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# Transparent Spectrum Co-Access in Cognitive Radio Networks

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# TRANSPARENT SPECTRUM CO-ACCESS IN COGNITIVE RADIO NETWORKS

by

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# ABSTRACT

## TRANSPARENT SPECTRUM CO-ACCESS IN COGNITIVE RADIO NETWORKS

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The licensed wireless spectrum is currently under-utilized by as much as 85%. Cognitive radio networks have been proposed to employ dynamic spectrum access to share this under-utilized spectrum between licensed primary user transmissions and unlicensed secondary user transmissions. Current secondary user opportunistic spectrum access methods, however, remain limited in their ability to provide enough incentive to convince primary users to share the licensed spectrum, and they rely on primary user absence to guarantee secondary user performance. These challenges are addressed by developing a Dynamic Spectrum Co-Access Architecture (DSCA) that allows secondary user transmissions to co-access transparently and concurrently with primary user transmissions. This work exploits dirty paper coding to precode the cognitive radio channel utilizing the redundant information found in primary user relay networks. Subsequently, the secondary user is able to provide incentive to the primary user through increased SINR to encourage licensed spectrum sharing. Then a *region of co-access* is formulated within which any secondary user can co-access the licensed channel transparently to the primary user. In addition, a Spectrum Co-Access Protocol (SCAP) is developed to provide secondary users with guaranteed channel capacity and while minimizing channel access times. The numerical results show that the SCAP protocol build on the DSCA architecture is able to reduce secondary user channel access times compared with opportunistic spectrum access and increased secondary user network throughput. Finally, we present a novel method for increasing the secondary user channel capacity through sequential dirty paper coding. By exploiting similar redundancy in secondary user multi-hop networks as in primary user relay networks, the secondary user channel capacity can be increased. As a result of our work in overlay spectrum sharing through secondary user channel precoding, we provide a compelling argument that the current trend towards opportunistic spectrum sharing needs to be reconsidered. This work asserts that limitations of opportunistic spectrum access to transparently provide primary users incentive and its detrimental effect on secondary user

performance due to primary user activity are enough to motivate further study into utilizing channel precoding schemes. The success of cognitive radios and its adoption into federal regulator policy will rely on providing just this type of incentive.

This work is dedicated:

To my grandfather, Dr. Vern Backens, who instilled in me the value of family, faith and a good education.

To my father, Dan Backens, who helped launch this journey with words of wisdom and has seen me through to the end with words of encouragement.

To my mother, Rhonda Backens, a tireless advocate and friend.

Most of all to my wife, Jillian, who has been unwavering in her support and love.

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# CHAPTER I

# INTRODUCTION

In recent years, there has been a significant push to better utilize the wireless communications spectrum for data networks. Traditionally, the allocation model developed and regulated by the FCC and NTIA allows for commercial and federal users to lease spectrum in static blocks. These licenses guarantee the *primary users* (PUs) or license holder to have exclusive use of the spectrum block. The limited number of these blocks and the increasing value of communication networks has led to ever increasing demand and value for this spectrum. Although this traditional allocation model was originally viewed as a spectrum scarcity problem, recent studies conducted by the FCC and others [1] have found that it led to significant under-utilization of the spectrum. In other words, there are abundant spectrum opportunities in the temporal, spatial and frequency domains. The exploitation of these spectrum opportunities or *white spaces* is currently an area of significant research known as *cognitive radio networks* (CRNs) or dynamic spectrum access. The goal of these CRNs is to facilitate increased utilization of the spectrum by providing methods for sharing the licensed spectrum between PU and SU networks.

One of the primary catalysts in the development of dynamic spectrum access models has been advances in the development of *software defined radios* (SDR). These radios were first conceptualized by Mitola [2, 3] in the 1990s as a multiband radio completely reconfigurable through software. This break from traditional communications devices that were fixed in their modulation and signal processing capabilities has quickly led to greater levels of adaptive and intelligent spectrum access. Improvements in capabilities have come on both the receiver side with discretization of the communications signal now at the Intermediate Frequency (IF) and the transmitter side with adaptive code word design. Cognitive Radios are thus SDRs that are context-aware intelligent radios capable of autonomous reconfiguration to adapt to the communications environment [4]. This intelligence allows cognitive radios to dynamically monitor the wireless spectrum in search of under-utilized *white spaces* and exploit these opportunities to increase spectrum utilization and channel capacity.

## I.1 SPECTRUM SHARING MODELS

There have been a large number of proposals for facilitating the sharing of spectrum between primary and secondary users. They can be categorized into three spectrum sharing models based on the primary user information they are attempting to exploit: the underlay model, the interweave model and the overlay model [5, 6, 7, 8]. The underlay model relies on the secondary user to operate in the licensed spectrum as long as it does not cause the interference at any primary user receiver to exceed a minimum threshold known as the *interference temperature*. The interweave model relies on the secondary user to opportunistically access the licensed spectrum when the primary user is not transmitting. Finally, the overlay model utilizes coding schemes and a priori knowledge of the primary user transmissions to perform joint code word design to allow it to access the licensed spectrum without disrupting the primary user transmissions.

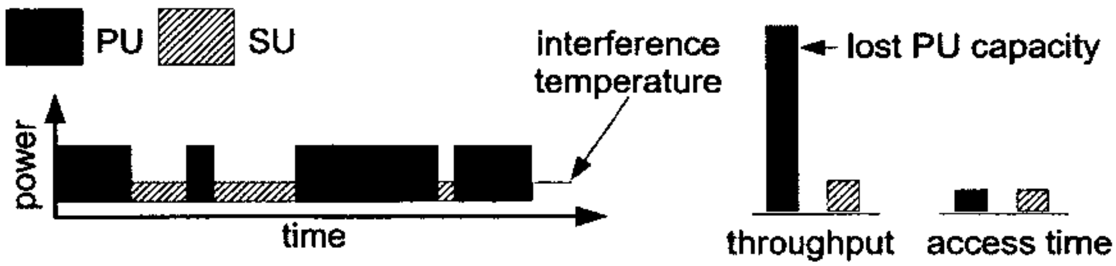



Fig. 1: Spectrum Sharing Underlay Model with Interference Temperature

### I.1.1 Underlay Model

The underlay model relies on a traditional spectrum sharing model where the primary user is willing to allow the secondary user access to the licensed spectrum but under transmission power constraints. Considering that any concurrent secondary user transmission will appear to the primary user receivers as interference, the primary user can set a limit on this noise to prevent significant reduction in channel capacity or increase in BER. How the primary user defines *significant* can be left to individual implementations; however, it is safe to assume that it will be as restrictive as possible. This model can be seen in Figure 1.

From the figure, it is clear that the secondary user network capacity is reduced, and the primary user loses some performance due to the increased noise. There are many proposed solutions for the secondary user to maintain this restriction; however, the most common is a simple transmitter power limitation. The result of such a power limitation combined with primary user transmissions also as interference to the secondary user results in limiting the secondary user to low-power transmission and with short transmission radius. The benefit of such a model, however, from a networking perspective is that this underlay model does support the secondary user's simultaneous access with the primary user. Subsequently, there is minimal access time delay for secondary users. However, since primary user and secondary user messages are not coded together, they are both determinants to the other. Plainly put, this is a win-lose scenario: the higher the primary user channel capacity, the lower the secondary channel capacity.

The underlay model was initially considered to be the spectrum sharing method of choice before the development of software defined radios. As recently as 2004, it remained one of the proposed solutions by both the FCC and NTIA for spectrum sharing; however, these proposals greatly limited its uses to only a small portion of the spectrum [71, 72].

### I.1.2 Interweave Model

In order to avoid the win-lose scenario of the underlay model that resulted from the mutual interference of the concurrent primary user and secondary user transmissions, the interweave model is based on the concept of spectrum sharing while avoiding simultaneous primary user and secondary user activity. If the secondary user can have access to the primary user's transmission schedule, then it is possible for the secondary user to *opportunistically* access the gaps in the primary user transmissions without interfering with the primary user transmission. This model is shown in Figure 2. In this ideal case, the primary user is unaware of the secondary user transmissions and unaffected by them. There are two fundamental issues with this model. First, the secondary user needs to acquire the primary user transmission schedule. This can be done using a primary user that has either easily accessible or predictable transmission schedules. For example, radar transmissions from weather towers have known transmission periods. However, in most cases, the primary

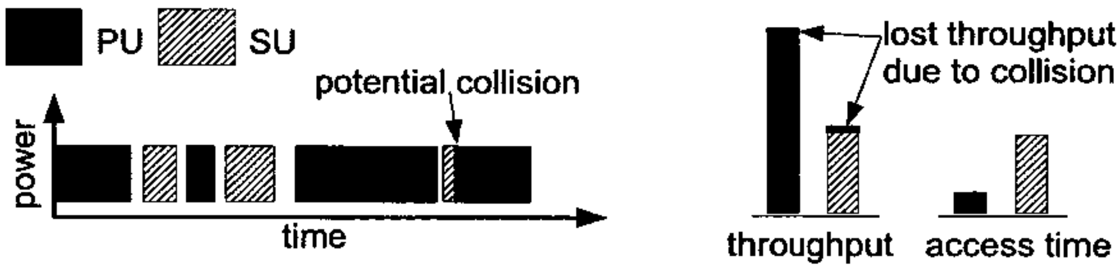



Fig. 2: Spectrum Sharing Interweave Model (Opportunistic) with Collision

user activity is driven by unknown data traffic and is not easily predicted.

Thus, the secondary user must detect the primary user activity dynamically and access the licensed spectrum when the primary user is absent. However, this also requires periodic monitoring of the spectrum while transmitting to ensure fast detection of the primary user's return to activity. Thus, with limited sensing capabilities while transmitting, the secondary user will overlap the primary user transmission for a small period of time. This will result in degradation of the primary user performance. The second challenge for the interweave model is the dependence of the secondary user transmission on the primary user activity. Specifically, if the primary user maintains a high level of channel activity, the secondary user will have few opportunities to access the channel. Once again, the model is faced with a win-lose scenario: the higher the primary user activity, the lower the secondary user overall capacity. The secondary user suffers from both reduced network throughput and potentially increased channel access times.

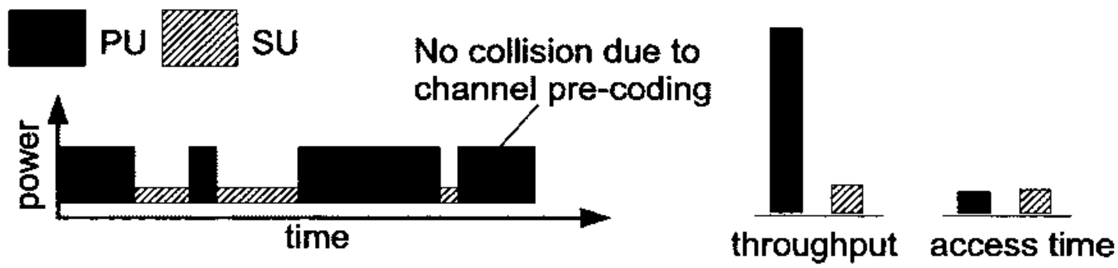



Fig. 3: Spectrum Sharing Overlay Model

### I.1.3 Overlay Model

The overlay cognitive radio model presents the opportunity for secondary users to access the licensed spectrum concurrently with primary users. As apposed to the underlay model with primary and secondary users having mutually interfering transmissions, the overlay model proposes leveraging code word design in the primary and secondary user to reduce this mutual interference. The gains in joint code word design for Multiple Input Multiple Output (MIMO) transceivers have given rise to the concept of collaborative precoding. The potential benefits can be seen in Figure 3. If the secondary user can have access to the primary user code word a priori, then there is the potential for the secondary user to use this information to reduce the mutual interference caused by simultaneous primary and secondary user transmissions. This is commonly referred to as side information. In the related works, we will discuss some of the methods that have been proposed realizing the overlay model and present our work based on dirty paper coding to realize such a model.

The benefit of the overlay model is that simultaneous primary user and secondary user

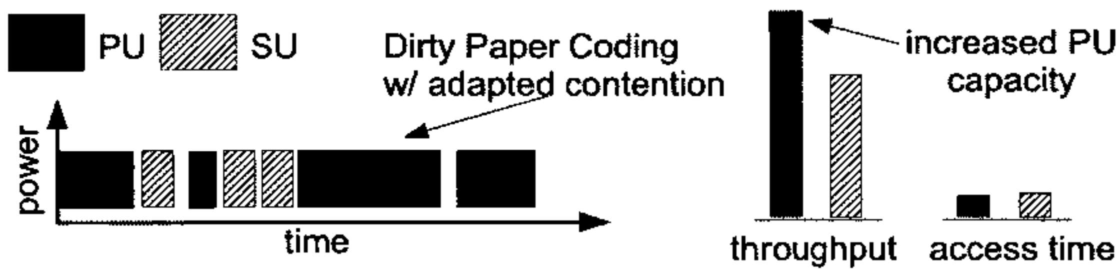



Fig. 4: Co-Access Spectrum Overlay Model

transmissions may be adapted to prevent mutual interference and thus loss of channel capacity. In fact, often through the use of dirty paper coding, the overall channel capacity can be increased due to the diversity of transmitters. We will consider the limitations of such increased channel capacity later in this work. The result of the overlay model is potentially a win-win scenario where the channel utilization is increased along with minimal secondary user access time while primary user performance is not reduced. Although this model relies heavily on coding theory and the manipulation of individual code works, we assert the benefits outweigh the added complexity. The concept of our new model is presented in Figure 4 and demonstrates the benefits of utilizing dirty paper coding to increase SU performance.

## I.2 DIRTY PAPER CODING

A key method for realizing the primary user and secondary user co-access model is dirty paper coding. First proposed by Costa in 1983 [9], the key concept relies on a unique interference cancelation model. It was commonly known that for a wireless communications transmission, if a receiver was able to know that channel state information (CSI) perfectly, then any noise added during transmission could be canceled without loss of information capacity. Costa considered a Gaussian channel where instead of the receiver knowing perfect CSI, the transmitter knew it a priori. He proposed that instead of the transmitter attempting to pre-cancel the known interference, it instead adapted its transmission code word in such a way that the receiver would be able to recover the code word without the associated power loss of cancelation. The well known analogy is that of a writer attempting to write a message that will be passed to a recipient but will collect dirt as it is being passed. Obviously the accumulation of dirt with the written message will make it more difficult for the receiver to recover the initial message; the dirt and the message will be indistinguishable. However, if the dirt will be normally distributed and the location and density known to the writer, then he will be able to adapt his writing in such a way that the recipient will be able to recover his original message. The key breakthrough of his proposal was that the pre-coding of the message was not simply subtracting the known CSI, but instead choosing a code word in the same direction as the noise but far enough apart from other code words to still be distinguished.

In this work, we will consider the dirty paper coding schemes, but instead of knowing the CSI perfectly a priori (which is difficult in fast fading channels), we will treat the primary user transmission as noise and pre-code with it. This method will be presented in more detail in the subsequent chapters.

It should be noted that the use of dirty paper coding to precode the secondary user code words is not to be confused with linear network coding techniques. Linear coding relies on the secondary user creating a packet to transmit that is a linear combination of its own packet and the primary user's decoded packet [73]. This resulting packet is then encoded and transmitted; however, there is no consideration for physical layer interference generated at the primary receiver by this new transmission. Dirty Paper coding attempts to precode individual code words to mitigate interference at the primary user. Although network coding increases the information in a single message in a multihop scenario, it does not support transparent co-access since it will be seen only as noise to the primary user receiver.

## I.3 PRIMARY USER INCENTIVE

One of the key obstacles to spectrum sharing is providing incentive for the licensed user to allow spectrum sharing with secondary users. Since the spectrum is considered a scarce natural resource and licenses given through an escalating auction process, primary users tend to be large companies with huge capital invested in acquiring the exclusive use license. As an example, in 2008, FCC auction 73 took place with 62 MHz of spectrum in the 700MHz TV bands up for sale with a net proceed of approximately 19 billion dollars. Among those most active during the bidding were tech and communication giants Verizon, AT&T and Google [10, 11]. Thus, in order to motivate the primary user to allow spectrum sharing, external influences are needed.

The federal government has become increasingly active in their support of sharing of licensed spectrum bands. In 2003, the Office of the President of the United States formed a Federal Government Spectrum Talk Force to study the current static spectrum policy [12, 13]. As a response to the recent awareness of the under-utilization of the spectrum, the Office of the President authored a memo in support of spectrum reallocation or sharing.

The 2010 Presidential Memo, "Unleashing the Wireless Broadband Revolution", called for 500 MHz of spectrum to be made available by federal and commercial users for exclusive use or made available for shared access [14]. However, after more than a year of pressure, the Presidents Council of Advisors on Science and Technology issued a report in July of 2012 "Realizing the Full Potential of Government Held Spectrum to Spur Economic Growth" that indicated that the cost for federal spectrum license holders to vacate under-utilized spectrum was too high. Instead, they recommended that spectrum be shared with commercial users [15]. Finally, in 2013, the DoD Electromagnetic Spectrum Strategy reaffirmed this new federal push to force primary users to share the spectrum. In it, was stated that "new access techniques will almost certainly create regulatory pressure to share Federal spectrum via dynamic access or other similar technologies [16]." Thus, licensed spectrum users are beginning to be pressured to find mutually beneficial spectrum sharing strategies.

As a result of this federal pressure, a number of studies have been conducted to consider if the current model for spectrum auctions is at fault for the lack of efficient use of the spectrum [17][18][19]. In response to FCC spectrum auctions being based solely on money, several proposed solutions use auction models that include network demand to dynamically allocate the spectrum lease [20][21][22][23][24][25]. Although the FCC is likely to continue to modify the spectrum auction rules for upcoming white space auctions to improve sharing incentive, the vast majority of spectrum has already been auctioned and will require sharing incentives for existing primary users. In addition, many of the existing primary users may be unwilling or unable to participate in any future spectrum sharing if it requires significant change to the primary user architecture or hardware.

## I.4 CHALLENGES

Mutually exclusive spectrum sharing models such as the opportunistic spectrum model suffer from a few fundamental problems. First, since the secondary user must vacate any spectrum when the licensed primary user becomes active, the secondary user communication is arbitrarily disrupted. This can result in incomplete transmission frames at the MAC layer, which can be just be retransmitted at a later time. However, the problem is that many higher layer networking protocols rely on active sessions. For example, the most popular transport layer protocol, TCP, has timeout thresholds on their sessions and will terminate them if transmission is disrupted at any point along a data flow. This is compounded by the need to re-establish application layer sessions when a secondary user regains access to the licensed spectrum. This means that the first portion of any secondary user transmission after a long PU transmission will be primarily comprised of a session establishing handshakes. In addition, in the case of TCP, the Slow Start mechanism and contention window will make SU nodes only reach maximum theoretical capacity after a ramp up period.

The second challenge with opportunistic spectrum access models is that once a secondary user gains access to the licensed spectrum, it must periodically halt transmission to attempt to detect primary user activity. The more difficult it is to detect the primary user, the longer the spectrum sensing period will be. Since spectrum sensing and transmitting are not possible concurrently, the secondary user again loses performance even if the primary user is not active. The possibility of activity is enough to reduce secondary user performance. The more precise the primary user constraints on collisions, the shorter the secondary user channel accesses can be. Since the secondary user is not providing benefit to the primary user for sharing, the primary user will be motivated to set very strict detection thresholds for the secondary user.

# CHAPTER II

# PROBLEM STATEMENT AND CONTRIBUTIONS

With increasing government pressure and secondary user demand on developing spectrum sharing techniques, a mutually beneficial spectrum sharing model is needed. The work presented in this dissertation develops a solution to the problem of secondary users transparently co-accessing the licensed spectrum with primary users. In developing a solution, this work will address the following three components of this problem.

- This work addresses the problem of providing incentive to the licensed primary user to motivate it to allow secondary user co-access opportunities.
- This work addresses the problem of providing a minimum secondary user networks performance regardless of primary user activity.
- This work addresses the challenge of increasing secondary user channel capacity during periods of primary user absence.

The work presented in this dissertation addresses the challenges of achieving transparent co-access in cognitive radio networks between primary and secondary users. The first contribution is a novel cognitive radio network architecture that allows simultaneous primary and secondary user spectrum access while providing a SINR incentive to the primary user. A mathematical model is derived to formulate the constraints necessary for this co-access and determine a *region of co-access* relative to the primary user networks where secondary users can co-access with primary users concurrently. An algorithm is also developed to select the co-accessible primary and secondary links within a cognitive radio network that will maximize the overall network performance. Since it is possible for multiple secondary user links to qualify for co-access with a single primary user link, this provides the optimal secondary user link to co-access with a primary user transmission.

The second contribution presented in this work is a spectrum co-access protocol (SCAP) to support performance guarantees for secondary users who are accessing licensed user spectrum concurrently with primary users. This protocol is motivated by the elimination of disruptions to secondary user communications due to primary user transmissions and the inclusion of secondary users that are outside of the *region of co-access* in the medium access control protocol. SCAP facilitates finding spectrum access opportunities for unqualified secondary user nodes and optimized channel co-access for qualified nodes. Through this adaptive co-access protocol, the secondary user networks are able to maintain low channel access latency and minimum throughput capacity.

The third contribution of this work is to determine the performance limits of the co-access dirty paper coding technique within a secondary user network. Motivated by the benefits of channel precoding to create co-access opportunities, this work considers utilizing the same technique between secondary user transmissions when the primary user is idle. The secondary user network is modeled as multihop network and the pre-coding technique is used to eliminate noise between secondary user transmissions. Under certain conditions, it is shown that the traditional secondary user channel capacity model of $O(1/n)$ can be improved to approach $O(1/2)$ using sequential secondary user transmissions.

The remainder of this dissertation is organized as follows. Chapter III presents the related work in the mentioned fields of research as well as their major contributions. Chapter IV presents the secondary user co-access architecture and defines the *region of co-access* for the secondary user based on the primary user incentive constraints. This chapter also provides an algorithm for selecting the optimal secondary users to co-access with each primary user relay link. This leads directly to the work in Chapter V, which develops a secondary user medium access control protocol termed SCAP that allows for secondary user capacity and channel access time to be improved when the primary user is active. This chapter presents both an adaptive round robin co-access scheme for when the primary user is active and a priority contention based access scheme when the primary user is absent. Motivated by the benefits of our channel precoding to increase the utilization of the licensed spectrum, in Chapter VI, we study the application of precoding on the secondary user multihop network, thus continuing our goals of providing primary user incentive and increasing secondary user performance in shared licensed spectrum. Finally, in Chapter VII, we discuss the conclusions of our work, implications in the field of cognitive radio networks and implications for federal spectrum policy management and consider future directions of this research.

# CHAPTER III

# LITERATURE REVIEW

In this chapter, we will discuss the background of cognitive radio networks, spectrum sharing models, secondary user MAC protocols and secondary user performance enhancements through channel precoding. Special care will be given to the study of dirty paper coding by secondary users for co-access with primary users and additionally with other secondary users for channel capacity improvements. The current research work that is closely related to this dissertation will be discussed, and we present motivation for our approach to solving the licensed spectrum sharing problem.

## III.1 DYNAMIC SPECTRUM ACCESS ARCHITECTURES

In the past decade, there have been extensive studies on opportunistic spectrum access and cognitive radio networks [26, 27, 28, 29, 30, 31, 32]. Good general overviews for dynamic spectrum access and cognitive radio networks can be found in [33, 34].

The issue of the disruption to secondary communications in the opportunistic spectrum access architecture has drawn attention recently, and several schemes have been proposed to enable SUs to continue to access spectrum after the PUs re-appear. For example, the authors in [35] proposed a scheme that exploits the network coding technique to incentivize PUs to cooperate with SUs in spectrum access so that SUs can access spectrum even when PUs are active. Nevertheless, the spectrum access of SUs is not transparent to PUs in this scheme. The PUs must have the knowledge of SUs and need to listen to the packets from

SUs.

Contrary to the scheme in [35], the spectrum access of SUs in the proposed DSCA architecture is transparent to PUs in that PUs do not need to have any knowledge of SUs. The DSCA architecture utilizes the DPC technique to achieve transparent incentivizing of PUs.

DPC was first introduced by Costa in [9] as a proof for maintaining *signal to interference plus noise ratio* (SINR) at the receiver, given the transmitter had prior knowledge of the interference state. It was shown that DPC could achieve the largest known capacity region for cognitive radio networks in a channel model with one PU node pair and one SU node pair as long as the SU transmitter had a priori knowledge of the PU messages [36]. Several later studies have shown that SUs can coexist with PUs without degrading the PU channel capacity [37, 38, 39].

However, the success of DPC in a cognitive radio network relies on the SU transmitter having a priori knowledge of the PU transmitted packet. This is a non-trivial problem, and there have been several proposed methods for achieving this. In traditional one-hop infrastructure networks, the authors of [40, 41] proposed using DPC for interference reduction between base stations by leveraging the high bandwidth of the wired backbone to obtain a priori knowledge of base stations downlink data. However, the PUs are unlikely to share a wired high-bandwidth backbone with SUs.

Another method is to use early decoding techniques to predict the PU packet before it is completely transmitted and use both the SU transmitter and SU receiver to relay the code word [42]. The proposed three stage transmission model consists of 1) the SU transmitter and SU receiver receiving the first portion of the PU transmission, 2) the SU transmitter conducting DPC with the transmission, and 3) the SU transmitter and SU receiver relaying the PU transmission. This, however, requires the PU to use a specific coding scheme that is compatible with early decoding (still an active area of research) and places extra constraints on both the SU transmitter and the SU receiver channel gains.

The authors in [43] considered SUs achieving a priori knowledge of the PU message by exploiting retransmission opportunities when PU transmissions are corrupted or lost due to poor channel conditions. This scheme requires the SU receiver to be able to decode corrupt PU transmissions and then signal the SU transmitter to transmit simultaneously with the PU retransmission. The SU receiver is able to recover the SU transmitter transmission successfully. However, this will result in a reduction in PU transmission rate due to increased noise and correlates SU increased performance to decreased PU channel quality, which is unlikely to be tolerated by any PU network for a prolonged period of time.

In contrast to these approaches, DSCA intelligently exploits the ability of SUs to overhear PU packet forwarding in multi-hop PU networks to obtain the PU packet a priori.

There has been significant attention to the use of *interference alignment* as a means of achieving channel capacity in a multi-user interference channel [44]. Interference alignment requires imposing a structured codebook on the PU network based on the presence or absence of SU transmissions. This adaptation comes with a potential reduction of PU capacity. For cognitive radio network models with PUs fully coordinating with SUs, interference alignment has a potential for maximizing the joint transmission capacities. However, this approach requires coordination between PUs and SUs and, hence, is not transparent to the PU network. Our proposed DSCA architecture is transparent to PU, i.e., it does not need coordination between PUs and SUs and transparently offers incentives to the PU.

## III.2 SU MAC PROTOCOLS

Recently, there has been significant interest in MAC-protocols for CRNs specifically. As every new method for accessing licensed spectrum is proposed, soon, a counterpart MAC protocol is developed. A sampling of some of the current challenges and the most popular cognitive MACs can be found in [45, 46].

The first challenge for multihop cognitive radio network is addressing the need for a control channel to synchronize and exchange sensing and scheduling information. One of the common assumptions is that a separate common control channel (CCC) that is interference free from the PU is accessible. In [47] the authors present such a model and use it to exchange distributed sensing information to better recognize when PUs are active. However, this static control channel is often unrealistic. If we are desiring the SUs to use licensed spectrum, then the CCC should also be using it.

In contrast, in [48] a multichannel cognitive protocol with distributed CCC is presented. This C-MAC protocol has the flexibility to move the CCC to more suitable channels as they become available but is limited to how quickly it can pass around the scheduling information. In this case, all the SUs have the same set of channels to choose from. However, in large SU networks, it is likely that this will not be the case. Thus, in [49], the authors look at the problem of synchronization of both the timing and the actual spectrum bands between SUs. It is easy to see the complications from needing a separate CCC. For our proposed SCAP protocol, we look to focus on using single channel co-access with the PU to reduce the need for a separate CCC.

In addition to control channel concerns, motivating PUs to allow SU access is also an active research challenge. In [50], the authors propose a method exploiting primary user retransmissions by acting as a relay for the PU. They exploit PU weak channel characteristics and subsequent retransmissions to act as a relay to incentivize the PU to allow them access to the channel. Further, in [51], the authors apply a cross-layer optimization of physical layer and MAC to show the significant performance benefits if a cognitive MAC layer can exploit physical layer coding techniques. However, as with [50], the authors attempt to exploit PU transmission failures. Our DSCA architecture and proposed SCAP protocol is not a direct cross-layer optimization, but rather exploits physical layer coding schemes to allows for co-access with successful PU transmissions. Our underlying architecture motivates the PU with increased received signal strength through dirty paper coding [52]. The SCAP protocol demonstrates that there are performance incentives to participating with PU transmissions.

## III.3 CAPACITY OF COGNITIVE RADIO NETWORKS

To improve secondary user performance, it is necessary to consider improving channel capacity. The discussion of capacity in wireless networks was defined in the seminal work [53], in which for an ad-hoc network, an upper theoretical bound was determined to be $\theta(\frac{1}{\sqrt{n}})$. This constraint was given with an optimally chosen geometric configuration with all nodes at a one hop distance. However, if this constraint is relaxed to randomly distributed nodes, then the capacity falls significantly to $\theta(\frac{1}{\sqrt{n \log n}})$. The consideration for the multi-hop nature of ad hoc networks was presented in [54]. This work used the opportunistic spectrum model with the assumption that two nodes within the same collision domain must use different time slots to transmit. The subsequent channel capacity was determined by the collision domain to be in the worst case $O(\frac{1}{n})$.

There have been several attempts at using the cognitive capabilities of secondary users in multi hop networks for increasing throughput. In [55], the authors present a quantitative comparison of the differences between traditional opportunistic interweave access models and the potential of overlay spectrum access models in general. The numerical results showed clearly that cognitive overlay models performed significantly better than the two switch interweave model for a single hop.

A model for a one hop cognitive overlay network is presented in [37] for the two receiver two transmitter case. Specifically, the case where the secondary user has *non-causal* knowledge of the primary user message is considered. This model is shown in Figure 23. As [37] concludes, the use of dirty paper coding or *Costa coding* in this model can achieve a capacity upper bounded by the interference free AWGN channel for both transmissions. This is an adaptive coding scheme which bases the secondary transmitter's code word on the primary transmission code word and requires the flexibility of a cognitive radio. The achievable rates in this two receiver two transmitter model are defined in [37].

Furthermore, in [56], the authors describe the throughput in multihop cognitive radio networks as a relaying problem with joint cooperation between the transmitters. Specifically, they study the exploitation of a broadcast channel with multiple receivers. This is similar to the MIMO broadcast channel but using multiple secondary users to achieve transmitter diversity. In the MIMO broadcast channel case, as the collision domain is reduced and transmitter cooperation is exploited, the utilization of the total channel capacity available increases. As shown in [25], when the capacity is maximized in a TDMA based

MIMO network, a natural byproduct is increased fairness. However, these techniques considered just the broadcast case and not the case of multihop traffic in the network. In [57], a comparison of ad hoc cooperative broadcast techniques is presented. Specifically, the performance of dirty paper coding was compared with both time division successive broadcast and time division relaying. The authors conclude that dirty paper coding can outperform other methods of relaying if all messages are known non-causally to all transmitters. Further studies into the performance benefits of cooperation in the two transmitter two receiver model were conducted in [58]. The cooperation among the transmitters was shown to outperform cooperation among receivers. This result gives support to the use of channel precoding at the transmitter over interference cancelation at the receiver to increase secondary channel capacity. This performance increase, however, was dependent on the high SINR of a separate transmitter cooperation channel to achieve a priori knowledge of the transmitted message. The higher the quality of this cooperation channel, the greater the overall capacity gain of the channel.

The clear potential benefit to utilizing channel precoding to increase the channel capacity leads to the consideration for application in multihop cognitive radio networks. This was initially exploited in [59], where pairwise channel precoding in a multihop cognitive network was considered. The throughput overall for the multihop topology was increased and demonstrated the potential that overlay techniques could improve multihop capacity overall beyond nominal limits found in [54]. These results found in [37] state that with small values of $a$ (see Figure 23), the capacity of a single primary and single secondary user would be $R_p = R_c = \gamma B$ with $0.937 \leq \gamma \leq 0.999$ for $0.1 \leq a \leq 0.9$. However, the extension of cognitive overlay beyond two node pairs was not considered.

The use of channel precoding to increase channel capacity for use in multihop secondary user networks is presented in Chapter VI. The work presented there seeks to exploit the multihop nature of secondary user networks to increase performance during periods of primary user inactivity.

# CHAPTER IV

# DYNAMIC SPECTRUM CO-ACCESS ARCHITECTURE

This chapter studies the dynamic spectrum sharing problem under two current cognitive radio models. The limitations of the interweave based opportunistic spectrum access scheme, which relies on primary user transmission gaps, is clearly defined, and a new spectrum sharing model is presented. In particular, the resurgence of primary users disrupts secondary communications, which can result in poor performance for secondary users. Our proposed novel architecture for dynamic spectrum access, termed *Dynamic Spectrum Co-Access* (DSCA), enables the primary user and the secondary user to simultaneously access licensed spectrum. With DSCA, secondary users transparently incentivize primary users through increasing the primary user performance so that secondary users can access spectrum simultaneously with primary users; hence, there is no disruption to secondary communications due to the resurgence of primary users. A mathematical model is developed in Section IV.2 to formulate the minimum incentives for the spectrum co-access between the primary user and the secondary user and compute the *region of co-access* to determine the secondary users that can co-access with a given primary user. An algorithm is then developed in Section IV.2.5 to select the co-access primary and secondary links to maximize network performance. Numerical results are presented in Section IV.3 that indicate that the DSCA architecture significantly improves performance compared with the current architecture of dynamic spectrum access. Conclusions and implications for this new spectrum sharing architecture are found in Section IV.4

## IV.1 INTRODUCTION

In recent years, there has been a significant push to better utilize the wireless communications spectrum for data networks. The traditional model for spectrum allocation by the FCC has been to give licenses for the majority of the usable spectrum to commercial *primary users* (PUs) for exclusive use. However, many studies have shown that a large portion of licensed spectrum is under-utilized. In other words, there are abundant *spectrum opportunities* in the temporal, spatial, and frequency domains. The exploitation of these spectrum opportunities is currently an area of significant research known as *dynamic spectrum access* or *cognitive radio networks*. In the current dynamic spectrum access architecture known as *opportunistic spectrum access*, *secondary users* (SUs) opportunistically access the licensed spectrum of PUs, while PUs have privileged access of the licensed bands. With OSA, SUs can access a licensed band only if this band is not being used by the PUs. Whenever the PU traffic re-appears on a band, SUs must vacate the band immediately and the on-going SU communication is disrupted. The requirement that SUs cannot access spectrum simultaneously with PUs results in significant overhead on spectrum sensing and spectrum handoff, which in turn results in poor performance for cognitive radio networks.

In this chapter, we propose a new architecture for dynamic spectrum access, termed *Dynamic Spectrum Co-Access* (DSCA), to enable SUs to simultaneously access licensed spectrum with PUs through transparently incentivizing PUs. Note that in this chapter, 'co-access' means that SUs simultaneously access spectrum with PUs, not time-share the spectrum with PUs as in opportunistic spectrum access. It is well understood that PUs are not willing to share their licensed spectrum without incentives. The novelty of DSCA is that the SU communication in a licensed band can provide a significant performance improvement to the PU communications. Hence, PUs are incentivized to welcome the spectrum co-access of SUs. DSCA has several merits: (1) PUs can achieve greater data rates when SUs co-access spectrum with PUs; (2) PU transmitters and receivers require no prior knowledge of SU transmitters or receivers; (3) PUs operate without knowledge of SU spectrum co-access, i.e., the SU spectrum access is transparent to PUs; (4) being able to access spectrum simultaneously with PUs, SUs significantly reduce the overhead of spectrum handoff since the disruption of PU resurgence to SU communication is eliminated.

DSCA utilizes a channel precoding technique, *dirty paper coding* (DPC), to achieve co-access between PUs and SUs. It exploits redundancies in PU transmissions to allow SUs the ability to precode SU transmissions with this knowledge. Specifically, DSCA exploits the redundant transmissions found in multihop wireless networks to provide mutually beneficial spectrum co-access for PUs and SUs.

Real world applications for multihop PU networks are common in modern wireless networks. As an example, in the United States currently, terrestrial digital TV broadcasts are routinely retransmitted by both high power and low power TV translators to help provide service to low signal areas. In addition, there is an increasing number of multi-hop wireless mesh network deployments. Since mesh nodes are required to relay transmissions for each other, DSCA would be able to take advantage of these wireless relays.

The main contributions of this chapter are summarized as follows.

- We propose a *dynamic spectrum co-access* (DSCA) architecture that enables SUs to simultaneously transmit with PUs through transparently providing incentives to PUs so that the SU communications are not disrupted by the resurgence of PUs.

- We have derived a mathematical model to characterize the *co-access incentives* of both PUs and SUs.

- We have developed a model to compute the *region of co-access* of each PU based on the co-access incentive requirements to identify the SUs that are eligible to co-access with the PU.

- We have developed an algorithm to select the co-access PU and SU links to obtain the maximum performance for SU network while satisfying PU incentive requirements.

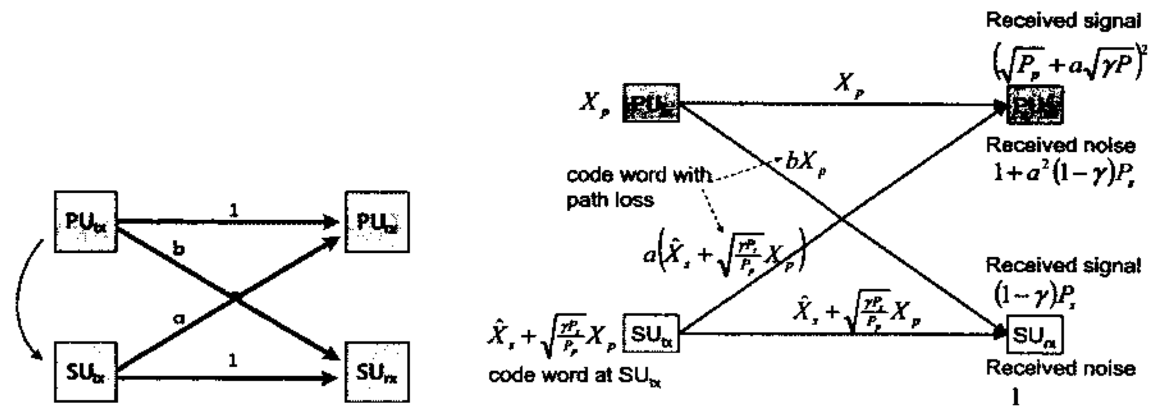
## IV.2 DYNAMIC SPECTRUM CO-ACCESS (DSCA)

In this section, we describe the DSCA architecture. With DSCA, when PUs are not transmitting, SUs freely access the spectrum, similar to the opportunistic spectrum access architecture. On the other hand, when PUs are active, SUs provide incentives to PUs so that simultaneous transmission by SUs is allowed. In the following, we focus on the operation of DSCA in the latter case, i.e., how the SU incentivizes the PU to enable spectrum co-access. We first consider a simple network with one PU node pair and one SU node pair and then discuss DSCA with multi-hop PU networks, such as cellular back-haul networks, emergency service networks, military networks, television networks, etc. We also introduce two key components of DSCA, *co-access incentives* and *region of co-access*. The co-access incentives ensure that both PUs and SUs benefit from the spectrum co-access. The region of co-access is the region where SUs can co-access spectrum with PUs.

### IV.2.1 One PU Node Pair with One SU Node Pair

The DSCA architecture utilizes the DPC technique to improve performance of SUs. Hence, we give a brief introduction of the DPC technique next. DPC is a term coined by Costa in [9] for channel pre-coding when interference is known. Specifically, it can be proved that for a Gaussian channel, if the interference is known by the transmitter, then a code word can be chosen such that to the receiver, it will appear as if there was no interference (fully achievable channel capacity). This is conceptually similar to interference cancelation at the transmitter. In [5, 37], the authors briefly discussed the possibility to apply DPC to cognitive radio networks. The SU network is assumed to have a priori knowledge of the PU transmission and, hence, can treat the PU transmission as known interference. The SU network precodes its message with this knowledge to allow the SU message to be sent simultaneously without reducing the PU SINR.

Next, we discuss how to utilize DPC to achieve simultaneous spectrum access of PUs and SUs. Figure 5 shows a normalized Gaussian path loss $(1,a,b,1)$ channel with one PU transmitter-receiver pair and one SU transmitter-receiver pair, where $a$ denotes the normalized path loss from the SU transmitter to the PU receiver. The PU transmitter sends a code word $X_p$ to the PU receiver. Assume that the SU knows the PU packet a priori through a side-information path. (We will discuss how the SU obtains this information later.) To provide incentives to the PU so that the PU allows simultaneous spectrum access from the SU, the SU transmitter uses a portion of its power to boost the SINR at the PU




(a) Path losses (b) Code words transmission and received signals

Fig. 5: One PU link and one SU link co-access spectrum on a normalized $(1, a, b, 1)$ channel. The legend on a link indicates the path loss. SU is assumed to know the PU code word a priori.

receiver. Let $\gamma \in [0, 1]$ denote the portion of the SU power used to transmit the PU code word and $(1 - \gamma)$ the portion of power used to transmit its own code word. Let $P_p$ and $P_s$ denote the transmit power of the PU and SU transmitters, respectively. In addition, let $X_p$ and $X_s$ be a single transmitted code word for the PU and SU, respectively. The major notations are listed in Table 1.

It should be noted that since the PU receiver will now be receiving signals from both the PU transmitter and the SU transmitter, this becomes a form of *cooperative diversity* similar to multiple antennae techniques used in MIMO. The PU transmitter acts as the primary transmission, and the SU precoded transmission contributes to the original signal, which is seen at the PU receiver as an increase in receive power. This does require the secondary transmitter to estimate the PU channel state information to synchronize its transmission to prevent interference. This can be accomplished using channel estimation by listening to PU transmissions or with a static PU network through fading estimation.

Table 1: Notations for Section IV.2.1

| | |
|---|---|
| $a, b$ | Normalized path losses as shown in Figure 5(a) |
| $\gamma$ | Portion of the SU power used to transmit the PU code word |
| $P_p, P_s$ | Transmit power of the PU and SU transmitters, respectively |
| $Q_p, Q_s$ | Received signal power (excluding interference) at the PU and SU receivers, respectively |
| $X_p, X_s$ | Transmitted code word of the PU and SU transmitters |
| $\hat{X}_s$ | Code word of the SU transmitter to carry the SU packet |
| $R_p, R_s$ | Achievable rate of the PU and the SU, respectively |

Over a large set of code words, the PU transmit power at the PU transmitter is $P_p = |X_p|^2$. As illustrated in Figure 5(b), the SU code word is generated using DPC such that $X_s = \hat{X}_s + X_p\sqrt{\gamma P_s/P_p}$, where $\hat{X}_s$ is the code word to carry the SU packet, and $X_p\sqrt{\gamma P_s/P_p}$ is the code word to carry the PU packet. The choice of this code word is done using random binning to ensure that the original SU code word $\hat{X}_s$ and $X_p$ are statistically independent. Hence, the PU receiver gets $X_p + a(\hat{X}_s + X_p\sqrt{\gamma P_s/P_p})$ such that $X_p + aX_p\sqrt{\gamma P_s/P_p}$ represents the desired code word and $a\hat{X}_s$ the noise incurred by the SU transmission, where $a$ is the normalized path loss as illustrated in Figure 5(a). Since the received desired code word is $X_p + aX_p\sqrt{\gamma P_s/P_p}$, the PU received signal power (excluding interference), denoted as $Q_p$, can be rewritten as follows, noting that $P_p = |X_p|^2$.

$$Q_p = \left(X_p + aX_p\sqrt{\gamma P_s/P_p}\right)^2 = (\sqrt{P_p} + a\sqrt{\gamma P_s})^2$$

We can compute the transmit power of the SU transmitter as

$$P_s = \left(\hat{X}_s + X_p\sqrt{\gamma P_s/P_p}\right)^2 = |\hat{X}_s|^2 + \gamma P_s,$$

where the term $2\hat{X}_s X_p \sqrt{\gamma P_s/P_p}$ vanishes since $\hat{X}_s$ and $X_p$ are statistically independent and, hence, $\hat{X}_s X_p = 0$. Therefore, we have

$$|\hat{X}_s|^2 = (1-\gamma)P_s.$$

At the PU receiver, the received noise power due to the SU transmission is $(a\hat{X}_s)^2$. Under the normalized channel noise of 1, the total noise at the PU receiver (including channel noise and SU transmission) is $1 + a^2(1-\gamma)P_s$. Thus, the resulting maximum achievable rate for the PU channel, $R_p$, is as follows.

$$R_p = \frac{1}{2}\log\left(1 + \frac{\left(\sqrt{P_p} + a\sqrt{\gamma P_s}\,\right)^2}{1 + a^2(1-\gamma)P_s}\right) \tag{1}$$

Likewise, the SU receiver receives code word $\left(\hat{X}_s + X_p\sqrt{\gamma P_s/P_p}\right) + bX_p$, where $\hat{X}_s + X_p\sqrt{\gamma P_s/P_p}$ is from the SU transmitter and $bX_p$ is from the PU transmitter. Here, $\hat{X}_s$ is the desired code word for the SU receiver and, hence, the received signal power at the SU receiver is

$$Q_s = |\hat{X}_s|^2 = (1-\gamma)P_s.$$

On the other hand, as discussed earlier, the SU transmitter is assumed to have the a priori knowledge of the PU transmission including the PU code word. As a result, the SU transmitter non-causally knows that the interference to the SU receiver would be $(b + \sqrt{\gamma P_s/P_p})X_p$ before starting the SU transmission. Based on this knowledge, the SU transmitter precodes it with random binning using DPC, and, hence, this interference vanishes at the SU receiver. In other words, the interference $bX_p$ from PU transmitter is cancelled by $\sqrt{\frac{\gamma P_s}{P_p}}X_p$ through DPC. Therefore, the total noise at the SU receiver is the channel noise. Under the normalized channel noise of 1, this results in an SU maximum achievable rate, denoted as $R_s$, as follows

$$R_s = \frac{1}{2}\log(1+(1-\gamma)P_s). \tag{2}$$

Note that normalizing the channels to a (1,$a$,$b$,1) channel includes the channel noise.

So far, we have introduced the basic idea to utilize DPC to allow spectrum co-access of a PU node pair and an SU node pair. The greatest challenge for using DPC in cognitive radio networks is that the SU must have the PU packet (code word) a priori. DSCA smartly utilizes the ability of the SU to overhear the PU transmission during the PU packet forwarding in the multi-hop networks to obtain this information. Before going into the details of this approach, we first discuss the co-access incentives for PUs and SUs in the DSCA architecture.

### IV.2.2 Co-Access Incentives

When the SU uses part of its power to help transmit the PU packet, there is a trade-off. In offering incentives to the PU, the larger $\gamma$ is, the better the PU's SINR. However, the SU would also like to maximize its own performance, and this means the smaller the $\gamma$ is, the less power is being used in DPC, and the better the SU's SINR. Next we derive the value for $\gamma$ such that a win-win situation is created for both the PU and the SU. From the PU's perspective, the achievable rate is the most important performance metric in spectrum co-access. Therefore, in the DSCA architecture, the incentive offered from the SU to the PU is to increase the achievable rate of the PU. Since the achievable rate depends on the SINR, we define the *co-access incentive* to the PU, denoted as $K$, to be the SINR increment at the PU receiver that the SU must provide to be allowed for simultaneous spectrum access. From the PU SINR in (1), the PU co-access incentive $K$ can be formulated as follows

$$\frac{\left(\sqrt{P_p}+a\sqrt{\gamma P_s}\right)^2}{1+a^2(1-\gamma)P_s} \geq P_p+K. \tag{3}$$

After some manipulation from (13), we obtain the minimum $\gamma$ to offer the PU co-access incentive $K$ as follows

$$\gamma \geq \left(\frac{\sqrt{(P_p+K)\left[1-P_p+a^2P_s(P_p+K+1)\right]}-\sqrt{P_p}}{a\sqrt{P_s}(P_p+K+1)}\right)^2. \tag{4}$$

Next, we discuss the value for $\gamma$ to guarantee a minimum achievable rate for the SU so that the SU desires co-access with the PU. That is, the DSCA architecture not only incentivizes the PU but also incentivizes the SU so that the SU splits a portion of its power to help the PU. Similar to the PU co-access incentive $K$, we define the SU co-access incentive $\lambda$ as the minimum received SINR at the SU receiver that is desired by the SU for participation in spectrum co-access. By the definition of $\gamma$, we must have $(1-\gamma)P_s \geq \lambda$ to ensure the SU co-access incentive. This can be represented as

$$\gamma \leq 1-\frac{\lambda}{P_s}. \tag{5}$$

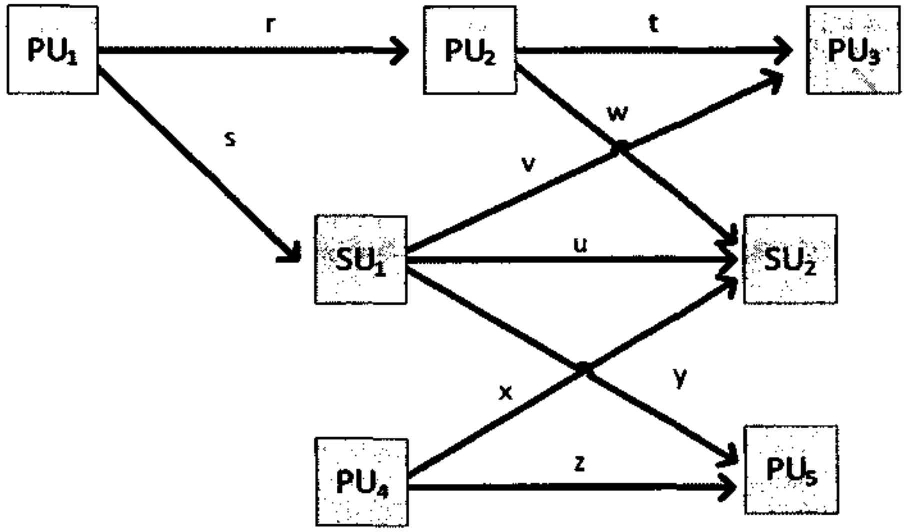



Fig. 6: A sample network topology. The legend on each link indicates the path loss.

Given the PU and SU co-access incentives $K$ and $\lambda$ and the channel gain relationship, we can now determine the value range of $\gamma$ for an SU transmitter and receiver pairs to co-access spectrum with a PU transmitter and receiver pair, based on (14) and (15).

### IV.2.3 A Multi-Hop PU Network with an SU Network

In Section IV.2.1, we discussed the difficulty for the SU transmitter to obtain the PU packet non-causally. For the DSCA architecture, we propose to exploit the multi-hop packet forwarding by PU nodes and the overhearing of PU forwarding by SU nodes to obtain the PU packets non-causally. Considering a standard TDMA access scheme with round-robin channel access by each PU node, it can be clearly seen that the forwarding nature of the PU packet along a multi-hop path allows for non-causal knowledge of the PU packet by an overhearing SU transmitter. For example, in Figure 6, if $PU_1$ sends a packet to $PU_3$ on the path $\{PU_1, PU_2, PU_3\}$, $SU_1$ can overhear the PU packet when $PU_1$ transmits it. Afterwards, when $PU_2$ forwards this PU packet, $SU_1$ already has the knowledge of the PU packet. Hence, the SU link ($SU_1$, $SU_2$) can co-access spectrum with the PU link ($PU_2$, $PU_3$) as in Figure 5.

Next, we use the sample topology in Figure 6 to illustrate the main idea of DSCA. In the figure, the symbol on each link denotes the path loss. Our objective is to find the parameter $\gamma$ that each link should use to maximize the achievable rate, given the path loss parameters and the co-access incentive requirements $K$ and $\lambda$. We assume that the PU network has some mechanism to avoid mutual interference among PUs. In Figure 6, there are two cases for the transmission by $PU_4$: (1) $PU_4$ acts like a repeater for $PU_1$ and accesses the channel at the same time as $PU_2$, or (2) $PU_4$ transmits an unrelated packet that is considered as noise. Next, we discuss the operations of DSCA for each case and derive the parameter $\gamma$ and the achievable rate on each link.

**Case 1: $PU_4$ transmits $X_P$**

Given the internode path losses shown in Figure 6 and that $PU_2$ and $PU_4$ share the same code word $X_P$ (which they both are repeating for $PU_1$), the achievable rate of link ($PU_2$, $PU_3$) is

$$R_{(\mathrm{PU}_2,\mathrm{PU}_3)} = \frac{1}{2}\log_2\left(1+\frac{(t\sqrt{P_s}+v\sqrt{\gamma P_s})^2}{N+v^2(1-\gamma)P_s}\right). \tag{6}$$

Considering the requirement for the PU co-access incentive, the minimum required rate of link ($PU_2$, $PU_3$) has to be

$$R^*_{(\mathrm{PU}_2,\mathrm{PU}_3)} = \frac{1}{2}\log_2\left(1+\frac{(1+K)t^2P_p}{N}\right).$$

Equating these two rates and solving the quadratic for $\gamma$ results in

$$\gamma = \frac{t\sqrt{P_P}\left(\sqrt{1+(1+(1+K)\frac{t^2P_p}{N})(K+(1+K)\frac{v^2P_s}{N})}-1\right)^2}{v\sqrt{P_s}(1+(1+K)\frac{t^2P_p}{N})}. \quad (7)$$

This is the minimum value for $\gamma$ to guarantee co-access incentive $K$ to the PU.

The achievable rate of link ($SU_1$, $SU_2$) with the added interference from $PU_4$ is

$$R_{(SU_1,SU_2)} = \frac{1}{2}\log_2\left(1+\frac{(1-\gamma)u^2P_s}{N+x^2P_p}\right), \quad (8)$$

and the overall achievable rate of link ($PU_4$, $PU_5$) is

$$R_{(PU_4,PU_5)} = \frac{1}{2}\log_2\left(1+\frac{(z\sqrt{P_p}+y\sqrt{P_s})^2}{N+y^2(1-\gamma)P_s}\right).$$

Link ($PU_4$, $PU_5$) would have an added boost to the received signal due to the SU transmission of the PU code word but would also have the added noise. Since $SU_1$ is helping link ($PU_2$, $PU_3$), link ($PU_4$, $PU_5$) may have adverse effects depending on the path loss between $SU_1$ and $PU_5$. However, since we are assuming that the PU will not allow for the $PU_4$ and $PU_2$ transmissions to interfere with each other, it is likely that $y$ is small and, thus, often negligible.

**Case 2: $PU_4$ transmits a different code word $X_{P2}$**

In this case, $PU_5$ is only interfered by the SU transmission since the PU code word $X_P$ transmitted by $SU_1$ is different from the PU code word from $PU_4$ to $PU_5$. It is safe to assume that link ($PU_2$, $PU_3$) is not interfered by the PU transmission from $PU_4$ to $PU_5$ since that would be counterproductive for the PU. With similar reasoning, link ($PU_4$,

$PU_5$) is also not interfered by a simultaneous $PU_2$ transmission. These mutually exclusive interference PU regions greatly reduce the likelihood of a significant $y$ channel gain of link ($SU_1$, $PU_5$). The resulting achievable rate for link ($PU_2$, $PU_3$) would be almost unaffected as in (6). The achievable rate of link ($SU_1$, $SU_2$) would now be

$$R^*_{(\mathrm{SU_1},\mathrm{SU_2})} = \frac{1}{2}\log_2\left(1+\frac{(1-\gamma)u^2P_s}{N+x^2P_{\mathrm{PU_4}}}\right). \tag{9}$$

This rate is dependent on the path loss from $PU_4$ to $SU_2$, which is likely to be small. Thus, co-access is still clearly possible as in Case 1 with possibly minor degradation in SU performance.

The achievable rate of link ($PU_4$, $PU_5$) would be

$$R^*_{(\mathrm{PU_4},\mathrm{PU_5})} = \frac{1}{2}\log_2\left(1+\frac{z^2P_{\mathrm{PU_4}}}{N+y^2P_s}\right). \tag{10}$$

This again is dependent on the path loss from $SU_1$ to $PU_5$. Note that since $SU_2$ does not know $X_{P2}$, it is unable to use DPC with its transmission and, thus, is seen by $PU_5$ as noise. However, the mutual exclusivity of the two PU interference regions and the constrained SU region of co-access will result in a very small $y$, reducing (10) to

$$R^*_{(\mathrm{PU_4},\mathrm{PU_5})} = \frac{1}{2}\log_2\left(1+\frac{z^2P_{\mathrm{PU_4}}}{N}\right),$$

which is the same as the achievable rate in the absence of the SU transmission.

Note that the co-access between the SU link and the PU link is still possible even if the SU receiver is surrounded by several PU transmitters, e.g., $PU_4$ may influence $SU_2$'s ability to decode the SU packet in Figure 6. First, if these PU transmitters transmit the same code word as the PU transmitter of the co-access PU link, i.e., link ($PU_2$, $PU_3$) in Figure 6, the SU receiver can still decode the intended packets unless the additional PU transmitter ($PU_4$) is very close to the SU receiver $SU_2$ resulting in a large $y$. However, this scenario is very unlikely since if $PU_4$ is closer to $SU_2$, then link ($PU_4$, $PU_5$) would have been a better candidate than link ($PU_2$, $PU_3$) to co-access with ($SU_1$, $SU_2$). Second, if the PU transmitters transmit a different code word, then the situation is similar to Case 2. The co-access between ($SU_1$, $SU_2$) and ($PU_2$, $PU_3$) is still possible although there may be a loss of data rate for the SU link. Furthermore, in the typical network topology, the PU transmitters surrounding the SU receiver often likely cause interference to the co-access PU link ($PU_2$, $PU_3$). In this case, these PU transmitters would be refrained from transmission when the co-access PU link is active to avoid the interference among the PU networks. Hence, these PU transmitters would not interfere with the SU link.

### IV.2.4 Region of Co-access

If the PU co-access incentive $K$ is not able to be offered by the SU, then the PU does not allow the SU to co-access the licensed spectrum with it. Therefore, it is necessary to be able to find an area within the PU network that if the SU were located within it, it would be able to provide enough incentive for co-access. This *region of co-access* is bounded by two relationships. Again, for the ease of description, let us consider the sample topology in Figure 6. First, the SU must be able to receive the $PU_1$ broadcast at least as well as $PU_2$. This leads to the constraint

$$|r|^2 \geq |s|^2. \tag{11}$$

Next, the achievable rate for the $PU_2$ transmission is dependent only on the channel gains of $t$ and $v$. Since we assume that the PU network is static (or at least has low mobility) and the channel is slow-fading, then the value of $t$ can be considered constant for the duration of a transmission. For the SU to successfully determine the region of co-access, it must be able to find these channel gains. Since the PUs are considered static and their locations are known, these gains can be estimated using a standard fading equation without needing coordination between SUs and PUs. Thus, once $t$ is determined, then we need to find a value of $v$ that still guarantees the conditions on $\gamma$. This can be solved using (7) and yields

$$v = \frac{1 - \sqrt{1 - K\left[\frac{t^2 P_p}{N}(K+1)(\frac{1}{\gamma} - 1) - 1\right]}}{\frac{t\sqrt{P_p P_s}}{N\sqrt{\gamma}}(K+1)(1-\gamma) - \frac{\sqrt{\gamma P_s}}{t\sqrt{P_p}}}. \tag{12}$$

The two constraints on $r$ and $v$ in (11) and (16) can be used to determine a region of co-access: the area within which an SU transmitter and receiver pair can safely co-access spectrum with the PU. Assuming a basic path loss model, these values are analogous to two circles around $PU_1$ and $PU_3$ with radius $r$ and $v$. The overlapping area between these two circles represents the region of co-access. This can be seen in Figure 7. In this figure, the location for the SU node that can co-access spectrum with $PU_2$ is shown. The graph represents the potential SU achievable rate, given that there is at least a 10% SINR increase ($K = 0.1$) for the ($PU_2$, $PU_3$) link from the SU transmission. In the figure, the increasingly

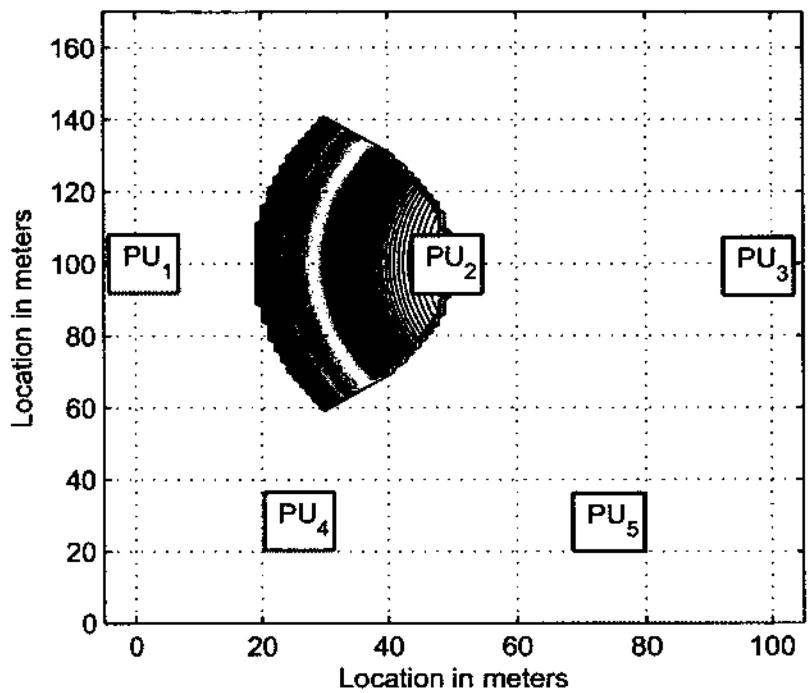



Fig. 7: Region of co-access of $PU_2$ for $K = 0.1$

redder bands indicate that if the SU is placed closer to $PU_2$, then a higher throughput can be achieved since the SU can use less power to provide the PU co-access incentive $K$ and more power for the SU transmission. This is equivalent to $\gamma \to 0$ since $\gamma$ represents the portion of power the SU uses for the PU transmission.

The relationship between the PU co-access incentive $K$ and the SU co-access incentive $\lambda$ provides the bounds for the region where SU transmitters can be placed to satisfy constraints (11) and (16). This region of co-access can thus be obtained for given $K$ and $\lambda$. Figure 8 illustrates the different regions of co-access for different values of $K$ and $\lambda$. Clearly, in this figure, the largest region of co-access is when $K$ is small and $\lambda$ is large. Furthermore, Figure 8 also indicates that the region of co-access is primarily influenced by

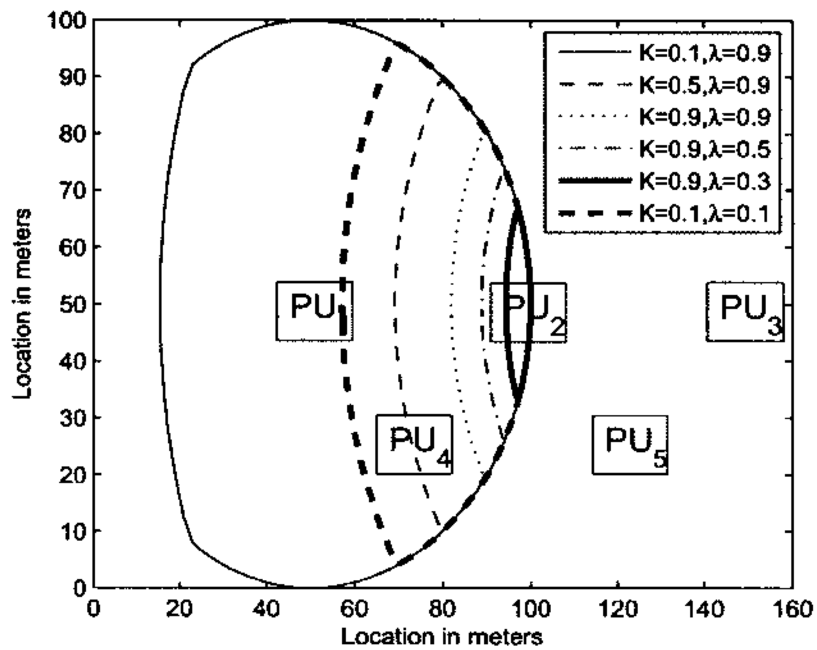



Fig. 8: Regions of co-access of $PU_2$ with varied $K$ and $\lambda$ values

the PU co-access incentive $K$.

Note that in the above formulation, we have assumed that the overhearing of PU packets by the SU does not have errors. This is a valid assumption as the errors of SU overhearing do not have significant impact. If a PU packet overhead by the SU is in error, then the SU simply gives up the opportunity to utilize this packet for co-access. As discussed earlier, the SU overhearing is required to be as good as the reception of the co-accessing PU, thanks to constraint (11). Since the reception error of the PU link is expected to be low, the overhearing error is also low. Hence, the impact on the performance is small.

### IV.2.5 Co-access Link Selection

Given the regions of co-access of each PU node, we develop an algorithm, termed *Co-access Secondary link Selection* (CoSS) as illustrated in Algorithm 1, to determine the most beneficial co-access pairs of PU/SU links. This resolves the issue that one SU link can co-access with multiple PU links and multiple SU links contend for co-access with a single PU link. The CoSS algorithm can be run at a designated node of the SU network, e.g., a cluster head, after obtaining all the required information, including the channel gains and the PU and SU co-access incentives. Alternatively, it can be run at each SU node in a distributed mode after completing the information exchange among the SU nodes in a similar way as in Internet routing.

The network is represented as weighted directed graphs $G1$ and $G2$. The PU network is represented by graph $G1 = G(N,L)$ consisting of PU node set $N$ and link set $L$, and the SU network is represented by graph $G2 = G(M,J)$ consisting of SU node set $M$ and link set $J$. Note that the PU network forms a multihop connected graph.

The CoSS algorithm determines the best SU link to pair with a PU link for spectrum co-access by first satisfying the PU co-access incentive requirement and then maximizing the SU achievable rate. It consists of two parts: first a selection of eligible candidate SU links and secondly the determination amongst eligible candidates of the SU links with the highest SINR.

Selection of eligibility in Part 1 is done by checking constraint (11) on all SU links with regard to a given PU link $l$ and placing all SU links satisfying this constraining into sets $C_l$. Note that it is possible for the same SU link to be in a candidate set for more than

**Algorithm 1** Co-access Secondary Link Selection (CoSS)

```
INPUT: Graphs G1 = G(N,L) and G2 = G(M,J)
OUTPUT: S is a set containing PU/SU pairs of co-access links
C_l = ∅, S = ∅
PART 1: Find Candidate
for all l ∈ L do
   for all j ∈ J do
      z_{l,j} = channel gain from l.head to k.head
      if weight(l) ≤ z_{l,j} then
         C_l = C_l ∪ {j}
      end if
   end for
end for
PART 2: Select Candidate
for all l ∈ C do
   for all y ∈ C_l do
      Calculate γ_{l,y} by (7)
   end for
   s = argmin_{y∈C_l} γ_{l,y}
   if 0 ≤ s ≤ 1 − λ/P_c then
      S = S ∪ (l,s)
   end if
end for
```

one PU link, i.e., an SU link may be able to co-access spectrum with multiple PU links. In Part 2, the $\gamma$ value for each link in set $C_l$ is determined using (14). Since this is directly related to the SU maximum achievable rate by (8) and (9), the SU candidate links can be sorted by the achievable rate. Then the one with the highest SINR potential is chosen for PU link $l$.

The CoSS selection is run for all PU links and results in the best (if any exist) SU co-access link for each PU link. After the algorithm terminates, we are left with a set of SU links paired with PU links that are the best co-access pairs to maximize performance. The CoSS algorithm's objective is to find the maximum achievable rate for the SU network.

Other potential considered objective functions could include maximizing SU channel access fairness. We will study the co-access link selection with these alternative objectives in our future work.

## IV.3 NUMERICAL RESULTS

We examine the performance of the proposed DSCA architecture through simulations. We compare the DSCA architecture with the *opportunistic spectrum access* (OSA) architecture under variable traffic conditions. As discussed in Section IV.1, with the OSA architecture, the SU accesses only the gaps between PU transmissions. This is accomplished by detecting the end of a PU transmission through spectrum sensing and then accessing the licensed band until the PU returns. We first consider a small topology illustrated in Figure 6 and then consider a large topology with a PU cellular network.

### IV.3.1 Small Topology

For the topology in Figure 6, we assume that there is one PU multicast flow from $PU_1$ to $PU_3$ and $PU_5$, with $PU_2$ and $PU_4$ as the relay nodes. The packet arrival is assumed Poisson with the mean inter-packet arrival time denoted as $\rho$. The packet size is assumed 500 bytes. To focus on evaluating spectrum co-access between the PU and the SU, we assume that $SU_1$ has backlogged traffic to $SU_2$, to eliminate the impact of the SU traffic load on the performance. The resulted SU throughput is called *saturation throughput*, which is approximately the system capacity for SU traffic. All PU and SU links are assumed 50 meters. We assume a 20 MHz channel with transmit power of 500 mW and a simple channel gain of $d^{-3}$, where $d$ is the distance between nodes. Using the findings in Figure

8, we create a co-access region based on co-access incentives $K = 0.5$ and $\lambda = 0.9$. We assume that in OSA, an SU requires at least 1 DIFS of 50 ns to detect PU inactivity. However, detecting PU activity on a channel that the SU is currently using requires 10 DIFS = 0.5 ms. These two parameters are similar to the *channel detection time* in IEEE 802.22, but are not directly comparable as IEEE 802.22 does not distinguish these two scenarios.

A simulation was run to determine the performance of the ($PU_2$, $PU_3$) and ($SU_1$, $SU_2$) links as the packet inter-arrival time increases. These results are shown for the SU in Figure 9 and the PU in Figure 10. In Figure 9, the advantage of DSCA is clear when the PU network is saturated with traffic ($\rho \rightarrow 0$). Since the PU network is using every available network channel access, the SU network under the OSA architecture is unable to gain access. However, the SU under the DSCA architecture is able to exploit spectrum co-access with the PU. As the packet inter-arrival time increases, the performance of the two architectures begins to converge since the simultaneous transmission becomes less needed.

Furthermore, when $\rho < 0.4$, the SUs with the DSCA architecture achieve guaranteed baseline performance of approximately $1.8 \times 10^6$ b/s. This is an important guarantee since it indicates that the SUs with the DSCA architecture would be able to find spectrum access and communicate at least at a minimum rate regardless of PU activity.

The effect on the PU transmissions can be seen in Figure 10. Since theoretically, the OSA architecture has minimal effect on the PU transmission, this is viewed as the baseline performance case. Clearly, the DSCA architecture provides a higher PU rate for all levels of PU traffic. It is able to provide the desired SINR increase for the PU and significantly improve the SU performance and thus provide the needed incentive for co-access.

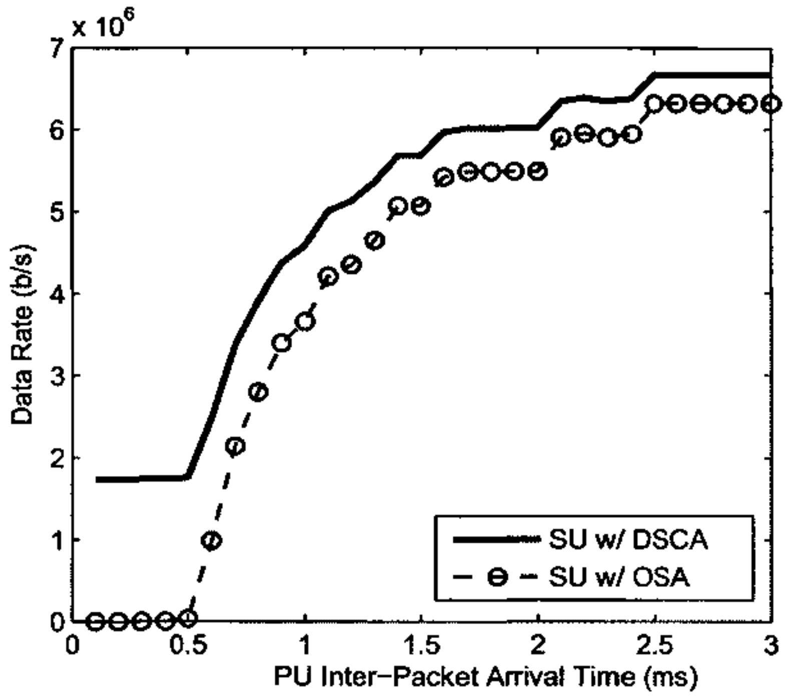



Fig. 9: Performance of co-access link ($SU_1$, $SU_2$)

### IV.3.2 Large Topology

In this subsection, we consider a large topology with 37 PU nodes deployed in a hexagonal cellular grid with 100 meters on each edge in an area of 600 meters by 600 meters. The node at the center of the network is called the *gateway*. The distance from the gateway node to any other node in the network is up to 4 hops. We assume that the gateway periodically broadcasts packets to the entire network as follows. The gateway first initiates a packet transmission, which is received by the PU nodes with one-hop distance to the gateway. Then the one-hop PU nodes access spectrum and relay the packet to the nodes with two-hop distance to the gateway. Once this is complete, the two-hop nodes access the spectrum and relay the packet to the nodes with three-hop distance to the gateway and

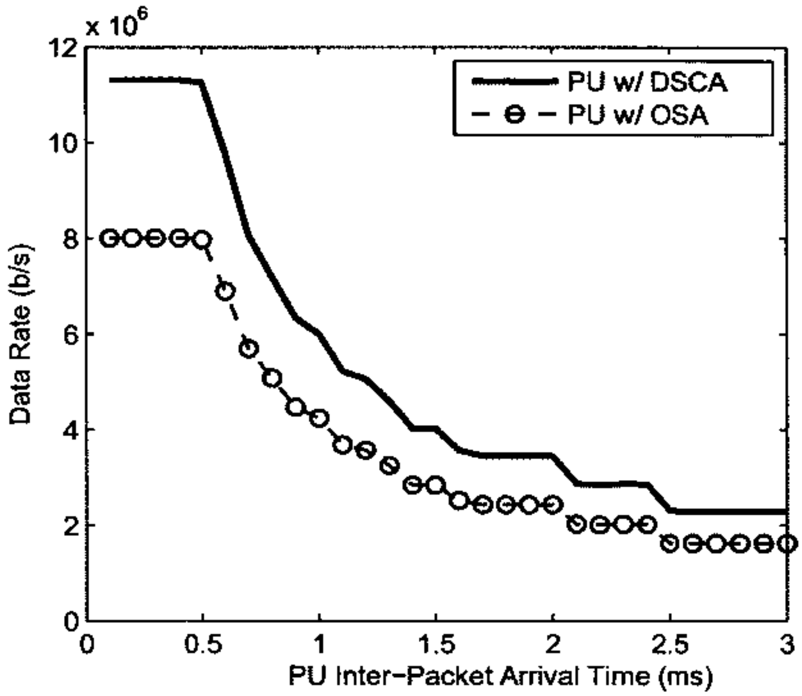



Fig. 10: Performance of co-access link ($PU_2$, $PU_3$)

so on, until the entire network has received the packet. The PU nodes have omnidirectional antennae with 0.5 Watt power limitation. The SU network consists of 30 randomly deployed nodes within the PU network area. Similar to the preceding subsection, we also assume each SU node has backlogged traffic to fully utilize the simultaneous spectrum access opportunities. The transmission radius of an SU node is 100 meters. The SU nodes use omnidirectional antennae at 0.5 Watt.

The simulation results are shown in Figs. 11 and 12. The PU co-access incentive is set from 10% to 100% ($K = 0.1$ to 1). In Figure 11, a 10% PU co-access incentive results in over 70% of PU links co-accessing with SU links. This number is more significant considering the gateway and that 1 hop nodes are not eligible for co-access, and thus, on average, 25 of the eligible 30 PU nodes are benefiting from SU co-access. This percentage

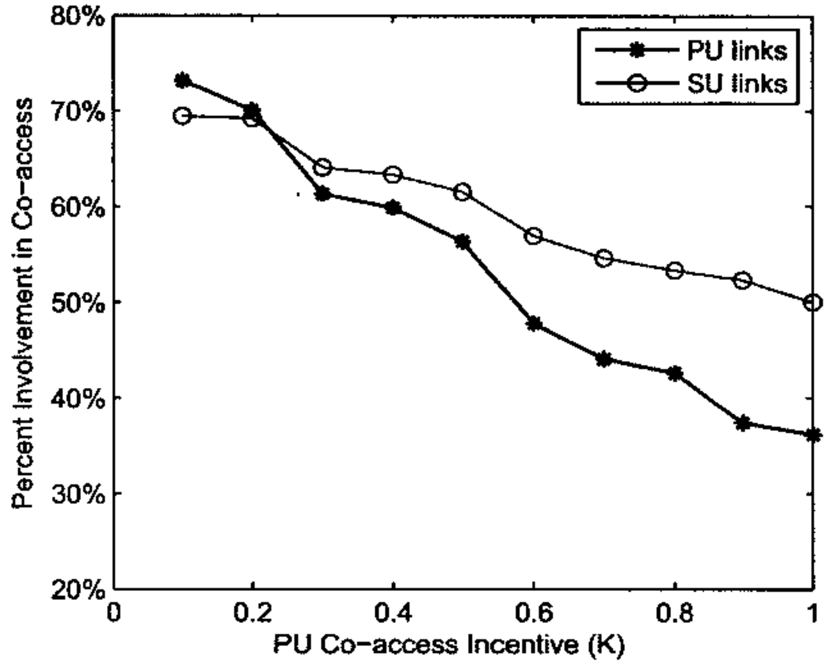



Fig. 11: Percentage of links involved in co-access in the large topology

of affected PU links decreases as the PU co-access incentive $K$ increases. However, it remains at nearly 35% or 11 active nodes when requiring a full doubling of the SINR ($K = 1$). The number of participating SU nodes selected by the CoSS algorithm is at almost 70% of the total number of nodes for low $K$ values.

In Figure 12, the overall network performance improvement can be seen when the SU nodes are actively co-accessing spectrum with PU nodes. The PU has an achievable rate advantage of 8% with the 10% co-access incentive. As the PU co-access incentive increases, fewer SU links qualify for co-access. However, at the highest co-access incentive requirement (SU must double the PU SINR to be allowed for co-access), the PU network maintains a 33% advantage in achievable rate.

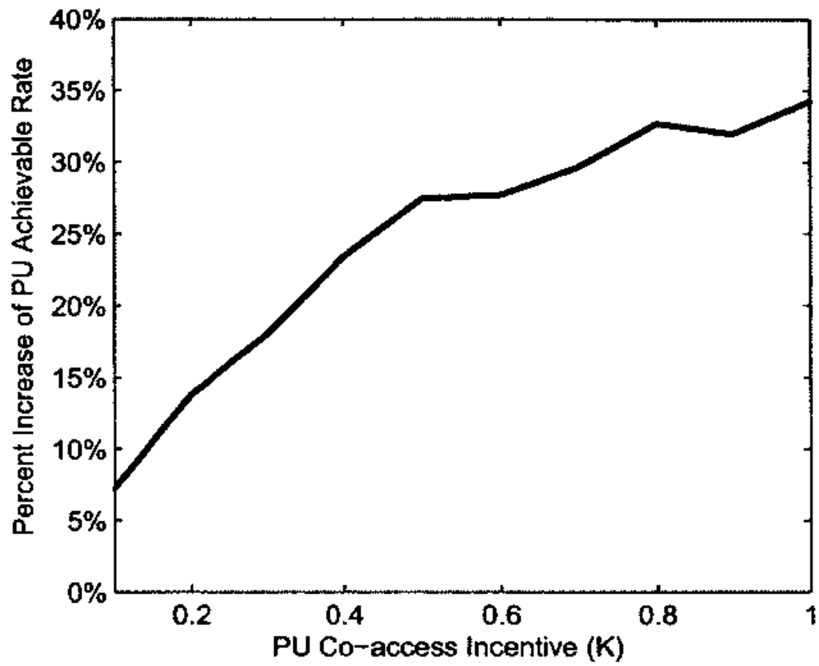



Fig. 12: PU network performance increase in the large topology

### IV.3.3 PU Participation in Co-access: How Useful is the Incentive?

A useful metric in determining the benefit of the DSCA architecture is the number of PU links that benefit from SU co-access. We run simulations with varying numbers of randomly placed SU nodes and plot the results in Figs. 13 and 14.

In Figure 13, one can see that decreasing the required PU co-access incentive $K$ results in clearly increased participation by PUs. As the number of SU nodes approaches the number of PU nodes in the simulation, a value of $K = 0.3$ results in over 63% of PU nodes being able to benefit from co-access. Thus, there is a significant number of PU nodes that would benefit from a low requirement of PU co-access incentive, and this would in turn increase the overall PU network throughput benefit. This is clear from the interdependence of PU nodes in multihop networks.

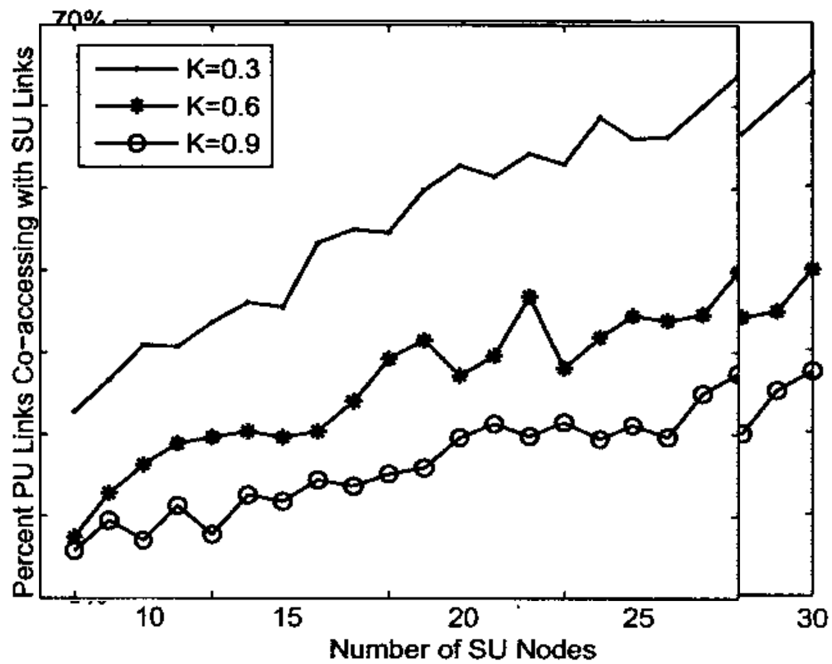



Fig. 13: Percent of PU links involved in co-access, $\gamma = 0.5$

In Figure 14, the same increase in PU participation is seen as we increase the percentage of transmission power that the SUs must use for transmitting PU packets ($\gamma$). An interesting observation can be made from the similarity of the PU participation at $\gamma = 0.5$ and $\gamma = 0.9$, where there are severe diminishing returns on increasing the requirement for the co-access incentive. A more severe requirement on SU power usage to help PU transmission does not directly translate to more PU participation.

From Figs. 13 and 14, one conclusion that can be drawn is that PUs have significant control over how many of their nodes benefit from co-access by adjusting the requirement of the co-access incentive $K$.

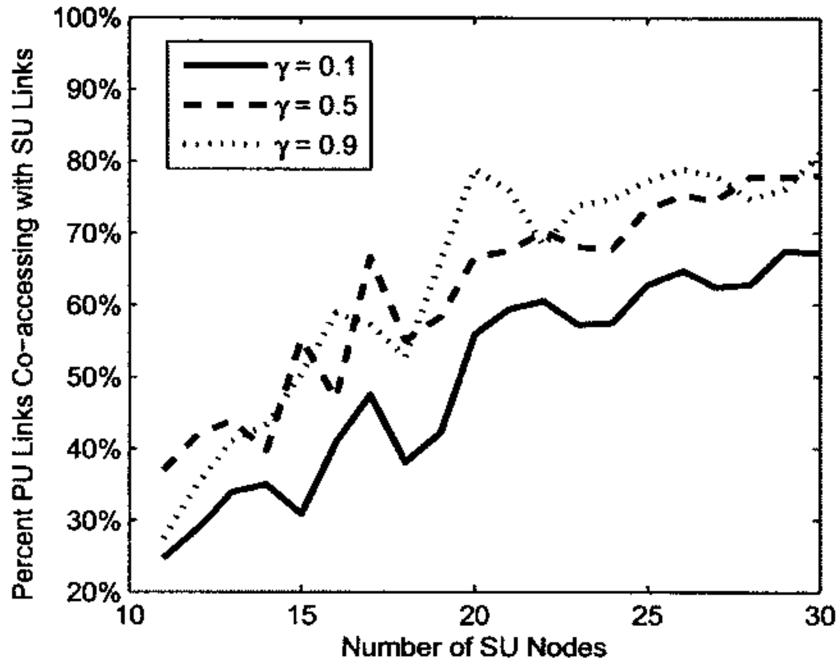



Fig. 14: Percent of PU links involved in co-access, $K = 0.1$

## IV.4 CONCLUSION

This chapter presents a dynamic spectrum access architecture termed DSCA. DSCA enables SUs to co-access spectrum with PUs, i.e., simultaneously transmit with PUs. This significantly reduces the disruption to SU communication due to the resurgence of PU traffic. Furthermore, it offers guaranteed incentives to PUs to allow the co-access of SUs, as well as guaranteed performance for SUs in spectrum co-access. Together, both PUs and SUs benefit from the DSCA architecture. We have defined the co-access incentives for both PUs and SUs and derived a model to compute the region of co-access based on the co-access incentives. Moreover, we have developed an algorithm termed CoSS to determine the most beneficial co-access incentives pairs of PU/SU links. The numerical results indicate that the DSCA architecture can significantly increase the performance for both PUs and SUs.

# CHAPTER V

# A TRANSPARENT MAC PROTOCOL FOR CRNS

In this chapter, we address the challenge of providing secondary users access to licensed spectrum when there are active primary user transmissions. The motivation is to eliminate the disruption to secondary user communications by the resurgence of primary user transmission. We propose a novel protocol, termed *spectrum co-access protocol* (SCAP), for secondary users to transparently and simultaneously access spectrum with primary users. This protocol enables mutually beneficial coexistence between the primary user network and the secondary user network. Through spectrum co-access, SCAP creates a *virtual* SU control channel in licensed spectrum that is transparent to the PU. The result is a unique *medium access control* protocol that allows for transparent simultaneous spectrum access between the SU and PU networks. The performance evaluation indicates that SCAP provides significant performance improvement for the SU network over the existing opportunistic spectrum access scheme.

The remainder of the chapter is organized as follows. Section V.2 provides an overview of a dynamic spectrum access architecture for which the SCAP protocol was proposed. Section V.3 describes the spectrum co-access and the corresponding constraints. Section V.4 describes the proposed SCAP protocol in details. The performance evaluation is presented in Section V.5. Section V.6 concludes the chapter.

## V.1 INTRODUCTION

Providing access to licensed spectrum for SU networks has become a major area of research in the last decade. This has been motivated by the well documented under-utilization of licensed spectrum and the growing interest in exploiting potential "white spaces." Research on the SU spectrum access can be categorized either as a geo-location based spectrum access approach [60, 61, 62] or *opportunistic spectrum access* [63, 28, 30, 27]. Geo-location based spectrum access relies on *primary users* (PUs) exhibiting spatially and/or temporally predictable behavior. These PUs represent categories of users such as terrestrial digital television and UMTS [64]. If PU behavior does not exhibit predictability or is not realistically measurable by the *secondary users* (SUs), then spectrum sharing often falls into opportunistic spectrum access. With opportunistic spectrum access, SUs perform spectrum sensing to dynamically detect PU channel access and opportunistically access the channel during the period between two PU transmissions. This type of access relies on fast, precise detection of PU channel access to prevent significant transmission collisions between PUs and SUs.

One of the major challenges to *medium access control* (MAC) protocols for SUs has been the inability of SU networks to remain active during PU transmissions. That is, SUs can be active on a licensed channel only during periods of PU inactivity. However, this leaves the SU network performance heavily dependent on PU transmission gaps. More simply put, the more the PU network is active, the less spectrum gaps the SU network can utilize, and subsequently, the poorer the SU performance is. However, as we will show in this chapter, certain types of PU networks can support *transparent and simultaneous*

SU transmissions. These transmissions were proven to be possible under certain scenarios [52] and represent a significant step in realizing spectrum co-access between PU nodes and SU nodes. However, not all SU nodes can meet the requirements for spectrum co-access. These unqualified SU nodes will once again only be able to transmit in the absence of PU activity. Thus, an SU MAC protocol is needed to facilitate both transparent spectrum co-access during PU activity and spectrum access for all SU nodes during PU absence.

With a large number of SUs attempting to access a limited number of PU transmission gaps, there is another problem with scheduling SU transmissions. Typically, SU networks rely on two basic techniques for solving this problem. First, they may use a designated control channel that is not affected by the PU to schedule transmissions among SU nodes [65, 66, 67]. This will either be done in an inefficient decentralized manner using a version of CSMA/CA or in a centralized optimal schedule that relies on extensive control messaging. Second, if a designated control channel is not available, SUs typically utilize some channel hopping algorithm to guarantee a reliable SU control channel [28, 68, 69, 70]. However, this method requires coordination amongst all SUs in order to maintain a shared control channel, and this becomes untenable as the number of SU nodes grows. Furthermore, all those protocols have been designed for the opportunistic spectrum access and cannot be used for spectrum co-access for SUs.

In this chapter, we present a *spectrum co-access protocol* (SCAP) that addresses both the concerns of opportunistic spectrum access and the challenge of facilitating fair SU channel sharing. First, we will show that in the case of multi-hop PU networks that use relaying, a subset of SUs will be able to co-access the licensed spectrum simultaneously with PU transmissions. This means that the PUs will be either unaware of the SU transmissions, i.e., without performance degradation, or they will benefit from spectrum co-access with an increase in SINR which results in a higher achievable rate. Hence, we can consider these SU transmissions through spectrum co-access as a *virtual* communication channel. It can be used for both SU message transport and an SU broadcast control channel.

## V.2 OVERVIEW OF THE DSCA ARCHITECTURE

The SCAP protocol is proposed for the *Dynamic Spectrum Co-Access* (DSCA) architecture, which was proposed in [52]. In this section, we give a brief introduction of the architecture. Figure 5 shows a normalized Gaussian path loss $(1,a,b,1)$ channel with one PU transmitter-receiver pair and one SU transmitter-receiver pair, where $a$ denotes the normalized path loss from the SU transmitter to the PU receiver. The PU transmitter sends a code word $X_p$ to the PU receiver. Assume that the SU knows the PU packet a priori through a side-information path. To provide incentives to the PU so that the PU allows simultaneous spectrum access from the SU, the SU transmitter uses a portion of its power to boost the SINR at the PU receiver. Let $\gamma \in [0,1]$ denote the portion of the SU power used to transmit the PU code word and $(1-\gamma)$ the portion of power used to transmit its own code word. Let $P_p$ and $P_s$ denote the transmit power of the PU and SU transmitters, respectively. In addition, let $X_p$ and $X_s$ be the transmitted code word for the PU and SU, respectively. A great challenge for the DSCA architecture is that the SU must have the PU packet (code word) a priori. DSCA smartly utilizes the overhearing during the PU packet forwarding in the multi-hop networks to obtain this information.

Over a large set of code words, the PU transmit power at the PU transmitter is $P_p = |X_p|^2$. As illustrated in Figure 5(b), the SU code word is generated using dirty paper coding [9], such that $X_s = \hat{X}_s + X_p\sqrt{\gamma P_s/P_p}$, where $\hat{X}_s$ is the code word to carry the SU packet, and $X_p\sqrt{\gamma P_s/P_p}$ is the code word to carry the PU packet. Hence, the PU receiver gets $X_p + a(\hat{X}_s + X_p\sqrt{\gamma P_s/P_p})$ such that $X_p + aX_p\sqrt{\gamma P_s/P_p}$ represents the desired code word and $a\hat{X}_s$ the noise incurred by the SU transmission, where $a$ is the normalized path loss as illustrated in Figure 5(a). It can be shown that the PU received signal power (excluding interference) is $\left(\sqrt{P_p} + a\sqrt{\gamma P_s}\right)^2$, which is larger than the PU received signal power $P_p$ without spectrum co-access of SU. On the other hand, it can be shown that the total noise at the PU receiver (including channel noise and SU transmission) is $1 + a^2(1-\gamma)P_s$, as illustrated in Figure 5(b). The SINR at the PU receiver with spectrum co-access by the SU is thus

$$\frac{\left(\sqrt{P_p} + a\sqrt{\gamma P_s}\right)^2}{1 + a^2(1-\gamma)P_s}.$$

One may note that the noise at the SU receiver is higher than the case without spectrum co-access due to the SU transmission of the SU code word. However, as long as the SINR is larger than $P_p$, i.e.,

$$\frac{\left(\sqrt{P_p} + a\sqrt{\gamma P_s}\right)^2}{1 + a^2(1-\gamma)P_s} \geq P_p,$$

where $P_p$ is the SINR without spectrum co-access, the achievable rate for the PU is not degraded by the spectrum access. By adjusting $\gamma$, we can actually increase the achievable rate for the PU and, hence, provide incentives to the PU for spectrum co-access.

On the other hand, utilizing the DPC technique, the interference from the PU transmission to the SU receiver can be cancelled, and, hence, the normalized channel noise is 1 at the SU receiver. It can be shown that the received signal power at the SU receiver is $(1-\gamma)P_s$. Hence, by setting $\gamma$ to an appropriate value, the DSCA architecture also guarantees a minimum achievable rate for the SU to participate in spectrum co-access (to help the PU to boost SINR). Therefore, the spectrum co-access in the DSCA architecture is not only possible but mutually beneficial to both the PU and the SU.

When the SU uses part of its power to help transmit the PU packet, there is a trade-off. To offer incentives to the PU, the larger the $\gamma$ is, the better. However, the SU would also like to maximize its own performance, which means the smaller the $\gamma$ is, the better. In [52], a parameter *co-access incentive* to the PU, denoted as $K$, is defined to be the SINR increment at the PU receiver that the SU must provide to be allowed for simultaneous spectrum access. The PU co-access incentive $K$ can be formulated as follows

$$\frac{\left(\sqrt{P_p}+a\sqrt{\gamma P_s}\right)^2}{1+a^2(1-\gamma)P_s} \geq P_p+K. \tag{13}$$

After some manipulations from (13), we obtain the minimum $\gamma$ to offer the PU co-access incentive $K$ as follows

$$\gamma \geq \left(\frac{\sqrt{(P_p+K)\left[1-P_p+a^2P_s(P_p+K+1)\right]}-\sqrt{P_p}}{a\sqrt{P_s}(P_p+K+1)}\right)^2. \tag{14}$$

Similar to the PU co-access incentive $K$, the SU co-access incentive $\lambda$ is defined as the minimum received SINR at the SU receiver that is desired by the SU for participation in spectrum co-access. By the definition of $\gamma$, we must have $(1-\gamma)P_s \geq \lambda$ to ensure the SU co-access incentive. This is transformed into

$$\gamma \leq 1 - \frac{\lambda}{P_s}. \tag{15}$$

Given the PU and SU co-access incentives $K$ and $\lambda$, and the channel gain relationship, we can determine the value range of $\gamma$ for an SU transmitter and receiver pairs to co-access spectrum with a PU transmitter and receiver pair, based on (14) and (15).

## V.3 SIMULTANEOUS SPECTRUM ACCESS

Although conceived as very difficult for a long time, co-accessing licensed spectrum by SUs together with PUs is still possible. In [52], we have proposed a dynamic spectrum access architecture for cognitive radio networks, termed DSCA, which exploits a technique known as *dirty paper coding* to enable SUs to simultaneously access spectrum with PUs. In that work, we have also proposed a centralized algorithm to select pairing PU and SU links to co-access spectrum. In this chapter, we propose a distributed MAC protocol for the DSCA architecture to address the coordinated channel access among SU nodes in larger SU networks. There are two objectives for the protocol: (1) provide fair channel access among SU nodes and (2) maximize the number of SU nodes to access the licensed spectrum.

While the DSCA architecture in [52] provides a great opportunity for SU nodes to co-access spectrum with PU nodes, it does have constraints on the locations of the SU transmitters for spectrum co-access. Hence, a subset of SU nodes may not qualify for spectrum co-access and, thus, are unable to simultaneously access the licensed spectrum with PUs. The work in this paper is towards the realization of providing access to licensed spectrum for all SU nodes and not just those who are able to co-access with PU transmissions. SU transmitters can be easily defined as either qualifying for co-access or not qualifying. It should be noted that we will see that a particular SU link qualifying for co-access is not automatically symmetric. More specifically, since the constraints on the SU transmitter and receiver are not symmetric, bi-directional, co-accessible SU links are not guaranteed. This can pose a significant problem due to the requirements for wireless links to acknowledge (ACK) transmitted frames at the link layer since bit errors are more likely than with wired links.

We will address two main problems. The first problem is to find the SU links that are co-accessible. Secondly, we will address the issue of providing licensed spectrum access to all of these SU links regardless of their ability to simultaneously transmit with PUs.

### V.3.1 Characterizing SUs

All SUs that are wishing to transmit data can be categorized in terms of their ability to access the licensed spectrum with the PU simultaneously or not. The first type of SUs are those that are fully co-accessible with a PU link. This means that they meet all of the spectrum co-access constraints required by DSCA. The second category of SU nodes are those that are unable to co-access to transmit a data packet but meet the constraints to co-access spectrum to transmit an ACK packet to acknowledge a data packet due to their ability to predict and estimate the PU ACK packets. The final SU category is those SUs that are desiring spectrum access but do not meet the co-access constraints neither for a data packet nor for an ACK packet. These last category nodes will have to rely on PU transmission gaps. We summarize the categories of SUs as follows.

- Co-accessible SU transmitters: CA
- Co-ACK SU receivers: CK
- Non-qualified SUs for co-access: NQ

In the following section, we will derive the channel gain constraints for each of these categories of SUs and present our SCAP protocol to facilitate fair co-access between these groups of SUs.

### V.3.2 Identifying Co-accessible Links

As discussed in Section V.2, under certain constraints, an SU link would be able to co-access a licensed channel simultaneously with a PU link. These constraints help to determine how much of the power for the transmitter of a given SU link should be used to boost the PU transmission. The constraints were specifically on the location of the SU transmitter in relation to the PU transmitter and receiver. Thus, a primary concern is to identify which SU links are co-accessible with PU transmissions. We consider a more challenging scenario of multiple SU links competing for co-access with a PU link and with the need for bi-directional traffic on an SU link. Specifically, due to the inevitable transmission errors in both the PU and SU communications, link layer ACK packets are usually needed to verify that transmissions are received. Thus, in order for a pair of SU nodes to successfully co-access with a PU link, constraints must be placed on both the SU transmitter to transmit the data packet and the SU receiver to transmit the ACK packet

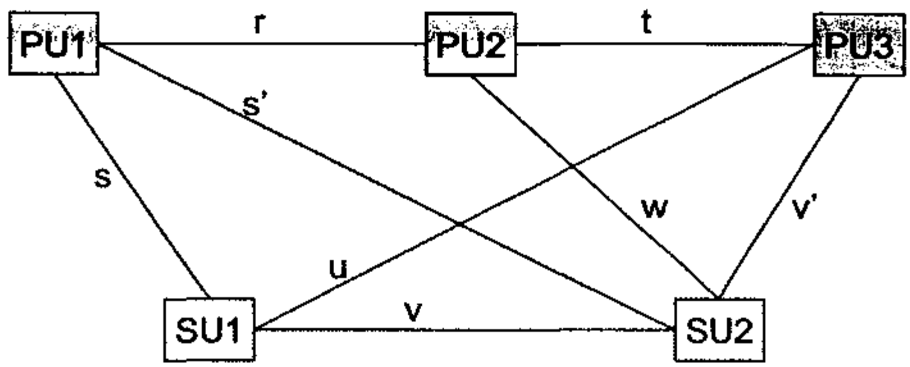



Fig. 15: Path loss model

back to the transmitter. There are two possible scenarios for successful SU receiver ACK transmission. First of all, if the SU receiver meets the same co-access constraints as the SU transmitter, then it will be possible to successfully transmit back and forth during the PU transmission. The second possibility is if the SU receiver can possibly transmit its ACK during the PU receiver's ACK transmission. This will require a new set of constraints that will be summarized below.

As shown in [52], the constraints for co-access for $SU_1$ are given as follows

$$v \geq \frac{1-\sqrt{1-(K(\frac{t^2 P_p}{N}(K+1)(\frac{1}{\gamma}-1)-1)}}{\frac{t\sqrt{P_p P_s}}{N\sqrt{\gamma}}(K+1)(1-\gamma)-\frac{\sqrt{\gamma P_s}}{t\sqrt{P_p}}} \tag{16}$$

$$s \geq r \tag{17}$$

$$u \geq t \tag{18}$$

where $v, t, s, r$, and $u$ are the channel path losses as shown in Figure 15, and $K$ is the PU co-access incentive, i.e., the added SINR that the PU requires the SU to provide for allowing SUs to co-access the channel. Again, although the PU requires an increase $K$ in SINR to allow the SU to co-access spectrum, it is done transparently to the PU and, thus, does not require any change on the PU side. It should be noted that more than one SU link may meet these constraints for a given PU link, and a MAC protocol is required to facilitate sharing.

In order for an SU receiver to be able to ACK an SU packet transmission, it too must be able to access the licensed channel simultaneously with PU transmissions. This can happen in two ways. First, the SU receiver may also be a fully qualified co-accessible SU and can reply to SU packet transmissions during the regular PU transmission period. In such a case, referring to Figure 15, we can simply exchange $s'$ for $'s$. The other scenario is where the SU receiver cannot meet the current co-access constraints; however, it is able to co-access with the ACK transmission from the PU receiver. Specifically, if the SU receiver knows when the PU ACK will occur, e.g., after PU TX + SIFS + DIFS in the case that the PU uses the IEEE 802.11 MAC protocol, it will be able to approximate the PU code word and co-access with this code word. Since the PU ACK packet for each PU data packet contains only addressing and error information, the PU ACK packets will be highly similar. The SU receiver does not need to decode the information but only estimates the PU code word (it already knows the codebook) and then co-access spectrum with the PU ACK transmission for its own ACK. The constraints to estimate this PU ACK packet and co-access spectrum with it are as follows.

$$w \geq \frac{1-\sqrt{1-(K(\frac{t^2 P_{p3}}{N}(K+1)(\frac{1}{\gamma}-1)-1)}}{\frac{t\sqrt{P_{p3}P_s}}{N\sqrt{\gamma}}(K+1)(1-\gamma)-\frac{\sqrt{\gamma P_s}}{t\sqrt{P_{p3}}}} \tag{19}$$

$$w \leq t \tag{20}$$

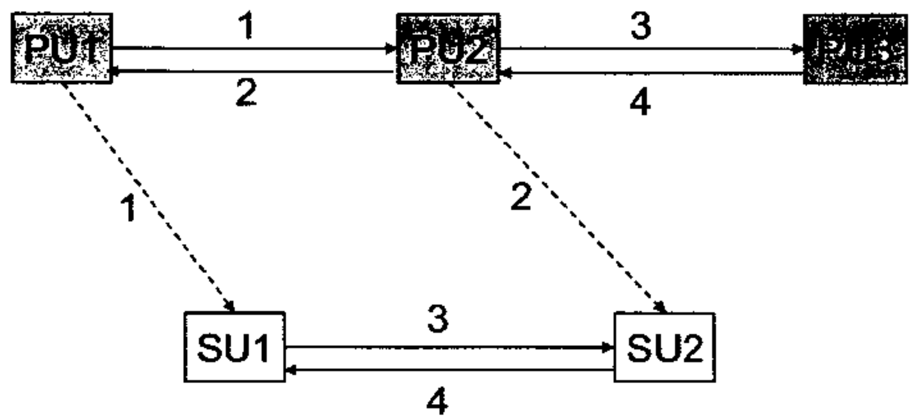



Fig. 16: SU co-access transmission sequences

Since constraint 18 will already be satisfied for the first SU transmission, it does not need to be reconsidered for the ACK transmission.

To clarify the typical transmission sequences that will occur for the SU to co-access with the PU, we refer to Figure 16. First the transmission of $PU_1$ is received by both $PU_2$, the intended receiver, and $SU_1$, the potential co-access SU. After the transmission is completed, $PU_2$ will acknowledge the transmission, which will subsequently also be received by the $SU_2$ node. Then while $PU_2$ is relaying the original message, $SU_1$ will transparently co-access the channel to transmit its own message. Finally, when $PU_3$ acknowledges the relayed transmission, $SU_2$ will be able to either ACK the $SU_1$ transmission or establish a transmission of its own.

## V.4 SPECTRUM CO-ACCESS PROTOCOL (SCAP)

The following section will describe the logic flow of SCAP. The SU networks will use a two stage access protocol based on the activity of the PU network as shown in Fig 17. First, during PU access to the licensed channel, SU nodes within the interference range of the transmission will use SCAP to co-access spectrum based on the constraints listed in Section III. All CA and CK nodes will have the opportunity to participate in a *co-access adapted round robin* (CAARR) scheduling process with details provided below. In the absence of PU transmissions, our protocol will enter a second access state, where SU nodes will perform an opportunistic access scheme relying on a modified contention window. Since the absence of the PU transmission will allow for CA, CK and NQ nodes to participate, this state will be termed *all SU adapted contention* (ASAC).

### V.4.1 Initial State

Initially, there are no SU users active on a given licensed channel. Subsequently, as SU nodes located within the interference region of a PU link have traffic to transmit, the SU nodes will begin to categorize themselves as CA, CK, or NQ based on the channel gain parameters listed in the preceding section. Since we are assuming that the PU relay nodes are stationary, it is possible within a few channel accesses to estimate the channel gains based on location and standard channel fading models. Once a node has categorized itself, then initiating channel access can begin.

### V.4.2 Co-Access Adapted Round Robin (CAARR)

CA nodes first attempt to access the licensed spectrum during a PU relay transmission. In order to do this, a CA node must first broadcast a basic control beacon to indicate to other CA and CK nodes that it is available. Qualifying CA and CK nodes can then use their respective transmission slots to respond. The success of the CAARR scheme is due to the co-access constraints guaranteeing that all qualifying CAs with specific PU relay will be within each other's transmission region. This means that there will be no hidden terminal possible during CA transmissions. This key feature makes a round-robin scheme possible without extensive overhead or message passing. This process is done during the joining frame (to be discussed). Since the CA node is transmitting simultaneously with the PU transmission, this is considered accessing a *transparent* control channel.

### V.4.3 Co-Access Transmission Sequence

The co-access transmission between SUs (either CA-CA or CA-CK) requires a basic four step process as described in Figure 16. First, a CA with data to send (SU1) will listen for the first PU1 transmission. This will be used to generate dirty paper code words according to the work above. Then during the subsequent PU ACK, the CA's destination node will be able to overhear the ACK and estimate a sequence of dirty paper code words of its own. Then when the PU relay begins access, the first CA can simultaneously access spectrum using the designed code words. Finally, when the second PU ACK is issued, the CA or CK can simultaneously ACK the first CA transmission.

Since the PU ACKs are likely to be somewhat different due to MAC layer addressing but of the same basic structure, SUs will be able to estimate the PU ACK. This may require listening for a few time slots to the correlation between the PU ACKs in stage two and stage four. Since these are typically simple packets of only one or two code words, estimation is simple.

### V.4.4 Joining a CA Group

A node qualified as a CA requires two things to be able to participate in CAARR. First, the node will need to be assigned a short unique identifier to distinguish itself from other SU nodes. This can be initially selected as a random value or something as simple as a hash function of its unique MAC address. Secondly, it must be made aware of its order in the round robin scheme. Specifically, it needs to be aware of the CA node that is scheduled immediately before itself. This process is accomplished with the previously mentioned beacon message. During the first PU transmission where the scheduled CA is absent, the joining CA will issue its beacon, which will be detected by all the current CA members. It must do this before the next round robin member begins transmission. Next, the current CA member with the next scheduled transmission slot will be required to respond to the joining CA with an acknowledgement that its ID is unique and with the ID of its current predecessor. The new CA will take the current CA's predecessor, and in turn, the current CA will set the new CA as its predecessor. Thus, the joining CA will be allocated the previous CA's time slot, and the acknowledging CA will have created a new entry into the round robin scheme. Note that this is analogous to adding and removing members from a linked list.

CA nodes utilize the CAARR access state by using their assigned node number to access the scheduled PU transmission. This is a variation of a classic round robin scheduling algorithm which ensures max/min fairness. Thus, if a CA node has data to transmit, it must do so on the PU frame immediately following the co-access of its predecessor.

### V.4.5 Unused Accesses

However, since many CA nodes may not have traffic and, thus, not desire access to PU channel at its assigned time slot, an adaptive algorithm is required. The CAARR phase will specify that a node desiring to access the network must listen to both its time slot and the time slot preceding it to detect if the node assigned to the previous time slot is idle or not. This can be seen in Figure 18. Since all of the CAs for a particular SU are within each other's interference range, the CA can detect an absent predecessor quickly. Then the CA node will immediately finish co-accessing with the PU. Since this detection can be done in only a few code words, the CA will be able to pick up the co-access *transparent* to the PU.

This *shifting* of the CA transmissions is essential to the round robin scheme and reduces lost channel access opportunities.

### V.4.6 Leaving CAARR

A CA can leave the CAARR in two ways. First, it can issue a termination message during its co-access slot. This message will contain its predecessor CA, which will be used by its successor as its new predecessor. Thus, with only a single control message, the CAARR schedule remains full and the old node is forgotten. The other method for leaving is if it has not used its co-access slot in the CAARR scheme for a given period of time, then the other CAs will automatically assume it is gone and remove it from the CAARR schedule. This will require no control messages but could result in missed transmission opportunities for the other CAs.

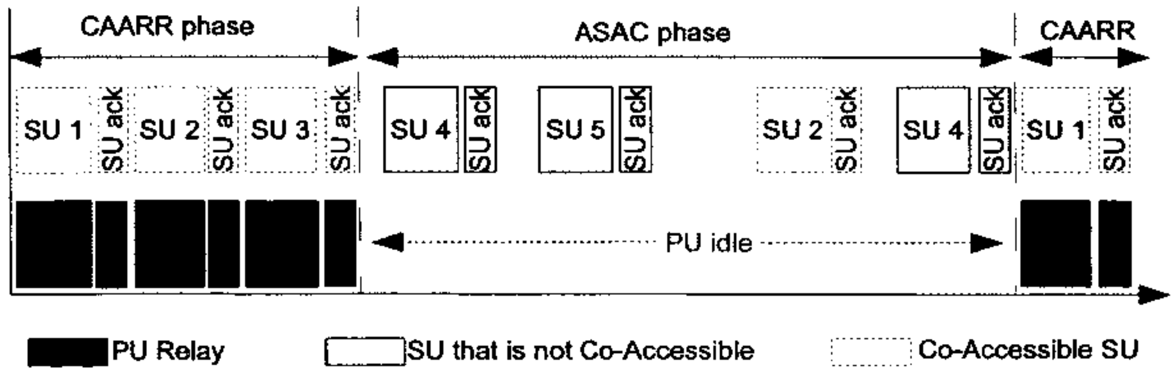



Fig. 17: Spectrum co-access illustration utilizing SCAP, with 1 PU relay, 3 Co-access SUs and 2 other SUs

### V.4.7 All SU Adapted Contention (ASAC)

During the PU transmission absences, the SUs will be allowed to access the network in an adapted contention method using the CSMA/CA binary exponential backoff method. However, since CA nodes will qualify to access the shared spectrum during both PU transmissions and absences, a method for prioritizing NQ nodes in ASAC is necessary to maintain fairness amongst all SUs. Specifically, the CA nodes are required to set their collision backoff exponential equivalent to the number of SUs that were active in the CAARR region of the protocol. However, SU nodes that are NQ will set their backoff windows to the minimum value, the result being that after the first collision, NQ nodes will have a much smaller backoff time and, thus, a higher probability of accessing the spectrum before CA or CK nodes.

## V.5 PERFORMANCE EVALUATION

We use simulations to evaluate the performance of the proposed SCAP. Of interest is the specific impact the CAARR component of the SCAP protocol will have on the overall

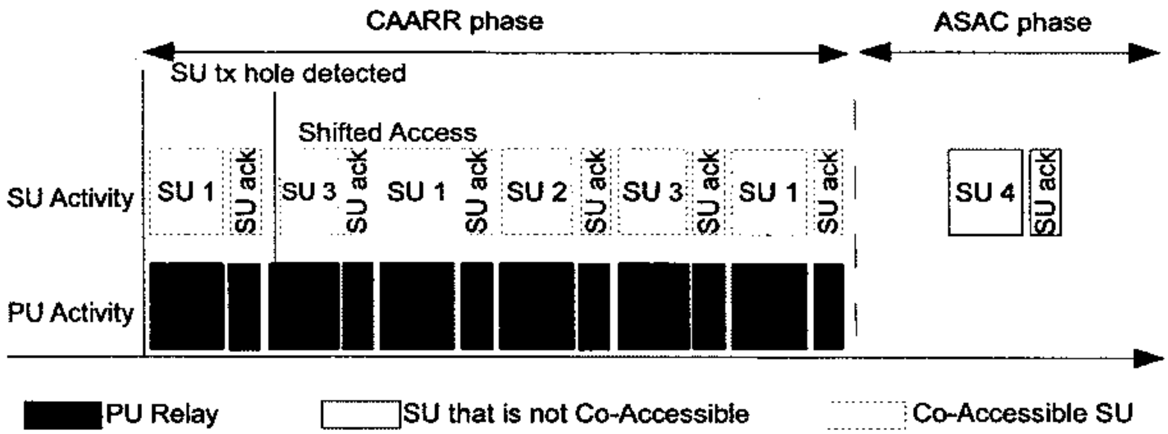



Fig. 18: SCAP adapted round robin scheme

performance of the SU network. We consider a 37 node PU network organized over a 600m x 600m area in a cellular grid topology. The PU traffic is broadcast from the central tower to the entire network through multihop relay. Each of the PU nodes operates with an omnidirectional antennae and a broadcast power of 0.5 Watt with a channel bandwidth of 20 MHz based on the WiFi model. The PU nodes are assumed to be stationary and follow a channel access scheme of broadcasting 500-byte frames with channel slot duration of 1 ms. SU nodes are uniformly randomly deployed across the network with similar channel and power characteristics as the PU nodes. We assume the packets generation at each SU node follows a Poisson process with the mean inter-packet arrival time as 50 ms. Furthermore, we assume that in all experiments, 10 percent of PU nodes are active if not otherwise noted. Finally, we consider the required PU incentive to allow SUs access to the network. Specifically, we require $K = 0.1$ or 10% increase in SINR at the PU receiver.

First, we look at how well the proposed SCAP supports a large number of SUs. As shown in Figure 19, we simulate the average throughput that an SU node acquires using

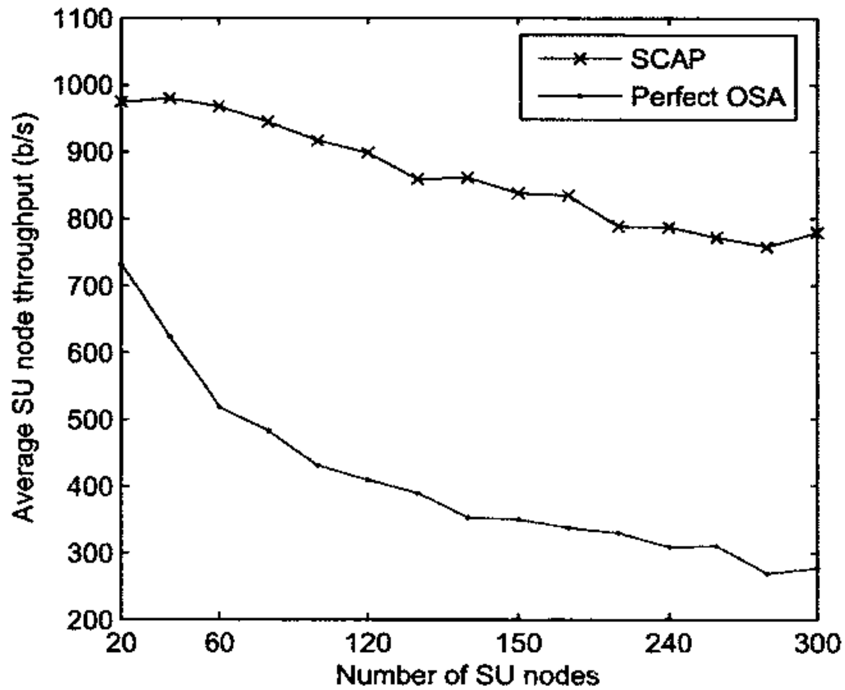



Fig. 19: Average SU node throughput with increasing number of SU nodes

the SCAP protocol. For comparison, we consider a perfect *opportunistic spectrum access* (OSA) protocol, which assumes that the SU nodes can instantly detect PU access and absence. From Figure 19, we find that the SCAP protocol clearly outperforms the OSA protocol with a large margin on throughput. Furthermore, when the number of SUs increases, the performance gap is even larger. This is because with more SU nodes, the contention for spectrum access to the channel idle periods is more severe under the OSA protocol. In contrast, the SU nodes can utilize spectrum co-access together with PU nodes under the SCAP protocol; hence, the contention for the channel idle periods does not increase as fast as in the case of the OSA protocol.

In Figure 20, the fairness of the SU nodes is shown by evaluating the variance of SU per-node throughput amongst all the SU nodes. This provides a good overview of how

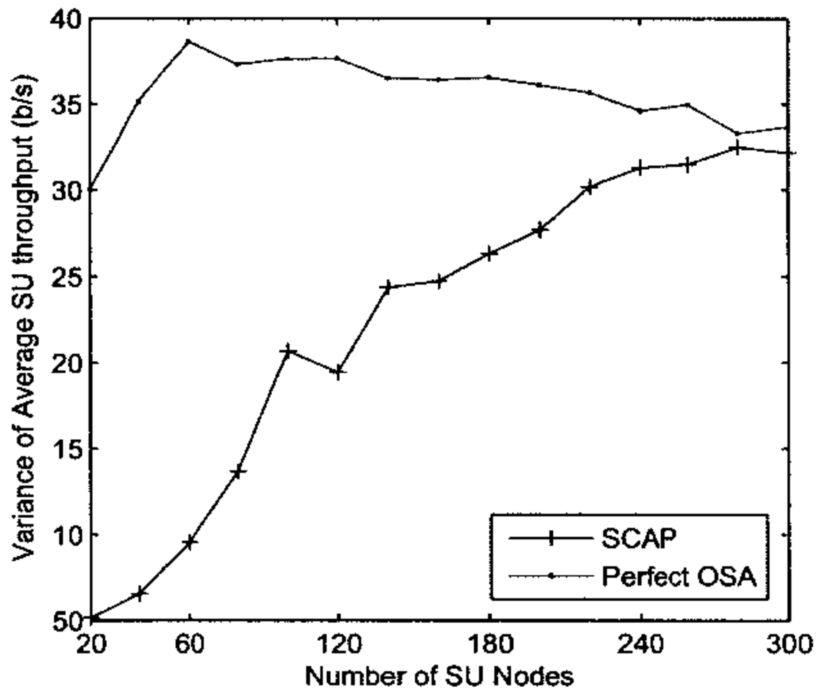



Fig. 20: Variance of SU node throughput with increasing number of SU nodes

spread out the performance of different SU nodes is relative to the number of SU nodes. Since the SCAP protocol has a smaller variance of the SU nodes throughput, especially when the number of SU nodes is small, it achieves a higher level of fairness. The trend towards decreased network fairness as network density increases is common for all ad-hoc MAC protocols. However, the most meaningful feature of simulation results is the how much better the SCAP protocol is able to take advantage of smaller SU networks to provide fairness, where the Perfect OSA model maintains roughly the same level of fairness regardless of the number of SU nodes. In addition, as the number of SU nodes increases, the SCAP protocol tends to converge with the perfect OSA model but never exceed it. This means SCAP achieves a better fairness on throughput for all the SU nodes.

In Figure 21, we present the performance of the entire SU network compared. Of considerable note is that the SCAP has a higher system throughput than the perfect OSA protocol. This is due to the increased spectrum efficiency of the CAARR scheme in the SCAP. Specifically, since we are able to assure successful round robin scheduling, the SCAP protocol utilizes the spectrum access during the PU activity period much more efficiently. The limiting factor on the performance of the OSA protocol is the extensive overlapping collision which a large widespread SU network typically has. The SCAP protocol can significantly mitigate such collisions and, hence, has a much better performance than the OSA protocol.

Figure 22 illustrates the mean channel access delay for the SU nodes as a function of the PU activity, where "$z\%$ PU active" indicates that $z\%$ PU nodes are active at any time. This figure clearly indicates the benefit of the SCAP protocol. While there are more active PU nodes, by intuition, the spectrum access opportunity for SU nodes decreases; as a result, the channel access delay increases. This is exactly what happens to the OSA protocol. However, for the SCAP protocol, the channel access delay does not increase, but decreases. This anti-intuition observation is thanks to the spectrum co-access feature of the SCAP protocol. This is because more active PU nodes means more opportunity for spectrum co-access by SUs. In other words, more SU nodes become qualified for spectrum co-access with PU nodes since with more active PU nodes, it is clear that more SU nodes are close to the active PU nodes and can meet the constraints for spectrum co-access. Thus, the mean channel access time decreases since more SU nodes can access the channel immediately when they have traffic to transmit.

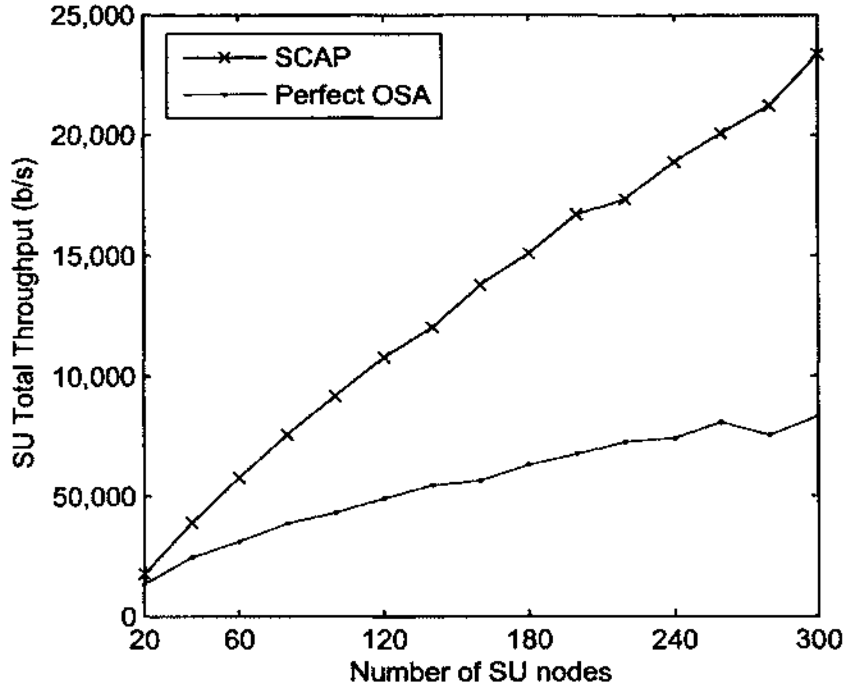



Fig. 21: Total SU node throughput with increasing number of SU nodes

## V.6 CONCLUSION

In this chapter, we have proposed a *spectrum co-access protocol* (SCAP) for the DSCA architecture in our earlier work. SCAP tries to find spectrum co-access opportunities for qualified SU nodes while giving spectrum access opportunities to the SU nodes that are not qualified for spectrum co-access with PU nodes. The performance evaluation indicates that SCAP significantly outperforms even the perfect opportunistic spectrum access protocol, which can 100% accurately detect the beginning and end of the PU transmission in spectrum sensing.

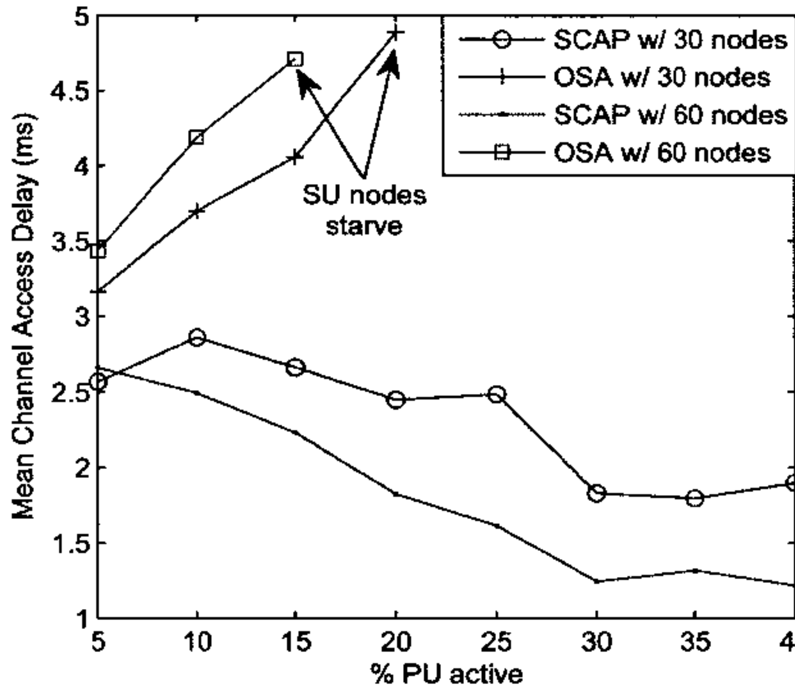



Fig. 22: Mean channel access time as PU activity increases

# CHAPTER VI

# INCREASING SU CHANNEL CAPACITY

In this chapter, we will consider increasing the performance of secondary user networks. Specifically, we use insights gained from channel precoding in Chapter IV between primary and secondary users to motivate the use of channel pre-coding between secondary users when they are in a multihop configuration. Instead of using precoding to transparently co-access the licensed spectrum during primary user activity, we will be seeking to use precoding to increase secondary user performance during periods of primary user absence. Specifically, the methods presented here could be used during the ASAC period presented in Section V.4 when the primary user is idle. The work in this chapter is motivated by our goal to provide secondary users in licensed spectrum with performance guarantees.

## VI.1 INTRODUCTION

The challenge of ubiquitous connectivity has given rise to the use of wireless networks around the world as effective and flexible real world solutions. However, there remain many challenges to providing performance guarantees in wireless networks. Overall, the challenge of providing higher capacity, better fairness and improved spectrum utilization are actively being researched. Much of the current cognitive mesh literature focuses on secondary users filling unused spectral holes; a technique known as dynamic spectrum access or the *interweave* model in cognitive radio networking. This interweave model is often referred to as a switching model as primary and secondary users have mutually exclusive access to the shared spectrum. In contrast, the cognitive *underlay* model allows for simultaneous primary and secondary user transmission through methods such as UWB [55]. By allowing the secondary transmission to use UWB, the overall incurred interference in the specific frequency range used by the primary user is small enough to be ignored. The model we have considered throughout this work is the cognitive *overlay* model. This model uses non-causal side knowledge of the primary message by the secondary transmitter and *dirty paper coding* or *Costa coding* to allow simultaneous transmission within the same spectrum and without altering the primary user transmitter. Costa proved in [9] that given a large enough code word set, the AWGN optimal capacity can be achieved, namely $C = \frac{1}{2}\ln(1+\frac{P}{N})$. Although this realization requires complex coding schemes, the potential for capacity increase in a normally interfering channel between two node pairs is quite enticing for use in increasing secondary user performance.

Traffic in many secondary user networks is multihop by nature destined to or from a single gateway node. This type of network is frequently referred to as a *mesh network* architecture. In this type of network, all traffic generally follows a series of backbone routes with traffic being forwarded/relayed by intermediary nodes. Messages being forwarded are known *a priori* to previous nodes in a transmission sequence, and the non-causal knowledge requirement for channel precoding of the message to be forwarded is already satisfied. In addition, since the collision domain is the bottleneck to capacity in any nominal mesh network [54], it can be concluded that by reducing the collision domain using simultaneous secondary user channel access, secondary user channel capacity can be increased.

The main contribution of this chapter is to present a method of improving a secondary user performance during primary user absence through channel precoding. Since a subset of secondary user nodes in a secondary user mesh network will be unable to co-access with the primary user network during primary user transmissions, these nodes will have reduced channel access opportunities. This may result in unfair starvation by secondary user nodes. Although the work in Chapter V presented a MAC protocol that uses adaptive prioritization of these unqualified secondary users, increasing secondary user channel capacity remains important to maintaining secondary user network performance. Since we are attempting to improve the secondary user network performance during periods of primary user inactivity, we will study the secondary user network capacity as a multihop mesh network problem.

The rest of the chapter is organized as follows. Section VI.2 provides a theoretical proof for our new approximations for capacity of the secondary user channel. In Section VI.3, the numerical results of simulations are presented to confirm our theoretical assertions and reveal an added increase in fairness. Section VI.4 draws conclusions from our results and considers future implications.

## VI.2 THEORETICAL ANALYSIS

The authors in [57] asserted that for a two transmitter two receiver cognitive radio model, the upper limit on achievable rate is found to be twice the achievable rate of a one transmitter one receiver model even if they share an interference region. One potential method for achieving this upper limit is channel precoding. However, when considering the multi-hop nature of secondary user networks and the likelihood of having multiple

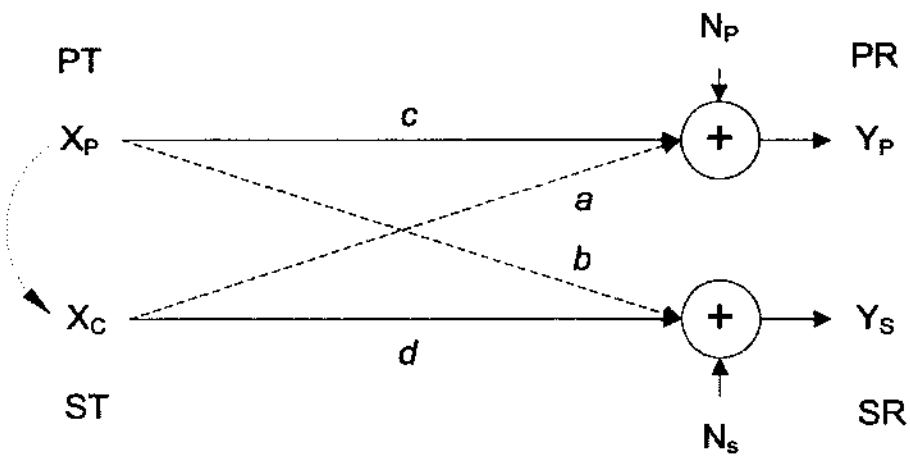



Fig. 23: Two Transmitter Two Receiver Cognitive Radio Model

transmitters and receivers within the same interference region, the theoretical limit becomes untenable. However, for secondary users who are forwarding/relaying in a multihop network, it may be possible to approach this upper limit.

The following basic model can be used to demonstrate the relationship between the primary users and secondary users in a typical two receiver, two transmitter overlay cognitive model as shown in Figure 23.

First, we consider the received signals corrupted by degraded by pathloss and additive Gaussian white noise.

$$Y_1 = X_1 + aX_2 + Z_1 \tag{21}$$

$$Y_2 = bX_1 + X_2 + Z_2 \tag{22}$$

Now, if the code word $X_1$ is formed using knowledge of the dirty paper coding and random banning, the received signal at both receivers is represented as

$$Y_1 = (1 + a\sqrt{\frac{\gamma P_2}{P_1}})X_1 + a\hat{X}_2 + Z_1$$

$$Y_2 = (b + \sqrt{\frac{\gamma P_2}{P_1}})X_1 + \hat{X}_2 + Z_2$$

According to [37], the process at the receiver for decoding these messages is as follows. Since $X_1$ and $\hat{X}_2$ are i.i.d. Gaussian and power constrained, Receiver 1 treats the value of $a\hat{X}_2$ as independent Gaussian noise and, thus, can be ignored up to a certain rate (namely the AWGN channel capacity for small $a \leq 1$). In addition, since Receiver 2 knows non-causally $X_1$, it can simply subtract $(b + \sqrt{\frac{\gamma P_2}{P_1}})X_1$ and recover $\hat{X}_2$.

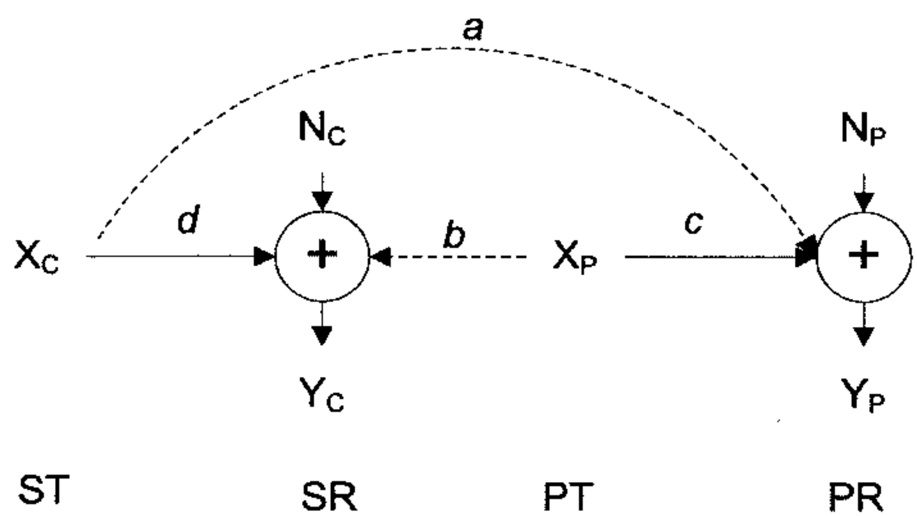



Fig. 24: Sequential Cognitive Radio Model

Now, instead of using the typical primary user secondary user model in Fig 23, consider the case where the secondary user is precoding with another secondary user in a sequential fashion. This is demonstrated in Figure 24, where the extension from the pairwise case to the $n^{th}$ case is shown in the next section with conclusions that similar message recovery is possible.

### VI.2.1 Extending to the $n^{th}$ case

Now, we extend the two transmitter two receiver pair to a sequential chain of $n$ nodes by extending to a model based on Figure 25. This model considers the effects on the received signal $Y_n$ due to this new chain topology. We seek to study the effect of precoding messages along the chain and analyze the interference collision domain under these new conditions. Simply put, if we can sequentially precode the secondary user message taking into account relay messages within its interference region, then it may be possible to increase networks throughput without causing collisions.

However, there will be a limit on how many simultaneous precoded messages can be sent within the same interference region. Simply put, it is not possible to dirty paper code an infinite number of messages together without some level of message degradation unless an infinitely large code word set is available. Since this is not possible, we attempt to show that a limited interference range allows for limited code word set sizes and, thus, achievable capacity gains for the secondary user.

We consider first that each transmitter has *non-causal* knowledge of all previously transmitted messages and is in fact using this information to precode its message using dirty paper coding. We then get a succession of transmissions generated of the form.

$$X_n = \hat{X}_n + \sum_{i=1}^{n-1} \sqrt{\frac{(\prod_{j=i}^{n-1} \gamma_j) P_n}{P_i}} \hat{X}_i \tag{23}$$

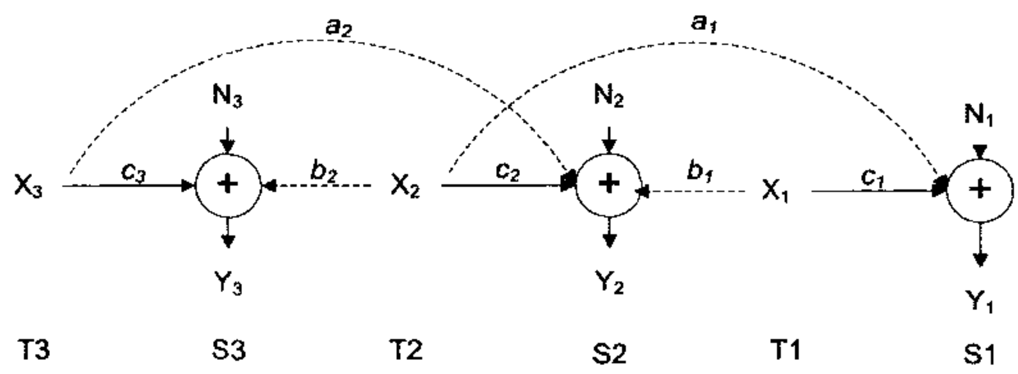



Fig. 25: Cognitive Overlay Model Extended

From 23, it is easy to see that previously transmitted messages are considered when forming each new message; however, the amount of secondary user power used for each message is reduced by a factor relative to $\sqrt{\gamma_i}$ each time. Thus, there are limitations to precoding with an already precoded message. The eventual effect of the previous messages becomes negligible. The smaller $\gamma$, the more quickly we can simplify the precoding process. This can also be seen in the received message as the interference of previously transmitted messages also falls off relative to $\gamma$. Since by definition $\gamma \leq 1$, the code word complexity is proportional to $\gamma$.

Recall from the shared spectrum model that the $\gamma$ value can be considered as the portion of $P_2$ used to transmit $P_1$'s message and is related only to the channel gain between the secondary transmitter and the primary receiver (value $a$). We generalize this relationship for our sequential secondary user and extend to the $n^{th}$ case. Thus, we can represent $\gamma$ for any arbitrary secondary user transmitter as follows.

$$\gamma_i = (\frac{\sqrt{P_i}(\sqrt{1+a_i^2 P_{i+1}(1+P_i)}-1)}{a_i\sqrt{P_{i+1}(1+P_i)}}\ ,\ i = 1...n-1$$

Furthermore, we can consider the $n^{th}$ case for the received signal as well.

$$Y_k = a_{k+1}X_{k+1} + X_k + b_{k-1}X_{k-1} + a_{k-2}X_{k-2} + Z_k \tag{24}$$

$$= a_{k+1}(\hat{X}_{k+1} + \sum_{i=1}^{k}\sqrt{\frac{(\prod_{j=i}^{k}\gamma_j)P_{k+1}}{P_i}}\hat{X}_i) + (\hat{X}_k + \sum_{i=1}^{k-1}\sqrt{\frac{(\prod_{j=i}^{k-1}\gamma_j)P_k}{P_i}}\hat{X}_i)$$

$$+b_{k-1}(\hat{X}_{k-1} + \sum_{i=1}^{k-2}\sqrt{\frac{(\prod_{j=i}^{k-2}\gamma_j)P_{k-1}}{P_i}}\hat{X}_i) + a_{k-2}(\hat{X}_{k-2} + \sum_{i=1}^{k-3}\sqrt{\frac{(\prod_{j=i}^{k-3}\gamma_j)P_{k-2}}{P_i}}\hat{X}_i) + Z_i$$

However, if the $\gamma$ values are again small, then we can consider reducing this expression to only its first few terms.

$$Y_k = (a_{k-2} + b_{k-1}\sqrt{\frac{\gamma_{k-2}P_{k-1}}{P_{k-2}}} + \sqrt{\frac{\gamma_{k-2}\gamma_{k-1}P_k}{P_{k-2}}} + a_{k+1}\sqrt{\frac{\gamma_{k-2}\gamma_{k-1}\gamma_k P_{k+1}}{P_{k-2}}})\hat{X}_{k-2}$$

$$+(b_{k-1} + \sqrt{\frac{\gamma_{k-1}P_k}{P_{k-1}}} + a_{k+1}\sqrt{\frac{\gamma_k\gamma_{k-1}P_{k+1}}{P_{k-1}}})\hat{X}_{k-1}$$

$$+(a_{k-2} + a\sqrt{\frac{\gamma_{k+1}P_{k+1}}{P_{k-1}}})\hat{X}_k + a_{k+1}\hat{X}_{k+1}, k = 2...n-1,$$

which can be written in a simplified form as

$$Y_k = b^*\hat{X}_{k-2} + b^{**}\hat{X}_{k-1} + \hat{X}_k + a_{k+1}\hat{X}_{k+1} \tag{25}$$

Now, we consider that the receiver $Y_k$ already knows non-causally the $b^*\hat{X}_{k-2} + b^{**}\hat{X}_{k-1}$

terms, which it can simply subtract from the message. In addition, as stated previously, with the characteristics of dirty paper coding, the $a_{k+1}\hat{X}_{k+1}$ values can be treated as simply independent Gaussian noise and, thus, ignored. Therefore, the $\hat{X}_k$ message is recovered with only standard noise interference. This conclusion provides evidence that a chain of nodes can achieve nearly the total throughput capacity of the AWGN channel individually using channel precoding regardless of length.

## VI.3 SIMULATION RESULTS

In the following section, a proof of concept network model is simulated to demonstrate the potential improvements of sequential channel precoding. Specifically, we will consider the case of the effects on throughput for both a network chain topology and a uniformly distributed topology. The simulations were run in Matlab using randomly generated secondary user mesh networks with single antenna nodes. Again, since this is a proof of concept for secondary user access when the primary user is idle, the results do not consider primary user activity. That work will be left for future consideration.

Nodes formed a fully connected graph with distances of 30m and a transmit power of 100mW. We employed distance based routing with free space path loss model. In addition, since precoding requires an estimation of CSI, each node's location is considered known to the other locations. This channel information could also be passed through broadcast trees in the network. We considered a basic TDMA access scheme with a 2 hop interference region (60m). Specifically, we looked to understand if the channel precoding would increase network capacity relative to the nominal opportunistic model and the single stage channel precoding. Our model will be considered the extended overlay model. It should be noted that since nodes were designed as half-duplex, the maximum channel capacity for a given mesh is 50%.

The simulations for performance were conducted for normalized channel capacity and, thus, only percentages of utilization are shown since individual channel capacity is dependent on coding scheme, channel bandwidth, and fading characteristics. As shown in Figure 26, the performance of the secondary user mesh network in a single chain topology with degree 1 gives the worst case performance in terms of collision domains as the number of nodes in the network is increased. The second part of Figure VI.3 shows the relative fairness of each of the models simulated.

It is clear that under the worst possible conditions, the nominal mesh has a difference in fairness of as much as 2:1. The general overlay model shows a significantly better performance than that nominal case with a channel utilization of roughly 35% over nominal's 26%. The proposed extended overlay presented in this chapter approaches the maximum throughput potential and, thus, roughly doubles the throughput of the nominal case and increases the basic overlay by over 40%.

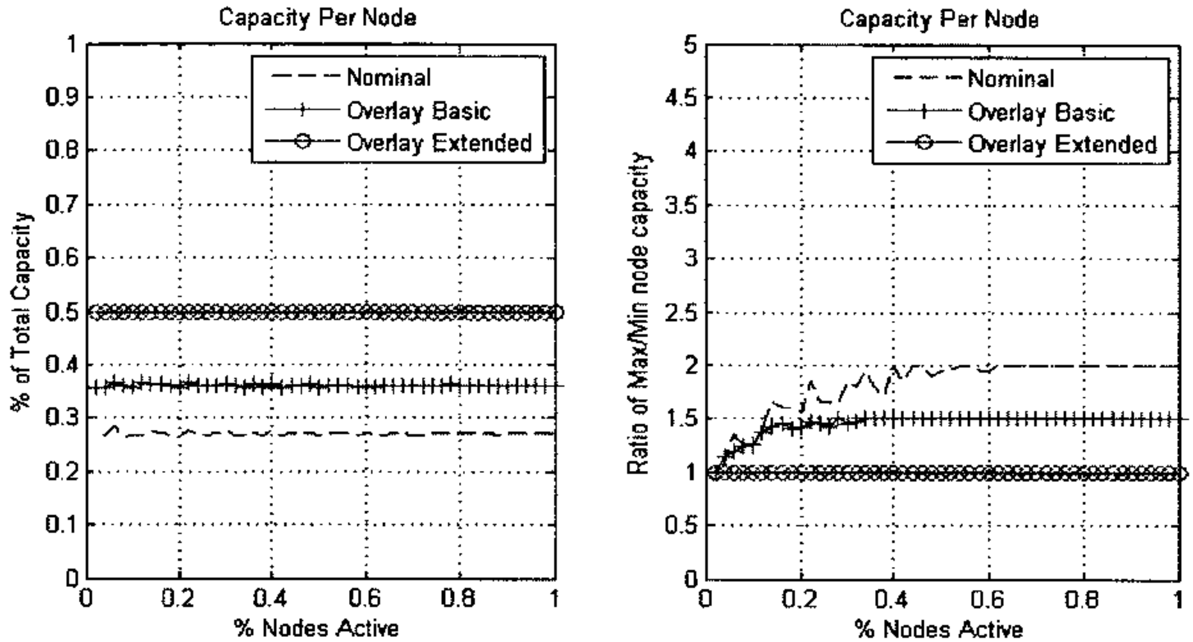
It is clear from Figure 26 that smaller network sizes have similar performance regardless of model. However, with networks greater than 20 nodes, the performance is noticeably less for the nominal and basic models. In networks of greater than 10 nodes, the fairness of the nominal stabilizes to 2:1, and the basic stabilizes to 1.5:1 with the extended maintaining overall fairness of 1:1. Thus, node starvation takes place quickly in larger networks with higher numbers of active nodes with the basic overlay and nominal cases. It is clear that each model converges as both the total nodes and active nodes grow.

The extension of these worst case models to the uniformly distributed random model was considered. As shown in Figure 27, the capacity remains constant independent of the number of active nodes in the network. However, clearly, fairness is dependent on the number of secondary users present. It is clear that this random case supports better overall performance than the basic overlay and the nominal cases, with values of 40% and 28%, respectively. Our extended overlay again provides consistent performance approaching the total capacity threshold of 50%.

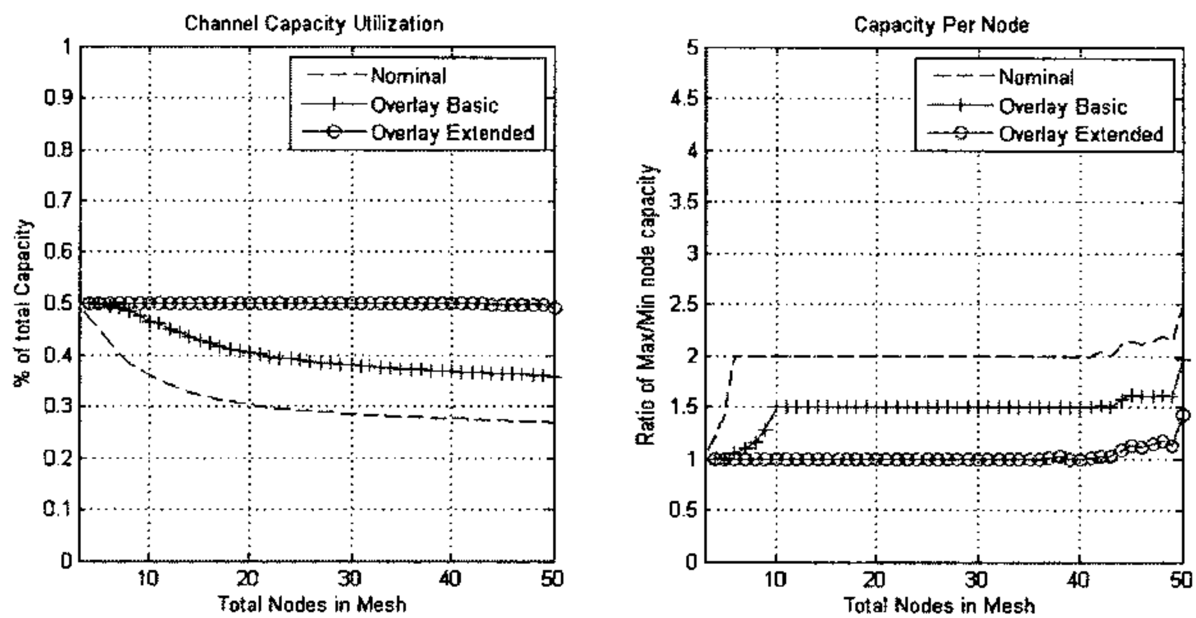
The results of Figure 27 provide a good overview of the performance and fairness increase of our extended overlay network. The falloff of the performance of the basic overlay and nominal cases is much more gradual than the extreme case presented in Figure 26. The capacities of these models approach the worst case, and it can be considered equivalent to worst case after the total number of nodes exceeds 45. Similarly, the fairness approaches worst case after only 5 nodes for the nominal case and 18 for the basic overlay case.

## VI.4 CONCLUSION

In this chapter, we have investigated the influence of cognitive overlay models on secondary users when the primary user is absent. By uptilting channel precoding, some of the secondary user collision domain can be reduced. Our simulated results demonstrate that cognitive overlay secondary users can achieve near optimal capacity of $O(B/2)$. In addition to increased capacity, the sequential precoding scheme allows an increase in fairness for secondary users.

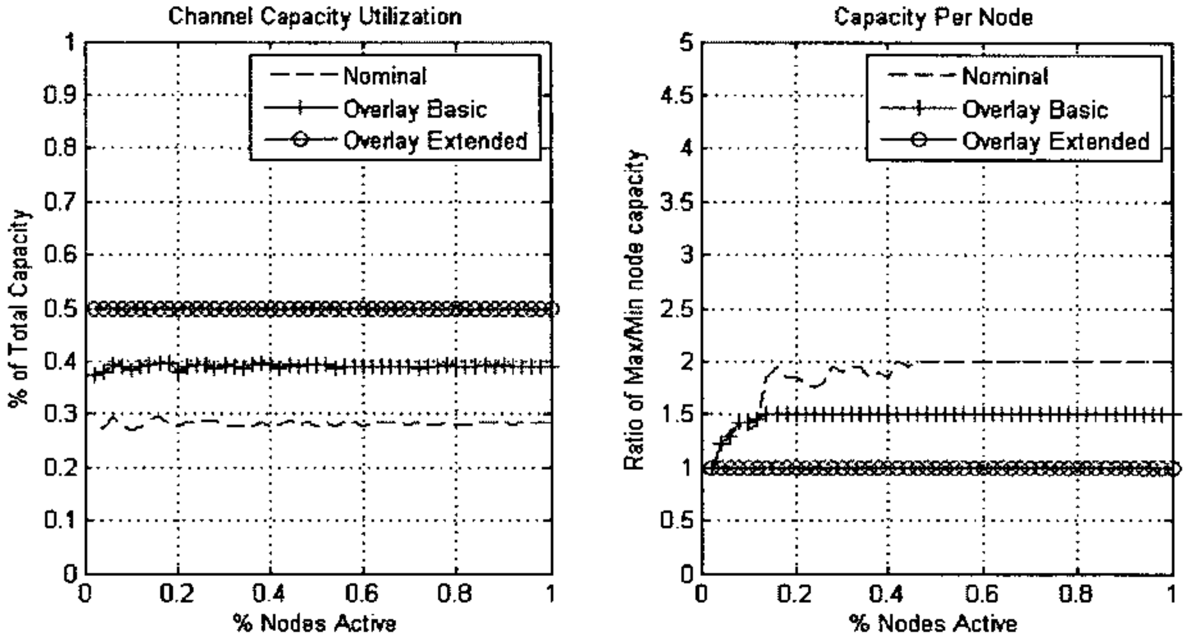



(a) 50 nodes, 20 trials

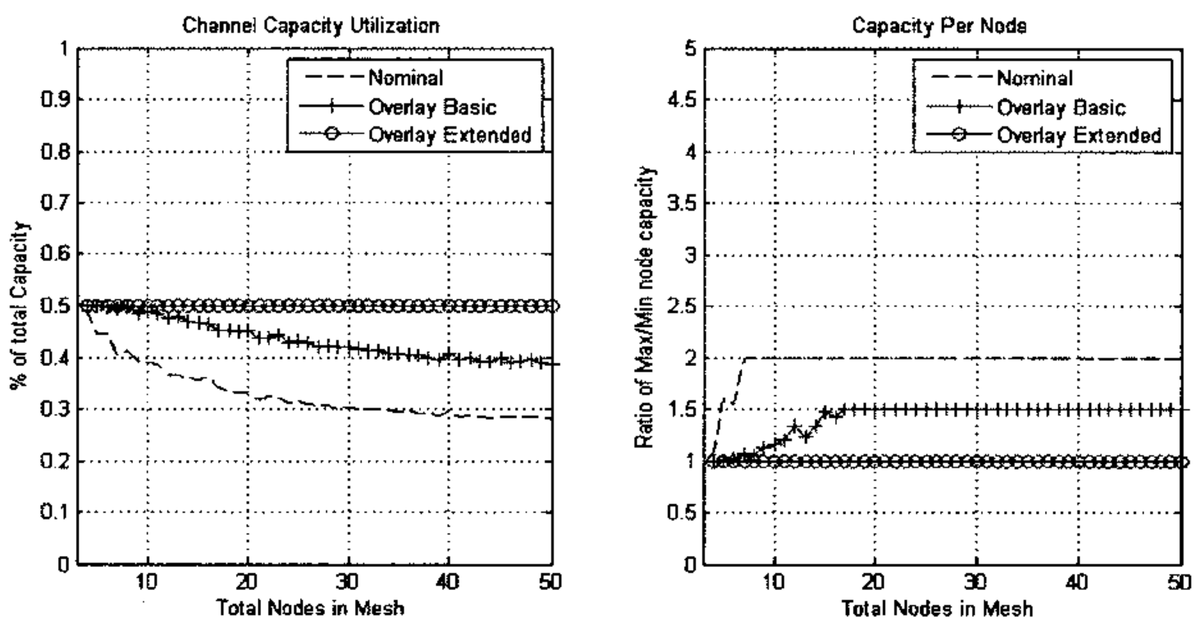



(b) 100% nodes active, 20 trials

Fig. 26: SU Chain Topology




(a) 50 nodes, 20 trials




(b) 100% nodes active, 20 trials

Fig. 27: Uniformly Randomly Distributed SUs

# CHAPTER VII

# DISSERTATION CONCLUSIONS

This work addresses the key issue of mutually beneficial transparent spectrum sharing between licensed primary users and unlicensed secondary users. As the number of wireless devices and users is rapidly increasing, it has become widely recognized that dynamically sharing spectrum is no longer a concept, but rather is a federally supported initiative. This push by both unlicensed users and now the federal government to encourage licensed users to share their spectrum has marked a huge turning point in modern wireless communication networks. Although there have been significant strides in providing practice opportunistic spectrum sharing models, three key questions remain.

1. How can secondary users transparently provide a performance incentive to primary users to motivate them to allow access to their licensed spectrum?

2. How can secondary user networks guarantee that a minimum performance metric can be achieved for all secondary user nodes while co-accessing the licensed spectrum with primary users?

3. If secondary users can use channel precoding to co-access channels with primary users, then what potential channel capacity is possible if they channel precode amongst themselves?

Since secondary users lack the monetary incentives to persuade primary users to share their licensed spectrum, a performance incentive is required. By utilizing dirty paper coding to enable the secondary user to transparently precode with a multi-hop primary user network, we clearly defined one such performance incentive: increased SINR at the primary user receiver. By precoding with the primary user transmission, the secondary user is able to meet a predetermined increase (K) in primary user SINR and, thus, reduce the primary user BER. Importantly, the proposed DSCA model performs this transparently to the primary user. We were able to clearly show that the more demanding the primary user incentive (K), the fewer secondary users would qualify to provide this incentive. Thus, primary users are motivated to keep incentive demands low to make them occur more often, which in turn allows a greater number of secondary user nodes to participate in co-access. In addition, this work presents an optimal algorithm for selecting secondary users from among all sets of qualified users to co-access the licensed channel with each primary user.

In response to the question of how to provide secondary user network performance with minimum guarantees, we developed in Chapter V medium access control protocol for secondary users to share licensed spectrum using the round robin based co-access protocol CAARR during primary user activity and contention based ASAC while the primary user is absent. Our model leveraged the limitation imposed by the primary user for the secondary user *region of co-access* to eliminate the hidden terminal problem for the secondary user and, thus, enable an optimal round robin strategy. However, since these primary user constraints prevent a subset of secondary user nodes from participating in co-access, the contention based MAC with weighted contention windows. The weighted contention window gives the secondary users who were unable to co-access priority in securing channel access during periods of primary user absence. The end result of the SCAP protocol was a limit in the secondary user access time to secure the channel. At worst (when the PU is never active), the SCAP performs as a standard contention CSMA/CD with binary exponential backoff. However, as the PU increases activity, the SCAP reduces secondary user access time and shows great improvement over traditional opportunistic spectrum sharing schemes.

The benefits of using pre-coding to take advantage of primary user relay redundancies motivated a study into the benefits of utilizing dirty paper coding amongst secondary user networks to take advantage of common secondary user network configurations. Specifically, our work in Chapter IV and Chapter V showed significant benefits to using the overlay model of channel access to exploit multi-hop primary user networks. Since secondary user networks are frequently organized as Ad-Hoc networks into a Wireless Mesh Network configuration, the motivation was there to determine if secondary user networks could also exploit channel precoding to increase their network performance when the primary user was absent. Our work on the SU channel capacity using sequential channel precoding in Chapter VI revealed that secondary users can extend precoding over multiple hops to increase secondary user performance.

As a result of our work in overlay spectrum sharing through secondary user channel precoding, we provide a compelling argument that the current trend towards opportunistic spectrum sharing needs to be reconsidered. This work asserts that limitations of opportunistic spectrum access to transparently provide primary users incentive and its detrimental effect on secondary user performance due to primary user activity are enough to motivate further study into utilizing channel precoding schemes such as dirty paper coding. In addition, our work in exploiting the primary user network dynamics (in our case its multihop relay characteristics) to facilitate the spectrum sharing model provides further motivation for spectrum sharing research focused on exploiting primary user characteristics instead of just detecting their network activity.

## VII.1 FEDERAL POLICY IMPLICATIONS

As we discussion in Chapter I, the current push by the federal government to allow spectrum sharing in licensed spectrum places significant pressure on developing mutually beneficial spectrum sharing strategies. The high cost of owning spectrum licenses makes the primary user difficult to motivate with monetary incentives. In addition, the management of such monetary incentives or *pay to play* type schemes are prohibitively difficult. Our model of secondary users improving SINR transparently to the primary user provides a much more compelling alternative. Potentially, this type of incentive could be standardized and regulated by the FCC or NTIA through a much simpler and more practical means than monetary incentives. Although much research remains to be done before such policy could be implicated, our work motivates that this type of regulation is theoretically possible and practically appealing to both primary and secondary users.

## VII.2 FUTURE RESEARCH

The result of our work to motivate the study of secondary user channel precoding leads us to a few areas of future research.

- The development of more secondary user encoding schemes that can implement dirty paper coding with a larger set of primary user codebooks
- The identification of all primary user spectrum where the networks rely on multihop

relay transmissions

- The creation of a cognitive overlay testbed from current USRP software defined radio hardware to implement our SCAP protocol
- The comparative study of precoding schemes for use in cognitive overlay networks
- Development of a federal policy proposal for allowing transparent spectrum co-access

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