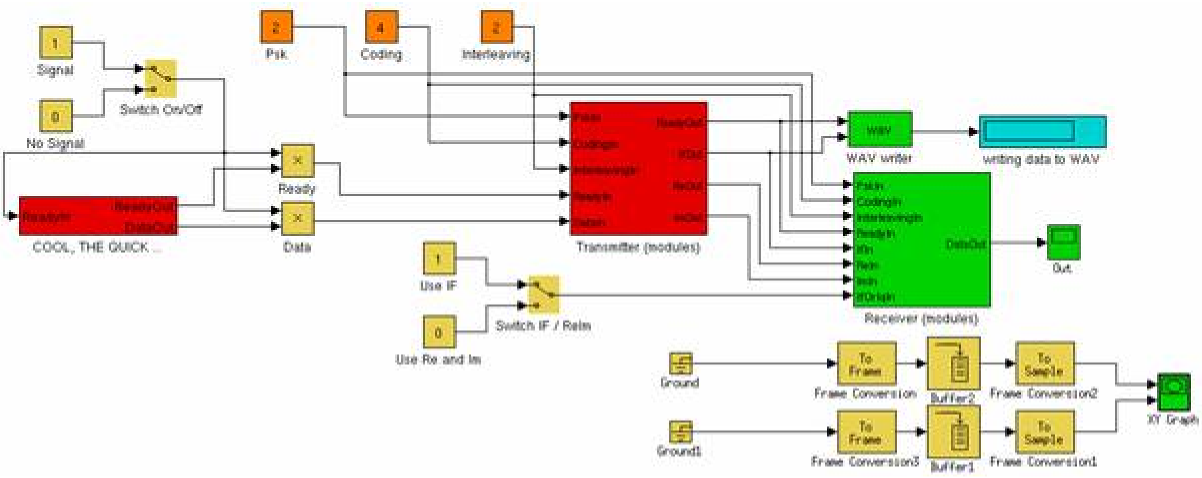


Figure A.1: Model top layer for STANAG4285 transmitter and receiver.

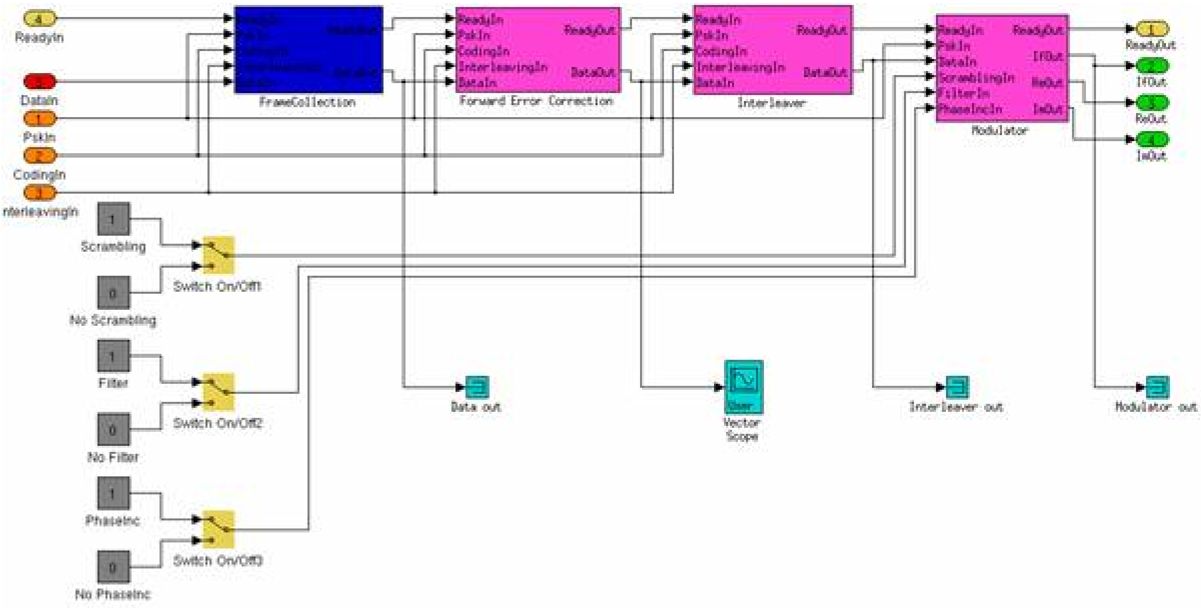


Figure A.2: Model for STANAG4285 transmitter.

bits to a digital signal with specific PSK modulation level and coding rate and then convert it to an IF signal which is the transmitter's output. The IF signal is input to the receiver. The receiver uses the same modulation and coding rate to demodulate and decode the signal and represents the decoded data at the output. Both transmitter and the receiver have masked several other blocks. In Figure A.2 and Figure A.3, these two are depicted in detail. Figure A.2 shows the transmitter in its componentized layout. It mainly consists of four components, "Frame Collection", "Forward Error Correction", "Interleaver" and "Modulator". The responsibility of each module is more or less clear and the transmitter has a sequential and simple structure. Figure A.3 shows the receiver's model. Contrary to the transmitter it has a more complicated structure and also a feedback. The block "Get Data" is to collect data from the input. Three magenta blocks, "Demodulator", "De-interleaver" and "Decoder", are for data processing which is obvious. There are two dark green blocks, "Doppler Correction" and "Doppler and Sync Tracker", for the correction of the Doppler Effect and the synchronization deviation. Also two light blue blocks, "Search Preamble" and "Search EOM", are for searching for the start and the end of the message. Although the general processing of data still works sequentially, several pieces of information need to be returned to a prior block to inform him e.g., whether the preamble is found, a Doppler or Synchronization correction has to be undertaken or the EOM was found [10].

A.2 Cognitive Engine for the STANAG4285 Receiver

Using the STANAG4285 transmitter, we implemented a cognitive engine which was able to do part of the spectrum sharing protocol described in Chapter 3. Our proposed protocol had two intermediate and important phases to be performed at the receiver

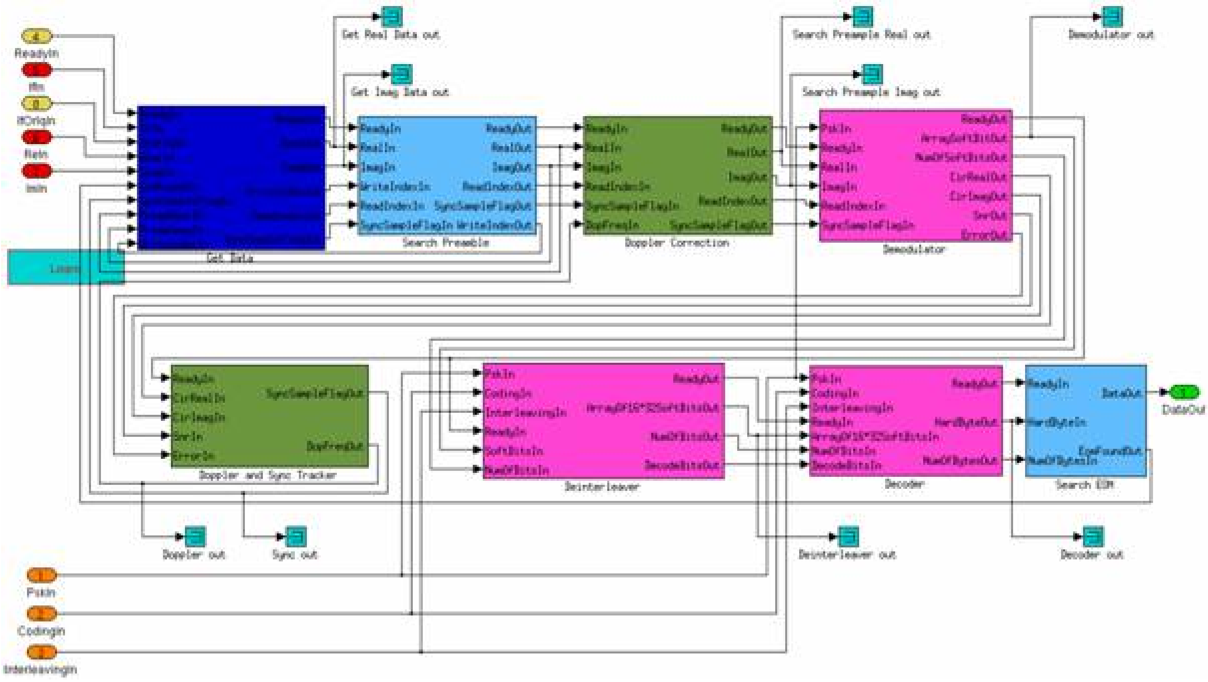


Figure A.3: Model for STANAG4285 receiver.

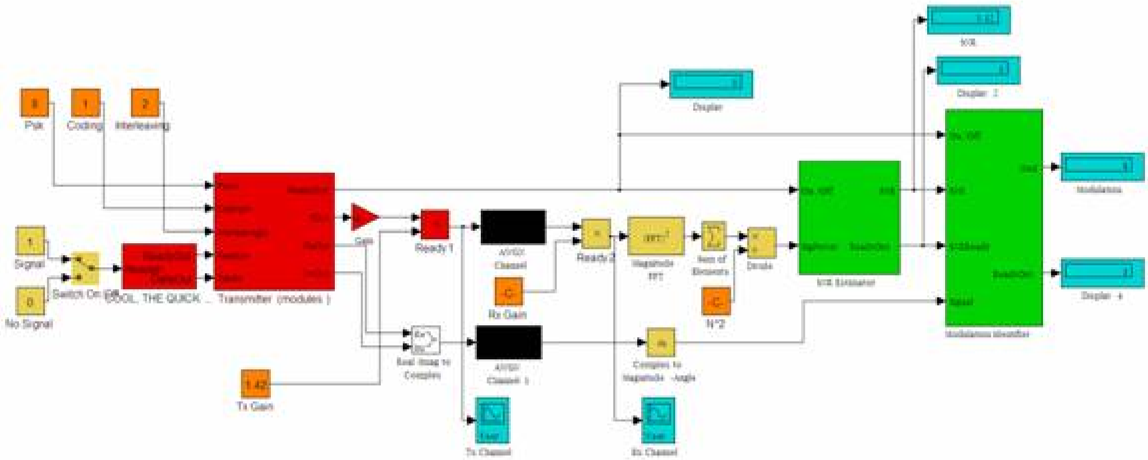


Figure A.4: Partly developed Cognitive Engine with SNR estimation and modulation recognition capabilities.

(callee) side, namely SNR estimation and modulation recognition. On the hand the signal source in the STANAG4285 model was revised to generate OOK signal as mentioned in the protocol description. Our customized communication system based on the model in the previous section is depicted in Figure A.4. The OOK signal generated by the STANAG4285 transmitter is input to the AWGN channel. Another capability added to the system was manual transmission power control with "Tx Gain" block as observed in Figure A.4. A magnitude FFT block is used, to transform a frame of signal sample to frequency domain and calculate the signal power in each burst of signal, depending of the ON or OFF period in the OOK signalling. The signal power is fed to the user-defined SNR Estimator S-Function block which estimates the amount of the SNR. The SNR estimate is then fed to the next S-Function block which is Modulation identifier. Based on the method illustrated in Chapter 4, the PSK modulation level is recognized in this block. Figure A.4 is a snapshot of the model after execution which shows an estimate of 3.12 dB for 3 dB SNR in the AWGN channel and also shows true recognition of 8-PSK modulation which is adopted in the transmitter. These results can be input to a receiver block for STANAG4285 receiver which makes it partly autonomous. Also if a block for channel coding recognition is developed, the receiver will have less cooperation with the transmitter. A full system including independent cognitive radios adopting the proposed protocol in Chapter 3, could not be modelled because of time limitations for this thesis, but with the given information on the protocol and having the above Simulink model as a base, having a full model is not a big challenge.

Bibliography

[1] Norman C. Beaulieu, Andrew S. Toms, and David R. Pauluzzi. Comparison of four snr estimators for qpsk modulations. *IEEE Commun. Lett.*, 4(2):43–45, February 2000.

[2] W.R. Bennett. Methods of solving noise problems. *Proceedings of the IRE*, 44(5):609–638, November 1956.

[3] Danijela Cabric. Cognitive radios: System design perspective. In *Phd Dissertation*, 2006.

[4] Danijela Cabric, Ian D. ODonnell, Mike Shuo-Wei Chen, and Robert W. Brodersen. Spectrum sharing radios. *IEEE Circuits Syst. Mag.*, 6(2):30–45, July 2006.

[5] Danijela Cabric, Artem Tkachenco, and Robert W. Broderson. Experimental study of spectrum sensing based on energy detection and network cooperation. In *Proc. TAPAS'06*, Boston, MA, USA, August 2006.

[6] T. Charles Clancy. Adaption overhead in time-varying cognitive radio channels. In *Proc. IEEE CCNC'08*, Las Vegas, NV, USA, January 1009–1013, 2008.

[7] Federal Communications Commission. Spectrum policy task force. In *Rep. ET Docket*, November 2002.

[8] Carlos Cordeiro and Kiran Challapali. C-mac: A cognitive mac protocol for multi-channel wireless networks. In *Proc. DySpan'07*, Dublin, Ireland, April 2007.

[9] Leon W. Couch. *Digital and Analog Communication Systems*. Jet Propulsion Laboratory, 2006.

[10] Stefan Couturier. Stanag 4285 - matlab/simulink implementation based on code delivered by telefunken racoms. 2008.

[11] O.A. Dobre, A. Abdi, Y. Bar-Ness, and W. Su. Survey of automatic modulation classification techniques: Classical approaches and new trends. *Communications, IET*, 1(2):137–156, April 2007.

[12] Joint Program Executive Office for Joint Tactical Radio System. Jpeo for the jtrs organization overview. http://jpeojtrs.mil/files/org_info/JPEO_JTRS_Org_Overview.pdf.

[13] Joint Program Executive Office (JPEO) for the Joint Tactical Radio System (JTRS). Software communications architecture specification. May 2006.

[14] Ping Gao and Cihan Tepedelenlioglu. Defining, designing, and evaluating digital communication systems. *IEEE Trans. Signal Processing*, 53(3):865–870, March 2005.

[15] Feng Ge, Qinqin Chen, Ying Wang, and Charles W. Bostian. Cognitive radio: From spectrum sharing to adaptive learning and reconfiguration. In *Proc. of Aerospace Conference*, Big Sky, MT, USA, March 2008.

[16] Jon Hamkins and Editors Marvin K. Simon. *Autonomous Software-Defined Radio Receivers for Deep Space Applications*. Jet Propulsion Laboratory, 2006.

[17] Brent Horine and Damla Turgut. Link rendezvous protocol for cognitive radio netwroks. In *Proc. DySpan'07*, Dublin, Ireland, April 2007.

[18] Brent Horine and Damla Turgut. Performance analysis of link rendezvous protocol for cognitive radio netwroks. In *Proc. CROWNCOM'07*, Orlando, FL, USA, August 2007.

[19] Kentaro Ikemoto and Ryuji Kohno. Adaptive channel coding schemes using finite state machine for software defined radio. In *Proc. WPMC'02*, Honolulu, Hawaii, USA, October 2002.

[20] Raymond J. Lackey and Donald W. Upmal. Speakeasy: The military software radio. *IEEE Commun. Mag.*, 33(5):56–61, May 1995.

[21] Vincent K.A. Lau and S.V. Maric. Variable coherent rate adaptive channel coding for and non-coherent rayleigh fading channel. In *Proc. of IEEE International Conference on Personal Wireless Communications*, Mumbai, India, December 1997.

[22] Jen Lung Lo and S. Sanei. An adaptive channel coding technique for progressive transmission of images. In *Proc. ICCCE'08*, Kuala Lumpur, Malaysia, May 2008.

[23] Liangping Ma, Xiaofeng Han, and Chien-Chung Shen. Dynamic open spectrum sharing mac protocol for wireless ad hoc networks. In *Proc. DySpan'05*, Baltimore, MD, USA, November 2005.

[24] The Mathworks. Simulink - simulation and model-based design. http://www.mathworks.com/products/simulink/.

[25] Henk Medenblik. Wintsec sdr transceiver report. 2008.

[26] Joseph Mitola. Cognitive radio: An integrated agent architecture for software defined radio. In *Phd Dissertation*, May 2000.

[27] Maruf Mohammad and R. Michael Buehrer. On the impact of snr estimation error on adaptive modulation. *IEEE Commun. Lett.*, 9(6):490–492, June 2005.

[28] Przemysław Pawełczak, Sofie Pollin, Hoi-Sheung Wilson So, Ahmad Bahai, R. Venkatesha Prasad, and Ramin Hekmat. Quality of service assessment of opportunistic spectrum access: a medium access control approach. *IEEE Wireless Commun. Mag.*, 15(5):20–29, October 2008.

[29] John Polson. *Cognitive Radio: The technologies*, pages 153–155. Elsevier, 2006.

[30] Christian J. Rieser, Thomas W. Rondeau, Charles W. Bostian, and Timothy M. Gallagher. Versatile low power media access for wireless sensor networks. In *Proc. MILCOM'04*, Monterey, CA, USA, October 2004.

[31] Thomas W. Rondeau, Bin Le, Christian J. Rieser, and Charles W. Bostian. Cognitive radios with genetic algorithms: Intelligent control of sfotware defined radio. In *Proc. SDR'04 Technical Conference and Product Exhibition*, Phoenix, AZ, USA, November 2004.

[32] Fredrick W. Seelig. A description of the august 2006 xg demonstrations at fort a.p. hill. In *Proc. DySpan'07*, Dublin, Ireland, April 2007.

[33] Bernard Sklar. Defining, designing, and evaluating digital communication systems. *IEEE Commun. Mag.*, 31(11):91–101, November 1993.

[34] Bernard Sklar. Defining, designing, and evaluating digital communication systems. *EURASIP Journal onWireless Communications and Networking*, 2005:275–283, March 2005.

[35] Larry Stotts. The next generation program. http://www.darpa.mil/sto/smallunitops/xg.html.

[36] Wei Su, John A. Kosinski, and Ming Yu. Dual-use of modulation recognition techniques for digital communication signals. In *Proc. LISAT'06*, May 2006.

[37] Walter Tuttlebee. *Software Defined Radio: Origins, Drivers and International Perspectives*. John Wiley & Sons, 2002.

[38] Kenta Umebayashi, Satoru Ishi, and Ryuji Kohno. Blind adaptive estimation of modulation scheme for software defined radio. In *Proc. PIMRC2000*, London, UK, February 2000.

[39] Jos Weber. Lecture notes: Error-corecting codes. January 2007.

[40] Dan Wu, Xuemai Gu, and Qing Guo. Blind signal-to-noise ratio estimation algorithm with small samples for wireless digital communications. 345:741–748, October 2006.

[41] Yawpo Yang and Samir S. Soliman. A suboptimal algorithm for modulation classification. *IEEE Aerosp. Electron. Syst. Mag*, 33(1):38–45, January 1997.