Resource-sharing cognitive radio networks in commercial and military environments

Ian Bajaj

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NETWORKS IN COMMERCIAL AND MILITARY
ENVIRONMENTS**

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**SCHOOL OF ELECTRICAL AND ELECTRONIC
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RESOURCE-SHARING COGNITIVE RADIO NETWORKS IN
COMMERCIAL AND MILITARY ENVIRONMENTS

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Resource-Sharing Cognitive Radio Networks in Commercial and Military Environments

IAN BAJAJ

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List of Symbols

h_i	i^{th} channel gain
γ_i	Power gain of i^{th} fading channel
α_i	Percentage power increment for i^{th} user
R_x	General notation for transmission rate
P_x	General notation for transmission power
N_0	Noise variance or noise power spectral density
R_t	PU target rate requirement
x^+	Positive-semidefinite of x
$\tilde{x}$	Estimate of x
$\bar{x}$	Ergodic average of x
C_x	Associated spectrum cost for $x = \{s, r, a\}$, s -sharing, r -relaying, a -access
U	PU Payoff
$\mathcal{P}(x)$	Probability of event x
$\mathcal{W}(x)$	Product log function of x
$\mathcal{I}(x)$	Indicator function of x
$\mathcal{Q}(x)$	Q-function of x
λ_x	Representative threshold for ED
H_X	Spectrum sensing hypothesis denoting $X = \{B, I, O, I_o\}$, B -busy, I -idle, O -occupied, I_o -occupied idle state of the PU spectrum
ρ_i	Received SNR at the i^{th} user
ε	PU Outage-limiting constraint
$\Gamma(x)$	Gamma function in x
$\Gamma(n, x)$	Incomplete Gamma function
SNR_i	SNR of the i^{th} channel link

$\exp(x)$	Exponential function of x
M	Number of sensing samples

List of Abbreviations

AF	Amplify-and-Forward
ANC	Analog Network Coding
ATR	Acknowledgement To Relay
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CF	Compress-and-Forward
CR	Cognitive Radio
CSI	Channel State Information
CTR	Confirm To Relay
CTS	Confirm To Share
DBR	Double Broadcast Relaying
DF	Decode-and-Forward
DH	Double Hopping
DT	Direct Transmission
ED	Energy Detection
FTR	Fail To Relay
ID	User Identifier
ITC	Interference Temperature Constraint

LOS	Line-of-sight
MRC	Maximal Ratio Combining
OFDM	Orthogonal Frequency Division Multiplexing
OSA	Opportunistic Spectrum Access
PIP	Peak Interference Power
PNC	Physical-Layer Network Coding
PR	Primary Receiver
PSK	Phase-Shift Keying
PT	Primary Transmitter
PTS	Permit To Share
PU	Primary User
QOS	Quality-of-Service
RTA	Request To Access
RTR	Request To Relay
SBR	Single Broadcast Relaying
SNR	Signal-To-Noise Ratio
SR	Secondary Receiver
ST	Secondary Transmitter
STBC	Space-Time Block Coding
SU	Secondary User
XOR	Exclusive Or
ZFE	Zero-Forcing Equalizer

Abstract

Cognitive radio (CR) provides the platform for dynamic spectrum sensing, spectrum allocation and intuitive decision making in a very rigid spectrum framework architecture. Accessing white spaces in licensed spectrum through spectrum hopping and managing interference in free-to-use spectrum are means by which CR can help improve the overall spectrum efficiency. But utilizing these spectrum resources generally comes at a price, whether that be a monetary cost or interference to transmission. Resource-sharing therefore demands a two-way exchange for users to effectively transmit simultaneously across any spectrum. We investigate how this cost changes given the application of CRs in a commercial or military setting.

With commercial or licensed spectrum, monetary incentives are important, and therefore spectrum leasing or spectrum trading is often sought as the avenue for resource-sharing. While the bulk of spectrum sharing research focuses on interference mitigation or rate maximization for the cognitive or secondary users (SU), the work in this Thesis deals with incentivizing the licensed or primary users (PU) that lease out their spectrum. The resource-sharing protocol incorporates three opportunities for spectrum exchange in the form of spectrum access, spectrum sharing and relaying, that each have a market-driven cost. With the highest SU bid gaining transmission rights to the leased PU spectrum, this model perfectly showcases the demand-and-supply economics involved in a commercial setting.

From a military standpoint, time is a commodity that is precious. Time-efficient re-

lays in particular, help play an important role in reestablishing non-LOS (line-of-sight) communications between military users stranded in the battlefield. With link quality-of-service (QOS) and cost measures to be considered as well, our design features a partial-relay node that serves to connect the stranded users while carrying out its own transmission needs. The relay node features a zero-forcing equalizer (ZFE) and space-time block coding (STBC) to mimic properties of physical-layer network coding in a practical sense. The result is a half-duplex communication setup that requires only 4 timeslots for three way non-LOS bi-directional communication, and bit error rates (BER) that are comparable to the direct link QOS.

We also see a great demand for blind and decentralized decision making amongst resource-sharing setups both in the military and commercial communication domains. Incognizance or anonymity is the requisite for the SUs that sense and utilize the spatial-temporal gaps in the spectrum. Moreover, for a network-blind and decentralized SU, this translates to using only statistical sensing information to carry out all spectrum allocation and transmission decisions. When sensing licensed subspace, the optimization goal is outage minimization at the primary receiver (PR), while for transmission over unlicensed bands, the goal is to meet a network-wide QOS for SU transmission. The work discussed in this Thesis demonstrates how outage-constrained threshold design using energy detection (ED) and adaptive power control can result in both harmonious and anonymous spectrum sharing across both platforms. The results justify our contributions to resource-sharing research in the CR domain, and its general applicability to both commercial and military markets.

Chapter 1

Introduction

1.1 Motivation

CR has played a crucial part in wireless communications research for almost a decade now. Its predecessor software-defined radio, allowed for programmable flexibility to carry out specific roles. But with CR, a level of self-awareness and adaptability, allowed it to be implemented in a variety of communication scenarios, operating and improving its performance with time. This adaptability propelled the attention it received in the research community, and continues to usher in possibilities for the next-generation of communication systems. From a broad perspective, this would be enough to pique anyone's interest on the topic. But as with research, this motivated us to look deeper into finer issues of CR implementation and its practicality in the context of both commercial and military communication networks.

CRs rely on statistical information to adapt to, and predict changes in its channel environment. This statistical information can come from both communicable and observational means. While the former requires a degree of cooperation and sharing channel and transmission statistics between nodes in the network, observational data is acquired from independent spectrum sensing, allowing the user to maintain anonymity. In CR

research, such systems that operate independent of external knowledge or cooperation are referred to as blind systems. Inherently, these blind systems can be computationally more demanding, as it makes objective decisions solely from sensing data in a dynamic network. However, cooperative systems or users that exchange information, also suffer from processing and computational time delays in the form of acknowledgments and centralized decision making. This dichotomy of knowledge versus complexity drove the idea to examine the role CRs have to play in each setting.

The application of CRs in a military or commercial setting also demonstrate a similar divide. While military communication protocols allow cooperation between users, their research interests are aligned towards automated, independent and decentralized tactical radios that can operate blind in the field. Commercially, CRs can be employed over PU subspace for spectral efficiency in a monetary or resource sharing capacity. This requires a degree of sharing that sees CRs through the lens of cooperative systems. We attempt to demonstrate the difference between interactive and independent, centralized and distributed, and, commercial and military CR applications through the work presented in this Thesis.

1.2 Objectives

- To understand the current gaps in CR research both in commercial and military scenarios, redefining the optimization objectives to appeal to the specific industry, and investigating challenging problems that other research work has failed to look into or possibly overlooked.
- Developing system models, optimizing key parameters and designing unique algorithms to promote cognitive-decision making wherever possible.
- Publishing scientific work through rigorous simulations for different channel envi-

ronments and network settings, backed by strong mathematical proofs to validate our results.

1.3 Major contribution of the Thesis

The common thread through all the system models and scenarios presented in our research, is a non-interfering resource-sharing system ideology. While improving spectral or time efficiency through resource sharing is important, spectrum assignment for SU transmission should not adversely affect ongoing PU transmissions. Whether in commercial or military applications, we see the practical means of deployment of CRs would be either in a non-interfering or assistive capacity. Therefore, our optimization goals, and corresponding contributions in the Thesis, are geared towards maximizing PU incentives for cooperation or minimizing PU outages in a blind setting. Compliance with existing standards is key and the simulation results presented in this Thesis, are a representation of the achievable SU network rates under such constraints.

Individual project goals that have been fulfilled are:

- The design of a spectrally efficient, fully cooperative, resource-sharing platform for cognitive and PU networks

We design a spectrum trading model that encompasses all modes of spectrum utilization (spectrum access, spectrum sharing and relaying) to guarantee SU spectrum rights regardless of the state of the PU channel. The pricing structure is modeled after the demand and supply flow of market economics, where the PU decides a monetary equivalent for the resource being shared, in line with the demand for said resource. We develop closed-form solutions to optimize the payoff the PU receives from this collaboration, through a simplified analytical model. The corresponding results demonstrate the advantage to both the SU in terms of rate and the PU

in outage reduction and payoff maximization, justifying the degree of information exchanged.

- A time-efficient relay transmission model for non-LOS military communication nodes

Here, we investigate time-efficiency in an emergency battlefield scenario. For this setup, we have a partial-relay military CR meant to serve as an intermediary for bi-directional communication between stranded units in the field. While transmitting its own data, the partial-relay relies on network coding to communicate the individual messages from each of the nodes, delivering the same or improved link BER than the non-existent direct link between them. A cyclic re-transmission protocol is also established which extends this 2-node exchange to bi-directional communication between 3 nodes in 4 timeslots.

- Blind and decentralized spectrum allocation based on outage-constrained spectrum sensing threshold design

For a completely blind system, spectrum sensing is a reliable source of unfiltered statistical information regarding channel occupancy and network dynamics. By designing outage-constrained sensing thresholds for spectrum access and spectrum sharing, back-end PU interference mitigation constraints are already dealt with, allowing SUs to operate both blind and decentralized over the spectrum. We have also developed an adaptive algorithm to distinguish between licensed and SU transmissions and determine changing network dynamics from patterns in the received sensing statistic. Moreover, we see an improvement in SU rate over the traditional sensing threshold design for an energy detector.

- A network-blind decentralized rate-achieving SU network

In the same capacity that spectrum sensing data serves as the only reliable information in a 2-tier PU-SU network setup; SU deployment over unlicensed bands rely on the statistical sensing data, in meeting a network QOS without centralization or

cooperation. Threshold design here is even more crucial as fair spectrum sharing behavior needs to be enforced in a network without any licensed control. With smart priority-enhanced power control strategies, and network-blind outage-constrained thresholds, we demonstrate how non-cooperative SUs meet a network target rate in a true distributed sense. In comparison to decentralized rate-achieving models in literature, our work stands out as being both general and practical, and can see value in both commercial and military platforms.

1.4 Organization of the Thesis

The Thesis is structured as follows. In Chapter 2, we introduce the topic of CR research, by highlighting its role and opportunities for use in current communication technology. In a resource-sharing capacity, CRs can be viable for both military and commercial purposes, and we discuss and differentiate the applications of CR models based on the way information is processed and made available in such networks. We look at the commercial side of spectrum trading in Chapter 3. Here, we highlight the need for licensee incentivization in spectrum trading research by demonstrating a resource-sharing model based on a demand-and-supply free market. The corresponding PU payoff and SU rate present a strong picture for collaborative trading models. Chapter 4 turns the table around to look at a military time-conscious CR application. Through broadcast transmissions with ZFE and STBC implemented at the support relay, stranded military nodes can establish bi-directional communication in 3 timeslots simultaneously as the relay maintains its own communication with its receiver. With a retransmission protocol, this model has been extended to 3-way bi-directional relay support in 4 timeslots, just one more than if direct communication links were present. We then move on to network-blind systems that operate without cooperation, centralization or any other channel knowledge information generally assumed for CR deployment. In Chapter 5, we focus on

designing outage-constrained thresholds that allow network-blind SUs to share and access PU spectrum without any added information. The corresponding results demonstrate the power that statistical sensing brings to such extreme network setups. We continue the study of network-blind deployment in Chapter 6 over unlicensed spectrum. With priority-enhanced water filling and outage-constrained threshold designs, we see how network-blind SUs can turn a pure-interference network into a rate-achieving network through just statistical sensed data. Our study on network-blind systems conclude the Thesis with a summary of our entire work in Chapter 7, and the possibilities we see for future research in these areas. It is to be noted that the terms cognitive user and licensed user have been replaced with the more common terminology of SU and PU, respectively, to maintain uniformity throughout the Thesis.

Chapter 2

Literature Survey

From tactical radios to software-defined radios to CRs, a trend for automated design and intuitive decision making is one that is clear, in the progress of wireless communication systems. With CRs, researchers now have access to a programmable interface to harness the most out of given resources for transmission over wireless spectrum. With time, these radios will be able to adapt and optimize their transmission parameters to cope with the changing network dynamics that they find themselves in. It is why Simon Haykin first addressed them as brain-empowered wireless communication systems [1]. But the need for adaptive control goes beyond the trend for automation across different industries. What spectrum bodies noticed was a dire need for a change in the way spectrum was allocated. Traditional characterization of spectrum involved breaking up the entire usable range of transmission frequencies into different bands, each representing specific channels for communication. Partitioning the spectrum this way into aeronautical, maritime, land mobile and satellite communications for example, avoided the need for unnecessary interference mitigation from users with different transmission purposes. This is even more crucial when discussing spectrum intended solely for military purposes. However, this introduced rigidity in the way users can be allocated spectrum. With higher demand for bandwidth this platform saturates in its capacity to accommo-

date more users. This is why CR was more importantly seen as a means to overlay the rigid allocation platform with users that could adaptively and flexibly accommodate the “holes” in the frequency spectrum. These holes refer to spatial and temporal gaps across the entire spectrum, generally categorized into unutilized or under-utilized spectrum. While unutilized spectrum refers to an absence of transmission over allocated spectrum, under-utilization is a reference that the capacity of the channel is not being fully utilized. Spectrum bodies across the world have conducted surveys [2] [3] that reveal on average an 85% inefficiency in spectrum utility. This has caused governing spectrum bodies to implement solutions [4] to this issue in the form of: i) spectrum reallocation, ii) spectrum leasing, and iii) spectrum sharing.

Spectrum reallocation is the means taken by the government to re-auction already assigned spectrum to new wireless services. The most common reallocation comes from the shift of analog to digital TV broadcasting, making a chunk of the spectrum available for wireless broadband services [5]. This global implementation can be seen from the industry’s standpoint as keeping up with the demands of the digital age, but from a spectrum perspective, this provides much needed relief for the growing needs of wireless communication. The GSM bands (900MHz and 1800MHz) have also seen changes through reallocation and bidding according to government regulations. While the Infocomm Development Authority of Singapore (IDA) established a framework for its reallocation in 2008 [6], Malaysian Communications and Multimedia Commission (MCMC) have just introduced more recent policies for change in the first quarter of 2016 [7]. In a market dominated by few telecom giants, reallocation is often seen as a chance for smaller companies to throw their proverbial hat in the ring. However, more often than not, it is faced with opposition. In the United States in 2010, private equity firms nicknamed “spectrum speculators”, bought out smaller TV stations and their licenses with the intent of auctioning it off for much high returns [8] during the reallocation period determined by the

government. Though completely legal, it prevents fair spectrum allocation, purely for economic gains.

Spectrum leasing is another area that spectrum bodies like the Federal Communications Commission (FCC) have looked into. Here, licensees are allowed to sublet or rent out their allocated spectrum as per their choosing. FCC introduced policy measures in 2003 [4] that allowed cellular voice or data licensees to take advantage of this opportunity to increase returns on spectrum as well as benefit the overall spectrum efficiency. This was immediately seen as a gap in CR research to facilitate incentivized spectrum leasing with these spectrum holders. With the ideology of CRs becoming more popular, the final proposition to the spectrum inefficiency issue was spectrum sharing. Initially meant as a reference to share the free-to-use 2.4GHz spectrum or ISM bands, now IEEE has established operations across the TV white space (licensed digital and analog TV broadcasting bands) as a standard for CR spectrum sharing in the IEEE 802.22 working group [9]. With the research community looking to the future, CR is now resonant with allocation and transmission efficiency across the sensed spectrum, regardless of its ownership. CR deployment over licensed or unlicensed spectrum only changes its in application across the industry. Other factors that determine its applicability to a specific market would be how information is exchanged between users in the network.

The information exchanged can be sensing information, channel knowledge, power and/or transmission statistics of the users in the network. Depending on their availability, the networks can be categorized into cooperative, non-cooperative, or network-blind, in decreasing orders of information available. Cooperative communications is a widely researched topic in the context of CRs, and generally refers to a network with no barriers on sharing information between users. From cooperative sensing to cooperative relaying and cooperative spectrum sharing, these networks are optimized for the best performance results with access to all the computational information needed. However,

different scenarios demand that users operate independently with little to no information about network statistics. This is where non-cooperative and network-blind schemes are relevant. In communications research, users that are “blind” generally have no channel information, and therefore we define the term “network-blind” in this Thesis to represent the extreme case where users cannot depend on external knowledge whatsoever. Generally speaking, networks with less information exchange, where nodes can maintain anonymity are more favored for military applications. However, what really determines the applicability of a particular network across different industries is also how decisions are made in the network. Centralized and decentralized/distributed networks characterize the way the received information is processed. For centralized systems, each node reports data it receives to a controller or overseer that makes a collective decision for the network. A centralized controller has the advantage of spatial diversity to make the most informed decision for the network of nodes. However for large networks, a centralized design is limited by time and complexity strains over the reporting and forwarding control channels. Decentralized designs on the other hand, are decisions made locally through one-hop communication or consensus sharing for a cooperative network, or individually at each node in a non-cooperative or network-blind setting. It is this combination of information exchange and decision-making that categorize a network as being applicable for either a commercial or military purpose. It is clear therefore that there is a cost for every return, regardless of the type of network, whether that be spectrum, time, complexity, or money, and this is the picture that a resource-sharing CR network presents. We will now look into commercial- and military-specific areas in CR research and certain applications from cooperative and centralized to non-cooperative and decentralized networks.

2.1 Cognitive Resource-Sharing from a Commercial Perspective

A commercial perspective as the name implies is one that is profit-oriented and is synonymous with the idea of trading. Commercial applications for a resource-sharing CR network would then imply deployment over a tradeable spectrum resource, like licensed subspace. Detection of these licensed white spaces and determining its suitability for transmission is however the CRs responsibility. The means of accurately detecting PU activity through spectrum sensing is an area of CR research that is so vast in its methodologies and objective implementations [10]-[15] that a whole Thesis could not cover it. But our goal here is to understand how the information is used.

In its simplest form, an energy detector [16] that is used for spectrum sensing, would compare the received sensing energy at a particular SU node to a pre-defined threshold to determine if the PU's channel was busy or idle. Upon making a decision regarding its activity, the SU would opportunistically access its spectrum if the PU is absent or its sensed channel statistics determine it to be idle. On the contrary, if PU activity is sensed, the SU can share transmission rights with the PU. These two modes of CR transmission are commonly referred to as Spectrum Access and Spectrum Sharing respectively. Spectrum access or opportunistic spectrum access (OSA) [17] as the name implies is a non-intrusive means of transmission. Therefore, it is understood that CR transmission must be halted when PU activity is sensed. This can result in choppy SU transmission with intermittent delays based on the spectrum usage. To combat this a lot of work on dynamic spectrum hopping (DSH) and double hopping (DH) can be found in literature [18] that allow SUs to jump to other available PU spectrum gaps without collision. Spectrum sharing on the other hand, allows simultaneous transmission over the spectrum. When SUs sense ongoing PU communication, spectrum sharing dictates that

the SU can simultaneously transmit over the spectrum but within a range of tolerable interference as measured at the PR. This interference measure (also called interference temperature constraint (ITC)) can be implemented as a peak interference power constraint (PIP) or frame-averaged interference power constraint (AIP) [19] depending on the PU QOS requirements. Research work on interference mitigation designs for spectrum sharing began as early as 2009, when plans for standardizing CR spectrum sharing on licensed TV bands were being laid out by the IEEE 802.22 working group. However from a commercial standpoint, interference mitigation or increase in spectral efficiency means nothing for a licensee. The industry is interested in return on investment, which in this case is the precious frequency spectrum. This is where spectrum trading research fits in.

Spectrum trading refers to the leasing of licensed spectrum resources for a monetary return. It is what incentivizes licensees to share their unused spectrum with SUs. Papers that discuss spectrum leasing can broadly be categorized into economic or game theory models. Economic models represent market strategies in determining the associated price for leased spectrum. Authors in [20] demonstrate a monopoly market setting, where the PU sets a fixed quality-based price for the spectrum it wishes to lease. The drawback in a monopoly market is that the price is not a reflection of the spending capital of the buyer. Therefore, the PU can receive lower returns from SUs that are willing to pay more for the opportunity to transmit over the leased spectrum. Other interesting work from an economic standpoint, is the concept of double leasing. Here, the licensee can lease out the same resource to multiple spatially separated SUs and derive greater revenue. The authors in [21] and [22] discuss the truthful double spectrum auctions framework that demonstrates the tradeoff in spectrum utilization and economic interests. Most other work that deal with spectrum pricing are from the context of game theorists. The popular Nash equilibrium is the pricing strategy used for these Stackelberg spectrum

leasing games. With Stackelberg games, the leader (or PU) has a competitive edge in terms of utility, as it determines what the expected response would be from the followers (or SUs) willing to access its spectrum. If the follower agrees with the pricing strategy it would result in a Nash equilibrium. However, as the case is with any economic market scenario, if the SU opts to pay less than the offered price, it can topple the PU out of its positional advantage and result in a non-optimal exchange. Another issue is that models based on game theory tend to associate decisions with intention, which can prove to be unfavorable. For example, if an SU is unwilling to access the licensed spectrum resource due to unfavorable channel conditions, regardless of the associated cost, a PU could interpret this decision to not cooperate as the SU's intention, and will lower the average cost for the spectrum resource, also resulting in a non-optimal scenario.

Other work in spectrum trading are models that are based on interference mitigation without monetary exchange. Game theory models that discuss this kind of spectrum trading, do not provide incentives for applications to the commercial space, and therefore can be categorized more generally under spectrum sharing models, which will be discussed in greater detail in Section 2.2.

2.1.1 Cooperative and Centralized Network Applications

Cooperative networks are those that are based around collaborative protocols that allow users to exchange and share information in order to achieve a common network goal. In its first instance, cooperation was seen in the spectrum sensing domain [23] [24]. The proposal to share spectrum sensing information with a centralized controller added a level of spatial diversity to negate channel fading or shadowing effects influencing an individual's sensing decision. This allowed a single network controller oversight regarding spectrum access decisions, through a weighted sum [25] or other collaborative operations on the independent sensing results [26], providing more accurate spectrum

readings. However, centralized control ends up being unfeasible especially when the network size is large. Bandwidth is also expended both by the users communicating their individual sensing information to the controller, and with dedicated feedback or control channels to relay the weighted sensing decisions back. This defeats the purpose of CR spectrum efficiency. In terms of processing, information flow disseminating from a single source also puts a strain on the network resulting in time delays. Consequentially, the achievable throughput for the network would be lower with longer sensing durations (i.e. the sensing time vs throughput tradeoff [27]). Therefore, work done on reducing the communication overhead in literature is crucial for a centralized design. The authors in [28] demonstrate the inverse effect that the communication overhead has on the detection performance of the system, and evaluate a smoothening factor that balances this trade-off well. Centralization in a network therefore, finds more application where higher level spectrum and power allocation decisions are necessary, where the users cannot make independent cognitive decisions. Hence, with the emergence of CR, distributed spectrum sensing techniques gained more popularity, as detailed in Section 2.2.1.

Other cooperative strategies that link directly to the commercial space are those that fit the brief of licensee incentivization. This is where cooperative cognitive relays found favor. A relay is a node that serves as an information forwarder and a communication link between two users that wish to improve their link signal-to-noise ratio (SNR) by utilizing the multipath relay channel. Cooperative relaying was first utilized in a spectrum sharing sense for a multi-hop network [29]-[32], to improve both the spectrum utility efficiency as well as the end-to-end throughput between the nodes. The space-time diversity introduced by relaying allows large networks to minimize delay, power consumption and the overall link errors per transmission link. Though it is clear how it serves to benefit SU networks, cooperative relaying only became favorable in a PU setting with the introduction of cooperative CR networks. The proposal was that an SU could serve as

a relay to a PU, boosting its link throughput and effectively minimizing the bit errors over a two-phase relay transmission. From the SU standpoint, coding at the relay could allow the SU to superimpose its own transmission signal atop the received PU signal, thus effectively sharing the spectrum resource. The first papers to highlight such a model were [33] [34]. More recent applications in this area, see the implementation of energy harvesting networks [35] that incorporate reinforced learning techniques at the CR relay, to minimize energy consumption while maximizing its own payoff. Other work in [36] suggest beamforming at the cognitive relay to separate out the PU and SUs signals, effectively not compromising the PU QOS. This idea of cross-tier cooperative cognitive relaying has resulted in significant increase in throughput and reduction in bit errors for the licensee, which qualifies it as step towards effective PU-SU hybrid networks.

Research Gap I: The idea that cooperative cognitive relays brought was the idea of a true hybrid network, where users can share the same resource while both benefiting from it. With research done in the spectrum trading space, it was only a natural connection, to propose a spectrum trading idea that involved relaying as well. Spectrum trading literature has more often than not, been seen from the standpoint of SU networks with very little attention to the economic sense it makes for a licensee to be involved. The problem we wished to address was a spectrum trading model that prioritized licensee payoff, both in link QOS as well as monetary returns, and one that incorporated all possible avenues for cooperative involvement with an SU network. This includes OSA, simultaneous spectrum sharing, as well as the opportunity for cooperative relaying. This hybrid underlay and overlay model poses some challenges for networks being able to switch dynamically between these spectrum opportunities but the expected returns from this cooperative exchange far outweigh these challenges.

2.2 Cognitive Resource-Sharing from a Military Perspective

Unlike the commercial sector, what matters most for military communications is transmission efficiency with regards to time and security. But what these different sectors do share, is a common goal to utilize the available spectrum efficiently. In terms of the spectrum licensed purely for military communications, each country's spectrum allocation differs based on the ruling of the governing spectrum body. But for the most part military communication occurs at the lower end of the frequency spectrum (3KHz-300KHz, 300KHz-3MHz), given the large distance that can be covered with minimum attenuation. However, as evidence from spectrum allocation charts [37] [38], these are licensed with priority for maritime radio communication. Military land communication would have to share these bands in the event of a national emergency. From a national security standpoint, crucial military communication should not be limited by bandwidth. The role CR can play in this is to provide a platform for secure resource sharing such that the entire available frequency spectrum is at the disposal of the military as and when needed. One means of accessing this spectrum was provided through CR relaying.

The idea of cognitive cooperative relaying was discussed earlier from a commercial standpoint with the goal of throughput maximization and licensee incentivization in Section 2.1. But to military communications, a relay serves as an alternate path or a space-time diversity for an end-to-end link. The kind of relay used also speaks of its purpose. Amplify-and-forward (AF) relays are simplest in implementation but propagate channel fading and noise through the process of relaying. Its application is more suitable for commercial cross-tier networks where CRs do not need to decode PU data but just support the primary link. However, decode-and-forward (DF) and compress-and-forward (CF) relay applications are seen for same-tier networks when perfect signal reconstruction

is necessary. Correspondingly these relaying schemes demonstrate higher sensitivity to BERs [39], while increasing the processing needed at the relay for the decoding and re-encoding the received signal before forwarding. Authors in [40] discuss a re-modulation option at the DF relay whose signal constellation can vary to accommodate for fading in the forward channel, such that the end-to-end throughput is maximized. On the other hand, work done in [41] focuses on the appropriate relaying strategy (AF/DF/CF) given the energy harvested for a two-way relay channel. The throughput of this network is controlled and maximized by varying the relaying strategy to adapt to the dynamic channel environment. Other interesting work that aims to further improve the network throughput can be seen in the implementation of buffer-aided relays [42] that can store data and transmit at a later stage. With knowledge of the transmission channel, the relay here can take advantage of the time-variance of the channel to best determine when to send the received data, maximizing the effective network throughput. It is clear that throughput maximization is so often the objective for relay networks. However, the authors in [43] propose an anti-jamming approach to prevent eavesdroppers from compromising relayed data. By utilizing other relay nodes to intentionally increase the noise floor of the eavesdropper, this scheme proves beneficial to information-sensitive military applications where relays are necessary.

Generally speaking, the majority of research done in this area falls under assisted-relay research, where the relay is seen as an added gain to an already existing communication link. But what if the relay channel was the only means for communication. In a battlefield scenario, it is likely that military communication suffers from non-LOS events, whether it is due to deep fading, unfavourable terrain or intentional signal jamming. Therefore, traditional frame retransmission or power adaptation to boost the link QOS is futile for such environments. Here, relaying is seen as the only means to re-establish communication between two incommunicable stranded military nodes in the field. The

application of relays in this sense however must be time-efficient, given the imminent nature of battle. For half-duplex relay networks, the time-scheduled nature of transmissions determine the exigency with which the stranded nodes can communicate via the relay. Coding at the relay in the form of analog network coding (ANC) [44] and physical-layer network coding (PNC) [45] were introduced to address the time inefficiencies of a traditional half-duplex setup. While the traditional half-duplex setup takes 4 timeslots for a two-way relay channel, ANC allows the relay to combine the received signals for broadcast forwarding to effectively transmit the same information in 3 timeslots. This combining is generally done through an XOR (Exclusive or) process, for simple self-decoding at the individual nodes. PNC on the other hand involves two broadcast phases, one where the nodes simultaneously transmit to the relay, and a second for the relay broadcast, effectively halving the transmission time as compared to the traditional setup. This mixing of the electromagnetic waves at the physical layer is possible through intelligent mapping at the relay with a pre-established codebook. The application of PNC to relays, though only recent, has already seen significant progress from work carried out by the research community. We see simulations for practical fading channels in [46] [47] that demonstrate the achievable BER and sum rate of the PNC relay setup. To further improve the BER performance, channel-coded PNC has been proposed by the authors in [48] at negligible complexity cost. Other practical implementations for PNC relays are in the area of asynchronous PNC. For out-of-sync PNC transmission frames, channel and time delay estimation are crucial, and the work in [49], demonstrates how prefix and suffix training sequences can be used to maintain frame synchronization. Orthogonal frequency division multiplexing (OFDM) has also found its way into PNC relays (commonly called FPNC) [50], given the natural properties the OFDM possesses in countering synchronicity issues. The same authors have extended their work to include belief propagation and channel-coding over an FPNC relay model in [51]. Overall, PNC has been well received

by the military communication sector, given the time-conscious nature of this approach for a pure relay network.

Research Gap II: The idea for pure relays with time-efficient coding (ANC or PNC) have presented military communications with a solution for non-LOS issues. However, the practicality of having a single relay node for every pair of stranded military users is debatable. With the heavy processing needed at the relay, one can imagine that it would be capable of carrying out simultaneous communication or reporting functions. The idea to emulate the concept of network coding for a partial relay that has the ability to maintain its own communication link, is more befitting, given the resources spent on military grade equipment. This bridges the conceptual design of cross-tier cooperative relays that support PU channels while benefiting from access to the spectrum resource, with military cognitive relays that operate within the same network.

Other means of utilizing the spectrum resource other than relaying would be through spectrum sharing or OSA. These two modes however operate independently on spectrum and are associated with different network topologies. Spectrum access is an overlay network topology that functions on unutilized spectrum, while spectrum sharing networks are an underlay design, sharing underutilized spectrum. The majority of CR research spanning spectrum access and spectrum sharing techniques, involve either minimizing interference or maximizing network rate, and in some cases a joint optimization of these two goals. For OSA opportunities, the interference is dealt with by avoiding a clash with the spectrum owner entirely. This allows the SU to access the entire spectrum resource during spatial or temporal periods of spectrum inactivity. Correspondingly, the achievable throughput for this mode of operation is significantly high, given that the SUs can transmit with maximum power. However, the downside of having to constantly sense for spectrum activity results in choppy or intermittent transmission which significantly

impairs the QOS for the link. IEEE 802.22 standard for wireless regional access networks mandates a sensing interval of two seconds. To mitigate this problem, dynamic frequency hopping (DFH) with simultaneous sensing and data transmissions (SSDT) were suggested in [52]. Here, with two antennas the SU can simultaneously transmit while sensing the frequency spectrum for available spectrum holes to jump to, prior to the return of the PU to the in-use frequency band. This works well for a single SU but in a network of competing SUs, there can be even more collisions. DH is a solution proposed by authors in [53], where each SU has a dedicated transmission frequency and a vacant working frequency that it can switch to in the event of a collision. However, this approach requires synchronization between the SUs for a time-slotted spectrum access design, which requires centralized control. On the other hand, spectrum sharing which is a interference-tolerable transmission opportunity, requires the SUs to maintain their cross-interference below a certain peak or frame-averaged interference limit [11] to avoid undue interference to the ongoing PU communication. Therefore, these interference limits serve as constraints to the maximum transmission power for these SUs, affecting the achievable throughput for the network [54]. This can be seen in [55] [56], where the authors optimize the power allocation strategy to maximize the ergodic capacity of the network while maintaining the average transmit and interference power constraints put in place. However, this reverts back to centralized design with full knowledge of all the transmission channels in the network. More often than not, these luxuries are not afforded to SUs, especially those deployed for ad-hoc purposes.

2.2.1 Non-cooperative and Decentralized Network Applications

Distributed or decentralized designs put the processing power into the hands of the individual SU. The decision-making process therefore involves aspects of sensing, learning and in some cases cooperation to fulfil the optimization goals. Both OSA and spec-

trum sharing lend themselves well to decentralized networks and in some instances non-cooperative strategies as well. We see that a distributed approach OSA opportunities in the form of distributed frequency assignment (DFA) in [53]. Here, SUs cooperate by broadcasting their current operating frequencies, such that each SU in the network can observe each neighbouring node's allocation pattern before making appropriate frequency assignment decisions. This cooperative control helps in minimizing collisions and improving the overall QOS for the network.

In spectrum sharing research we see power allocation is key, both with respect to the dynamic fading channel in maximizing the network capacity, as well as in mitigating interference to other users. Prior centralized designs focused on offline power allocation strategies to maximize the ergodic capacity of the network. One such scheme is the traditional water-filling power assignment [57] that inversely relates the power adaptation to the channel power gain to effectively fill the capacity of the channel. However, as pointed out by the authors in [58], mobility and fading in communication networks can cause the channel conditions and user QOS requirements to vary arbitrarily over time, requiring the system to adapt its power configuration. For such dynamic networks, the FoschiniMiljanic power control scheme proposed in [58], allows the SU to anticipate and adapt to changes on the fly, based on an online optimization methodology that outperforms previous fixed transmit profile strategies. Other notable work on distributed power control is the GADIA scheme (greedy asynchronous distributed interference avoidance algorithm) [59] where interference mitigation as the optimization objective allows the network to match the performance of a centralized allocation strategy. Inspired by the GADIA algorithm, the authors in [60] demonstrate how building the power control strategy around rate maximization can outperform both water-filling and GADIA approaches in a sparse network, while matching the counterparts' achievable rate performance for a dense network setting. Work in queuing theory [61] has also crossed paths with distributed power

control by observing that a network's throughput is determined by its weakest channel link. By decoupling the optimization problem into local subproblems, scheduling, and spectrum allocation can be carried out in a distributed and scalable manner for fast convergence. Another area that ties spectrum sharing and spectrum trading together is the implementation of game theory models for distributed power control [62]. These models focus on joint optimization of PU and SU payoffs with a cooperative Stackelberg game. Moreover, work in [63] demonstrates how distributed interference alignment is possible in a cooperative game, where no one user can unilaterally gain by changing the strategy in achieving the Stackelberg equilibrium.

However all these models require information in one sense or the other, whether it be through cooperative knowledge regarding transmission and power control strategies of the PU or other SUs, or in channel knowledge for the PU-SU cross-links or interfering SU co-channels in the networks. As highlighted earlier, stranded military users that do not have access to this information, cannot utilize any of these model for power control or spectrum allocation. Though a lot of work has been carried out for blind channel estimation [64]-[67], there is little to no work on non-cooperative distributed optimization for hybrid networks. Much of the information that an SU can derive from a non-cooperative network is through sensing. Spectrum sensing provides not just spectrum utility information but interference signatures of other users transmitting in the network. When sensing the forward PU link, distributed spectrum sensing [68] [69] provides information regarding spectrum activity but does not contribute towards informed power control decisions for the SU. On the contrary, some papers have discussed how sensing the PU feedback link, can provide more information for spectrum sharing SUs. The idea of sensing PU feedback was previously used in a channel estimation sense [67] and to improve PU detection [70]-[72]. However, the authors in [73] demonstrate how distributed power control can be carried out by a network of SUs to assure the PU's QOS by observing this feedback link.

Alternative optimization parameters like PU outage or rate loss constraint (RLC) have also been considered for distributed system setups. As shown in [74], the RLC allows for a significant rate gain for an OFDM-based CR network as compared to the ITC that were previously used for PU protection during spectrum sharing.

Research Gap III: The research work in non-cooperative and distributed networks are scarce for the reason that such networks lack reliable information for the CR to carry out decision-making. Even though exemplary work has been carried out for distributed networks without cooperation [73] [74], these systems are dependent on knowledge of the channel power gain for all communication links in the system. From the perspective of military communications, when purposing to transmit over foreign subspace with a priority to maintain anonymity, or in the event of signal jamming where no access to network information is available, existing schemes for distributed control fail. We refer to this gap in research as network-blind systems. These systems are solely reliant on sensing information to carry out spectrum allocation, power control and distributed decisions in a network, without cooperation or channel knowledge. This requires a higher level of cognitive decision-making that demonstrates the processing power CRs have with just raw statistical data. The applications of network-blind SUs are not solely for military communications but any future ad-hoc deployment of SUs in the commercial space or otherwise that prioritizes learning and individual decision-making to contribute to a network.

We will now look at how these research gaps can be addressed through the work carried out in the following chapters.

Chapter 3

Commercial Cooperative Spectrum Trading Model

Spectrum trading is an area of research that prioritizes PU incentives in a hybrid and cooperative PU-SU network. Prior to spectrum trading, models that were designed for collaborative networks that included one or more spectrally-efficient transmission schemes (spectrum access, spectrum sharing, or relaying) [33] [75], all prioritized interference mitigation to the PU. But from a practical standpoint, the PU has nothing to gain from this exchange. Spectrum trading thus fills the gap in facilitating incentivized PU involvement, by allowing the PU to charge a spectrum fee for its shared resources. The general spectrum trading model features one PU with a network of competing or collaborative SUs that wish to engage the unutilized or underutilized spectrum opportunities of the PU, in exchange for a cost. As highlighted in Chapter 2, most work in spectrum trading follow either economic models or game theory models, with the focus of optimization on the throughput of the SU network. The gap in research in the field of spectrum trading, is one which can maximize the returns to the PU, providing incentive for participation, and allowing the SU to decide if it sees positive utility in engaging these spectrum resources. In this chapter, we design our spectrum trading scheme on an

economic demand and supply model that awards the highest bidder with the opportunity for transmission. Moreover, our work stands apart from other literature in that, spectrum trading has been carried out for a hybrid network topology. This allows cooperative exchange between the PU and SU, regardless of the state of the PU link, i.e. strong or poor, busy or idle. Prior work in spectrum trading, considers only one avenue for transmission, either OSA, spectrum sharing or relaying. Though, the idea of a system that can switch between these three modes of operation, depending on the channel conditions, is a new concept, we wish to highlight through our work, the implications it can have on the average achievable rate of the SU network and PU spectrum utility efficiency.

3.1 System Description

The spectrum trading system model that we consider, consists of one PU and k SU transmitter-receiver pairs, with the channels between the respective nodes following flat slow Rayleigh fading. The transmitter-receiver pairs for the PU are referred to as PT-PR, and for the SU as ST-SR, for short. In this work, we consider a closed-access network, where the number of SUs, i.e. k , does not change. The reasoning behind this decision and the implications if this model is considered for an open access network, are discussed later in Section 3.1.4. As seen in the system setup in Fig. 3.1, the channel gain between the PT and PR is denoted by h_p , between the k ST and SR pairs, by h_{si} , and the cross-channels between PU and the k SUs, by h_{1i} , h_{2i} , and h_{3i} , for $i \in [1, k]$. The corresponding power gains for these channels are given by $\gamma_j = |h_j|^2$, where $j = \{p, si, 1i, 2i, 3i\}$.

The goal here, is to establish a protocol that allows the PU to interact with the network of k SUs, and determine the optimized spectrum costs that can maximize its payoff. The payoff of the PU is determined by its overall rate, and cost accorded it, from leasing its spectrum. The protocol is designed to work with every state of the licensed link, with opportunities for OSA and relaying in a poor channel, and spectrum

sharing when the channel is strong. These modes of operation will be further elaborated in Section 3.2. We will begin by investigating how the protocol is initiated.

3.1.1 Handshaking

The proposed protocol is initiated when the PU receives a Request To Access (RTA) message, sent out by any of the k SUs, as an indication that it wishes to trade resources to gain a transmission opportunity over licensed spectrum. The proposal of incentivized collaboration is then at the discretion of the PU, who can accept or reject this message. If the PU chooses to collaborate, then the PR can respond to this request with either of two messages: Request To Relay (RTR) or Permit To Share (PTS), based on its current channel condition. If the PR surpasses the instantaneous target rate for the underlying fading channel, and can accommodate additional interference from simultaneous SU transmissions, it uses this opportunity to lease this additional resource for a revenue stream. It does this by sending a PTS message to its PT, that acknowledges it by broadcasting a Confirm To Share (CTS) message to the SUs. This scenario can then be defined as the Sharing Mode, where the licensed link supports simultaneous PU and SU transmissions.

On the other hand, if the PU is in outage (i.e. a frame outage; where it cannot meet the target rate for the current transmission frame), and needs the relay support of an SU, the PR can inform the PT through a RTR message. This request is then backed up by an Acknowledgement To Relay (ATR) message broadcast by the PT to the SU network. On receiving the RTR and ATR messages, the respective SU can determine if it can support the PU transmission, in preventing outage for the current channel realization. It does this by verifying if an α_i percentage of its power (less than 100%) dedicated to relaying the PU data, can prevent outage for PU communication. The calculation of this dedicated power percentage α_i , can be seen later in Section 3.2.2. Therefore, if the

Figure 3.1: System Model.

respective ST can support PU communication, it broadcasts a Confirm To Relay (CTR) message. This scenario is defined as the Relaying Mode, and the PT and PR switch to accommodate a two-phase relaying scheme to prevent outage at the PR. In this scheme, the ST receives the PU data in the first phase, which it superimposes with its own signal and then broadcasts this over the next transmission phase to the PR, thus gaining an opportunity to transmit its data over licensed spectrum.

If however, the respective SU is not able to support the PU given its limited transmission power, it broadcasts a Fail To Relay (FTR) message, which informs the PU to stop transmission, and to preserve its power for a better channel. This then implies full spectrum access for that particular SU. This mode is appropriately named the Access Mode, as the given SU can have interference-free access to licensed spectrum. Here, the SU can transmit with maximum power, as the PU ceases to operate. These are all the handshaking messages involved, in establishing which mode of operation the PU is willing to lease its spectrum, and if the respective SU sees any utility in engaging these resources. So the question to answer now is, how is utility measured?

3.1.2 Utility Comparison

Utility or payoff is merely a term implying positive benefit or gain derived from an exchange. In spectrum trading, the PU is given incentives to lease spectrum, through payment of a spectrum cost. Each mode of operation has its own unique cost, optimized to maximize the PU's returns. Therefore, if the rate the particular SU derives, from utilizing the licensed resource is R , and the cost associated with this spectrum resource is C , the corresponding utility the SU would derive, is $R - C$. However, it is clear that the rate cannot be directly compared to a monetary cost, and therefore, we express this rate as $R = \mathcal{Q} \cdot \mathcal{B} \log_2(1 + SNR)$, where $\mathcal{B}$ represents the bandwidth, and $\mathcal{Q}$, the conversion coefficient, that allows the rate to be equated to a factor of cost. Here, without loss of generality, we make the assumption that both $\mathcal{B}$ and $\mathcal{Q}$ are 1, to represent the rate equations later.

Therefore, in comparing the rate against a particular cost, the given SU would only participate if it derives positive utility from the exchange. Also, the SU could make the decision to choose one scheme of operation over another, say Access Mode over Relaying Mode, given that it derives greater utility from the former. These utility comparisons help the PU determine the demand for a particular mode of operation, and certainly affect the optimized cost values that eventually decide the PU payoff. It is here we see the demand and supply nature of this economic spectrum trading model. To better understand how these handshaking messages and costs are communicated back and forth between the PU and SU network, we will now look at the frame design.

3.1.3 Frame Design

For the handshaking messages to be interpreted correctly, and for the utility comparisons to be made at the respective SUs, channel knowledge is essential. As with any spectrum trading approach, channel estimation is crucial for collaboration. We propose

Figure 3.2: Symbol Frame.

to use a common pilot signal, as part of the pilot sequence in every frame. As depicted in Fig. 3.2, we see that every symbol frame comprises of a pilot sequence, followed by transmission. This pilot sequence forms the overhead for each transmission frame, and must aim to be minimized for maximum transmission throughput. The pilot sequence comprises of the pilot signal, the handshaking message, and a user identifier (ID). The pilot signal has traditionally been used [76] [77] for work that relies on instantaneous channel state information (CSI). Depending on the fading of the channel, the level of computational complexity, and the error threshold, any standard estimator can be used in gauging the CSI; the most common ones being the minimum mean-square-error (MMSE) and least squares (LS) channel estimation techniques [78] [79]. After the pilot signal, the handshaking messages are exchanged between the PU and the k SUs. Here, we notice that only three of the messages (RTA, CTR, FTR) are sent by the SUs, and the remaining messages (RTR, PTS, CTS, ATR) are communicated by the PU. This can easily be digitized to a 2-bit message, with a single bit (0 - PU, 1 - SU) as the ID, as shown in Fig. 3.2. The ID helps a particular SU to ignore broadcast pilot sequences from

other SUs, and only look for the PU pilot sequence. To distinguish between each of the k SUs, the ID could take on more bits (i.e. $\log_2 k$), but as part of our training exercise, this is not a requirement at the PU, as we will see in the following subsection.

3.1.4 Channel Training

Channel training is generally used to make a system more robust to variations in the fading channel, or the surrounding noise. Here, we utilize this opportunity for the PU to also gauge the demand in the network for its spectrum resource. During the initial setup, the training exercise is carried out for a sufficient number of dynamic channel realizations, for the PU to optimize the costs for access, sharing and relaying. These optimized costs are then made public knowledge, for the SUs to make utility comparisons and determine if they wish to collaborate. As mentioned earlier, there is no need for separate IDs for each of the k SUs, as the PU does not need to distinguish between the users, but to ensure if and how many of the k SUs are interested in transmitting at the current price. Optimizing the costs implies that there would be only one interested SU (usually the highest bidder) for a given set of channel realizations. Therefore, ensuring that this is a closed-access network (i.e. a fixed SU network size) is crucial in determining that only one of k SUs will be engaging licensed resources at a given time. On the other hand, if the network follows an open-access topology, the optimized costs would be outdated information if new SUs enter the system after the training phase. In this scenario, the issue is that, for a given cost, there might be two or more SUs that are willing to enter into access, sharing or relaying modes based on this outdated cost information. This would result in unavoidable interference to the PU and reduced overall capacities for the SUs wishing to transmit. From a practical standpoint, if this open-access scheme were to be used, certain considerations must be made: 1) the channels follow slow fading, and 2) the training exercise must be carried out as a function of the coherence time of the

channel. Understandably, for an urban environment and for fast fading channels, only closed-access networks could be considered, and it is why we have adopted this access mechanism.

Alternatively, if the average received SNR of the given SU can be estimated, with closed-form theoretical costs, our simplified analytical model (demonstrated in Section 3.3) could be employed for a closed- or open-access network. We will now describe the formulation involved in our general model, before moving on to the aforementioned analytical model.

3.2 General Model

In this section, we discuss the formulation of the rates involved with each of the three modes of operation, i.e., sharing, relaying, and access, and how PU payoff is calculated. We begin by defining R_d as the instantaneous data rate the PU can support on its channel, in the absence of any collaboration/interference from the SUs. This rate is given by

$$R_d = \log_2 \left(1 + \frac{P_p \cdot \gamma_p}{N_0} \right) \quad (3.1)$$

where P_p is the PU's transmit power and N_0 is the noise variance at the PR. From here on out, we assume unity noise variance (i.e. $N_0 = 1$) for all the noise terms involved. This instantaneous rate, R_d , is compared against a quality target rate, R_t , to determine the different modes in which the PU can lease its spectrum resource to the SUs. We will now look at these different modes of operation.

3.2.1 Sharing Mode

The sharing mode comes into play when R_d , surpasses the quality target rate, R_t , set by the PR. In this case, the PU experiences a surplus gain in terms of its transmission

rate, which it can redirect to accommodating an SU on the same spectrum. In exchange for a spectrum cost, the SU gains an opportunity to transmit simultaneously over the same PU spectrum, within a margin of interference. The corresponding PU rate would now be

$$R_p^s = \log_2 \left(1 + \frac{P_p \cdot \gamma_p}{P_s \cdot \gamma_{3i} + 1} \right). \quad (3.2)$$

Here, P_s , is representative of the all the SU's transmit power, which for simplicity, has been considered equal across all SUs in the network. Now, this instantaneous PU sharing rate, must be maintained to the target quality rate, R_t , implying that P_s , must be limited by a power constraint, P_{ci} , to protect the PU from undesired interference. This can be calculated through the PIP constraint made public by the PU. This PIP constraint, denoted by $\mathcal{V}$, is necessary to guarantee a cross-interference lower than the acceptable margin for an outage-free PU. It follows that

$$\mathcal{V} = \left[\frac{P_p \cdot \gamma_p}{2^{R_t} - 1} - 1 \right]^+ \quad (3.3)$$

$$P_{ci} = \frac{\mathcal{V}}{\gamma_{3i}} \quad (3.4)$$

where $[x]^+$ is the positive-semidefinite, which is equal to x when $x > 0$, and equal to 0 otherwise.

The corresponding sharing rate achieved by the i^{th} SU is given by

$$R_{si}^s = \log_2 \left(1 + \frac{P_s \cdot \gamma_{si}}{P_p \cdot \gamma_{2i} + 1} \right) \quad (3.5)$$

where we recollect that the instantaneous transmission power must be limited as

$$P_s = \min(P_{ci}, P) \quad (3.6)$$

where P is the maximum available instantaneous transmission power for all k SUs.

3.2.2 Relaying Mode

Unlike spectrum sharing, the relaying mode is activated, when the instantaneous PU rate drops below the target rate (R_t), and the PU seeks for assistance from an SU in the form of relaying. Here, an SU can gain spectral rights to simultaneously transmit its own message, while helping the PU meet its target rate requirement. The PT and PR adopt a two-phase network with the given ST as a relay point. In the first transmission phase, the PU broadcasts its signal, x_p with power P_p . The signal received at the i^{th} ST and the PR in this first transmission phase can be given by y_{sti} and y_{lr_1} respectively,

$$y_{sti} = \sqrt{P_p} \cdot h_{1i} \cdot x_p + n_1^{sti} \quad (3.7)$$

$$y_{lr_1} = \sqrt{P_p} \cdot h_p \cdot x_p + n_1^{lr} \quad (3.8)$$

where n_1^{sti} and n_1^{lr} represent the additive white Gaussian noise (AWGN) at the i^{th} ST and PR respectively, during the first transmission phase.

With AF relaying, the ST normalizes the received PU signal, and amplifies it with a percentage of its power given by α_i . It then is superimposed with the given ST's signal, x_{si} of power P_s , to be forwarded in the second transmission phase to the PR. This composite signal is given by

$$x_{sti} = \sqrt{\alpha_i \cdot z_i} \cdot y_{sti} + \sqrt{P_s \cdot (1 - \alpha_i)} \cdot x_{si} \quad (3.9)$$

where $z_i = \frac{P_s}{P_p \cdot \gamma_{1i} + 1}$ is the normalization factor. Thus, the signal received at the PR from

the i^{th} SU in the second transmission phase then becomes

$$\begin{aligned}
 y_{lr_2} &= x_{sti} \cdot h_{3i} + n_2^{lr} \\
 &= (\sqrt{P_p \cdot \alpha_i \cdot z_i} \cdot h_{1i} \cdot h_{3i})x_p + (\sqrt{P_s(1-\alpha_i)} \cdot h_{3i})x_{si} \\
 &\quad + \sqrt{\alpha_i \cdot z_i} \cdot h_{3i} \cdot n_1^{sti} + n_2^{lr}
 \end{aligned} \tag{3.10}$$

where n_2^{lr} represents the AWGN at the PR in phase two of transmission.

Therefore, from (3.8) and (3.10), the PU rate for a 2-phase relay system can be written as

$$R_p^r = \frac{1}{2} \log_2 \left(1 + P_p \cdot \gamma_p + \frac{P_p \cdot \gamma_{1i} \cdot \gamma_{3i} \cdot z_i \cdot \alpha_i}{P_s \cdot (1 - \alpha_i) \cdot \gamma_{3i} + \alpha_i \cdot z_i \cdot \gamma_{3i} + 1} \right). \tag{3.11}$$

However, prior to accepting the relay opportunity, the given SU must check to ensure that it can sustain the instantaneous PU rate, R_p^r , to be no less than the target rate R_t . For this to happen, the ST can at most assign 100% (i.e. $\alpha_i = 1$) of its transmission power, acting as a pure relay to the PU in outage. With dynamic channel information made available through the pilot symbols, the given SU can calculate α_i as

$$\alpha_i = \left[\frac{(P_p \cdot \gamma_{1i} + 1)(P_s \cdot \gamma_{3i} + 1)(P_p \cdot \gamma_p - 4^{R_t} + 1)}{P_p \cdot P_s \cdot \gamma_{1i} \cdot \gamma_{3i} \cdot (P_p \cdot \gamma_p - 4^{R_t})} \right]^+. \tag{3.12}$$

During the broadcast of the PU's message to the i^{th} ST, its SR also eavesdrops on the transmitted signal, x_p , as

$$y_{sri_1} = \sqrt{P_p} \cdot h_{2i} \cdot x_p + n_1^{sri} \tag{3.13}$$

where n_1^{sri} is the AWGN at the i^{th} SR for the first transmission phase. With the received

signal, y_{sri_1} , the given SR has a zero-forcing estimate of x_p , given by

$$\tilde{x}_p = x_p + \frac{n_1^{sri}}{\sqrt{P_p} \cdot h_{2i}}. \quad (3.14)$$

The i^{th} SR also receives the composite relayed signal from its ST, during the phase two broadcast transmission, as

$$\begin{aligned} y_{sri_2} &= x_{sti} \cdot h_{si} + n_2^{sri} \\ &= (\sqrt{P_p \cdot \alpha_i \cdot z_i} \cdot h_{1i} \cdot h_{si})x_p + (\sqrt{P_s \cdot (1 - \alpha_i)} \cdot h_{si})x_{si} \\ &\quad + \sqrt{\alpha_i \cdot z_i} \cdot h_{si} \cdot n_1^{sti} + n_2^{sri} \end{aligned} \quad (3.15)$$

where n_2^{sri} is the AWGN at the i^{th} SR for the second transmission phase. With the estimate of x_p from (3.14), the SR can cancel out the PU interference from the received signal to get

$$\begin{aligned} \tilde{y}_{sri_2} &= y_{sri_2} - (\sqrt{P_p \cdot \alpha_i \cdot z_i} \cdot h_{1i} \cdot h_{si})\tilde{x}_p \\ &= (\sqrt{P_s \cdot (1 - \alpha_i)} \cdot h_{si})x_{si} - \frac{\sqrt{\alpha_i \cdot z_i} \cdot h_{1i} \cdot h_{si} \cdot n_1^{sri}}{h_{2i}} \\ &\quad + \sqrt{\alpha_i \cdot z_i} \cdot h_{si} \cdot n_1^{sti} + n_2^{sri}. \end{aligned} \quad (3.16)$$

From (3.16), we can calculate the instantaneous rate for the i^{th} SU in relaying mode as

$$R_{si}^r = \frac{1}{2} \log_2 \left(1 + \frac{P_s(1 - \alpha_i) \cdot \gamma_{2i} \cdot \gamma_{si}}{\alpha_i \cdot z_i(\gamma_{1i} + \gamma_{2i})\gamma_{si} + \gamma_{2i}} \right). \quad (3.17)$$

3.2.3 Access Mode

As we saw in relaying, the given SU can only support the PU in preventing an outage, only if $0 < \alpha_i \leq 1$. For the case where $\alpha_i = 0$ or $\alpha_i > 1$, the SU fails to support PU transmission even as a pure relay. The PU here, will face an outage, and does not benefit

from transmitting. So instead, the PU leases out the spectrum to the given SU on an interference-free basis for a spectrum access cost. We term this opportunity for the SUs as the Access Mode. The maximum achievable rate for the i^{th} SU is given by

$$R_{si}^a = \log_2 (1 + P \cdot \gamma_{si}) . \quad (3.18)$$

3.2.4 Secondary User Rates

With the rate formulations for the three modes of operation above, the average achievable rate of each of k SUs, and consequently of the entire SU network can be computed. However, as we mentioned earlier in Section 3.1.2, the SU will enter into any of these modes of collaboration, only if it derives positive utility from the exchange. To each of the three modes the PU assigns a cost: a sharing cost, C_s , a relaying cost, C_r , and an access cost, C_a . On comparing the achievable rates against the set costs, the SU then makes the decision to collaborate. Also, the case may arise where, even though the SU has sufficient power to support PU communication during relaying (i.e. $\alpha_i \leq 1$), it can choose to access the PU spectrum, by sending a FTR handshaking message, if it derives greater comparative utility in doing so (i.e. $R_{si}^a - C_a > R_{si}^r - C_r$). Thus, this trading of resources becomes an interesting demand and supply model, as only the perfect balance between the spectrum costs, would entertain maximum returns for the PU while satisfying the price that an SU would be willing to pay for its spectrum needs. Thus, the overall average achievable rate over all the SUs in the network, and for all possible

channel realizations, is given by

$$\begin{aligned} \overline{R}_s = & \frac{1}{k} \sum_i \left[\overline{R}_{si}^s \cdot \mathcal{P}(R_d > R_t, R_{si}^s > C_s) \right. \\ & + \overline{R}_{si}^a \cdot \mathcal{P}(R_d < R_t, \alpha_i > 1, R_{si}^a > C_a) \\ & + \overline{R}_{si}^a \cdot \mathcal{P}(R_d < R_t, \alpha_i \leq 1, R_{si}^r - C_r < R_{si}^a - C_a, R_{si}^a > C_a) \\ & \left. + \overline{R}_{si}^r \cdot \mathcal{P}(R_d < R_t, \alpha_i \leq 1, R_{si}^r - C_r \geq R_{si}^a - C_a, R_{si}^r > C_r) \right] \end{aligned} \quad (3.19)$$

where $\mathcal{P}(x)$ defines the probability of event x , and $\overline{R}_{si}^s$, $\overline{R}_{si}^r$, and $\overline{R}_{si}^a$ are the individual average rates of the i^{th} SU described in (3.5), (3.17), and (3.18), respectively.

3.2.5 Licensed User Payoff

The demand and supply trading model discussed thus far, has relied on the probability of the SUs finding utility in a particular PU spectrum resource. These utility measures are key in determining its involvement in trading for PU resources. For illustrative purposes, this is well described in Fig. 3.3. For this trading model, we choose PU payoff as the maximization goal. Contrary to popular spectrum trading papers, where average SU rate or throughput is the considered optimization parameter, we believe that since the PU is the one leasing out its spectrum resource, it must be the recipient of maximum gain from this exchange. The challenge here, is in optimizing the spectrum costs (C_s , C_r , C_a), to ensure maximum PU payoff while maintaining a demand (from the SUs) for the spectrum resource. The training for costs allows us to find the optimal tipping point, where there exists one of k SUs willing to engage in sharing, relaying or access for a particular channel realization. The corresponding PU payoff averaged over all possible channel realizations would then represent the probability that the SU enters the sharing, relaying or access modes, awarding the PU payoff in terms of a spectrum cost and/or

Figure 3.3: Flowchart of Operations.

rate. The PU payoff is given by

$$\begin{aligned}
 U = & \mathcal{P}(R_d > R_t, R_{si}^s > C_s) \cdot (R_t + C_s) + \mathcal{P}(R_d < R_t, \alpha_i > 1, R_{si}^a > C_a) \cdot C_a \\
 & + \mathcal{P}(R_d < R_t, \alpha_i \leq 1, R_{si}^r - C_r < R_{si}^a - C_a, R_{si}^a > C_a) \cdot C_a \\
 & + \mathcal{P}(R_d < R_t, \alpha_i \leq 1, R_{si}^r - C_r \geq R_{si}^a - C_a, R_{si}^r > C_r) \cdot (R_t + C_r). \quad (3.20)
 \end{aligned}$$

The first probabilistic event in (3.20) corresponds to a spectrum sharing agreement, where the PU transmits at the target rate, and offers sharing rights to the SU in exchange for

the spectrum cost, C_s . While both the second and third probabilistic events in (3.20) represents a spectrum access agreement, the difference is that the former represents a situation where the SU cannot serve as a relay to the PU (because of power restrictions, $\alpha_i > 1$) and sends an FTR message to the PU, which then terminates its transmission to make way for SU spectrum access. On the other hand, the latter is the case where the SU derives greater utility from accessing rather than relaying the PU data, and requests for spectrum access in exchange for the spectrum cost, C_a . The final probabilistic event corresponds to a SU relaying PU data so as to meet the target rate, R_t , while superimposing its own message for transmission. Here, neither power restrictions, nor the lure of greater utility in the form of spectrum access, stop the SU from entering into a relay agreement with the PU in exchange for the cost, C_r . We now will look at achieving closed-form results for these costs with our analytical model in the following section.

3.3 Analytical Model

In this section, we attempt to provide closed-form solutions for the different spectrum costs involved in maximizing the PU payoff. We propose an amendment to the general model to help create exclusivity between the modes of collaboration, in arriving at these optimized costs. This analytical model makes the assumption that the PT and the k SRs are geographically separated, and cannot interfere with each other. This implies that with no direct link between them, the given SR cannot overhear the PU's message in the first phase of transmissions during relaying (3.13). Therefore, it also cannot cancel out the PU's signal (3.14) from the superimposed composite message it receives from its ST. This would mean that the SU rate during relaying would be negligible, and it would not derive utility from this mode of operation. Eliminating relaying as an option for collaboration, would then leave only two modes of operation, i.e. sharing and access. The PU would entertain interference from the given SU, when it has a surplus instantaneous rate above

the expected target rate R_t , in the form of spectrum sharing, and would alternatively lease out its spectrum to the SU, when in outage.

Therefore, by maximizing the PU payoff as a result of spectrum sharing and access alone, we can find the optimal theoretical costs that can be preset by the PU, and made available to the SUs that wish to collaborate. The updated instantaneous rate of the i^{th} SU in the sharing mode is given by

$$R_{si}^{s'} = \log_2(1 + P_s \cdot \gamma_{si}). \quad (3.21)$$

The corresponding average PU payoff can now be updated as

$$U' = \mathcal{P}(R_d > R_t, R_{si}^{s'} > C_s) \cdot (R_t + C_s) + \mathcal{P}(R_d < R_t, R_{si}^a > C_a) \cdot C_a. \quad (3.22)$$

This can also be expressed as

$$U' = \exp\left(-\frac{2^{R_t} - 1}{SNR_p}\right) \cdot \frac{\mathcal{V}}{2^{C_s} + \mathcal{V} - 1} \cdot (R_t + C_s) + \left(1 - \exp\left(-\frac{2^{R_t} - 1}{SNR_p}\right)\right) \cdot \exp\left(-\frac{2^{C_a} - 1}{SNR_{si}}\right) \cdot C_a \quad (3.23)$$

where SNR_p and SNR_{si} refer to the average SNR of the PU link (h_p), and the i^{th} SU link (h_{si}), respectively. Given the exclusivity of access and sharing modes, the corresponding closed form solution for sharing and access costs are

$$C_s^* = \mathcal{I} \left[\frac{\mathcal{W}\left(\frac{2^{R_t}(\mathcal{V}-1)}{e}\right) - \ln 2 \cdot R_t + 1}{\ln 2} \right] \quad (3.24)$$

$$C_a^* = \frac{\mathcal{W}(SNR_{si})}{\ln 2} \quad (3.25)$$

where $\mathcal{W}$ is the product log function [80] [81], which is the inverse function of $f(\mathcal{W}) = \mathcal{W} \cdot \exp(\mathcal{W})$, and the indicator function $\mathcal{I}[x] = x; x \geq 0$, otherwise the optimal cost does

not exist and sharing cannot take place. A detailed derivation of the optimal costs, and the discussion of their optimality can be found in Appendix A.

The optimized PU payoff for both the analytical and general models are compared and analyzed in the following results section.

3.4 Numerical Results

In this section, we plot the numerical results for the analytical and the general spectrum trading model, to demonstrate the achievable gains for the PU and SU network. For the simulations, we have assigned the transmission powers of the PU and the k SUs to be 10 dBW and 20 dBW, respectively (i.e. $P_p=10$ dBW, $P_s=20$ dBW), and the instantaneous target rate for the PU, R_t , to be 1 bps/Hz, unless otherwise specified.

We begin by corroborating the theoretically optimized closed-form results, obtained through our analytical model in Section 3.3, against simulations run for the same model, in plotting the PU payoff. We see in Fig. 3.4, the variation in the PU payoff against its own transmission power, being representative of the mode of operation, namely sharing or access. At lower PU transmission powers, when the PU is in outage, the PU payoff remains unchanged. It is here that the probability of the given SU entering into access mode is high, but with the SU power fixed, there will be no increase in its achievable rate. Therefore, to maintain demand for this spectrum leasing opportunity, the PU cannot increase the associated cost, and consequently the PU payoff remains the same. After a certain point, we see a drop in PU payoff, which represents the phasing out of the access opportunities. With more power available for its own transmission, the PU becomes self-sufficient, and we see a greater probability of spectrum sharing opportunities come into play. The SU power though fixed (i.e 20 dBW), is still limited by a PIP constraint, determined by $\mathcal{V}$ (in (3.3)), and therefore the increase in PU payoff with further increase in PU transmission power, can be credited to the higher interference tolerance for spectrum

Figure 3.4: PU payoff versus available PU transmission power for the Analytical Model.

sharing in the form of the PIP constraint. After a point however, the PU payoff will again saturate, when the given SU reaches its available transmission power limit. The higher transmission powers considered in this and the following graphs in the Thesis are an illustration of the relationship between the variables potted on each axis. Though acceptable transmission power limits should be within 30 dBW, these graphs serve to demonstrate the interaction at different levels of the SNR regime.

We know that when the power available for SU transmission increases, so does its achievable rate (3.19). This allows the PU to set a higher cost for the particular spectrum opportunity, leading to an increase in the PU's payoff, as seen in Fig. 3.5. Here, we see a comparison made between the average PU payoff for the general and analytical models, with varying target rate requirements for the PU. For a lower target rate (like 1 bps/Hz), the PU is for the most part, self-sufficient, allowing the given SU to share its spectrum within the acceptable margin of interference. This constraint on the SU's power causes

Figure 3.5: PU payoff comparison against SU transmission power.

the PU's payoff to saturate for lower target rates, as evident from the graph. We notice a small deviation between the analytical and general models here, because on the off-chance that the PU cannot meet its target rate, the relaying and access modes come into play. However, with no relay mode available in our analytical model, the given SU has the opportunity to lease the PU's spectrum for interference-free transmission, and enjoys a higher achievable rate. This influences the optimized costs, and conversely the overall payoff to the PU. This trend is noticed even at higher target rates, where the analytical model presents interference-free transmission opportunities to the SU in the form of spectrum access, that translates to greater monetary return for the PU, as well as higher achievable SU rate. Though this might seem like the general model is not beneficial to either PU or SU, that is far from the truth, as relaying allows the PU's transmission to be more reliable, with fewer outages over the fading channel, when the given SU steps in as a relay.

Figure 3.6: PU payoff comparison against PU transmission power.

We now look at the comparison of the general and analytical models, for the change in their PU payoffs against an increase in the available PU transmission power in Fig. 3.6. The trend of a declining PU payoff with increasing PU transmission power, brings us to the conclusion that self-sufficiency for the PU, or the lack of collaboration with the SUs thereof, works against the idea of spectrum trading, thus limiting the payoff generated as a result. The non-uniform decline across the range of target rates, can be attributed to the different modes of operation with their corresponding costs, coming into play. But after a specific threshold value of the PU transmit power, all the payoff curves for the general model drop to a point of null PU payoff, indicating a lack of positive utility for SU participation. We also observe the points of similarity in the graph for the analytical and general models. We know that with no link between the PT and the k SRs in the analytical model, there would be no cross-interference, and hence this would liken it to the case where insignificant levels of interference are experienced in the general model.

Figure 3.7: SU Rate comparison against access and sharing protocols.

This can be observed at smaller PU transmission powers (given the target rate), where the payoff curves of the two models match up. Also, when the target rate set at the PU is very high, only access opportunities are available to the SUs, and therefore we see the similarity in the PU payoffs for the target rate of 15 bps/Hz.

Thus far, we have focused our attention on the gains the PU would derive from this collaborative exchange by sharing its resources. The SU network involved also benefits greatly through increased spectrum transmission opportunities and significant rate gains for its users. Given the utility comparisons made by each of the k SUs, the assignment of spectrum costs is optimized to meet the demand for the given spectrum resource. The average achievable rate for the SU network, as defined in (3.19), is plotted in Fig. 3.7. We first observe the change in the average SU rate for changing levels of PU transmission power for our spectrum trading scheme. As the PU transmission power increases, we notice a drop in the achievable rate for the SU. As described earlier in Fig. 3.6, with

more power available for its transmission, the PU is self-sufficient, and there would be fewer opportunities for collaboration with the SUs. Therefore, this lack of transmission opportunities for the SU translates to an overall reduction in its achievable rate. More importantly, in this graph, we make a comparison between the rate gains achieved through our general spectrum trading model, with an example of OSA or spectrum sharing applied to a spectrum trading environment. The achievable rates for OSA and spectrum sharing can be given by (3.26) and (3.27) respectively. We can express them as

$$\overline{R}_{dsa} = \overline{R}_s^a \cdot \mathcal{P}(R_d < R_t) \quad (3.26)$$

$$\overline{R}_{ss} = \overline{R}_s^s \cdot \mathcal{P}(R_d > R_t) \quad (3.27)$$

where $\overline{R}_s^a$ and $\overline{R}_s^s$ are the average access and sharing rates described in (3.18) and (3.5) respectively.

From Fig. 3.7, we notice that the performance of our spectrum trading scheme is equivalent or better than both the current benchmarks used in spectrum trading literature. The achievable SU rate is higher because our scheme works for all states of the licensed link. We see for a weak PU (-20dBW power), the performance of our scheme is equivalent to the OSA approach to spectrum trading, but significantly outperforms the spectrum sharing technique. Conversely, when spectrum sharing is strong, that is when the PU link is self-sufficient (40dBW power), our scheme shows equal performance, but also outperforms the OSA scheme. Thereby using access, relaying and sharing techniques, we are able to utilize any spectrum opportunity, to maximize the SU network rate.

3.5 Summary

The underlying focus of this chapter is to emphasize the need for a PU incentive-based approach for spectrum trading environments. In this work, we look at a resource-sharing model established between a PU and a network of SUs, for three modes of collaboration, namely, spectrum sharing, spectrum access and relaying. Our model is designed after the demand and supply economics of a trading environment, to optimize the costs for each mode of operation, depending on the need for the spectrum resource. Utility measures implemented at the SU network level, allows each user to identify its need, and indicate their collaboration through handshaking messages embedded in the pilot sequence of each frame. Consequently, the optimized costs can be arrived at numerically through our general model, or theoretically from our analytical model, to demonstrate the achievable payoff gains for the PU. In terms of the PU's perspective, this model improves the overall spectral utility efficiency, and provides monetary returns for leased spectrum. And from an SU's perspective, this scheme allows for increased transmission opportunities and higher rate gains, than previously seen for a spectrum trading model. It is here that we conclude that the idea of a spectrum trading scheme that celebrates collaboration for mutual gain, is realized and achieved through this work.

Chapter 4

Cooperative Relaying Model for In-battle Military Scenario

Military communication relies on robust and secure physical links that adhere to regulatory protocols and standards for communication. In unfamiliar terrain or hostile conditions these physical links can undergo deep-fading or intentional signal jamming, deteriorating the ongoing communication. Relaying has been sought as the solution to stranded military communication nodes. However, given the exigency related to in-battle military communications, the latency with relaying cannot be tolerated and designing a scheme that is time-efficient is crucial. ANC and PNC [44] [45] have become popular in network coding research for a half-duplex relay design, given the significant advantage it brings in terms of throughput and particularly time-efficiency. However, the application of these network coding schemes have not been seen in a military setting, and therefore we must look at a different approach in handling these latency issues. Being inspired by the broadcast nature of these network coding schemes, we propose a broadcast relaying protocol that utilizes a ZFE and STBC at the relay, to handle all the processing strain in establishing bi-directional communication between the stranded users. Moreover, given the practical considerations that need to be taken for a military protocol, the assumption

that a specific military unit must act as a dedicated relay to all stranded military users in the field is unrealistic, particularly given the time and money spent on the state-of-the-art communication technology. The gap in research we wish to answer is the design of a partial-relay support protocol, wherein the relay node can maintain its ongoing communication with its own receiver, while assisting the stranded military nodes. Given that this relay node must also be mobile and present in the vicinity of the stranded users, our protocol allows any military infantry vehicle to take up this support role, while still communicating with its end user. The significance of this approach can be visualized in that 3 way bi-directional communication can be achieved through the relay in 4 timeslots, just one more than if all the direct communication links were present. More importantly the BERs achievable through this implementation show improvement over the direct links at high SNRs and comparable performance over the rest of the observed SNR regime. The proposed methodology, system setup and performance measures can be seen in the sections to follow.

4.1 System Model

Consider a pair of transceiver nodes A and B that take the role of the stranded military units in the field, and a single relay node R and its receiver pair C. For the first part of this setup, we establish that the link between R and C only allows single way reporting, where the node C can be visualized as a reporting station receiving updates from the military units in the field. For the purposes of implementing ZFE and STBC at the relay, we need to incorporate two antennas at the relay node. All the communication channels here, are designed to follow slow Rayleigh fading with AWGN at the receivers. The respective communication channels between the nodes (A,B,C) and the relay R can be denoted by $h_a^1, h_a^2, h_b^1, h_b^2, h_c^1$, and h_c^2 , with the superscript specifying antenna 1 or 2 on the relay.

As demonstrated in Fig. 4.1, the first phase of transmissions are by A and B, simultaneously sending their messages to the relay node R. The corresponding first phase signal reception at the two antennas of the relay are,

$$y_r^1 = \sqrt{p} \cdot h_a^1 \cdot x_a + \sqrt{p} \cdot h_b^1 \cdot x_b + n_r \quad (4.1)$$

$$y_r^2 = \sqrt{p} \cdot h_a^2 \cdot x_a + \sqrt{p} \cdot h_b^2 \cdot x_b + n_r \quad (4.2)$$

where p is the transmit power of all the nodes (A,B,C,R), x_a and x_b are the modulated messages of nodes A and B respectively, and n_r is the AWGN at the relay node. With the diversity provided through the additional antenna at the relay, the simultaneously transmitted signals can be separated out and equalized to be void of any channel impairments. This is possible through a ZFE [82] implemented at the relay. Here, the channel semi-positive definite matrix $H^+ = (H^H H)^{-1} H^H$ is used where $H = \begin{bmatrix} h_a^1 & h_b^2 \\ h_a^2 & h_b^1 \end{bmatrix}$ from (4.1) and (4.2). The noisy demodulated signals are then XORed ($\tilde{s}_a \oplus \tilde{s}_b$) and remodulated to form a composite message x_{ab} , to be sent out by the relay in the second timeslot. The relay also has its own signal to transmit, x_c . The power distributed between x_{ab} and x_c is determined by a metric α . α is representative of the power assigned to relaying A and B's information, while the remaining power $(1 - \alpha)$ is allocated to the relay's own transmission. Considering the need for high quality time-efficient relaying for military communication, STBC comes into play here.

STBC first introduced by Alamouti in [83], was seen as a means to reduce outage with the diversity provided through a secondary antenna for transmission. Generally, the same symbols of the users message were retransmitted in their complex conjugate form to devise a matrix that counters the effect of the channel, resulting in clean received information. However, we implement STBC with the purpose of efficacy and urgency in

Figure 4.1: System Model.

Figure 4.2: STBC at relay.

relaying the communication signals. In this approach, the first symbols from two different messages (i.e. x_{ab} and x_c) form the Alamouti matrix, with their complex conjugates, thereby requiring one additional timeslot to completely send both users information, as demonstrated in Fig. 4.2. The received STBC signal matrix at node A is,

$$Y_a = \begin{bmatrix} y_{a1} \\ y_{a2}^* \end{bmatrix} = \begin{bmatrix} h_a^1 & h_a^2 \\ h_a^{2*} & -h_a^{1*} \end{bmatrix} \begin{bmatrix} x_{ab} \cdot \sqrt{\alpha p} \\ x_c \cdot \sqrt{(1-\alpha)p} \end{bmatrix} + \begin{bmatrix} n_{a1} \\ n_{a2}^* \end{bmatrix} \quad (4.3)$$

where y_{a1} and y_{a2} are the signals received in timeslots 1 and 2 respectively at node A, and

n_{a1} and n_{a2} are the independent AWGN as measured at timeslots 1 and 2 at the node A.

The transmitted signal is recovered by multiplying with the semi-positive definite matrix

H^+ , where $H = \begin{bmatrix} h_a^1 & h_a^2 \\ h_a^{2*} & -h_a^{1*} \end{bmatrix}$. The recovered signal matrix at A is,

$$\widetilde{\begin{bmatrix} x_{ab} \\ x_c \end{bmatrix}} = \begin{bmatrix} x_{ab} \cdot \sqrt{\alpha p} \\ x_c \cdot \sqrt{(1-\alpha)p} \end{bmatrix} + \begin{bmatrix} \frac{h_a^{1*} \cdot n_{a1} + h_a^2 \cdot n_{a2}^*}{|h_a^1|^2 + |h_a^2|^2} \\ \frac{h_a^{2*} \cdot n_{a1} - h_a^1 \cdot n_{a2}^*}{|h_a^1|^2 + |h_a^2|^2} \end{bmatrix} \quad (4.4)$$

From this recovered composite message $\widetilde{x_{ab}}$, the node A can XOR its self-information (i.e. x_a) to retrieve an estimate of B's transmitted signal. In similar fashion, each of the nodes can retrieve their intended signals through this relay support. Here, we leverage on the added degree of freedom through the second antenna to complete 2-way bi-directional communication and single way reporting through the relay in 3 timeslots. We thus name this protocol the ‘‘Double Broadcast Relaying’’ (DBR) scheme, as both phases of transmissions are of a broadcast nature.

4.1.1 Cyclic Retransmission Protocol

The model used thus far only allowed single way reporting between the relay node R and its receiver C. However ideally we would assume that the relay and its receiver must function as a transceiver pair exchanging information with each other in the field. This can also be visualized as 3 stranded nodes A, B and C that have no direct means of communication and are dependent on the relay to help exchange their messages. This attempt at bi-directional relaying with more than 2 nodes through network coding has only been carried out by [84], to the best of our knowledge, where the ANC model (or in essence XOR) is employed. Through digital spatial multiplexing, in the form of ZFE and STBC we present a more time-efficient approach to this problem.

We also present a scalable model for this 3-way bi-directional communication through the relay with the help of a cyclic retransmission protocol. As depicted in Fig. 4.3, the nodes A and B begin by simultaneously transmitting their messages to relay node R in the first timeslot. In the second timeslot, nodes B and C do the same. Here, B is the node that retransmits its message. However, with the round robin order, the retransmission responsibility is cyclically distributed among the nodes to account for uniform overall power consumption. The relay node is able to separate out each of the received signals, XOR and remodulate them to form two composite messages x_{ab} and x_{bc} for broadcast transmission. These composite messages are the modulated and XORed versions of the decoded signals that form the STBC matrix at R as shown in Fig. 4.4. The next phase is a relay broadcast that requires two timeslots to send the STBC matrix of signals. As before, each of the 3 nodes can retrieve the intended signals through XORing with their own self-information, in just 4 timeslots (which is one more than if direct communication links were present) with the DBR approach.

4.2 Performance Comparison

In this section, we establish a set of benchmarks that can be used as standards in comparing the performance measures for our DBR scheme. The first and most strict benchmark for comparison is the communication over the direct link. Though the focus of this model is on highly faded or unavailable direct links, this benchmark will give us a good understanding of how far from ideal our stand-in relaying method is. We refer to this direct transmission approach as DT.

We also consider a second benchmark which mimics the implementation of the ANC protocol [84] over the same system setup, by allowing the nodes A and B in Fig. 4.1 to transmit their messages in an un-interfered time scheduled sense. Therefore, the entire process with ZFE and STBC would take an additional timeslot, with the end

Figure 4.3: System Model for 3 node setup.

Figure 4.4: STBC for 3-node relay scenario.

users receiving their intended communication signals in a total of 4 timeslots. Given that the first phase of transmissions from the end users are time-scheduled, and only the relaying phase is of a broadcast nature, we aptly name this benchmark the “Single Broadcast Relaying” (SBR) scheme. Moreover, with 2 antennas at the relay, maximal ratio combining (MRC) can be carried out on the time-scheduled transmissions of A and B, to further improve the BER of the system. As we will see later, MRC allows this SBR model to have an upper hand even over the DT approach for higher SNR regimes.

But to compare our DBR scheme against these benchmarks, we must maintain uni-

form spectral efficiency. With the DT, DBR, and SBR models taking 2, 3 and 4 timeslots respectively, assigning 4-PSK (phase-shift keying), 8-PSK, and 16-PSK as the respective modulation patterns gives us a spectral efficiency of 1, and allows us to compare the BER of each of the schemes on the same playing field. This works fine for the simplified 2-way bi-directional communication with single-way reporting model. However with 3-node bi-directional relaying and further scalable models, SBR loses its efficacy in being time-conscious for urgent in-battle military communication. Its high latency and constellation size that increases with the size of the network, makes it impractical to use. Therefore, our results for the 3-node bi-directional relay scenario only compare DT against our DBR scheme with 8-PSK and 16-PSK modulations, for the 3 and 4 timeslot approaches respectively.

4.3 Simulation Results

In this section, we demonstrate the achievable gains through this time-efficient relaying model for military communications by comparing it against the aforementioned benchmarks. We carry out Monte carlo simulations for 10^5 dynamic channel realizations and varying relay support power (α) for a grouping of 12Kbits with equal power assignment among the nodes, A, B, C, and R. The focus of this chapter is on time-efficiency through relaying and therefore we have assumed that the channel information across the various links is perfect in carrying out ZFE and STBC.

4.3.1 Simplified Setup

We first plot the results for the simplified system model (in Fig. 4.1), where the relay supports 2 node bi-directional communication while maintaining single way reporting to the terminal station C. In Fig. 4.5, we measure the end-to-end BER at node A and

B, for a varying range of SNR, representative of the normalized transmission powers of the nodes (A,B,C,R). Here, we observe that DBR shows comparable performance to the strictest benchmark (DT) across the entire SNR regime, and identical BERs against SBR at lower SNRs. Above 20dB of SNR however, the diversity gain from MRC allows SBR to do better, even surpassing the DT benchmark at the 30dB of SNR. Though SBR shows better overall QOS, it also requires an additional timeslot over DBR for bi-directional relay support. Therefore, the priority for exigency against QOS in a battlefield scenario will be crucial in determining the appropriate coding to be carried out at the relay. From Fig. 4.5, we also note that the performance curve for DBR is unchanged for variation in the relay power support. This result is vital when considering the relay's receiver (node C) performance, as we see in the next graph in Fig. 4.6. Here, DBR as expected outperforms SBR across the board. Moreover, this informs us that DBR allows the relay to allocate more power for its own transmission (to the reporting station C), without affecting the QOS of the stranded nodes A and B.

An important concern brought forward by the research community in implementing network coding designs has been synchronicity between the end nodes (A and B in this case). In fact, a lot of work has been focused on addressing this issue with regard to PNC [51] and ANC [85]. The majority of the work covers timing, phase and frequency synchronization, but have not tackled power asynchronicity. Therefore, we wish to demonstrate that through our DF relaying scheme, power asynchronicity is no longer a concern. In Fig. 4.7, we plot the difference in BER performance for power asynchronous nodes A and B. We see here that when node B's SNR changes with respect to node A, the performance deteriorates but maintains the same BER profile across the entire SNR range. This shift in the threshold points where SBR shows improved performance over DBR and DT, indicate that the spatial multiplexing employed in our model is impervious to the actual asynchronous nature of transmission power but rather is reflective of the performance

Figure 4.5: Average BER comparison for end nodes A and B.

Figure 4.6: Average BER comparison for end node C.

Figure 4.7: Average BER comparison for power asynchronous nodes A and B.

degradation of that of a faded signal, given that the average SNR of A and B is reduced. This can be verified by reversing the scenario, where if B's SNR were to be higher than that of A, we would have improved performance but with shifted threshold points for comparison.

4.3.2 3-Node Relay Model

As addressed earlier, we can extend the simplified model to allow bi-directional communication between the relay and its receiver. In a way this can also be represented as 3-node bi-directional relaying scenario, where each node (A,B,C) is stranded, and relies on relay support to establish communication. The cyclic retransmission protocol that we used (in Section 4.1.1), allows us to visualize the BER performance for DBR against DT for varying SNR regimes. Fig. 4.8 plots this comparative performance, showing that DBR can achieve decent performance compared to the strictest DT benchmark, which

Figure 4.8: Average BER comparison for 3-node case.

is proof that this scheme can be applicable in the case of direct link shutdown (due to fading, outage, or jamming). DBR with the cyclic re-transmission protocol, also requires only an extra timeslot for 3-way bi-directional communication through the relay. Therefore, we believe this protocol has merit particularly in the area of time-efficient relaying which can serve as a backup to ensure secure and reliable military communication links.

4.4 Summary

In military settings, link outages cannot be dealt with in the traditional sense, through re-transmission of erroneous frames or increase in transmission power. With relaying as the most applicable solution, this chapter focuses on achieving time-efficient and reliable communication support to stranded military units in the field. We have demonstrated how the relay can support bi-directional communication with these nodes, while maintaining its own transmission with a receiver. The simplified model was extended to include

3-way relaying through a cyclic retransmission protocol. Our performance curves show that the spatial multiplexing schemes with ZFE and STBC are suitable substitutes that meet the QOS and time-efficient constraints of dire battlefield scenarios. The advantage seen for both relaying approaches (DBR, SBR) however is different and its application will be based on the intended optimization parameter. On one hand, SBR shows improved performance at higher SNR regimes but requires more timeslots for transmission. DBR on the other hand shows comparable performance to the benchmark (DT), requires one less timeslot per frame of transmission (bandwidth-efficient) and allows the relay to retain maximum power for its own transmission without affecting the QOS of the end nodes (power-efficient). Power asynchronicity at the end nodes was also studied and ruled out as a concern with the DF nature of relaying.

Chapter 5

Network-Blind Outage-Constrained CR Setup over Licensed Spectrum

Network-blind systems are those that operate independent of external knowledge, whether that be transmission or power control strategies of the rest of the users, or external communication or interference channel knowledge between the nodes in the network. This extreme exclusion serves two purposes: 1) with few or no assumptions regarding the network setup, these systems can be generalized in its application, and 2) in the event that a user finds itself in such severe channel conditions, it can still carry out spectrum and power allocation while respecting outage and QOS constraints for a distributed sharing system. With such exclusion, the only means of information for a network-blind node is spectrum sensing.

Spectrum sensing has previously been seen as a means of observing spectrum activity, and determining opportunities for SU transmission. Unutilized spectrum in the form of spatial (inactive) or temporal (absent) holes guarantee uninterferred spectrum access rights for the SU, while underutilized spectrum presents opportunities for spectrum sharing. This classification of spectrum transmission opportunities into access or sharing is called hypothesis testing. In hypothesis testing, any sensing result that falls

under an idle PU test case would be classified as a spectrum access opportunity for the SU, and conversely a busy PU hypothesis would correspond with spectrum sharing opportunities. An idle or busy primary link is based entirely on the detection probability, or ideally the activity probability of a PU on its spectrum. It is common therefore to see, spectrum sensing research plots on the probability of PU detection for a range of operating SNRs. However, ensuring a good detection rate does not translate to safety or accuracy in SU transmissions when measuring the interference felt at the PR. Similar concerns are highlighted in the spectrum sharing research space, where ITCs are enforced on SU transmission power, representing the maximum perceived interference that can be accepted at the PU without disrupting its transmission. This also generally involves estimating the cross-channel between the two parties. Therefore, as it stands, the quality of spectrum sensing work for the most part, has been weighed against the results from the front-end statistical sensing data, i.e., the probability of PU detection or false alarms, and the sensing time, for the purposes of SU spectrum access. Conversely, those opportunities that cannot be utilized for spectrum access are classified as busy PU spectrum and are seen as spectrum sharing opportunities, where research work is mainly involved in improving the accuracy of the interference mitigation results at the PR end (or at the back-end). The disconnect between these two transmission opportunities that originate from the same statistical data, is what motivated our work on network-blind systems.

In this chapter, we propose to utilize the statistical sensing data to give an advantage to both spectrum access and spectrum sharing fields, by bringing the back-end PU outage-constraints into the front-end design of the spectrum sensing thresholds that primarily govern spectrum allocation decisions. We thus design two thresholds, and therefore three decision regions for SU spectrum allocation, namely, spectrum access, spectrum sharing, and idle or no transmission opportunity. Consequently, SUs that utilize these thresholds

Figure 5.1: General Topology

while sensing, would automatically be in compliance with outage standards needed to share or access the PU spectrum. The authors in [86] discuss a similar model that utilizes the bandwidth and power allocation for each user as a utility measure for optimization, constrained by certain PU interference constraints. The main distinguishing factor is the assumption of channel knowledge between the nodes and a centralized architecture for spectrum allocation. On the other hand, our work has been developed with decentralized and non-cooperative decision-making in mind, where the statistical sensing data is the only information that is needed for a network-blind SU to make dynamic allocation decisions and power adjustments that consequently determine the SU network rate while guaranteeing PU outage-constraints for spectrum sharing.

5.1 System Description

For this hybrid topology we consider one PU and k SUs in the vicinity of sensing and utilizing this PU's resources. Though it should be understood that each SU will have the ability to sense and utilize the statistical information from all the PUs in its vicinity, and correspondingly make a utility decision as to which spectrum to use. Here, we are interested in understanding the workings of the decision-making algorithm and in optimizing the sensing thresholds to constrain the outage to the PU while achieving the highest utility (or rate) for each SU that transmits on this PU's spectrum. The corresponding transmitter-receiver pairs for the PU and the k SUs, will be referred to as PT-PR, and ST $_i$ -SR $_i$, respectively, where $i \in [1, k]$, as depicted in the general topology in Fig. 5.1. We see that for a general network model (Fig. 5.1(a)), path loss as a function of distance is key in determining the nodes that interfere with each other, represented by the region of interference (ROI). An algorithm for spectrum allocation that is designed after such a model will not effectively represent close-proximity nodes or dense networks. Therefore, for our setup, we consider an equidistant channel model, where $\forall d_k = d$. This then represents the worst-case scenario, where each node will equally interfere with all other nodes in the network. The corresponding results shown later in Section 5.5 are a representation of this strong interference model, and therefore more optimistic results can be expected from a relaxed network model.

The representative channel model in Fig. 5.1(b) depict the channel gains between the PT-PR pair as h_p , between the k ST-SR pairs, by h_{si} , and the cross-channels originating from the PT to the i^{th} ST and SR, as h_{pti} , and h_{pri} , respectively, and similarly those originating from the i^{th} ST to the PR, and other j^{th} STs and SRs, as h_{sip} , h_{stij} , and h_{srij} , respectively for $j \neq i, i \in [1, k]$. We have modelled these channels to follow Rayleigh block-fading with additive Gaussian noise at the receivers. The corresponding channel power gains can be given by $\gamma_m = |h_m|^2$, where $m = \{p, si, pti, pri, sip, stij, srij\}$. The

PU setup we consider, is one which is QOS-constrained and has its own power control to maintain a specified target rate. The focus of our work is in designing the thresholds for sensing, and establishing an adaptive algorithm for the SUs to carry out its own power control and decision making. We will now look at the spectrum sensing threshold design.

5.2 Spectrum Sensing

The importance of spectrum sensing cannot be emphasized enough, as it is the first step towards efficient spectrum utilization decision-making. An error in the sensing result will often be propagated over the phases of spectrum allocation and transmission, and is expected to reflect as a system outage at the PR or a reduced achievable rate for the SU network. Varied approaches for spectrum sensing have been carried out [10] [87] to provide more information regarding the PU activity, based on varying degrees of PU channel or signal information available to the SU. These approaches range from ED to matched filtering, as well as, cyclostationary feature detection, and waveform based sensing. ED is most commonly used in literature given its ease of implementation, and the need for no prior information. Given that the network model we have considered is decentralized and non-cooperative, ED also happens to be the most appropriate sensing detector. The traditional threshold design for an ED depends solely on the number of samples used in sensing and on the noise variance. Given the fading characteristics of the channel, the corresponding probability of detection ($\mathcal{P}_d$, true positives) or false alarm ($\mathcal{P}_f$, false positives) can be calculated as a Q-function of these factors. From [71] [72], we can see that for a PU signal and noise modeled after a circularly symmetric complex Gaussian random variable, we can expect a $\mathcal{P}_d$ and $\mathcal{P}_f$ as follows,

$$\mathcal{P}_d = Q \left(\frac{\lambda_i - (1 + \rho_i) \cdot N_0}{\sqrt{\frac{1}{M}(1 + \rho_i)^2 \cdot N_0^2}} \right) \quad (5.1)$$

$$\mathcal{P}_f = Q \left(\frac{\lambda_i - N_0}{\sqrt{\frac{1}{M} \cdot N_0^2}} \right) \quad (5.2)$$

where, $Q(x)$ is the Q-function, λ_i , the sensing threshold, ρ_i , the received SNR at the i^{th} ST, N_0 , the noise power, and M , the number of samples used for sensing. For a PU transmission power of P_p , the received SNR at ST i can be represented as

$$\rho_i = \frac{P_p \cdot \gamma_{pti}}{N_0}. \quad (5.3)$$

Therefore, conversely we can represent the traditional ED sensing threshold as a function of $\mathcal{P}_d$ by

$$\lambda_i = Q^{-1}(\mathcal{P}_d) \sqrt{\frac{1}{M} (1 + \rho_i)^2 \cdot N_0^2} + (1 + \rho_i) \cdot N_0. \quad (5.4)$$

It is clear to see here, that the sensing threshold will guarantee a certain level of detection for PU activity, and conversely limit the number of missed detections $(1 - \mathcal{P}_d)$. However, we cannot directly equate these missed detections to a PU's outage, which is measured at the receiver-end. Therefore, in designing the threshold, a conservative approach would result in a lower achievable SU rate, while a more lenient threshold will probably result in higher outages seen at the PR. We recognize this gap in spectrum sensing research, in designing sensing thresholds that are linked to the consequence of transmitting on these spectrum opportunities. We refer to this as outage-constrained threshold design and through this work, we propose practical means of being able to utilize these thresholds for spectrum allocation for network-blind SUs.

Another area that has not been discussed in spectrum sensing research is what we define as the "safe zone" for PU communication.

Definition 1. *Safe Zone.* Spatial-temporal periods of non-accessability for an SU, guaranteeing QOS-secure frames for PU communication. To understand where this safe zone lies on the ED sensing threshold axis, let us first look at the traditional ED design

Figure 5.2: Threshold Design for a) Traditional ED, b) Outage-constrained ED.

in Fig. 5.2. Here, the hypothesis testing is either H_B , a busy PU, or H_I , an idle PU spectrum. If the received SNR at the respective ST happened to fall below the sensing threshold, $\rho_i < \lambda_i$, we would categorize this as an idle PU, and proceed with SU spectrum access. Conversely, if $\rho_i \geq \lambda_i$, the SU would be asked to remain silent for an overlay topology, or asked to utilize this opportunity to share spectrum with the PU under certain back-end interference mitigation constraints for a hybrid underlay-overlay topology.

Proposition 3.1. *Given an instantaneous PU target rate, R_t , for a given PU transmission power of P_p , and a channel realization, h_p , there exists an intermediate hypothesis region or safe zone, H_0 , that if the i^{th} SU were to transmit over, even with power, $P_{s_i} \rightarrow 0$, the average outage constraint at the PU will be violated.*

This becomes clearer when we see how our outage-constrained thresholds are formulated giving us these three distinct hypothesis, namely H_I (the idle hypothesis representing spectrum access opportunities), H_0 (the safe zone or silent period for SU communication), and H_B (the busy hypothesis representing spectrum sharing opportunities for the SU).

5.2.1 Outage-Constrained Threshold Design

In designing these new thresholds, we must first establish our outage limiting constraint. For spectrum access transmissions, the sensing error is usually a false positive

(or false alarm), i.e. sensing PU activity when the spectrum is idle, or a false negative (or missed detection), i.e. sensing idle spectrum when the PU is transmitting. For a pure overlay topology, the SU would miss an opportunity to transmit during a false alarm, and would cause outage to the PU if it were to transmit for every missed detection. Therefore, we aim to design our access threshold by limiting this error as

$$\mathcal{P}_r(\rho_i \geq \lambda_{a_i} | H_I) + \mathcal{P}_r(\rho_i < \lambda_{a_i} | H_B) = \varepsilon. \quad (5.5)$$

Here, ρ_i represents the received SNR at the respective ST_i, which is compared against our new spectrum access sensing threshold, λ_{a_i} , and constrained by a quantitative outage measure, ε . We can classify the PU as truly busy (H_B), when its instantaneous rate R_l surpasses a quality target rate, R_t , set at the PR. For a PU transmission power of P_p , R_l represents the achievable PU rate in the absence of SU interference, and can be defined as

$$R_l = \log_2 \left(1 + \frac{P_p \cdot \gamma_p}{N_0} \right) \quad (5.6)$$

where, N_0 is noise variance at the PR. Conversely if $R_l < R_t$ for a given channel realization, we can classify this as idle spectrum, as the PU would already be in outage without any SU involvement. Therefore, our constraint in (5.5) can be written as

$$\begin{aligned} & \mathcal{P}_r \left(\frac{P_p \cdot \gamma_{pti}}{N_0} \geq \lambda_{a_i} \right) \cdot \mathcal{P}_r \left(\log_2 \left(1 + \frac{P_p \cdot \gamma_p}{N_0} \right) < R_t \right) + \\ & \mathcal{P}_r \left(\frac{P_p \cdot \gamma_{pti}}{N_0} < \lambda_{a_i} \right) \cdot \mathcal{P}_r \left(\log_2 \left(1 + \frac{P_p \cdot \gamma_p}{N_0} \right) \geq R_t \right) = \varepsilon. \end{aligned} \quad (5.7)$$

For Rayleigh fading channels, these probabilities can be calculated, and expressed as

$$\begin{aligned} & \exp\left(-\frac{\lambda_{a_i} \cdot N_0}{P_p \cdot \gamma_{pti}}\right) \cdot \left(1 - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{P_p \cdot \gamma_p}\right)\right) + \\ & \left(1 - \exp\left(-\frac{\lambda_{a_i} \cdot N_0}{P_p \cdot \gamma_{pti}}\right)\right) \cdot \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{P_p \cdot \gamma_p}\right) = \varepsilon. \end{aligned} \quad (5.8)$$

Therefore, we can obtain the outage-constrained spectrum access threshold as

$$\lambda_{a_i}^* = \ln \left(\frac{1 - 2 \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{P_p \cdot \gamma_p}\right)}{\varepsilon - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{P_p \cdot \gamma_p}\right)} \right) \cdot \bar{\rho}_i \quad (5.9)$$

where $\bar{\rho}_i = \frac{P_p \cdot \gamma_{pti}}{N_0}$ is the average received SNR at ST_i from sensing, and $\bar{x}$ represents the ergodic average of x .

Now in designing the spectrum sharing threshold, we first define the PU rate with SU interferers as

$$R'_l = \log_2 \left(1 + \frac{P_p \cdot \gamma_p}{\sum_{i=1}^k P_{si} \cdot \gamma_{sip} + N_0} \right) \quad (5.10)$$

where P_{si} is the transmission power of the i^{th} ST. When this PU rate does not meet the quality target of R_t , sharing PU spectrum would result in outage, which we can term as an error hypothesis, H_E . Therefore, the outage constraint for the design of the spectrum sharing threshold can be defined as

$$\mathcal{P}_r(\rho_i > \lambda_{s_i} \mid H_E) = \varepsilon. \quad (5.11)$$

This can be written as

$$\mathcal{P}_r(\rho_i > \lambda_{s_i}) \cdot \mathcal{P}_r(R'_l < R_t) = \varepsilon \quad (5.12)$$

or,

$$\mathcal{P}_r(\rho_i > \lambda_{s_i}) \cdot \left(1 - \mathcal{P}_r \left(\gamma_p \geq (2^{R_t} - 1) \cdot \left[\frac{N_0}{P_p} + \sum_{i=1}^k \frac{P_{s_i}}{P_p} \cdot \gamma_{sip} \right] \right) \right) = \varepsilon. \quad (5.13)$$

For Rayleigh fading channels, we can express this as

$$\exp \left(-\frac{\lambda_{s_i}}{\bar{\rho}_i} \right) \cdot \left(1 - \exp \left(-\frac{(2^{R_t} - 1) \cdot N_0}{\bar{P}_p \cdot \gamma_p} \right) \cdot \prod_{i=1}^k \left(\frac{\bar{P}_p}{\bar{P}_p + (2^{R_t} - 1) \cdot \bar{P}_{s_i}} \right) \right) = \varepsilon. \quad (5.14)$$

This give us a sharing threshold of

$$\lambda_{s_i}^* = \ln \left(\frac{1 - \exp \left(-\frac{(2^{R_t} - 1) \cdot N_0}{\bar{P}_p \cdot \gamma_p} \right) \cdot \prod_{i=1}^k \left(\frac{\bar{P}_p}{\bar{P}_p + (2^{R_t} - 1) \cdot \bar{P}_{s_i}} \right)}{\varepsilon} \right) \cdot \bar{\rho}_i. \quad (5.15)$$

A detailed simplification of these closed-form derivations can be found in Appendix B. We will now discuss how we can tackle some of the common assumptions made with this network topology.

5.3 Practical Outage-Constrained Sensing

With the hybrid underlay-overlay topology, a lot of common assumptions have been made in literature to allow researchers to focus on specific open problems in the model. We aim to make our spectrum learning scheme as practical as possible, by eliminating most of these concerns and implementing our own decision-making algorithm. Some of the common assumptions are:

1. Weak or absent PT-SR_i and ST_i-SR_j ($j \neq i$) communication links - The assumption

that the PT cannot communicate or has negligible interference towards a respective SR has generally been made [88] to attain good achievable SU rates to warrant sharing PU spectrum. If the PU transmits with high power, the corresponding achievable SU sharing rate maybe too insignificant to justify the resources used. Similarly, assumptions have been made so that SRs can neglect interference from other STs, for the same justification.

In our model, we retain these communication links, allowing the channels to act as interference channels, and plot the corresponding achievable SU rates in our simulations. When working decentralized, and with no cooperation, it is mathematically impossible to cancel out interference. However, with SU cooperation, an open area of research exists in utilizing the sensing statistics to estimate the received signal at the SR and consequently cancel out the interference.

2. Neglecting other SU's transmissions while sensing - This is to allow the SUs to accurately sense PU activity on the link without interference from other SU's transmission signals in the received sensing metric. Much of the research work that has made this assumption [23] [89] [90], have designed their models around cooperative sensing, where SUs can collectively make weighted sensing decisions through a central controller. Consequentially, a lot of the corresponding formulations in these research papers rely on isolating the PU's signal to provide closed-form results for sensing.

With decentralized decision-making, we see this interference as added information from the network. Not only do we include all transmitting users in the sensing metric, but we design our algorithm to function around the changes in received SNR at the sensing ST. This level of cognition translates to recognizing patterns and determining the state of the PU link amidst all the dynamic changes in channels and SU transmissions in the network. We will describe the algorithm in more detail

in Section 5.4.

3. Cross-channel knowledge for spectrum sharing - For the purposes of interference mitigation, many spectrum sharing or overlay papers [67] [91]-[94] discuss having some knowledge to limit the SU's cross-interference felt at the PR. Though there is a lot of work on blind and semi-blind techniques for channel estimation between a transmitter and receiver pair, when talking about the cross-channel between two different users, i.e. SU and PU, few works exist that discuss estimation techniques, but are still reliant on some form of knowledge.

Therefore, to avoid any assumptions regarding the cross-channel knowledge, we incorporate the outage constraints at the PR into the design of the sharing threshold (5.15), so that any SU that utilizes this threshold will already be in compliance with the outage standard. However, the perfect closed-form thresholds in (5.9) and (5.15), still require some knowledge, and we will tackle how we can work around it with the limited sensing statistic information we have in the following subsection.

5.3.1 Practical Considerations

We aim to make our thresholds practical, by allowing some simplifications to the closed-form solutions provided. The impracticalities we wish to remove are:

1. Assumption of unknown channel power gains - It is fair to make the assumption that each transmitter and receiver pair, know its own transmission channel through simple pilot training sequences [76] [77]. We must also understand that we are dealing with close-proximity nodes that cause significant interference to each other. Otherwise, the assumption that papers make regarding weak PT-SR channels can hold, if the users are distant. Therefore, for our model, we assume the same unit distance between all nodes in the network, i.e. SUs and PU. Because of their close

proximity, it is fair to say that these interference channels experience the same fading, and for a large number of samples will have equivalent average power gains. We can then replace the average unknown channel power gains with known primary channel information to re-construct our sensing thresholds in (5.9) and (5.15) as

$$\lambda_{a_i} = \ln \left(\frac{1 - 2 \exp \left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p} \cdot \gamma_{pti}} \right)}{\varepsilon - \exp \left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p} \cdot \gamma_{pti}} \right)} \right) \cdot \overline{\rho_i} \quad (5.16)$$

or,

$$\lambda_{a_i} = \ln \left(\frac{1 - 2 \exp \left(-\frac{2^{R_t} - 1}{\overline{\rho_i}} \right)}{\varepsilon - \exp \left(-\frac{2^{R_t} - 1}{\overline{\rho_i}} \right)} \right) \cdot \overline{\rho_i}. \quad (5.17)$$

and,

$$\lambda_{s_i} = \ln \left(\frac{1 - \exp \left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p} \cdot \gamma_{pti}} \right) \cdot \prod_{i=1}^k \left(\frac{\overline{P_p} \cdot \gamma_{pti}}{\overline{P_p} \cdot \gamma_{pti} + (2^{R_t} - 1) \cdot \overline{P_{si}} \cdot \gamma_{pti}} \right)}{\varepsilon} \right) \cdot \overline{\rho_i} \quad (5.18)$$

or,

$$\lambda_{s_i} = \ln \left(\frac{1 - \exp \left(-\frac{2^{R_t} - 1}{\overline{\rho_i}} \right) \cdot \prod_{i=1}^k \left(\frac{\overline{P_p} \cdot \gamma_{pti}}{\overline{P_p} \cdot \gamma_{pti} + (2^{R_t} - 1) \cdot \overline{P_{si}} \cdot \gamma_{si}} \right)}{\varepsilon} \right) \cdot \overline{\rho_i}. \quad (5.19)$$

2. Number of users in the network (or within a PU's region of interference), k - Without any cooperation, each of the SUs has no shared information regarding other

SU activity in the network. Though our decision-making algorithm can tackle understanding of the network dynamics despite this knowledge, we still need to know k , to guarantee an accurate sharing threshold. We know that, with similar fading, the corresponding average mean and variances of all the interference channels will be the same, and therefore we can employ a variance check on the received SNR, to determine when an SU begins or stops transmission on the spectrum. However, each new SU in the network has less information than the one before it and so its estimate of k will be off by 1 for every new user. Therefore, the network size estimate will be $k - N$ for the $(N + 1)^{th}$ SU that enters the network, which can result in sub-optimal sharing rates for the SU network. However, each individual SU is aware of its achievable sharing rate and can improve its estimate of the network size through feedback from its receiver.

Another concern is the actual power levels of the k users. Without cooperation, there is no means to knowing this information, and each i^{th} SU can only assume $\overline{P_{sj}} = \overline{P_{si}}, j \neq i$, re-defining the practical sharing threshold to be

$$\lambda_{s_i} = \ln \left(\frac{1 - \exp \left(-\frac{2^{R_t} - 1}{\overline{\rho_i}} \right) \cdot \left(\frac{\overline{\rho_i}}{\overline{\rho_i} + (2^{R_t} - 1) \cdot \overline{SNR_{ci}}} \right)^k}{\varepsilon} \right) \cdot \overline{\rho_i} \quad (5.20)$$

where $\overline{SNR_{ci}}$ is the average SNR of the i^{th} SU channel. It is to be noted that these spectrum sharing and access thresholds are not the optimal thresholds presented earlier in (5.9) and (5.15), but are practical and can guarantee a certain level of protection to the PU and overall rate to the SU network to validate its significance. We will see the simulation results with these practical thresholds later in Section 5.5.

Figure 5.3: Decision-making Algorithm.

3. Knowledge of the PU QOS target, R_t - For safe coexistence on PU spectrum, this quality measure is essential for SU's to maintain a level of interference control. It is almost always an unstated assumption in literature, that this knowledge is available to SUs for spectrum sharing purposes, to design cross-channel estimates or maintain a peak power limit for transmissions. This is not a problem that we aim to tackle here, but in designing a completely blind system, we believe this to be an open area of research, where ideally, SUs will be able to estimate R_t through supervised probing and feedback. Although this might result in higher outages at the PU, the application can definitely be seen, where anonymity is desired.

5.4 Decision-making Algorithm

With the optimized outage-constrained thresholds, the SU still needs to process the received sensing statistics to understand the network dynamics, and correspondingly adapt its power for transmission opportunities over PU spectrum. This is where our decision-making algorithm comes into play. This algorithm is heuristic, in the sense

that it improves over time, which is the best that can be done for a pure interference channel with no cooperation. We will now explain each stage of the algorithm presented in the flowchart in Fig. 5.3. The first obvious decision to be made is whether the PU spectrum opportunity is suitable for access or sharing. As discussed earlier, an SU makes this decision by comparing the sensing metric ρ_i to the optimized sensing thresholds presented. Generally, if $\rho_i < \lambda_{a_i}$, the SU can access the spectrum, if $\rho_i > \lambda_{s_i}$, it can share the spectrum, and otherwise it remains silent. However, the PU can also default to an idle hypothesis (i.e. $\rho_i < \lambda_{a_i}$) when:

1. The PU is silent (activity probability),
2. The PU is in outage because of channel fading, or,
3. The PU experiences forced outage because of excessive SU interference.

From the SU's standpoint, distinguishing between the first 2 cases is not important, but it is essential for the SU to realize when it is transmitting with excessive power. To eliminate the chance of a forced outage, we first verify if the SU had been sharing the PU spectrum in the previous frame, through a mode counter, mc . If so, we attribute the last SU transmission power increment to the forced outage, and ensure the SU reduces its power by two incremental states to when the network was stable. If it so happens that ρ_i is still less than λ_{a_i} , it implies that the PU is idle or silent and the i^{th} SU can access the spectrum freely. Finally, to ensure that only one user accesses the spectrum at a time, we introduce a check threshold in the form of λ_{chk_i} , to ensure that the other SUs remain silent even though the PU statistics indicate inactivity. We define this new threshold for the occupied idle case hypothesis, H_{I_0} .

Definition 2. *Occupied Idle Case Hypothesis, H_{I_0} .* This represents the idle spectrum opportunity, H_I , that has been occupied by the i^{th} SU, making it unavailable for the other $k - 1$ SUs that sense the same opportunity. We now define the check threshold as

$$\mathcal{P}_r(\rho_i < \lambda_{chk_i} \mid H_{I_0}) = \varepsilon \quad (5.21)$$

$$\mathcal{P}_r(\rho_i < \lambda_{chk_i}) \cdot \mathcal{P}_r\left(\log_2\left(1 + \frac{P_p \cdot \gamma_p}{P_{s_{max}} \cdot \gamma_{sip} + N_0}\right) < R_t\right) = \varepsilon. \quad (5.22)$$

where $P_{s_{max}}$ is the maximum available instantaneous power for SU transmission. We can solve for λ_{chk_i} as

$$\left(1 - \exp\left(-\frac{\lambda_{chk_i}}{\bar{\rho}_i}\right)\right) \cdot \left(1 - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\bar{P}_p \cdot \gamma_p}\right) \cdot \left(\frac{\bar{P}_p}{\bar{P}_p + (2^{R_t} - 1) \cdot P_{s_{max}}}\right)\right) = \varepsilon. \quad (5.23)$$

This give us the optimal threshold check of

$$\lambda_{chk_i}^* = \ln \left(\frac{1 - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\bar{P}_p \cdot \gamma_p}\right) \cdot \left(\frac{\bar{P}_p}{\bar{P}_p + (2^{R_t} - 1) \cdot P_{s_{max}}}\right)}{1 - \varepsilon - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\bar{P}_p \cdot \gamma_p}\right) \cdot \left(\frac{\bar{P}_p}{\bar{P}_p + (2^{R_t} - 1) \cdot P_{s_{max}}}\right)} \right) \cdot \bar{\rho}_i \quad (5.24)$$

or with the simplifications discussed before, we have a practical check threshold of

$$\lambda_{chk_i} = \ln \left(\frac{1 - \exp\left(-\frac{2^{R_t} - 1}{\bar{\rho}_i}\right) \cdot \left(\frac{\bar{\rho}_i}{\bar{\rho}_i + (2^{R_t} - 1) \cdot P_{s_{max}} \cdot \bar{\gamma}_{si}}\right)}{1 - \varepsilon - \exp\left(-\frac{2^{R_t} - 1}{\bar{\rho}_i}\right) \cdot \left(\frac{\bar{\rho}_i}{\bar{\rho}_i + (2^{R_t} - 1) \cdot P_{s_{max}} \cdot \bar{\gamma}_{si}}\right)} \right) \cdot \bar{\rho}_i. \quad (5.25)$$

where $\bar{\gamma}_{si}$ is the average power gain of the i^{th} SU channel.

Now, when looking at spectrum sharing side of the algorithm (i.e. $\rho_i > \lambda_{s_i}$), we ideally want our adaptive algorithm to best utilize the available resources with all the SUs present. Through our coding, we try and emulate a water-filling idea in terms of the capacity the PU spectrum can handle, as depicted in Fig. 5.4. Here, SUs that enter the network, accommodate underutilized spectrum resources, by adaptively increasing

SU rate in the network as

$$\begin{aligned} \alpha_i^* &= \max_{P_{si}} R_c \\ \text{s.t.} \quad & 0 \leq P_{si} \leq P_{smax} \end{aligned}$$

where R_c is the overall average SU network rate given by

$$R_c = \frac{1}{m} \cdot \frac{1}{k} \cdot \sum_m \sum_i \log_2 \left(1 + \frac{P_{si} \cdot \gamma_{si}}{P_p \cdot \gamma_{pri} + \sum_{j, j \neq i} P_{sj} \cdot \gamma_{srji} + N_0} \right). \quad (5.26)$$

This optimization of α_i need only be calculated by an SU once on entering a new network. This is because the changes in the optimized α_i^* can be attributed to network size and density. To understand this, we look again at the water-filling idea for capacity maximization in Fig. 5.4. It can be seen that with more users in the network, for example, in a dense urban environment, power increment has to be more conservative to maintain network stability, and therefore we can expect a smaller α_i^* . Conversely, when there are fewer users or a sparse network arrangement similar to networks setup in a rural environment, aggressive power increments will help converge faster to the network capacity, and therefore a higher α_i^* can be expected. We will now demonstrate these achievable network rates along with the the corresponding PU outage in the following Simulation Results section.

5.5 Simulation Results

In this section, we plot the average achievable SU network rate and corresponding PU outage, comparing our practical-outage constrained thresholds in (5.17), (5.20), and (5.25), against the traditional ED threshold design in (5.4). To plot our results, Monte Carlo simulations for 2×10^6 channel realizations have been carried out, with every 20 consecutive frames coherent. For this we consider a system bandwidth of 40MHz, and a

Figure 5.5: PU Outage against maximum PU transmission power.

channel coherence time of 5.28ms, which allows for as much as 10^4 symbols per frame. It is to be understood that for fewer symbols per frame, we could allow for greater number of coherent transmission frames, and more precision in the decision-making algorithm. Since, the PU system we are considering is QOS-centric and can update its transmission power based of its own feedback loop, we utilize the maximum available power to the PU, P_{pmax} , as the variable to plot our graphs. Here, we have set the maximum transmission power of the SU, P_{smax} , to be 50dBW, the noise variance at the receivers, N_0 , to unity, and the probability of PU activity as 0.9 (i.e. the PU is present 90% of the time on its channel). With 30 samples per frame (M), we plot the results for an error measure, $\varepsilon = 10^{-3}$, and therefore correspondingly we use a probability of detection, $\mathcal{P}_d = 0.999$ for the traditional threshold design.

In these simulations, we compare our thresholds against two benchmarks: one being the aforementioned traditional threshold design in (5.4), and the second is the PU channel

outage, void of any SU involvement. In Fig. 5.5, we demonstrate the corresponding PU outage for SU transmissions using these thresholds. It is to be noted that the graphs will not be representative of the traditional Rayleigh fading BER vs SNR curves, as we plot the PU outage against P_{max} , its maximum available transmission power. Therefore, the information that this graph provides is the maximum interference compensation available to a QOS-sensitive PU. In Fig. 5.5, the performance of our outage-constrained thresholds is denoted by the solid green line, while the traditional ED threshold is depicted by the dashed red, and the PU channel outage by the dotted blue line, respectively. The general trend that can be seen is that our threshold results in lower PU outages than the traditional design. We have also considered different target rates for the PU. When we look at a higher target rate like 3 bps/Hz (denoted by the square in the legend), we expect to see more spectrum access opportunities, and therefore our outage-constrained threshold curve defaults to the PU's own channel outage curve, until sufficient transmission power allows for spectrum sharing opportunities, which then conform to the acceptable outage limit of 10^{-3} . On the other hand for lower target rates like 0.01 bps/Hz and 0.1 bps/Hz (denoted by the circle and triangle, respectively), there is a clear distinction between our outage-constrained curve and the traditional ED threshold curve, as part of our hybrid design involves utilizing spectrum sharing opportunities, which can be seen here. At the low SNR regime, our outage-constrained curve demonstrates the spectrum access opportunities within an error of ε , while the more erratic behavior at higher SNRs can be attributed to freedom in SU transmission power control for spectrum sharing opportunities within the limitations (below 10^{-3} mark) of the predesigned outage constraint. It is clear to see that with these thresholds we can guarantee an error floor for PU communication, something that has not been addressed in a decentralized manner in spectrum sensing research before.

When considering the benefit to the SUs, Fig. 5.6 demonstrates the average achiev-

Figure 5.6: Average achievable SU network rate for varying PU target rates.

able network rate for our decentralized scheme. While being outage-constrained, we can still see comparable rate gains at higher QOS margins using our approach. It is to be understood that these rate curves for the outage-constrained thresholds represent a stable and non-cooperative hybrid network topology, i.e. the PU is QOS-secure while being unaware of the SUs in the network. In comparison, the average SU rate for the traditional threshold design (black dotted line) remains unchanged for a varying range of QOS margins in R_t , being oblivious to the state of PU transmissions. Therefore, a threshold design that is independent of the PU target rate will provides lesser protection to the PU, and also lesser flexibility in spectrum sharing opportunities for the SU. The reported higher average achievable rate for the traditional threshold is only a misrepresentation of how detection measures, like missed detection probability or probability of detection cannot be used as an effective outage measure for threshold design. We also observe that though our outage-constrained threshold design provides spectrum sharing opportunities

at higher PU SNRs, with no shared information between the SUs themselves, the spectrum sharing rate shown is the best achievable rate for a pure interference network under the strong interference model. Ideally, with a less stringent model or with the introduction of cooperation, the SUs can carry out interference alignment or simple mitigation techniques, to achieve better spectrum sharing rates using these thresholds. This idea of cooperation however, does not fall within the framework of this network-blind model, and so we reserve that research as a future direction for outage-constrained threshold design.

5.6 Summary

In this chapter, we discuss the need for outage-constrained threshold design for spectrum sensing in a decentralized and network-blind setting. Prior work in spectrum sensing has prioritized sensing PU activity, over the consequence of SU transmissions over the sensed spectrum. In this work, we bring the power-limiting constraints from the PR end to the front end of threshold design, so that any SU in the network that carries out spectrum sensing with these thresholds, would already be in compliance with the QOS requirements of the PU when they transmit over the sensed spectrum. The work done also discusses a QOS-secure region for the PU in threshold design, through the introduction of a spectrum sharing threshold, for simultaneous SU transmissions over PU spectrum. This helps bring spectrum efficient design into spectrum sensing decisions made by the SUs in a network. Moreover, the SUs in the network do not cooperate, and operate decentralized with a decision-making algorithm that utilizes only the sensed channel statistics to make spectrum allocation and smart utility decisions. We have demonstrated that with these thresholds, we can guarantee an error-floor for PU communication at high SNRs and cause no interference at the lower SNR regime with a user-specified error control measure. Also the achievable SU rates for a pure interference network have been

plotted, demonstrating even raw statistical information in the form of spectrum sensing can provide sufficient information for a network-blind user to make intelligent decisions.

Chapter 6

Network-Blind Rate-Achieving CR Setup over Unlicensed Spectrum

In the last chapter, we saw a network-blind application over licensed subspace. The recent buzz for CR deployment over licensed spectrum in the spectrum management community is due to the IEEE 802.22 guidelines for sharing TV white space bands [52] [95] [96] for SU transmissions. This compliance hinges on the fact that the cross-interference from simultaneous SU transmissions are kept below an acceptable limit to maintain a minimum primary link QOS. This requirement is generally met through supervised power control by an SU centralized controller or through cooperation with the PU. This is because the rate optimization problem for an SU network that is outage-constrained at the PR is a non-convex optimization problem. But with certain simplifications, it can be shown to be convex [97] and solvable with a centralized design that is reliant on cross-channel knowledge. Though a lot of papers on spectrum sharing research [91] [98] [99] discuss distributed power control designs for a rate-achieving network under certain QOS constraints, what is often treated as common knowledge in these papers is the cross-channel between the respective SU's transmitter and PU's receiver, that is needed for interference mitigation. This information cannot be known without cooperation with

the PU or a geolocation database with PU location estimates, which essentially falls back to a centralized design. Other work that tackles this problem, utilize primary link feedback to estimate the cross-interference from simultaneous SU transmissions, through a power-feedback loop [97]. However, as mentioned in the paper, the scheme is reliant on knowledge of the modulation used for the PU feedback link, which is possible only if the network operator in which the CRs were deployed, were to provide such information. The idea presented for QOS control also depends entirely on the fact that the spectrum under consideration for SU transmission is licensed spectrum. If unlicensed spectrum were to be used, the power-feedback loop employed for a single PU cannot be scaled (time and complexity) to n SUs, even if their feedback link of all n SUs could be decoded and sensed.

Having already addressed the solution for licensed deployment in the last chapter, we now look at unlicensed spectrum deployment (like the ISM bands). We first establish the closed-form solutions for outage-constrained sensing thresholds for a network of n SUs. These thresholds essentially incorporate the receiver-end interference mitigation constraints into front-end ED threshold design. The significance here, is that through only a sensing threshold, an ad-hoc user that enters the network can be in compliance with, and participate in achieving a network-wide rate in a distributed and non-cooperative manner. To demonstrate the performance capabilities of these thresholds, we propose a heuristic power control algorithm that allows both spectrum access and spectrum sharing transmission opportunities for the SUs for a range of possible network rates. The convergence to network rates, and compliance to the outage constraint as evidence from our simulations, prove that a decentralized and non-cooperative rate-achieving network is possible, and can be seen implemented in a variety of applications for both military and ad-hoc commercial networks.

Figure 6.1: System Model.

6.1 System Model

Our system setup consists of n SUs with the ability to sense and allocate unlicensed spectrum for its transmission needs based on a predefined outage constraint for the network. We represent the respective SU transmitter and receiver pairs by ST_i and SR_i , with the channel gains between an ST_i - SR_i pair by h_i , and their cross channels from ST_i - ST_j by h_{tij} and from ST_i - SR_j by h_{rij} for $j \neq i, i \in [1, n]$, as shown in Fig. 6.1. We have modelled these channels to follow Rayleigh block-fading with additive Gaussian noise at the receivers. Their corresponding channel power gains can be given by $\gamma_m = |h_m|^2$, where $m = \{i, tij, rij\}$. We now begin to formulate the optimization problem, and design the respective sensing thresholds to achieve this objective.

6.2 Problem Formulation

The objective of this work is a rate-achieving decentralized and non-cooperative SU network that functions solely on the statistical sensed energy through outage-constrained sensing thresholds. Therefore, we first begin by defining the instantaneous network rate

given by

$$R = \sum_{i=1}^n \log_2 \left(1 + \frac{P_i \cdot \gamma_i}{\sum_{j=1, j \neq i}^n P_j \cdot \gamma_{rji} + N_0} \right). \quad (6.1)$$

where P_i is the transmission power of the ST_{*i*}, and N_0 is the noise variance at the respective receiver. Next, we develop a QOS measure for this SU network in the form of a network outage constraint. In literature, it is common to see outage being addressed at the individual link level [100] [101], such that a receiver can feedback to its corresponding transmitter, the power adaptation necessary to maintain the link QOS. However, this is a both an easy and futile problem to solve for a non-cooperative and decentralized network. This is because each user in the network will be self-serving (i.e. achieve its own link QOS), and will correspondingly increase its transmission power to offset the interference from other users in the network. With each SU transmitting at maximum power, P_{max} , this results in an individual link rate of $\log_2 \left(1 + \frac{P_{max} \cdot \gamma_i}{\sum_{j=1, j \neq i}^n P_{max} \cdot \gamma_{rji} + N_0} \right) \approx \log_2 \left(\frac{n}{n-1} \right)$. As one can see the achievable rate here is capped by, and is only a function of, the number of users in this pure interference network.

Therefore, we solve the problem by defining our outage constraint at the network level. We can visualize this as all the SUs working together (but still decentralized and without cooperation) in achieving the network QOS. We define this instantaneous network target rate as R_t . Therefore, an outage for our decentralized network can be defined as the event $\{R < R_t | P_i \neq \emptyset, i \in [1, n]\}$. We will now look at how spectrum sensing thresholds can be designed to meet this outage-constraint for a rate-achieving SU network.

6.3 Spectrum Sensing Threshold Design

For the decentralized and non-cooperative network presented, spectrum sensing takes on the role as the only reliable information source for an individual node. Therefore, all allocation and transmission power control decisions will be made via this information.

To this end, we utilize the sensing detector that requires the least apriori information to make spectrum allocation decisions, i.e. the energy detector (ED). ED functions purely based on knowledge of the noise level at the sensing node in characterizing spectrum as idle or busy, with a threshold to determine the difference. We utilize this sensing threshold to incorporate our network optimization constraints and allow a node to make independent but distributed decisions in the network.

In the past, threshold design has often been based on sensing PU activity to opportunistically access licensed spectrum for an overlay topology, or to simultaneously share the licensed band for an underlay topology. Therefore, the metrics previously used to define the sensing threshold were either probability of detection or false alarm probability, to effectively determine PU activity. However, this threshold design is different in three ways:

1. The spectrum sensed is unlicensed, changing the way an SU would interpret a spectrum opportunity (we will cover more on this in Section 6.5)
2. Our design metric is to constrain the overall network outage, and not the activity probability of the user on the spectrum (which is what a threshold design based on probability of detection will result in [90])
3. We incorporate two thresholds and three decision regions to distinguish spectrum opportunities. This hybrid underlay-overlay topology has been previously employed [33] and acknowledged for the superior rate and spectrum efficiency it provides the SU network. However, here we look at the threshold design for this topology, where the SU compares the sensing metric, ρ_i , to these different thresholds to:
 - (a) Access the spectrum alone if $\rho_i < \lambda_{a_i}$, the access threshold,
 - (b) Share the spectrum with other SUs if $\rho_i > \lambda_{s_i}$, the sharing threshold, or,
 - (c) Remain silent, for all other cases.

This metric ρ_i is the received SNR at ST_i and is given by

$$\rho_i = \sum_{j=1, j \neq i}^n \frac{P_j \cdot \gamma_{tji}}{N_0}. \quad (6.2)$$

Given these two modes of transmission for the SU, we can define the individual SU access and sharing rates respectively as

$$R_{ai} = \log_2 \left(1 + \frac{P_i \cdot \gamma_i}{N_0} \right) \quad (6.3)$$

$$R_{si} = \log_2 \left(1 + \frac{P_i \cdot \gamma_i}{\sum_{j, j \neq i} P_j \cdot \gamma_{rji} + N_0} \right). \quad (6.4)$$

We will now look at the probability of a network outage for each of these transmission modes.

6.3.1 Spectrum Access Threshold

Spectrum access opportunities refer to the space-time sensitive windows of the spectrum that allow for uninterferred transmission by a sole SU. Therefore, if the instantaneous network rate, R_t , cannot be met by this individual user's transmission, the network will incur an outage. Also, in the absence of a spectrum owner (or PU), we must program the need to share spectrum into the decentralized self-serving nature of SUs, in the form of this access threshold. This implies that if the network rate can be met through more users sharing and transmitting on the spectrum together, rather than one user accessing the spectrum alone, the user must switch from access to sharing purely based on the sensing metric. We can now define the outage constraint as

$$\mathcal{P}_r(\rho_i > \lambda_{a_i}) \cdot \mathcal{P}_r(R < R_t) \cdot \mathcal{P}_r(R_{ai} \geq R_t) + \mathcal{P}_r(\rho_i < \lambda_{a_i}) \cdot [\mathcal{P}_r(R \geq R_t) + \mathcal{P}_r(R_{ai} < R_t)] = \varepsilon. \quad (6.5)$$

where ε is the outage constraint imposed for this threshold. There are three events that count towards the network outage in (6.5). The first probabilistic event is the case of missed detection, when the threshold reading fails to indicate an opportunity to access, as R_{ai} meets or surpasses the network target rate, R_t . The second term in the summation is two separate events; the first corresponding to the enforcing of spectrum sharing behavior into the decentralized decision-making process by prioritizing a sharing opportunity whenever present, and the second corresponding to a false alarm for spectrum access, when R_{ai} fails to meet R_t .

We will now look at how we can solve these individual probabilities. From (6.2), we can see that ρ_i is the sum of n independent random variables whose pdf (probability density function) will be an n -fold convolution of the individual pdfs. Given Rayleigh faded channels, the power gain would then take the form of the exponential distribution with a sum pdf given by $f_{S_i}(x) = \frac{\nu_i \exp(-\nu_i x) \cdot (\nu_i x)^{n-1}}{(n-1)!}$, where ν_i is the mean of the distribution. Therefore, we can solve our probability by integrating to find

$$\mathcal{P}_r(\rho_i > \lambda_{a_i}) = \sum_{k=0}^{n-1} \frac{\left(\frac{\lambda_{a_i} \cdot N_0}{P_j \cdot \gamma_{tji}}\right)^k \cdot \exp\left(-\frac{\lambda_{a_i} \cdot N_0}{P_j \cdot \gamma_{tji}}\right)}{k!} \quad (6.6)$$

or,

$$\mathcal{P}_r(\rho_i > \lambda_{a_i}) = \frac{\Gamma\left(n, \frac{\lambda_{a_i} \cdot N_0}{P_j \cdot \gamma_{tji}}\right)}{\Gamma(n)} \quad (6.7)$$

where $\bar{x}$ refers to the mean of x , and $\Gamma(n, x)$ is commonly referred to as the incomplete gamma function. Similarly, the access rate takes an exponential distribution whose complementary cdf (cumulative distribution function) is

$$\mathcal{P}_r(R_{ai} \geq R_t) = \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{P_i \cdot \gamma_i}\right). \quad (6.8)$$

Though there exists a defined pdf for the individual sharing rate R_{si} in (6.4), which is given by the product log-logistic distribution [54] [102]; there is no distribution that well defines R in (6.1). Therefore, let us consider the following proposition.

Proposition 3.1. *For k independent random variables x_k , and an arbitrary value z , $\mathcal{P}_r(\sum_k x_k > z)$ will be bounded by $\prod_k \mathcal{P}_r(x_k > z/k)$.*

Proof. Let all $x_1, x_2, \dots, x_k$ be equal. Then if $\sum_k x_k > z \Rightarrow x_1 > z/k, x_2 > z/k, \dots, x_k > z/k$. If then, they are not equal, but $x_1 > z/k, x_2 > z/k, \dots, x_k > z/k$, we will have $\sum_k x_k > z$. Therefore, if $\prod_k \mathcal{P}_r(x_k > z/k) = \epsilon$, it implies that $\mathcal{P}_r(\sum_k x_k > z) \geq \epsilon$, and is thus bounded by the product. This completes the proof.

We can now represent the complementary cdf of R as

$$\begin{aligned} \mathcal{P}_r(R \geq R_t) &= \mathcal{P}_r\left(\sum_{i=1}^n \frac{P_i \cdot \gamma_i}{\sum_{j=1, j \neq i}^n P_j \cdot \gamma_{rji} + N_0} \geq 2^{R_t} - 1\right) \\ &\equiv \prod_{i=1}^n \mathcal{P}_r\left(\frac{P_i \cdot \gamma_i}{\sum_{j=1, j \neq i}^n P_j \cdot \gamma_{rji} + N_0} \geq \frac{2^{R_t} - 1}{n}\right) \\ &= \prod_{i=1}^n \left[\exp\left(-\frac{(2^{R_t} - 1) N_0}{n \cdot \overline{P_i} \gamma_i}\right) \cdot \prod_{j=1, j \neq i}^n \frac{\overline{P_i}}{\overline{P_i} + \frac{2^{R_t} - 1}{n} \overline{P_j}} \right]. \end{aligned} \quad (6.9)$$

With these closed-form results we can now express the access threshold in (6.5) as

$$\begin{aligned} \Gamma\left(n, \frac{\lambda_{a_i}^*}{\rho_i}\right) &= \left(\exp\left(-\frac{2^{R_t} - 1}{\overline{SNR_i}}\right) - \prod_{i=1}^n \left[\exp\left(-\frac{2^{R_t} - 1}{n \cdot \overline{SNR_i}}\right) \cdot \prod_{j=1, j \neq i}^n \frac{\overline{P_i}}{\overline{P_i} + \left(\frac{2^{R_t} - 1}{n}\right) \overline{P_j}} \right] + \epsilon - 1 \right) \\ &\quad \left(2 \cdot \exp\left(-\frac{2^{R_t} - 1}{\overline{SNR_i}}\right) - \left(1 + \exp\left(-\frac{2^{R_t} - 1}{\overline{SNR_i}}\right) \right) \right) \\ &\quad \left(\prod_{i=1}^n \left[\exp\left(-\frac{2^{R_t} - 1}{n \cdot \overline{SNR_i}}\right) \cdot \prod_{j=1, j \neq i}^n \frac{\overline{P_i}}{\overline{P_i} + \left(\frac{2^{R_t} - 1}{n}\right) \overline{P_j}} \right] - 1 \right)^{-1} \cdot \Gamma(n) \end{aligned} \quad (6.10)$$

where $\lambda_{a_i}^*$ is the optimized access threshold that solves (6.10), $\bar{\rho}_i = \frac{\overline{P_j \gamma_{tji}}}{N_0}$ is the average received SNR at STi, and $\overline{SNR}_i = \frac{\overline{P_i \gamma_i}}{N_0}$ is the average SNR of the i^{th} SU link.

6.3.2 Spectrum Sharing Threshold

For spectrum sharing, the threshold simply allows the user to share the spectrum as long as the instantaneous target rate can be met as a network. Therefore, we constrain this outage as

$$\mathcal{P}_r(\rho_i > \lambda_{s_i}) \cdot \mathcal{P}_r(R < R_t) = \varepsilon. \quad (6.11)$$

$$\Gamma\left(n, \frac{\lambda_{s_i}^*}{\rho_i}\right) = \frac{\varepsilon}{1 - \prod_{i=1}^n \left[\exp\left(-\frac{2^{R_t} - 1}{n \cdot \overline{SNR}_i}\right) \cdot \prod_{j=1, j \neq i}^n \frac{\bar{P}_i}{\bar{P}_i + \left(\frac{2^{R_t} - 1}{n}\right) \bar{P}_j} \right]} \cdot \Gamma(n) \quad (6.12)$$

where $\lambda_{s_i}^*$ is the optimized sharing threshold that solves (6.12). The entire derivation of the closed-form solutions can be found in Appendix C. We will now look at how decentralized and non-cooperative users can effectively use this threshold for spectrum allocation.

6.4 Practical Network-Blind Thresholds

As we have just seen, the above outage-constrained thresholds can work for ad-hoc users but still requires knowledge of interference cross-channels and other SU channel links. This is not information available to a non-cooperative and blind network. Therefore, in this section we make certain proposals that pertain to this network model and allow network-blind users to make informed distributed decisions using closed-form thresholds. We now address three of those simplifications:

1. Network size, n - If the network coverage is small, such that the fading is similar across the interference channels, then we can employ a variance check on the average

received SNR to determine new user activity within the network. However, each new node entering the network is blind to the previous users transmitting in the network and considers the base SNR (first reading) to be the interference of a single user. Therefore, each $(k+1)^{th}$ user in the network will have a network size estimate of $n-k$. Though there exists many works on gossip-based aggregation or averaging for decentralized network size estimates [103] [104]; this is the best that can be done for a non-cooperative network at the physical layer.

2. Power and Cross-channel knowledge of other SUs - With no cooperation, SUs are unaware of these statistics, and at best can assume that the average network statistics are similar to its own. However, each SU still has information in the form of the average received SNR, $\bar{\rho}_i$. For a network with similar channel fading, the average power gain of the interference channels will be the same, and with a few manipulations we can arrive at the practical access and sharing thresholds.
3. The incomplete Gamma function, $\Gamma(n, x)$ - The incomplete gamma function is well-defined for an integer $n \geq 0$, and can be solved numerically. However, in obtaining a closed-form analytical solution, we observe that (6.6) is an exponentially decreasing function with increasing number of users in the network, n , and at high SNR, it will reduce to the single user case of $\exp\left(-\frac{\lambda_{a_i}}{\bar{\rho}_i}\right)$.

With these simplifications, the practical closed-form access and sharing thresholds

can respectively be given by

$$\begin{aligned} \lambda'_{a_i} = & \ln \left(\left(2 \cdot \exp \left(-\frac{2^{R_t} - 1}{\overline{SNR}_i} \right) - \left(1 + \exp \left(-\frac{2^{R_t} - 1}{\overline{SNR}_i} \right) \right) \right) \cdot \right. \\ & \left. \left(\exp \left(-\frac{2^{R_t} - 1}{k \cdot \overline{SNR}_i} \right) \cdot \left(\frac{\overline{P_i \cdot \gamma_i}}{\overline{P_i \cdot \gamma_i} + \left(\frac{2^{R_t} - 1}{n} \right) \overline{P_j \cdot \gamma_{tji}}} \right)^{n-1} \right)^n - 1 \right) \cdot \\ & \left. \left(\exp \left(-\frac{2^{R_t} - 1}{\overline{SNR}_i} \right) - \left(\exp \left(-\frac{2^{R_t} - 1}{k \cdot \overline{SNR}_i} \right) \cdot \left(\frac{\overline{P_i \cdot \gamma_i}}{\overline{P_i \cdot \gamma_i} + \left(\frac{2^{R_t} - 1}{n} \right) \overline{P_j \cdot \gamma_{tji}}} \right)^{n-1} \right)^n + \varepsilon - 1 \right)^{-1} \right) \cdot \overline{\rho_i}. \end{aligned} \quad (6.13)$$

or,

$$\begin{aligned} \lambda'_{a_i} = & \ln \left(\left(2 \cdot \exp \left(-\frac{2^{R_t} - 1}{\overline{SNR}_i} \right) - \left(1 + \exp \left(-\frac{2^{R_t} - 1}{\overline{SNR}_i} \right) \right) \right) \cdot \right. \\ & \left. \left(\exp \left(-\frac{2^{R_t} - 1}{k \cdot \overline{SNR}_i} \right) \cdot \left(\frac{\overline{SNR}_i}{\overline{SNR}_i + \left(\frac{2^{R_t} - 1}{n} \right) \overline{\rho_i}} \right)^{n-1} \right)^n - 1 \right) \cdot \\ & \left. \left(\exp \left(-\frac{2^{R_t} - 1}{\overline{SNR}_i} \right) - \left(\exp \left(-\frac{2^{R_t} - 1}{k \cdot \overline{SNR}_i} \right) \cdot \left(\frac{\overline{SNR}_i}{\overline{SNR}_i + \left(\frac{2^{R_t} - 1}{n} \right) \overline{\rho_i}} \right)^{n-1} \right)^n + \varepsilon - 1 \right)^{-1} \right) \cdot \overline{\rho_i}. \end{aligned} \quad (6.14)$$

and,

$$\lambda'_{s_i} = \ln \left(\frac{1 - \left(\exp \left(-\frac{2^{R_t} - 1}{k \cdot \overline{SNR}_i} \right) \cdot \left(\frac{\overline{P_i \cdot \gamma_i}}{\overline{P_i \cdot \gamma_i} + \left(\frac{2^{R_t} - 1}{n} \right) \overline{P_j \cdot \gamma_{tji}}} \right)^{n-1} \right)^n}{\varepsilon} \right) \cdot \overline{\rho_i}. \quad (6.15)$$

or,

$$\lambda'_{s_i} = \ln \left(\frac{1 - \left(\exp \left(-\frac{2^{R_t} - 1}{k \cdot \overline{SNR}_i} \right) \cdot \left(\frac{\overline{SNR}_i}{\overline{SNR}_i + \left(\frac{2^{R_t} - 1}{n} \right) \overline{\rho}_i} \right)^{n-1} \right)^n}{\varepsilon} \right) \cdot \overline{\rho}_i. \quad (6.16)$$

We now will look at different power control strategies in the form of algorithm design for an SU network.

6.5 Power Control Algorithm Design

With SU networks, many power control strategies [55] [88] [105] have been studied in literature ranging from dynamic and adaptive, to heuristic and random power assignments to best accommodate users on the spectrum. We also notice water-filling ideas that have been applied to improve spectrum efficiency, and maximize the achievable network rate. However, most of the strategies revolve around knowledge regarding both transmit power of users or channel knowledge that is unavailable to a network-blind SU. For the system model presented, each SU can only rely on sensed SNR and the pre-designed threshold for allocation and transmit power decisions. Therefore, a common technique that is used, is to compare two SNR readings to determine changes in the network. When employed over licensed spectrum, all SUs follow what we call ‘reverse power adaptation’, i.e. if an increase in SNR is sensed, the SU would reduce its power, and conversely increases its power when the current SNR reading is lower than the previous reading. This strategy allows SUs to converge to the channel capacity in a water-filling idea, as demonstrated in Fig. 6.2a). However, as can be seen this does not facilitate fair spectrum

Figure 6.2: Water-filling Power Control Strategy for a) Licensed and b) Unlicensed Spectrum.

Figure 6.3: Priority Mode enhanced Water-filling Power Control Strategy.

sharing, when the spectrum in question is unlicensed in Fig. 6.2b).

To solve this, we introduce a priority mode, to distinguish the first SU that senses an empty unlicensed channel. This priority user has the advantage of inverting its power adaptation, allowing it to increase its transmission power for a higher sensed SNR (or interference) and reduce its power when the SNR sensed is lower than the previous read-

ing, thus allowing the unlicensed network to converge to the capacity of the channel. The benefit of this mode is that it allows complete decentralization, as priority is assigned by each SU when it senses a vacant channel. Therefore, this priority also switches hands when another SU in the network is the first to sense an uninterfered spectrum access opportunity. This makes this heuristic power control strategy both dynamic and adaptive, and we can see how it converges in Fig. 6.3.

We now utilize this enhanced power control strategy in our decision-making algorithm depicted in Fig. 6.4. When sensing for spectrum opportunities, if the ST_i sees an access opportunity (i.e. $\rho_i < \lambda'_{a_i}$), it could imply one of two scenarios:

1. Unoccupied spectrum - When no other SUs are transmitting, SU_i's own rate determines the network rate, and therefore with feedback from its own receiver, ST_i will know the exact power it needs to transmit with. This power control loop only works for spectrum access, as the only channel knowledge needed is the SU's own transmit link. There is a lot of research on limited power feedback loops in literature [92] [106], which we have just incorporated here, as it is not the focus of this work.
2. Forced access - If the priority SU forces other users to stop sharing the spectrum, a forced check is introduced to reduce its power by two incremental states. The percentage power increment/decrement, α_i , is only responsible for the speed of convergence of the network, and not its achievable rate or outage performance. In our algorithm, we utilize the counter fc to recognize decentralized behavior and determine the state of the SU transmission, to prevent any forced access behavior.

Once the SU enters into spectrum access, the priority mode counter denoted by PM_i is activated. This helps the SU determine its power control strategy for spectrum sharing. Once a spectrum sharing opportunity is detected (i.e. $\rho_i > \lambda'_{s_i}$), the current SNR reading, ρ_i is compared to the previous stored SNR in ρ_{mem_i} to determine the power

Figure 6.4: Decision-making Algorithm.

adaptation. As mentioned earlier, we employ the priority mode enhanced water-filling strategy presented in Fig. 6.3, where an SU reverses its power adaptation if it happens to be the priority user for that channel. After transmission, the sensing thresholds (λ'_{a_i} , λ'_{s_i}) are then updated, and the iterative algorithm continues.

From an experimental standpoint, for faster convergence, we choose the α_i^* that maximizes the perceived average network rate as seen by each SU_i given by

$$\alpha_i^* = \max_{P_i} R'$$

$$\text{s.t.} \quad 0 \leq P_i \leq P_{max}$$

where R' is the perceived average network rate as seen by SU_i,

$$R' = \frac{1}{m} \cdot \sum_m n \cdot \log_2 \left(1 + \frac{P_i \cdot \gamma_i}{\sum_{j=1, j \neq i}^n P_j \cdot \gamma_{rji} + N_0} \right). \quad (6.17)$$

Here, m represents the number of unique channel realizations in the Monte Carlo simulation setup to determine α_i^* . This iterative optimization for α_i need only be done once the SU enters a new network, as the main factors that influence α_i^* are network size and density. This helps in converging to the achievable rate faster which we will now demonstrate in the Simulation Results section that follows.

6.6 Simulation Results

In this section we plot the results for the rate-achieving decentralized and non-cooperative SU network presented. Our Monte Carlo setup consists of 10^5 channel realizations with every 20 consecutive frames coherent. The maximum allowable SU transmit power, P_{max} is 35dBw, with unity noise variance and an error measure of $\varepsilon = 10^{-3}$. The following results have been carried out for varying network target rates, as depicted in the legends shown.

In Fig. 6.5, we see the outage performance of the network for the decentralized and network-blind users. We plot these results against the maximum available transmission power for each user, i.e. P_{max} , as the actual power levels of the users will vary for every channel realization given the adaptive power control employed. Our goal here is not outage minimization, but to constrain the outage, as determined by the limiting constraint, ε , in our thresholds. It is clear to see from this graph that the outage saturates close to $\varepsilon = 10^{-3}$. We do expect some performance degradation here, as these are not the perfect optimized thresholds in (6.10) and (6.12), but the practical network-blind thresholds, (6.14) and (6.16), that we have used. However, at the lower range of network target rates (0.1 bps/Hz and 0.01 bps/Hz) that this experiment has also been run for, we do not see any outage for the network. This is because with the rate-achieving thresholds developed, SUs that cannot meet the network target rate remain silent and do not consume any power. This can also be seen as beneficial to a system that prioritizes

Figure 6.5: SU Network Outage compared against maximum SU transmission power.

power conservation for the network.

The next result plotted in Fig. 6.6 is the average achievable SU network rate for a range of P_{max} . What we see here, is a clear representation of the goal of our work, which is a decentralized rate-achieving network. The higher target rates of 3bps/Hz and 5bps/Hz saturate at 10dBW and 15dBW of the maximum transmit power respectively, while the lower target rates saturate instantly as evidence from our no-outage results. Both these results demonstrate that a pure interference network can comply to a network QOS in the form of a target rate, without the need for cooperation between nodes in the network or unrealistic cross-channel knowledge at any node. We hope that this work highlights the benefits that spectrum sensing threshold design has to offer to a decentralized network-blind system.

Figure 6.6: Average achievable SU network rate for varying network target rates.

6.7 Summary

In this chapter we undertake solving the decentralized SU network rate-achieving problem from a sensing threshold design perspective. Most work done in this field relies on a centralized design, or unrealistic knowledge for a distributed setup. More relevant applications of a rate-achieving networks also depend entirely on the sensed spectrum being licensed. Here, we tackle unlicensed spectrum deployment of a pure interference network. We also introduce another constraint in the form of non-cooperative or network-blind users. With no information exchange between users, we still demonstrate how a network rate can be achieved with only the statistical sensing data received during spectrum sensing. For the hybrid underlay-overlay topology considered, we design optimized outage-constrained thresholds for spectrum access and spectrum sharing. We then present practical network-blind thresholds that through our adaptive enhanced water-filling power control strategy prove as effective in achieving the network rate. The re-

sults presented justify the decentralized and non-cooperative approach to a rate-achieving network, something that has not been addressed in literature thus far.

Chapter 7

Conclusions and Future Work

7.1 Conclusion

The picture presented in this Thesis for resource-sharing CR systems was in demonstrating commercially-viable and military-applicable solutions to current research problems. With the priority of incentive based collaboration for commercial networks and time- and secrecy-sensitive communication for the military domain, we highlight three different gaps in research that the work in this Thesis has covered:

1. Incentive-based demand-and-supply spectrum trading model - Our work in this area looked at a hybrid network topology that allowed for dynamic switching between spectrum access, spectrum sharing and relaying opportunities for trading in a PU-SU cross-tier network. Based on a demand-and-supply free market, the value associated with the leased spectrum is solely determined by the need of the spectrum resource. Handshaking messages allow each SU to value the spectrum according to its associated cost and achievable rate to make local utility decisions for collaboration. The significance of this scheme lies in the fact that the licensee governs the trade, and with the focus of optimization on its payoff function, the

PU cannot be cheated out of its positional advantage. Through three collaborative measures, the PU will always have spectrum to lease, and the corresponding results of this setup demonstrate the significant rate gain that the SU network enjoys over single access or sharing models. Unlike most spectrum trading work, the change in focus to maximize PU returns also allows this model to be more appealing for commercial licensees to be involved.

2. Time-efficient relaying protocol for in-battle military communication - The gap in relaying research was the application of pure relays to non-LOS military scenarios. Relays often end up being the only practical solution to stranded or incommunicable military nodes in adverse channel environments. But traditional relays lack exigency in being relevant to crucial in-battle military scenarios. Therefore, the inspiration of broadcast transmissions from network coding (ANC/PNC) research provided us with the motivation to look at alternate military-viable relay setups. The first step was to ensure that the relay could carry out its own communication, and play the role of a support unit in the battalion. We incorporated two-way support relaying and single way reporting through this relay node with the use of ZFE and STBC to remain time- and BER-conscious. We also extended this model to include 3-way bi-directional relay communication through a cyclic retransmission protocol for end-to-end transmission in just 4 timeslots. The proposed double-broadcast framework was also compared against single-broadcast relaying which is more QOS-efficient but lacks in being exigent. DBR on the other hand is power-, time- and bandwidth-efficient when it comes to setting up a secure relay protocol for dire in-battle military scenarios.
3. Network-blind CR deployment over licensed and unlicensed subspace - Rate-achieving CR networks with QOS constraints for spectrum sharing is a well developed area of research. However, the work carried out in this area depends on one or more avail-

able information sources, in the form cooperation, centralization or perfect channel knowledge for the scheme to be viable. Though few exemplary papers have been constructed removing two out of three of these information sources, there is a gap in pure network-blind research that brings utility for either licensed or unlicensed CR deployment. With no external information source, the network-blind user must default to spectrum sensing as the only reliable information source regarding network statistics. Therefore, in our work, we incorporated the interference-mitigation constraints at the PR into front-end spectrum sensing threshold design, to allow SUs to safely transmit over licensed and unlicensed spectrum with no cooperation (between themselves or the PU), no centralization and no unrealistic channel knowledge assumptions. The result is a outage constrained and rate-achieving CR model for a network-blind setting. The applications of such a model can extend to both commercial ad-hoc and military communication domains, appropriately concluding the Thesis.

7.2 Future Work

Resource-sharing networks allow for a lot of flexibility both in programming and protocol design that allows for a number of viable extensions of our models for future work.

1. Spectrum trading model with buffer-aided relays - Buffer-aided relays have been shown to be more throughput-efficient than traditional relays, by analyzing the time-variance of the channel to determine the perfect relaying scenario. Spectrum trading with buffer-aided CR relays presents a new long-term pricing strategy that could fit in well with the evolution of licensee resource-sharing. This also opens up the idea for priority SUs that sacrifice short term goals in relaying PU communica-

tion for unrestricted transmission rights over licensed spectrum to meet long term QOS goals.

2. Practical extensions to in-battle military relays - More accurate studies can be carried out for imperfect channel knowledge to the ZFE and STBC approach to military relays. The result would be achievable BERs and throughput performance for a fading relay channel. Another possible extension would be to scale the relay model to a n-hop ad-hoc network of nodes. For military reporting this can be useful if the relay has several stranded parties to support, where each hop allows decoding and re-encoding to communicate information along the way.
3. Defining PU QOS-specific hysteresis regions through spectrum sensing - CR deployment over licensed subspace through outage-constrained threshold design demonstrated that a network-blind SU can still respect PU ITCs without added knowledge. This opens up an area in sub-classification of QOS-secure regions for PU spectrum sharing. By establishing a range of PU outage constraints for different SNR regimes, an adaptive threshold design can see more opportunities for SU transmission over licensed spectrum and correspondingly a higher achievable network rate.
4. Other statistical sensing applications for network-blind users - We have demonstrated how statistical sensing can allow network-blind users to allocate and communicate over sensed spectrum. However, from an observational capacity, this statistical information can be used in deriving network information for covert military operations. Network density, allocation and transmission patterns can all be extracted from just statistical sensing data with new and unique threshold design optimization goals, that will invaluable for military communications.

Appendices

Appendix A

Proof of Optimal Costs for PU

Payoff

The probabilistic events in the average PU payoff function are independent, and therefore we can represent (3.22) as

$$U' = \mathcal{P}(R_d > R_t) \cdot \mathcal{P}(R_{si}^{s'} > C_s) \cdot (R_t + C_s) + \mathcal{P}(R_d < R_t) \cdot \mathcal{P}(R_{si}^a > C_a) \cdot C_a. \quad (\text{A.1})$$

To solve for these probabilistic events we need to know the pdf of the distribution function. With Rayleigh fading channels, the channel power gains would follow an exponential distribution, and with unity noise variance, we can arrive at

$$\begin{aligned} \mathcal{P}(R_d > R_t) &= \mathcal{P}(P_p \cdot \gamma_p > 2^{R_t} - 1) \\ &= \int_{2^{R_t}-1}^{\infty} \frac{1}{SNR_p} \exp\left(-\frac{x}{SNR_p}\right) dx \\ &= \exp\left(-\frac{2^{R_t} - 1}{SNR_p}\right) \end{aligned} \quad (\text{A.2})$$

and similarly,

$$\mathcal{P}(R_{si}^a > C_a) = \exp\left(-\frac{2^{C_a} - 1}{SNR_{si}}\right) \quad (\text{A.3})$$

For the spectrum sharing probability event $\mathcal{P}(R_{si}^{s'} > C_s)$, the power of the i^{th} SU must be bounded by the instantaneous interference constraint in PIP (3.4), giving us a log-logistic distribution [54],

$$\begin{aligned}\mathcal{P}(R_{si}^{s'} > C_s) &= \mathcal{P}\left(\frac{\gamma_{si}}{\gamma_{3i}} > \frac{2^{C_s} - 1}{\mathcal{V}}\right) \\ &= \int_{\frac{2^{C_s} - 1}{\mathcal{V}}}^{\infty} (x + 1)^{-2} dx \\ &= \frac{\mathcal{V}}{2^{C_s} + \mathcal{V} - 1}.\end{aligned}\tag{A.4}$$

This gives us U' in (3.23), which is a sum of two univariate functions in C_s and C_a . Therefore, given the exclusivity of the sharing and access modes, we can differentiate U' against C_s and C_a respectively,

$$\frac{\partial U'}{\partial C_s} = \exp\left(-\frac{2^{R_t} - 1}{SNR_p}\right) \left[\frac{\mathcal{V}}{2^{C_s} + \mathcal{V} - 1} - \left(\frac{2^{C_s} \cdot \mathcal{V} \cdot \ln 2}{(2^{C_s} + \mathcal{V} - 1)^2} \right) \cdot (R_t + C_s) \right] \tag{A.5}$$

and,

$$\frac{\partial U'}{\partial C_a} = \left(1 - \exp\left(-\frac{2^{R_t} - 1}{SNR_p}\right) \right) \left(\exp\left(-\frac{2^{C_a} - 1}{SNR_{si}}\right) \right) \left[1 - \frac{2^{C_a} \cdot C_a \cdot \ln 2}{SNR_{si}} \right]. \tag{A.6}$$

It is clear to see that the partial derivatives, $\frac{\partial U'}{\partial C_s}$ and $\frac{\partial U'}{\partial C_a}$, have only one solution on equating to zero, giving us the optimal sharing and access costs in (3.24) and (3.25), respectively. It can also be verified that these costs are local maxima, given that both $\frac{\partial^2 U'}{\partial C_s^2} < 0$ and $\frac{\partial^2 U'}{\partial C_a^2} < 0$, and can be confirmed to be global maxima by plotting the payoff function, which shows only one maximum at $U'(C_s^*, C_a^*)$ for the feasible range of $C_s > 0$ and $C_a > 0$.

Appendix B

Proof of Closed Form Solutions for Outage-Constrained Thresholds for Licensed Deployment

These are well established closed-form results for Rayleigh fading channels, but for completeness we will elaborate them below. With Rayleigh fading, the channel power gains would follow an exponential distribution, therefore we represent the probability, $\mathcal{P}_r\left(\frac{P_p \cdot \gamma_{pti}}{N_0} \geq \lambda_{a_i}\right)$ in (5.7) as

$$\begin{aligned}\mathcal{P}_r\left(\frac{P_p \cdot \gamma_{pti}}{N_0} \geq \lambda_{a_i}\right) &= \mathcal{P}_r\left(\gamma_{pti} \geq \frac{\lambda_{a_i} \cdot N_0}{P_p}\right) \\ &= \int_{\frac{\lambda_{a_i} \cdot N_0}{P_p}}^{\infty} \frac{1}{\gamma_{pti}} \exp\left(-\frac{x}{\gamma_{pti}}\right) dx \\ &= \exp\left(-\frac{\lambda_{a_i} \cdot N_0}{P_p \cdot \gamma_{pti}}\right)\end{aligned}\tag{B.1}$$

and similarly, we get $\mathcal{P}_r\left(\log_2\left(1 + \frac{P_p \cdot \gamma_p}{N_0}\right) \geq R_t\right) = \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{P_p \cdot \gamma_p}\right)$.

APPENDIX B. PROOF OF CLOSED FORM SOLUTIONS FOR
OUTAGE-CONSTRAINED THRESHOLDS FOR LICENSED DEPLOYMENT

In solving the spectrum sharing threshold, the probability, $\mathcal{P}_r(R'_l < R_t)$ in (5.12) can be written as

$$\begin{aligned}
\mathcal{P}_r(R'_l < R_t) &= \mathcal{P}_r\left(\log_2\left(1 + \frac{P_p \cdot \gamma_p}{\sum_{i=1}^k P_{si} \cdot \gamma_{sip} + N_0}\right) < R_t\right) \\
&= 1 - \mathcal{P}_r\left(\gamma_p \geq (2^{R_t} - 1) \cdot \left[\frac{N_0}{P_p} + \sum_{i=1}^k \frac{P_{si}}{P_p} \cdot \gamma_{sip}\right]\right) \\
&= 1 - E\left[\exp\left(-(2^{R_t} - 1) \left[\frac{N_0}{P_p} + \sum_{i=1}^k \frac{P_{si}}{P_p} \cdot \gamma_{sip}\right]\right)\right] \\
&= 1 - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p} \cdot \gamma_p}\right) \cdot E\left[\exp\left(-\sum_{i=1}^k \frac{P_{si}}{\overline{P_p}} \cdot \gamma_{sip}\right)\right] \\
&= 1 - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p} \cdot \gamma_p}\right) \cdot \prod_{i=1}^k \left(\frac{\overline{P_p}}{\overline{P_p} + (2^{R_t} - 1) \cdot \overline{P_{si}}}\right). \quad (\text{B.2})
\end{aligned}$$

We can arrive at this because for a single SU interferer, P_{sj} , the distribution follows a log-logistic distribution [54] as

$$\begin{aligned}
\mathcal{P}_r\left(\frac{\gamma_p}{\gamma_{sjp}} \geq (2^{R_t} - 1) \left(\frac{\overline{P_{sj}}}{\overline{P_p}}\right)\right) &= \int_{(2^{R_t} - 1) \left(\frac{\overline{P_{sj}}}{\overline{P_p}}\right)}^{\infty} (x + 1)^{-2} dx \\
&= \frac{\overline{P_p}}{\overline{P_p} + (2^{R_t} - 1) \cdot \overline{P_{sj}}}. \quad (\text{B.3})
\end{aligned}$$

We can thus solve for (5.22) in a similar fashion.

Appendix C

Proof of Closed Form Solutions for the Optimized Thresholds for Unlicensed Deployment

These are well established closed-form results for Rayleigh fading channels, but for completeness we will elaborate them here. With Rayleigh fading, the channel power gains would take on an exponential distribution, whose pdf is given by $f_{X_i}(x) = \nu_i \exp(-\nu_i x)$ and a n-sum pdf given by $f_{S_i}(x) = \frac{\nu_i \exp(-\nu_i x) \cdot (\nu_i x)^{n-1}}{(n-1)!}$, where ν_i is the mean of the

distribution. Therefore, the probability event in (6.6) can be solved as

$$\begin{aligned}
 \mathcal{P}_r(\rho_i > \lambda_{a_i}) &= \mathcal{P}_r\left(\sum_{j=1, j \neq i}^n \frac{P_j \cdot \gamma_{tji}}{N_0} > \lambda_{a_i}\right) \\
 &= \mathcal{P}_r\left(\sum_{j=1, j \neq i}^n \gamma_{tji} > \frac{\lambda_{a_i} \cdot N_0}{P_j}\right) \\
 &= \int_{\frac{\lambda_{a_i} \cdot N_0}{P_j}}^{\infty} \frac{\frac{1}{\gamma_{tji}} \exp\left(-\frac{x}{\gamma_{tji}}\right) \cdot \left(\frac{x}{\gamma_{tji}}\right)^{n-1}}{(n-1)!} dx \\
 &= \sum_{k=0}^{n-1} \frac{\left(\frac{\lambda_{a_i} \cdot N_0}{P_j \cdot \gamma_{tji}}\right)^k \cdot \exp\left(-\frac{\lambda_{a_i} \cdot N_0}{P_j \cdot \gamma_{tji}}\right)}{k!}
 \end{aligned} \tag{C.1}$$

and therefore, similarly we can solve for $\mathcal{P}_r(R_{ai} \geq R_t) = \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{P_i \cdot \gamma_i}\right)$ in (6.8), which is the individual complementary cdf of the distribution.

When solving the probability event $\mathcal{P}_r(R \geq R_t)$ in (6.9), from our Proposition 3.1,

we have

$$\begin{aligned}
 \mathcal{P}_r(R \geq R_t) &= \prod_{i=1}^n \left[\mathcal{P}_r \left(\frac{P_i \cdot \gamma_i}{\sum_{j=1, j \neq i}^n P_j \cdot \gamma_{rji} + N_0} \geq \frac{2^{R_t} - 1}{n} \right) \right] \\
 &= \prod_{i=1}^n \left[\mathcal{P}_r \left(\gamma_i \geq \left(\frac{2^{R_t} - 1}{n} \right) \cdot \left[\frac{N_0}{P_i} + \sum_{j=1, j \neq i}^n \frac{P_j}{P_i} \cdot \gamma_{rji} \right] \right) \right] \\
 &= \prod_{i=1}^n \left[E \left[\exp \left(- \left(\frac{2^{R_t} - 1}{n} \right) \cdot \left[\frac{N_0}{P_i} + \sum_{j=1, j \neq i}^n \frac{P_j}{P_i} \cdot \gamma_{rji} \right] \right) \right] \right] \\
 &= \prod_{i=1}^n \left[\exp \left(- \frac{(2^{R_t} - 1) \cdot N_0}{n \cdot \overline{P_i} \gamma_i} \right) \cdot E \left[\exp \left(- \sum_{j=1, j \neq i}^n \frac{P_j}{P_i} \cdot \gamma_{rji} \right) \right] \right] \\
 &= \prod_{i=1}^n \left[\exp \left(- \frac{(2^{R_t} - 1) N_0}{n \cdot \overline{P_i} \gamma_i} \right) \cdot \prod_{j=1, j \neq i}^n \frac{\overline{P_i}}{\overline{P_i} + \frac{2^{R_t} - 1}{n} \overline{P_j}} \right]. \tag{C.2}
 \end{aligned}$$

We can arrive at this because for a single interferer SUj, the distribution follows a log-logistic distribution [54] as

$$\begin{aligned}
 \mathcal{P}_r \left(\frac{\gamma_j}{\gamma_i} \geq (2^{R_t} - 1) \left(\frac{\overline{P_j}}{\overline{P_i}} \right) \right) &= \int_{(2^{R_t} - 1) \left(\frac{\overline{P_j}}{\overline{P_i}} \right)}^{\infty} (x + 1)^{-2} dx \\
 &= \frac{\overline{P_i}}{\overline{P_i} + \left(\frac{2^{R_t} - 1}{n} \right) \overline{P_j}}. \tag{C.3}
 \end{aligned}$$

Author's Publications

- [1] I. Bajaj, Y. Gong, and X. J. Zhang, "Proactive spectrum sensing with probing power control in cognitive radio," *Int. Conf. on Sig. Proc. and Commun. Systems (ICSPCS 2010)*, Dec. 2010, pp. 1-5.
- [2] I. Bajaj and Y. Gong, "Cross-channel estimation using supervised probing and sensing in cognitive radio networks," *IEEE Int. Conf. on Commun. (ICC 2011)*, Jun. 2011, pp.1-5.
- [3] I. Bajaj, Y. Gong, and Y. H. Lee, "Time-efficient relaying strategies for military communication," *IEEE Military Commun. Conf. (MILCOM 2014)*, Oct. 2014, pp. 513-517.
- [4] I. Bajaj, Y. H. Lee, and Y. Gong, "A spectrum trading scheme for licensed user incentives," *IEEE Trans. on Commun.*, vol. 63, no. 11, pp. 4026-4036, Sep. 2015.
- [5] I. Bajaj and Y. H. Lee, "Outage-constrained sensing threshold design for decentralized decision-making in cognitive radio networks," *IEEE Trans. on Commun.*, vol. PP, no. 99, Oct. 2016.
- [6] I. Bajaj and Y. H. Lee, "Unlicensed spectrum assignment for a decentralized, network-blind and rate-achieving cognitive radio network," *under review IEEE Trans. on Veh. Tech.*, June. 2016.

Bibliography

- [1] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Jour. on Sel. Areas in Commun.*, vol. 23, no. 2, pp. 201-220, Feb. 2005.
- [2] Federal Communications Commission, Spectrum Policy Task Force, Nov. 2002, rep. ET Docket no. 02-135.
- [3] M. H. Islam, C. L. Koh, S. W. Oh, X. Qing; Y. Y. Lai, C. Wang; Y. -C. Liang; B. E. Toh, F. Chin, G. L. Tan, and W. Toh, “Spectrum survey in singapore: occupancy measurements and analyses,” *3rd Intl. Conf. on Cognitive Radio Oriented Wireless Netw. and Commun. (CROWNCOM 2008)*, Jul. 2008, pp. 1-7.
- [4] G. Staple and K. Werbach, “The end of spectrum scarcity [spectrum allocation and utilization],” *IEEE Spectrum*, vol. 41, no. 3, pp. 48-52, Mar. 2004.
- [5] T. Johnson, “FCC unveils roadmap for auctioning broadcast spectrum,” *The Chicago Tribune (Variety)*, Apr. 2014.
- [6] “Decision and explanatory memorandum issued by Infocomm Development Authority of Singapore on the framework for the reallocation of spectrum in the 900 MHz and 1800 MHz frequency bands,” *IDA Report*, Jan. 2008.
- [7] P. Jaya, “MCMC to reallocate more spectrum bands,” *The Sun Daily*, Apr. 2016.

- [8] B. Mook, "Speculators betting big on FCC TV spectrum auctions," *Current.org*, Feb. 2013.
- [9] "Standard for Cognitive Wireless Regional Area Networks (RAN) for Operation in TV Bands," *IEEE 802.22 WG on WRANs (Wireless Regional Area Networks)*, Jul. 2011.
- [10] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Commun. Surveys and Tutorials*, vol. 11, no. 1, pp. 116-130, Mar. 2009.
- [11] S. M. Kay, *Fundamentals of Statistical Signal Processing, Detection Theory*, Prentice Hall, 1993.
- [12] D. Cabric, A. Tkachenko, and R. Brodersen, "Spectrum sensing measurements of pilot, energy, and collaborative detection," in *Proc. IEEE Military Commun. Conf.*, Oct. 2006, pp. 1-7.
- [13] P. Wang, L. Xiao, S. Zhou, and J. Wang, "Optimization of detection time for channel efficiency in cognitive radio systems," in *Proc. IEEE Wireless Commun. and Networking Conf.*, Mar. 2007, pp. 111-115.
- [14] K. Kim, I. A. Akbar, K. K. Bae, J. -S. Uhn, C. M. Spooner, and J. H. Reed, "Cyclostationary approaches to signal detection and classification in cognitive radio," *2nd IEEE Intl. Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN '07)*, Apr. 2007, pp. 212-215.
- [15] Y. H. Zeng and Y. -C. Liang, "Covariance based signal detections for cognitive radio," in *Proc. 2nd IEEE Int. Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN '07)*, pp. 202-207, Apr. 2007.

- [16] H. Urkowitz, "Energy detection of unknown deterministic signals," in *Proc. IEEE*, vol. 55, no. 4, pp. 523-531, Apr. 1967.
- [17] M. Song, C. Xin, Y. Zhao and X. Cheng, "Dynamic spectrum access: from cognitive radio to network radio," *IEEE Trans. on Wireless Commun.*, vol. 19, no. 1, pp. 23-29, Feb. 2012.
- [18] T. Jing, W. Huarui, Y. Changchuan, M. Yan, and L. Jianfeng, "Dynamic frequency hopping vs. non-hopping in IEEE 802.22 systems," *IEEE Int. Conf. on Network Infrastructure and Digital Content, (ICNIDC 2009)*, Nov. 2009, pp. 95-99.
- [19] R. Zhang, "On peak versus average interference power constraints for protecting primary users in cognitive radio networks," *IEEE Trans. on Wireless Commun.*, vol. 8, no. 4, pp. 2112-2120, Apr. 2009.
- [20] L. Gao, X. Wang, Y. Xu, and Q. Zhang, "Spectrum trading in cognitive radio networks: a contract-theoretic modeling approach," *IEEE Journal on Sel. Area in Commun.*, vol. 29, no. 4, pp. 843-855, Apr. 2011.
- [21] X. Zhou and H. Zheng, "TRUST: A general framework for truthful double spectrum auctions," *IEEE INFOCOM 2009*, Apr. 2009, pp. 999-1007.
- [22] E. Yao, L. Lu, and W. Jiang, "An efficient truthful double spectrum auction design for dynamic spectrum access," *6th Intl. ICST Conf. on Cognitive Radio Oriented Wireless Netw. and Commun. (CROWNCOM 2011)*, Jun. 2011, pp. 181-185.
- [23] D. -J. Lee, "Adaptive cooperative spectrum sensing using random access in cognitive radio networks," *24th Annual Intl. Symp. on Pers., Indoor, and Mob. Radio Commun. (PIMRC 2013)*, Sep. 2013, pp. 1835-1839.

- [24] D. Treeumnuk, S. L. Macdonald, and D. C. Popescu, "Optimizing performance of cooperative sensing for increased spectrum utilization in dynamic cognitive radio systems," *IEEE Intl. Conf. on Commun. (ICC 2013)*, Jun. 2013, pp. 4656-4660.
- [25] L. Xiao, K. Liu, and L. Ma, "A weighted cooperative spectrum sensing in cognitive radio networks," *Intl. Conf. on Info., Netw. and Automation (ICINA 2010)*, Oct. 2010, vol. 2, pp. 45-48.
- [26] A. Ghasemi and E. S. Sousa, "Opportunistic spectrum access in fading channels through collaborative sensing," *Jour. of Commun.*, vol. 2, no. 2, pp. 71-82, Mar. 2007.
- [27] Y. -C. Liang, Y. Zeng, E. C. Y. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks," *IEEE Trans. on Wireless Commun.*, vol 7, no. 4, pp. 1326-1337, Apr. 2008.
- [28] N. Zhang, H. Chen, and L. Xie, "A Communication-overhead-aware cooperative spectrum sensing scheme in cognitive radio networks," *Intl. Conf. on Wireless Commun. and Sig. Proc. (WCSP 2012)*, Oct. 2012, pp. 1-5.
- [29] T. Andre, "Multi-hop networks with cooperative relaying assisted links," *IEEE Global Commun. Conf. (GLOBECOM 2013)*, Dec. 2013, pp. 115-120.
- [30] H. Adam, C. Bettstetter, and S. M. Senouci, "Multi-hop-aware cooperative relaying," *IEEE 69th Veh. Tech. Conf. (VTC 2009)*, Apr. 2009, pp. 1-5.
- [31] J. Zhang, H. Zhuang, Z. Luo, and Y. Li, "Opportunistic relay selection for rateless-coded cooperative relaying," *5th Intl. ICST Conf. on Commun. and Networking in China (CHINACOM 2010)*, Aug. 2010, pp. 1-5.

- [32] S. S. Ikki and M. H. Ahmed, "Performance Analysis of Cooperative Diversity with Incremental-Best-Relay Technique over Rayleigh Fading Channels," *IEEE Trans. on Commun.*, vol. 59, no. 8, pp. 2152-2161, Jun. 2011.
- [33] Y. Han, A. Pandharipande, and S. H. Ting, "Cooperative spectrum sharing via controlled amplify-and-forward relaying," *IEEE 19th Int. Symp. on Personal, Indoor and Mobile Radio Comm. (PIMRC 2008)*, Sep. 2008, pp. 1-5.
- [34] P. Gong, J. H. Park, J. M. Yoo, B. -S. Yu, and D. K. Kim, "Throughput maximization with multiuser non-selfish cognitive relaying in CR networks," *4th Intl. Symp. on Wireless Pervasive Computing (ISWPC 2009)*, Feb. 2009, pp. 1-5.
- [35] A. E. Shafie, T. Khattab, H. Saad, and A. Mohamed, "Optimal cooperative cognitive relaying and spectrum access for an energy harvesting cognitive radio: Reinforcement learning approach," *Intl. Conf. on Computing, Networking and Commun. (ICNC 2015)*, Feb. 2015, pp. 221-226.
- [36] S. H. Song, M. O. Hasna, and K. B. Letaief, "Prior zero forcing for cognitive relaying," *IEEE Trans. on Wireless Commun.*, vol. 12, no. 2, pp. 938-947, Jan. 2013.
- [37] National Telecommunications and Information Administration, United States Frequency Allocation Chart, Retrieved Jul. 16, <<https://www.ntia.doc.gov/files/ntia/publications/2003-allochrt.pdf>>.
- [38] Infocomm Development Authority of Singapore, Singapore Allocation Chart, Retrieved Jul. 16, <<https://www.ida.gov.sg/~media/Files/PCDG/Licensees/SpectrumMgmt/SpectrumNumMgmt/SpectrumChart.pdf>>.
- [39] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Trans. on Info. Theory*, vol. 51, no. 9, pp. 3037-3063, Sep. 2005.

- [40] N. Debbabi, I. Kammoun, and M. Siala, "Throughput maximization through adaptive decode-remodulate-and-forward relaying scheme," *IEEE 14th Workshop on Sig. Proc. Advances in Wireless Commun. (SPAWC 2013)*, Jun. 2013, pp. 545-549.
- [41] K. Tutuncuoglu, B. Varan, and A. Yener, "Throughput maximization for two-way relay channels with energy harvesting nodes: The impact of relaying strategies," *IEEE Trans. on Commun.*, vol. 63, no. 6, pp. 2081-2093, Apr. 2015.
- [42] S. Huang, J. Cai, and H. Zhang, "Relay selection for average throughput maximization in buffer-aided relay networks," *IEEE Intl. Conf. on Commun. (ICC 2015)*, Jun. 2015, pp. 1994-1998.
- [43] L. Wang, C. Cao, M. Song, and Y. Cheng, "Joint cooperative relaying and jamming for maximum secrecy capacity in wireless networks," *IEEE Intl. Conf. on Commun. (ICC 2014)*, Jun. 2014, pp. 4448-4453.
- [44] S. Katti, S. Gollakota, and D. Katabi, "Embracing wireless interference: analog network coding" *ACM SIGCOMM Comp. Comm. Review*, vol. 37, no. 4, pp. 397-408, Oct. 2007.
- [45] S. Zhang, S. C. Liew, and P. P. Lam, "Physical-layer network coding," *12th Annual Intl. Conf. on Mob. Computing and Networking (MobiCom 06)*, Sep. 2006, pp. 358-365.
- [46] R. H. Y. Louie, Y. Li, and B. Vucetic, "Practical physical layer network coding for two-way relay channels: performance analysis and comparison," *IEEE Trans. on Wireless Commun.*, vol. 9, no. 2, pp. 764-777, Feb. 2010.
- [47] H. Gacanin and F. Adachi, "Performance of physical layer network coding in a frequency-selective fading channel," *20th IEEE Intl. Symp. on Pers., Indoor and Mob. Radio Commun. (PIMRC 2009)*, Sep. 2009, pp. 928-932.

- [48] S. Zhang and S. C. Liew, "Channel coding and decoding in a relay system operated with physical-layer network coding," *IEEE Journ. on Sel. Areas in Commun.*, vol. 27, no. 5, pp. 788-796, Jun. 2009.
- [49] Y. Li and F. -C. Zheng, "Physical layer network coding with channel and delay estimation," *IET Commun.*, vol. 7, no. 11, pp. 1109-1116, Jul. 2013.
- [50] L. Lu, T. Wang, S. C. Liew, and S. Zhang, "Implementation of physical-layer network coding," *IEEE Intl. Conf. Commun. (ICC 2012)*, Jun. 2012, pp. 4734-4740.
- [51] L. Lu and S. C. Liew, "Asynchronous physical-layer network coding," *IEEE Trans. on Wireless Commun.*, vol. 11, no. 2, pp. 819-831, Feb. 2012.
- [52] W. Hu, D. Willkomm, M. Abusubaih, J. Gross, G. Vlantis, M. Gerla, and A. Wolisz, "Dynamic frequency hopping communities for efficient IEEE 802.22 operation," *Communications Magazine, IEEE*, vol. 45, no. 5, pp. 80-87, May 2007.
- [53] D. Willkomm, M. Bohge, D. Hollos, J. Gross, and A. Wolisz, "Double hopping: a new approach for dynamic frequency hopping in cognitive radio networks," *IEEE 19th Intl. Symp. on Personal, Indoor and Mobile Radio Comm, 2008*, Sept. 2008, pp. 1-6.
- [54] A. Ghasemi and E. S. Sousa, "Fundamental limits of spectrum-sharing in fading environments ," *IEEE Trans. on Wireless Commun.*, vol. 6, no. 2, pp. 649 - 658, Feb. 2007.
- [55] X. Kang, Y. -C. Liang, A. Nallanathan, H. K. Garg, and R. Zhang, "Optimal power allocation for fading channels in cognitive radio networks: ergodic capacity and outage capacity," *IEEE Transactions on Wireless Communications*, vol. 8, no. 2, pp. 940 - 950, Feb. 2009.

- [56] S. Stotas and A. Nallanathan, "Enhancing the capacity of spectrum sharing cognitive radio networks," *IEEE Trans. on Veh. Tech.*, vol. 60, no. 8, pp. 3768-3779, Aug. 2011.
- [57] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Trans. on Info. Theory*, vol. 43, no. 6, pp. 1986-1992, Nov. 1997.
- [58] I. Stiakogiannakis, P. Mertikopoulos, and C. Touati, "No regrets: Distributed power control under time-varying channels and QoS requirements," *52nd Annual Allerton Conf. on Commun., Control, and Computing (Allerton 2014)*, Oct. 2014, pp. 213-220.
- [59] B. Babadi and V. Tarokh, "GADIA: A greedy asynchronous distributed interference avoidance algorithm," *IEEE Trans. on Info. Theory*, vol. 56, no. 12, pp. 6228-6252, Dec. 2010.
- [60] S. Baksi and D. C. Popescu, "Distributed power allocation for rate maximization in cognitive radio networks with horizontal spectrum sharing," *IEEE Wireless Commun. and Netw. Conf. (WCNC 2015)*, Mar. 2015, pp. 932-936.
- [61] A. A. El-Sherif and A. Mohamed, "Decentralized throughput maximization in cognitive radio wireless mesh networks," *IEEE Trans. on Mob. Computing*, vol. 13, no. 9, pp. 1967-1980, Feb. 2014.
- [62] Y. Xiao, G. Bi, and D. Niyato, "Distributed optimization for cognitive radio networks using Stackelberg game," *IEEE Intl. Conf. on Commun. Sys. (ICCS 2010)*, Nov. 2010, pp. 77-81.
- [63] Y. Xu and S. Mao, "Stackelberg game for cognitive radio networks with MIMO and distributed interference alignment," *IEEE Trans. on Veh. Tech.*, vol. 63, no. 2, pp. 879-892, Aug. 2013.

- [64] B. Baykal, "Blind channel estimation via combining autocorrelation and blind phase estimation," *IEEE Trans. on Circuits and Systems I: Regular Papers*, vol. 51, no. 6, pp. 1125-1131, Jun. 2004.
- [65] T. Kim and I. Eo, "Reliable blind channel estimation scheme based on cross-correlated cyclic prefix for OFDM system," *8th Int. Conf. on Advanced Commun. Tech. (ICACT 2006)*, Feb. 2006, pp. 1-5.
- [66] C. Shin, R. W. Heath, and E. J. Powers, "Blind channel estimation for MIMO-OFDM systems," *IEEE Trans. on Veh. Tech.*, vol. 56, no. 2, pp. 670-685, Mar. 2007.
- [67] I. Bajaj and Y. Gong, "Cross-channel estimation using supervised probing and sensing in cognitive radio networks," in *IEEE Intl. Conf. on Commun. (ICC 2011)*, Jun. 2011, pp. 1-5.
- [68] S. Maleki, G. Leus, S. Chatzinotas, and B. Ottersten, "To AND or to OR: on energy-efficient distributed spectrum sensing with combined censoring and sleeping," *IEEE Trans. on Wireless. Commun.*, vol. 14, no. 8, pp. 4508-4521, Apr. 2015.
- [69] J. Lai, E. Dutkiewicz, R. P. Liu, and R. Vesilo, "Comparison of cooperative spectrum sensing strategies in distributed cognitive radio networks," *IEEE Global Commun. Conf. (GLOBECOM 2012)*, Dec. 2012, pp. 1513-1518.
- [70] R. Zhang and Y. C. Liang, "Exploiting hidden power-feedback loops for cognitive radio," in *3rd IEEE Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2008)*, Oct. 2008, pp. 1-5.
- [71] C. Yang, G. Y. Li, and G. Zhao, "Proactive detection of spectrum opportunities in primary systems with power control," *IEEE Trans. on Wireless Commun.*, vol. 8, no. 9, pp. 4815-4823, Sep. 2009.

- [72] I. Bajaj, Y. Gong, and X. J. Zhang, "Proactive spectrum sensing with probing power control in cognitive radio," *4th Int. Conf. on Sig. Proc. and Commun. Systems (ICSPCS 2010)*, Dec. 2010, pp. 1-5.
- [73] S. Huang, X. Liu, and Z. Ding, "Decentralized cognitive radio control based on inference from primary link control information," *IEEE Jour. on Sel. Areas in Commun.*, vol. 29, no. 2, pp. 394-406, Feb. 2011.
- [74] X. Kang, H. K. Garg, Y. -C. Liang, and R. Zhang, "Optimal power allocation for OFDM-based cognitive radio with new primary transmission protection criteria," *IEEE Trans. on Wireless Commun.*, vol. 9, no. 6, pp. 2066-2075, Jun. 2010.
- [75] Y. Zou, Y. -D. Yao, and B. Zheng, "Cooperative relay techniques for cognitive radio systems: spectrum sensing and secondary user transmissions," *IEEE Commun. Magazine*, vol. 50, no. 4, pp. 98-103, Apr. 2012.
- [76] B. Gedik, O. Amin, and M. Uysal, "Power allocation for cooperative systems with training-aided channel estimation," *IEEE Trans. on Wireless Commun.*, vol. 8, no. 9, pp. 4773-4783, Sep. 2009.
- [77] M. Morelli and U. Mengali, "A comparison of pilot-aided channel estimation methods for OFDM systems," *IEEE Trans. on Sig. Proc.*, vol. 49, no. 12, pp. 3065-3073, Dec. 2001.
- [78] J. -J. van de Beek, O. Edfors, M. Sandell, S. K. Wilson, and P. O. Borjesson, "On channel estimation in OFDM systems," *45th IEEE Veh. Tech. Conf.*, vol. 2, Jul. 1995, pp. 815-819.
- [79] L. Ye, L. J. Cimini, and N. R. Sollenberger, "Robust channel estimation for OFDM systems with rapid dispersive fading channels," *IEEE Trans. on Commun.*, vol. 46, no. 7, pp. 902-915, Jul. 1998.

- [80] L. Euler, “De serie Lambertina plurimisque eius insignibus proprietatibus,” *Opera Omnia*, vol. 6, no. 1, pp. 350 - 369, 1921 (orig. date 1779).
- [81] R. M. Corless, G. H. Gonnet, D. E. Hare, D. J. Jeffrey, and D. E. Knuth, “On the LambertW function,” *Advances in Computational Mathematics*, vol. 5, no. 1, pp. 329 - 359, 1996.
- [82] G. Choi, W. Zhang, and M. Xiaoli, “Achieving joint diversity in decode-and-forward MIMO relay networks with zero-forcing equalizers,” *IEEE Trans. on Commun.*, vol. 60, no. 6, June 2012.
- [83] S. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE Journ. on Sel. Area in Commun.*, vol. 16, no. 8, Oct. 1998.
- [84] S. K. Kuek, C. Yuen and W. H. Chin, “Four-node relay network with bi-directional traffic employing wireless network coding with pre-cancellation,” *IEEE Veh. Tech. Conf.*, May 2008, pp. 1201-1205.
- [85] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, “XORs in the air: practical wireless network coding,” *IEEE/ACM Trans. on Networking*, vol. 16, no. 3, pp. 497-510, May 2008.
- [86] Y. Tachwali, B. F. Lo, I. F. Akyildiz, and R. Agusti, “Multiuser resource allocation optimization using bandwidth-power product in cognitive radio networks,” *IEEE Jour. on Sel. Areas in Commun.*, vol. 31, no. 3, pp. 451-463, Mar. 2013.
- [87] R. Wang and M. Tao, “Blind spectrum sensing by information theoretic criteria for cognitive radios,” *IEEE Trans. on Veh. Tech.*, vol. 59, no. 8, pp. 3806-3817, Oct. 2010.

- [88] L. Sboui, Z. Rezki, and M. -S. Alouini, "Achievable rate of spectrum sharing cognitive radio systems over fading channels at low-power regime," in *IEEE Trans. on Wireless Commun.*, vol. 13, no. 11, pp. 6461-6473, Nov. 2014.
- [89] A. S. Kannan and E. M. Manuel, "Performance analysis of blind spectrum sensing in cooperative environment," in *Intl. Conf. on Control Commun. and Computing (ICCC 2013)*, Dec. 2013, pp. 277-280.
- [90] J. Zhu, Z. Xu, F. Wang, B. Huang, and B. Zhang, "Double threshold energy detection of cooperative spectrum sensing in cognitive radio," *3rd Intl. Conf. on Cog. Radio Oriented Wir. Netw. and Commun. (CROWNCOM 2008)*, May 2008, pp. 1-5.
- [91] J. C. F. Li, W. Zhang, and J. Yuan, "Opportunistic spectrum sharing in cognitive radio networks based on primary limited feedback," *IEEE Trans. on Commun.*, vol. 59, no. 12, pp. 3272 - 3277, Dec. 2011.
- [92] R. Zhang, "On active learning and supervised transmission of spectrum sharing based cognitive radios by exploiting hidden primary radio feedback," *IEEE Trans. on Commun.*, vol. 58, no. 10, pp. 2960 - 2970, Oct. 2010.
- [93] H. YuanYuan and S. Dey, "Power allocation in spectrum sharing cognitive radio networks with quantized channel information," *IEEE Trans. on Commun.*, vol. 59, no. 6, pp. 1644 - 1656, Jun. 2011.
- [94] L. Zhang, G. Zhao, G. Wu, and Z. Chen, "Proactive channel gain estimation for co-existence between cognitive and primary users," in *Global Commun. Conf. (GLOBE-COM 2012)*, Dec. 2012, pp. 1410-1415.
- [95] M. Nekovee, "Cognitive radio access to TV white spaces: spectrum opportunities, commercial applications and remaining technology challenges," *IEEE Symp. on New Frontiers in Dynamic Spectrum (DySPAN 2010)*, Apr. 2010, pp. 1-10.

- [96] M. Fitch, M. Nekovee, S. Kawade, K. Briggs and R. MacKenzie, "Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience," *IEEE Commun. Magazine*, vol. 49, no. 3, pp. 64-73, Mar. 2011.
- [97] S. Huang, X. Liu, and Z. Ding, "Distributed power control for cognitive user access based on primary link control feedback," *Proc. IEEE INFOCOM*, Mar. 2010, pp. 1-9.
- [98] H. Wang, J. Wang, and Z. Ding, "Distributed power control in a two-tier heterogeneous network," *IEEE Trans. Wireless Commun.*, vol. 14, no. 12, pp. 6509-6523, Dec. 2015.
- [99] S. Im, H. Jeon, and H. Lee, "Autonomous distributed power control for cognitive radio networks," *IEEE 68th Veh. Tech. Conf. (VTC 2008)*, Sep. 2008, pp. 1-5.
- [100] N. Gatsis, A. G. Marques, and G. B. Giannakis, "Power control for cooperative dynamic spectrum access networks with diverse QoS constraints," *IEEE Trans. on Commun.*, vol. 58, no. 3, pp. 933-944, Mar. 2010.
- [101] N. U. Hassan, C. Yuen, S. Saeed, and Z. Zhang, "Power control for sum-rate maximization on interference channels under sum power constraint," *IEEE Trans. on Veh. Tech.*, vol. 64, no. 2, pp. 593-609, Feb. 2015.
- [102] S. Kandukuri and S. Boyd, "Optimal power control in interference-limited fading wireless channels with outage-probability specifications," *IEEE Trans. on Wireless Commun.*, vol. 1, no. 1, pp. 46-55, Jan. 2002.
- [103] T. M. Shafaat, A. Ghodsi, and S. Haridi, "A practical approach to network size estimation for structured overlays," *3rd Intl. Workshop on Self-Organizing Systems (IWSOS 2008)*, vol. 5343, pp. 71-83, Dec. 2008.

- [104] N. Evans, B. Polot, and C. Grothoff, "Efficient and secure decentralized network size estimation," *11th Intl. Netw. Conf.*, vol. 7289, pp. 304-317, May. 2012.
- [105] S. Stotas and A. Nallanathan, "On the throughput maximization of spectrum sharing cognitive radio networks," *IEEE Global Telecomm. Conf. (GLOBECOMM 2010)*, Dec. 2010, pp. 1-5.
- [106] H. -J. Su and E. Geraniotis, "Adaptive closed-loop power control with quantized feedback and loop filtering," *IEEE Trans. on Wireless Commun.*, vol. 1, no. 1, pp. 76-86, Jan. 2002.