Cross-Layer Design For Multimedia Applications in Cognitive Radio Networks

Submitted to the School of Engineering in fulfilment of the academic requirements for the degree of Doctor of Philosophy in Electronic Engineering

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in fulfillment of the requirements for the degree of

Doctor of Philosophy

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Thesis Supervisor

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Dedication

TO ALMIGHTY GOD BE THE GLORY.

Abstract

The exponential growth in wireless services and the current trend of development in wireless communication technologies have resulted into an overcrowded radio spectrum band in such a way that it can no longer meet the ever increasing requirements of wireless applications. In contrary however, literature surveys indicate that a large amount of the licensed radio spectrum bands are underutilized. This has necessitated the need for efficient ways to be implemented for spectrum sharing among different systems, applications and services in dynamic wireless environment. Cognitive radio (CR) technology emerges as a way to improve the overall efficiency of radio spectrum utilization by allowing unlicensed users (also known as secondary user) to utilize a licensed band when it is vacant.

Multimedia applications are being targeted for CR networks. However, the performance and success of CR technology will be determined by the quality of service (QoS) perceived by secondary users. In order to transmit multimedia contents which have stringent QoS requirements over the CR networks, many technical challenges have to be addressed that are constrained by the layered protocol architecture. Cross-layer design has shown a promise as an approach to optimize network performance among different layers. This work is aimed at addressing the question on how to provide QoS guarantee for multimedia transmission over CR networks in terms of throughput maximization while ensuring that the interference to primary users is avoided or minimized. Spectrum sensing is a fundamental problem in cognitive radio networks for the protection of primary users and therefore the first part of this work provides a review of some low complex spectrum sensing schemes. A cooperative spectrum sensing scheme where multi-users are independently performing spectrum sensing is also developed. In order to address a hidden node problem, a cooperate relay based on amplify-and-forward technique (AF) is formulated. Usually the performance of a spectrum sensor is evaluated using receiver operating characteristic (ROC) curve which provides a trade-off between the probability of miss detection and the probability of false alarm. Due to hardware limitations, the spectrum sensor can not sense the whole range of radio spectrum which results into partial information of the channel state. In order to model a media access control(MAC) protocol which is able to make channel access decision under partial information about the state of the system we apply a partially observable Markov decision process (POMDP) technique as a suitable tool in making decision under uncertainty. A throughput optimization MAC scheme in presence of spectrum sensing errors is then developed using the concept of cross-layer design which integrates the design of spectrum sensing at physical layer (PHY) and sensing and access strategies at MAC layer in order to maximize the overall network throughput. A problem is formulated as a POMDP and the throughput performance of the scheme is evaluated using computer simulations under greedy sensing algorithm. Simulation results demonstrate an improved overall throughput performance. Further more, multiple channels with multiple secondary users having random message arrivals are considered during simulation and the throughput performance is evaluated under greedy sensing scheme which forms a benchmark for cross-layer MAC scheme in presence of spectrum sensing errors. By realizing that speech communication is still the most dominant and common service in wireless application, we develop a cross-layer MAC scheme for speech transmission in CR networks. The design is aimed at maximizing throughput of secondary users by integrating the design of spectrum sensing at PHY, quantization parameter of speech traffic at application layer (APP), together with strategy for spectrum access at MAC layer with the main goal to improve the QoS perceived by secondary users in CR networks. Simulation results demonstrate throughput performance improvement and hence QoS is improved.

One of the main features of the modern communication systems is the parameterized operation at different layers of the protocol stack. The feature aims at providing them with the capability of adapting to the rapidly changing traffic, channel and system conditions. Another interesting research problem in this thesis is the combination of individual adaptation mechanisms into a cross-layer that can maximize their effectiveness. We propose a joint cross-layer design MAC scheme that integrates the design of spectrum sensing at PHY layer, access at MAC layer and APP information in order to improve the QoS for video transmission in CR networks. The end-to-end video distortion which is considered as an APP parameter resides in the video encoder. This is integrated in the state space and the problem is formulated as a constrained POMDP. H.264 coding algorithm which is one of the high efficient video coding standards is considered. The objective is to minimize this end-to-end video distortion while maximizes the overall network throughput for video transmission in CR networks. The end-to-end video distortion has significant effects to the QoS the perceived by the user and is viewed as the cost in the overall system design. Given the target system throughput, the packet loss ration when the system is in the state i and a composite action is taken in time slot t, the system immediate cost is evaluated. The expected total cost for overall end-to-end video distortion over the total time slots is then computed. A joint optimal policy which minimizes the expected total end-to-end distortion in total time slots is computed iteratively. The minimum expected cost (which also known as the value function) is also evaluated iteratively for the total time slots. The throughput performance of the proposed scheme is evaluated through computer simulation. In order to study the throughput performance of the proposed scheme, we considered four simulation scenarios namely simulation scenario A, simulation scenario B, simulation scenario C, and simulation scenario D. These simulation scenarios enabled us to study the throughput performance of the proposed scheme by by computer simulations. In the simulation scenario A, the average throughput performance as a function of time horizon is studied. The throughput performance under channel access decision based on belief vector and that of channel access decision based on the end-to-end distortion are compared. Simulation results show that the channel access decision based on end-to-end distortion outperforms that of channel access decision based on a belief vector. In the simulation scenario B we aimed at studying the spectral efficiency as a function of prescribed collision probability. The simulation results show that, at large values of collision probability the overall spectral efficiency performs poorly. However, there is an optimal value of collision probability of which the spectral efficiency approaches that of the perfect channel access decision. In the simulation scenario C, we aimed at studying the average throughput performance and the spectral efficiency both as a function of prescribed collision probability. The simulation results show that both average throughput and the spectral efficiency are highly affected by the increase in collision probability. However, there is an optimal prescribed collision probability which achieves the maximum average throughput and maximum spectral efficiency.

Declaration

I, ________________________________, declare that:

(i) The research reported in this thesis, except where otherwise indicated, is my original work.

(ii) This thesis has not been submitted for any degree or examination at any other University.

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Contents

List of Figures

List of Tables

List of Symbols

$(\bullet)^2$	Squaring function
$\int_0^T$	integrating function
$x(t)$	continuous time input signal
$x(n)$	discrete-time input signal
$y(t)$	continuous time output signal
$y(n)$	discrete-time output signal
H_0	hypothesis corresponding to absence of the primary (licensed) user
H_1	hypothesis corresponding to presence of the primary (licensed) user
σ_w^2	the variance of additive white Gaussian noise
Y_0	signal input to energy detector
σ_x^2	variance of the user signal
τ	system threshold
$Q(\bullet)$	complimentary distribution function of the Gaussian
$erfc(\bullet)$	cumulative error function
γ	relay gain
$\mathcal{W}_n$	the bandwidth of channel n
$S_n(t)$	channel state of n^{th} channel in time slot t
$P(i,j)$	transition probability from state i to state j
Θ	a set of all observations

$\Phi_n(t)$	observations of n^{th} channel in time slot t
b_0	initial belief probability distribution
ϵ	probability of false alarm
δ	probability of miss-detection
$\mathcal{R}_n^k(t)$	reward gained by cognitive radio node
$a(t)$	composite action
J	total number of transmitted bits
$\mathcal{B}_i(t)$	belief vector in current state i
$\mathcal{B}_j(t)$	belief vector in current state j
π_s	spectrum sensing policy
π_δ	sensor operating point policy
π_c	transmission probability policy
π_q	step-size quantization policy
π_α	end-to-end distortion policy
f_a^1	transmission probability, action a taken and idle channel
f_a^0	transmission probability, action a taken and busy channel
$\mathcal{Q}_i(1)$	probability of successful transmission, current state is i
$\mathcal{V}_t(\bullet)$	maximum total reward accumulated over total time slot
λ	packet arrival rate

List of Acronyms

AF	amplify-and-forward
ADC	analogue-to-digital converter
APP	application layer
ARQ	automatic-repeat request
AWGN	additive white Gaussian noise
BER	bit error rate
BPF	band-pass filter
CFD	cyclostationary feature detection
CDMA	code division multiple access
CR	cognitive radio
CPDAND	cooperative probability of detection using AND rule
CPFAND	cooperative probability of false alarm using AND rule
CPD	cooperative probability of detection
CPDOR	cooperative probability of detection using OR rule

CPF	cooperative probability of false alarm
CPFOR	cooperative probability of false alarm using OR rule
CR	cognitive radio
CSMA	carrier sense multiple access
CTS	clear-to send
DSA	dynamic spectrum access
DSP	digital signal processing
ED	energy detector
FCC	federal communication commission
FDMA	frequency division multiple access
FPGA	field-programmable gate array
GSM	global system for mobile communication
MAC	media access control
MB	macroblock
MDC	multiple description coding
MDP	Markov decision process
MF	matched filter
MIMO	multiple-input multiple-output
No	additive complex white Gaussian noise with zero mean and double sided power spectral density

PC	personal computer
PER	packet error rate
POMDP	partially observable Markov decision process
QoS	quality of service
P_D	probability of detection
P_F	probability of false alarm
PHY	physical layer
PU	primary user
ROC	receiver operating characteristics
ROPE	recursive optimal per-pixel estimate
RF	radio frequency
RTS	request-to-send
SDR	software-defined radio
SINR	signal-to-interference and noise ratio
SNR	signal-to-noise ratio
SU	secondary user
TCP	transmission control protocol
TDMA	time division multiple access
UMTS	universal mobile telecommunication system

Chapter 1

Introduction

1.1 Research Motivation

The current trend of development in wireless communication technologies has resulted into an overcrowded radio spectrum band in such a way that it can no longer meet the ever increasing requirements of wireless applications [2]. The bandwidth requirement for multimedia traffic is significantly high while on the other hand the radio spectrum is insufficient to satisfy the need for multimedia application in wireless communication. In contrary however, literature survey indicates that, a large amount of the licensed radio spectrum bands are under-utilized [3]. This has necessitated the need for efficient ways to be implemented for spectrum sharing among different systems, applications and services in dynamic wireless environment. Cognitive radio (CR) which was first envisioned by Mitola [4] emerges as a way to improve the overall efficiency of radio spectrum utilization by exploiting spectrum opportunities. In a typical CR scenario, users of a given frequency band are classified into primary users (or licensed users) and secondary users (also known as unlicensed users). Media access control (MAC) protocols for CR differ from that of a traditional wireless networks in that it has to exploit the spectrum opportunities, manage the interference to licensed users, and coordinate the spectrum access amongst unlicensed users. The design of such a protocol needs to achieve the highest spectrum utilization by detecting all spectrum opportunities and access the spectrum in a way that the interference to other unlicensed users is minimized. This results into a significant challenges for MAC protocol designs. Since spectrum sensing is required over a wide range of licensed channels, a decision needs to be made on the sensing sequences and on which channels is to be sensed [5]. Several MAC protocols have been suggested in the literature so far for the implementation of dynamic spectrum access (DSA) in CR networks [5]. Many researchers [6–9] worked out on the MAC protocol design with optimal decision for spectrum sensing and spectrum access. The main goal is to use some optimization techniques for optimal spectrum sensing and spectrum access decision [10]. The primary user (PU) activities are usually random and therefore leads to the application of stochastic optimisation model.

The main functions of CR include spectrum sensing, spectrum management, spectrum sharing, and spectrum mobility. These functions require a large amount of network state information that must be shared simultaneously between multiple protocol layers of the CR. In other words, the cross-layer design is considered whenever the information is exchanged among protocol layers. This has a significant effect to the user perceived quality of service (QoS) especially for multimedia traffic. Cross-layer design approach has shown promises in providing QoS guarantee to multimedia traffic by violating the traditional protocol stack design [2, 11]. However, most these works in the literature are based on the design of MAC and PHY layers of CR while little attention is given to upper layers of the protocol stack such as application layer. In CR networks the spectrum resource is shared among all the cognitive radio users in absence of the primary user. The spectrum sharing depends directly on the spectrum sensing since the CR monitors spectrum bands and captures information about the state of the channel.

Transmission of multimedia traffic over the wireless networks experiences a number of constraints that result into low QoS that is offered to the end user. These constrains have mainly to do with the requirements of multimedia traffic including high bandwidth and stringent QoS. In order to reliably transmit multimedia traffic over CR networks, several technical challenges need to be addressed that are constrained by the traditional layered protocol architecture. Improving the throughput performance of wireless systems through cross-layer optimization is an area that has received considerable attention by many researchers. In deed, improving system's throughput performance of secondary users is a vital factor that hinges on the success of CR technology for wireless multimedia applications. However, literature survey shows that there is a significant gap on cross-layer design that integrates the design of PHY layer and that of upper layers of the protocol stuck. This has a significant effect in the user perceived QoS for multimedia applications in CR networks. This research gap has motivated us to work on this area and propose a cross-layer MAC scheme for multimedia application in CR networks.

1.2 Thesis Contributions

The main contributions in this thesis are summarized in the following subsections:

1.2.1 Spectrum Sensing Techniques for Cognitive Radio

Spectrum sensing is the chief goal of cognitive radio networks since it enables the secondary user to continuously sense the channel and identify spectrum opportunities (spectrum holes) before accessing it in order to avoid interference to PU. In this thesis a review of the most commonly used spectrum sensing techniques which are classified as cooperative detection technique, transmitter detection technique and interference based technique are presented. The comparisons in terms of complexity of different technique is presented and much focus is put on the transmitter detection technique (specifically the energy detector) due to its simplicity. The goal is to develop a simple spectrum sensing scheme to be used in the proposed cross-layer design scheme for multimedia applications in CR networks. The performance of the developed schemes is evaluated in terms of the receiver operating characteristic (ROC) curves performance which gives a measure of the probability of miss detection as a function of the probability of false alarm. A cooperative relay based spectrum sensing using AF technique is also developed in order to address the hidden node problem in CR networks. Spectrum sensing schemes developed in this section forms a bases of an error model which is incorporated in the cross-layer design MAC scheme for multimedia applications in CR networks. Part of this work **is published** in *Proc. IEEE AFRICON 2011 International Conference* , Livingstone, Zambia, 13–15 September, 2011.

1.2.2 Cross-layer MAC Scheme for Throughput Maximization in Presence of Spectrum Sensing Errors

In this chapter the concept of partially observable Markov decision process (POMDP) as an optimization tool is introduced in order to formulate a cross-layer MAC scheme which integrates the design of PHY and that of MAC layer in presence of errors from the spectrum sensor. Errors due to spectrum sensors can not be ignored due to hardware limitations and wireless channel dynamics. Under this channel condition the state of the system can not be fully observed. By using cross-layer design concept whereby the design of spectrum sensing at PHY layer and access strategies at MAC layer considered jointly and by incorporating spectrum sensor parameter into a state space, a problem is formulated as a POMDP. The main goal being to maximize the overall network throughput in presence of spectrum sensing errors under the constraint that the primary users are protected. By considering multiple channels with multiple secondary users with random message arrivals, the throughput performance of the proposed scheme is evaluated using the greedy sensing approach in presence of spectrum sensing errors. Simulation results demonstrate the improved throughput performance under this non-ideal condition. This work creates a benchmark for our cross-layer MAC scheme in presence of errors due to spectrum sensors. Part of this work **is published** in the *Computer Science and Application Journal* (Print ISSN: 2333-9071; Online ISSN: 2333-908X).

1.2.3 Cross-layer MAC Scheme for Speech transmission in CR Networks

Speech communication is still the most dominant and common service and its popularity is expected to remain steady for the foreseeable future. Cross-layer design for wireless multimedia transmission where the parameter optimization is considered jointly across the protocol layers has been studied well in the literature. However, most of the works in the literature focus on the joint design between MAC layer and the PHY while upper layers are given little attention. This has significant effects for real-time multimedia traffic including speech communication in wireless networks. A cross-layer MAC scheme which integrates the design of spectrum sensing at PHY and spectrum sensing and access at MAC layer together with the application layer parameter is developed. Adaptive quantization feature of the speech encoder (quantization step-size parameter) is integrated into the design of MAC scheme. The optimal joint policy is than computed using the POMDP framework in order to maximize the throughput which has a significant effect to the user perceived QoS. The constraint of this optimization problem is that the collision to the primary user has to be avoided. The throughput performance of the proposed system is evaluated using computer simulations under different transition probabilities for equal and unequal bandwidths. The results show an improved throughput performance and spectrum efficiency for the proposed scheme. Part of this work **has been submitted for publication** to *SAIEE African Research Journal.*

1.2.4 Cross-layer MAC Scheme for Video Transmission in CR Networks

One of the main features of the modern communication systems is the parameterized operation at different layers of the protocol stack. The feature aims at providing them with the capability of adapting to the rapidly changing traffic, channel and system conditions.

An interesting research problem is the combination of individual adaptation mechanisms into a cross-layer that can maximize their effectiveness. In this chapter a joint cross-layer design MAC scheme that integrates the design of spectrum sensing at PHY layer, access at MAC layer and APP layer information in order to improve the QoS for video transmission in CR networks is presented. End-to-end video distortion which is considered as an APP parameter resides in the video encoder. This is integrated in the state space and the problem is formulated as a constrained POMDP. In this scheme, we use H.264 video coding standard due to the fact that it is one among the high efficient video coding algorithms. The objective is to minimize end-to-end video distortion while maximizing the overall network throughput for video transmission in CR networks. Since the end-to-end video distortion affects the QoS perceived by the user, it is viewed as the cost in the overall system design. By assuming that the system is in the state i, and the composite action is taken in time slot t, then the system immediate cost can be evaluated provided that the target system throughput and the packet loss ratio are known. The expected total cost for overall end-to-end video distortion over the total time slots is then computed. A joint optimal policy which minimizes the expected total end-to-end distortion in total time slots is computed iteratively. The minimum expected cost (which also known as the value function) is also evaluated iteratively for the total time slots. The performance of the proposed scheme is evaluated through computer simulation. The objective is to study the performance of the system under three scenarios. The In the first scenario the average throughput performance as a function of time horizon is studied. The performance under access decision based on belief vector and that of access decision based on the end-to-end distortion (which is proposed in this scheme) are compared. Simulation results show that the access decision based on end-to-end distortion outperforms that of access decision based on a belief vector. The second simulation scenario aimed at studying the spectral efficiency as a function of prescribed collision probability. The simulation results show that, at higher values of collision probability the overall spectral efficiency performs poorly. However, there is an optimal value of collision probability of which the spectral efficiency approaches that of the perfect channel access decision. In the third scenario, the simulation is aimed at studying and compare between the average throughput and the spectral efficiency both as a function of prescribed collision probability. The simulation results show that both, average throughput and the spectral efficiency are highly affected by increased collision probability. However, there is an optimal prescribed collision probability which achieve maximum average throughput and maximum spectral efficiency. Part of this work **has been submitted for publication** to *International Journal of Multimedia Technology*, USA.

1.3 Thesis Organization

The rest of the thesis is organized as follows: Chapter 2 presents a literature review which includes the evolution of radios and CR concept, spectrum sensing for CR networks, cross-layer design concept and related work done on the CR application on dynamic spectrum access and multimedia transmission over CR network. Chapter 3 presents a cross-layer MAC scheme for throughput maximization in presence of spectrum sensing errors while chapter 4 proposes a cross-layer MAC scheme for speech transmission over CR networks and chapter 5 proposes a cross-layer MAC scheme for video transmission over CR networks. The conclusion and future work is presented in chapter 6.

1.4 Publications

- J. A. Msumba, H. Xu, "Video over Cognitive Radio Networks: A Cross-Layer MAC Scheme for Quality of Service Provision," Submitted to *International Journal of Multimedia Technology*, USA in November, 2014.

- J. A. Msumba, H. Xu, "Speech Transmission in Cognitive Radio Networks: A Cross-layer MAC Scheme for Throughput Optimisation," Submitted to the *SAIEE Africa Research Journal* in October 2014.

- J. A. Msumba, H. Xu, "A POMDP Framework For Throughput Optimization MAC Scheme in Presence of Sensing Errors for Cognitive Radio Networks," *Computer Science and Applications Journal on*, Volume 1, No 4, pp. 205-216, 2014.

- J. A. Msumba, H. Xu, "Throughput Optimization MAC Scheme for Cognitive Radio Networks: A POMDP Framework," in Proc. *IEEE AFRICON 2013 International Conference*, Le Meridien-Ile Maurice, Mauritius, 09–12 September, 2013.

- J. A. Msumba, H. Xu, "A POMDP Framework For Throughput Optimization MAC Scheme in Presence of Sensing Errors for Cognitive Radio Networks," in Proc. *SATNAC 2013 Conference*, Spier Wine Estate, Stellenbosch, 01–04 September, 2013.

- J. A. Msumba, H. Xu, "Enabling Broadband Wireless Access Using Cognitive Radio Technology in TV Whitespace to Provide ICT Services in Rural Tanzania," in Proc. *IST-Africa 2012 Conference*, Dar-ES-Salaam, Tanzania, 09–11 May, 2012.

- J. A. Msumba, H. Xu, "Spectrum Sensing for Cognitive Radio Networks: The need for Cross-layer Design Approach for Multimedia Applications," in Proc. *IEEE AFRICON 2011 International Conference* , Livingstone, Zambia, 13–15 September, 2011.

Chapter 2

Literature Review

2.1 The Cognitive Radio and Radio Spectrum

2.1.1 Evolution Cognitive Radio Concept

Three main entities of wireless communication devices are signalling, hardware, and their functionalities. These three main streams complement each other and have evolved since the invention of the radio transmission by Guglielmo Marconi [12]. The primitive communications devices had very simple signalling, analogue hardware, and limited functionality. Over the past 15 years, notions about radios have been evolving away from pure hardware-based radios to radios that involve a combination of hardware and software. The concept of software-defined radio (SDR) was introduced way back in 1990 by Mitola [4]. Under SDR concept the radios typically have radio frequency (RF) front end with a software-controlled tuner [13]. Baseband signals are passed into an analogue-to-digital converter (ADC). The quantized baseband is then demodulated in a reconfigurable device such as a field-programmable gate array (FPGA), digital signal processing (DSP), or a personal computer (PC). The reconfigurability of the modulation scheme makes it an SDR.

Joseph Mitola in [4] took the SDR concept further by coining the term CR. Since the

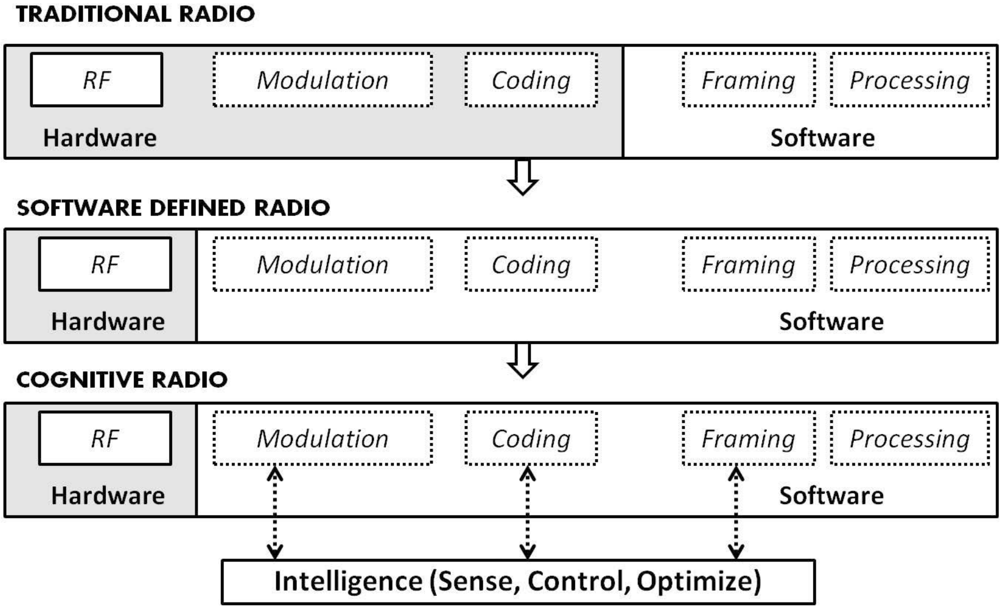

Fig. 2.1: Evolution of radios

coining of the phrase, the term CR has grown and expanded and has tended to be used in very many ways. Essentially CRs are SDRs equipped with some kind of artificial intelligence which make them be capable of sensing and reacting to their environment. Fig. 2.1 shows a simplified view of the evolution of radios from the traditional radio, SDR, to CR which is summarized in [14]. Looking at this figure, it is clear that SDR is the core enabling technology for CR. One of the most popular definitions of CR supports this argument clearly that a CR is an SDR that is aware of its environment, internal state, and location, and autonomously adjusts its operations to achieve designated objectives [12]. Thus, CR architecture augments SDR with computational intelligence and learning capability. There have been many different definitions of the buzz word CR in the past few years [12, 15–18]. However, a more common definition which is also adapted in this thesis restricts the radio's cognition to more practical sensory inputs that are aligned with typical radio operation. Thus, a CR is a radio which is able to sense the current spectral environment, has some memory of past activities along with typical radio operation. It should also be able to sense the current spectral environment while keeping some memory of past activities along with their power, bandwidth, and modulation [14]. As a result of this information the radio can make better decisions about how to best optimize some overall goal such as achieving an optimal network capacity or minimizing interference to other signals.

2.1.2 Cognitive Radio Technology for Dynamic Spectrum Access

Radio spectrum is the lifeblood of RF communications and that without it, there is no electromagnetic communications [15]. Many significant research works have addressed the value of radio spectrum which is usually considered as a scarce resource. However, a recent survey of radio spectrum utilization performed by federal communication commission (FCC) of America indicated that the actual licensed radio spectrum is heavily underutilized in both temporal and spatial dimensions which make the efficient utilization of radio spectrum becoming a central theme of the research recently [3]. Spectrum utilization can be improved significantly by allowing unlicensed user also known as secondary user (SU) to utilize a licensed band when the licensed user also known as primary user (PU) is not using the radio spectrum [4]. The CR technology that we introduced in section 2.1.1 has been considered as a solution to improve the efficient utilization of the radio spectrum. Current communication systems use radios that can adapt their behaviour in many ways.

Haykin in [19] defined CR as an intelligent wireless communication system that is aware of its surrounding environment. It uses the methodology of understanding-by-building to learn from the environment and adapt its internal states. The two primary objectives in mind being highly reliable communications whenever and wherever needed and efficient utilization of the radio spectrum. The CR is the core technology behind spectrum reuse [20], which consists of three essential components as summarized in Fig. 2.2:

(i) *Spectrum sensing*: The secondary users are required to sense and monitor the radio spectrum environment within their operating range to detect the frequency bands that are not occupied by primary users.

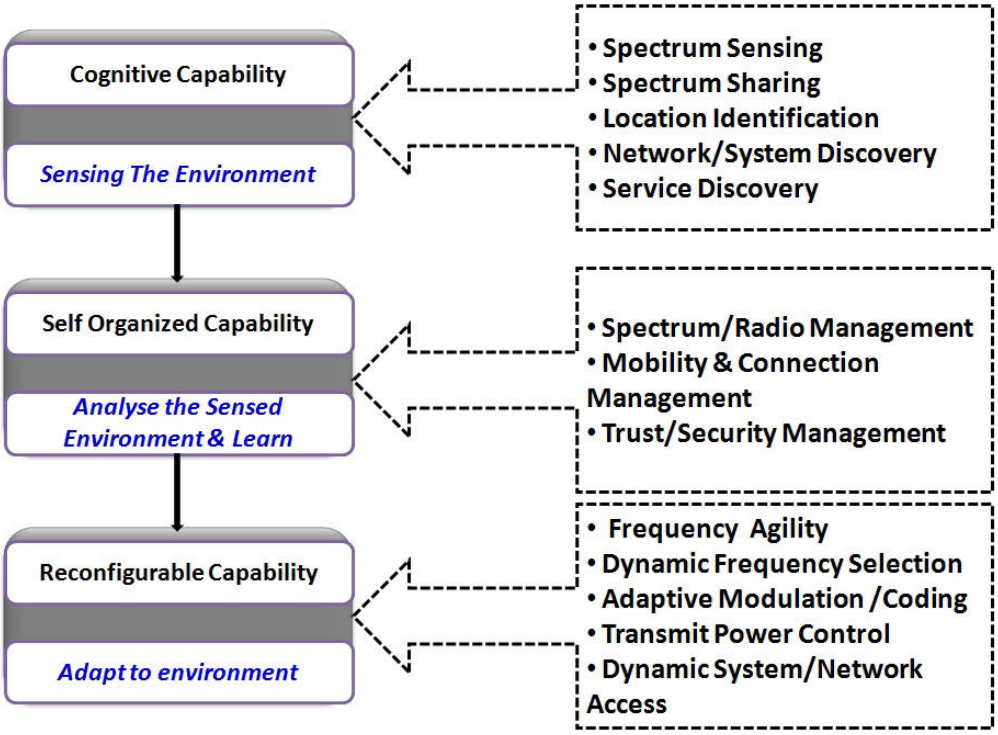

Fig. 2.2: A summary of a CR Device Capabilities

(ii) *Dynamic spectrum management*: Cognitive radio networks are required to dynamically select the best available bands for communication.

(iii) *Adaptive communication*: A cognitive radio device can configure its transmission parameters such as carrier frequency, bandwidth, and transmission power to opportunistically make the best use of the ever-changing available spectrum.

2.2 Spectrum Sensing for Cognitive Radio Networks

One of the most prominent feature of CR networks is their ability to switch between different portions of the radio spectrum and detect the availability of vacant spectrum. There are several techniques available for spectrum sensing, each with its own set of advantages and disadvantages that depend on specific scenario. Some works in the literature consider spectrum sensing as a method for distinguishing between two or more different types of signals or technologies in operation. In this section a review of most common spectrum sensing techniques is presented. Spectrum sensing enables unlicensed users to continuously sense the channel before accessing it in order to avoid interference to licensed user and other radio systems. Most of existing research in cognitive radio had been mainly dedicated to the PHY aspect of the cognitive radio design. Recently, some research efforts were carried out to investigate the impact of PHY information on upper layer performance. We review the conventional energy detection spectrum sensing, and a cooperative relay diversity-based spectrum sensing using AF protocol. We also discuss cooperative spectrum sensing where multi-user are involved in spectrum sensing. Finally we briefly present a cross-layer design approach proposal for multimedia transmission over cognitive radio networks framework as our work in progress.

2.2.1 Introduction

The basic idea behind CR is spectral reusing or spectrum sharing, which allows unlicensed spectrum users to communicate over the spectrum allocated to the licensed network users when they are not fully utilizing it. To do so, the unlicensed users are required to frequently perform spectrum sensing, that aimed at detecting the presence of the licensed users. Whenever the licensed users become active, unlicensed users have to detect their presence with a high probability and vacate the channel or reduce transmit power within certain amount of time to avoid interference. In this way, unlicensed users adapt to the environment by detecting spectrum holes. The most efficient way to detect the spectrum holes is to detect the presence of licensed users [21]. Fig. 2.3 broadly shows the aspect of spectrum sensing. Spectrum sensing can be looked at in terms of approaches, hardware or cooperative sensing. Different types of spectrum sensing can be viewed in terms of the enabling algorithm such as energy detection algorithm, wavelet based sensing. On the other hand different wireless standards can be viewed in terms of standard what employing sensing such as IEEE 802.11k, and blue tooth as shown in Fig. Fig. 2.3.

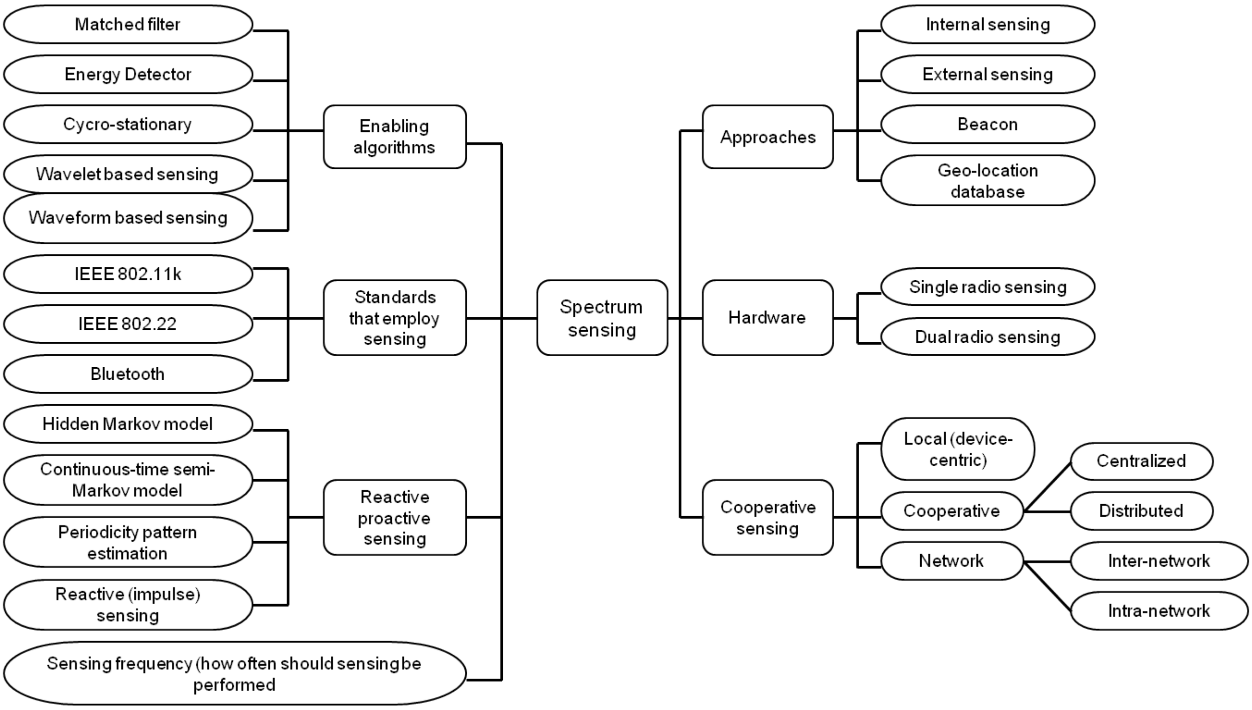

Fig. 2.3: Aspects of spectrum sensing techniques.

Thus, SUs are considered lower priority users of spectrum allocated to a PU, therefore a fundamental requirement is to avoid interference to potential PUs in their vicinity. On the other hand, PUs have no requirement to change their parameters for spectrum sharing with SUs. Thus, cognitive radios should be able to independently detect PU presence through continuous spectrum sensing. Different classes of PUs would require different sensitivity and rate of sensing for the detection. However, it is difficult for a cognitive radio to have a direct measurement of the channel between a primary receiver and a transmitter. Therefore, the most recent works focus on the primary transmitter detection based on local observations of SUs. Generally, the spectrum sensing techniques can be classified as transmitter detection (non-cooperative), cooperative detection, and interference-based detection as summarized in Fig. 2.4 [22]. Although spectrum sensing has a long history, it has been reborn as a very active research area recently due to the fact that it is a fundamental problem for cognitive radio.

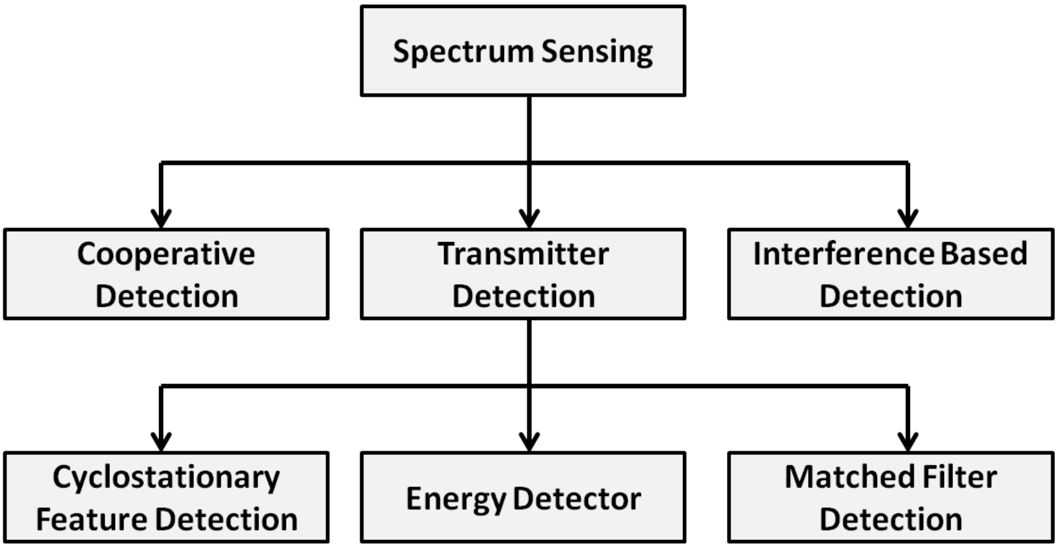

Fig. 2.4: Classification of spectrum sensing techniques.

2.2.2 Non-Cooperative/Transmitter Spectrum Sensing

Currently, three non-cooperative/ transmitter detection methods, namely, the matched filter detection, the energy detection and the cyclo-stationary feature detection, have been presented for cognitive radio networks as pointed out in [21].

2.2.2.1 Energy Detection Spectrum Sensing

The energy based spectrum sensing and detection is the simplest method for detecting primary users in the environment in a blind manner. It has been widely used for detecting unknown deterministic signals in many applications. It is known as a suboptimal detector, which can be applied to detect unknown signals as it does not require a priori knowledge on the transmitted waveform [23]. Usually, a non-fading additive white Gaussian noise (AWGN) channel is assumed when studying the performance of energy detection. Energy detector measures energy of primary signal band and compares with a proper set threshold. It requires longer sensing time to achieve desired level of performance. It has low computational complexity which makes it an attractive candidate for cognitive radio. Fig. 2.5 shows a simplified block diagram of an energy detector which consists of four blocks namely band-pass filter (BPF), squaring device $(\bullet)^2$, integrating device $\int_0^T$ and threshold device.

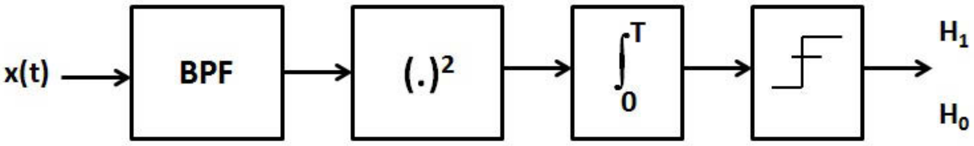

Fig. 2.5: Block diagram of an energy detector

For input signal $x(t)$, BPF will select the center frequency and the bandwidth of interest. BPF is followed by a squaring device which measures the received energy. Integrating device determines the observation interval and the last device receives the output of integrator which serves as decision statistic and is compared with a threshold value to decide whether signal is present or not.

2.2.2.2 Binary Hypothesis Testing Problem of Energy Detector

The basic hypothesis model for energy detector is defined as

$$y(n) = \begin{cases} w(n) & H_0 \\ x(n) + w(n) & H_1 \end{cases} \tag{2.1}$$

where $y(n)$ represents the received signal at CR user, $w(n)$ is the AWGN with zero mean and the variance σ_w^2, H_0 denotes the hypothesis corresponding to the absence of the primary signal, H_1 denotes the hypothesis corresponding to the presence of primary user signal, and (n belongs to $[1 : N]$) is the number of samples while $x(n)$ is the primary user's signal and is assumed to be random Gaussian process with zero mean and variance σ_x^2.

2.2.2.3 Decision Statistic of Energy Detector

Let the output of the energy detector be Y_o and serve as decision statistic. Assuming that $(y[n]$ is a real value, then we have

$$Y_o = \sum_{n}^{N} (y[n])^2 \tag{2.2}$$

Comparing with the threshold say τ and based on optimal decision yield by likelihood ratio Neyman-Pearson hypothesis testing as presented by Mishra in [24], the probability of detection (P_D) and the probability of false alarm (P_F) can be defined as the probability that the sensing algorithm of CR users detects a primary user under H_0 and H_1, respectively. Thus

$$\begin{aligned} P_F &= P(Y_o > \tau | H_0) \\ P_D &= P(Y_o > \tau | H_1) \end{aligned} \tag{2.3}$$

where $P(\bullet)$ is the conditional probability. When the interest is in low signal-to-noise ratio (SNR) then a large number of samples should be used. The central limit theorem can be used to approximate the decision statistic as Gaussian as follows:

$$\begin{aligned} P_F &= Q\left(\frac{\tau - N\sigma_w^2}{\sqrt{2N\sigma_w^4}}\right) \\ &= \frac{1}{\pi}\int_{\left(\frac{\tau - N\sigma_w^2}{\sqrt{2N\sigma_w^4}}\right)}^{\infty} exp\left(\frac{t^2}{2}\right) dt \\ &= \frac{1}{2} erfc\left(\frac{\left(\frac{\tau - N\sigma_w^2}{\sqrt{2N\sigma_w^4}}\right)}{\sqrt{2}}\right) \end{aligned} \tag{2.4}$$

$$\begin{aligned} P_D &= Q\left(\frac{\tau - N\left(\sigma_w^2 + \sigma_x^2\right)}{\sqrt{2N\left(\sigma_w^2 + \sigma_x^2\right)}}\right) \\ &= \frac{1}{2\pi}\int_{\left(\frac{\tau - N\left(\sigma_w^2 + \sigma_x^2\right)}{\sqrt{2N\left(\sigma_w^2 + \sigma_x^2\right)}}\right)}^{\infty} exp\left(\frac{t^2}{2}\right) dt \\ &= \frac{1}{2} erfc\left(\frac{\left(\frac{\tau - N\left(\sigma_w^2 + \sigma_x^2\right)}{\sqrt{2N\left(\sigma_w^2 + \sigma_x^2\right)}}\right)}{\sqrt{2}}\right) \end{aligned} \tag{2.5}$$

where $Q(\bullet)$ is the complimentary distribution function of the Gaussian and $erfc(\bullet)$ is the complimentary error function [24]. Given that SNR is represented as $\frac{\sigma_x^2}{\sigma_w^2}$, then (2.4) and (2.5) can be combined such that P_D is expressed in terms of SNR and number of samples (N) as

$$P_D = Q\left[\frac{Q^{-1}(P_F) - SNR\sqrt{\frac{N}{2}}}{1 + SNR}\right] \tag{2.6}$$

Thus, from (2.6), the number of samples needed for primary user detection can be evaluated as

$$N = \left[\frac{Q^{-1}(P_F) - Q^{-1}(P_D)}{SNR} - Q^{-1}(P_D)\right] \tag{2.7}$$

The number of samples (N) can also be defined as the product of sensing time and sampling frequency [25]. Likewise, (2.7) shows that the number of samples required to meet specified P_D and P_F depends on SNR. This means that the number of samples for primary user detection increases as the SNR decreases which result into longer sensing time. It should be noted that the higher P_D, the better the PU is protected. However, from the CR user perspective, the lower the P_F the more chances the channel can be reused when it is available thus the higher the achievable throughput for CR network. The probability of miss detection (P_{MD}) can be evaluated as

$$P_{MD} = 1 - Q\left[\frac{Q^{-1}(P_F) - SNR\sqrt{\frac{N}{2}}}{1 + SNR}\right] \tag{2.8}$$

2.2.3 Cooperative Detection Using AF Relay Diversity Protocol

In this section we develop a cooperative detection spectrum sensing model based on AF cooperative relay diversity in order to address a hidden node problem and improve the performance of spectrum sensing for CR networks. In this scheme a network shown in Fig. 2.6 is considered where two PUs namely PU1 and PU2 co-exist with two CR network users namely CU1 and CU2. The wireless link between the primary network transmitter (T) and CU2 is assumed to be obstructed by the wall. This causes CU2 to experience a considerable low SNR due to shadowing effect. This results into CU2 failing to detect the presence of the signal from the T and therefore results into interference with PU2. CU1 can therefore act as a cooperative relay for CU2 in order to improve the detection probability of CU2. In this model, the following assumptions are made:

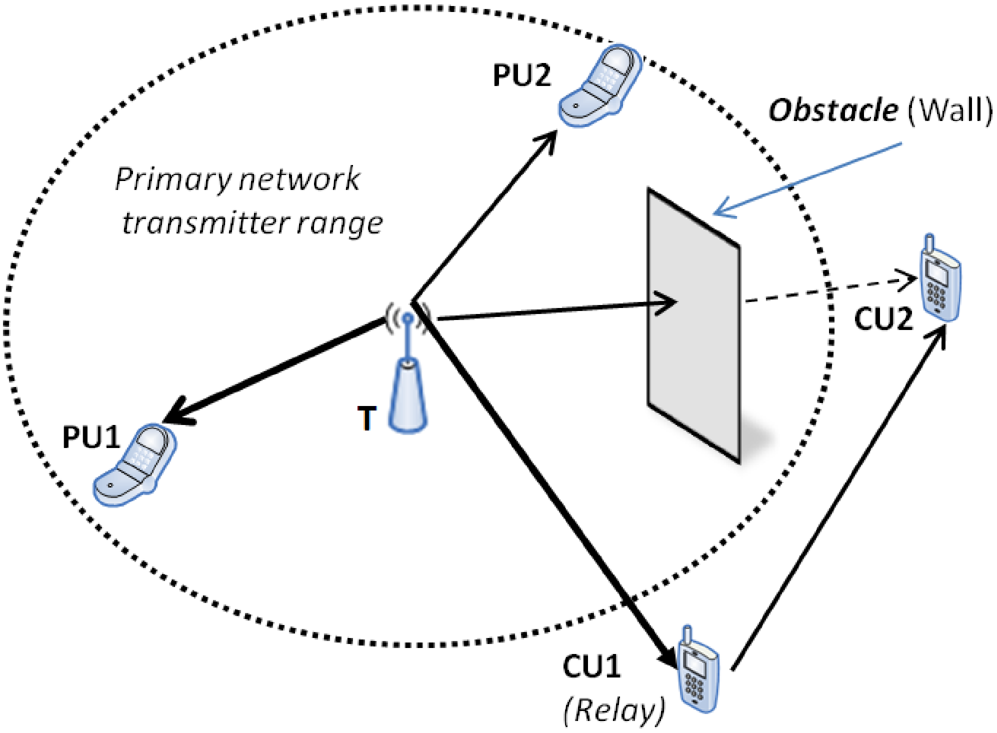

Fig. 2.6: Amplify and forward cooperative relay spectrum sensing scheme.

- All users in the cognitive radio network are equipped with single antenna.

- The antenna at any user can be utilized for both, transmission and reception.
- There is independent, additive complex white Gaussian noise with zero mean and double sided power spectral density (No) at each receiver.
- All wireless channels are independent from each other in space.

Let p_1 represent the transmission path from T to CU1, p_2 represent the transmission path from T to CU2, $hp1(k)$, $hp2(k)$ and $h12(k)$ represent the fading coefficients from T to CU1, T to CU2 and CU1 to CU2 respectively. All these coefficients are assumed to be random variables with variances σ_{p1}^2, σ_{p2}^2, and σ_{p12}^2 respectively. Then for a given primary signal power P , the signals received by CR users can be expressed as:

$$y_1(k) = h_{p1}(k)P + n_1(k) \tag{2.9}$$

$$y_2(k) = h_{p2}(k)P + n_2(k) \tag{2.10}$$

SUs need to detect the presence of PUs as quick as possible. Thus, when the PU starts using the radio spectrum band, the two SUs have to detect the presence of the PUs and quickly vacate the band to avoid causing interference. Contrary to that, if a wireless link between T and CU2 encounters fading due to shadowing then the signal received by CU2 from T is such a week that it takes long time to detect its presence. CU2 needs to cooperate with CU1 to improve the detection probability and hence reduce the overall detection time of CR network which has significant effect to the QoS for delay sensitive traffic such as multimedia traffic over CR networks. In order to address a hidden node problem in this topology AF protocol presented in [26] can be adapted to improve the P_D of primary user signal by CU2. By referring to Fig. 2.6 a scenario whereby two CR users are involved in detecting the presence of spectrum holes and the PU in a particular band can be described. The whole implementation process of AF can be separated into two consecutive phases. Given that k is a time slot then,

- In odd time slot $2k$-1, both CU1 and CU2 receive the signal transmitted from T.
- In even time slot $2k$, where CU1 starts relaying its received information to CU2 based on AF protocol. In this time slot CU2 will receive two copies of signals at the same time, thus from Pt and from CU1.

Considering the odd time slot, the signal received by CU1 and CU2 can be expressed respectively as

$$y_1(2k-1) = h_{p1}(2k-1)P + n_1(2k-1) \tag{2.11}$$

$$y_2(2k-1) = h_{p2}(2k-1)P + n_2(2k-1) \tag{2.12}$$

where, $n_1(2k-1)$ and $n_2(2k-1)$ are assumed to be additive complex Gaussian noise with zero mean and double-sided power spectral density, and independent from each other. In the even slot CU1 relays the message from T to CU2 as a cooperative user. Based on the AF protocol, let γ be the relay gain, then signal $y_1(2k-1)$ will be multiplied by γ and forwarded to CU2. Meanwhile, in the even slot, CU2 will receive the signal from T. The signal received by CU2 in the even slot can then be expressed as

$$y_{2k} = h_{p2}P + \gamma h_{12}(2k)y_1(2k-1) + n_2(2k) \tag{2.13}$$

where γh_{12} is the instantaneous fading coefficient of the wireless channel from CU1 to CU2 and $n_2(2k)$ is the additive complex white Gaussian noise with zero mean and double sided power spectral density (No). Substituting $y_1(2k-1)$ from (2.11) into (2.13), we obtain

$$\begin{aligned} y_{2k} = h_{p2}(2k)P &+ \gamma h_{12}(2k)h_{p1}(2k-1)P \\ &+ \gamma h_{12}(2k)n_1(2k-1) \\ &+ n_2(2k) \end{aligned} \tag{2.14}$$

For convenience of theoretical analysis, let $\gamma = \frac{1}{h_{12}}$. Then (2.14) can be re-written as

$$\begin{aligned} y_{2k} = h_{p2}(2k)P &+ \frac{1}{h_{12}}h_{12}(2k)h_{p1}(2k-1)P \\ &+ \frac{1}{h_{12}}h_{12}(2k)n_1(2k-1) \\ &+ n_2(2k) \end{aligned} \tag{2.15}$$

Which is simplified to

$$y_{2k} = \left[h_{p2}(2k) + h_{p1}(2k-1)\right]P + n_1(2k)(2k-1) + n_2(2k) \tag{2.16}$$

The detection problem of CU2 under AF protocol can be stated as follows: Given the observation $y_2(2k-1)$ in the odd time slot and $y_2(2k)$ in the even time slot the detector will decide on the two hypothesis

$$y_2 = \begin{cases} H_0 : & n_2(2k-1) \\ H_1 : & \left[h_{p2}(2k) + h_{p1}(2k)(2k-1)\right]P + n_1(2k)(2k-1) + n_2(2k) \end{cases} \tag{2.17}$$

where H_0 denote the absence of the PU signal and H_1 denote the presence of primary transmitter signal. Based on the binary hypothesis in (2.1), energy detector (ED) presented in section 2.2.2.2 can be used to evaluate the P_D of the primary signal for CU1 and CU2 and show the effects of cooperation on detection of the primary user signal in cognitive radio networks using AF protocol. However, the main downfall of this protocol is that the received noise to the relay CU1 is also amplified.

2.2.3.1 Multi-user Cooperative Spectrum Sensing

In this section we present a cooperative spectrum sensing for multi-user in CR networks. Cooperative spectrum sensing can be implemented in either a centralized or distributed architecture [27]. In a centralized architecture a fusion centre collects sensing information from CR users and then identifies the available spectrum and broadcasts the fused results to another CR user or directly controls CR users traffic. The centralized architecture can further be categorized into two groups, namely partially cooperative spectrum sensing and totally cooperative spectrum sensing. In partially cooperative spectrum sensing, each CR user detects the spectrum independently and directly transmits its sensing information to the fusion centre [28]. In totally cooperative spectrum sensing, CR users cooperatively exchange the sensing information and send to the fusion centre. Let us consider a number of CR users $(1, 2 \cdot \cdot\cdot, N)$, perform spectrum sensing independently and send the sensing information to a fusion centre (centralized architecture). Thus, by means of fusion the decision of presence or absence of the primary signal is made. Without loss of generality we make the following assumptions:

- Each CR user is independent and has the same average probability of detection probability of detection (P_D) and false alarm probability probability of false alarm (P_F) under AWGN
- All CR users are in the same region and equipped with identical spectrum sensing detector with the same sensing time T_d and decision threshold τ.
- The values of path-loss experienced by all CR users are the same.
- The channel corresponding to each CR user is independent and follows the identical distribution.
- The AWGN is modelled with the same variance σ_w^2.

The performance of the spectrum sensing represents the reliability which is measured by P_D and P_F. On the other hand the performance of cooperative spectrum sensing also represents the cooperative reliability which can be measured by cooperative probability of detection (CPD) and cooperative probability of false alarm (CPF). CR users cooperate by sending their local observations to the fusion centre which makes a final decision on the absence or presence of the primary user signal. However there are some practical constraints such as bandwidth and therefore CR users may report only quantized observations. The classes of fusion algorithms may be hard decision combining or soft decision combining. In the hard decision combining, each CR user performs a local hypothesis test and reports a binary decision 1 if it believes that the primary user signal is present and 0 otherwise. In the soft decision, each user reports the full observations to the fusion centre. The local observations and fusion rule determine the cooperative spectrum sensing performance. Counting rule (voting rule) is one of the simplest suboptimal solutions for sensing information fusion problem [29–31]. It counts the number of CR users voted for the presence of the primary user signal and compares it with a set threshold value. The decision is mainly based on the type of received vector of bits. By using the counting rule, the fusion of information can be by either OR logic operation or AND logic operation for combining decision from several CR users. Based on the assumptions made above, we evaluate the reliability of cooperative spectrum sensing using P_D and P_F as follows: For a given i^{th} radio and assuming that the fusion decision is based on hard decision OR rule, then the cooperative probability of detection using OR rule (CPDOR) and cooperative probability of false alarm using OR rule (CPFOR) can be evaluated as follows:

$$\begin{aligned} CPDOR &= Pr\{fusion - decision = 1/H_1\} \\ &= 1 - \prod_{i=1}^{N}(1 - P_D i) \end{aligned} \tag{2.18}$$

$$\begin{aligned} CPFOR &= Pr\{fusion - decision = 1/H_0\} \\ &= 1 - \prod_{i=1}^{N}(1 - P_F i) \end{aligned} \tag{2.19}$$

where N is the number of independent CR users. Similarly, given i_{th} radio and assume that the fusion decision is based on hard decision AND rule, then cooperative probability of detection using AND rule (CPDAND) and cooperative probability of false alarm using AND rule (CPFAND) can be evaluated as:

$$\begin{aligned} CPDAND &= Pr\{fusion - decision = 1/H_1\} \\ &= 1 - \prod_{i=1}^{N}(P_D i) \end{aligned} \tag{2.20}$$

$$\begin{aligned} CPFAND &= Pr\{fusion - decision = 1/H_0\} \\ &= 1 - \prod_{i=1}^{N}(P_F i) \end{aligned} \tag{2.21}$$

2.2.4 Matched Filter Spectrum Sensing

When primary user signal information, such as modulation type, pulse shape, and packet format is known to a CR user, the optimal detector in stationary Gaussian noise is the matched filter (MF) since it maximizes the received SNR. Assuming that the signal samples $x[n]$ are white or orthogonal to the pilot tone, the noise samples $w[n]$ are white, the pilot tone $X_p[n]$ is known, and the fraction of total power allocated to the pilot tone is give by θ, then in a coherent detection, the hypothesis given in (2.22) should be tested.

$$\begin{aligned} &H_0 : Y[n] = w[n] \\ &H_1 : Y[n] = w[n] + \sqrt{(1-\theta)} \times x[n] + \sqrt{\theta} \times X_p[n] \end{aligned} \tag{2.22}$$

Detection by using MF is useful only in cases where the information from the primary users is known to the CR users. MF detection requires less detection time since it requires only

(1/SNR) samples to achieve a given P_D constraint. When the information of the licensed user signal is known to the CR user, MF detection is optimal in stationary Gaussian noise. However, since it requires a prior knowledge of every primary signal. If the information is not accurate, then MF performs poorly. The most noteworthy disadvantage of MF is that a CR would need a dedicated receiver for every type of licensed user.

2.2.5 Cyclostationary Feature Detection

The cyclostationary feature detection (CFD) makes use of the periodicity in the signal transmitted by the licensed user to discover the presence of licensed users. The periodicity is commonly embedded in sinusoidal carriers, pulse trains, spreading code, hopping sequences or cyclic prefixes of the primary signals [32,33]. Due to the periodicity, these cyclostationary signals exhibit the features of periodic statistics and spectral correlation, which is not found in stationary noise and interference. Thus, CFD is robust to noise uncertainties and performs better than energy detection in low SNR regions. Although it requires a priori knowledge of the signal characteristics, CFD is capable of distinguishing the CR transmissions from various types of licensed users signals. This eliminates the synchronization requirement of energy detection in cooperative sensing. Moreover, CR users may not be required to keep silent during cooperative sensing and thus improve the overall CR throughput. The significant shortcomings of this technique are its high computational complexity and long sensing time. Due to these issues, this detection method is less common than energy detection in cooperative sensing [34]. Fig. 2.7 presents the comparison of different transmitter detection techniques for spectrum sensing and the spectrum opportunities in terms of complexity and accuracy as presented in [1]. As it can be seen from the Fig. 2.7, that MF based detection is complex to implement in CRs, but has highest accuracy. Similarly, the energy based detection is least complex to implement in CR system and least accurate compared to other approaches which are in the middle of these two.

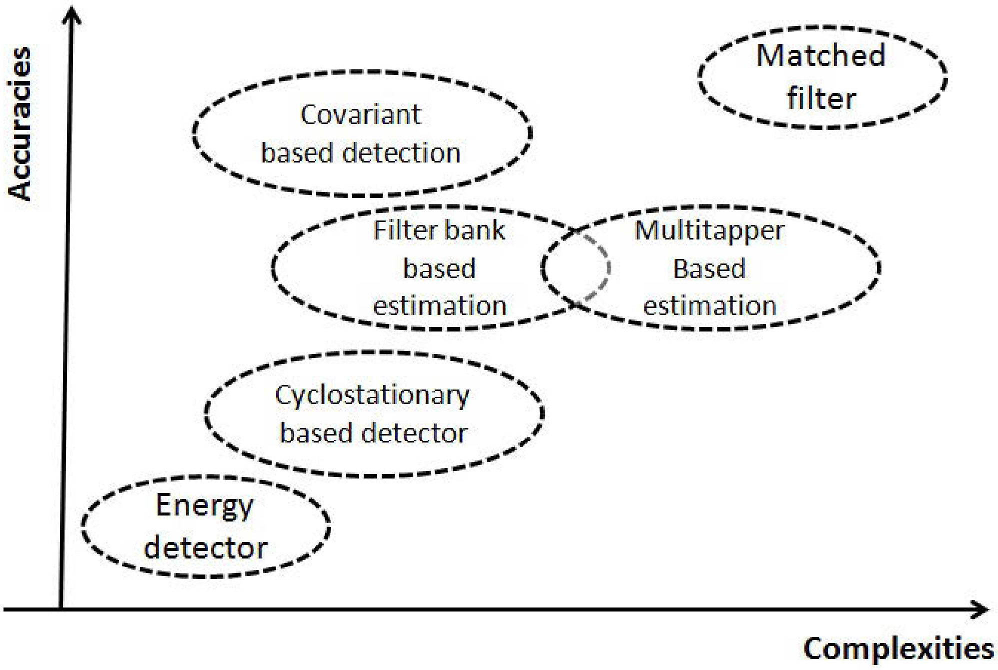

Fig. 2.7: Sensing accuracy and complexity of various sensing methods [1].

2.3 Cross-layer Design For Wireless Networks

2.3.1 Introduction

Protocol is a common abstraction in network design, since it provides design modularity for the network protocols that facilitates standardization and implementation. However, this does not work well in wireless networks where many protocol design issues are intertwined [35]. Protocol layering works reasonably in wired networks where data rate associated with the PHY layer exceeds gigabits per second and packets are rarely lost. However, even in this setting, layering makes it difficult to support high data rate applications with hard delay constraints such as video and voice. Wireless networks pose more new challenges [36–38]. Some of these challenges are:

- Receiver and background noises which result into higher bit error rate (BER) and dynamic changes of channel quality.

- Wireless link path loss and inaccuracies.
- Multipath signal propagation which results into fading effects and signal dispersion.
- Interference problem:which may be from other stations within the range (*co-channel*), from other devices/technologies (*universal mobile telecommunication system (UMTS), global system for mobile communication (GSM), blue tooth, 802.11*), or electromagnetic interference (*microwaves, electric engines, vacuums*).
- Mobility: which may either be with the same frequency/channel, or with different frequency/channel.
- Limited resources: such as energy.

Wireless can have very low PHY layer data rate with very high BER. This can give rise to tremendous inefficiencies and also produce exploiting interactions between protocol layers for better performance. Cross-layer design considers multiple layers of protocol stack together, either in terms of a joint design or in information exchange between the layers. Exploiting the dependencies and interactions between layers as well as sharing knowledge about layer state and conditions proved to be a promising paradigm for performance optimization in wireless systems. This exhibits improved performance advantages over a strictly layered approach [35]. There are several questions to answer when considering cross-layer design [39–43]. Some of these questions are:

- which layer should respond to channel variations?
- which layers should be jointly optimized?
- what information should be exchanged between layers?
- how should this information be used by adaptation protocol at each particular layer?
- how to handle the trade-offs between performance and complexity as well as scalability?

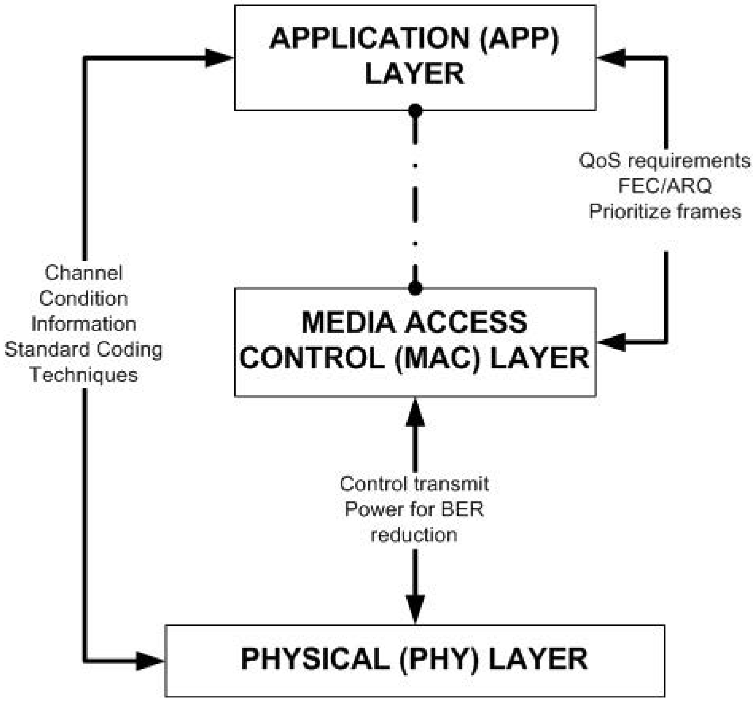

Fig. 2.8: Interaction between APP, MAC, and PHY layers

In this work we consider the interaction between three layers (PHY, MAC and APP) as shown in Fig. 2.8 in which their performances are briefly explained in the following sections.

2.3.1.1 PHY Layer Performance in Wireless Networks

There are several design trade-offs associated with PHY layer, which includes modulation, coding, diversity, adaptive techniques, multiple-input multiple-output (MIMO), equalization, multi-carrier modulation and spread spectrum. However, the design trade-offs for a link is part of wireless network impact protocol layers above PHY layer. Only some few aspects of the PHY layer design in wireless network do not have an impact to the protocols associated with higher layers. For example, a wireless network where bits are packetized for transmission, the design choices at the PHY layer along with the channel and interference conditions determine the link packet error rate (PER). Many MAC layer protocols retransmit packets that are received in error, so PER based on PHY layer design affects the retransmission requirements at the MAC layer [35]. The best use of multiple antennas in wireless networks can simultaneously impact the PHY, MAC, network, and transport layers. For example, multiple antennas give rise to a multiplexing /diversity/directionality trade-offs. Thus, the antenna can be used to increase the data rate on the link in order to provide diversity so that BER is reduced, or to provide directionality to reduce fading and the interference a signal cause to other signals. Diversity gain will reduce PER leading to fewer retransmissions. Multiplexing will increase the link rate, which reduces congestion and delay on the link [44] and benefits all multihop routes using that link. The directionality reduces interference to other links, thereby improves their performance. The transmit power of a node at the PHY layer also has a broad impact across many layers of the protocol stack. Increasing transmit power at the PHY layer reduces PER, thereby impacts the retransmissions required at the MAC layer. In fact any two nodes in the network can communicate directly with sufficiently high transmit power, so this power drives link connectivity [35]. However, a high transmit power from one node in the network can cause significant interference to other nodes, thereby degrade their performance and breaking their connections to other nodes. In particular, link performance in wireless network is driven by signal-to-interference and noise ratio (SINR), so the transmit power of all nodes impacts the performance of all links in the network. Broadly speaking, the transmit power coupled with adaptive modulation and coding for a given node defines its local neighbourhood. This is the collection of nodes that it can reach in a single hop and thus defines the context in which access, routing, and other higher layer protocols operate. Therefore, the transmit power of all nodes in the network must be optimized with respect to all layers that it impacts. As such, it is a prime motivator for a cross-layer design.

2.3.1.2 MAC Layer Performance in Wireless Networks

The MAC layer controls how different users share the available radio spectrum. It ensures the successful reception of packets transmitted over this shared radio spectrum. Allocation of signalling dimensions to different users is done through either multiple access or random access, and a detailed discuss of these access techniques can be found in [35] Chapters 14.2-

14.3. Multiple access divides the signalling dimensions into dedicated channels via orthogonal or non-orthogonal channelization methods. The most common of these methods are time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA). The access layer must also provide control functionality to assign channels to users and to deny access to users when they cannot be accommodated in the system. In random access, channels are assigned to active users dynamically, and in multi hop networks these protocols must contend with hidden and exposed terminals. The most common random access methods are different forms of ALOHA, carrier sense multiple access (CSMA), and scheduling. These random access methods incorporate channel assignment and access denial into their protocols. Transmit power associated with a single node impacts all other nodes. Thus, power control across all nodes in the network is part of the MAC layer functionality. The main role of power control is to ensure that SINR targets can be met on all links in the network which is often infeasible [45]. The MAC layer is also responsible for retransmissions of packets received in error. This is referred to as the automatic-repeat request (ARQ) protocol. Specifically, data packets typically have an error detection code that is used by the receiver to determine if one or more bits in the packet were corrupted and cannot be corrected. For such packets, the receiver will typically discard the corrupted packet and inform the transmitter via a feedback channel that the packet must be retransmitted. However, rather than discarding the packet, the access layer can save it and use a form of diversity to combine the corrupted packet with the retransmitted packet for a higher probability of correct packet reception. Alternatively, rather than retransmitting the original packet in its entirety, the transmitter can just send some additional coded bits to provide a stronger error correction capability for the original packet to correct for its corrupted bits. This technique is called incremental redundancy, since the transmitter needs only to send enough redundant bits to correct for the bits corrupted in the original packet transmission. The diversity and incremental redundancy methods have been shown to substantially improve throughput in comparison with simple retransmissions [45–48].

2.3.1.3 Impact of APP Layer on Other Layer's Performance

In the protocol stack, the APP layer is responsible for generating data to be sent over the network and processes the corresponding data received over the network. Thus, it provides the compression of the application data along with error correction and concealment. The compression must be lossless for data applications, but can be lossy for video, voice, or image applications, where some loss can be tolerated in the reconstruction of the original data [49, 50]. The higher the level of compression, the less the data rate burden imposed on the network. However, highly compressed data is more sensitive to errors since most of the redundancy is removed [51]. Data applications cannot tolerate any loss, so packets that are corrupted or lost in the end-to-end transmission must be retransmitted, which can entail significant delay. Voice, video, and image applications can tolerate some errors, and techniques like error concealment or adaptive playback can mitigate the impact of these errors on the perceived quality at the receiving end [52, 53]. Thus, a tradeoff at the application layer is data rate versus robustness: the higher its rate, the more it burdens the network, but the more robust that data is to network performance. The application layer can also provide a form of diversity through multiple description coding (MDC) [54, 55]. MDC is a form of compression whereby multiple descriptions of the data are generated. The original data can be reconstructed from any of these descriptions with some loss, and the more descriptions that are available, the better the reconstruction. If multiple descriptions of the source data are sent through the network, some of these descriptions can be lost, delayed, or corrupted without significantly degrading overall performance. Thus, MDC provides a form of diversity at the application layer to unreliable network performance. Moreover, MDC can be combined with multipath routing to provide cross-layer diversity in both the application description and the routes over which these descriptions are sent [56–58]. The trade-off is that for a given data rate, MDC entails a higher resolution loss than a compression technique that is not geared to providing multiple descriptions. This can be viewed as a performance-diversity trade-off: the application sacrifices some level of performance in order to provide robustness to uncertainty in the network. Many applications require a guaranteed end-to-end data rate and delay for good performance, collectively referred to as QoS. The Internet today, even with high-speed high-quality fixed communication links, is unable to deliver guaranteed QoS to the application in terms of guaranteed end-to-end rates or delays. For ad hoc wireless networks, with low-capacity error-prone time-varying links, mobile users, and a dynamic topology, the notion of being able to guarantee these forms of QoS is simply unrealistic. Therefore, ad hoc wireless network applications must adapt to time-varying QoS parameters offered by the network. While adaptivity in the physical, access, and network Layers, as described in previous sections, will provide the best possible QoS to the application, this QoS will vary with time as channel conditions, network topology, and user demands change. Applications must therefore adapt to the QoS that is offered. There can also be a negotiation for QoS such that users with a higher priority can obtain a better QoS by lowering the QoS of less important users. As a simple example, the network may offer the application a rate-delay trade-off curve that is derived from the capabilities of the lower layer protocols [59] [80]. The application layer must then decide at which point on this curve to operate. Some applications may be able to tolerate a higher delay but not a lower overall rate. Examples include data applications in which the overall data rate must be high but latency might be tolerable. Other applications might be extremely sensitive to delay (e.g. a distributed-control application) but might be able to tolerate a lower rate (e.g. via a coarser quantization of sensor data). Lossy applications like voice or video might exchange some robustness to errors for a higher data rate. Energy constraints introduce another set of trade-offs related to network performance versus longevity. Thus, the trade-off curves in network design will typically be multidimensional, incorporating rate, delay, robustness, and longevity trade-offs. These tradeoffs will also change with time as the number of users in the network and the network environment change [35].

2.3.2 Cross-layer Design Approach

Wireless links have unique properties which make it difficult to support applications with high data rate requirements and hard delay constraints. Under stringent performance requirements, the layering approach to wireless network design has not worked well in general [41,60]. Layering precludes the benefits of joint optimization and a good protocol designs for isolated layers often interact in negative ways across layers, which can significantly degrade end-to-end performance as well as making the network extremely fragile to network dynamics and interference [61]. Thus, stringent performance requirements for wireless networks can be met through a cross-layer design. Such a design requires that the interdependencies between layers are characterized, exploited, and jointly optimized. Cross-layer design clearly requires information exchange between layers, adaptivity to this information at each layer, and diversity built into each layer to ensure robustness. While cross-layer design can be applied to both wireless and wired networks, wireless CR networks pose unique challenges and opportunities for this design framework due to the characteristics of their PHY layer. The existence of a link between nodes, which can be used to communicate between the nodes or cause them to interfere with each other, can be controlled by adaptive protocols such as adaptive modulation and coding, adaptive space-time signal processing, and adaptive power control. Since higher layer protocols depend on underlying node connectivity and interference, adaptivity at the physical layer can be exploited by higher layer protocols to achieve better performance. At the same time, some links exhibit extreme congestion or fading. Higher layer protocols can bypass such links through adaptive routing, thereby minimizing delays and bottlenecks that arise due to weak links. At the highest layer, information about the throughput and delay of end-to-end routes can be used to change the compression rate of the application or send data over multiple routes via MDCs. Thus, higher layer protocols can adapt to the status of lower layers. Adaptation at each layer of the protocol stack should compensate for variations at that layer based on the time scale of these variations. Specifically, variations in link SINR are very fast, on the order of microseconds for fast fading [62]. Network topology changes more slowly, on the order of seconds, while variations of user traffic based on their applications may change over tens to hundreds of seconds. The different time scales of the network variations suggest that each layer should attempt to compensate for variation at that layer first. If adapting locally is unsuccessful then information should be exchanged with higher layers for a broader response to the problem. For example, suppose the link SINR in an end-to-end route is low. By the time this connectivity information is relayed to a higher level of the protocol stack (i.e. the network layer for rerouting or the application layer for reduced rate compression), the link SINR will most likely have changed. Therefore, it makes sense for each protocol layer to adapt to variations that are local to that layer. If this local adaptation is insufficient to compensate for the local performance degradation then the performance metrics at the next layer of the protocol stack will degrade as a result. Adaptation at this next layer may then correct or at least mitigate the problem that could not be fixed through local adaptation. For example, consider again a low SINR link. Link SINR can be measured quite accurately and quickly at the PHY layer. The physical layer protocol can therefore respond to the low SINR by increasing transmit power or the level of error correction coding. This will correct for variations in connectivity due to, for example, multipath flat-fading. However, if the weak link is caused by something difficult to correct for at the physical layer, e.g. the mobile unit is inside a tunnel, then it is better for a higher layer of the network protocol stack to respond by, for example, delaying packet transmissions until the mobile leaves the tunnel. Similarly, if nodes in the network are highly mobile then link characteristics and network topology will change rapidly. Informing the network layer of highly-mobile nodes might change the routing strategy from unicast to broadcast in the general direction of the intended user. Ultimately, if the network cannot deliver the QoS requested by the application, then the application can adapt to whatever QoS is available. It is this integrated approach to adaptive networking how each layer of the protocol stack should respond to local variations given adaptation at higher layers - that comprises an adaptive cross-layer protocol design.

Diversity is another mechanism to be exploited in cross-layer design. Diversity is commonly used to provide robustness to fading at the physical layer. However, the basic premise of diversity can be extended across all layers in the network protocol stack. Cooperative diversity provides diversity at the access layer by using multiple spatially-distributed nodes to aid in forwarding a given packet. This provides diversity against packet corruption on any one link. Network layer diversity is inherent to multipath routing, such that multiple routes through the network are used to send a single packet. This induces a similar diversity /throughput tradeoff at the network layer [35]. Specifically, a packet transmitted over multiple routes through the network is unlikely to get dropped or significantly delayed simultaneously on all routes. Thus, the packet dropping probability and average delay are decreased by the network diversity. However, the packet utilizes network resources that could be used to send other packets, thereby reducing overall network throughput. Application layer diversity follows from using MDCs to describe the application data, such that as long as one of the descriptions is received, the source data can be reproduced, albeit with higher distortion than if the reproduction is based on all descriptions. Diversity across all layers of the protocol stack, especially when coupled with adaptive cross-layer design, can insure reliability and good performance over wireless ad hoc networks despite their inherent challenges. Cross-layer design across multiple protocol layers below the application layer were discussed in the preceding sections. Cross-layer design that includes the application layer along with lower layers is a difficult challenge requiring interdisciplinary expertise, and there is little work addressing this challenge to date. However, the potential performance gains are significant, as illustrated by the cross-layer designs in [63–65] for video and image transmission in ad hoc wireless networks. Cross-layer design is particularly important in energy-constrained networks, where each node has a finite amount of energy that must be optimized across all layers of the protocol stack. Energy constraints pose unique challenges and opportunities for cross-layering.

2.4 Related Works in Dynamic Spectrum Access, and Cross-layer Design for Multimedia transmission over Cognitive Radio

In order to match the QoS requirements for multimedia application at the APP layer of the communication protocol stuck with the time-varying channel condition of wireless media in CR networks, some cross-layer design methods have been studied in the literature. Zhao et al [7] were among the first researchers to work on the concept of opportunistic spectrum access by adopting a POMDP to model DSA. The discussion presented by Zhao et al in their work created a benchmark towards building spectrum agile CR. They proposed a decentralized cognitive MAC protocols that allow secondary users to independently search for spectrum opportunities without a central coordinator or a dedicated communication channel. They developed an analytical framework for opportunistic spectrum access based on the theory of POMDP. The decision-theoretic approach integrates the design of spectrum access protocols at the MAC layer with spectrum sensing at the physical layer and traffic statistics determined by the application layer of the primary network. Authors in [66, 67] presented an integrated design approach to jointly optimize multimedia intra refreshing rate, an application layer parameter, together with access strategy, and spectrum sensing for multimedia transmission in a CR system with time varying channels. They formulated the QoS optimization problem as a POMDP and presented a low complexity dynamic programming framework to obtain optimal policy. Djonin et al in [68] developed a decentralized cognitive MAC protocol that allows secondary users to independently search for spectrum opportunities without a central coordinator or dedicated communication channel. In their work they developed a truncated Markov decision process (MDP) formulation of opportunistic spectrum access and reduced computation complexity from growing exponentially to lineally with horizon length. Chen et al [10] developed optimal strategy for opportunistic spectrum access by integrating the design of spectrum sensor at physical layer with that of spectrum sensing and access policies at the MAC layer. In their work they used a separation principle whereby the design of spectrum sensor and access policy can be decoupled from that of sensing policy without losing optimality. Luo et al [69] developed a cross-layer design to jointly consider the spectrum sensing, access decision, physical layer modulation and coding scheme and data-link layer frame size to maximize the transmission control protocol (TCP) throughput in CR networks. They formulated the cross-layer TCP throughput optimization problem as a POMDP. In [70] authors proposed a rate-less coded transmission protocol in a multi-channel cognitive radio system, addressing the MAC layer sensing issues. Specifically, how many channels and which ones should be sensed in each time slot. In their work authors analysed the average throughput and formulated an optimization problem to find the optimal sensing policy based on the POMDP theory due to the dynamics of channel. However, there are still remaining challenges on how to provide a QoS guarantee for multimedia traffic over CR networks.

2.5 Chapter Summary

Cognitive Radio is a radio which is able to sense the current spectral environment and have some memory of past activities along with their power, bandwidth, and modulation. Thus, CR architecture augments SDR with computational intelligence and learning capability. Radio spectrum is considered to be scarce resource, but experimental results show that there is inefficient use of the available radio spectrum. Cognitive radio technology has been considered as a solution to improve the efficient utilization of the radio spectrum. One of the most prominent feature of CR networks is the ability to switch between different portions of the radio spectrum and detect the availability of vacant spectrum. There are several techniques available for spectrum sensing, each with its own set of advantages and disadvantages that depend on specific scenario. The energy based spectrum sensing and detection is the simplest method for detecting primary users in the environment in a blind manner. It has been widely used for detecting unknown deterministic signals in many applications. The receiver operating characteristics (ROC) curves analysis are used to study the performance of energy detector since they have been used widely in the signal detection theory. Traditional protocol layering does not work well in wireless networks where many protocol design issues are intertwined since it precludes the benefits of joint optimization. Wireless links have unique properties which make it difficult to support applications with high data rate requirements and hard delay constraints. Cross-layer design that includes the application layer along with lower layers is a difficult challenge requiring interdisciplinary expertise, and there is little work addressing this challenge to date. In order to match the QoS requirements for multimedia application at the APP layer of the communication protocol stuck with the time-varying channel condition of wireless media in CR networks, some cross-layer design methods have been studied in the literature. Although many works have been done on physical layer of CR networks, there are still remaining challenges on how to provide a QoS guarantee for multimedia traffic over CR networks. Cross-layer design approach has shown promises in providing QoS guarantee to multimedia traffic by violating the traditional protocol stack design.

Chapter 3

Cross-layer MAC Scheme for Throughput Maximization in Presence of Spectrum Sensing Errors

3.1 Introduction

The MAC protocol for CR networks is very crucial part due to the fact that it is responsible for providing coexistence between primary users (PUs) and secondary users (SUs) without or with minimum interference. Thus, the MAC protocol in CR networks is responsible for channel access decision which is the key feature of CR. Spectrum sensing is required over a wide range of licensed channels and the decision needs to be made on which channels to sense and in which sequence. Due to the dynamics of wireless channel, spectrum sensing results may contain errors leading to incorrect spectrum access decision which may cause interference to PUs. In order to efficiently implement this concept of CR networks, MAC protocols with optimal decision on spectrum sensing and access have been suggested in the literature [6, 8–10, 71], aiming at using some optimization techniques for optimal sensing and spectrum access decision. These optimal sensing and access decisions are based on the objectives and constraints. Primary user activities are generally random in nature and therefore stochastic optimization model is usually applied. However, most of the works in the literature considers the design of MAC and physical (PHY) layers jointly in such a way that the binary decision based on the set threshold is made on the presence or absence of the PU while very little attention is given to errors which are due to spectrum sensing.

In this chapter we develop a cross-layer MAC scheme for throughput maximization in CR networks taking into consideration errors due to spectrum sensing. We assume that the CR node has hardware limitations and therefore can not sense the overall range of radio spectrum. Instead, the node selects a set of channels to sense and access the idle one for transmission. This leads to partial information about the state of the system. Due to dynamics of the wireless channel, spectrum sensing errors are likely to be introduced leading to imperfect spectrum access decisions to be made by a CR node. Thus, we assume that the state of the system is not fully observable due to sensing errors and hardware limitations. We model the system using the theory of partially observable Markov decision process (POMDP) which is a suitable techniques in decision making under uncertainty. We extend the concepts presented by previous researchers [7, 8, 10, 72], and we hereby wish to acknowledge their valuable contribution in this topic. We analyse the system by considering multiple secondary users with random message arrivals in presence of spectrum sensing errors. This approach was initially presented by Zhao et al in [7] and it forms a bench mark for our formulation. By using cross-layer design concept, the design of spectrum sensing at PHY layer and access policy at the MAC layer are considered jointly in order to maximize the throughput of the CR network. We formulate the problem as a constrained POMDP and use techniques available in the literature to evaluate the optimal policies and hence compute the total reward. We evaluate the throughput performance of the proposed scheme using greedy sensing approach [7, 73] in presence of spectrum sensing errors at PHY layer. The simulation results demonstrate that the proposed system outperforms the random sensing scheme and approaches that of perfect sensing in terms of the overall throughput.

3.2 POMDP Framework

Partially observable Markov decision process provides a natural model for sequential decision making under uncertainty. This model augments a well researched framework of Markov decision process (MDP) to situations where the secondary user cannot reliably identify the underlying environment of spectrum occupancy state. The key characteristic that set POMDP apart from many other probabilistic models is the fact that the state is not directly observable. Instead the agent can only perceive observations which convey incomplete information about the worlds state [74]. It is a very general and powerful tool which extends the application of MDP to many realistic problems. An MDP which can be viewed as an extension of Markov chains with a set of decisions (actions) and a state-based reward or cost structure has been most commonly formal model for fully-observable sequential decision process [75]. For each possible state of the process, a decision has to be made regarding which action should be executed in that state. The chosen action affects both the transition probabilities and the costs (or rewards) incurred. The goal is to choose an optimal action in every state to increase some predefined measures of performance. Formally, POMDP is characterized by seven distinct quantities namely states (S), actions (A), observations (Θ), reward R and the three probability distributions namely transition probabilities (P), initial belief (b_o),and observation probabilities (θ) [74]. These items together define the probabilistic system model that underlies each POMDP. In this work we do not intend to delve deep into the development and analysis of the POMDP solutions, in stead we will make use of available POMDP solutions in the literature in order to formulate and model our optimization problem.

3.3 System Model

In this formulation we assume that a radio spectrum with N channels such that these channels are licensed to a slotted primary network. Each channel is assumed to have a bandwidth $\mathcal{W}_n(n = 1, \cdots, N)$. The evolution (channel occupancy state) of these channels is assumed to follow a Markov chain model. The reason for choosing Markov process model is the fact that it is the most commonly and widely accepted approach to model a wireless channel evolution [76, 77]. Let the channel state of the n^{th} channel in slot t be $S_n(t) \in (0, 1)$, where "0" represents busy channel and "1" represents idle channel. We consider a finite state space of 2^N and that the transition probabilities from one state to another is known and remain unchanged for the number of slots in a specific period of time. In this formulation, we adopt the approach presented by previous works in [78, 79] whereby for the total time slot T, the transition probability from one state to another $(P(i, j))$ is assumed to be known and does not change. A CR network whose users independently and selfishly search for and utilize instantaneous radio spectrum opportunities in these N channels is considered. Fig. 3.1 shows an example of a discrete Markovian model for one channel with two-states,where P_{00} is the probability of the channel to remain in the busy state, P_{01} is the probability of the channel to change from busy state to idle state, P_{11} is the probability that the channel remain in the idle state and P_{10} is the probability that the channel change from idle to busy state. Fig. 3.2 shows the network model for the proposed scheme whereby a set of CR users co-exists with primary network users (licensed users). In this chapter we assume that the channel fading effect is neglected and that the channel sensing errors are only due to spectrum sensor. Thus, the probability of transition between the busy state and idle state, the probability of the primary user staying in the same state, the stationary distribution and the channel transition matrix can be easily evaluated. For simplicity of presentation a system with single channel is assumed in the formulation. The transition probability matrix of this channel is $P(i, j)$ which can be represented by a 2×2 matrix as shown in (3.1) for

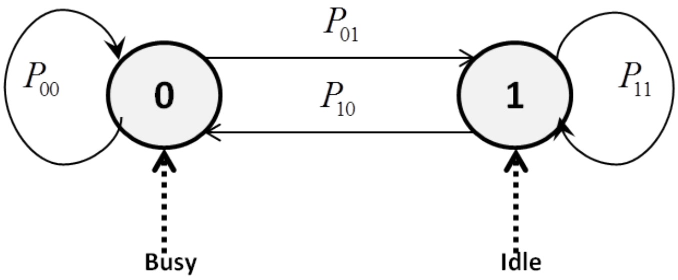

Fig. 3.1: Two-states discrete Markov model for a single channel.

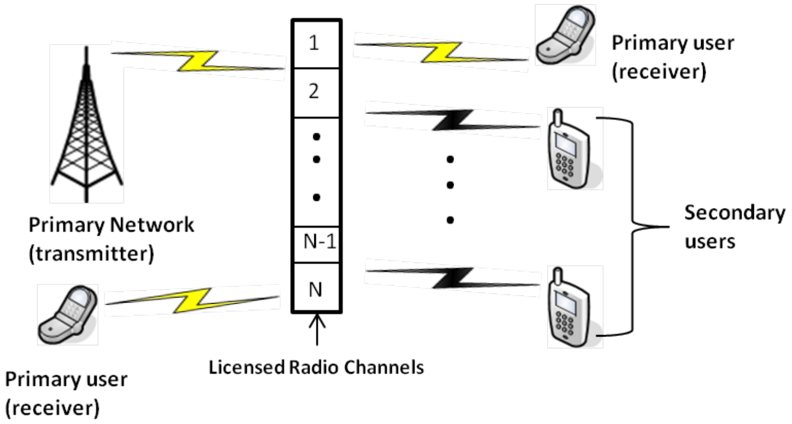

Fig. 3.2: Network model for cognitive radio.

the case of a single channel.

$$P(i,j) = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \tag{3.1}$$

Each CR node is assumed to be equipped with an Neyman-Peason detector [80–82] of which its performance is represented by the receiver operating characteristics (ROC) curves of the detector. At the beginning of each time slot t, CR node with data to transmit chooses a set of channels to sense and the valid spectrum sensor operating point (ϵ_n, δ_n) on the ROC curve. Based on the sensing outcome, it decides whether or not to access the channel. If it decides to access the channel, it will send request-to-send (RTS) message to the intended CR receiver. When the receiver receives the RTS message it replies with clear-to send (CTS)

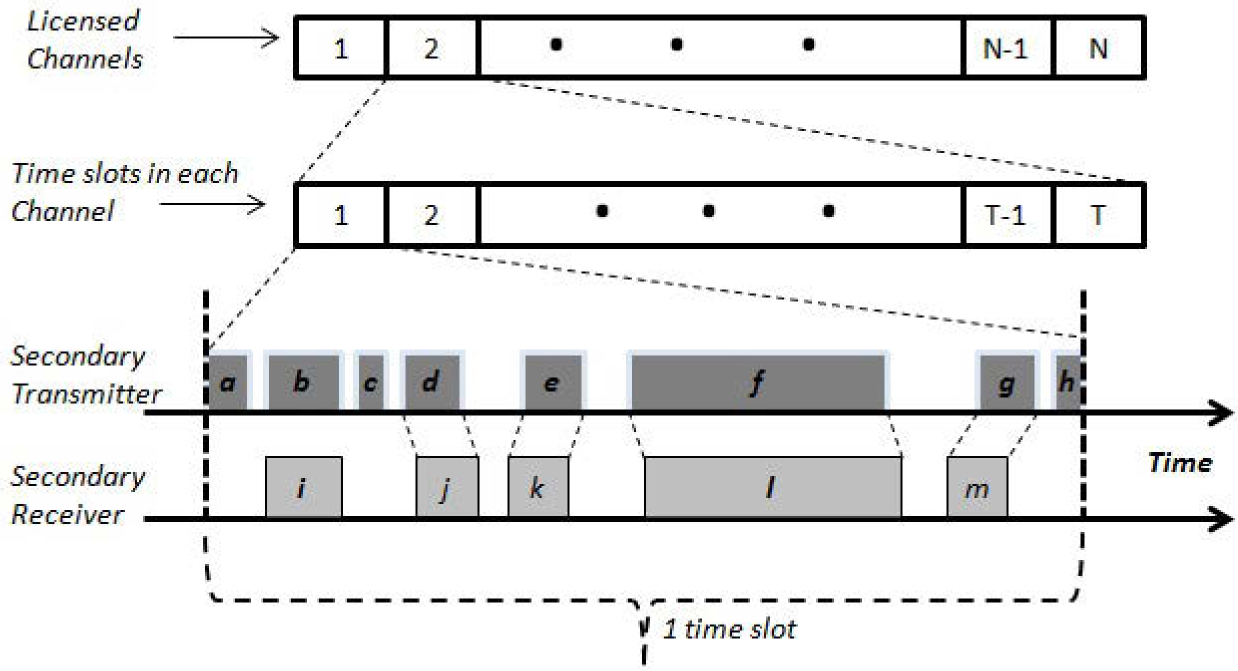

Fig. 3.3: A sequence of operation in one time slot for proposed MAC scheme

message provided that the channel is also idle at the receiver side. When the transmitter and receiver are tuned to the same channel after the initial handshake they will hop to the same channel at the beginning of every time slot in order to ensure transceiver synchronization without the need of a dedicated channel for synchronization purpose [83]. At the end of the time slot, the CR receiver will acknowledge the successful transmission of the packets. Assumption is made that the packets are discarded if the channel is occupied (busy) by the PU [67], and that a channel only presents opportunity to a pair of CR nodes if and only if it is available to both CR transceivers which necessitate the joint identification of the channel opportunities between the two nodes [7]. The two transceivers can only start communicating over this identified idle channel after the successful exchange of the messages. The simplified sequence of activity in one time slot of N channels and a total of T time slots for the CR transceivers are summarized in Fig. 3.3, while Fig. 3.4 shows a simplified flow chart of the protocol (RTS and CTS messages are omitted in order to simplify the presentation). The descriptions of symbols from Fig. 3.3 are shown in table 3.1

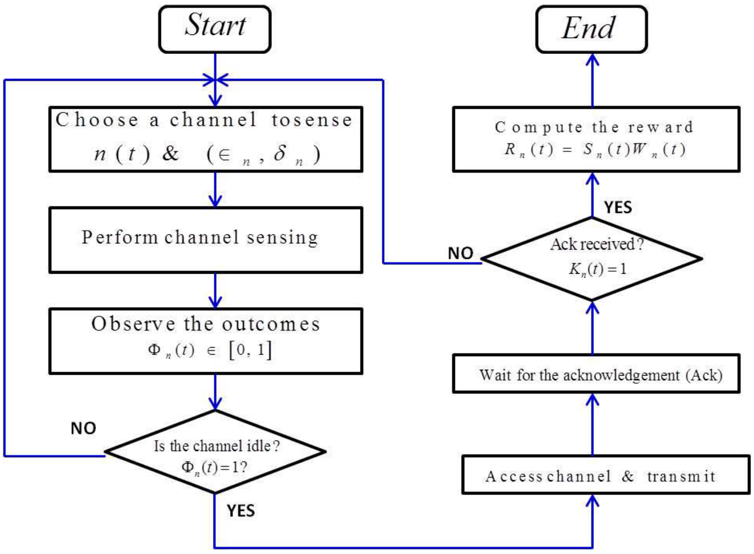

Fig. 3.4: Simplified one time slot transmission protocol

Table 3.1: The descriptions of symbols in Fig. 3.3

Symbol	**Description**
$\boldsymbol{a}$	Transmitter (TX) choose a channel to sense
$\boldsymbol{b}$	TX performs sensing action
$\boldsymbol{c}$	TX observes the sensing results
$\boldsymbol{d}$	TX Sends RTS signal
$\boldsymbol{e}$	TX Waits for CTS signal
$\boldsymbol{f}$	TX Transmits
$\boldsymbol{g}$	TX receives acknowledgement
$\boldsymbol{h}$	TX computes reward
i	Receiver (RX) performs sensing
j	RX receives RTS signal
k	RX sends CTS signal
l	RX receives traffic
m	RX sends acknowledgement

3.4 POMDP Formulation

Let us denote the instantaneous state of the system by s, whereby the finite set of all states denoted by $S = \{s_1, s_2, \cdots\}$ as well as the state of the n^{th} channel at time slot t as $s_n(t)$. It should be noted here that under POMDP framework, the state of the system is not directly observable and therefore the CR node can only compute a belief over the state space. In order to infer a belief regarding the state of the system, the CR node takes sensor measurements (spectrum sensing results). A set of all sensing results (observations) is denoted by $\Theta = \{\Phi_1, \Phi_2, \cdots\}$. The observations of n^{th} channel at time t is denoted by $\Phi_n(t)$. Thus the observation $\Phi_n(t)$ is usually an incomplete projection of the system state $s_n(t)$ due to spectrum sensing errors. The observation is very much depending on the sensor capability and channel estimation technology used [78].

In order to define a POMDP framework precisely, probabilistic laws that describe the state transitions and observations have to be specified. These include the *initial belief probability* distribution (b_o), which is the probability that the system is in state s at time $t = 0$. This distribution is defined over all states in S. Mathematically it can be represented as

$$b_o(s) := Pr(s_o = s) \tag{3.2}$$

Another quantity is the *state transition probability* $P(i, a, j)$, which is defined as the probability of transition from state i to state j given that the CR node was initially in state i and choose the action a for any (i, a, j). This quantity can be expressed mathematically as

$$P(i, a, j) := Pr(s(t) = j | s(t-1) = i, a(t-1) = a) = P(i, j) \tag{3.3}$$

where $P(i, a, j)$ is a conditional probability distribution. Therefore, it follows that

$$\sum_{j \in S} P(i, j) = 1 \qquad \forall (i, a) \tag{3.4}$$

which also suggests that $P(i, j)$ is time-invariant, and thus the stochastic matrix $P(i, j)$ does not change over time. We also need to specify the *observation probability distribution*, $\Theta(s, a, \Phi)$ which is defined as the probability that CR node will perceive observation Φ upon executing the action a in state s. This can be expressed mathematically as

$$\Theta(s, a, \Phi) := Pr(\Phi(t) = \Phi | \Phi(t-1) = \Phi, a(t-1) = a) \tag{3.5}$$

This conditional probability is defined over all (s, a, Φ) triplets for which

$$\sum_{\Phi \in \Theta} \Theta(s, a, \Phi) = 1 \qquad \forall (s, a) \tag{3.6}$$

3.5 Spectrum Sensing Error Model

In chapter 2 we presented a review of spectrum sensing techniques available in the literature which briefly discusses several spectrum sensing algorithms in the context of cognitive radio [1, 84–89]. Spectrum sensing errors in CR are inevitable. In the event of a false alarm, a spectrum opportunity is overlooked by the sensor, and eventually wasted if the access strategy trusts the sensing outcome. On the other hand, miss-detection may lead to collisions with primary users. The trade-off between false alarm and miss-detection is captured by the receiver operating characteristic curves of the spectrum sensor. These curves provide the probability of detection as a function of probability of false alarm. The design of the spectrum sensor and the choice of the sensor operating point are thus important issues and should be addressed by considering the impact of sensing errors on the MAC layer performance in terms of throughput and collision probability. In this section we do not intend to develop any spectrum sensing scheme, in stead we make use of the ROC curve for the energy detector that we developed in our previous work found in [90]. The ROC curve presents the measure of false alarm P_F and the probability of miss detection P_{MD} which are the performance measure for the spectrum sensor. Thus, we assume that the CR nodes are equipped with a Ney-man Pearson energy detector ED which is a preferred approach for spectrum sensing in CR due to its simplicity and applicability as well as its low computational and implementation costs. Thus, based on this work in [90], the spectrum sensor of the CR node performs a binary hypothesis tests. We have H_0 indicates that the channel is idle and only AWGN is present, while H_1 indicates that the channel is busy. We can express this binary hypothesis in terms of channel sensing observations as:

$$\begin{aligned} H_o &: \Phi_n(t) = 1 \\ H_1 &: \Phi_n(t) = 0 \end{aligned} \tag{3.7}$$

Thus, the results of the binary hypothesis test $\Phi_n \in \{0, 1\}$ means that If the sensor mistakes H_0 for H_1 in a channel, a *false alarm* occurs which lead to spectrum opportunity overlooked by the sensor. This generally means that the sensing outcome indicates that the channel is busy while in reality the channel is idle. On the other hand, if the sensor mistakes H_1 for H_0 , we have a *miss detection* which leads to collision with the PU. We denote the *probability of false alarm* and the *probability of miss detection* respectively, bye ϵ and δ which can be defined mathematically as:

$$\begin{aligned} \epsilon_n(t) &\triangleq Pr\{\Phi_n(t) = 0 | \Phi_n(t) = 1\} \\ \delta_n(t) &\triangleq Pr\{\Phi_n(t) = 1 | \Phi_n(t) = 0\} \end{aligned} \tag{3.8}$$

Usually, the performance of the spectrum sensor is characterized by ϵ and δ on the ROC curve. Fig. 3.5 shows the ROC curve achieved by the ED which is the theoretical and simulation results based on the following equations which were developed in chapter 2 section 2.2.2.3

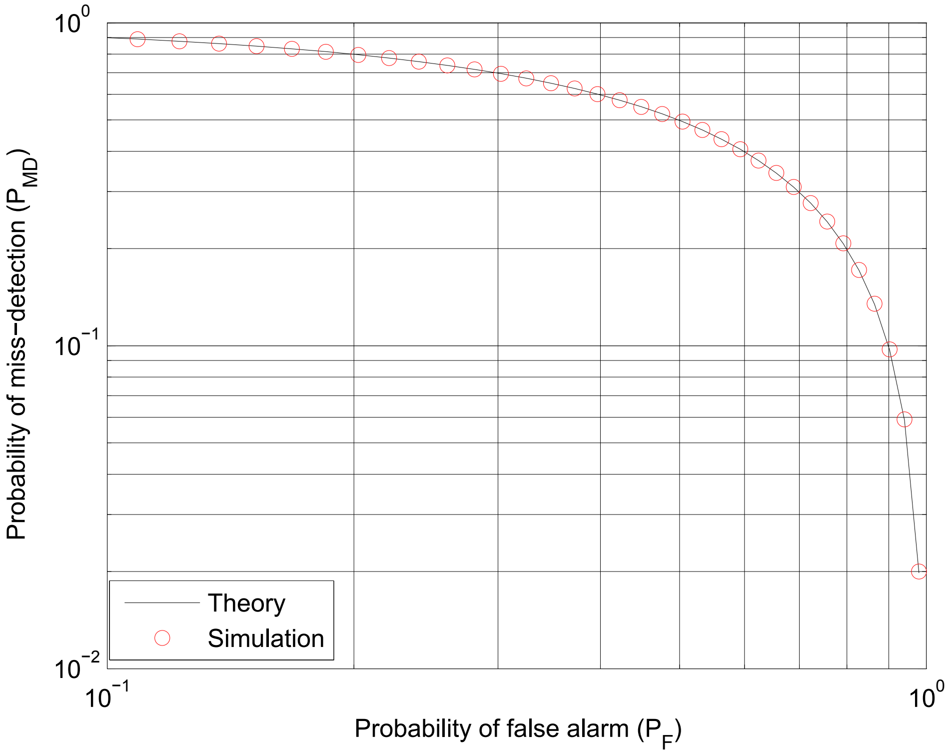

Fig. 3.5: Receiver operating characteristic (ROC) curve for energy detector.

equations (2.4) and (2.6). Thus

$$\epsilon = \frac{1}{2} erfc\left(\frac{\left(\frac{\tau - N\sigma_w^2}{\sqrt{2N\sigma_w^4}}\right)}{\sqrt{2}}\right), \qquad and \qquad \delta = 1 - Q\left[\frac{Q^{-1}(P_F) - SNR\sqrt{\frac{N}{2}}}{1 + SNR}\right]$$

These results are incorporate into the proposed MAC scheme focusing on the trade-off between ϵ and δ. The idea is to find in which point on the ROC curve should spectrum sensor operate at for the optimal performance of the proposed MAC scheme. Fig.3.6, shows how the valid sensor operating point (ϵ_n, δ_n) lies below the ROC curve, and thus the operating points can be achieved by randomizing between the two operating Ney-man Pearson detectors with properly chosen conditions (constraints) on the probability of false alarm (ϵ) [81, 82]. Thus the sensor operating point (ϵ_n, δ_n) in Fig.3.6 can be achieved by applying the optimal

Ney-man Pearson detector under the condition that $P_F \leq \epsilon_n$, with probability p, such that $p = \frac{\epsilon_n - \epsilon_2}{\epsilon_1 - \epsilon_2}$ and Ney-man Pearson detector under the constraint that $P_F \leq \epsilon_n$ with $1-p$ which makes the design of spectrum sensor to reduce to the choice of the desired sensor operating point (ϵ_n, δ_n) on the ROC curve. The main objective is to find the optimal sensor operating point $(\epsilon_n^*, \delta_n^*)$ on the ROC curve in order to achieve the best trade-off between false alarm and miss-detection.

3.6 The Reward Computation

The objective of the POMDP framework is to optimize action selection, so that the CR node is given a reward function describing its performance. The reward function assigns a numerical value quantifying the utility of performing action a while in state s. The goal of

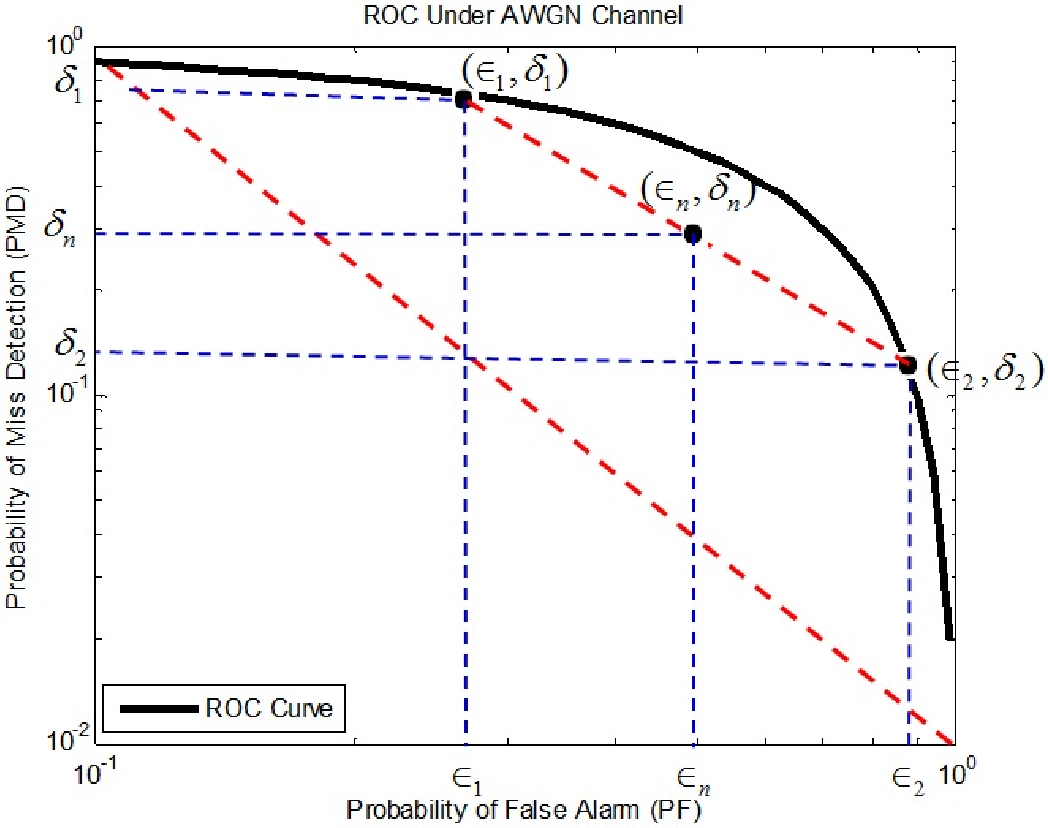

Fig. 3.6: ROC curve for ED showing the trade-offs between δ and ϵ.

CR node is to maximize the sum of its reward over time. The reward gained by CR node can be defined in many ways depending on the design objective such as minimizing the BER, minimizing the time delay, maximizing the data rate,and so on. However, in this scheme we define the reward as the amount of information transmitted by the CR node under the constraint that the collision with primary user is avoided. We adopt the assumptions made by previous works in $[7, 10, 71, 91]$ whereby the number of bits delivered by CR node over a channel is assumed to be proportional to the channel bandwidth. Let $\mathcal{R}_n^k(t)$ denote the reward gained by a CR node after transmitting in channel n having the bandwidth of $\mathcal{W}$ which is in state S in time slot t and receiving acknowledgement k from the CR receiving node, then the reward can be expressed as

$$\mathcal{R}_n^k(t) = S_n^k(t)\mathcal{W}_n(t) \tag{3.9}$$

3.7 Belief Computation

Similar to our problem formulation, the system cannot be fully observable because of partial sensing of the radio spectrum (due to hardware limitation) as well as the spectrum sensing errors. The CR node can instead maintain a complete trace of all observations and all actions it ever executed, and use this to select its actions. The action/observation trace is known as history [75],and this can be very long as time goes on. A well-known fact is that this history does not need to be represented explicitly, but can instead be summarized via a belief distribution, which is the posterior distribution over the states [74]. Smallwood et al in [92] suggested that the belief vector which is defined as the probability distribution over the state space can summarize their knowledge of all past actions and observations. Let us denote the belief vector space as $\mathcal{B}_i(t)$ (refer to 3.10). This can be defined as the probability that the current state in time slot t is i, and that at the end of each time slot, the belief vector is updated using Bayes rule as in (3.11).

$$\mathcal{B}_i(t) \triangleq \{b_0(t), b_1(t), \cdots, b_S(t)\} \tag{3.10}$$

$$\mathcal{B}_i(t+1) = \frac{\sum_i \mathcal{B}_i(t) P(i,j) \Theta^a_{j,\Phi}}{\sum_{i,j} \mathcal{B}_i(t) P(i,j) \Theta^a_{j,\Phi}} \tag{3.11}$$

Given belief vector $\mathcal{B}_i(t)$, the distribution of the system state in the time slot t after the state transition is then given by

$$Pr\{S(t) = i\} = \sum_{j \in S} \mathcal{B}_i(t) P(i,j) \qquad \forall j \in S \tag{3.12}$$

This belief vector $\mathcal{B}_i(t)$ is a sufficient statistic for the history; it suffices to condition for selection of the action on $\mathcal{B}_i(t)$, in stead of ever-growing sequence of past observations and actions. The belief $\mathcal{B}_i(t)$ is calculated recursively, thus using only the belief one time step earlier $\mathcal{B}_i(t-1)$ along with the most recent action $a(t-1)$ and the observation $\Phi(t)$. After taking the action a which is based on the spectrum sensing and the observation from the acknowledgement, the belief vector is updated by

$$\mathcal{B}_i(t+1) = \frac{\sum_j \mathcal{B}_i(t) P(j,i) \Theta_{i,k} a_{\{s,\delta,c\}}}{\sum_i \sum_j \mathcal{B}_i(t) P(j,i) \Theta_{i,k} a_{\{s,\delta,c\}}} \tag{3.13}$$

Eqn. (3.13) specifies the probability of observing $K_n = k$ when the belief vector is given by $\mathcal{B}_i(t)$ and the action $a_{\{s,\delta,c\}}$ is taken as $p\{k|a_{\{s,\delta,c\}}, \mathcal{B}_i(t)\}$ which is obtained by averaging the conditional observation probability over the current spectrum occupancy state [93]. Thus (3.13) becomes

$$p\{k|a_{\{a,\delta,c\}}, \mathcal{B}(t)\} = \sum_i \sum_j \mathcal{B}_i(t) P(j,i) \Theta_{i,k} a_{\{a,\delta,c\}} \tag{3.14}$$

3.8 Joint Optimal Policy Computation

The key objective of POMDP perspective is to compute a joint policy for choosing actions such that the expected cumulative reward is maximized. In this scheme, we need three different policies namely: optimal spectrum sensing policy $\{\pi_s^*\}$, optimal sensor operating point policy $\{\pi_\delta^*\}$ and optimal transmission policy $\{\pi_c^*\}$. Let $\{\pi_s^*, \pi_\delta^*, \pi_c^*\}$ be the joint optimal policy strategy to maximize the total number of information bits that can be delivered by the CR node in the finite period of time. Mathematically this policy can be expressed as

$$\begin{aligned}
\{\pi_\delta^*, \pi_s^*, \pi_c^*\} &= \arg\max_{\pi_\delta, \pi_s, \pi_c} \sum_{t=1}^{T} \mathbb{E}_{\{\pi_\delta, \pi_s \pi_c\}} \left[R_{K_n}^{(a, \Phi_n)}(t) | \mathcal{B}(1) \right] \\
&= \arg\max_{\pi_\delta, \pi_s, \pi_c} \sum_{t=1}^{T} \mathbb{E}_{\{\pi_\delta, \pi_s \pi_c\}} \left[S_{k_n}^{\Phi_n}(t) W_n(t) | \mathcal{B}(1) \right] \qquad (3.15) \\
&\textit{Subject to} \qquad Pr\{\Phi_n = 1 | S_n = 0\} \leq \tau
\end{aligned}$$

where $\mathbb{E}\{\pi_s, \pi_\delta, \pi_c\}$ is the mathematical expectation for given policies $\{\pi_s, \pi_\delta, \pi_c\}$ and $\mathcal{B}(1)$ is the initial belief state and τ is the maximum allowable probability of miss detection. The optimal policy strategy which is the design objective in (3.15) is a constrained POMDP which usually requires randomized policies to achieve optimality. Chen et al [93] established a separation principle for the optimal joint design. This separation principle reveals the existence of deterministic optimal sensing and access policies, leading to significant complexity reduction. The proof of this separation principle can be found in [93]. With a separation principle theorem, the optimal access policy is time-invariant and belief independent. Thus the optimal transmission probabilities are solely determined by the sensor operating point δ and the maximum allowed probability of miss detection τ. For any chosen action a, the information state (belief) $\mathcal{B}(1)$ and time slot t, the transmission probability can be evaluated as

$$(f_a^1(\mathcal{B}(t),t), f_a^0(\mathcal{B}(t),t)) = \begin{cases} \left(1, \frac{\tau-\delta}{1-\delta}\right), \; for \; \delta < \tau \\ \\ (1,0), \; for \; \delta = \tau \\ \\ \left(\frac{\tau}{\delta}, 0\right), \; for \; \delta > \tau \end{cases} \tag{3.16}$$

where f_a^1 is the transmission probability after taking action a when the channel is detected idle and f_a^0 is the transmission probability after taking action a when the channel is detected busy. Given the information state $\mathcal{B}(1)$ at the beginning of time slot t, the constraint $Pr\{\Phi_n = 1|S_n = 0\} \leq \tau$ can be rewritten as

$$Pr\{\Phi_n = 1|S_n = 0\} = \delta f_a^1(\mathcal{B}(t),t) + (1-\delta) f_a^0(\mathcal{B}(t),t) \tag{3.17}$$

The algorithm 1 in the appendix section shows how the joint optimal policy is computed iteratively.

3.9 Value Iteration

Computing the optimal policy is very challenging mainly due to two reasons namely the curse dimensionality and the curse history [74, 75, 94]. These two problems are related in such a way that the higher the dimension of a belief space, the higher probability that it has different histories. But they often act independently. The complexity can grow exponentially with time horizon even a problem with only few states, and problems with a large number of physical states may still only have a small number of relevant histories [75]. Sondik et al [95] proposed *value-iteration approach* as the most straight forward approach to find optimal policies where iterations of *dynamic programming* are applied to compute increasingly more accurate values for each belief state. We need to evaluate a value function (maximum expected remaining reward) that can be accumulated starting from slot 1 to slot T, $(1 \leq$

$t \leq T$) for a given initial belief vector $\mathcal{B}_i(t)$. Let the value function be denoted by $\mathcal{V}_t(\mathcal{B}_i(t))$. Similar to approach in [7], this value function has two parts namely, immediate reward obtained in slot t and the maximum expected remaining reward which is obtained starting from slot $(t+1)$ given the belief vector $\mathcal{B}_i(t+1)$. Given the optimal sensor operating point policy δ^* and the optimal access policy c^*, the value function can be obtained recursively by

$$\begin{aligned} \mathcal{V}_t(\mathcal{B}_i(t)) = &\max_{a_{\{s,\delta,c\}} \in \mathbb{A}} \textstyle\sum_i \sum_j B_j(t) P_{j,i} \sum\limits_{k_a=0}^{1} Pr\{K_a = 1 | S(t) = i\}) \\ &\times \left[k_a \mathcal{W}_a + V_{t+1}((\mathcal{B}_i(t)|a, k_a)) \right], \qquad 1 \leq t \leq T \end{aligned} \tag{3.18}$$

$$\mathcal{V}_T(\mathcal{B}_i(t)) = \max_{a_{\{s,\delta,c\}} \in \mathbb{A}} \sum_i \sum_j B_j(t) P_{j,i} \mathcal{Q}_i(1) \mathcal{W}_a \tag{3.19}$$

where $\mathcal{Q}_i(1) \triangleq Pr\{K_a = 1 | S(t) = i\}$ is a probability of successful transmission under the current spectrum state. Likewise, belief vector can be updated using Baye's rule as

$$\mathcal{B}_i(t+1) = \frac{\sum_j \mathcal{B}_i(t) P_{j,i} \mathcal{Q}_i(k_a)}{\sum_i \sum_j \mathcal{B}_j(t) P_{j,j+1} \mathcal{Q}_{j+1}(k_a)} \tag{3.20}$$

The value function in (3.18) needs to be evaluated recursively in order to obtain the maximum total reward accumulated in T slots. Smallwood et al [92] proved that,the value function $\mathcal{V}_t(\mathcal{B}_i(t))$ is piecewise linear and convex. Therefore, the joint optimal policy is evaluated by linear programming technique which is an iterative solution. Algorithm 2 in the appendix section shows how the value function is evaluated iteratively.

3.10 Simulation Results and Discussions

In order to study the performance of the proposed scheme, we considered multiple channels and multiple CR nodes co-exist with primary network users. Random message arrivals were considered with the aim to investigate the performance of greed sensing approach in multiple CR users in presence of spectrum sensing errors. We considered four simulation scenarios namely simulation scenario A, simulation scenario B, simulation scenario C, and simulation scenario D. These simulation scenarios enabled us to study the throughput performance of the proposed scheme by computer simulations. The basic simulation parameters used are shown in Table 3.2.

Table 3.2: Simulation Set up for MAC Scheme With Sensing Errors

Parameter	**Assigned Value**
Number of independent channels (N)	10
Bandwidth per channel	2
Transition probability P(i,j) for each channel	(0.2, 0.8) equal for each node
Error model (ϵ, δ)	ROC curve (10 cooperative sensing users)
Message arrival rate (λ)	Form a Poisson process
Message length	50 packets geometrically distributed
Packet transmission time of one packet	Assumed to be one time slot

3.10.0.1 Simulation Scenario A

In this scenario, we consider 10 independent channels ($N = 10$) with equal bandwidth ($\mathcal{W} = 2$) and equal transition probability $(P_{01}, P_{11}) = (0.2, 0.8)$ for each channel. It was assumed that the message arrives at the CR node form a Poisson process with arrival rate of λ. It was further assumed that the message length is geometrically distributed with average message length of 50 packets. The transmission time of one packet was assumed to be one time slot.

Upon the arrival of the message, the whole message will be randomly assigned to a secondary user. In each slot, those CR nodes who do not have packets to transmit will turn to sleep in order to conserve energy. They do not participate in channel selection and sensing, and their belief states are updated according to the Markovian model of spectrum occupancy. On the other hand, those CR nodes with data to transmit will choose a channel according to greedy approach, and then update their belief states according to the sensing outcomes. When an available channel is chosen by multiple users, the assumption was made that one of these users will succeed. For the purpose of a comparisons of the schemes, we implemented the scheme using greedy sensing algorithm as was previously presented by Zhao et al in [7]. Fig. 3.7 shows the overall throughput performance as a function of message arrival rate λ for multiple SUs accessing multiple channels in presence of spectrum sensing errors. We implemented the greed sensing algorithm for 10 independent channels with equal bandwidth and equal transition probabilities. As it can be seen from Fig. 3.7 that the proposed greedy sensing scheme with sensing errors outperforms that of random sensing scheme in terms of throughput. By implementing the random sensing policy, the throughput increases and reaches the maximum of 1.3 with the packet arrival rate of 0.2. Under ideal case where the sensing errors are ignored (greedy sensing policy without errors), the throughput approaches 1.55 with the packet arrival rate of 0.2. Thus the throughput performance for the proposed scheme is much better than that of the random sensing.

3.10.0.2 Simulation Scenario B

In this scenario we aimed at studying the throughput performance of the proposed multichannel multiuser scheme as a function of prescribed collision probability τ (which indicates the level of sensing errors). During simulation, we considered 10 independent channels ($N = 10$), with equal bandwidth ($\mathcal{W} = 1$) and equal transition probabilities $(P_{01}, P_{11}) = (0.5, 0.5)$. It can be seen from Fig. 3.8 that the average throughput of the proposed scheme (with sensing errors) is outperformed by that without errors. This is due to the fact that by introducing errors for the spectrum sensor in the system, the overall throughput of the system is affected. However this scheme reflects the practical scenario since it is almost impossible to have an error free spectrum sensor in wireless communication. Some more research is needed to improve the throughput performance under dynamic wireless environment where spectrum sensing errors are unavoidable. Under optimal sensing

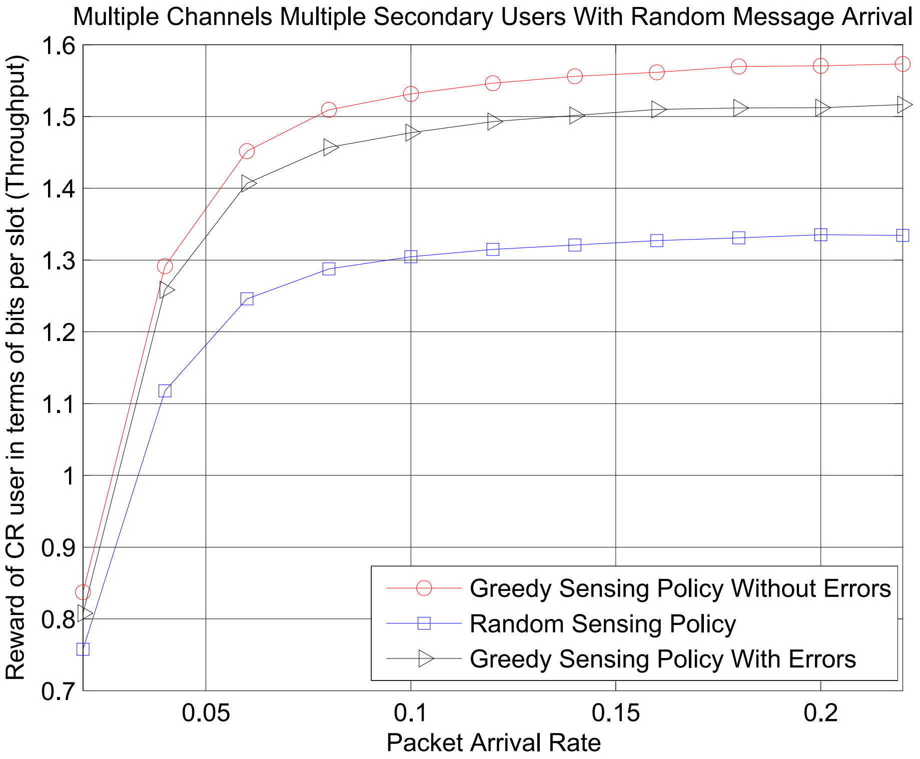

Fig. 3.7: Performance of the multiple SUs multiple channels scheme in presence of sensing errors using.

strategy the throughput performance of the system reaches above 0.45 with the prescribed collision probability of 0.4. By introducing sensing errors in the system, the throughput of the system is affected and falls below 0.45 for the prescribed collision probability of 0.4 as shown in Fig. 3.8.

3.10.0.3 Simulation Scenario C

In this scenario we aimed at studying the throughput performance of the proposed MAC scheme by considering 3 independent channels ($N = 3$) with equal bandwidth ($\mathcal{W} = 1$) and equal transition probability $(P_{01}, P_{11}) = (0.2, 0.8)$. It can be seen in Fig. 3.9 that under such condition, the performance of a proposed scheme under greedy sensing algorithm approaches that of optimal sensing and greedy sensing that was proposed by Zhao et al [7]. Random sensing performs poorly with the average throughput of about 0.5. The throughput

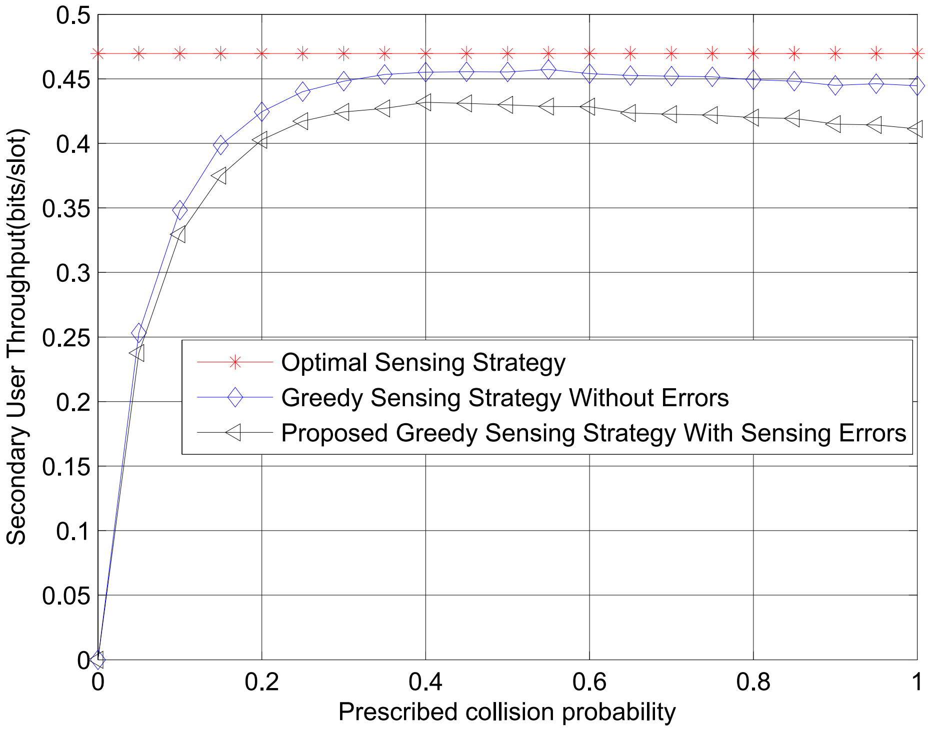

Fig. 3.8: Performance of the proposed scheme in presence of sensing errors for equal bandwidth and equal transition probabilities.

performance of the proposed scheme under the greedy sensing closely relates to that of the optimal sensing scheme. Thus, the average throughput increases as the time horizon increases. This shows the that the POMDP formulation is very useful in modelling these types of problems.

3.10.0.4 Simulation Scenario D

In this scenario we assumed the same number of channels ($N = 3$), but different bandwidth and different transition probabilities. We used the same values of bandwidth and transition probabilities as used in [7] for comparison purposes. Thus $P_{01} = [0.8, 0.6, 0.4]$, $P_{11} = [0.6, 0.4, 0.2]$ and $\mathcal{W} = \left[\frac{3}{4}, 1, \frac{3}{2}\right]$. It can be seen from Fig. 3.10 that the average throughput of the proposed scheme is much better than that of greedy sensing and random sensing schemes. Although the average traffic load of the primary network is the same in all

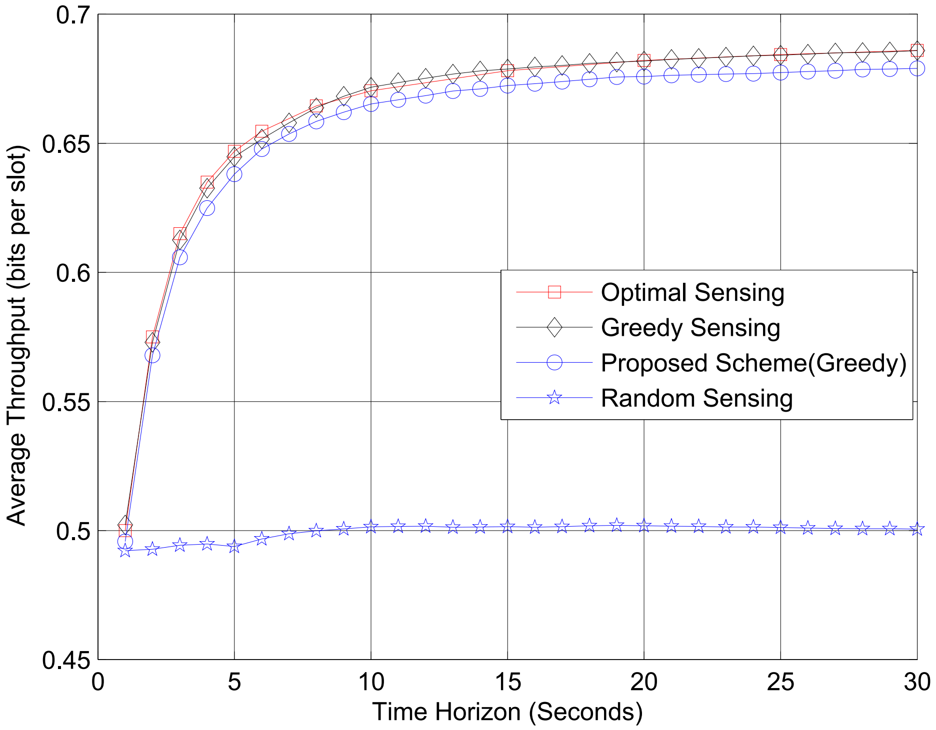

Fig. 3.9: Performance of the proposed scheme under greedy sensing algorithm for 3 independent channels with equal bandwidth and equal transition probabilities.

scenarios, different traffic statistics of the primary network with large inter-arrival time and message length. The throughput of the CR user increases over time which results from improved information on the network state drawn from accumulating observations. Thus, this demonstrates the cognitive nature of the proposed scheme under the POMDP framework.

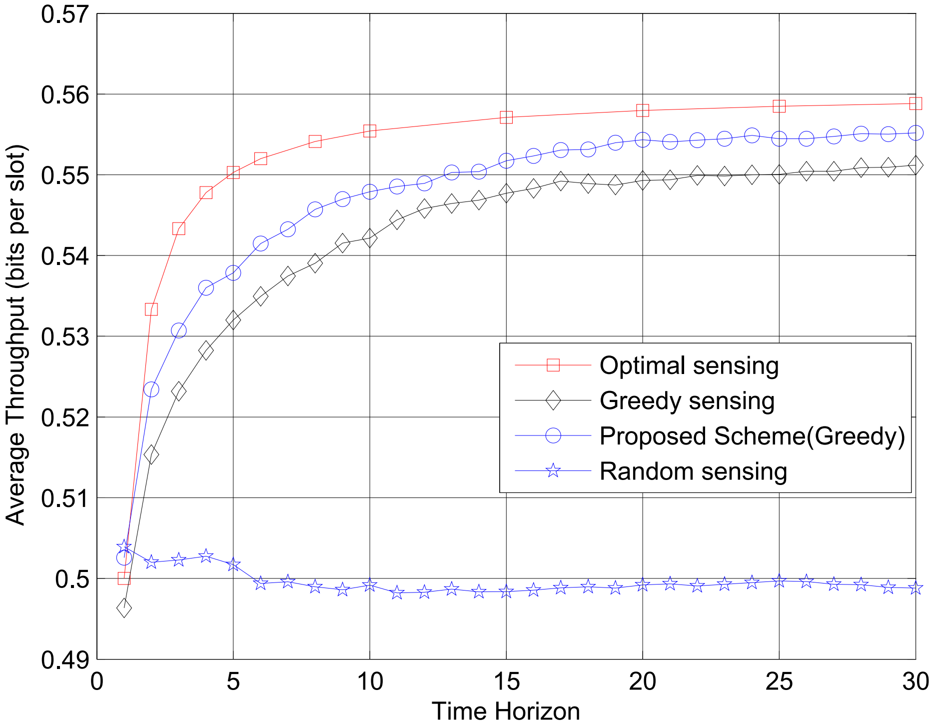

Fig. 3.10: Performance of the proposed scheme under greedy sensing algorithm for 3 independent channels with unequal bandwidth and unequal transition probabilities.

3.11 Chapter Summary

In this chapter, a decision-theoretic framework for the optimal joint design MAC scheme based on the theory of POMDP was established to capture the fundamental design trade-offs between the P_D and the P_F for the design of a CR network. The POMDP framework is found to be very useful for modeling problems in which the state of the system can not be directly observed due to noise and fading effects in a wireless channel. Within this framework, the optimal MAC strategy is given by the optimal policy of a constrained POMDP. However, while powerful in problem modeling for decision making under uncertainty, POMDP suffers from the curse of dimensionality and does not easily lend itself to tractable solutions. Constraints on a POMDP further complicate the problem, often demanding randomized policies to achieve optimality. There is no closed form solution for a constrained POMDP framework so far. However, due to the fact that the belief vector is piece-wise linear and convex, linear programming is used to compute the optimal policy by iteration. Thus, in this chapter, a MAC scheme for throughput maximization in presence of spectrum sensing errors for CR networks was developed. The cross-layer design approach was achieved by jointly considering the design of spectrum sensing at PHY layer and access at MAC layer in order to obtain a joint optimal policy for throughput maximization in CR networks. We assumed that each CR node is equipped with a Ney-man Pearson energy detector and therefore the ROC curve were used to model the spectrum sensing errors. By integrating the spectrum sensor information (ϵ, δ) at PHY layer sensing, and accessing at MAC layer into the system state space, we formulated a problem as a constrained POMDP. Computer simulation was used to study the throughput performance as a function of packet arrival rate, prescribed collision probability and time horizon. The simulations were carried out in four scenarios namely A, B, C, and D. In the scenario A, the study of the of the throughput performance as a function of the packet arrival rate was performed. The results show that the throughput of the proposed scheme increase as the packet arrival rate increase. Thus, using greedy sensing policy, we compare the throughput performance with and without errors of which both of them outperform the random sensing policy. Furthermore, the throughput performance of the proposed scheme (greedy sensing policy with errors) approaches that of greedy sensing policy without errors. In the simulation scenario B we aimed at studying the throughput performance of the proposed scheme as a function of prescribed collision probability. We compared it with optimal sensing strategy and the greedy sensing without errors. The results show that as the prescribed collision probability increase, the throughput of the secondary user also in crease for both, with and without errors. However, increasing the probability of collision beyond 0.4 affects the throughput of the system. Under all prescribed collision probabilities, the throughput performance of the proposed scheme approaches that of greedy sensing without errors. In the simulation scenarios C we aimed at studying the throughput performance as a function of time by considering three independent channels with equal bandwidth and equal transition probabilities. On the other hand, for the simulation scenario C we consider unequal bandwidth and unequal transition probabilities. Under both these scenarios the throughput performance of the proposed scheme perform much better as compared to that of greedy sensing and the random sensing. Thus, the throughput performance of the proposed scheme approaches that of the optimal sensing scheme. These results demonstrate that the POMDP framework is a convenient and realistic way for modeling a decision process under uncertainty. This scheme forms a bench mark for later chapters of this thesis.

Chapter 4

Cross-layer MAC Scheme for Speech Transmission in CR Networks

4.1 Introduction

With the explosive growth of wireless communications, multimedia applications are being targeted for CR networks. However, the success of CR technology determine the perceived QoS of users. Different applications require different QoS which is constrained by dynamics of wireless channels. Speech communication is still the most dominant and common service and its popularity is expected to remain steady for the foreseeable future [96]. Digitally-encoded speech posses many advantages over its analogue counterpart. However, the transmission of speech signal over the wireless channel without any compression requires additional bandwidth. The signal compression is achieved via elaborate DSP techniques that are facilitated by rapid improvement in digital hardware. This has enabled the use of sophisticated DSP techniques that were not feasible before [96]. Many different speech compression strategies have been developed for bandwidth-restricted applications [96–99]. In order to reduce the bit rate while maintaining good speech quality over wireless transmission media, various types of speech quantizers have been designed and used in practice [96, 100–102]. The main objective of a specific quantizer is to match the input signal characteristics both in terms of its dynamic range and probability function.

Although substantial research has been carried out in PHY layer perspective of CR system, there is little work done on the speech application in cognitive radio networks. This chapter attempts to extend the existing research paradigm to integrate the MAC layer design and APP layer parameter using cross-layer design concept. Cross-layer MAC design approach for speech transmission in CR networks is proposed in this scheme in order to maximize the throughput under the constraint that the licensed user is protected. The formulation presented in chapter 3 is extended to include the application layer information for joint cross-layer design. The design is aimed at maximizing the throughput of CR users by integrating the PHY layer information, adaptive quantization parameter for speech traffic at application layer, together with strategy for spectrum access at MAC layer with the main goal to improve the QoS for speech transmission in CR networks. Being an extension of the work presented in chapter 3, we assume that the PU network is modelled as a homogeneous finite state Markov process. We consider a non-ideal case where there exist some sensing errors at PHY layer and that the radio spectrum is monitored partially which results into incomplete information about the state of the system (partially observable). By integrating the adaptive quantization step-size parameter of the speech signal at APP layer into the system state space, The design problem is formulated as a constrained POMDP. The scheme is evaluated by computer simulation in order to study the throughput performance. The results show an improved QoS in terms of throughput performance for the proposed scheme under non-ideal condition. It is assumed in this scheme that the CR nodes are equipped with speech encoders and decoders and therefore we adopt the use of the adaptive quantization features whereby the quantization parameters are dynamically adjusted based on the signal variance. These parameters are matched according to the variation of the signal in order to reduce the bit rate while maintaining good speech quality over wireless transmission media and hence improve QoS perceived by CR network network users.

4.2 An Overview of Adaptive Quantization Techniques

There are basically two ways to achieve adaptive quantization available in the literature [103–107]. One way is to vary the quantization step-size $q(n)$ parameter, where n is a parameter corresponding to a sequence. In a variable step-size adaptive quantization technique the step-size is increased when the signal variance (σ_x) increases. Thus, for large signal variance, the corresponding larger value of quantization step-size is selected. On the other hand, for small signal variance, the small value of quantization step-size is selected. By assuming a uniform quantization, then the quantization parameter is basically divided into a finite number of equal interval and a single quantization value is assigned to all values within that interval.

Another method used to achieve adaptive quantization is that of multiplying the signal with some gain $G(n)$ before the quantization is performed. This gain corresponds to the signal and changes according to the signal variance. Using this technique, the original signal $x(n)$ is multiplied by the variable gain $G(n)$ and therefore the output $y(n)$ is expressed as

$$y(n) = x(n)G(n) \tag{4.1}$$

The product $x(n)G(n)$ has to be maintained as independent as possible with signal variance σ_x. Thus, it should adapt itself with the signal variance. In the first technique, the quantization step-size is made to be proportional to the signal variance. This means that for large signal variance, the large step-size should be applied and vice versa. The two adaptive quantization techniques can be treated simultaneously because, in whatever methodology used, it is still possible to extract the time-varying properties of the signal and use it control either adaptive step-size or the adaptive gain. In principle, both techniques are the same and can therefore be treated simultaneously. Furthermore, these two techniques (variable gain and variable step-size) which are employed to achieve adaptive quantization are essentially of two types namely **feed forward adaptation** and **feedback adaptation**. We adopt the variable step-size feed forward adaptive quantization scheme while the other technique will be studied in the later stage. Thus, in a variable step-size adaptive quantization technique, the quantization step-size increases with the increase of the signal variance σ_x and decreases with the decrease of the signal variance [108, 109]. In other words we can say that, for large signal variance, the corresponding lager quantization step-size is used and for small signal variance, the small quantization step-size is used. The quantization step-size is made to be proportional to signal variance [110]. The block diagram of the proposed feed forward adaptation step-size quantization scheme is shown in Fig. 4.1. Given the scheme presented in Fig. 4.1, in order to know about the step-size adaptation, the signal variance has to be estimated by looking at the short term energy. Assuming that the signal is zero-mean, the short term energy can provide a measure of the variance and can be expressed as

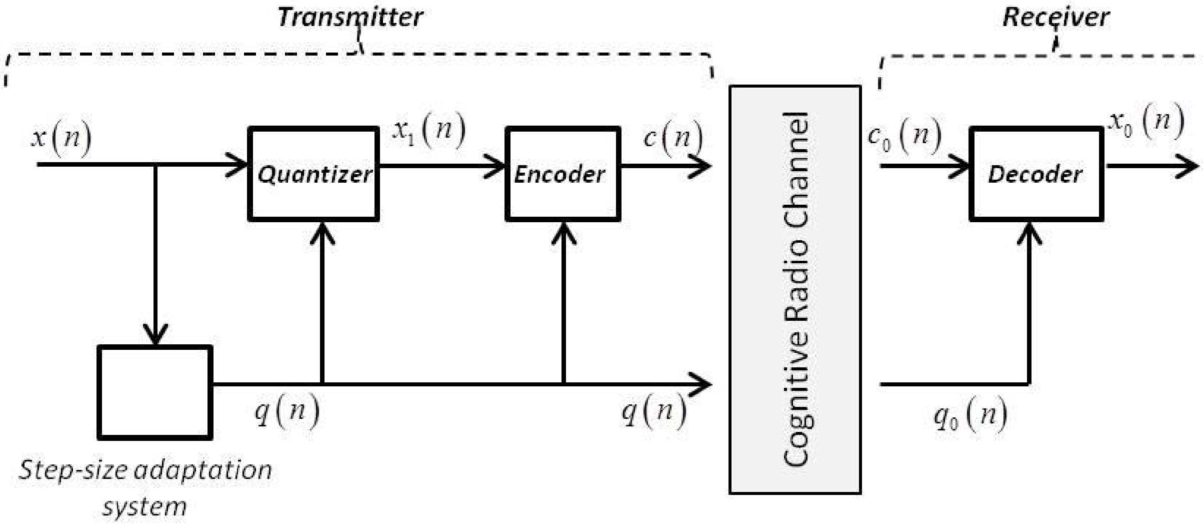

Fig. 4.1: A block diagram of the proposed scheme for a feed forward variable step-size adaptive quantization for speech transmission in CR networks

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$$\sigma^2(n) = \sum_{m=-\infty}^{\infty} x^2(m)h(n-m) \tag{4.2}$$

where $h(n-m)$, represent a low pass filter which typically can be finite impulse response (FIR) or infinite impulse response (IIR) filter [108, 109]. Let us assume that

$$h(n) = \begin{cases} \alpha^{n-1}, & for\ n \geq 1 \\ 0, & otherwise \end{cases} \tag{4.3}$$

For stability purposes it is assumed that the parameter α is lying between 0 and 1, so by using this assumption we can write down the variance of the signal as follows

$$\sigma^2(n) = \sum_{m=-\infty}^{\infty} x^2(m)\alpha^{n-m-1} \tag{4.4}$$

which can also be written as

$$\sigma^2(n) = \alpha\sigma^2(n-1) + x^2(n-1) \tag{4.5}$$

This expression is very useful as we know the previous estimate of the signal variance multiply by the parameter α and then we add up with $x^2(n-1)$ term. Thus the new sample that we add gives us the new estimate of $\sigma^2(n)$. This is a recursive way of computing $\sigma^2(n)$, where we get updated estimate of $\sigma^2(n)$ and then accordingly we can vary the quantization step-size. The step-size is made proportional to the standard deviation of the signal. Thus if we get an update estimate of $\sigma^2(n)$ then accordingly we can vary the quantization step-size. For the time varying step-size, $q(n) = q_0\sigma(n)$, where q_0 is some constant, and $\sigma(n)$ is what will be estimated for $q(n)$.

To the best of our knowledge, little work has been done in the cross-layer design for CR networks that integrates the design of spectrum sensor at physical layer and spectrum sensing and access at MAC layer together with application layer parameters jointly in order to improve QoS for speech transmission in CR networks. In this chapter, we extend the work presented by the previous researchers [7, 10, 72] by incorporating the adaptive quantization step-size of the speech encoder into the design of MAC protocol in order to improve the QoS of speech transmission over CR networks. This is an extension of the scheme presented in chapter 3 of this thesis.

4.3 System Model

In this scheme, we adopt the channel model presented in chapter 3. The state S of the Markov chain model is completely described by the stationary distribution of each channel state i and the transition probability from state i to state j. This transition probability is denoted by $P(i, j)$ and this transition happens at the beginning of each time slot. We consider a radio spectrum which consists of N independent channels licensed to primary network whose users communicate according to synchronous structure whereby the time is divided into slots of equal length with total length of T slots. The n^{th} channel is assumed to have a bandwidth of $\mathcal{W}_n$ and the traffic statistics of the primary network follows discrete-time homogeneous Markov process with 2^N finite state space. The channel state of the n^{th} channel in t time slot is denoted by $S_n(t)$. In order to simplify this formulation we assume that, for the total time slot T the transition probability $P(i, j)$ is known and does not change with time, which was assumed by previous works in [72, 79, 83, 93]. Thus, the CR nodes search for instantaneously exploitation of these N channels selfishly.

At the beginning of each time slot a CR node with speech content to transmit chooses a set of channels to sense. Based on the sensing outcome, it decides whether or not to access the channel. If it decides to access the channel, the corresponding quantization step-size (q) of speech signal at the application layer will be selected based on the signal condition which is reflected by the signal variance and hence the speech contents will be transmitted. At the end of the time slot, the CR receiver node acknowledges the successful transmission by sending the acknowledgement signal to the transmitting CR node. The sequence of activities in one time slot for CR transmitter node and CR receiver node is summarized in Table 4.1. It is assumed that a channel only presents an opportunity to a pair of CR nodes if and only if it is available to both CR transceiver nodes which necessitate the joint identification of the channel opportunities between the two CR nodes. Fig. 4.2 shows a cross-layer framework for the proposed scheme where the joint design between PHY, MAC, and APP are implemented. Spectrum sensing errors are considered at PHY layer while adaptive quantization feature of the speech encoders is considered at the APP layer. These parameters are optimized at MAC layer using cross-layer design approach. We further assume that when the transmitter and receiver are tuned to the same channel after the initial handshake, they will hop to the same channel at the beginning of every time slot in order to ensure transceiver synchronization without the need of a dedicated channel for synchronization purpose as approached previously by Chen et al in [83].

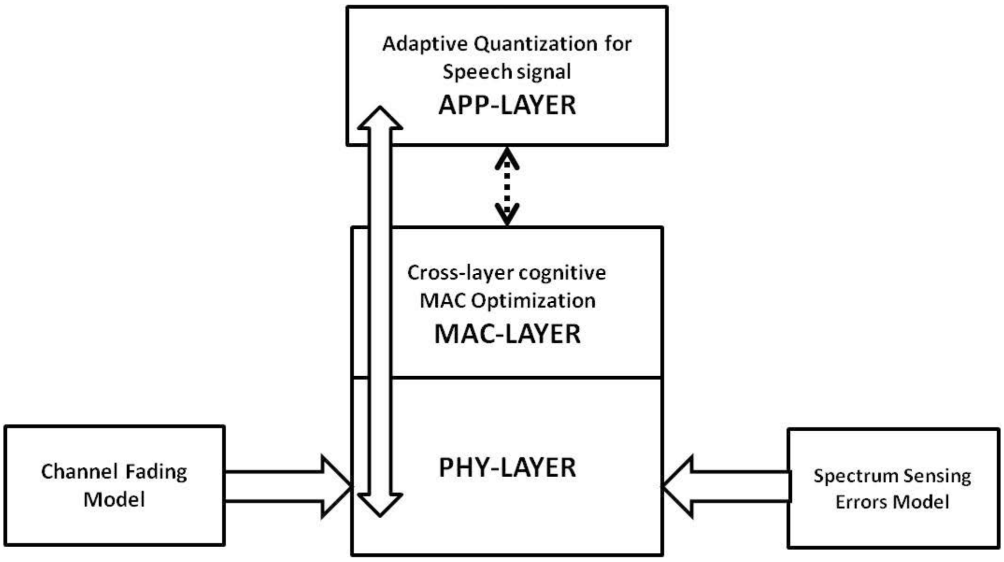

Fig. 4.2: Cross-layer design framework for speech transmission in CR networks

Table 4.1: Sequence of activities in one time slot performed by CR transmitter and CR receiver

Secondary user transmitter (T_x) action in a time slot
1. T_x chooses a channel to sense
2. T_x performs a sensing action
3. T_x observes sensing outcome and make channel access decision
4. T_x sends RTS signal to the secondary receiver
5. T_x receives a CTS signal from the receiver piggybacked with channel quality
6. T_x transmits the signal to the CR receiver
7. T_x receive an acknowledgement signal from secondary receiver
8 T_x computes the reward for successful transmission
Secondary user receiver (R_x) action in a time slot
1. R_x perform channel sensing
2. R_x receives the RTS signal from the transmitter
3. R_x sends a CTS signal to the transmitter piggybacked with the channel quality
4. R_x receives the speech signal from the transmitter
5. R_x sends an acknowledgement to the transmitter

4.4 POMDP Formulation and Solution

4.4.1 Action Space, State Space, and Observation space

Due to channel dynamics, multipath fading and partial spectrum sensing the whole state of the system can not be observed. Thus, the problem is formulated as a POMDP as presented in chapter 3 section 3.4. However, unlike the POMDP formulation presented in earlier chapter, in this formulation the action space ($\mathbb{A}$) consists of an addition part of step-size quantization space ($\mathbb{A}_q$). The action space will now consist of the following parts: sensing action space ($\mathbb{A}_s$), sensor operating point space ($\mathbb{A}_\delta$) and access (transmission probabilities) space ($\mathbb{A}_c$) and the step-size quantization action space ($\mathbb{A}_q$). We incorporate an APP layer step-size quantization parameter (q) in the state space in order to simulate the adaptive quantization feature in the problem. After the state transition of the channel at the beginning of each time slot, the CR node needs to sense the spectrum (spectrum sensing strategy), determine the valid sensor operating point on the ROC curve to use, decide whether to access the channel or not (spectrum access strategy), and choose the optimal quantization step-size at the APP layer based on the channel quality in order to optimize speech transmission without causing the interference to the licensed spectrum users. The joint action (composite action) in the time slot t is represented as:

$$a\{t\} = \{a_s(t), a_\delta(t), a_c(t), a_q(t)\} \in \mathbb{A} \tag{4.6}$$

The CR node can only compute a belief over the state space. In order to act in the system, a CR node is given a finite set of actions. Let us denote $\Theta^a_{j,\Phi} = Pr\{\Phi|j, a\}$ as the probability that the CR node observes $\Phi \in \{\Theta\}$ when the system is in the state $j \in \{\mathbb{S}\}$, and the composite action $a(t) \in \{\mathbb{A}\}$ was taken in the last time slot. We adopt the previous spectrum sensing error model as presented in section 3.5.

4.4.2 The Reward Function

Under POMDP's framework, the reward function assigns a numerical value quantifying the utility of performing an action $a \in \{\mathbb{A}\}$ when in state $s \in \{\mathbb{S}\}$.The goal of the CR node is to maximize the sum of its reward over time. The reward gained by CR node can be defined in many ways depending on the design objective [7]. Just as we defined and assumed in previous chapter, our objective in this scheme is to maximize the amount of information (throughput) transmitted by the CR node given that the collision with primary user is avoided as a constraint. We adopt the assumptions made by previous researcher in [5, 7, 79, 93] whereby the number of bits that can be delivered over a channel is assumed to be proportional to the channel bandwidth. Let $\mathcal{R}^k_n(t)$ denote the reward gained by a CR node after transmitting in the n^{th} channel in time slot t and receiving acknowledgement k. This reward is calculated in the same way as in (3.9). The objective function is the total number of transmitted bits in the total time slot T which can be denoted by J and is mathematically related to the reward as.

$$J \triangleq \left[\sum_{t=1}^{T} \mathcal{R}_n^k(t) \right] \triangleq \left[\sum_{t=1}^{T} S_n^k(t) \mathcal{W}_n \right] \tag{4.7}$$

4.4.3 Belief Computation

Under this POMDP framework, CR node can use the observations to learn its most likely state [67, 69]. The knowledge of the *current channel state* based on all *past actions* and *observations*, are not directly observable due to sensing errors and partial sensing of the radio spectrum as pointed out in chapter 3. Instead Smallwood et al in [92] suggested that the belief vector can summarize their knowledge of all past actions and observations.The belief vector is defined as the probability distribution over the state space. However, the state space in this formulation has additional quantity q which represents the step size quantization of the speech signal. Let the belief vector at time slot t be denoted by $\mathcal{B}_q(t)$. As computed in chapter 3, after taking the optimal action $a \in \{\mathbb{A}\}$ which is based on system state and the observation from the acknowledgement, the belief vector is updated by

$$\mathcal{B}_q(t+1) = (\mathcal{B}_q(t) | a_{\{s,\delta,c,q,k\}}) \tag{4.8}$$

The subscript q in (4.8) indicates that the belief is computed based on the state space of which the step-size quantization parameter is taken into consideration. Thus, (4.8) is defined as the probability of observing $K_n = k$ when the belief vector is $\mathcal{B}_q(t)$ and the composite action $a_{\{s,\delta,c,q\}}$ is taken. Thus $b_i(t+1) = p(k | a_{\{s,\delta,c,q\}}, \mathcal{B}_q(t))$. This is obtained by averaging the conditional observation probability $\Theta_{i,k} a_{\{s,\delta,c,q\}}$ over the current spectrum occupancy state [93]. We need to evaluate the joint optimal policy $\pi_{op}^* = (\pi_\delta^*, \pi_s^*, \pi_c^*, \pi_q^*)$ that maximizes the total number of information bits that can be delivered by the cognitive radio user in the finite period of time under the constraints that the primary users are protected from collision. Let $\pi_\varrho = \{\pi_\delta, \pi_s, \pi_c, \pi_q\}$ represent a joint policy for sensor operating point, sensing, access and quantization step-size. Then π_{op}^* can mathematically be expressed as

$$\pi_{op}^* = \arg\max_{\varrho} \sum_{t=1}^{T} \mathbb{E}_{\varrho}\left[R_{K_n}^{(n,\Phi_n)}(t)|\mathcal{B}_q(1)\right] \tag{4.9}$$

$$\text{s.t. } Pr\{\Phi_n = 1|S_n = 0\} \leq \tau$$

where $\mathbb{E}_{\varrho}$ is the expectation given the policies $\{\pi_\delta, \pi_s, \pi_c, \pi_q\}$ are employed and thus the spectrum sensor operates at δ, $\mathcal{B}_q(1)$ is the initial belief state and τ is the maximum allowed probability of collision. Chen et al [83] established a separation principle for the optimal joint design. This separation principle reveals the existence of deterministic optimal sensing and access policies, leading to a significant complexity reduction (appendix: A). Based on the separation principle, the optimal access policy is time-invariant and belief-independent. Thus the optimal transmission probabilities are solely determined by the sensor operating point δ_n and τ. Thus for any action a chosen, belief state $B_q(1)$ and time slot t , we have

$$(f_n^1(\mathcal{B}_q(t),t), f_n^0(\mathcal{B}_q(t),t)) = \begin{cases} \left(1, \frac{\tau-\delta_n}{1-\delta_n}\right), \; for\ \delta_n < \tau \\ \\ (1,0), \; for\ \delta_n = \tau \\ \\ \left(\frac{\tau}{\delta_n}, 0\right), \; for\ \delta_n > \tau \end{cases} \tag{4.10}$$

where f_n^1 is the transmission probability in channel n given that the channel is idle, and f_n^0 is the transmission probability in the channel n given that the channel is busy. Looking at the constraint in a joint optimal policy strategy equation, and given the belief state $\mathcal{B}_q(1)$ at the beginning of time slot t, the constraint $Pr\{\Phi_n = 1|S_n = 0\} \leq \tau$ can be rewritten as

$$Pr\{\Phi_n = 1|S_n = 0\} = \delta_n f_n^1(\mathcal{B}_q(t),t) + (1-\delta_n) f_n^0(\mathcal{B}_q(t),t) \tag{4.11}$$

The solution to equ. (4.9) is found by evaluating the value function which is defined as the maximum expected remaining reward that can be accumulated starting from slot $1 \leq t \leq T$ for a given initial belief vector $\mathcal{B}_q(t)$. Let the value function in the given time slot t be denoted by $\mathcal{V}_t(\mathcal{B}_q(t))$. Similar to the approach in chapter 3, this value function has two parts namely, immediate reward obtained in slot t and the maximum expected remaining reward which is obtained starting from slot $(t+1)$ for a given the belief vector. Given the optimal valid sensor operating point δ^* and access policy c^*, the value function can be obtained recursively by

$$\mathcal{V}_t(\mathcal{B}_q(t)) = \max_n \sum_i \sum_j \mathcal{B}_{qj}(t) P_{j,i} \sum_{k_n=0}^{1} \mathcal{Q}_s(k_n) \left[k_n \mathcal{W}_n + \mathcal{V}_{t+1}((\mathcal{B}_q(t)|n, k_n)) \right], \tag{4.12}$$

$$for 1 \leq t \leq T$$

$$\mathcal{V}_T(\mathcal{B}_q(t)) = \max_n \sum_i \sum_j \mathcal{B}_{qj}(t) P_{j,i} \mathcal{Q}_i(1) \mathcal{W}_n(t) \tag{4.13}$$

$$\mathcal{Q}_i(1) \triangleq Pr\{K_n = 1 | S(t) = i\} \tag{4.14}$$

where $\mathcal{Q}_i(1)$ is a probability of successful transmission under current spectrum state i [83]. The belief vector can be updated by applying Baye's rule as shown in (4.15) as

$$\mathcal{B}_{qi}(t+1) = \frac{\sum_j \mathcal{B}_q(t) P_{j,i} \mathcal{Q}_i(k_n)}{\sum_{j+1} \sum_j \mathcal{B}_{qj}(t) P_{j,j+1} \mathcal{Q}_{j+1}(k_n)} \tag{4.15}$$

The joint optimal policy π^*_{op} can be obtained by solving the optimality equ. (4.12) recursively. Smallwood et al [92] showed that, the value function $\mathcal{V}_t(\mathcal{B}(t))$ is piecewise linear and convex and hence, (4.12) and (4.13), are evaluated by using linear programming technique.

4.5 Simulation Results and Discussion

Computer simulation were carried out in order to study the throughput performance of the proposed scheme. Matlab software version 7.5.0.342 (R2007b) running on a 64-bit windows 7 operating system, 3.00GB RAM, AMD Turion II Dual-Core Mobile M500 2.2GHz was used. In order to study the throughput performance of the proposed MAC scheme under different transition probabilities $P(i, j)$, we set the number of channels and channel bandwidth to 3 and 1 respectively. Stationary transition probabilities were assumed in order to simplify the simulation. The average reward was recursively evaluated according to (4.13) using greedy algorithm scheme for both, perfect and imperfect sensing. Under perfect sensing scheme we ignore the spectrum sensing errors and channel errors due to fading effects while for the imperfect sensing scheme incorporate the spectrum sensing errors. We formulate the greedy algorithm function that uses the *number of channels* (N), the *channel bandwidth* $(\mathcal{W})$, *transition probabilities* (P_{01}, P_{11}), and the *time horizon* (T) in order to compute the initial channel occupancy state according to the initial belief vector. Under the imperfect sensing scheme, the miss detection is assumed to be equal to the probability of collision. In Fig. 4.3, we aim at showing the performance of optimal cognitive MAC protocol under different spectrum occupancy statistics for a given number of independent channels having the same bandwidth and transmission probabilities (α, β). For the purpose of comparison between our scheme and the previous works, we present the simulation results considering the perfect sensing scheme as well as the imperfect sensing scheme for both existing scheme and the proposed scheme. It can be seen from Fig. 4.3 that the average throughput of the secondary user for the proposed scheme improves to above 0.8 in just 10 time slots given the transition probability of $\{0.2, 0.8\}$ for the perfect greedy sensing algorithm (error free). The throughput drops to 0.75 when we incorporate spectrum sensing errors together with adaptive quantization. However, the throughput performance still performs much better as compared to previous system presented by Zhao et al in [7] with the throughput of about 0.68

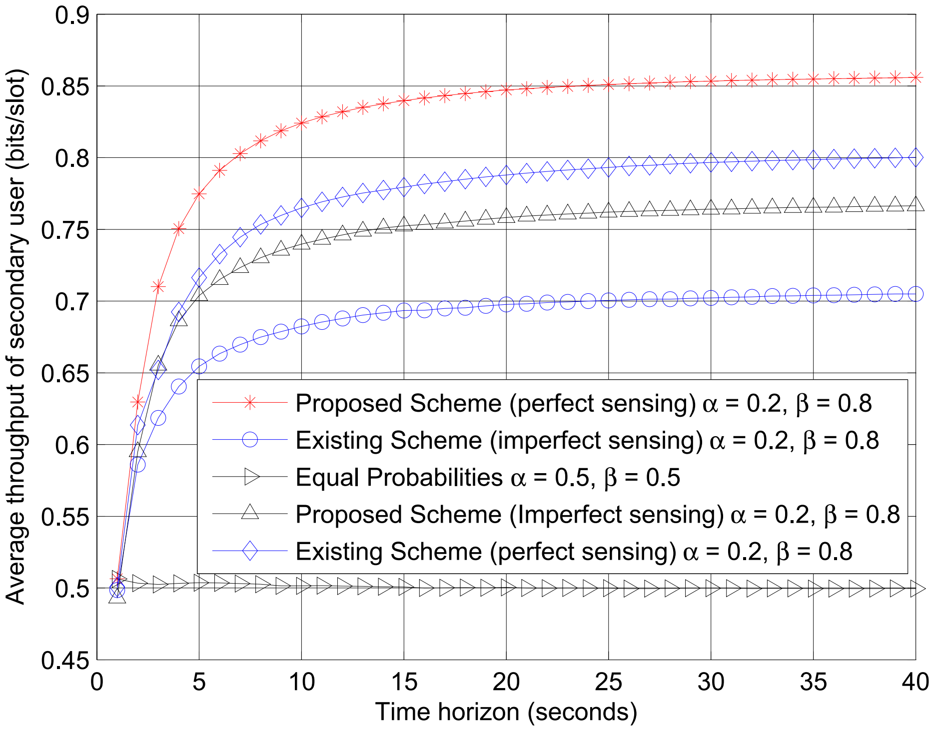

Fig. 4.3: Performance of the proposed cognitive MAC scheme , under different transition probabilities (α, β) for 3 independent channels with equal bandwidth $(\mathcal{W} = 1)$.

which considered only data transmission. These results demonstrate an improved throughput performance for the proposed scheme.

In Fig. 4.4 and Fig. 4.5, we aim at studying the throughput performance of the proposed scheme using *greedy sensing strategy* and compare it with *optimal sensing strategy*. The objective is to study the throughput performance of the proposed scheme in presence of sensing errors given the number of independent channels with equal bandwidth. It can be seen from Fig. 4.4 that the throughput of the proposed scheme as a function of prescribed collision probability improves and approaches that of optimal sensing (without errors). The maximum throughput for both schemes is achieved when the prescribed collision probability λ is approximately 0.4. On the other hand the maximum spectrum efficiency in Fig. 4.5 is achieved when λ is approximately 0.15. Thus there is a trade-off between throughput

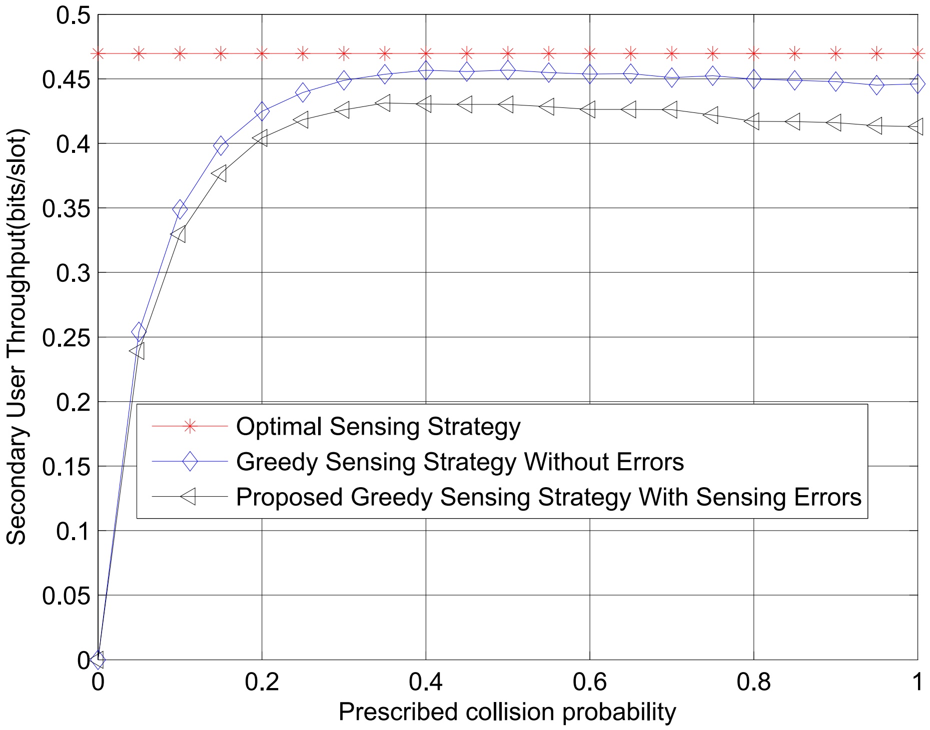

Fig. 4.4: Performance of proposed cognitive MAC in presence of sensing errors for 3 independent channels with equal bandwidth of 1, and $\{\alpha, \beta\} = \{0.4, 0.5\}$.

and spectrum efficiency. With larger values of λ, the probability of false alarm ϵ is very small leading to improved throughput of the secondary user at a price of more collision with primary user. The results in Fig. 4.5 shows that, when the probability of collision exceeds 0.15 the overall spectrum efficiency decreases. Thus, the best overall efficiency for the proposed scheme is achieved at $\lambda = 0.15$.

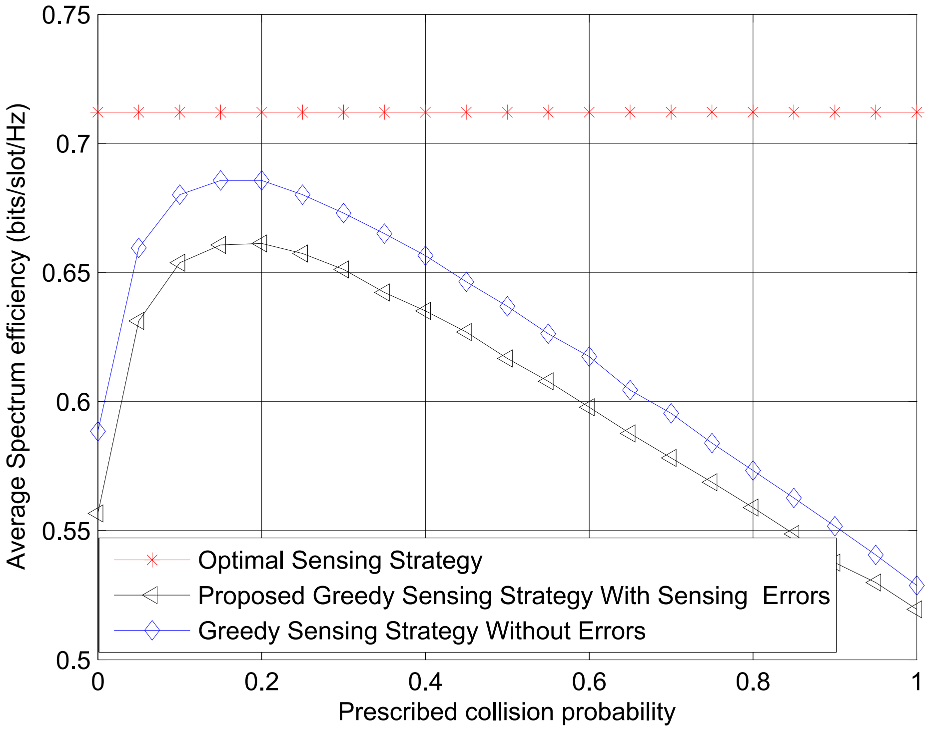

Fig. 4.5: Spectrum efficiency performance for the proposed cognitive MAC in presence of sensing errors for 3 independent channels with equal bandwidth of 1, and $\{\alpha, \beta\} = \{0.4, 0.5\}$.

4.6 Chapter Summary

We presented in this chapter a cross-layer design approach that maximises the throughput of the secondary users by jointly consider the design of spectrum sensing at physical layer, quantization parameter for speech traffic at application layer, together with strategies for spectrum sensing and access at MAC layer with the main goal to improve the QoS perceived by user for speech communication in CR networks. We defined the state of the system in terms of channel occupancy, the action in terms of sensing and accessing subset of radio channel, and observation in terms of sensing outcomes (results). We also defined a reward as a number of transmitted bits in a certain number of slots under the constraints that the interference to the primary users is avoided. By application of POMDP optimization technique, the quantization parameter at the application layer of the speech encoder is integrated into state space and formulate the optimal joint policy which resulted into constrained POMDP problem which usually requires randomized policies to achieve optimality. By using the separation principle proposed by previous researchers, we reduced complexity of the problem while maintaining the optimality. Computer Simulations were carried out by considering both cases, thus a perfect scheme and imperfect scheme using greedy sensing algorithm. The results demonstrate an improved performance of the proposed scheme.

Chapter 5

Cross-layer MAC scheme for Video Transmission Over Cognitive Radio Networks

5.1 Introduction

The upcoming new applications for wireless multimedia communications open new opportunities for many interesting and comprehensive research topics targeting at concepts, methodologies, and techniques to support the future advanced mobile wireless applications. Multimedia traffic are generally categorized into two main categories namely real time and non-real time traffic. Real-time applications such as voice and video, require a stringent QoS and cannot tolerate time delay and delay variability, but can tolerate a small BER. Whereas, for applications like data can tolerate time delays but cannot tolerate high BER. Advances in wireless communications provide ample opportunities for introducing new services. Supporting video applications and services over CR networks is challenging due to constraints and heterogeneities such as limited battery power, limited bandwidth, random time-varying fading effect, different protocols and standards, and stringent QoS requirements. Cross-layer design methodologies however have shown promises in addressing these challenges and achieving reliable and high-quality end-to-end throughput performance in wireless multimedia communications. One of the main features of the modern communication systems is the parameterized operation at different layers of the protocol stack [111]. The feature aims at providing them with the capability of adapting to the rapidly changing traffic, channel and system conditions. An interesting research problem is the combination of individual adaptation mechanisms into a cross-layer that can maximize their effectiveness.

Literature surveys show that many cross-layer design approaches consider MAC and PHY layers interaction while a significant research gap exists for a cross-layer design between APP, MAC, and PHY layers specifically for multimedia transmission over CR networks. It is clear that, the developments of the new schemes, mechanisms, and systems associated with the cross-layer designs and protocols will have a significant impact on the next generation of wireless communications and networks. It is from this literature survey results that we are motivated to devote this chapter in providing a joint cross-layer design MAC scheme that integrates the design of spectrum sensing at PHY layer, access at MAC layer, and APP layer information in order to address the QoS issues set by the multimedia application.

In chapter 4, we introduced the adaptive quantization feature of the speech encoders as one of the APP layer parameter that is integrated in the joint design of MAC and PHY layers for throughput maximization of speech transmission in CR networks. In this chapter we introduce a cross-layer MAC optimization technique that integrates the design of PHY, MAC, and APP layers whereby end-to-end video distortion is considered as the application layer parameter. The scheme considers the H.264 coding algorithm which is one of the high efficient video coding standard. The objective is to minimize this end-to-end video distortion while maximizing the overall network throughput for video transmission in CR networks.

5.2 Video Transmission Over CR Networks and related works

In video coding, the rate control is used to control the video encoder output bit rate on various condition to improve video quality [67]. H.264 and MPEG-4 are among the highly efficient coding algorithms used in video compression to reduce the required bandwidth for video. MPEG-4 object-based video coding determines how many bits are assigned to each video object in the scene and adjusts the quantization parameter to accurately achieve the target coding bit rate. Highly compressed video data is vulnerable to packet losses where a single bit error may cause severe distortion [112]. This vulnerability makes error resilience at the video encoder essential. Intra update, also called intra refreshing, of macrobloks is one approach for video error resilience and protection as presented by Liao in [113]. An intra coded macroblock (MB) does not need information from previous frames which may have already been corrupted by channel errors. This makes intra coded MBs an effective way to mitigate error propagation. Alternatively, with inter-coded MBs, channel errors from previous frames may still propagate to the current frame along the motion compensation path [67]. Given a source-coding bit rate (Rs) and intra refreshing rate, a model is needed in order to estimate the corresponding source distortion (Ds). The authors in [114] provide a closed form distortion model taking into account varying characteristics of the input video, the sophisticated data representation scheme of the coding algorithm, and the intra refreshing rate. Based on the statistical analysis of the error propagation, error concealment, and channel decoding, a theoretical framework is developed to estimate the channel distortion (Dc). Coupled with the rate distortion model for source coding and time varying wireless channels an adaptive mode selection is proposed for wireless video coding and transmission. The estimated video distortion for video applications is popularly used as most important design metric. Video encoders reside at the APP layer. We consider the H.264 video codec whereby each video frame is represented by block shaped units of the associated luminance and chrominance samples called MBs which are 16 by 16 pixel regions. These MBs can further be intra-coded and inter-coded from samples of previous frames.

5.2.1 H.264 Standard Overview

H.264 is an industry standard for video compression, the process of converting digital video into a format that takes up less capacity when it is stored or transmitted. Video coding is an essential technology for applications such as digital television, DVD-Video, mobile television, video-conferencing and internet video streaming. Standardising video compression makes it possible for products from different manufacturers (e.g. encoders, decoders and storage media) to inter-operate. An encoder converts video into a compressed format and a decoder converts compressed video back into an uncompressed format

The H.264 standard was first published in 2003 [115]. It builds on the concepts of earlier standards such as MPEG-2 and MPEG-4 Visual and offers the potential for better compression efficiency (i.e. better-quality compressed video) and greater flexibility in compressing, transmitting and storing video. Figure 5.1 shows the encoding and decoding processes and highlights the main parts that are covered by the H.264 standard. It carries out prediction, transform and encoding processes to produce a compressed H.264 bit stream. Thus, it carries out the complementary processes of decoding, inverse transform and reconstruction to produce a decoded video sequence. The encoder processes a frame of video in units of a MB (16 × 16 displayed pixels). It forms a prediction of the MB based on previously-coded data, either from the current frame (intra prediction) or from other frames that have already been coded and transmitted (inter prediction). The encoder subtracts the prediction from the current MB to form a residual[1].

The prediction methods supported by H.264 are more flexible than those in previous stan-

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[1] Finding a suitable inter prediction is often described as motion estimation. Subtracting an inter prediction from the current MB is motion compensation

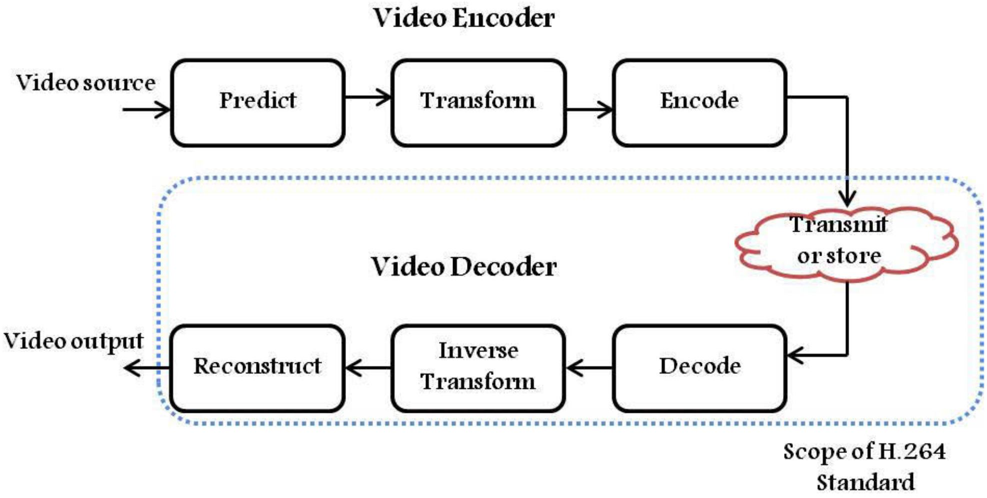

Fig. 5.1: The H.264 video coding and decoding process

dards, enabling accurate predictions and hence efficient video compression. Intra prediction uses 16×16 and 4 by 4 block sizes to predict the MB from surrounding, previously-coded pixels within the same frame. Inter prediction uses a range of block sizes (from 16×16 down to 4×4) to predict pixels in the current frame from similar regions in previously-coded frames.

5.2.2 Video Quality Performance Metric

Recently, Luo et al in [116] presented a quality-driven cross-layer optimized system that includes different modules, such as video encoder module, cognitive MAC module, modulation and coding module, cross-layer optimization module and wireless video transmission module. These system modules represent different network functions residing in different network layers. Video encoder usually resides in the APP layer, the cognitive MAC module resides in the MAC layer, while modulation and encoding module resides in the PHY layer. Without losing generality we adopt the video quality performance metric model presented by Luo et al in [116] in order to formulate throughput optmization problem in this scheme. Generally, Intra-coding is performed in the spatial domain by referring to neighbouring samples of previously coded frames [112]. There are some factors that need to be considered in order to accurately estimate the end-to-end distortion. These factors include source coding, error propagation, and channel coding. There have been several efforts put by researchers which can be found in the literature with regards to distortion estimation for hybrid motion-compensated video coding and transmission over lossy channels [114,117]. For real-time source coding, Zhang et al in [117] showed that the estimated distortion caused by quantization, packet loss, and error concealment at the encoder can be calculated using recursive optimal per-pixel estimate (ROPE) technique, providing an accurate optimization metric on video quality. As for the source coding parameter, we consider the quantization step-size q that was used in chapter 4 for speech traffic, which can also be applied for video traffic under H.264 video coding standard. In this scheme, one packet is set to be one row of MBs, which is also called one slice. Thus, in this formulation, slice and packet are used interchangeably. Given the dependencies introduced by error concealment scheme, the expected distortion of the packet x of a video frame κ can be calculated at the encoder by using ROPE technique [116] as shown in (5.1).

$$\begin{aligned}\mathbb{E}[\mathcal{D}_{\kappa,x}] &= (1-\rho_x)\mathbb{E}\left[\mathcal{D}^{r}_{n,x}\right] \\ &\quad + \rho_x(1-\rho_{x-1})\mathbb{E}\left[\mathcal{D}^{lr}_{\kappa,x}\right] \\ &\quad + \rho_x\rho_{x-1}\mathbb{E}\left[\mathcal{D}^{ll}_{\kappa,x}\right] \qquad (5.1)\end{aligned}$$

where ρ_x is the loss probability of packet x with consideration of packet delay bound given as T^{max}_{κ}. $\mathbb{E}\left[\mathcal{D}^{r}_{\kappa,x}\right]$ is the expected distortion of packet x when it is successfully received. Furthermore, depending on whether packet $(x-1)$ is received or lost, $\mathbb{E}\left[\mathcal{D}^{lr}_{\kappa,x}\right]$ and $\mathbb{E}\left[\mathcal{D}^{ll}_{\kappa,x}\right]$ are the corresponding expected distortion after concealment after packet x is lost. Consider the SNR which is measure of signal strength relative to background noise. Let the BER for the received SNR be denoted by $\varepsilon(SNR)$ and the frame error rate for a given received SNR be denoted by $\rho(SNR)$. Then frame error rate and BER are related as

$$\rho(SNR) = 1 - (1 - \varepsilon(SNR))^{l} \tag{5.2}$$

where l is the MAC frame size. Let us further assume that the x^{th} packet of video frame κ is fragmented into Z MAC frames, and the MAC frames are transmitted along a path with H hops. Then, the packet loss rate for a given packet x can be expressed as

$$\rho_x = 1 - \left[\prod_{z=1}^{Z} (1 - \rho_x^z(SNR)) \right] \tag{5.3}$$

where $\rho_x^z(SNR)$ is the rate of MAC frame z of packet x. Therefore, the expected distortion of the whole video frame κ can be represented as

$$\mathbb{E}[\mathcal{D}_\kappa] = \sum_{x=1}^{X_\kappa} \mathbb{E}[\mathcal{D}_{\kappa,x}] \tag{5.4}$$

where X_κ is the total number of packets in the video frame κ. Thus, the expected end to end video distortion is accurately calculated by ROPE under instantaneous network conditions which we make it our objective function. For a given video packet x, the expected packet distortion only depends on packet error rate ρ_x and quantization step size q. Considering the fact that the individual contribution of each packet is continuously updated, this parameter is updated after each packet is encoded.

5.3 System Model

We adopt the system model that was introduced in chapters 3 and 4 whereby a spectrum that consists of N channels each with bandwidth of $\mathcal{W}_n$ where $(1 \leq n \leq N)$ licensed to PUs is considered. In addition, in order to simplify the analysis of the model, we make the following assumptions:

- time is divided into slots of equal length T and slot t refers to the discrete time period $[tT, (t+1)T]$.
- when the channel is idle, it will be comprised of only AWGN while fading effects are neglected
- The primary usage for a channel is represented by stationary and ergodic S-state Markov chain.
- the phase of the channel attenuation can be perfectly estimated and removed at the receiver.
- a system for real-time multimedia applications and thus, the packets are discarded if the channel is busy.

A cognitive MAC scheme is required for secondary users to efficiently share the available radio spectrum whenever it is idle. A cognitive MAC scheme has basically two functions [118]. The first one is to ensure that the secondary user do not interfere with the PUs. The second function is to achieve low complexity, high efficiency, and fair media access among secondary users. Thus, difference cognitive MAC schemes achieve different throughput performance leading to different system capacities for secondary users. The simplified MAC scheme proposed in this formulation of which its flow chart is the same as that in Figure 3.4. works as follows:

1. At the beginning of a time slot t, the CR transmitting node with video contents to transmit will choose a set of channel to sense.
2. Based on the sensing outcome, it will decide whether to access the channel or not.
3. If it decides to access the channel, the optimal application layer parameter (end-to-end video distortion) is selected and the video content is transmitted.

4. At the end of the time slot, the CR receiving node will acknowledge the transfer by sending the acknowledgement signal to the transmitting node.

5.4 Problem Formulation and Solution

In order to transmit multimedia contents in CR networks, we need to determine the joint optimal policy which comprises of the following policies: Optimal policy for channel access π_c^*, optimal policy for channel sensing selection π_s^*, optimal policy for for sensor operating point π_δ^* and the optimal policy for application layer end-to-end distortion π_α^*. The constraint in this joint policy is that, the interference to PU has to be avoided. Due to the fact that there are errors due to channel sensing and partial information of the whole range of the radio spectrum, the whole state of the system can not be observable. POMDP is a suitable model for this problem and therefore we apply it in this formulation. However, deriving a joint policy POMDP under the constraint of the probability of collision to PU results into a constrained POMDP optimization problem which requires a randomized policies to achieve optimality. Separation principle which was used in previous chapter is used to determine the joint optimal policy to achieve optimality. Thus, under separation principle, the spectrum sensor operation point on the ROC curve is set such that the probability of miss detection of the busy channel used by PUs is equal to the required probability of collision. The problem is formulated as a POMDP with channel states, a set of actions, a set of channel transition probabilities, a set of channel observations and a reward structure. Thus, at the beginning of the time slot t, the system transit to a new state and channel is selected for sensing and channel access decision is made based on either belief vector on the sensing observations or the end-to-end video distortion. The video content is then transmitted and the receiver acknowledges the receiving of the video contents by sending the acknowledgement signal back to the transmitter. The immediate reward in terms of throughput is computed based on the previous activities in the time slot.

5.4.1 Objective and Constraint of The System

The end-to-end video distortion can be viewed as the cost in the overall system which has a significant effect to QoS perceived by the user. In this proposed scheme the end-to-end distortion is minimized while the overall throughput is maximized under the constraint that the interference to PUs is avoided. This forms a min-max constrained problem. By modelling the end-to-end video distortion as the immediate cost, we define the immediate cost as C_t. Given the target system throughput, the packet loss ration $p(s_t, a_t)$ when the system is in the state s_t and a composite action a_t is taken in time slot t, the system immediate cost can be evaluated as

$$C_t = \mathcal{D}(\xi, p(s_t, a_t), \alpha(t)) \tag{5.5}$$

The expected total cost for overall end-to-end video distortion over the T time slots is denoted as Ω_π. Mathematically this can be written as

$$\Omega_\pi = \mathbb{E}_{\{\pi_s, \pi_{\epsilon\delta}, \pi_c, \pi_\alpha\}} \left[\sum_{t=1}^{T} \mathcal{D}(\xi, p(s_t, a_t), \alpha(t)) \right] \tag{5.6}$$

where $\mathbb{E}_{\{\pi_s, \pi_{\epsilon\delta}, \pi_c, \pi_\alpha\}}$ indicates the mathematical expectation that the policies $\{\pi_s, \pi_{\epsilon\delta}, \pi_c, \pi_\alpha\}$ are employed whereby

- a channel sensing policy π_s: specifies which channel to sense a_s.
- a sensor operating policy $\pi_{\epsilon,\delta}$: specifies a spectrum sensor design (ϵ, δ) based on the system maximum probability of miss detection τ.
- an access policy π_c: specifies the channel access decision $a_c \in \{0, 1\}$
- end-to-end distortion policy π_α: specifies the channel distortion decision based on the current information state.

Having formulated the end-to-end distortion model and the overall expected cost of the POMDP problem, we need a joint optimal policy for video transmission over CR network. This joint policy will minimize the expected total end-to-end distortion in T slots under the condition that the interference to the PUs is avoided. Let the optimal joint policy be denoted by $\{\pi_s^*, \pi_{\epsilon\delta}^*, \pi_c^*, \pi_\alpha^*\}$. Thus, we can represent it mathematically as

$$\{\pi_s^*, \pi_{\epsilon\delta}^*, \pi_c^*, \pi_\alpha^*\} = \arg \min_{\pi_s, \pi_{\epsilon\delta}, \pi_c, \pi_\alpha} \mathbb{E}_{\{\pi_s, \pi_{\epsilon\delta}, \pi_c, \pi_\alpha\}} \left[\sum_{t=1}^{T} \mathcal{D}(\xi, p(s_t, a_t), \alpha(t)) \right] \tag{5.7}$$
$$S.t \qquad Pr\{a_c(t) = 1 | \Phi_t = \iota_S\} < \tau, \qquad \forall t \in T.$$

5.4.2 Value function

In this formulation, the value function represents the minimum expected cost that can be obtained starting from the slot t where $1 \leq t \leq T$ given the information state at the beginning of the time slot t. Let us denote the value function as $\Omega_t(\pi)$. Given that the CR node takes action a_t and observe acknowledgement $\Phi_t = \phi_t$, the cost that can be accumulated starting from the slot t comprises of the two parts namely the immediate cost $C_t = \mathcal{D}(\xi, p(s_t, a_t), \alpha_t)$ and the minimum expected future cost $\Omega_{t+1}(\pi+1)$, where $\pi_{t+1} = \{\psi_s(t+1)\}_{s \in \mathbb{S}} = U(\pi_t | a_t, \phi_t)$, which represents the update knowledge of the system state after incorporating the action a_t and the acknowledgement ϕ_t in the time slot t. The value function is then evaluated as

$$\begin{aligned}
\Omega_t(\pi_t) &= \min_{a\in\mathbb{A}} \sum_{s\in\mathbb{S}} \sum_{s'\in\mathbb{S}} \psi_{s'}(t) A_{s',s} \\
&\times \sum_{j=\iota_1}^{\iota_S} B(\phi_t, j, a_t)[\mathcal{D}(\xi, p(s_t, a_t), \alpha(t)) \\
&+ \Omega_{t+1}(U(\pi_t|a_t, \phi_t))], \qquad 1 \le t \le T-1 \qquad (5.8) \\
\Omega_T(\pi_T) &= \min_{a\in\mathbb{A}} \sum_{s\in\mathbb{S}} \sum_{s'\in\mathbb{S}} \psi_{s'}(\xi) A_{s',s} \\
&\times \left[\sum_{j=\iota_1}^{\iota_S} B(\phi_t, j, a_t)[\mathcal{D}(\xi, p(s_t, a_t), \alpha(T)) \right]. \qquad (5.9)
\end{aligned}$$

Under unconstrained POMDP with finite action and state space the value function is a piecewise linear. It can therefore be evaluated by linear programming as presented by Sondok et al in [95]. Casandra et al in [119] provided an excellent overview of computationally efficient algorithms which can be used to evaluate the optimal policy iteratively. Solving the POMDP can be done off-line during system initialization. During the real-time video transmission, a CR node just needs to find the value for specific information state using equ. (5.8) and update the information which introduces computational complexity. Further more, by imposing structural assumptions on the transition probabilities, cost and observation probabilities, one can prove in some cases that the optimal policy is a threshold policy [67]. As for a selected channel, the optimum video distortion α selected corresponds to the most likely available state based on π_t. Due to asymptotic nature of the end-to-end video distortion, a busy channel has infinite distortion. In this case α has no influence on the total channel distortion. If the most likely state based on π_t corresponds to a busy state, then the optimum α is to select α corresponding to the most likely available state. That way, if the information suggests the channel is busy but in reality it is available, then α has been selected that will minimize the effect of this error.

5.5 Simulation results and discussions

In order to evaluate the throughput performance of the proposed scheme, we carried out a set of simulation experiments using matlab software version 7.5.0.342 (R2007b) running on a 64-bit windows 7 operating system, 3.00GB RAM, AMD Turion TM II Dual-Core Mobile M500, 2.2GHz. The choice of the total time slot number T depends on the convergence rate of the POMDP program. However, the state transition probabilities, observation probabilities and the value functions have significant effects to the convergence rate. Some of the simulation parameters set are shown in the Table 5.1. We aimed at studying the channel access decision based on belief computation and the channel access decision based on the end-to-end distortion and compare between the two. For a given prescribed probability of collision, we studied the spectrum efficiency and the average throughput and compare between the channel access decision based on belief computation and channel access decision based on end-to-end distortion. The simulations were carried out and studied in four different scenarios namely A, B, C and D as follows:

Table 5.1: Simulation Parameters Set for Video Transmission in CR Networks

Parameter	**Value**
Number channels (N)	10-channels independent identically distributed (iid)
Bandwidth per channel	3
video input	Foreman.qcif
Frame size (μsec)	1-65536 (dynamic)
Message length	50 packets geometrically distributed
Error model (ϵ, δ)	ROC curve (10 cooperative sensing users)
Message arrival rate (λ)	Form a Poisson process
MAC header	9
PHY header	15 μsec
Packet transmission time of one packet	Assumed to be one time slot

5.5.0.1 Simulation Scenario A

In this scenario the average throughput performance as a function of time horizon was studied. Fig. 5.2 shows the simulation results of which the throughput performance under access decision based on belief vector and that of access decision based on the end-to-end distortion are compared. Fig.5.2 shows the average throughput performance for three different cases. In the first case it is assumed that the channel access decision is based on the perfect knowledge of the system (optimal channel access decision). This is an ideal condition and as it can be seen from Fig. 5.2 that the average throughput performance increases with time reaching 2.17 in 10 seconds. In the second case, the channel access decision is based on the belief vector of the POMDP solution. This belief vector is the probability distribution over system state where the optimal decision can be read from the value function for any belief state. This channel access decision method does not perform well when transmitting real-time traffic such as video. As shown in Fig. 5.2, the throughput performance 1.9 in 10 seconds which is the difference of about 0.27 from the ideal case. However, for real time applications such as video, the throughput performance can be improved using channel access decision based on end-to-end video distortion (proposed scheme). Thus, in the third case the throughput performance is improved to about 2.2. This generally shows that for real time traffic such as video, the channel access decision based on end-to end decision performs much better (in terms of average throughput) as compared to channel access decision based on the belief vector.

5.5.0.2 Simulation Scenario B

In this simulation scenario we aimed at studying the spectral efficiency performance as a function of prescribed collision probability for the proposed scheme. The perfect optimal channel access decision was compared with the channel access decision based on the end-to-end distortion. The simulation results show that at large values of collision probability the overall spectral efficiency performs poorly. The reason for this is that, by increasing the

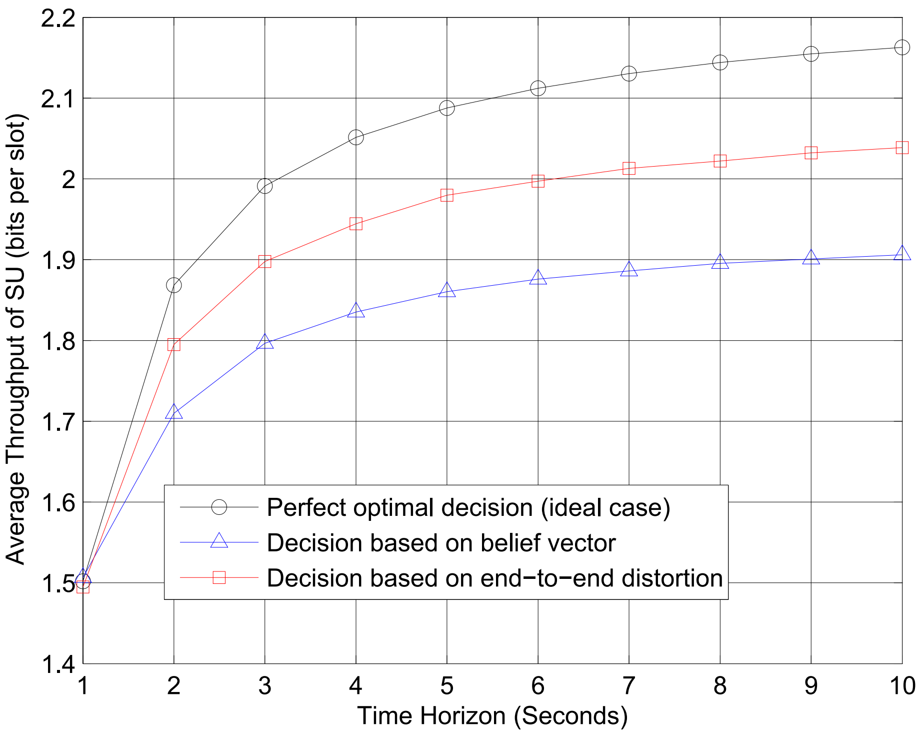

Fig. 5.2: Throughput performance for the proposed system under different channel access decision.

chances of collision the effective usage of spectrum is affected since the secondary users will not transmit due to collision. However, there there is an optimal value of collision probability of which the spectral efficiency approaches that of the perfect channel access decision. Thus, the simulation results in Fig. 5.3 indicates that at the prescribed collision probability of about 0.2, the spectral efficiency approaches that of the optimal channel access decision. However, beyond the collision probability of about 0.2, the spectral efficiency falls due to the effects of collision. Thus, the proposed scheme achieves its optimal value of spectral efficiency at the prescribed probability of collision of about 0.2.

5.5.0.3 Simulation Scenario C

In this scenario we aimed at studying the throughput performance of the proposed system in terms of prescribed collision probability as a function of average throughput. We make

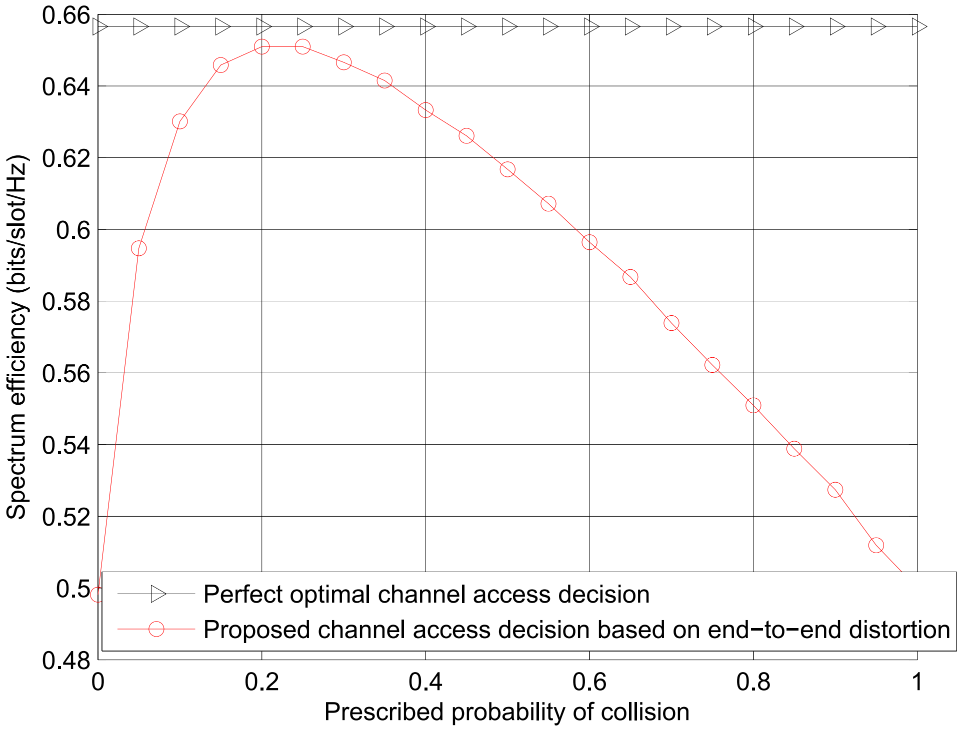

Fig. 5.3: Spectral efficiency as a function of the prescribed collision probability.

comparison between the channel access decision based on the perfect optimal scheme and the channel access decision based on the end-to-end video distortion. As it can be seen from Fig. 5.4 that the average throughput increases with the prescribed probability of collision. From the simulation results it is noted that the proposed scheme perform much better than that of optimal decision in terms of average throughput. Thus, the scheme performs better at the interval of prescribed collision probability of about 0.1 to about 0.4 and then the throughput starts to fall as the collision probability increases.The reason for this is that, at low values of collision probability the channel is likely to be unoccupied and hence the successful transmission by secondary user is possible. On the other hand, increased prescribe collision probability, unsuccessful transmission by secondary user is likely to happen and hence the average throughput is affected. However, we need to find an optimal point where the throughput and the spectral efficiency are optimal because increasing the average throughput while jeopardising the spectral efficiency is contrary to the role of cognitive radio. On the other hand, throughput has a significant effects to the QoS for multimedia applications such as video applications in cognitive radio networks.

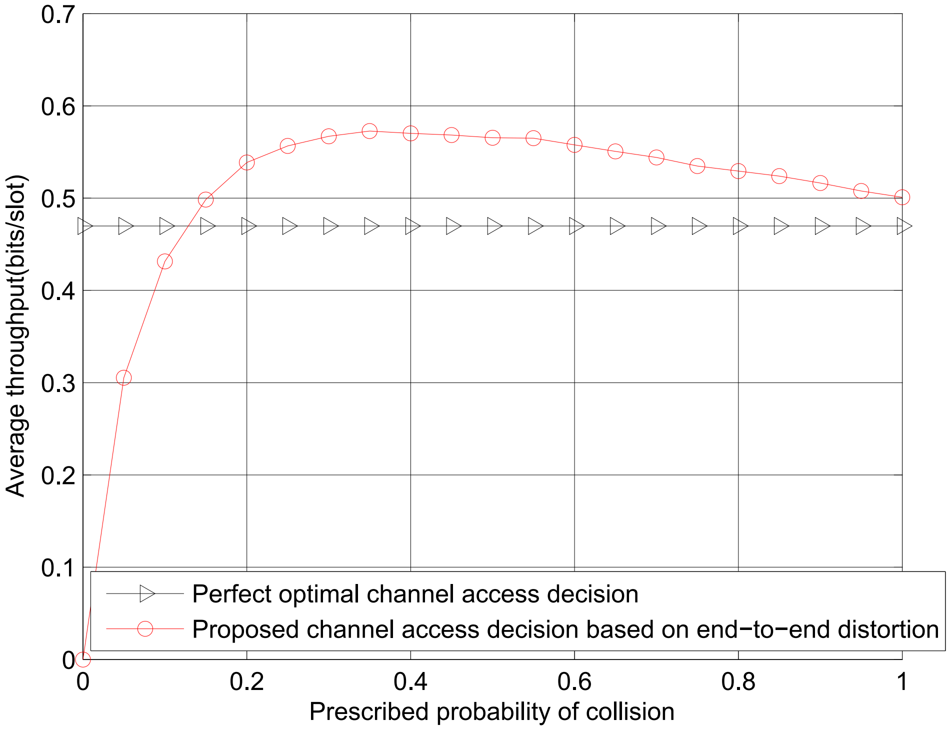

Fig. 5.4: Throughput performance as a function of prescribed collision probability.

5.5.0.4 Simulation Scenario D

In this simulation scenario, we aimed at showing the average throughput and the spectral efficiency both as a function of prescribed collision probability. As it can be seen from Fig. 5.5 that both average throughput and the spectral efficiency are highly affected by increased collision probability. However, at the prescribed collision probability of about 0.2, the scheme achieves the maximum average throughput and maximum spectral efficiency.

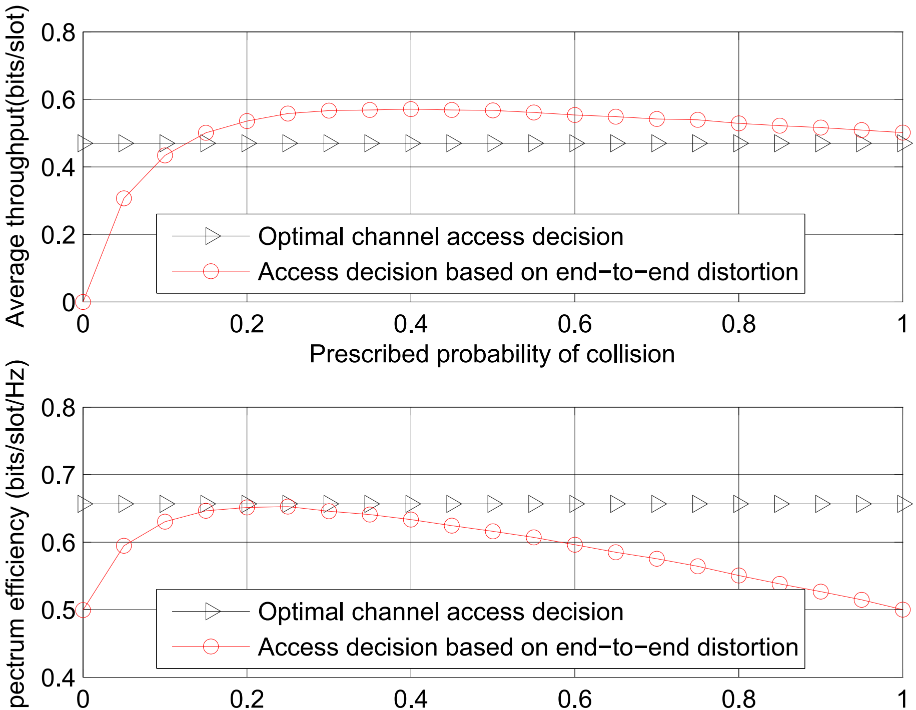

Fig. 5.5: Probability of miss detection vs average throughput and spectral efficiency performance comparisons.

5.6 Chapter Summary

In this chapter, a joint cross-layer design MAC scheme that integrates the design of spectrum sensing at PHY, access at MAC layer and APP layer information in order to improve the QoS for video transmission in CR networks is presented. The end-to-end video distortion which is an APP layer parameter resides in the video encoder is integrated in the state space and the problem is formulated as a constrained POMDP. H.264 coding algorithm which is one of the high efficient video coding standards is considered. The objective is to minimize this end-to-end video distortion while maximizing the overall network throughput for video transmission in CR networks. The end-to-end video distortion has significant effects to QoS perceived by the user and is viewed as the cost in the overall system design. Given the target system throughput, the packet loss ration when the system is in the state i and a composite action is taken in time slot t, the system immediate cost is evaluated. The expected total cost for overall end-to-end video distortion over the total time slots is then computed. A joint optimal policy which minimizes the expected total end-to-end distortion in total time slots is computed iteratively. The minimum expected cost (which also known as the value function) is also evaluated iteratively for the total time slots. Computer simulations were carried out in order to study the average throughput and spectral efficiency as a function of collision probability as well as the time horizon. We compared the throughput performance for channel access decision based on belief computation and the channel access decision based on end-to-end video distortion. In both case the proposed system outperforms the channel access decision based on belief computation.

Chapter 6

Conclusion and future work

6.1 Conclusions

In this section, a summary of the work done is given as well as the contributions in this thesis.

Radio spectrum is considered to be a scarce resource. However the experimental results indicate that there is inefficient utilization of the available spectrum. The CR technology emerges as a way to improve the overall efficiency of radio spectrum utilization and exploiting spectrum opportunities. One of the most prominent feature of CR technology is the ability to switch between different portions of radio spectrum and detect the availability of the vacant spectrum. Spectrum sensing which has a long history enables unlicensed user to continuously sense the channel before accessing it in order to avoid interference. In chapter 2 a review of the most commonly used spectrum sensing techniques is presented. Spectrum sensing techniques are classified as cooperative detection, transmitter detection and interference based. The comparisons in terms of complexity of different technologies is presented focusing much on the transmitter detection technique (specifically the energy detector) due to its simplicity. A simple spectrum sensing scheme is developed to be used in the proposed cross-layer design scheme for multimedia applications in CR networks. The sensing capability of spectrum sensing technique is usually evaluated in terms of the ROC curves which gives a measure of the probability of miss detection as a function of the probability of false alarm. A cooperative relay based spectrum sensing using AF technique is also developed in order to address a hidden node problem in CR networks. Spectrum sensing schemes developed in chapter 2 form the bases for error model which is incorporated in the design of MAC scheme for multimedia applications in CR networks. There are several challenges on spectrum sensing which include sensing delay and accuracy in detecting the idle spectrum as well as delay in switching from one frequency to another. This has a significant impact to delay-sensitive applications (real-time applications) such as voice and video. Thus, spectrum sensing has reborn as a very active research area recently due to the fact that it is a fundamental problem for cognitive radio.

Media access control is a crucial part of cognitive radio because, it is responsible for providing the coexistence between licensed and unlicensed radio spectrum users with minimum probability of interference. Due to the dynamics of wireless channel, spectrum sensing results may contain errors leading to incorrect spectrum access decision which may lead to either interference to licensed user or miss opportunity of the idle spectrum. Thus, in chapter 3, a cross-layer MAC scheme is developed with the objective to maximize the throughput of the system under the constraints that the interference to the licensed user is kept minimum. The concept of partially observable Markov decision process (POMDP) as an optimization tool is introduced in order to formulate a cross-layer MAC scheme that integrates the design of physical layer (PHY) and that of MAC layer in presence of sensing errors from the spectrum sensor. In the design and modelling of the media access control protocol, errors due to spectrum sensing must be taken into account in order to improve the accuracy of designed system for channel access decision. However, adding constraints to a POMDP problem complicates its solution which often demands a randomized policies to achieve optimality. Thus, there is no closed form solution so far for a constrained POMDP framework. Linear programming is used in this scheme to compute optimal policies iteratively. POMDP has been proved to be a convenient and realist way of modelling a decision process under uncertainty.

Different wireless applications require different quality of services which are constrained by the dynamics of wireless channels. Multimedia applications are being targeted for cognitive radio networks. Speech is still the most dominant and common service, and digitally encoded speech signal poses many advantages. However, direct transmission of speech signal over wireless channel without compression requires additional bandwidth. Many different strategies have been developed for suitability compression of speech for bandwidth-restricted applications. In order to reduce the bit rate while maintaining good speech quality over CR networks, the cross-layer MAC scheme is proposed in chapter 4. The design of the scheme integrates the PHY information and the step-size quantization of the speech signal at application layer while ensuring that the licensed users are protected from interference. With the application of POMDP technique, the quantization step-size is incorporated into state space and the constrained POMDP problem was formulated. The main objective was to maximize the network throughput while avoiding interference to licensed user. Based on the simulation results, throughput performance is improved in this scheme. However, the overall delay of the system is not analysed which can have significant effects to the QoS of the speech application since it is a real-time application. This delay constraint is earmarked in our future research.

Supporting video applications and services over CR networks is very challenging due to the constraints and heterogeneities such as limited battery power, limited bandwidth, random time-varying fading effects, different protocols and standards, and stringent QoS requirements. Cross-layer design methodologies have shown a great promises for addressing these challenges and achieving reliable and high-quality end-to-end performance in wireless multimedia communications. Thus, in chapter 5, a cross-layer MAC optimization scheme that enables the interaction between PHY, MAC, and APP layers in order to take advantages of the multi-rate feature of modern multimedia standards at the APP layer for video transmission in CR networks is introduced. H.264 video coding standard which is the latest video encoding standard is considered in this scheme. The estimated end-to-end video distortion for application layer which is popularly used as most important design metric is used as the design metric and it is therefore incorporated in the MAC design. The end-to end video distortion is considered as the cost in the overall system which have significant effects to the user perceived QoS. The objective is to minimize this end-to-end distortion while maximizing overall system throughput under the constraint that the interference to licensed users is avoided. Simulation results show an improved performance of the proposed system.

6.2 Future Work

The following are some topics of interest for further investigations of this research:

1. In Chapter 2, a brief survey on some common spectrum sensing techniques is presented. Spectrum sensing is a very complicated problem demanding coordinated efforts of the regulatory and technical sides. One particular example is the case of cooperative sensing, which requires a flexible policy, regulating the dynamic access to spectrum based on the behaviour and capabilities of a cognitive radio network as a whole rather than individual users. Thus, research on spectrum sensing thus far has mainly focused on meeting the regulatory requirements for reliable sensing. However, an important venue for further research is the interplay of spectrum sensing and higher-layer functionalities to enhance the end users perceived QoS

2. In Chapter 3, a cross-layer MAC scheme in presence of spectrum sensing errors is presented. The cross-layer design approach is achieved by jointly considering the design of spectrum sensing at PHY layer and that of sensing and access strategy at MAC layer. The assumption made in this scheme was that each CR node is equipped with a Ney-man Pearson energy detector and therefore the ROC curve is used to model the spectrum sensing errors. A constrained POMDP problem is formulated for throughput

maximization. However, other spectrum sensing techniques may be applied to the proposed scheme in order to study the overall system throughput performance. We consider this as one of the research area in our future work. Some other optimization techniques need to be studied and implemented in order to compare with that of POMDP technique. Other system errors which are caused by channel fading should be looked at and the throughput performance of the system be evaluated. We find these areas very interesting for future work.

3. In chapters 4 and 5, the cross-layer MAC schemes for speech and video respectively are considered. In both of the two schemes the throughput performance of the system was evaluated since it is one of the performance metric for user perceived QoS. However, being real-time applications, speech and video are very much affected by long time delay. It is therefore important that apart from evaluating the throughput performance of the network, the the overall system delay have also to be evaluated in order to decide whether the system's QoS meet the users' requirements. This is one of the area we consider in our future work.

Appendix A

A.1 Separation Principle

The joint design can be carried out in two steps without losing optimality. The optimal sensor operating policy π_δ^*, the optimal spectrum access policy π_c^* and speech quantization policy π_q^* are chosen to maximize the instantaneous reward (throughput in this case) under the design constraint that the collision probability is equal or below the threshold τ. Therefore, given any belief vector $\mathcal{B}(t)$ at the beginning of any time slot t, the optimal sensor operating point δ_n^*, optimal transmission probabilities $\{f_n^*(0), f_n^*(1)\} = c_n^*$ and the optimal speech quantization value q_n^* for a given channel n are given by

$$\{\delta_n^*, f_n^*(0), f_n^*(1), q_n^*\} = arg \max_{\delta_n, \{f_n(0), f_n(1)\}, q_n} \mathbb{E}[\mathcal{R}_{K_n}^n(t)|\mathcal{B}(t)] \tag{A.1}$$

$$= arg \max_{\delta_n, \{f_n(0), f_n(1)\}, q_n} \epsilon_n f_n(0) + (1-\epsilon_n) f_n(1) \tag{A.2}$$

$$s.t \qquad (1-\delta_n f_n)(0) + \delta_n f_n(1) \leq \tau$$

Next, the optimal spectrum sensing policy π_s^* is selected in order to maximize the total expected reward whereby the optimal sensing policy is obtained by evaluating the following an unconstrained POMDP:

$$\pi_s^* = arg \max_{\pi_s} \mathbb{E}_{\{}\pi_s, \pi_\delta^*, \pi_c^*, \pi_q^*\} \left[\sum_{t=1}^{T} \mathcal{R}_{K_n}^n(t) | \mathcal{B}(t) \right] \tag{A.3}$$

A.2 Optimality Equation

The value function given in equations 4.12 and equation 4.13 is the key in finding a POMDP solution.

Given $p(k|n, \delta, c, q, \mathcal{B}(t)) = \sum_i \sum_j b_i(t) P(j, i) \Theta_{i,k}(a, \delta, c, q)$ the value function $\mathcal{V}_t(\mathcal{B}(t))$ in a slot t can be obtained as:

$$\begin{aligned} \mathcal{V}_t(\mathcal{B}(t)) = \max_n \max_\delta \max_c \max_q & \sum_{k=0}^{1} p(k|n, \delta, c, q, \mathcal{B}(t)) \\ & \times [k\mathcal{W}_n + V_{t+1}(\mathcal{I}(\mathcal{B}(t)|n, \delta, c, q, k))], \qquad \text{(A.4)} \\ & for \qquad 1 \leq t \leq T. \end{aligned}$$

$$\begin{aligned} \mathcal{V}_T(\mathcal{B}(T)) &= \max_n \max_\delta \max_c \max_q p(1|n, \delta, c, q, \mathcal{B}(t)) \qquad \text{(A.5)} \\ where & \qquad a \in \{1, 2, ..., N\} \\ & \qquad \delta \in \{0, 1\} \\ & \qquad q \in \{q_0, q_1, ...\} \\ s.t. Collision Probability &= \sum_{\theta=0}^{1} Pr\{\theta_n = \theta | S_n = 0\} Pr\{k_n = 1 | \theta_n = \theta\} \\ &= (1-\delta) f(0) + \delta f(1) \leq \tau, \qquad \text{(A.6)} \\ Where \qquad (f(0), f(1)) &= c = Transmission Probabilities \end{aligned}$$

A.3 Optimal policy computation by iteration

```
Algorithm 1: OPTIMAL policy computation by iteration
Input: Policy $\pi$ to be computed
Output: Optimal policy ($\pi^*$) for action taken
$\mathcal{B}_i(1) = 0, \forall_i \in \mathbb{S}$    {initialize}
$\pi^* \leftarrow \{a, \delta, c\}$
Repeat
$\hat{b} = 0$
for all    $i \in \mathbb{S}$ do

$b = \mathcal{B}_i(1)$
$\mathcal{B}_i(1) = \sum_a \pi(s,a) \sum_j P(j|i,a) \left(\mathcal{R}(j|i,a) + \tau \mathcal{B}_i(j)\right)$
if $a_i > max$ then
    $max \leftarrow a_i$
return Optimal policy ($\pi^*$)
```

A.4 Value Iteration for Optimal Policy Computation

Algorithm 2: Value Iteration Optimal for Policy Computation

```
$Assumption: \ policy \ \pi \ is \ proper$
$Initialize \ \mathcal{V}_0^\pi \ arbitrally \ for \ each \ state$
$t \leftarrow \emptyset$
repeat
$t \leftarrow t + 1$
for $i \in \mathbb{S}$ do
    $Compute \quad \mathcal{V}_t^\pi \leftarrow \sum_{j \in \mathbb{S}} P\{i, \pi(i), j\} \left[C(i, \pi(i), j) + \mathcal{V}_{t-1}^\pi(j)\right]$
    $Compute \quad resdual_t(i) \leftarrow |\mathcal{V}_t^\pi(i) - \mathcal{V}_{t-1}^\pi(i)|$
end
until $max_{i \in \mathbb{S}} residual_t(i) < Threshold$
return $\mathcal{V}_t^\pi$
```

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