Enabling Dynamic Spectrum Access in 4G Networks and Beyond

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As early as 2014, mobile network operators' spectral capacity will be overwhelmed by the demand brought on by new devices and applications. To augment capacity and meet this demand, operators may choose to deploy a Dynamic Spectrum Access (DSA) overlay. Spectrum regulation is following suit, with regulators attempting to incorporate spectrum sharing through the design of spectrum access rules that support DSA. This dissertation explores the idea of DSA applied to Long Term Evolution Advanced (LTE+) networks. This idea is explored under functional, architectural, and spectrum policy aspects.

Under the functional and architectural aspects of this topic, the signaling and functionality required by such an overlay have not yet been fully considered in the architecture of an LTE+. This dissertation presents a Spectrum Accountability framework to be integrated into LTE+ MacroNet and HetNet architectures, defining specific element functionality, protocol interfaces, and signaling flow diagrams required to enforce the rights and responsibilities of primary and secondary users. We also identify and propose three DSA management frameworks for LTE+ HetNets: Spectrum Accountability Client Only, Cell Spectrum Management, and Domain Spectrum Management. Our Spectrum Accountability framework may serve as a guide in the development of future LTE+ network standards that account for DSA.

We also quantify, through simulation and integer programs, the benefits of using DSA channels to augment capacity under a scenario in which LTE+ network can opportunistically use TV and GSM spectrum. In our first experiment, we a consider a scenario where three different operators share the same cell site with LTE+ equipment and a Dynamic Spectrum Access (DSA) band to augment spectral capacity. Our experiments show that throughput can increase by as much as 40%. We develop integer programs to model the assignment of spectrum channels to both a MacroNet and HetNet. In our selected scenario, we observe TV white spectrum provides the largest gain in performance for both Nets: 27% for MacroNet and 9% increase for the HetNet over our measured ranges. Although the gains in using opportunistic use of GSM is more modest, 10% and 2% for the Macro and HetNet, respectively, we believe that these gains will significantly increase as operators continue to migrate users to LTE+, thus freeing up portions of the bands currently used for GSM service. In our final analytical model, we create integer program sets to represent the different three DSA management frameworks for LTE+ HetNets and compare their results.

Under the spectrum policy aspects, this dissertation develops a decision-theoretic framework for regulators to assess the impacts of different spectrum access rules on both primary and secondary operators. We analyze access rules based on sensing and exclusion areas, which in practice can be enforced through geolocation databases. Our results show that receiver-only sensing provides insufficient protection for primary and co-existing secondary users and overall low social welfare. On the other hand, combining sensing information of only the transmitter and receiver of a communication link provides dramatic increases in system performance. The performance of using these link end points is relatively close to that of using many cooperative sensing nodes associated to the same access point and large link exclusion areas. We hope these results will prove useful to regulators and network developers in un and developing rules for future DSA regulation.

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Chapter 1

Introduction

The recent spectrum crisis has caused regulators and network operators to investigate new ways to make more spectrum available and to make spectrum usage more efficient. To this end, regulators are examining the use of opportunistic spectrum sharing to provide new and innovative services to meet the new demand for data. Network operators are also migrating systems to Long Term Evolution Advanced (LTE+), which is likely to be the next worldwide mobile wireless network standard. LTE+ networks will require new spectrum to meet the rising demand for data and the idea of opportunistic spectrum seems a cogent option for new spectrum. In addition to using opportunistic spectrum, network operators will likely deploy Heterogeneous Networks (HetNets), where networks will comprise small and large cell sizes, to augment system capacity. In this dissertation, we explore these ideas and consider the functional, architectural, and spectrum policy aspects to bring DSA into LTE+ and beyond.

1.1 Background and Motivation

With at least 20 commercial deployments since 2009, Long Term Evolution (LTE) has the fastest adoption rate of any mobile network technology to date. More than 200 operators in 80 countries are investing in LTE, positioning LTE as the future global standard for mobile wireless technologies [3]. Despite the rapid deployment of LTE networks, smart phone devices and applications will create a data tsunami so massive the Federal Communications Commission (FCC) is predicting a 300 MHz spectrum deficit for mobile wireless broadband by 2014 [4]. In a separate report, the FCC also found that spectrum is mostly underutilized throughout time and space [5]. One key feature of LTE+ is spectrum aggregation, which allows the aggregation of discontiguous spectrum channels of up to 100MHz [6]. Spectrum aggregation brings the likely possibility of hybrid carriers, which consist of a combination of licensed and DSA channels [7]. Therefore, one option for increasing spectral capacity is through a DSA overlay, which provides extra capacity through secondary opportunistic spectrum use.

Although hybrid carriers can provide additional capacity, they will also require modifications to existing architectural models to support the use of DSA carriers. Work in [8, 9] proposes a spectrum broker architecture to manage a segment of spectrum known as the Coordinated Access Band (CAB). Through spectrum leases, the spectrum broker issues channels from the CAB for use in cellular networks. The work in [10] proposes a Dynamic Spectrum Access Protocol (DSAP) for coordinating spectrum access between arbitrary wireless technologies on a per-host basis. Works in IEEE 802.22 Wireless Regional Area Network (WRAN) and 802.11af (WhiteFi) [11] are also proposing architectural frameworks for supporting the use of TV white spaces [12] through a combination of sensing techniques and database queries coordinated by a spectrum manager. None of these papers, however, discusses the architectural and signaling elements required to incorporate DSA into 4G networks such as LTE+.

In addition to using DSA overlay to increase capacity, LTE+ standards also support Relay Nodes (RNs) and femto-cell sized Evolved Node Bs (eNBs), called Home Evolved Node Bs (HeNBs) to extend coverage, increase spectrum efficiency, and augment capacity. To increase the capacity of a traditional cellular network, or MacroNet, operators will deploy HetNets in high traffic areas and inside edifices (e.g., stadiums, campuses, shopping centers, etc.). Recognizing these trends, this work also examines the architectural and operational aspects of deploying a DSA overlay in LTE HetNets. Most HetNet research focuses on cross-tier interference (i.e., interference between femto-cell and macro cell layers) [13–17]. Many of these works assume an architectural and regulatory framework to support DSA for cognitive femto-cells, which may make use of opportunistic spectrum. Work in [18, 19] both propose spectrum management architectures and discuss fundamental research issues related to femto-cells. However, these works do not explore how the network would manage the combined licensed and DSA usage of spectrum, nor the architecture and signaling for management of DSA spectrum. Therefore, the purpose this dissertation is to holistically examine the functional, architectural, and spectrum policy aspects necessary for DSA to be successful in an LTE+ MacroNet and HetNet.

1.2 Research Questions and Methodology

In alignment with the purpose of this dissertation, we pose the first research question: what functional components are required in an LTE+ network to support DSA in an LTE+ MacroNet? In LTE+ there is a well defined standard and several protocols within that standard. Are there functional elements and protocol that can be modified or leveraged? Are new network elements required? What signaling mechanisms would be needed to support the resulting architecture? The challenges for DSA have been very well articulated in [20]. How can these challenges be addressed in a DSA architectural framework, when considering an LTE+ MacroNet?

Although traditional cellular networks use a MacroNet topology, when network operators begin deploying HetNets, what kind of different considerations are required? For example, when we consider an LTE HetNet, rather than a MacroNet, could the HetNet use the same architecture as the

MacroNet? Is there a need for local spectrum management? If so, which network elements should perform these local management roles? Furthermore, if DSA was used in an LTE+ MacroNet and HetNet, what kind of comparative performance benefits could be realized? Finally, what types of spectrum management frameworks would be necessary in an LTE+ HetNet?

In addition to the architectural frameworks, there is a variegated taxonomy of DSA spectrum policy paradigms. Additionally, spectrum regulation in DSA is still nascent. Regulators struggle to regulate DSA networks, since their method of operation lies outside the norm of traditional regulation. Traditionally, harmful interference was strictly managed by allocating spectrum bands for specific purposes and assigning licenses to geographical markets. DSA regulation is a new challenge, since methods and technologies are nascent and/or unproven. Additionally, in a regulatory framework, a harmful interference event is difficult to quantify and identify. Thus, the functional and architectural frameworks to support DSA must be flexible to spectrum policy. We also pose the question: what methods can help regulators select between alternative DSA rules? Finally, what standard decision methodology could regulators use to identify the most beneficial spectrum regulation quickly?

1.3 Contributions

We have three major contributions in this dissertation. Our first major contribution proposes an architectural and operational framework to support a DSA overlay for LTE+ MacroNets, which has been published in [21] and further extended and accepted for publication in [22]. In our second major contribution, work for spectrum management frameworks for HetNets was submitted for publication in [23]. These first two contributions represent the capstone and major portions of the work in this dissertation. In our last contribution, we propose a decision analysis method for spectrum access rules, which appears in [24].

In our first major contribution, we propose the architectural elements needed to incorporate DSA into an LTE+ MacroNet through our proposed Spectrum Accountability (SA) framework. In the SA framework, an eNB with cognitive capability, called a cognitive Base Station (cBS), issues spectrum lease requests. The cBS sends these lease requests to a centralized entity that manages spectrum lease policies, sets spectrum access rules, and issues leases. At the end of the lease, or at periodic intervals, the cBS reports usage metrics. Regulators or spectrum managers can use these metrics for detecting violations, resolving conflicts, and setting DSA policies. The SA framework provides the means by which regulators can define, enforce, and manage spectrum access rules among competitive secondary operators and protect primary operators from harmful interference.

Our framework makes the following additional contributions. First, we analyze the effects of a DSA overlay on the operational architecture of LTE+ MacroNet. We propose modifications to existing interfaces and network elements to support the DSA architecture. Our second contribution is our SA framework, which provides the mechanisms to coalesce many different aspects of DSA into specific network element functionality, protocol interfaces, and signaling flow diagrams, in a manner that is agnostic to the spectrum policy paradigm [25]. The SA framework focuses on the operational signaling scenarios to support cooperative sensing techniques [26] and coordination and monitoring of spectrum access through an Spectrum Accountability Server (SAS). To support the benefits of DSA in LTE+ networks, we illustrate, through simulation, the quantifiable benefits for LTE+ network operators using DSA spectrum to increase their spectral capacity. In this scenario, we examine the benefits of opportunistically using spectrum bands to serve overflow traffic at an LTE+ eNB. We also determine the optimal assignment of LTE+ channels in a hybrid carrier network. We develop and apply integer programs to a scenario in which an LTE+ network uses TV white spaces and also shares spectrum from a GSM system. Through our integer programs we illustrate the quantifiable benefits of using hybrid carriers in an LTE+ network.

In our second major contribution we identify and propose three DSA management frameworks for LTE+ HetNets: Spectrum Accountability Client Only, Cell Spectrum Management, and Domain Spectrum Management. Using our management frameworks, we define protocol interfaces and operational signaling scenarios to support cooperative sensing, spectrum lease management, and alarm scenarios for rule adjustment to extend our the role of our SA framework. Our work in the LTE+ HetNets frameworks also makes the following additional contributions. In an additional contribution, we formulate integer programs to quantify benefits of deploying DSA spectrum in an LTE+ HetNet. Using these programs, we can compare optimal channel assignment for an LTE+ HetNet that uses only licensed spectrum against another that takes advantage of hybrid carriers using opportunistic GSM and TV white space spectrum. Furthermore, we also include a performance comparison of the LTE+ MacroNet under the same scenarios. In our scearios, we model a MacroNet and HetNet topology using Geographic Information System (GIS) data, e.g., population data, building footprints, existing transmitter locations, and FCC allocated spectrum bands to assess the realistic benefits of using DSA in an LTE+ HetNet. We believe that using this GIS data produces more detailed, richer, and more realistic inputs for our integer programs. In our last additional contribution, we model our different DSA spectrum management frameworks through integer program sets, generate an additional topology using GIS data, and compare their relative performance to the optimal.

Our final major contribution in this dissertation applies decision theory to analyze the impact of different spectrum access rules. Recent trends in regulatory paradigms have been shifting from the traditional command and control model of spectrum management to one of shared use through Dynamic Spectrum Access (DSA) [27–29]. Both the FCC and Office of Communications (OFCOM) in the United Kingdom have released initial regulation for unlicensed used of TV white space devices, and the FCC, in a recent Notice of Inquiry (NOI), is requesting information on the viability of DSA techniques [29]. In this effort, the FCC seeks to understand how spectrum access rules based on spectrum sensing and geolocation databases can be useful in providing secondary operators with opportunistic access, while protecting primary users from harmful interference.

Using decision analysis provides regulators with a methodology to evaluate spectrum access rules based on the resulting utility to the various constituencies that are vying for spectrum. Our first contribution in this study is a multi-attribute utility model for evaluating spectrum access rules. This multi-attribute utility model is based on the fundamental objectives of primary and secondary operators deploying DSA. Through the Analytical Hierarchy Process (AHP) [30], we weight the relative importance between objectives, using input from experts in network performance. In our second contribution, we propose and evaluate nine spectrum access rules based on spectrum sensing and geolocation databases. Here, we simulate a scenario in which a primary operator shares spectrum with a secondary operator. The results of the simulation are then evaluated through our multi-attribute utility model and we calculate the utility of each rule.

1.4 Outline

This dissertation is divided into eight chapters. The next chapter, Chapter 2, builds the foundation of the dissertation through a presentation of relevant literature in DSA systems, spectrum policies and LTE+. In Chapter 3, we present the SA framework for the LTE+ MacroNet architecture. The SA framework includes an outline of the new and affected LTE+ network elements, control planes, and operational procedures. In Chapter 4, we illustrate, through simulation and integer programs, the potential benefits for using a DSA overlay in LTE+ networks through two cases. In the first case, multiple operators share the same site and use a DSA carrier to augment licensed capacity and serve overflow traffic. We extend this idea in our second case, by considering optimal assignment of LTE+ channels, which opportunistically use GSM and TV white spaces. We extend the SA framework for LTE+ HetNets in Chapter 5, where we introduce three spectrum management frameworks for LTE+ HetNets: Spectrum Accountability Client (SAC), Cell Spectrum Management (CSM), and Domain Spectrum Management (DSM). Using integer programs to model network channel assignment and GIS data to generate realistic topologies, we evaluate the performance of using DSA to augment an LTE+ HetNet and MacroNet in Chapter 6. Additionally, we develop integer program sets to model each of the spectrum management frameworks we defined in Chapter 5 and compare their performance to the optimal. Chapter 7 presents our work on decision analysis of spectrum access rules, where we apply decision theory to current regulatory considerations for spectrum access rules. This dissertation concludes with Chapter **??**, which summarizes our work and proposes new research for future work.

Chapter 2

Literature Review

IEEE 1900.1 defines DSA as: “The real-time adjustment of spectrum utilization in response to changing circumstances and objectives” [31]. In this dissertation, a secondary user and primary user comprise a DSA system, in which the secondary user has the objective of utilizing primary spectrum under the changing circumstances of primary use. Military-based DSA radio systems have been demonstrated through the xG Network [32] and also the Wireless Network after Next (WNaN) [33]. Both of these systems identify and opportunistically occupy locally unused spectrum without causing interference to other non-cooperative users. Commercial-based applications of DSA are being pursued through IEEE 802.22 WRAN [12] and 802.11af (WhiteFi) [11, 34] standards, which will make use of unoccupied TV spectrum (e.g., TV white spaces). 802.22 plans to bring broadband access to rural environments while not interfering with TV operation. WhiteFi 802.11af seeks to define modifications to 802.11 physical and Medium Access Control (MAC) to access TV white spaces. In any case, DSA networks seek to identify primary spectral vacancies and fill those vacancies with secondary transmissions through spectrum management.

IEEE 1900.1 defines is spectrum management as:“The process of developing and executing policies, regulations, procedures, and techniques used to allocate, assign, and authorize frequencies in the radio spectrum to specific services and users” [31]. Spectrum management is the fundamental means in which DSA networks operate and includes a mix of spectrum policy (e.g., regulation) as well as operational techniques to execute the objectives of the DSA system. Discussions in DSA spectrum policy propose different regulation paradigms in which DSA systems can operate. Each paradigm has different economic and technical performance implications and drives the implementation of DSA techniques. In any case, study within DSA systems is dependent on these spectrum policy paradigms, which can define operating rules (i.e., etiquette) of systems.

Like 802.22 and 802.11af, LTE is also incorporating aspects of spectrum management into new releases of the standard. LTE+, beginning with Release 10, will create carriers of 100MHz through spectrum aggregation (the aggregation of discontiguous spectrum channels) [6]. Spectrum aggregation brings the possibility of hybrid carriers, which consist of a combination of licensed and

DSA channels [7] to support traffic. Given the demand for mobile wireless data, DSA will likely play a role in future standards of LTE+ for augmenting capacity.

This chapter builds the foundation for this dissertation through a presentation of relevant literature in DSA systems, spectrum policies and LTE+. Our review begins with section 2.1, by introducing a functional model of a DSA system. Using this model, we describe the relevant body of work according to functionality. In Section 2.2, we review spectrum policy frameworks and how they form the foundation of DSA literature. We then examine work in spectrum etiquette to illustrate and compare different policy paradigms. Additionally, we also provide a summary and comparison of DSA regulation recently issued by the FCC and the OFCOM for the opportunistic use of TV white spaces. In Section 2.3, we examine the work of different proposed DSA architectures. In Section 2.4, we diverge from the discussion on DSA and present an overview of LTE+. We conclude in Section 2.5 by using the body of work as motivation to address our research questions.

2.1 DSA Networks

In this section, we identify the functional components associated with a DSA system. Figure 2.1 illustrates our function model of a DSA system [1]. Figure 2.1 shows a radio node, which could belong to a Mobile Ad Hoc Network (MANET) or be associated with network infrastructure. Generally, the radio nodes obtain spectrum information by sensing radio bands, through external sensors, and/or from a spectrum server. The available spectrum is channelized (i.e., spectrum assigned carrier frequencies and bandwidth) through identifying unoccupied bands from sensing information and/or other spectrum management techniques, (e.g., geolocation techniques). After channelization, each frequency is assigned a transmission schedule, power level, and communication role as a traffic or control channel. In the remaining subsections, we describe each of the functional components shown in Figure 2.1 and the associated works from the literature.

2.1.1 Spectrum Sensing

At the physical layer, spectrum sensing is the action of measuring radio signals, generally for determining spectral vacancy for opportunistic use. A variety of techniques have been studied and developed for this purpose. [26, 35–37] present surveys on the many different sensing techniques proposed in the literature. When considering spectrum sensing for the given application, operational complexity, and accuracy trade-offs should be examined. In general, trade-offs exist between complexity, sensing accuracy, and throughput. When considering spectrum sensing, the challenge becomes analyzing these trade-offs for a specific application. Table 2.1 summarizes some of these techniques as well as the associated trade-offs.

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[1] A similar perspective was captured in [35].

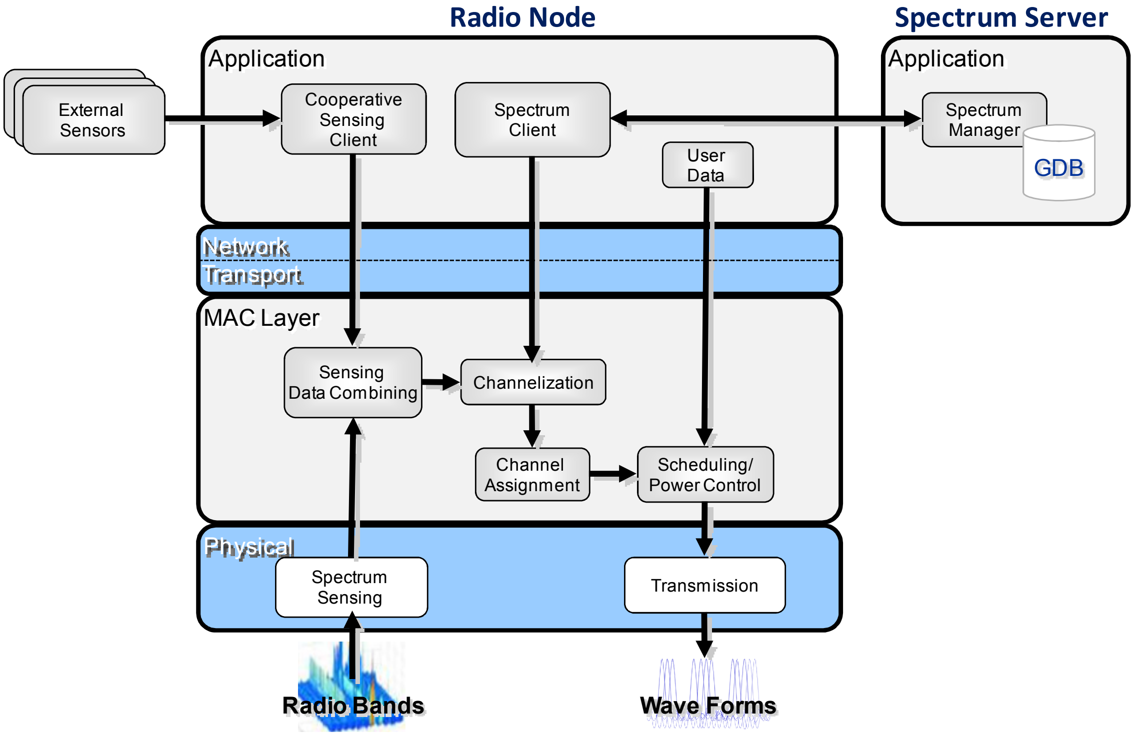

Figure 2.1: An illustration of the generic components contained in a DSA system.

Sensing Technique	Advantages	Disadvantages
Energy Detection	Low Computational and Implementation Complexities	Non-stationary noise variance, filter effects, spurious tones, and Rayleigh fading degrade performance. Detection of signals below noise power is not possible. Longer sensing times required to achieve low probability of false alarm and missed detection.
Cyclostationary	Unaffected by non-stationary noise.	Fading affects cyclostationary features of signals and degrades performance.
Radio Identification	Complete knowledge of transmission technology can be obtained.	Higher complexity, combination of neural networks, energy and cyclostationary detection is used.
Waveform Sensing	High Accuracy, lower complexity.	Knowledge of technology transmission patterns and signal type is needed. Susceptible to synchronization errors.
Matched Filtering	Optimum method of detection, short sensing time to achieve needed probability of false alarm and missed detection.	Complex demodulator, perfect knowledge of primary user signal features is needed.

Table 2.1: A relative comparison of the advantages and disadvantages of different spectrum sensing techniques.

2.1.2 Cooperative Sensing

External sensors and other radios can cooperate by exchanging sensing information to improve the accuracy of spectrum sensing. Cooperative sensing can cope with uncertainties and decrease sensing time [26]. In cooperative sensing, nodes share their sensing information with each other through an application level client, and then combine the sensing information to determine if the spectrum is available for opportunistic use. Combining sensing data is based on one of two techniques: hard or soft combining [38]. In hard combining, channel availability is determined if a certain proportion of the network users detect the measured energy below the detection threshold. In soft combining, the weighted average of the cooperative sensing results from each node is used to determine channel availability. Regardless, [39] demonstrated small differences in performance between hard and soft combining schemes.

2.1.3 Channelization

Ideal DSA transceivers could sense over a wide bandwidth and may identify discontiguous spectrum vacancies available for opportunistic use [40]. DSA transceivers require channelization algorithms. Work in [41] proposes the Aggregation-Aware Spectrum Assignment (AASA) algorithm for channelization. AASA assumes that all nodes require a bandwidth of R Hz and channelizes the discontiguous opportunistic spectrum fragments from lowest frequency into highest frequency in R Hz channels.

In lieu of sensing information, identification of available spectrum can be assisted through a Geolocation DataBase (GDB) of available spectrum [11, 12]. At the application layer, a spectrum client can obtain information on available spectrum from a spectrum manager (i.e., an application at the spectrum server). When the available spectrum information is obtained, the spectrum channels can determine the available spectrum and pass the information to the assignment function. In this case, channelization may be predefined, since specific bands available for opportunistic use may be known in advance.

2.1.4 Channel Assignment, Scheduling and Power Control

Channel assignment has the purpose of assigning logical traffic and control channels to frequency or time slots to minimize interfering transmissions. When coordinating channel assignment in a MANET, scheduling may be used to avoid conflicts among many nodes [42–44]. Additionally, exclusive channel assignment may require dynamic power control to minimize aggregate interference among nodes [41, 45–47]. Furthermore, the dynamic nature of channels could result in channels becoming unusable because of primary user occupation and require occupancy prediction techniques to determine channel assignment [48, 49]. Assigning control channels can be problematic if spectrum availability is dynamic and no preexisting channels are defined, resulting in the rendezvous problem [50]. Thus, techniques have been developed for assigning a common control channel between nodes in a DSA environment with dynamic channel conditions with no predefined control channel frequency [43, 50, 51]. In summary, channel assignment, scheduling and power control are tightly coupled functions used to maximize the throughput of network users by minimizing interfering transmissions.

2.2 Spectrum Policy Paradigms

We refer to spectrum policy paradigms as the set of rules or regulations used to manage the use of wireless spectrum. In this dissertation, we are interested in how policy models affect the functional framework of DSA. These policy models can constrain or specify every functional component and interface shown in Figure 2.1. Within these models, many variants of spectrum policies have emerged, and with them, different rules, procedures and protocols for sharing spectrum among primary and secondary users (i.e., a spectrum etiquette). In the remaining subsections, we provide an overview of spectrum policy paradigms, different spectrum etiquette techniques within those paradigms, and a comparison between DSA regulation in the U.S. and the U.K.

2.2.1 Overview of DSA Spectrum Policy Paradigms

Historically, regulators have sought to manage interference between wireless network operators through the adoption of an exclusive use model. Under the exclusive use model, entities transmit in specified spectrum bands and geographical areas only through owning a spectrum license. Since 1989, most network operators have purchased spectrum licenses through auctions, within geographic areas drawn by the regulator [52]. Within the exclusive use model, regulators can allocate spectrum for a specific purpose [e.g., Personal Communications Service (PCS)], combined with specific technology [e.g., GSM]. The antithesis of the exclusive use model is the open access model. Under the open access model, no license is required and any user can transmit at any power level at any time [53]. This approach has also been referred to as the *open commons*, since the common spectrum pool can be shared by all [54, 55]. Within these spectrum policy paradigms, a variegated taxonomy exists, which stems from these two basic models.

Under the exclusive use model, rigidly allocated spectrum can cause spectrum to become underutilized and lead to inefficiencies [25]. To overcome these inefficiencies, regulators introduced the flexible use model [52]. Under the flexible use model, a licensee can use the spectrum for any purpose that it sees fit and may lease the spectrum to other network operators. Through spectrum leases, secondary spectrum markets can more fully utilize spectrum. Policy models within these secondary markets are often referred to as *private commons* [52]. Each primary spectrum holder effectively becomes a spectrum manager. In another variant of this model, spectrum is pooled by many different license owners and mutually used by many different operators [56]. In the pooled variant, spectrum within this private commons could be shared or traded like a commodity. This has given rise to ideas of dynamic spectrum markets or real-time spectrum markets in which primary spectrum holders market their spectrum to secondary users [57, 58]. In any case, in an ideal secondary market, secondary networks would lease spectrum dynamically and self-allocate this spectrum without human intervention. The idea of secondary spectrum markets is to overcome the inefficiencies associated with a rigid exclusive use model, through trading or sharing for maximal use of spectrum.

Like the exclusive use model, the open commons access model can also lead to inefficiencies in spectrum utilization. In the open commons model, users do not have incentives for efficient spectrum use and sharing. As a result, individual users could greedily transmit for longer durations and higher power levels to insure that their transmission is successful[59, 60]. Thus, the opens commons model cannot guarantee quality of service and can result in the well-known *Tragedy of the Commons*. A variant of this model, the *managed commons*, implements commonly held rules to manage the spectrum of the commons as appropriate [54]. In the managed commons, secondary users could use spectrum as long as they follow the rules to access primary spectrum (i.e., avoid causing harmful interference to primary users) and share spectrum with other secondary users equitably.

2.2.2 Spectrum Etiquette

In all DSA spectrum policy models, sharing of spectrum is governed through a *spectrum etiquette*. IEEE 1900.1 defines spectrum etiquette as: “A set of rules, policies, procedures, and protocols that govern spectrum sharing behavior,” [31] specifically to avoid interference with each other. Sharing can occur within two different domains: 1. between primary and secondary users, and 2. among secondary users. Sharing within each domain can be further characterized through a cooperation or coexistence technique [61]. When devices share through cooperation, a common protocol is used to communicate sharing arrangements. Using coexistence, devices do not explicitly communicate among one another and instead may rely on other sources of information to determine the sharing arrangement. Permutations between different spectrum etiquette models are illustrated in Figure 2.2. Using these four spectrum etiquette models, we can represent and describe many spectrum etiquette techniques used in the literature.

In the first model, primary and secondary users use cooperation with one another to coordinate spectrum sharing. This first model best represents a real-time spectrum market, in which primary spectrum holders lease their spectrum to secondary users and secondary spectrum users can trade spectrum among each other. In this model, primary users and secondary users both sell and buy spectrum. Spectrum etiquette in this model leverages auction-based algorithms using automated real-time spectrum trading. For example, work in [62] proposes a centralized iterative bidding algorithm to maximize profits in a real-time spectrum market. Pricing models and bidding formats to control the trade-offs between revenue and fairness are examined in [63]. While secondary markets do exist, the mechanisms to support automated spectrum trading do not and have been a subject of interest recently to the FCC [29, 64].

In the second model, a primary user coordinates spectrum assignments to secondary users. Eti-

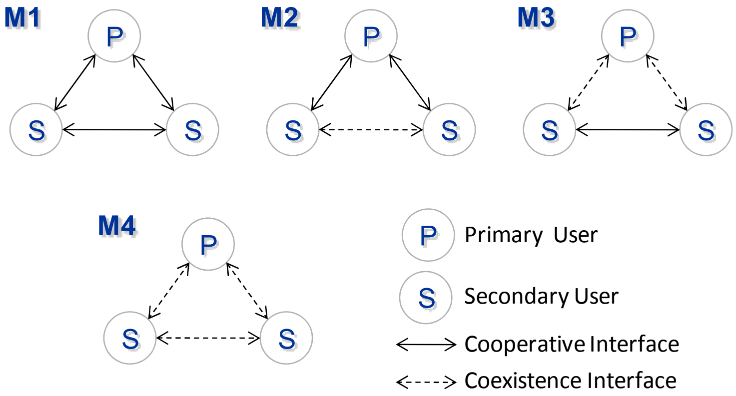

Figure 2.2: An illustration of the different spectrum etiquette models.

quette in this model is based on spectrum requests sent from secondary users to a spectrum server or spectrum broker, which owns or manages the spectrum as the primary user. The spectrum broker receives the spectrum requests and determines the optimal assignment for those requests. Work in [9] introduced a spectrum broker which owns and manages a spectrum band known as the Coordinated Access Band (CAB). The spectrum broker receives spectrum lease requests from cellular infrastructure and issues leases, using channels from the CAB. Work in [8] and [65], builds on this architectural framework determining optimal assignments for spectrum lease requests in Code Division Multiple Access (CDMA) networks through Mixed Integer Linear Programs (MILPs) and heuristics. Work in [8] uses MILPs to maximize the weighted sum of the total assigned channels and minimize the sum of penalties from interference. [65] uses similar optimization problems and solves them through heuristic algorithms based on a Max-k-Cut formulation. Other work in [10] specifies signaling to allocate spectrum per host or per access. In these cases, the primary user manages and/or owns the spectrum and manages interference among secondary users.

In the third model, secondary users obtain information from primary users indirectly but communicate using a common protocol to avoid interference. In this case, primary users' spectrum information is obtained either through sensing or through a geolocation database. 802.22 networks obtain information from primary users in exactly this fashion, using a combination of sensing and database requests to determine spectrum availability [12, 66]. Spectrum usage between secondary users can be communicated through beacon protocols using common control channels to determine channel availability [12, 42, 43]. Similar work in [67] considers coordination of DSA among heterogeneous technologies sharing a given frequency band. Coordination in [67] is performed through using independent control channels among neighbors, which can share channel occupancy information. Fundamentally, this etiquette model requires that secondary users communicate using a common protocol, while primary spectrum information is obtained indirectly using spectrum sensing or database requests.

In the fourth model, coexistence techniques are used to coordinate sharing between primary and secondary users. In this model, secondary users could use sensing or database requests to determine spectrum availability of primary users and secondary users. However, in other cases, secondary users may pay no regard to one another, accepting interference from one another. Current DSA regulations issued by the FCC and the OFCOM currently support this model, where secondary users use coexistence protocols with primary users and accept interference from one another. We explore the details of this regulation in the subsequent section.

2.2.3 DSA Regulation in the US and UK

Preliminary regulation for White Space Devices (WSDs) was issued in 2008 and 2009 by the FCC and OFCOM respectively [68, 69]. This initial regulation allowed the use of unoccupied TV channels using spectrum sensing. The FCC and OFCOM both selected extremely conservative threshold levels for sensing that required the WSD to sense primary users below the noise floor [20]. In addition to the sensing requirement, the FCC also required that WSDs consult a Geolocation DataBase (GDB) to determine the availability of white spaces. Simultaneously, the OFCOM proposed the use of a GDB for identification available channels and requested comments. Both the FCC and OFCOM received many objections to the spectrum sensing requirement, since identification of primary transmitters below the noise floor requires sophisticated sensing techniques and degrades throughput of devices. Additionally, requiring sensing would lead to increased device cost of WSDs. Comments issued to the FCC and OFCOM suggested raising or eliminating the low threshold sensing requirement [27, 28].

In 2010, in response to the comments from [68], the FCC issued a second memorandum and order [27], with new and updated rules. In this second memorandum and order, the FCC removed the sensing requirement for those WSDs that use a GDB for determining white space availability. Additionally, this order also updated the rules for sensing only devices, lowering the detection threshold of sensing only devices to -107 dBm and limiting transmit power to 50 mW. Similarly, in the U.K., the OFCOM removed the sensing requirement and selected the pure GDB approach for WSDs.

The GDB database solutions for both operators are operationally identical. OFCOM and the FCC both proposed a master (Mode II) and slave devices (Mode I). The master will query the GDB to obtain white space information and the slave will select channel information from a query to the master. However, the FCC leaves the database implementation, protocols, power control, and administration exclusively for the market to determine. OFCOM on the other hand, requires WSDs to follow a database query protocol and power control algorithms. Regardless, the existing regulation has been moving from an exclusive use spectrum model into a shared-use access model. Additionally, regulation also requires users to obey a set of rules when accessing the common shared spectrum, treating the spectrum as a managed commons.

While regulations have been established in [27] and [28], regulatory frameworks for DSA are still nascent. In a recent NOI [29], the FCC has requested comment on opening other bands for DSA to provide relief from the spectrum shortage. The FCC opened inquiries on state-of-the-art DSA techniques, spectrum auctions, and how these techniques could establish a DSA network and market. In some ways, regulators struggle to determine the appropriate rules for DSA, since the technology is not yet fully developed. Conversely, deployment of DSA networks struggles, since they will not be developed without proper regulations. Regardless, current regulation follows a managed commons approach using the fourth model for spectrum etiquette.

2.3 Dynamic Spectrum Access Architectures

In this section, we examine the architectural frameworks used to support DSA. The most salient works are the spectrum broker architecture and the 802.22 architecture. In Section 2.2.2, we discussed the spectrum broker architecture from [9] when introducing the second model of spectrum etiquette. We also discussed 802.22, supporting our third model of spectrum etiquette. Additionally, we close this section by discussing cognitive femtocell networks, where a cognitive femtocell is a femtocell network which uses DSA frequencies to augment its capacity. We use these architectures to form the basis of understanding how a DSA framework can be applied to next generation wireless networks.

2.3.1 Spectrum Broker Architecture

Buddhikot in [8, 9] introduced a centralized infrastructure-based DSA network we refer to as the Spectrum Broker Architecture (SBA). In the SBA, the Spectrum Broker (SB) has the responsibility of coordinating spectrum assignments to Base Stations (BSs) using spectrum leases. Spectrum leases issued by the SB can be limited by geographical areas, power, and temporally, where the lease is returned to the broker at the end of the leasing period. The SBA introduces the concept of a CAB, a contiguous spectrum block allocated for the use of DSA and held by the license owner. The SB uses the CAB for assignments through spectrum leases. To determine optimal assignment, the SB receives request for leases in batches and uses automated auctions to resolve demand conflicts. Figure 2.3 shows a pictorial representation of the SBA architecture.

Requests for spectrum leases (demand information) and spectrum sensing snap shots from each BS are forwarded through the Radio Network Controller (RNC) to the SB. Combining the spectrum demand information, snap shots, geographical terrain features, and using auctions to resolve conflicts, the SB determines the optimal spectrum assignment for the requests through spectrum allocation algorithms. To determine optimal assignment, work in [8] proposes solving different optimization problems through use of branch and bound techniques. Work in [70] proposes heuristic algorithms to solve the assignment problem leveraging existing Max-k-cut algorithms and also tabu-search. Once the SB determines the optimal assignment, the spectrum leases are sent to the respective RNCs and deployed at the BSs. Additionally, the spectrum assignment algorithms, leases, and auctions would be driven by policies set by the regulators. Currently, the SBA architecture does not have a specific role in regulation. However, in a recent NOI, the FCC inquires on the

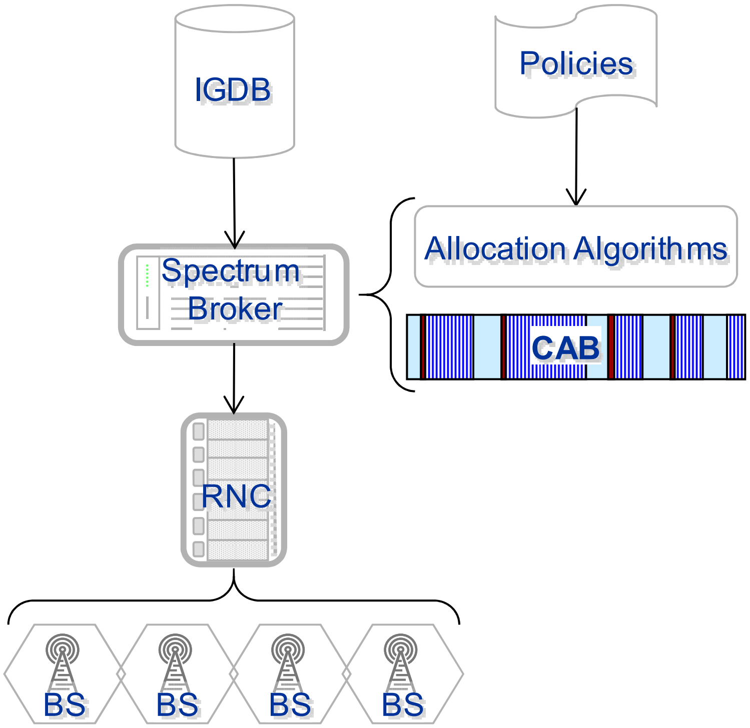

Figure 2.3: The SBA.

feasibility of auction based systems for DSA [29]. However, not all auction based systems require a SBA.

2.3.2 802.22 Spectrum Management Architectures

Unlike the work in [8], 802.22 provides a more flattened architecture for providing DSA services. The 802.22 architecture consists of two network elements: the Base Station (BS) and the end device referred to as the Customer Premise Equipment (CPE) [12]. Within the BS, the spectrum manager has the responsibility of channel, coexistence, sensing, and power management. Similar functionality in the CPE, called the spectrum automaton, provides sensing and location information to the spectrum manager to support the aforementioned functions. Figure 2.4 shows a pictorial representation of this architecture.

The spectrum manager and automaton provide the functionality for available channel identification, coexistence/spectrum etiquette and cooperative sensing. Following the regulations provided in [27, 28], the spectrum manager uses the Incumbent Geolocation Data Base (IGDB) and locations of the CPE and BS for channel identification. Instead of using assignment coordination through a centralized manager, 802.22 provides coexistence with other 802.22 BS using beacons and the Coexistence Beacon Protocol (CBP). CBP uses beacons to broadcast occupied channels and negotiate contention among BSs. These beacons can be broadcast over the air or through a wired IP

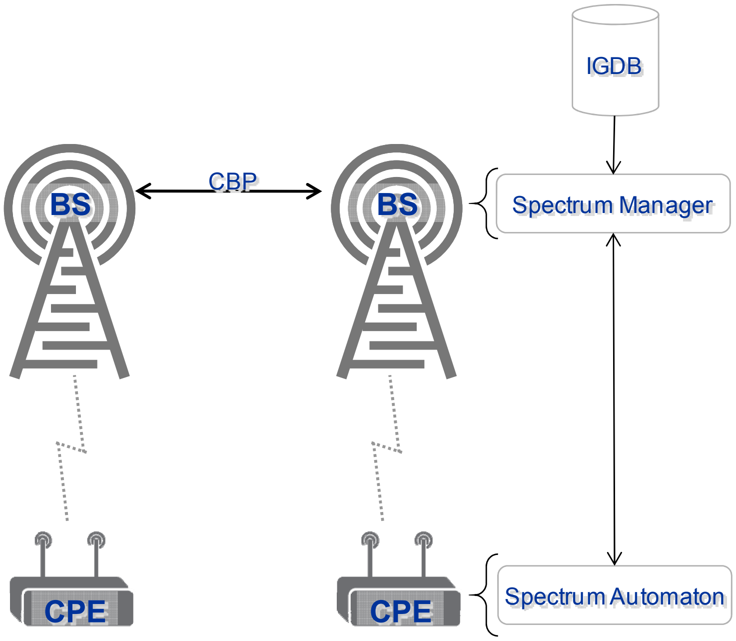

Figure 2.4: The 802.22 spectrum management architecture.

network. Cooperative spectrum sensing is also supported in 802.22. The spectrum automaton, on the CPE, is responsible for providing spectrum sensing reports to the spectrum manager at the BS. The spectrum manager receives these reports and combines it with its own sensing information to make decisions on channel availability. Pending regulation and other standards, 802.22 networks could be the first DSA networks deployed using TV white spaces to provide commercial services.

2.3.3 Cognitive Femtocell networks

Similar to the DSA architectures discussed in [9], work in [18] introduces an architecture for supporting DSA in a femtocell network. Leveraging the traditional femtocell network, with User Equipment (UE), Femtocell Base Station (FBS), and femtocell gateway connected to the core network, [18] proposes that the FBS and the UE gain cognitive capabilities through spectrum agile radios. Figure 2.5 illustrates the cognitive femtocell architecture. Through the spectrum agile radios, the cognitive User Equipment (cUE) and the Cognitive Femtocell Base Station (CFBS), sense and change channel usage dynamically. Using sensing, the CFBS creates a radio environment map, which indicates spectrum usage of the network. This sensing information can be reported to the Cognitive Femtocell (CF) sub-network where the information is used in combination with incumbent databases and policies to direction spectrum usage of the CFBS and cUE. When the cUE accesses the network it will request a frequency channel from the CFBS. After the CFBS receives the requests, it assigns the cUE a frequency channel according to the policies and data from the CF sub-network.

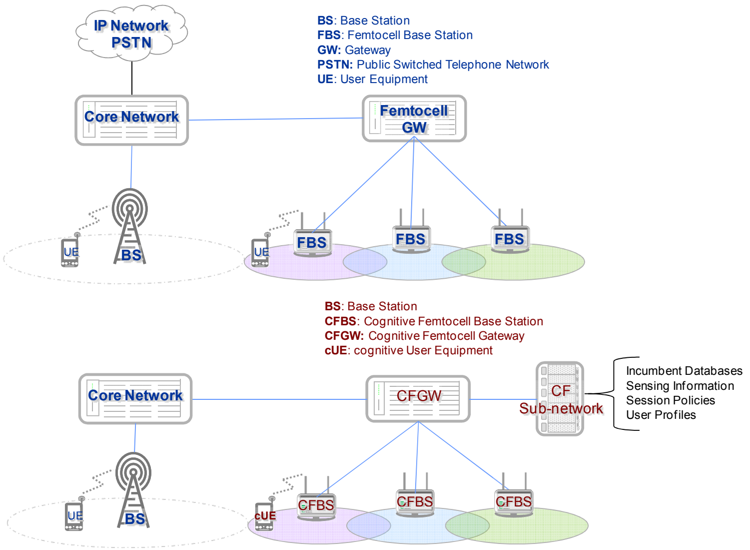

Figure 2.5: A comparison between a standard femtocell architecture (top) and a cognitive femtocell architecture (bottom).

2.4 Long Term Evolution Advanced

In this section we provide a brief overview of LTE+. We first review the architectural elements and interfaces which comprise LTE: the Evolved Universal Terrestrial Radio Access (E-UTRAN) and Evolved Packet Core (EPC). Next, we review the basic characteristics of physical layer, logical channels, and Radio Resource Control (RRC) used to support the air interface. The following subsections are not intended to be a thorough review of LTE, but rather highlight functionality of 3rd Generation Partnership Project (3GPP) standards from [71] and [1] that is most relevant to this dissertation.

2.4.1 LTE Architecture: E-UTRAN and EPC

Two main components comprise the LTE+ architecture: the E-UTRAN and the EPC. The E-UTRAN includes many eNBs, which provide service to the UE, where the UE is the *mobile device* of the LTE network. The eNB is responsible for managing radio bearers, inter-cell radio resources, and scheduling resources with the UEs. The EPC has three components: the Mobility Management Entity (MME), Signaling Gateway (SGW), and the Packet Gateway (PGW). In contrast to earlier core architectures, the EPC does not support circuit switched data or voice and only supports packet data. The MME is responsible for mobility management and access control, through cooperation of the Home Subscriber Server (HSS). Using Diameter [72], the HSS authorizes UE access into the network similar to a Home Location Register (HLR). Access control mechanism between the UE and MME is provided through the Non-Access Stratum (NAS) protocol. Figure 2.7 shows the LTE control plane, which uses NAS between network elements. The SGW provides a mobility

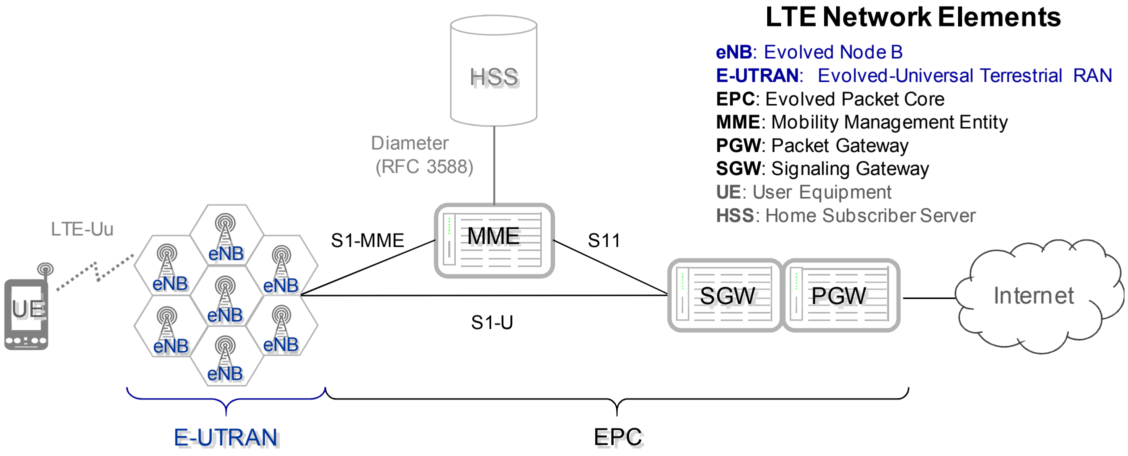

Figure 2.6: Basic LTE Architecture.

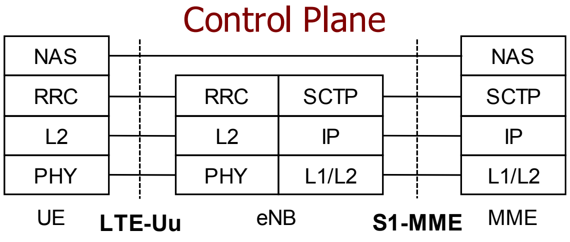

Figure 2.7: LTE Control Plane.

anchor to physically route packets to external hosts. The PGW provides and external IP address, similar to mobile IP, in order for packets to travel between hosts and UEs. Figure 2.8 shows the user plane used to send application data from the UE to hosts outside the network.

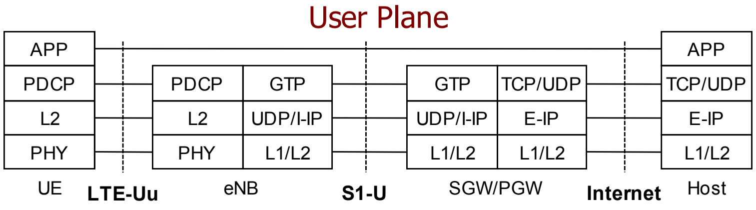

Figure 2.8: LTE User Plane.

Channel	Description
Broadcast Control Channel (BCCH)	A downlink channel for broadcasting system control information.
Paging Control Channel (PCCH)	A downlink channel that transfers paging information and system information change notifications. This channel is used for paging when the network does not know the location cell of the UE.
Common Control Channel (CCCH)	Channel for transmitting control information between UEs and network. This channel is used for UEs having no RRC connection with the network.
Dedicated Control Channel (DCCH)	A point-to-point bi-directional channel that transmits dedicated control information between a UE and the network. Used by UEs having an RRC connection.
Dedicated Traffic Channel (DTCH)	A Dedicated Traffic Channel (DTCH) is a point-to-point channel, dedicated to one UE, for the transfer of user information. A DTCH can exist in both uplink and downlink.

Table 2.2: Summary of descriptions of logical channels from [1]

2.4.2 Physical Layer: Resource Blocks, Scheduling and Carrier Aggregation

The physical layer in LTE is based on Orthogonal Frequency Division Multiplexing (OFDM) in the downlink. Each carrier has a spacing of 15 kHz with consecutive sub-carriers arranged in groups of 12 carriers for a total bandwidth of 180 kHz. A radio frame is 10ms long and within this frame there exists 10 scheduling blocks each of 1ms each [73]. One 180 kHz group of carriers in one time slot corresponds to one resource block. The number of resource blocks in LTE+ can range from 6 to 110 per cell. LTE+ supports bandwidths of up to 100MHz through carrier aggregation. The eNB and UE may simultaneously use multiple aggregated component carriers, which can be non-contiguous.

2.4.3 E-UTRAN Layer 2: Logical Channels

Within layer 2 of the E-UTRAN is the MAC sub-layer. The MAC sub-layer has the responsibility mapping segments from the physical channels into logical channels. Logical channels provide the means for identifying traffic or control information. The logical channels are used by the eNB to control UEs and also support data traffic for customer service. Table 2.2 provides a list of the unicast logical channels used in LTE+ from [1]. The MAC also plays a critical role in carrier aggregation by supporting the appropriate transport channels for each component carrier.

2.4.4 RRC

RRC is the key protocol used by the eNB for controlling radio bearers and managing the UEs under its control. In RRC, each UE is given a state of IDLE or CONNECTED. The UE in IDLE state is able to receive broadcast information from the broadcast control channel, receive pages, and re-select the eNB when mobile. An IDLE UE does not consume radio bearers and must undergo an attach procedure through NAS before the eNB will allocate resources. An UE in the CONNECTED state can be allocated radio bearers and can transmit and receive data from an eNB. The UE can perform hand-offs and reports channel quality information to the eNB.

2.4.5 Support for Relaying

LTE+ supports relaying through RNs, which improves and extends coverage area by serving as proxy for an eNB known as the Donor Evolved Node B (DeNB). RNs appear to UEs as an eNB, while supporting a unique interface to the DeNB called the *Un*. The DeNB serves as a proxy through embedding SGW and PGW interfaces, X2 and, over the Un to the RN. Functions to support RN connection to the DeNB are based on functionality contained in the UE. However, the RN also has unique authorization since the HSS must have subscription information for the RN. The RN uses the UE attach procedure described in [1] to establish and RRC connection with the DeNB. After the RN attaches using the RN attach procedure to the E-UTRAN it then receives its complete configuration and then attaches for RN operation.

2.4.6 HeNB Subsystems

LTE+ supports femtocell sized base stations called HeNBs to increase service capacity. The idea of the HeNB is to use customer infrastructure for backhaul to the core network, while providing a wireless interface to operator devices. Additionally, HeNBs provide Dynamic Host Configuration Protocol (DHCP) and IP address allocation for UEs. HeNBs may use an HeNB gateway to serve as a concentrator for the S1 interface for many HeNBs and relay between HeNB and the MME.

2.5 Conclusions

This chapter builds the foundation of the dissertation through a presentation of relevant literature on DSA systems, spectrum policies, and LTE+. We have shown the functional model of a DSA system and presented the associated works with each component. DSA systems are dependent on spectrum policy and regulation, which drive the system design. The spectrum policy model of the private commons gives way to dynamic spectrum markets, which could use an auction-based etiquette. The private commons model with real-time auctions is of interest to regulators, but has yet to be implemented. Current regulation relies on the use of a managed commons approach, which uses coexistence techniques with primary users. Although 802.22 provides cooperative techniques between secondary users, existing regulations in the U.K. and the U.S. do not require secondary users to cooperate. This could still lead to the tragedy of the commons problem. Additionally, managed commons approaches require all users to follow rules. Detection and identification of rule breakers remains a challenge in this model [74]. Spectrum squatters could occupy spectrum, preventing other secondary access or interfering with primary users with no recourse.

LTE+ will likely be the future of wireless communication, yet there is little in the current standards which can support DSA. Carrier aggregation provides a means for deploying additional DSA carriers onto the LTE+ networks. However, DSA architectural frameworks for LTE+, similar to ones in [9] and [12], have not been examined in literature. Furthermore, these architectures do not provide the means to prevent or detect rogue users. With the opening of opportunistic use of TV white spaces, network operators will likely take advantage of this spectrum. However, the uncertainties associated with nascent regulation makes it difficult for the development of standards. Regardless, 3GPPP standards should examine possible DSA frameworks to support future versions of LTE+.

Another problem for regulators is determining how to choose a regulatory framework and the associated etiquette with the framework. Current regulatory frameworks propose coexistence with primary users through databases or spectrum sensing. A framework for evaluating the differences between these techniques has not currently been studied. This will require input from regulators, primary and secondary users. Additionally, a method to examine and measure preferences between alternatives is required to make this evaluation. Through evaluating these coexistence techniques in equivalent scenarios, regulators can be assisted in understanding the trade-offs of enacting specific regulation. In the following chapters we address these challenges through identifying a framework to support DSA in LTE+ and a decision method for spectrum access rules.

Chapter 3

DSA Architecture in LTE+ MacroNets

In this chapter, we provide an operational and architectural overview of the effects of a DSA overlay in LTE+ networks. This chapter introduces the proposed DSA network elements. We also suggest how a cognitive Base Station (cBS) might deploy and request spectrum from the Spectrum Accountability Server (SAS) in the form of a spectrum lease. The chapter closes by presenting the reference architecture, which illustrates the logical signaling endpoints and introduces a basic scenario for our operational procedures presented in Section 3.2 and 3.3.

3.1 DSA Elements and Functions

We propose to support the DSA overlay through the introduction of the Spectrum Accountability Server (SAS), cognitive Base Station (cBS), and cognitive User Equipment (cUE) shown Figure 3.1. The SAS manages spectrum access policies and monitors spectrum leases. Spectrum access policies are sent to the cBS, and are then distilled into spectrum access rule sets for spectrum lease requests or opportunistic use of spectrum[1]. Additionally, the SAS maintains a geolocation database that contains the IP addresses of all cognitive Base Station (cBS) and TV broadcasters, if available. The database also maintains spectrum lease and usage information for spectrum management. In addition to maintaining the database, the SAS performs spectrum management through monitoring usage metrics from the cBS, Key Performance Indicators (KPI), and alarms from Integrated Receivers (IRs). Upon detection of harmful interference, the IR, e.g. an IP-connected TV, can send interference alarms to the SAS through the Spectrum Accounting Protocol (SAP). Using SAP, the SAS maintains spectrum-leasing policies, coordinates spectrum leases, monitors spectrum usage, and manages spectrum access rules. The registration and reporting control plane to support SAP is shown in Figure 3.2.

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[1] cBS rule sets could include but are not limited to detection thresholds, power spectrum masks, or maximum power limits for spectrum channels. Work in [24] evaluates and defines some spectrum access rule sets.

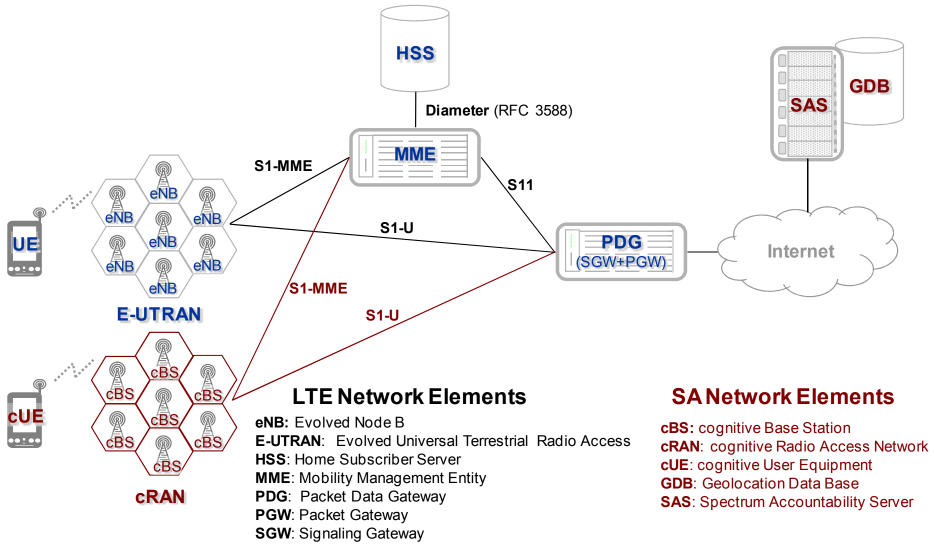

Figure 3.1: DSA overlay in an LTE+ architecture is supported through the introduction of the SAS, cBS and the cUE.

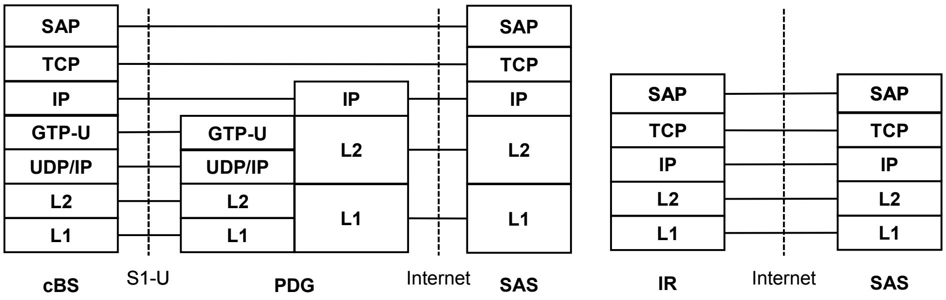

Figure 3.2: SAP control plane for cBS registration and reporting functions.

In the SA framework, communication among external network entities is required to support cooperative sensing and spectrum trading with geographic neighbors. To support communication with external network entities, the cBS must have an external IP address and a default bearer through the Packet Data Gateway (PDG). This functionality does not exist in current LTE+ standards. To establish an external IP address, the cBS should register with the MME, similar to a UE, to create a default data bearer with the PDG for signaling to external network entities. We assume a default bearer for cBS signaling for external network communication. Using external signaling interfaces, the cBS registers with the SAS to find the IP addresses of geographic neighbors, issue spectrum lease requests, and report KPI.

The cUE carries all the same functionality as the UE. However, the cUE also has a spectrum agile radio, capable of operating on and sensing using multiple bands as directed by the network. We call the sensing function and protocol Radio Resource Control-Spectrum Sensing (RRC-SS). The cUE uses a cBS for network service. Like the cUE, the cBS is also capable of spectrum sensing and

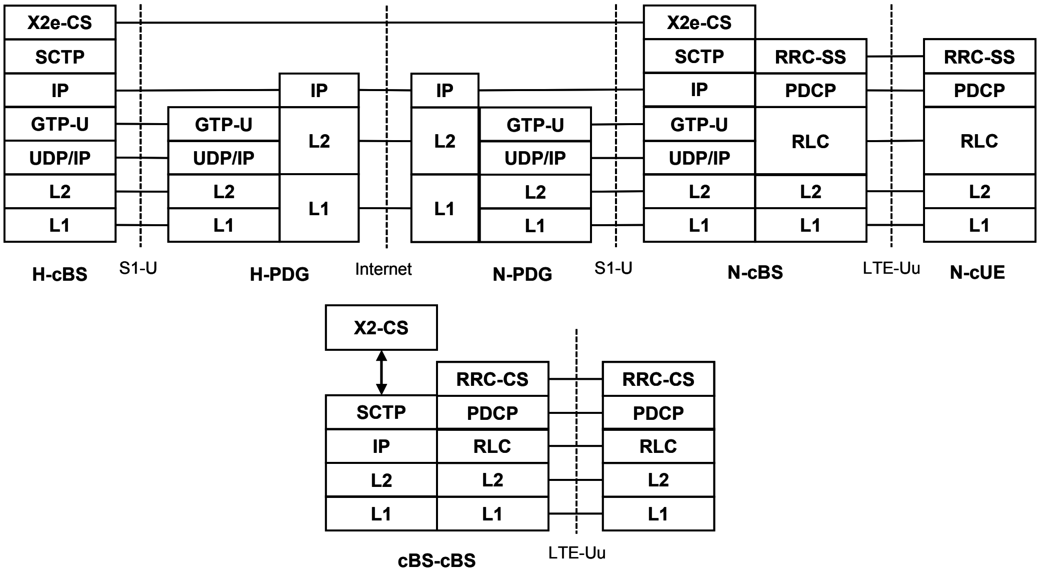

Figure 3.3: Cooperative sense control planes for external (top) and internal (bottom) networks. H- and N- indicate Home and Neighboring networks, respectively.

determining the need for spectrum lease requests. Additionally, the cBS provides the capability of coordinating spectrum sensing with the cUEs and combining the information obtained from the cUEs with its own sensing to produce a spectrum utilization snapshot. This cBS coordinating and combining sensing function is named Radio Resource Control-Cooperative Sensing (RRC-CS). The control planes to support cooperative sensing are shown in Figure 3.3.

3.1.1 Requesting and Deploying DSA Carriers

LTE+ deploys spectrum as carriers on the eNBs to support traffic; e.g., an LTE+ carrier size of 3 MHz consists of 15 resource blocks used for radio bearers. In our study, licensed and DSA sub-carriers comprise a hybrid carrier, where spectrum rights for licensed sub-carriers are through a spectrum license and DSA carriers through a spectrum lease. Since spectrum for DSA sub-carriers could differ by geographic location, DSA sub-carriers should support only data bearers whereas the licensed sub-carriers should support control channels and data bearers. In this way, cUE establishes initial communication with the cBS on a predetermined licensed channel, avoiding the rendezvous problem [50]. If the license spectrum capacity is exceeded, DSA sub-carriers could be used to serve additional traffic. Figure 3.4 shows an IDLE cUE requesting a radio bearer on the licensed sub-carrier, i.e. using the Common Control Channel for an RRC connection request. When the cUE transitions from IDLE to CONN, and if there is no capacity on the licensed sub-carrier it will become connected (CONN) to the DSA sub-carrier. In summary, licensed sub-carriers are used to bootstrap DSA sub-carriers for tasks like cUE synchronization and access, while DSA carriers are used to increase cBS operating capacity by adding more traffic channels.

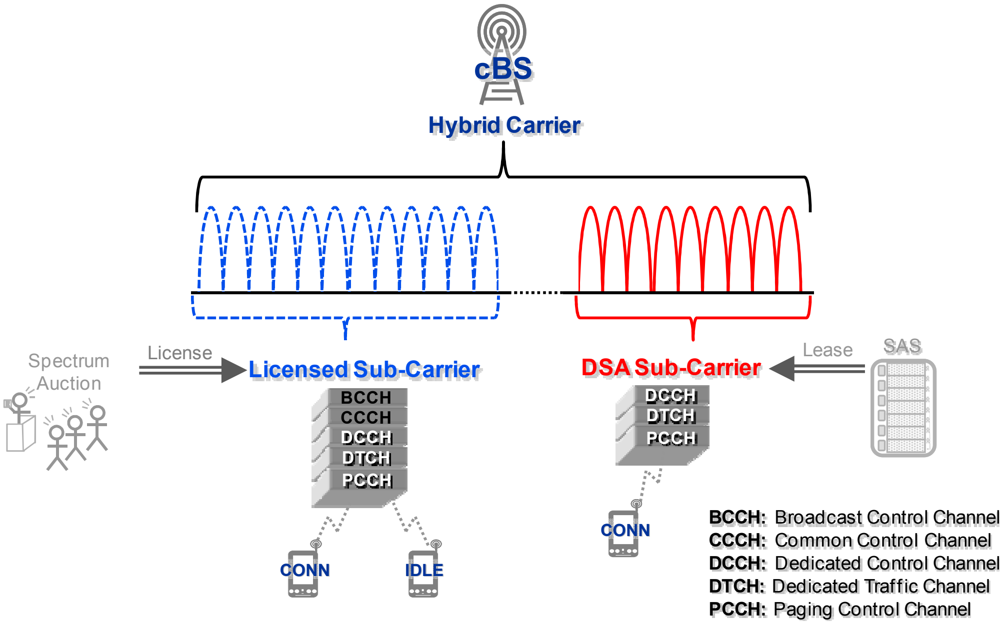

Figure 3.4: cBS Carrier Channel Anatomy: The licensed sub-carrier channels shown in black are not supported by the DSA sub-carrier. IDLE mobiles always request access on the licensed sub-carrier. After connected (CONN), cUEs use the DSA sub-carrier to support the radio bearer.

To determine when a lease request should be issued, a cBS must determine when the demand will exceed licensed carrier capacity. A rise in demand can happen for two main reasons: unanticipated events [75] and growth in services [76]. In both cases, the needed spectrum and duration the spectrum is required must be calculated by the network and conveyed to the SAS when sending the spectrum lease request. Work in [8] proposes a batch method, where leases are processed in periodic intervals. Demand predictions could be combined with sensing information and rule sets from the SAS to determine the spectrum bandwidth to be requested and the requested duration of the lease.

3.1.2 Reference Architecture and Interfaces

In Figure 3.5, we provide a reference architecture to introduce our signaling interfaces and operational procedures. In our reference architecture, we consider a simple use-case in which OPERATOR A and OPERATOR B have adjacent sites. OPERATOR A's network is labeled the home (H) network, and OPERATOR B is the neighboring (N) network. Although we show the simple case of a single neighbor, there could be many. Figure 3.5 also captures the protocol and signaling endpoints of SAP, X2e: Cooperative Sense, and X2e: Spectrum Trading. In addition to showing signaling interfaces, Figure 3.5 introduces a new network element, the IR.

Figure 3.5 also introduces the Spectrum Accounting Protocol (SAP). SAP enables cBS registra-

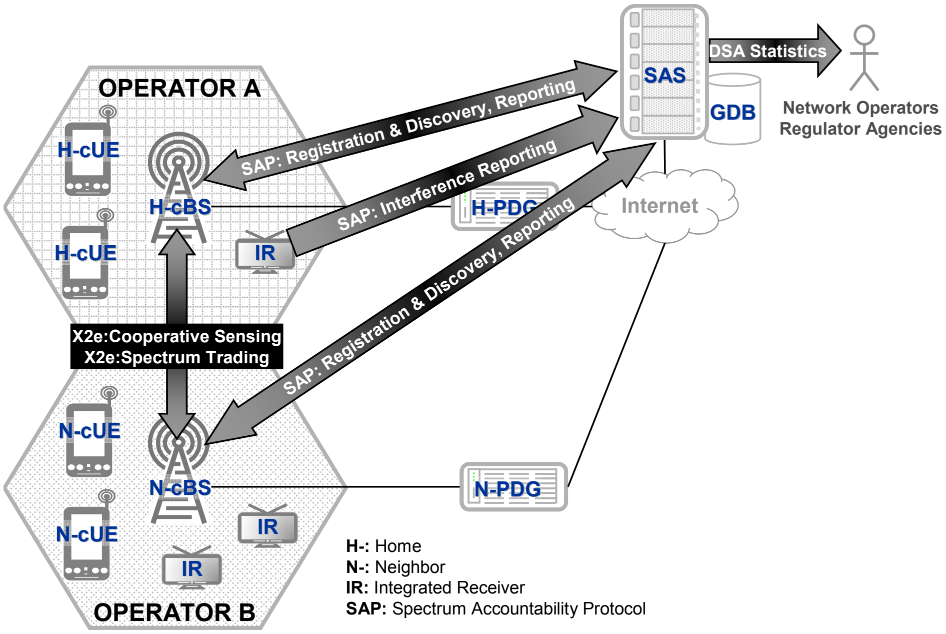

Figure 3.5: Reference architecture and logical signaling endpoints.

tion, neighbor discovery, KPI reporting for spectrum monitoring, and alarms. Through registration, the Spectrum Accountability Server (SAS) is able to store the locations of geographic neighbors, along with IP addresses, to support neighbor discovery. Using the neighbor discovery information supplied by the SAS, the cBSs form X2 links among themselves to support cooperative sensing and spectrum trading requests. X2e links are for supporting external network geographic neighbors, whereas X2 links support internal network geographic neighbors. Through SAP, cBSs also report their use of DSA carriers to the SAS via KPI. The KPI contains sets of metrics used to monitor the usage of the DSA carriers. The KPI could track the number of blocked, lost, and successful service attempts, or other metrics, such as block error rates at each cBS. Using KPI, the SAS compiles statistics and provides reports to operators and regulators for monitoring spectrum usage. With IP connectivity, an IR is also able to report loss of service to the SAS using SAP. SAP forms the basis for supporting cooperative sensing, spectrum lease requests, spectrum trading, and spectrum management.

3.2 Service Request Supporting Procedures

Throughout all of our procedure descriptions we remain agnostic of how the SAS decides to allocate leases and when cBSs make lease requests. These decisions could be the result of a specific policy and implementation, whereas our goal is to provide the mechanisms to support a variety of policies. In this section, we first present the operational procedures that support service requests. We use the name *service request supporting procedures* to emphasize that these procedures are all necessary to establish and support a bearer service to a cUE. We present these procedures in the order that they are likely to occur, similar to “a day in the life” scenario. We have named the operational procedures that support service requests using the DSA overlay as: cBS Registration and Neighbor Discovery, Periodic Cooperative Sensing, Spectrum Lease Request, Spectrum Sharing, and Service Request Procedure.

The cBS Registration and Neighbor Discovery procedure is the genesis of all other procedures. Using SAP, cBS registration is performed to open a spectrum account with the SAS. Registration with the SAS is necessary for validating spectrum lease requests, discovering neighbors, establishing X2e links with N-cBSs, and obtaining the spectrum access rules. After registration, the Periodic Cooperative Sensing Procedure could be performed so neighboring cBSs can exchange sensing information to aid in selecting and requesting specific spectrum channels, if required by the spectrum policy. When licensed spectral capacity is exceeded, the Spectrum Lease Request Procedure is triggered to send a spectrum lease request to the SAS, which may leverage sensing information to calculate an interference temperature. In the event that the cBS cannot obtain a lease from the SAS, the Spectrum Trade Procedure can be initiated to obtain a spectrum lease, using licensed or DSA spectrum from a neighboring cBS in similar manner. While trading of licensed spectrum is straight-forward, the trade-ability of the DSA spectrum could be specified through spectrum lease from the SAS or spectrum policy. Once the spectrum is obtained, the Service Request Procedure can place overflow traffic onto the DSA carriers. The following subsections provide signaling diagrams for detailed discussion of each of these procedures.

3.2.1 cBS Registration and Neighbor Discovery

The cBS Registration and Neighbor Discovery procedure is shown in Figure 3.6. In the first SAP message, the H-cBS sends a registration request to the SAS. This registration request contains the IP address of the H-cBS, as well as geolocation information. When this request is received at the SAS, the SAS creates a spectrum account for the H-cBS and updates the geolocation database. The H-cBS spectrum account will be used by future N-cBSs to discover the H-cBS and monitor spectrum usage. After the SAS creates the H-cBS account, the SAS responds with a cBS registration response, indicating that the registration was successful, and sends the spectrum access rule set based on the SAS policy. After registration is complete, the H-cBS then discovers the N-cBSs through a request/response signaling to the SAS. The SAS neighbor response contains the IP addresses of all the N-cBSs. Using the N-cBS’s IP addresses, the H-cBS then sends an X2e: Link setup request to support the exchange of sensing information and spectrum trading with N-cBSs.

3.2.2 Periodic Cooperative Sensing Procedure

The Periodic Cooperative Sensing Procedure, shown in Figure 3.7, supports sensing functions in the Radio Resource Control-Spectrum Sensing (RRC-SS) and the Radio Resource Control-Cooperative Sensing (RRC-CS) protocols. The RRC-SS and the RRC-CS functions are performed

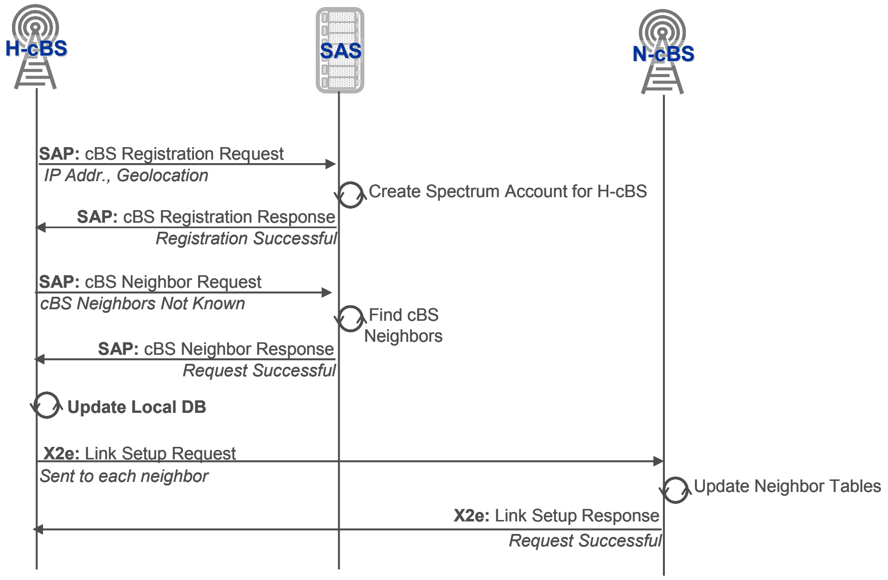

Figure 3.6: Registration & Neighbor Discovery Procedure.

by the cUE and the cBS, respectively. The procedure begins with the N-cBS performing spectrum sensing. Subsequently the N-cBS issues a cUE Spectrum Sense Order for the cUEs to collect sensing information. Once the cUEs have completed their sensing, this information is sent to the N-cBS. The N-cBS then combines the cUE sensing information with its own spectrum sensing and forwards the information to the H-cBS. The H-cBS receives the information and updates the spectrum sensing database. Likewise, the H-cBS will provide sensing information to the N-cBS in the same manner.

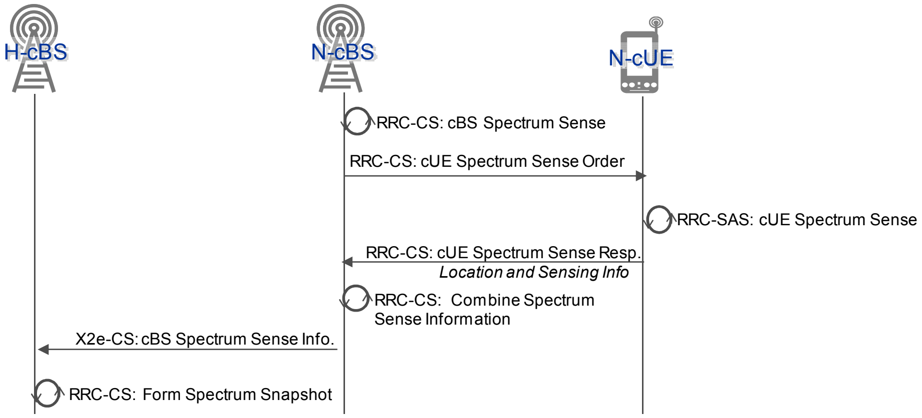

Figure 3.7: Periodic Cooperative Sensing Procedure.

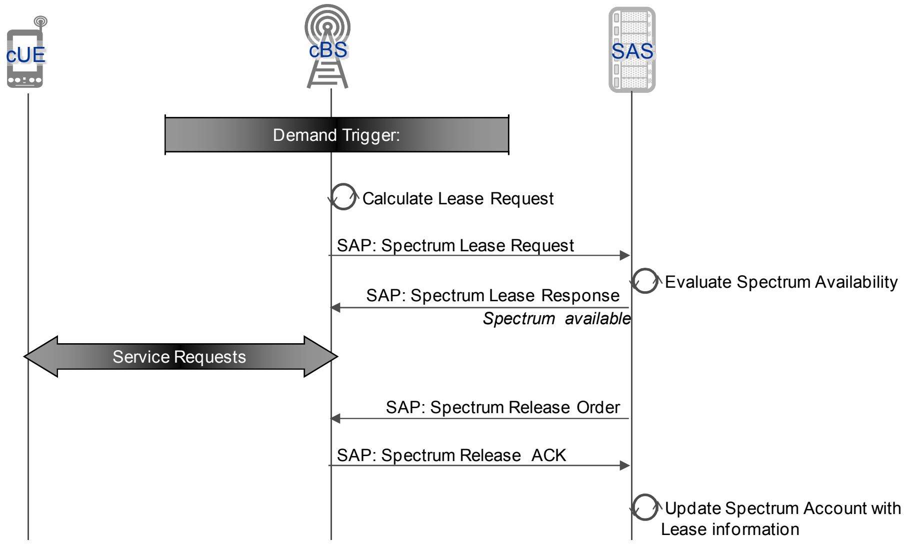

Figure 3.8: Spectrum Lease Request Procedure.

3.2.3 Spectrum Lease Request Procedure

At the beginning of the Spectrum Lease Request Procedure, shown in Figure 3.8, the cBS has been triggered to send a spectrum lease request because of an increase in traffic. After this trigger, the cBS calculates the parameters of the spectrum lease using the traffic load and spectrum statistics collected from the Periodic Cooperative Sensing Procedure. After determining the spectrum lease parameters, a spectrum lease request is sent to the SAS indicating the desired spectrum channels, bandwidth and period of the request. The SAS examines the request and, using the spectrum-leasing policies, validates the lease and issues the lease to the requesting cBS. After the time period of the lease has expired, the SAS issues a spectrum release order and the cBS responds with a spectrum release acknowledgment (ACK). In this ACK message, the cBS can also provide the KPI used by the SAS to monitor the spectrum usage. The SAS uses the KPI to update the spectrum account of the cBS, recording how the spectrum lease was used.

In the spectrum lease request procedure, we have described one simple case. However, different variations of this procedure are also supported. For example, there could be automatic lease renewals or changes to existing lease requests. Automatic lease renewals could be used, for example, to support periodic load from commuter traffic at a roadside cBS, while changes to existing leases would account for an increase in overall demand. Additionally, spectrum negotiation could occur as a sub-procedure, where the cBS and SAS exchange information on spectrum needs and lease availability. Finally, this procedure could be executed on demand or during an off-peak hour when cBS resources are available for performing optimization tasks.

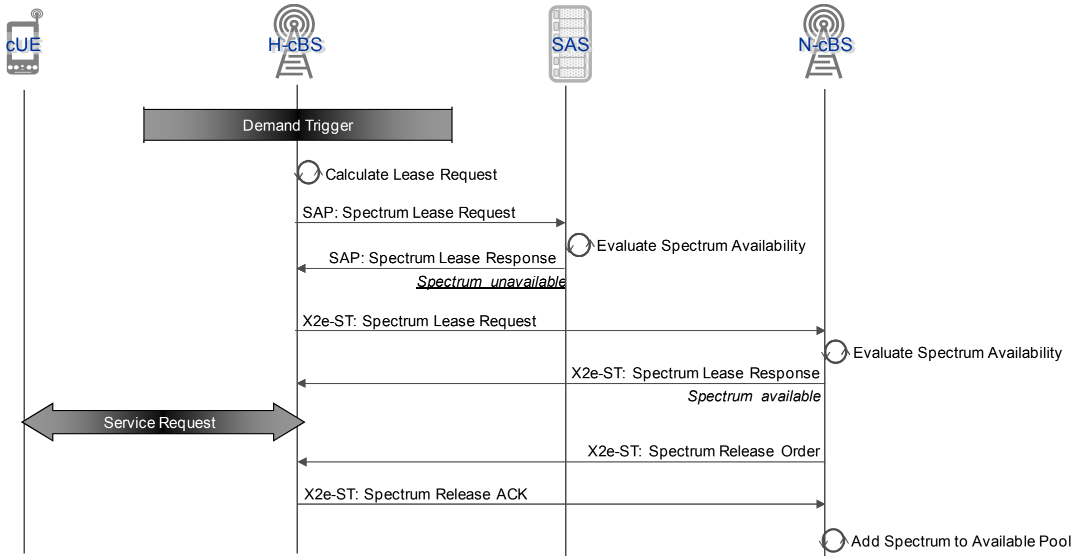

Figure 3.9: Spectrum Sharing Procedure.

3.2.4 Spectrum Sharing Procedure

As an alternative to obtaining a lease from the SAS, lease requests to the N-cBSs are also a possibility. We call the procedure to make such requests the Spectrum Sharing Procedure (shown in Figure 3.9). The Spectrum Sharing Procedure begins with the H-cBS experiencing the same types of triggers as in the spectrum lease request. However, in this case, the SAS cannot validate the lease. As a result, the H-cBS inquires with the N-cBSs whether there is a lease available, using a Spectrum Lease Request Procedure. The N-cBS examines the request and responds after examining current the rules of its valid leases within the H-cBS's geographic area. These rules could either be predetermined by spectrum policy or part of the spectrum lease. The remaining procedure is similar to the Spectrum Lease Request procedure, with the spectrum release order and ACK being sent to the N-cBS from which the spectrum was obtained.

3.2.5 Service Request Procedure

In the Service Request Procedure, some DSA carrier has been deployed and is in use at the cBS. The procedure, shown in Figure 3.10, begins with the cUE issuing a connection request on a licensed carrier. At this point in the procedure, the network operator has a policy directing traffic to a specific carrier type. For example, the policy could place all overflow from licensed carriers onto the DSA carrier. In any case, messaging to hand-off CONN_cUEs (Connected cUEs) among carriers is considered in this procedure. We highlight this part of the procedure as the spectrum sensing Carrier Optimization subprocedure. After the cBS has determined which carrier to assign to the IDLE_cUE, a Service Response is sent indicating which carrier the cUE will use. After or

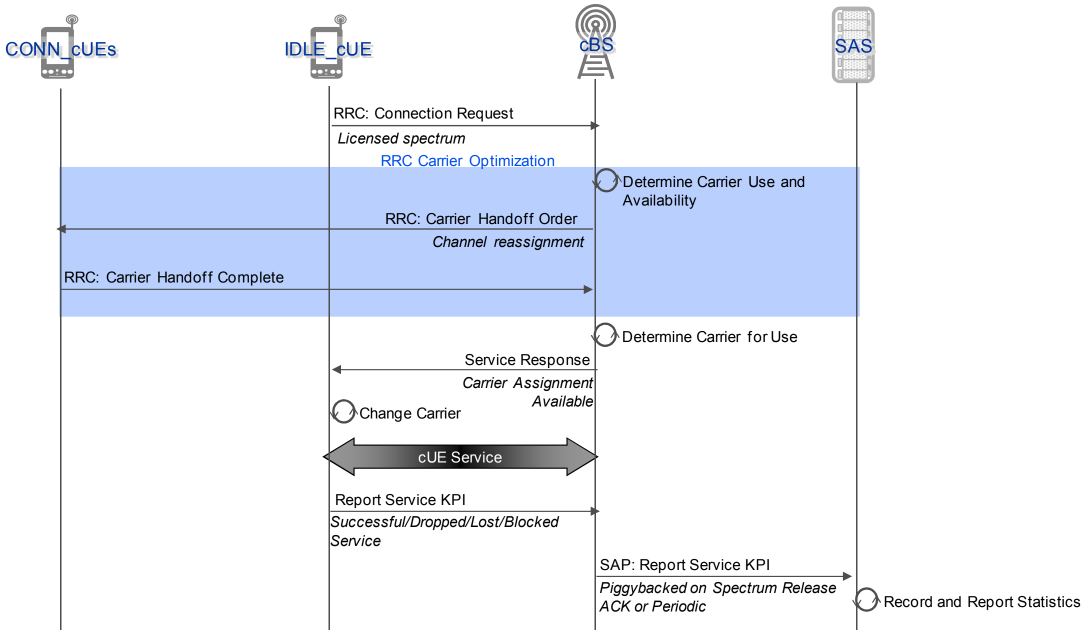

Figure 3.10: Service Request Procedure.

during service, KPI are collected from the cUE and the cBS. These KPI are then forwarded to the SAS, which may be done via individual messaging or piggybacked onto the Spectrum Release ACK. We expect incoming handoffs from neighboring cBS would also follow a similar procedure when requesting a connection with the destination cBS.

3.3 Spectrum Lease Management Procedures

In this section, we present operational procedures of the SA framework for spectrum lease management. Spectrum lease management in SA is concerned with monitoring KPI and adjusting spectrum leases to handle problems with interference, performance issues, and policy changes. When changes to spectrum leases are needed, the SAS sends notifications to the affected cBSs, which adjust their local leases and DSA carriers. Additionally, spectrum lease policies could result in changing rule sets of the cBSs. We have identified five new procedures to perform spectrum management: New Primary User Alert, IR Interference Alarm, High Interference Spectrum Lease, Spectrum Unavailable Alarm, and Rogue Transmitter Detection.

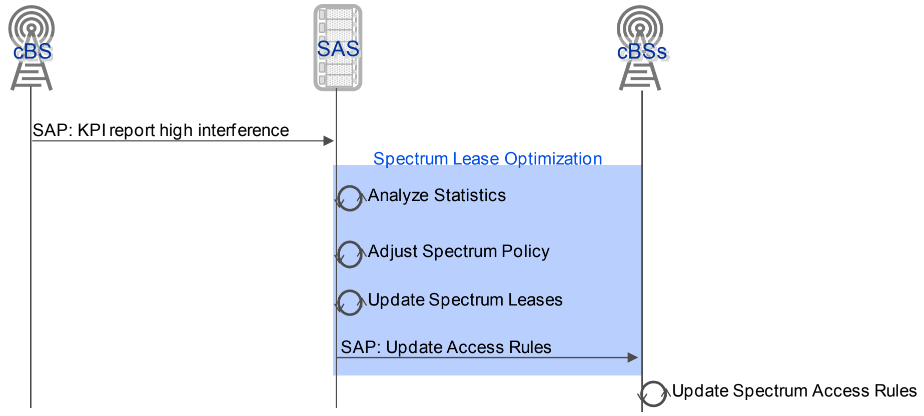

Figure 3.11: New Primary User Alert Procedure.

3.3.1 New Primary User Alert

While spectrum sensing is a certainly a valuable tool and method for DSA techniques, it still cannot determine whether hidden receivers are experiencing interference. Additionally, in the event a new primary transmitter becomes present, receivers within the service area may be hidden from secondary transmitters, cBSs, opportunistically using the spectrum. Therefore, the purpose of this procedure is to notify secondary transmitters, cBSs using TV white spaces, of a new primary operator, (such as a TV broadcaster), so spectrum can be vacated. The procedure flow diagram is shown in Figure 3.11. Using SAP, the primary operator issues a registration request to the SAS. This request contains information about the licensed spectrum, such as center frequency, bandwidth, and licensed geographic area. The SAS updates the geolocation database and returns a registration response. Using the geolocation database, the SAS then identifies and notifies the associated cBSs that there is a new primary operator active on a specific channel. The cBSs then update their spectrum access rules, mark the channel as belonging to a primary operator, and vacate the channel. After the channel is vacated, the cBS sends an ACK to the SAS. Once all the cBSs have vacated the spectrum, the SAS notifies the primary operator.

3.3.2 IR Interference Alarm

Hidden receivers can be a problem in DSA. In the hidden receiver problem, a primary operator transmits to a primary receiver and a secondary operator, unaware of the primary receiver and the primary operator, interferes. The IR Interference Alarm provides a method to avoid interference to hidden receivers by using the Integrated Receiver (IR) to detect the loss of service and report this loss to the SAS. In this scenario, the IR has knowledge of its location by either a postal address provided by the end user or geolocation provided by GPS. Additionally, the IR is able to

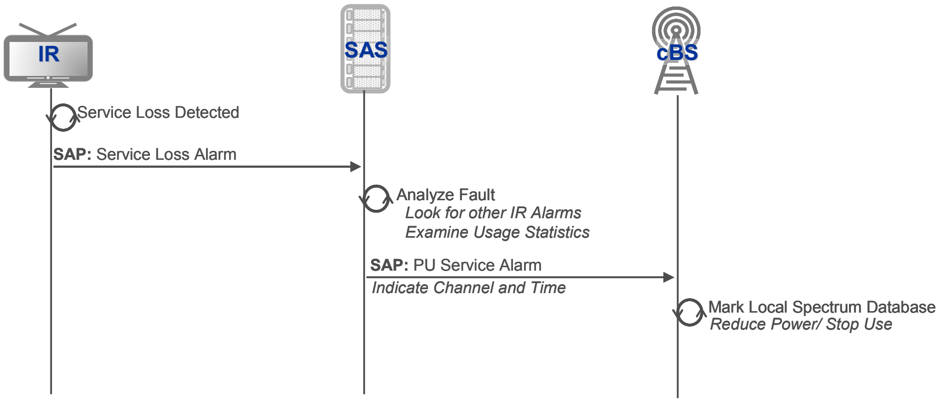

Figure 3.12: IR Interference Alarm Procedure.

discover the SAS by a query to a server, similar to a DNS server, which resolves the proper regional SAS. The procedure, shown in Figure 3.12, begins with the IR detecting service loss because of interference. Once this problem has been detected, the IR sends a Service Loss Alarm to the SAS. After receiving the service loss alarm, the SAS analyzes the existing spectrum leases to determine the potential interferers and sends alarms to those cBSs. The cBSs then take some action, such as relinquishing the channel or reducing power.

3.3.3 High Interference Spectrum Lease

The purpose of the High Interference Spectrum Lease Procedure is to detect the spectrum leases that experience high amounts of interference and adjust spectrum policy, if possible. The procedure, shown in Figure 3.13, begins with an H-cBS reporting KPIs that indicate poor service or the inability to provide service using the spectrum lease. The SAS analyzes these statistics and makes changes to the set of spectrum leases. It then sends updates to all cBSs that are affected by these changes, and the cBSs update their spectrum leases and carriers accordingly. In addition to adjusting spectrum access rules through a policy change, the SAS can also look for rogue transmitters.

3.3.4 Rogue Transmitter Alarm Procedure

Another possible cause of high call blocking or service loss is a rogue transmitter. A rogue transmitter is a transmitter that uses frequencies without a lease or license. In this procedure, shown in Figure 3.14, instead of adjusting the set of spectrum leases the SAS determines the location of the rogue transmitter. After receiving indication that a spectrum lease is experiencing poor service, the SAS determines which cBSs are in the area from which the transmission is occurring. It then sends a Spectrum Snapshot Request to each of the cBSs in the area. Once each cBS replies with the Spectrum Snapshot ACK, the SAS then uses the spectrum sensing information to determine

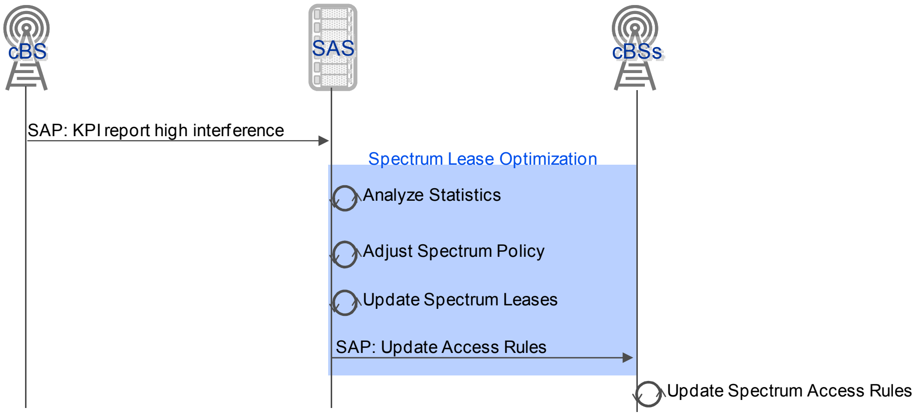

Figure 3.13: High Interference Spectrum Lease Procedure.

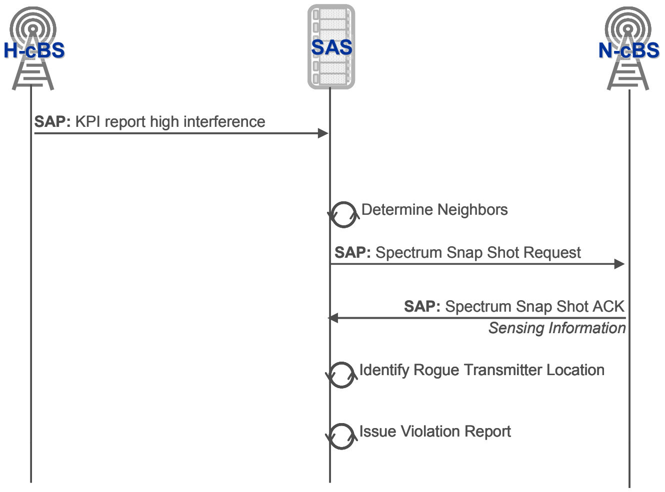

Figure 3.14: Rogue Transmitter Alarm Procedure.

the geolocation of the rogue transmitter. This information is then used by regulators to issue fines or take other appropriate measures.

3.3.5 Spectrum Unavailable Alarm

In this final procedure, a cBS has detected that future demand from customers will exceed its capacity. However, the cBS is unable to issue a spectrum lease request given the existing rule set from the SAS. This procedure is useful since the SAS is able to notify regulators and operators of either policies that may be overly strict or the simple lack of spectral resources. In this case, the SAS can gradually relax policy restrictions and observe interference alarms from IRs or other cBS. The procedure is shown in Figure 3.15. In the first message of the procedure, the cBS identifies

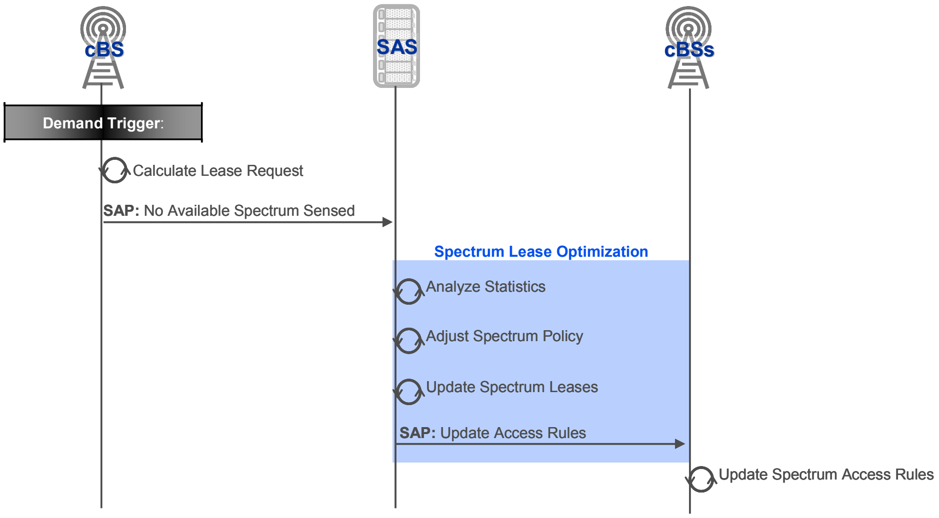

Figure 3.15: Spectrum Unavailable Alarm Procedure.

a need for more spectrum and begins to calculate a spectrum lease request. When examining the spectrum information and existing rule set, the cBS finds there is no available spectrum. As a result, the cBS issues a Spectrum Unavailable Alarm to the SAS. In response to the alarm, the SAS examines the current statistics and policy and determines it can change the spectrum leases or adjust the cBS rule set. The cBSs then use the updated rule sets to update their future leases.

3.4 Summary

In this chapter, we proposed to support the DSA overlay through the introduction of the SAS, cBS, and cUE. Through SAP, the SAS maintains spectrum-leasing policies, coordinates spectrum leases, monitors spectrum usage, and manages spectrum access rules with the cBS. Through the SA framework, we examined two sets of operational procedures: service request supporting procedures and spectrum lease management procedures. Spectrum lease management of the SA framework can be used to monitor KPI and adjust spectrum leases for performance issues and policy changes. We illustrated spectrum lease management through different alarm and response procedures that could be dynamically used to adapt spectrum leases through the adjustment of spectrum access policies and rules. Defining and understanding these operational effects will be important for future LTE+ standards, infrastructure vendors, and network operators to deploy a DSA overlay in next generation wireless networks.

Chapter 4

Performance Evaluation of DSA in LTE+

In the previous chapter, we presented the affected control planes, new network elements, operational procedures, and the SA framework to support a DSA overlay in an LTE+ network. In this chapter, we examine the benefits of adding a DSA overlay in an LTE+ network through use of the SA by examining two cases. In the first case, multiple operators share the same site and use a shared DSA carrier to serve overflow traffic. In our second case, we consider optimal assignment of licensed and DSA LTE+ channels in a network with multiple cBSs. In this network, cBSs opportunistically use GSM and TV white spaces. We present each case in the following sections.

4.1 DSA Overlay to Augment LTE+ cBS Capacity

To illustrate the quantifiable benefits of using a DSA overlay in LTE+ networks, in our first case, we consider a scenario in which three operators share the same site, tower or hilltop, to provide services. In this case we assume the SA framework, as described in Chapter 3, has been integrated into the existing LTE+ cBSs deployed at the site, allowing the cBS to sense and use a DSA carrier to augment licensed capacity and serve overflow traffic. Since in this model cBSs are co-located, each DSA channel can be used by a single cBS at a time. Channel availability (in particular, the duty cycle of the channel use) is modeled by the modified beta distribution, as proposed in [2]. The modified beta distribution probability density function is given by:

$$\begin{aligned} f_{m\beta}(x;\alpha,\beta) &= p_{DC=0}\cdot\delta(x) && (4.1)\\ &+ (1-p_{DC=0}-p_{DC=1})\cdot f_{\beta}(x;\alpha,\beta) && (4.2)\\ &+ p_{DC=1}\cdot\delta(x-1), \end{aligned}$$

where $x \in [0,1]$, $p_{DC=0}$ and $p_{DC=1}$ are parameters used to characterize the duty cycle, $\delta(x)$ is the Dirac delta-function and $f_{\beta}(x;\alpha,\beta)$ is the probability density function for the beta distribution, given by:

$$f_{\beta}(x;\alpha,\beta) = \frac{1}{\mathcal{B}}x^{\alpha-1}(1-x)^{\beta-1}, \tag{4.3}$$

Band Descriptor	$p_{DC=0}$	$p_{DC=1}$	α	β
TV 770 MHz AB	0.189	0.342	0.414	1.103
GSM 1800 DL AB	0.193	0.616	0.716	1.202
DECT 1900 MHz AB	0.073	0.0	1.688	4.927
ISM 2.4 GHz AB	0.144	0.0	0.84	5.947

Table 4.1: Band parameters used in simulation to determine DSA channel duty cycle, determined by [2].

and where $\mathcal{B}$, the beta function, is given by:

$$\mathcal{B}(\alpha, \beta) = \int_0^1 t^{\alpha-1}(-t)^{\beta-1}dt. \tag{4.4}$$

The beta function is parameterized by α and β. Wellens, in [2], developed this model by applying energy detection to 200kHz-wide channels in one-second intervals. Bands were considered off, available, if the measured energy on the channel was below -107 dBm. Based on this model from [2] we form two assumptions for our simulation. We assume a set of 200kHz-wide downlink channels, where each channel supports one LTE+ resource block (LTE+ resource blocks use 180 kHz). Furthermore, we assume spectrum access rules allow the use of a DSA channel as long as the measured energy on the channel is below -107 dBm.

Arrivals are assumed Poisson and each arrival generates certain a demand for data. Following [77], we model the session demand using the Pareto distribution. The Pareto distribution probability density function is given by:

$$p(x) = \sigma k^{\sigma} x^{-\sigma-1}, \quad \sigma, k > 0, \quad x \geq k, \tag{4.5}$$

with parameters from [77], $\sigma = 1.06$ and $k = 8000$ bits. Each session generates a demand as a number of bits. We assume the cBS scheduler provides best effort service for all the traffic. Additionally, requests for resources which cannot be serviced by the cBS within a one-second time period are sent to the DSA carrier. If the DSA carrier cannot service this traffic within the one-second time period it is then considered blocked. Instead of using adaptive modulation for each arrival, we assume a 10 dB SNR ratio, and estimate the capacity of a resource block from Shannon's capacity theorem, of 700 kbps per resource block. Using our assumptions, we compare the blocking probability of the three network operators sharing the same site using 10 MHz licensed carriers under two scenarios: (i) no additional carriers are available for DSA; and (ii) an additional shared 10 MHz carrier is available for overflow traffic. Using these assumptions, we compare the blocking probability of the three cBSs using 10 MHz licensed carrier with a shared 10 MHz DSA carrier against the case without. A illustration of our simulation model is shown in Figure 4.2.

From [2], we used four different parameter sets to model the DSA channel availability. The parameter set is shown in Table I. Figure 4.1 shows different cumulative distribution functions for the duty cycles of the four different DSA band types. Using these four different band types, we

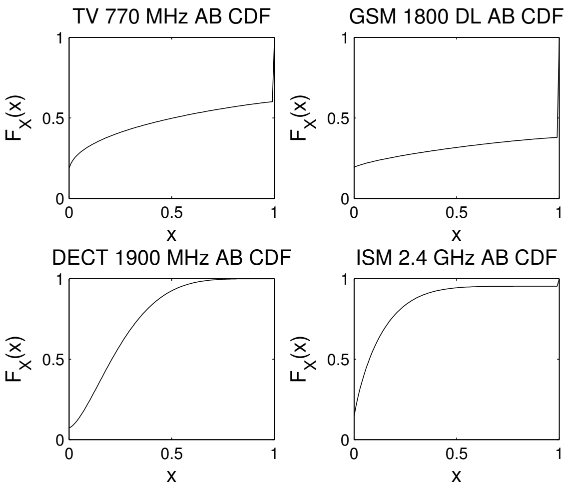

Figure 4.1: Cumulative distribution functions for duty cycles of the four different DSA carrier types used in our simulation.

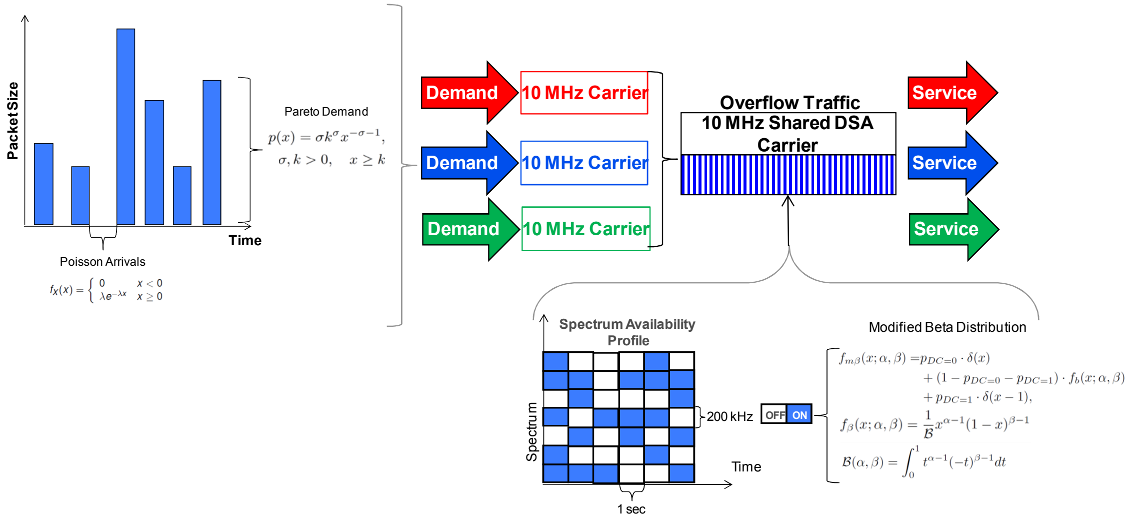

Figure 4.2: Illustration of simulation model used

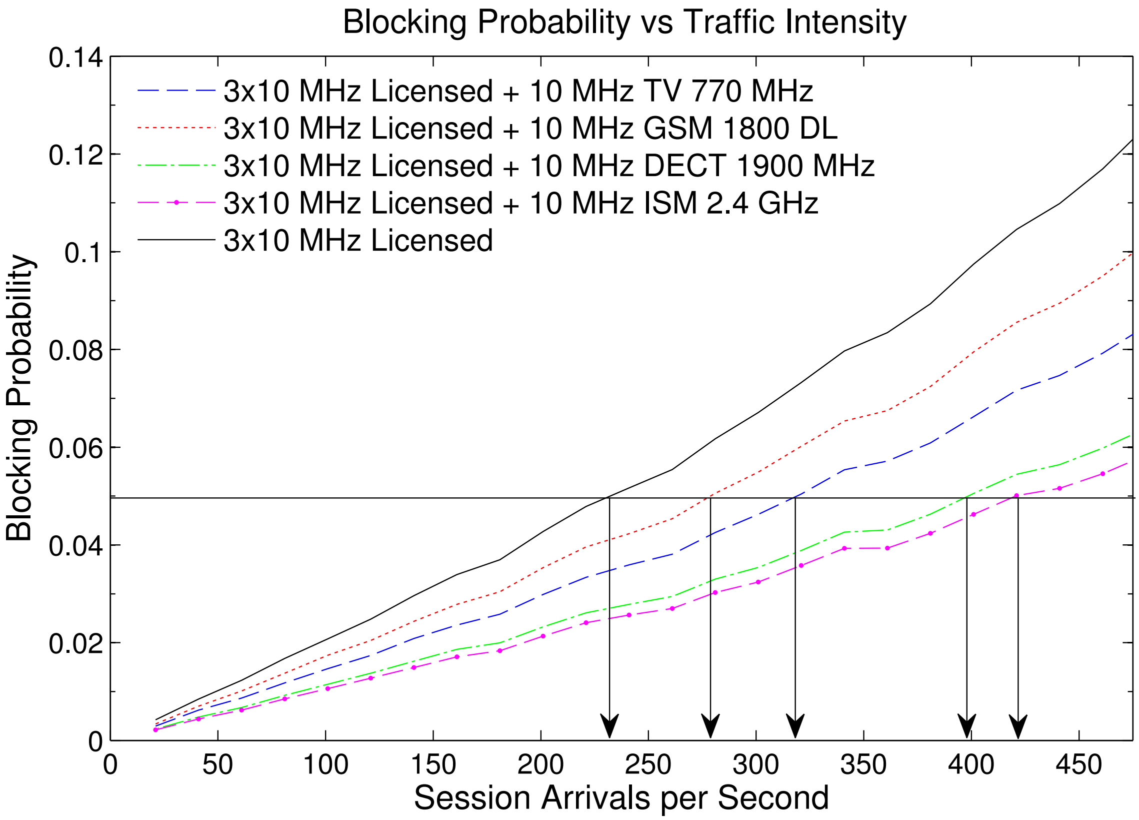

Figure 4.3: Comparison of the blocking probability of the three cBSs using licensed channels only with blocking probability of the three cBSs with a shared DSA carrier used for overflow traffic.

simulated the availability of the DSA channels to show the difference in blocking probability for each band. We vary session arrival rates and observe overall blocking of resource requests. Figure 4.3 shows the blocking probability of these four DSA carrier types, plus the baseline scenario of using licensed channels only. We focus on a blocking probability of 5%, because this is a common operating point for many cellular network operators [78]. Figure 4.3 shows approximate gains of 22%-83% in network capacity, when considering a 5% blocking probability of resource requests, using the four different DSA band types. Intuitively, more overflow traffic can be served on the DSA channels if the DSA channel availability is higher, but there are gains in all scenarios. This insight provides additional motivation for using a DSA overlay in LTE+ networks, allowing network operators to capture more revenue.

4.2 Optimal Assignment of DSA Carriers

In this section, we develop two integer programs considering channel assignment and spectrum aggregation in LTE+ networks. In the first program, we provide a formulation for the basic channel

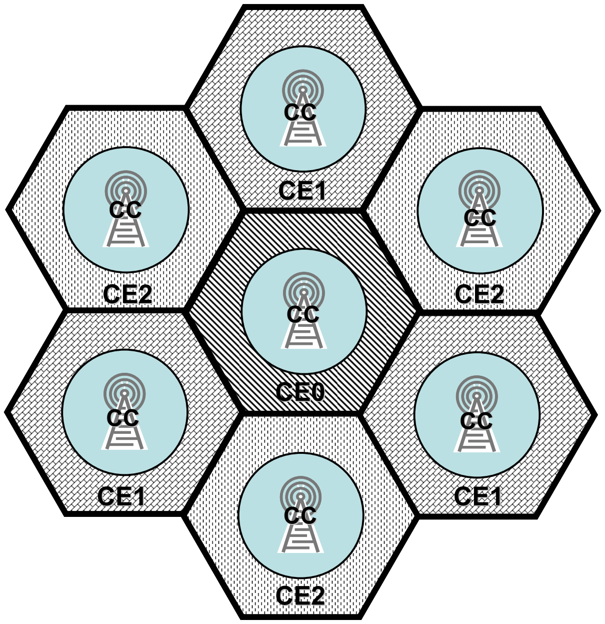

Figure 4.4: Example of frequency reuse scheme for LTE+. Cell-center carriers do not generate inter-cell interference, while cell-edge carriers do and are required to be different for neighboring cells.

assignment problem in LTE+ networks. In the second program, we consider the aggregation of licensed channels with DSA spectrum through the use of our SA framework. In this scenario, the network is allowed to use TV spectrum, when sufficiently far away from transmitting stations. Additionally, we also assume a GSM overlay with the LTE+ network, owned by the same operator. The LTE+ network with SA framework senses vacancies in the GSM spectrum and is allowed to use the GSM spectrum if it is unoccupied. Our integer programs represent a snapshot in time, which could be used by LTE+ networks to optimally self-configure during periodic intervals.

In the scenario of interest, an LTE+ network is allowed to assign channels (licensed, DSA, or both) onto cBS carriers to serve a given load [6].[1] To manage inter-cell interference in LTE+, channels are aggregated into a cell-edge or cell-center carrier [73], where channels in the cell-edge carriers must be different among neighboring base stations. An example of this type of frequency assignment is shown in Figure 4.4. Our first integer program examines the basic LTE+ channel assignment problem, which considers only demand and assignment constraints given a set of licensed channels. In our second problem, we consider the same scenario with a set of licensed LTE+ channels, a set of TV channels, and a set of GSM channels, which can be used to meet the demand.

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[1] In LTE+, a resource block is based on 180 kHz. Without loss of generality, we consider a 200 kHz block the LTE+ channel.

4.2.1 Problem Formulation

In the basic LTE+ channel assignment problem, cell edge frequencies must be different between neighboring cells to prevent inter-cell interference. Clearly, channels deployed within the same cell cannot be used by both the cell-edge and cell-center carriers. Licensed spectrum is limited to W channels, which are available to deploy throughout a network with B base stations. Let $x_{i,c,k} = 1$ when cBS i assigns channel c to carrier k, where $k = 1$ and $k = 2$ indicate a cell-center and a cell-edge carrier, respectively. Denote $d_{i,k}$ as the demand, in number of channels, at cBS i on carrier k. Through an adjacency matrix $\mathbf{N}$, we define neighbor relationships, where $n_{i,j} = 1$ indicates cBS i is a neighbor to cBS j. The objective of the network is to maximize the assignment of the channels on each carrier such that the demand at each cBS and carrier is met. Here we present the basic channel assignment problem for an LTE+ network as integer program $\mathcal{P}_1$:

Maximize:

$$\sum_{i=1}^{B}\sum_{c=1}^{W}\sum_{k=1}^{2} x_{i,c,k} \tag{4.6}$$

Subject to:

$$\sum_{c=1}^{W} x_{i,c,k} \leq d_{i,k} \quad \forall\, i,k \tag{4.7}$$

$$\sum_{k=1}^{2} x_{i,c,k} \leq 1 \quad \forall\, i,c \tag{4.8}$$

$$n_{i,j}(x_{i,c,2} + x_{j,c,2}) \leq 1 \quad \forall\, i,j,c \tag{4.9}$$

$$\sum_{c=1}^{W}\sum_{k=1}^{2} x_{i,c,k} \leq W \quad \forall\, i \tag{4.10}$$

$$x_{i,c,k} \in \{0,1\} \quad \forall\, i,c,k \tag{4.11}$$

Constraint (4.7) requires that channels only be assigned as required to meet demand. Constraint (4.8) only allows channels to be assigned once per cell, i.e. cell-edge and cell center carriers cannot have the same channel. Constraint (4.9) prevents neighboring cells from having the same channels in the cell-edge carriers. Lastly, Constraint (4.10) enforces the total channel limit for the network operator.

Leveraging the architecture we proposed in Chapter 3, cBSs are allowed to reuse TV spectrum and GSM spectrum when available. Channel assignment or assignment rules can be provided by an SAS and knowledge of primary users can be stored in the GDB. DSA channels can only be used when cBSs will not interfere with primary stations. Therefore, we define an interference matrix $\mathbf{P}$, where $p_{i,l} = 1$ if cBS i is not within interfering distance of TV station l. We further denote $y_{i,l,c,k} = 1$ to indicate when cBS i uses TV station l's channel c on carrier k, where there are P TV stations, each with V channels available. GSM channels available at the local cell can also be used when unoccupied. Thus, we denote matrix $\mathbf{A}$, where $a_{i,c} = 1$ if the base station i's channel c, from the

GSM spectrum, is available for secondary use. We further denote $z_{i,c,k} = 1$ to indicate when cBS i uses channel c, from the GSM spectrum, on carrier k, where each base station has U potential channels available. We assumed that GSM frequencies are previously deployed to minimize inter-cell interference and, therefore, GSM channels can only be opportunistically used within the same cell. We now extend the objective function and constraints from the previous problem to include these new concepts as a new integer program to solve the DSA channel assignment problem $\mathcal{P}_2$:

Maximize:

$$\sum_{i=1}^{B}\sum_{c=1}^{W}\sum_{k=1}^{2} x_{i,c,k} + \sum_{i=1}^{B}\sum_{l=1}^{P}\sum_{c=1}^{V}\sum_{k=1}^{2} y_{i,l,c,k} + \sum_{i=1}^{B}\sum_{c=1}^{U}\sum_{k=1}^{2} z_{i,c,k} \tag{4.12}$$

Subject to:

$$\sum_{c=1}^{W} x_{i,c,k} + \sum_{c=1}^{V}\sum_{l=1}^{P} y_{i,l,c,k} + \sum_{c=1}^{U} z_{i,c,k} \le d_{i,k} \qquad \forall\ i,k \tag{4.13}$$

$$\sum_{c=1}^{W} x_{i,c,k} \ge 1 \qquad \forall\ i,k \tag{4.14}$$

$$\sum_{k=1}^{2} x_{i,c,k} \le 1 \qquad \forall\ i,c \tag{4.15}$$

$$\sum_{k=1}^{2} y_{i,l,c,k} \le p_{i,l} \qquad \forall\ i,l,c \tag{4.16}$$

$$\sum_{k=1}^{2} z_{i,c,k} \le a_{i,c} \qquad \forall\ i,c \tag{4.17}$$

$$n_{i,j}(x_{i,c,2} + x_{j,c,2}) \le 1 \qquad \forall\ i,j,c \tag{4.18}$$

$$n_{i,j}(y_{i,l,c,2} + y_{j,l,c,2}) \le 1 \qquad \forall\ i,j,l,c \tag{4.19}$$

$$\sum_{c=1}^{W}\sum_{k=1}^{2} x_{i,c,k} \le W \qquad \forall\ i \tag{4.20}$$

$$\sum_{l=1}^{P}\sum_{c=1}^{V}\sum_{k=1}^{2} y_{i,l,c,k} \le \sum_{l=1}^{P} p_{i,l}V \qquad \forall\ i \tag{4.21}$$

$$\sum_{c=1}^{U}\sum_{k=1}^{2} z_{i,c,k} \le U \qquad \forall\ i \tag{4.22}$$

$$x_{i,c,k}, y_{i,l,c,k}, z_{i,c,k} \in \{0,1\} \qquad \forall\ i,l,c,k \tag{4.23}$$

Constraint (4.13) is analogous to Constraint (4.7) in $\mathcal{P}_1$. However, in the case of the second problem we must also include the DSA channels from TV stations and GSM spectrum. Constraint (4.14) insures that there are at least one licensed channel per carrier, which is necessary for initial network access as described in Figure 3.4. Constraints (4.15), (4.16), and (4.17), analogous to Constraint

(4.8) in $\mathcal{P}_1$, prevent a given channel from being used both in the cell-center and the cell-edge; this holds for licensed LTE+ channels as well as TV or GSM channels occupied opportunistically by an LTE+ operator. Additionally, Constraints (4.16) and (4.17) ensure that DSA channels are only allocated by the cBS when transmission will not interfere with the primary user. Constraints (4.18) and (4.19), analogous to Constraint (4.9) in $\mathcal{P}_1$, prevent neighboring cells from allocating the same channels in the cell-edge carriers. Constraints (4.20), (4.21), and (4.22) limit the number of channels deployed at a cBS to the total number of channels used from the licensed LTE+, TV, and GSM channels sets.

4.2.2 Simulated Scenarios and Results

To illustrate the use of this formulation for optimal deployment of carriers in an LTE+ network, we use random network configurations as inputs for our integer program and use the CPLEX [79] solver to determine optimal solutions. We do this to show the quantifiable benefits of using DSA spectrum in an LTE+ network. Our scenarios are based on an 8x8 hexagonal cell lattice, where a cBS, GSM base station, or TV station may reside in the center of a cell. cBSs and GSM base stations reside in all cells and the locations of TV stations are determined by a randomly selected cell. Additionally, TV stations have an interference radius of 2, where any cell outside of the interference radius is allowed to reuse the TV station's spectrum. This lattice and the primary interference region are shown in Figure 4.5.

For our input variables we vary $d_{i,k}$, W, V, U, and the number of available TV stations to share spectrum with. The demand, $d_{i,k}$, is modeled as a uniformly-distributed random variable. We consider scenarios where the network has $W = 75$ and $W = 150$ LTE+ channels (15 MHz,30 MHz) available for distribution among the cBSs. Each TV station has $V = 30$ potential DSA channels (6 MHz) that can be used by the LTE+ network, when outside the interference radius of the TV stations. Our scenarios consider cases when there is one or two primary TV stations whose channels can be used opportunistically. For GSM spectrum, we consider cases of $U = 5$ and $U = 10$ DSA channels (1 MHz,2 MHz) for each cell, where each DSA channel can be allocated to LTE+ traffic in the same cell if available. The GSM spectrum availability (in particular, the duty cycle of the channel use) is modeled by the modified beta distribution, as proposed in [2]. The modified beta distribution probability density function is given by:

$$\begin{aligned} f_{m\beta}(x;\alpha,\beta) &= p_{DC=0}\cdot\delta(x) \\ &+ (1-p_{DC=0}-p_{DC=1})\cdot f_b(x;\alpha,\beta) \\ &+ p_{DC=1}\cdot\delta(x-1), \end{aligned}$$

where $x \in [0,1]$, $p_{DC=0}$ and $p_{DC=1}$ are parameters used to characterize the duty cycle, $\delta(x)$ is the Dirac delta-function and $f_b(x;\alpha,\beta)$ is the probability density function for the beta distribution, given by:

$$f_\beta(x;\alpha,\beta) = \frac{1}{\mathcal{B}}x^{\alpha-1}(1-x)^{\beta-1},$$

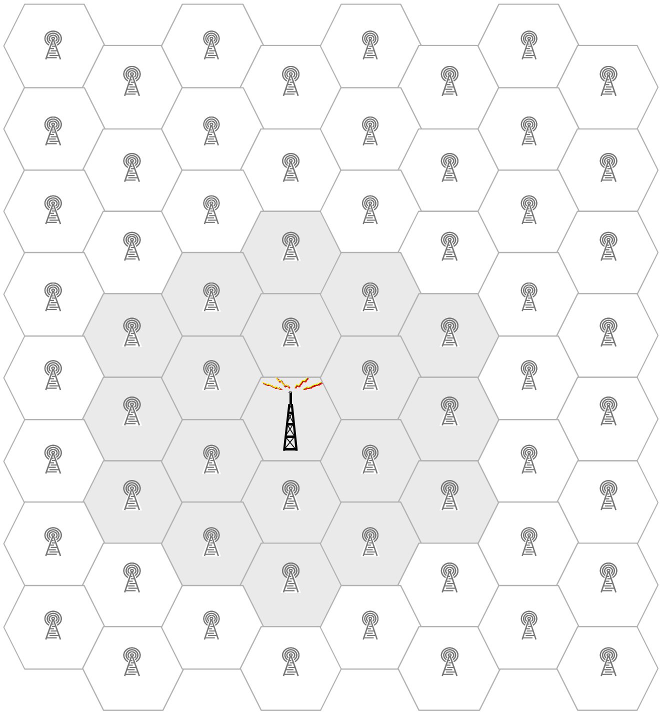

Figure 4.5: Simulated hexagonal lattice used to create integer program input parameters. Primary station and interference region are shown in bold and darker cells.

Band Descriptor	$p_{DC=0}$	$p_{DC=1}$	α	β
GSM900 DL AB	0.000	0.934	3.677	1.336
GSM900 DL IN	0.044	0.401	0.575	1.528
GSM1800 DL AB	0.193	0.616	0.716	1.202
GSM1800 DL IN	0.344	0.111	0.698	1.317

Table 4.2: Band parameters used to determine GSM channel duty cycle from [2]

and where $\mathcal{B}$, the beta function, is given by:

$$\mathcal{B}(\alpha,\beta) = \int_0^1 t^{\alpha-1}(-t)^{\beta-1}dt.$$

The beta function is parameterized by α and β. Wellens, in [2], developed this model by performing energy detection of 200kHz-wide channels in one-second intervals. Bands were considered available if the measured energy on the channel was below -107 dBm. In our scenario, opportunistic LTE+ channels in GSM spectrum is considered under the same circumstances. We simulate different loading on each base station by randomly selecting one of the parameter sets from Table 4.2.2, which represent the distribution of the GSM channels for each base station.

Figure 4.6 shows the results of the integer programs using the given scenarios and a baseline of 15 MHz of licensed LTE+ channels. Intuitively, more traffic can be served if the DSA channel availability is higher. There is a significantly higher increase in total capacity with additional 6 MHz TV channels in comparison to the use of GSM spectrum. GSM spectrum contributes less because in some cases, many of the GSM channels are being occupied by primary users, in accordance with [2]. TV spectrum is always available when cells reside outside the interference radius and thus provides more benefit. As highlighted in our introduction, we would expect the benefits from the opportunistic use of GSM spectrum to increase as more users migrate from GSM to LTE+. One other observation is that past a certain threshold the curves become almost linear, creating a proportional benefit at a fixed demand. Using this observation, we compare cross sections of fixed demands to show the quantitative benefits of additional DSA spectrum.

Figure 4.7 shows the comparison of the additional proportional traffic that can be served given additional DSA spectrum, for a constant demand. The set of bars on the left illustrate the benefits of additional DSA channels under the 15 MHz baseline, while the bars on the right illustrate the 30 MHz baseline. In both cases, we observe that as the amount of TV spectrum increases, the proportion of additional traffic served by GSM channels decreases. The bars for the 30 MHz case also show similar trends. Thus, our experiments show that additional DSA spectrum results in slightly diminishing returns.

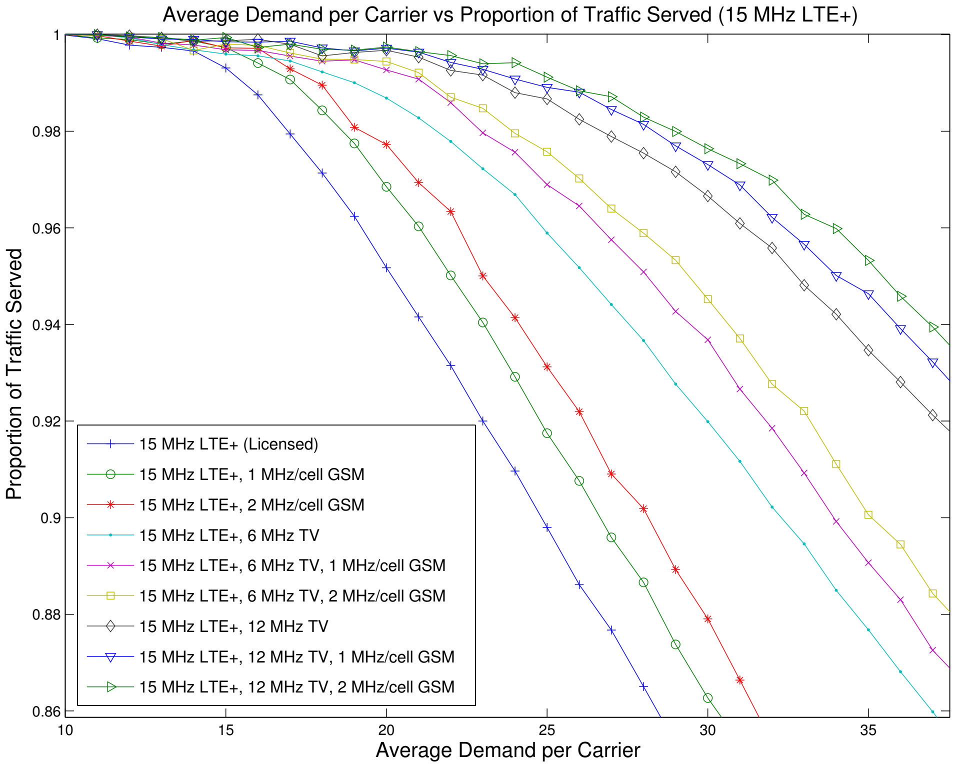

Figure 4.6: Optimal channel assignment of 15 MHz of licensed LTE+ spectrum channels compared with the same assignment with additional DSA spectrum. There is a significantly higher increase in overall capacity with additional 6MHz TV channels in comparison to the opportunistic use of GSM spectrum

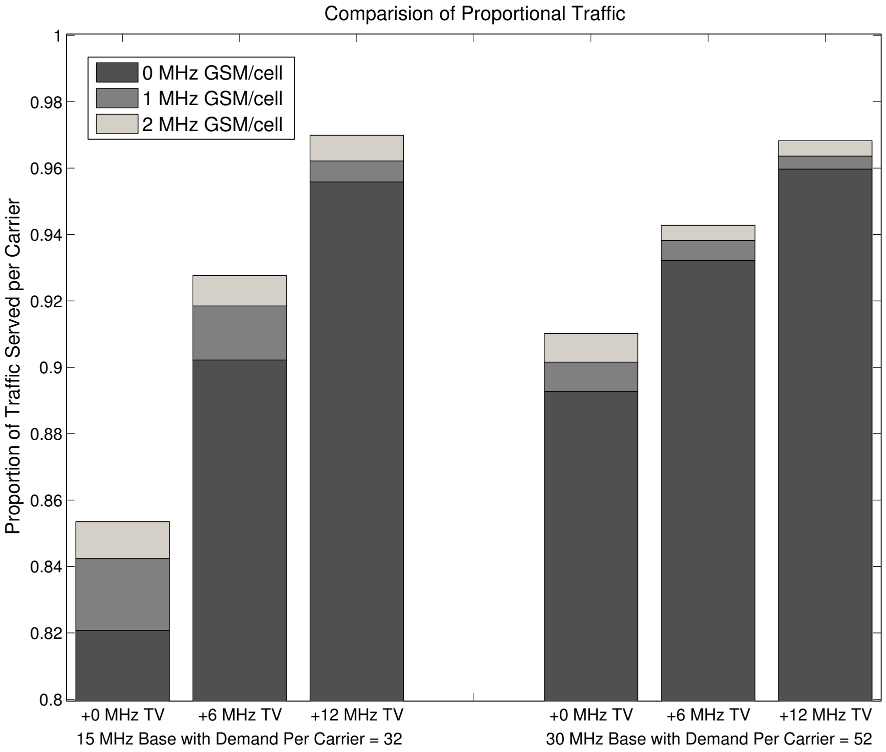

Figure 4.7: Comparison of proportional traffic served given additional DSA spectrum for a 15 MHz baseline with average demand of 32 channels per carrier (left bars) and 30 MHz baseline with average demand of 52 channels per carrier (right bars).

4.3 Summary

In this chapter, we illustrate the benefits of using an SA framework to support a DSA overlay in an LTE+ network through two cases. In the first case, we created a simulation model to illustrate the benefits of using a DSA carrier to serve overflow traffic. In the second case, we modeled the optimal channel assignment of DSA carriers to show the benefits of using a DSA overlay in LTE+ networks through integer programs. In summary, this chapter presented the quantifiable benefits of a DSA overlay in LTE+ networks using an SA framework.

Chapter 5

DSA Architecture in the LTE+ HetNet

In the earlier chapters, we presented the effects of a DSA overlay to the LTE+ architecture and showed the benefits of such an architecture using a macro-cell network. Network operators will also likely increase their capacity by building LTE+ HetNets, including Relay Nodes (RNs) and Home Evolved Node Bs (HeNBs), which can be deployed in institutional settings (e.g., stadiums, campuses, shopping centers, etc.), improving customer service and generating additional revenue. In this chapter, our work examines the architectural and operational aspects of deploying a DSA overlay in LTE HetNets.

5.1 Effects of DSA in the LTE+ HetNet Architecture

In this section, we provide an architectural overview of the effects of a DSA overlay in the LTE+ HetNet architecture. This section first presents a brief overview of the LTE+ HetNet architecture. Next, using the SA framework from [21], we propose new network elements, interfaces, and functionality in the LTE+ HetNet to support DSA. At the end of this section, we introduce our three proposed DSA management frameworks for LTE+ HetNets: SAC, CSM, and DSM.

5.1.1 The LTE+ HetNet

Figure 5.1 illustrates the LTE+ HetNet architecture (it also includes an acronym list for convenience). In LTE+, the UE is the end user, which only has access to packet-switched services (i.e., no circuit switched voice). Through the LTE+ air interface (LTE-Uu), the UE connects to the LTE+ network using the eNB, where the eNB has the important function of RRC. RRC is responsible for the establishment, configuration, maintenance, and release of radio bearers. The X2 link is used for communication between eNBs to assist in handoffs between neighboring eNBs and in the exchange of signaling information. The EPC is a combination of many network elements that

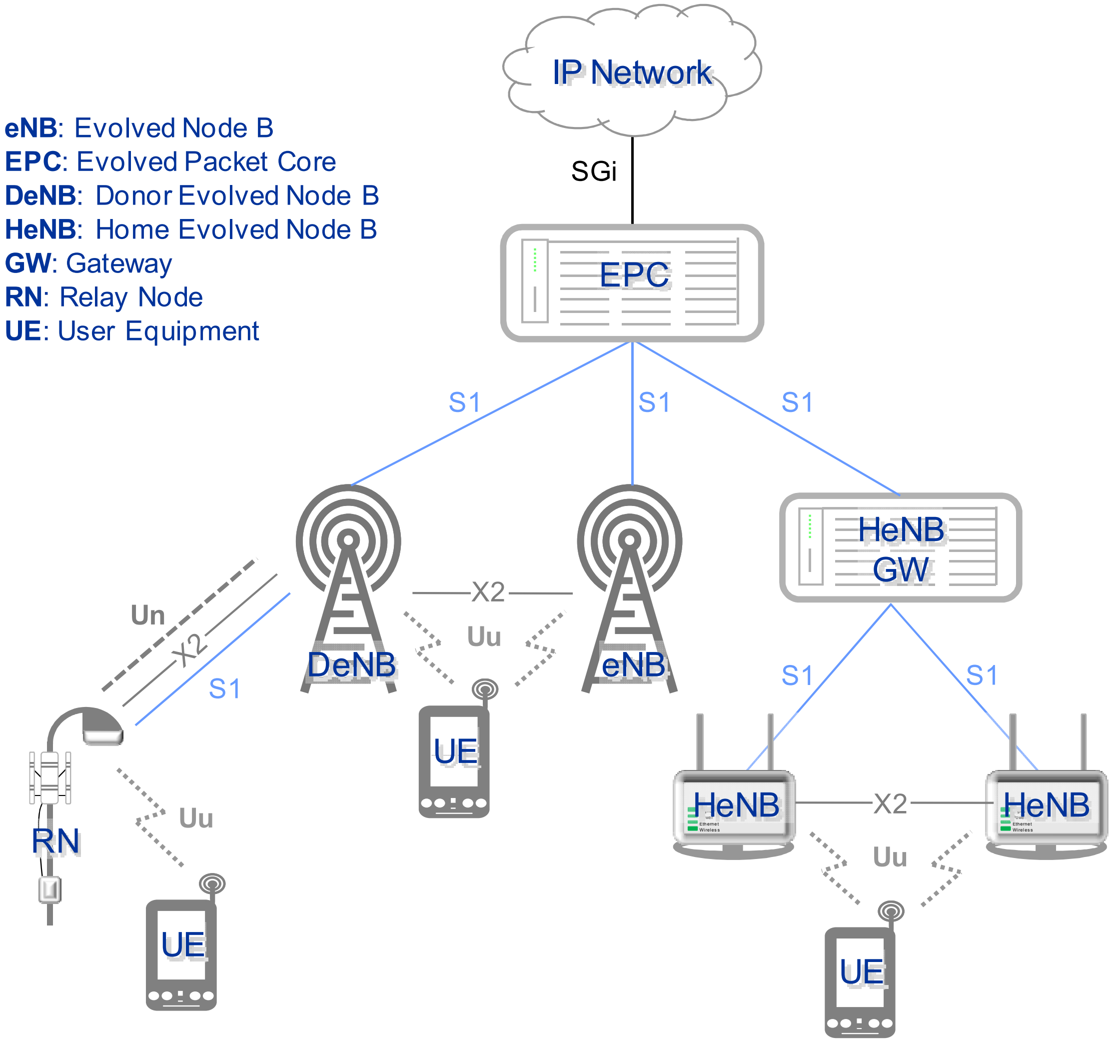

Figure 5.1: The addition of the RN and HeNB to the standard LTE architecture creates the LTE+ HetNet architecture.

authorizes network access, coordinates data bearers, manages mobile addressing, and provides an IP anchor for UEs to communicate with external network hosts. The S1 is used to carry control information as well as user traffic from the eNB to the EPC. S1 is also capable of carrying signaling information among the eNBs.

In LTE, a HetNet is formed through the introduction of either of two new network elements: the Relay Node (RN) and the Home Evolved Node B (HeNB). LTE+ supports relaying through RNs, which extend coverage and use an eNB, known as the DeNB, for backhaul. RNs appear to UEs as an eNB, while supporting a unique interface to the DeNB called the Un. The DeNB serves as an EPC proxy to the RN by embedding S1 and X2 over the Un to the RN (See Figure 5.1). Femtocells are supported through network elements called the HeNBs and HeNB Gateways. The HeNB supports eNB functionality with a femto-sized cell coverage and can use the premises infrastructure for backhaul. HeNBs may use an optional HeNB Gateway to serve as an S1 concentrator and relay between many HeNBs and the EPC. Although the HeNB is connected to the premises IP network, all user traffic from the UEs uses an IP anchor at the EPC (i.e., all user traffic flows through the core network). HeNBs also support X2 links to other HeNBs for handoffs. While this brief introduction to LTE+ is sufficient to support further discussion in this paper, the reader is encouraged to consult [1, 71] for more detailed information.

5.1.2 DSA in the LTE+ Heterogeneous Network

We propose to support the DSA overlay through the introduction of the following network elements: the Spectrum Accountability Server (SAS), cognitive Base Station (cBS), cognitive User Equipment (cUE), cognitive Relay Node (cRN), and the cHeNB. These network elements are shown in Figure 5.2. The SAS manages spectrum access policies and monitors spectrum leases through KPI reported through the leasing entities (e.g., cBS, cHeNB, and cRN). Through an external IP address, the leasing entities register with the SAS, discover neighbors, exchange sensing information, request leases, and report KPI to the SAS. The cUE carries all the same functionality as the UE. However, the cUE also has a spectrum agile radio, capable of operating on and sensing multiple bands as directed by the network. The cRN and cHeNB both have similar functionality, albeit more limited, as a cBS (e.g., spectrum sensing, SAS client, RRC, etc.); however, functionality can vary depending on the management framework for the HetNet.

5.1.3 DSA Management Frameworks for the LTE+ Heterogeneous Network

Extending our work in [21], we propose three different spectrum management frameworks for the LTE+ HetNet: SAC only, CSM, and DSM. Network elements impacted by these management frameworks are indicated in Figure 5.3. In the SAC only framework, shown in Figure 5.3 top left, both the cRN and the cHeNB behave like a cBS in the SA framework and communicate directly with the SAS. Spectrum leases are managed directly through the SAS and deployed as carrier resources for cRNs and cHeNBs without any interaction from other network elements. In contrast to

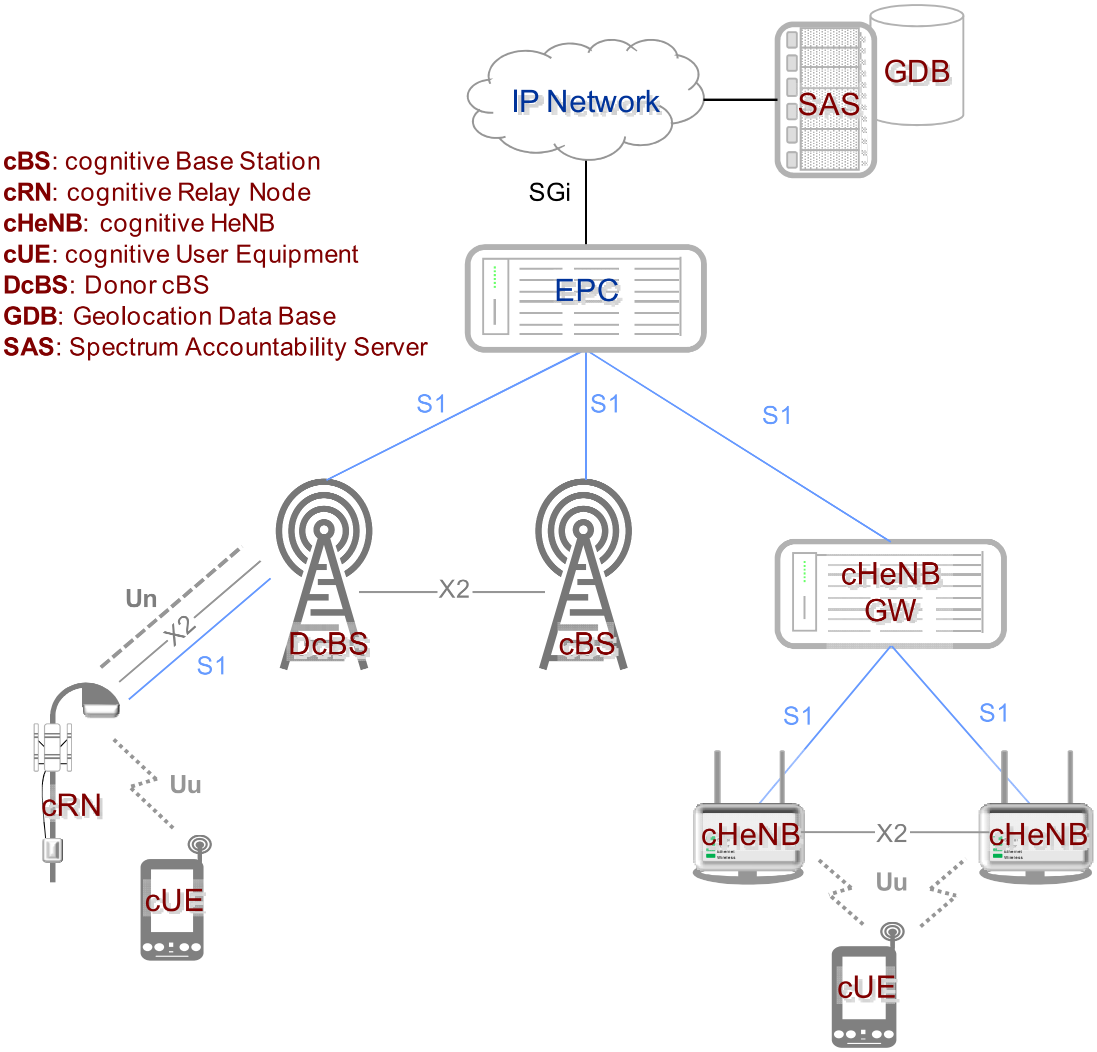

Figure 5.2: The introduction of DSA within the LTE+ HetNet introduces cognitive network elements and the SAS.

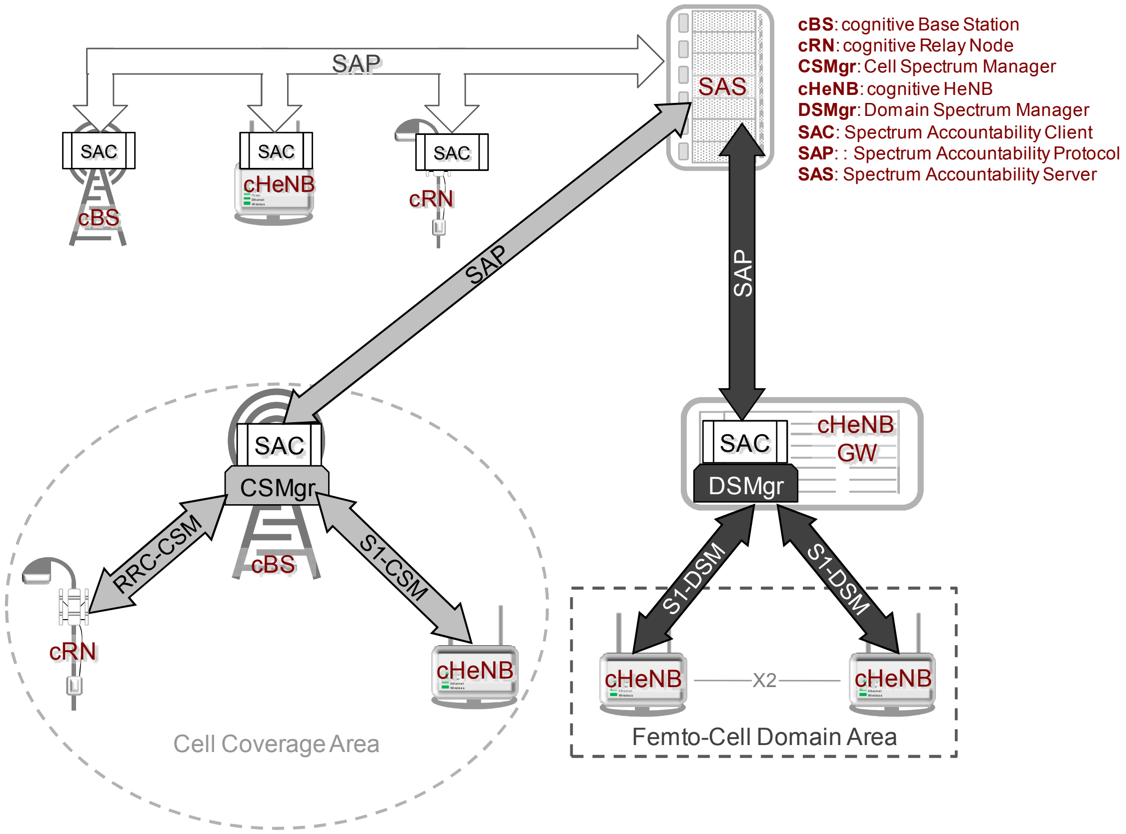

Figure 5.3: The use of DSA within the LTE+ HetNet introduces three options for spectrum resource management: SAC only (top left), CSM (bottom left), and DSM (bottom right).

SAC, in CSM, shown in Figure 5.3 bottom left, the cRNs and cHeNBs request spectrum resources from the Cell Spectrum Manager (CSMgr) instead of the SAS. In CSM, the CSMgr requests spectrum leases from the SAS and manages a local spectrum pool for the cRNs and cHeNBs within the cell coverage area. DSM is similar to CSM; however, in DSM the cHeNB Gateway serves as the local spectrum manager for the domain where the cHeNBs reside. In DSM, Figure 5.3 bottom right, only cHeNBs are assigned spectrum resources through the Domain Spectrum Manager (DSMgr). In the sequel, we present each of these spectrum management options individually and discuss their operational and interface effects on the cRN and cHeNB.

5.2 DSA Spectrum Frameworks

5.2.1 SAC Only

When the SAC framework only is used, cRNs and cHeNBs communicate directly with the SAS for spectrum leases. In these cases, the Donor cognitive Base Station (cBS) (DcBS) and the cHeNB Gateway serve as proxies for the cRNs and cHeNBs, respectively. As with the cBS, both the cRN and cHeNB have IP anchors supported by the EPC to enable communication with external networks. This functionally serves as the basis for the SAP, which supports the DSA service request and spectrum management procedures [21]. The protocol stacks and interfaces for each network element to support SAP for the SAC configuration are shown in Figure 5.4. For the SAC configuration, DSA supporting procedures from [21] remain unchanged, because the cRN and cHeNB are seen exactly as cBSs.

5.2.2 CSM

In contrast to SAC, CSM provides local spectrum management of the coverage area of the cBS, through a logical entity known as the CSMgr. All cRNs and cHeNBs that reside in the geographic coverage area of the cBS are assigned spectral resources by the CSMgr. Spectrum resources are managed through a local spectrum pool, which the CSMgr assigns to the cRNs and cHeNBs within the cell coverage area. When the demand within the cell exceeds the available spectral capacity, the cBS, through its own Spectrum Accountability Client (SAC) and the CSMgr, will generate a lease request or obtain more spectrum for the spectrum pool.

CSM Interfaces

The CSMgr communicates directly with the cRN using the RRC-CSM protocol, over the Un interface, but uses the cHeNB Gateway and EPC as relays for communication between the cHeNB and the cBS. The protocol stack showing the DSA interfaces for the cRN and the other network

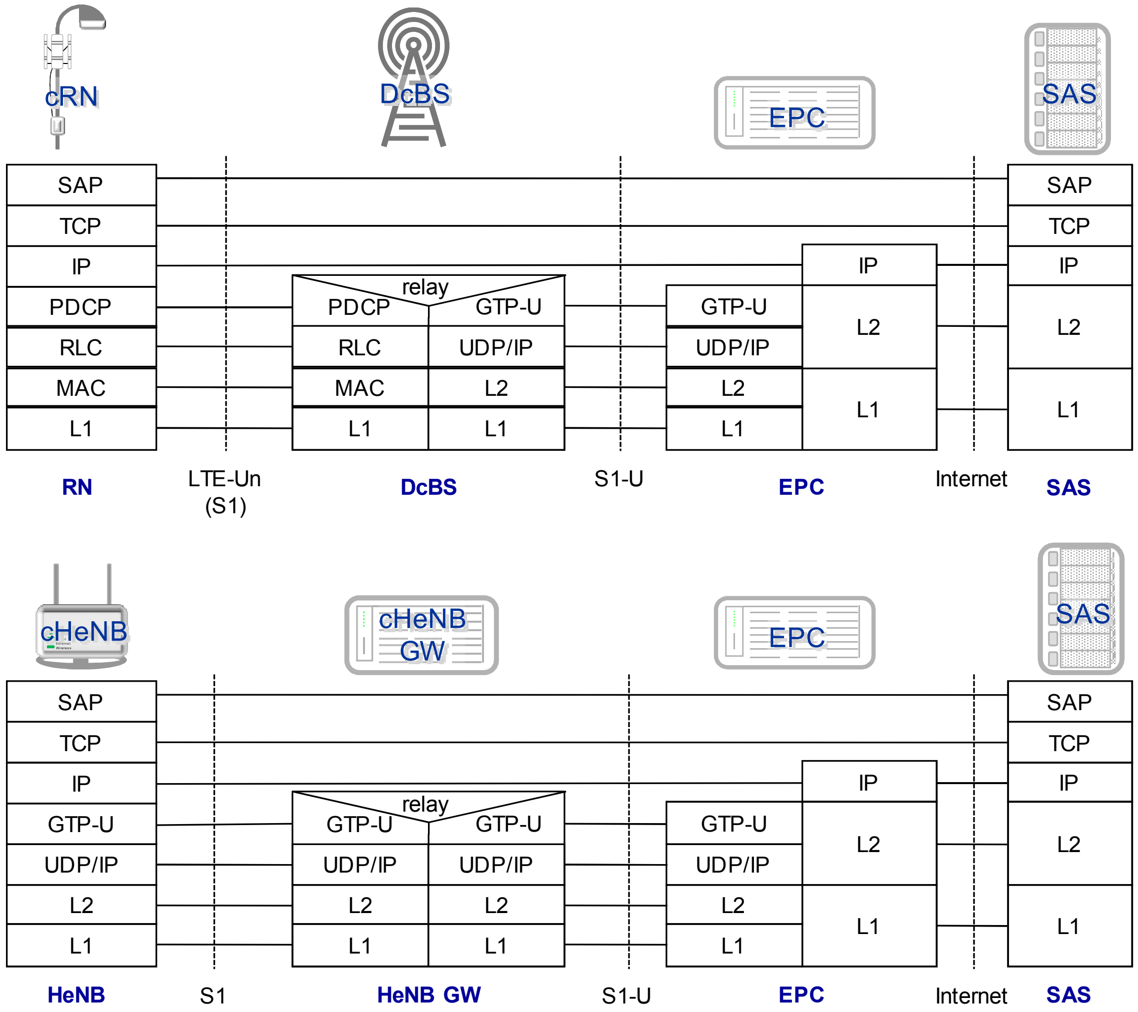

Figure 5.4: When using a SAC configuration to support DSA within the LTE+ HetNet, the DcBS and the cHeNB Gateway serve as proxies for the cRN and cHeNB, respectively, to communicate with the SAS.

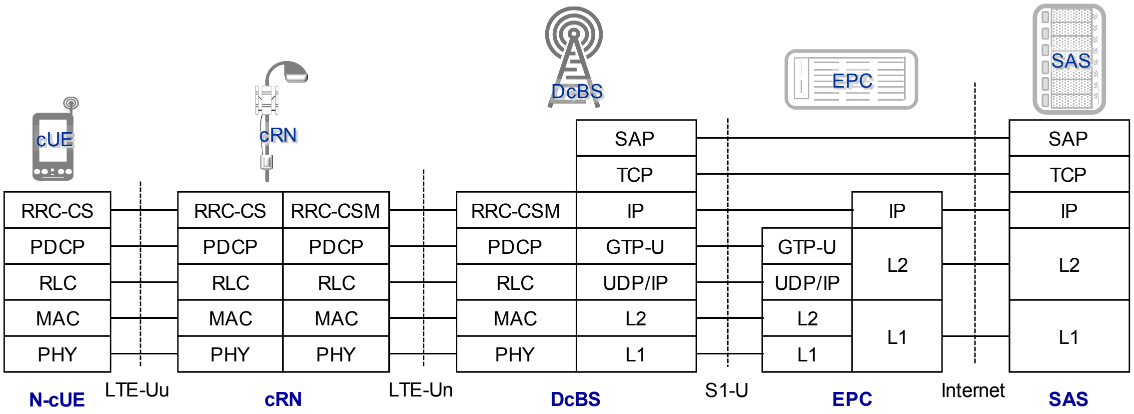

Figure 5.5: RRC-CSM signaling is used to locally manage the cRN in CSM, where the CSMgr, on the DcBS, translates orders and information to and from other cBS and the SAS.

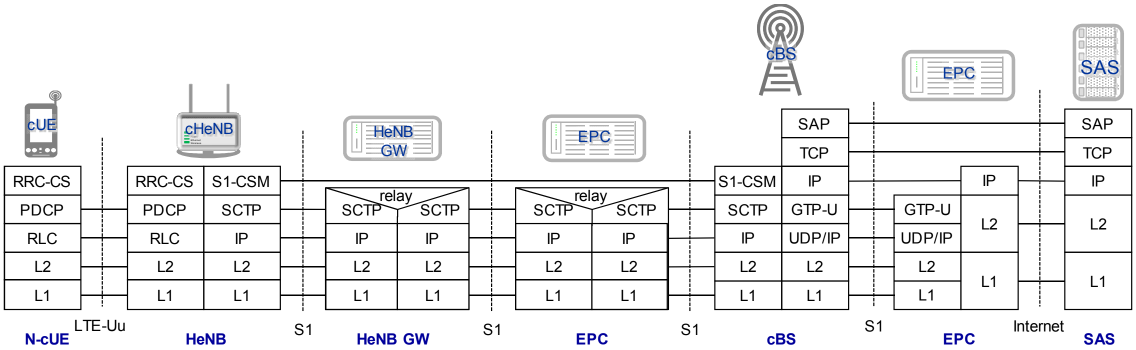

Figure 5.6: S1-CSM signaling is used to locally manage the cHeNB in CSM, where the CSMgr, on the cBS, translates orders and information to and from other cBS and the SAS.

elements is shown in Figure 5.5. When the CSM configuration is used with the cRN, the cRN receives orders from the DcBS for spectrum sensing and then translates those sensing orders to the cUEs for which it provides service. Spectrum resource requests are performed using the RRC-CSM protocol over the Un interface. The resource requests are evaluated by the spectrum manager and then translated into spectrum lease requests to the SAS to increase the cell capacity when needed. Similarly, the cHeNB also receives orders for sensing and sends requests for resources to the CSMgr. The protocol stack showing the DSA interfaces for the cHeNB and the other network elements is shown in Figure 5.6. However, in the case of the cHeNB, this signaling is performed over the S1-CSM interface, which uses relay functions on the cHeNB Gateway and the EPC. We also note that the RRC-CSM protocol is a possible option for cHeNBs as well.

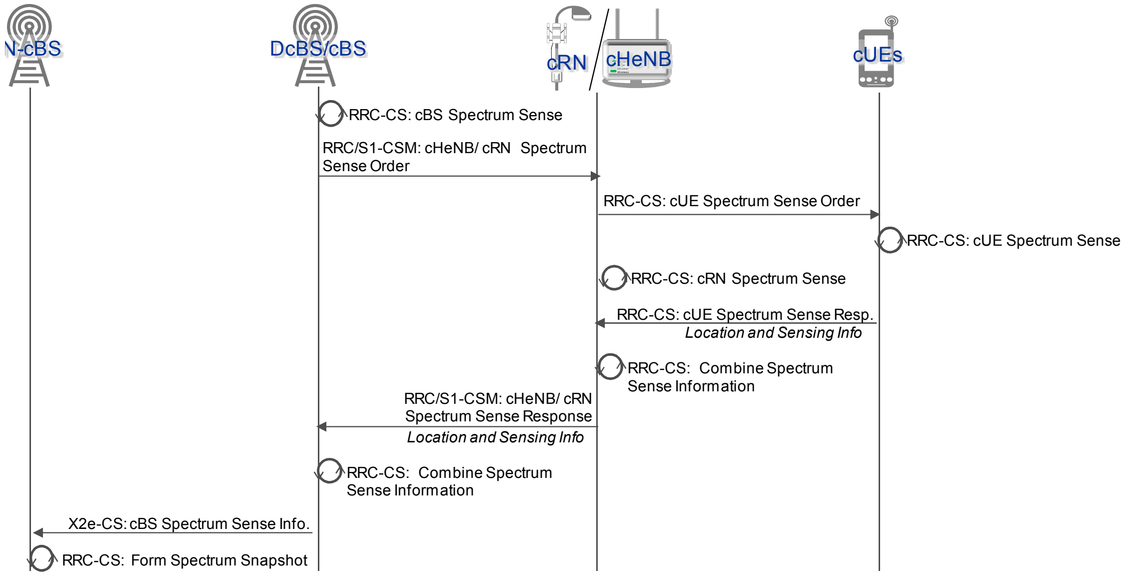

Figure 5.7: Cooperative sensing procedure for both the cRN and the cHeNB in the CSM configuration.

CSM Procedures

In the CSM configuration, the CSMgr translates orders and information between the cRN and cHeNB within the local cell and the SAS and other cBSs. We illustrate how this translation occurs through modifying the following procedures from [21]: cooperative sensing, spectrum lease request, and new primary operator alerting procedure. Operationally, these procedures are identical for the cRN and the cHeNB. The primary difference is the interface between the cRN/cHeNB and the cBS. In the interfaces that we have described, we assume the RRC-CSM for the cRN and the S1-CSM for the cHeNB in the subsequent procedures. When more thorough knowledge of spectral conditions is required, cooperative sensing can be used. The cooperative sensing procedure is illustrated in Figure 5.7. In the cooperative sensing procedure, the CSMgr on the DcBS/cBS sends spectrum sensing orders to cRNs/cHeNBs for the collection of spectrum sensing information. The cRNs/cHeNBs translate the spectrum sensing orders to the cUEs that they serve, and the cUEs perform local sensing. After all cUEs have returned their sensing response, the cRNs/cHeNBs combine this sensing information and send it to the DcBS/cBS, in the spectrum sensing responses. After receiving this response, the DcBS/cBS combines this information and shares it with the Neighboring-cognitive Base Station (N-cBS) or the SAS. When the cRNs/ cHeNBs encounter the need for more spectrum (i.e., a trigger event) they send spectrum requests to the DcBS/cBS. This signaling procedure is illustrated in Figure 5.8. Trigger events are the result of traffic trending/prediction algorithms, which could detect and predict sharp rises in traffic from an unexpected event or a more gradual increase in load. In our example, the cRN/cHeNB does not have sufficient spectral resources to serve the spectral needs of its cell and sends resource requests to the DcBS/cBS, using the RRC/S1-CSM. Based on the local needs of the cell, the DcBS/cBS calculates the resources needed and then forms a spectrum lease request and sends that lease request to

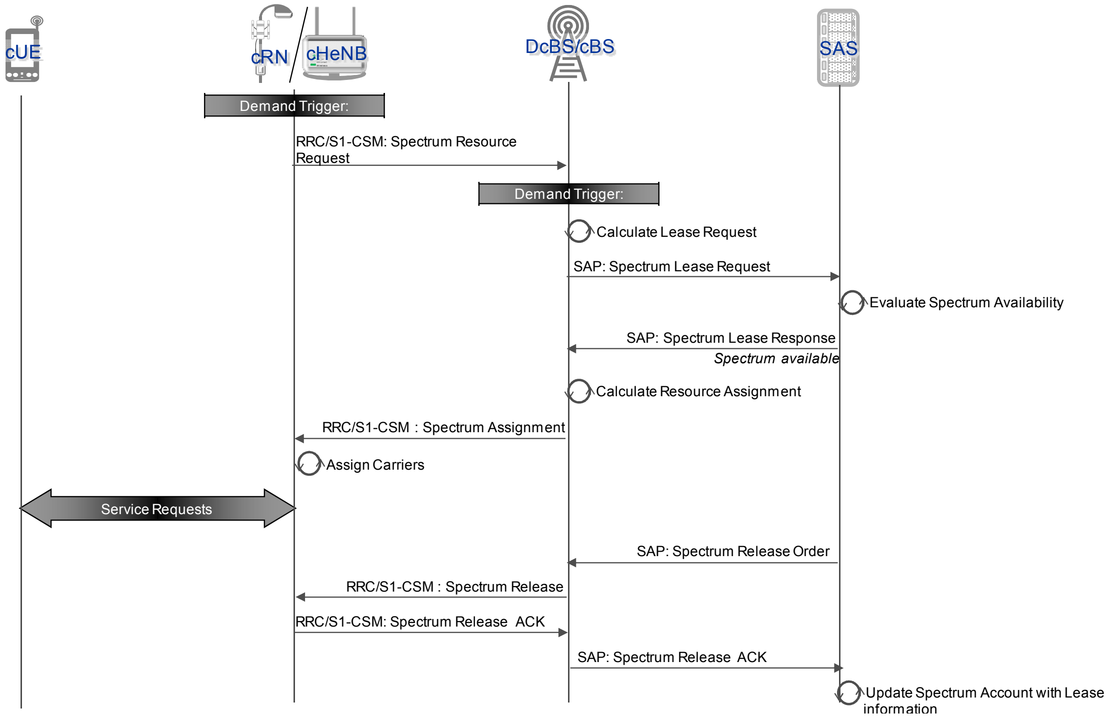

Figure 5.8: Spectrum lease request procedure for both the cRN and the cHeNB in the CSM framework.

the SAS. The SAS evaluates the spectrum availability and then issues the lease to the DcBS/cBS. After receiving the spectrum lease, the DcBS/cBS calculates the resource assignment for the local cell and assigns the specific spectral resources to each of the cRNs/cHeNBs requesting resources. Using these spectral resources, the cRNs/cHeNBs service the requests of the associated cUEs. Once the lease has expired, a notification is sent from the SAS to the DcBS/cBS to release the spectral resources. The cRN/cHeNB then translates this information into spectral resource orders for the local cell. An Acknowledgment (ACK) is returned from each of the cRNs/cHeNBs to the DcBS/cBS indicating a release of the spectrum as well as the KPI of the spectrum use. After all the spectrum release ACKs are collected from the cRNs/cHeNBs, the DcBS/cBS sends a message to the SAS indicating that the resources have been released and KPIs are reported for the spectrum usage of the cell. The purpose of this procedure is to notify the DcBSs/cBSs and associated cRNs/cHeNBs of a newly active primary operator so spectrum can be vacated. The procedure signaling diagram is shown in Figure 5.9. Using SAP, the primary operator issues a registration request to the SAS. This request contains information about the licensed spectrum, such as center frequency, bandwidth, and licensed geographic area. The SAS updates the geolocation database and returns a registration response. Using the geolocation database, the SAS then identifies and notifies the associated DcBS/cBS that there is a new primary operator active on a specific channel. The cBSs then update their spectrum access rules, mark the channel as belonging to a primary operator, and determine new spectrum resource assignments. These new spectrum assignments are then sent to the cRNs/cHeNBs. Using these assignments, the cRNs/cHeNBs augment their respective carriers with the licensed spectrum to be used opportunistically. Each cRN/cHeNB then sends

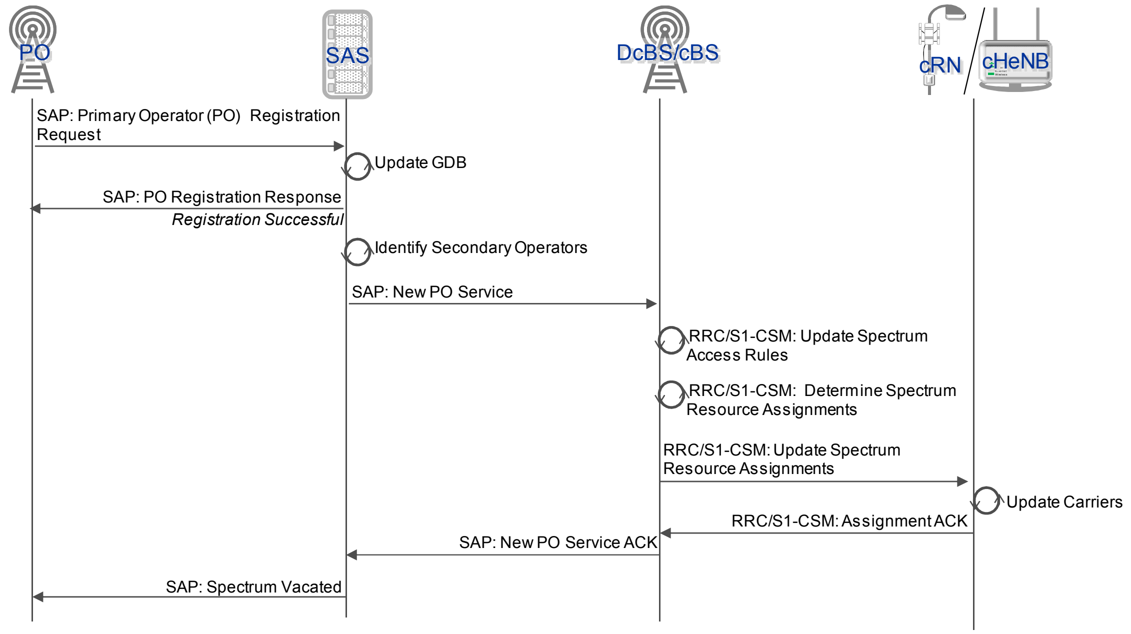

Figure 5.9: New primary operators alerting procedure for the cRN and the cHeNB in the CSM framework.

an assignment ACK to the DcBS/cBS, to indicate the perviously utilized channels are vacated. After the channel is vacated, the cBS sends an ACK to the SAS. Once all of the cBSs have vacated the spectrum, the SAS notifies the primary operator.

5.2.3 Domain Spectrum Management

As with CSM, DSM provides local spectrum management of a geographic coverage area or domain. However, this domain could be a campus, stadium, or neighborhood in which a multitude of cHeNBs are deployed and managed by a cHeNB Gateway. Within this domain, the cHeNBs are assigned resources by the DSMgr, which resides on the cHeNB Gateway. Through a locally managed spectrum pool, the DSMgr assigns spectrum to cHeNBs within the domain. When the demand within the cell exceeds the available spectral capacity, the cHeNB Gateway, through its own SAC and the DSMgr, will send a lease request to obtain more spectrum for the spectrum pool.

DSM Interfaces

Similar to the CSMgr, the Domain Spectrum Manager (DSMgr) communicates directly with the cHeNB, using the S1-DSM protocol. The cHeNB Gateway uses its own SAC client, using the EPC as a relay and IP anchor to communicate with the SAS. Through the S1-DSM interface, the cHeNB sends resource requests and receives spectrum sensing orders to and from the cHeNB

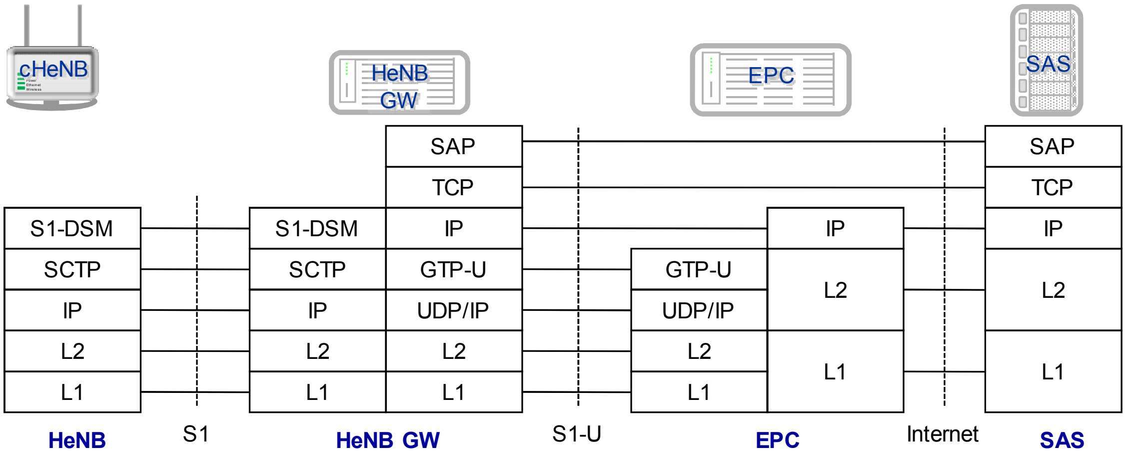

Figure 5.10: S1-DSM signaling is used to locally manage the cHeNB within the domain of the cHeNB Gateway. Residing on the cHeNB Gateway, the DSMgr translates orders and information to and from other cBS and the SAS.

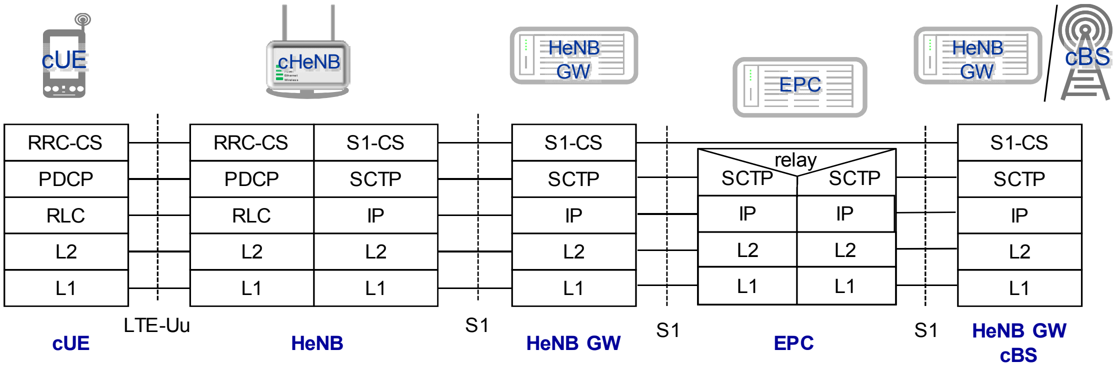

Figure 5.11: S1-CS signaling is used to share spectrum sensing information among cHeNB Gateways and cBSs.

Gateway. These messages are translated into spectrum lease requests, using SAP, to the SAS, or cooperative sensing information to neighboring cBSs or cHeNB Gateway Domains. Spectrum sensing information is shared with other cHeNB Gateways or cBSs through the S1-CS link. These links are established using the neighbor discovery procedures based on [21]. The protocol stacks for each of these interfaces are shown in Figures 5.10 and 5.11.

DSM Procedures

Like the CSMgr, the DSMgr translates orders and information from the cHeNB Gateway domain to other cBSs, cHeNB Gateways, and the SAS. Operationally, many of the procedures are similar to the ones adopted with CSM. The differences are primarily in the network elements exchanging messages and the S1-DSM and S1-CS interfaces. We illustrate these similarities and differences

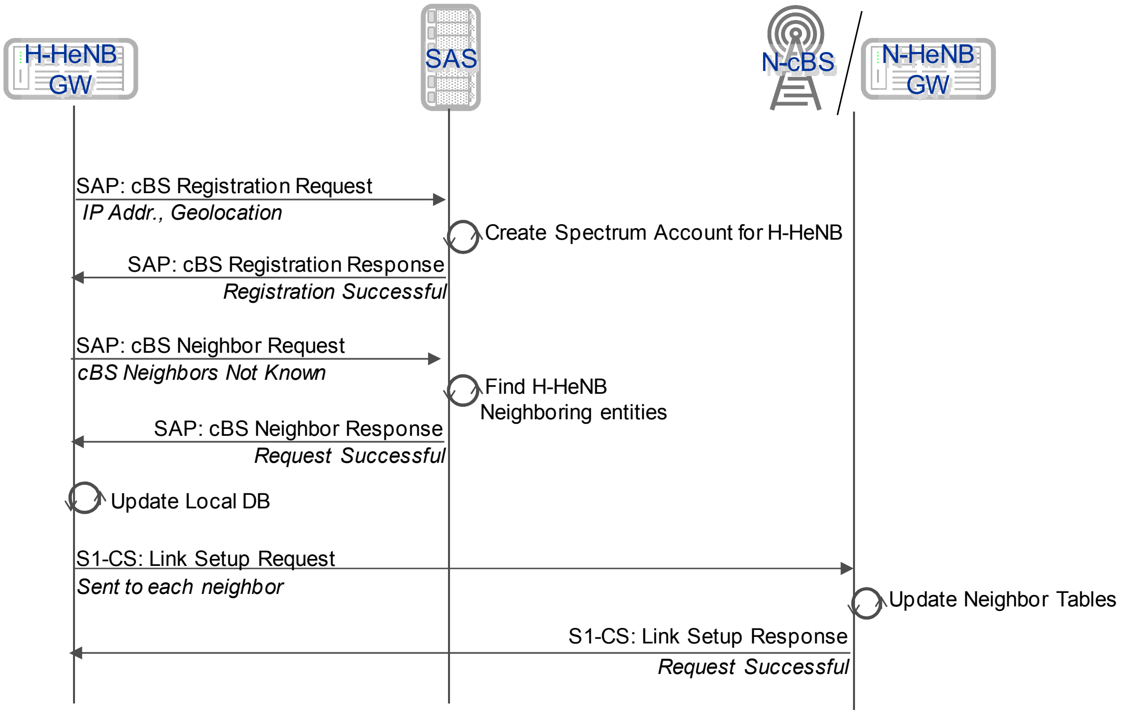

Figure 5.12: cHeNB Gateway registers with the SAS, discovering the neighboring cHeNB Gateways and cBS.

by introducing two modified procedures from [21]: registration/discover and cooperative sensing. The cBS Registration and Neighbor Discovery procedure is the genesis of all other procedures. When using SAP, all management entities must register with the SAS. Registration with the SAS is necessary for generating spectrum lease requests and discovering neighbors for the exchange of spectrum sensing information. Similarly, the cHeNB Gateway also registers with the SAS. This procedure is shown in Figure 5.12.

In the first SAP message, the DSM, on the Home-cHeNB Gateway (H-cHeNB Gateway), sends a registration request to the SAS. This registration request contains the IP address of the H-cHeNB Gateway, as well as geolocation information of the H-cHeNB Gateway domain. When this request is received at the SAS, the SAS creates a spectrum account for the H-cHeNB Gateway and updates the geolocation database. After the SAS creates the H-cHeNB Gateway account, the SAS responds with a registration response, indicating that the registration was successful, and sends the spectrum access rule set based on the SAS policy. After registration is complete, the cHeNB Gateway then discovers the Neighboring-cBSs and also Neighboring-cHeNB Gateways through request/response signaling to the SAS. The SAS neighbor response contains the IP addresses of all the neighboring entities. Using the neighboring entities' IP addresses, the cHeNB Gateway then sends an S1-CS: Link setup request to support the exchange of sensing information. In the DSM configuration, the cHeNB Gateways periodically collect spectrum sensing information from their own domain and share it with other cHeNB Gateways and cBSs. This procedure is illustrated in Figure 5.13. The procedure begins with the H-cHeNB Gateway issuing the command to the cHeNB to collect

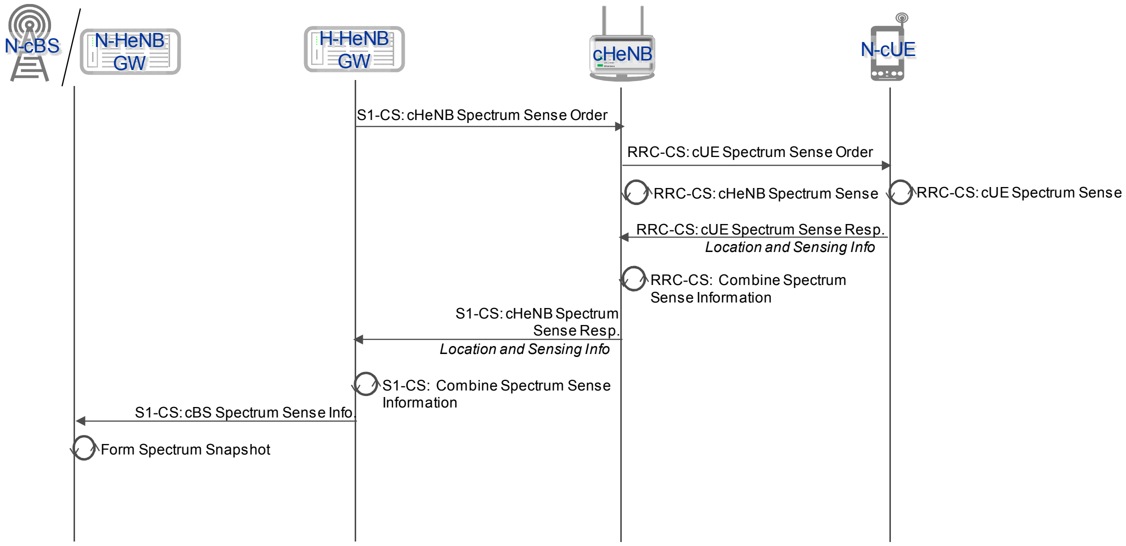

Figure 5.13: cHeNB shares sensing information.

sensing information. After receiving the spectrum sensing order, the cHeNB forwards this message to the cUEs and performs its own sensing. After receiving spectrum sensing information from all of the cUEs, the cHeNB then combines and reports this information to the cHeNB Gateway. After receiving all of the spectrum sensing information from all of the cHeNBs, the cHeNB Gateway then shares this information with the neighboring entities (i.e., N-cBSs and N-cHeNB Gateways) to form spectrum snapshots.

5.2.4 Tradeoffs Between Architectures

The choice of an appropriate management framework (SAC, CSM, or DSM) for a DSA HetNet depends on the usage scenario. If a substantial number of cHeNBs and RNs are deployed in a SAC configuration, the number of spectrum lease requests could potentially overload the EPC and the SAS. Considering this disadvantage, SAC makes more sense when the cHeNBs or RNs are deployed sparsely. In the case of dense deployments or a substantial number of cHeNBs and RNs, the CSM or DSM configurations clearly impose the least overhead. In a suburban setting, cHeNBs may be deployed within households and perhaps have some macro-cell coverage. In this case, cHeNB deployments would be less dense than in an institutional deployment, such as what would be found at a campus or a stadium. Thus, CSM may make more sense in a suburban setting, because spectrum management of a macro-cell coverage area is already being performed. In the case of densely deployed cHeNBs, DSM may be preferable to CSM, since signaling from densely deployed cHeNBs may overload the local CSMgr. Signaling loads could be balanced through the use of cHeNB Gateways and DSMgrs. We envision that future HetNet deployments which use DSA will likely adopt a combination of these different frameworks to meet the needs of their local markets.

5.3 Summary

In this chapter, we proposed three new management frameworks for DSA in HetNets: Spectrum Accountability Client, Cell Spectrum Management, and Domain Spectrum Management. For these spectrum management frameworks, we defined protocol interfaces and operational signaling scenarios to support cooperative sensing, spectrum lease management, and alarm scenarios for rule adjustment. Through this work, future LTE+ standards, infrastructure vendors, and network operators can gain a better understanding of the effects and benefits of using DSA in HetNets. In summary, this chapter defined the operational effects of deploying DSA in HetNets.

Chapter 6

Performance Evaluation DSA in LTE+ HetNet

In the previous chapter, we presented the affected control planes, new network elements, operational procedures, and our three proposed DSA management frameworks to support a DSA overlay in an LTE+ HetNet. In this chapter, we formulate integer programs to assess the benefits of using DSA in an LTE+ HetNet and compare our spectrum management frameworks (i.e., SAC, CSM, or DSM). In the Sections 6.1 and 6.2 of this chapter, we compare an LTE+ HetNet with a DSA management framework to one without, using integer programs. We apply these programs to realistic topologies formed using GIS data. Additionally, we use the GIS formed topology and compare the performance of our MacroNet integer program discussed in Chapter 4. In Section 6.3 we leverage our integer programs to create program sets, to model each of the spectrum management frameworks we introduced in the previous chapter.

6.1 Modeling DSA the LTE+ HetNet

In our first formulation, we seek to establish a baseline. To this end, we first formulate an integer program such that only licensed spectrum is available to an LTE+ HetNet, which includes cHeNBs and cBSs. In our second formulation, we allow the LTE+ HetNet to use DSA and licensed spectrum. We compare the optimal solutions of each of these integer programs to understand the benefits of using DSA spectrum in a LTE+ HetNet with the objective of maximizing the assignment of the spectrum to meet a given demand.

We consider an LTE+ HetNet with W licensed channels, which can be deployed throughout a network with B cBSs and H cHeNBs. To manage inter-cell interference between cBS, channels are aggregated into cell-edge or cell-center carriers [73], where channels in the cell-edge carriers must be different among neighboring base stations. This frequency/channel assignment forms the first of our assignment constraints. Additionally, we prevent inter-tier interference by assuming orthogonal channel assignment of LTE+ channels between cHeNB and cBS. cHeNB deployments should also avoid inter-cell interference by assigning orthogonal frequencies between neighbors.

Let $x_{i,c,k} = 1$ when cBS i assigns channel c to carrier k, where $k = 1$ and $k = 2$ indicate a cell-center and a cell-edge carrier, respectively. Denote $d_{i,k}$ as the demand in number of channels at cBS i on carrier k and d_h as the demand, in number of channels, at cHeNB h. Through an adjacency matrix $\mathbf{N}$, we define neighbor relationships between cBSs, where $n_{i,j} = 1$ indicates cBS i is a neighbor to cBS j. cHeNBs follow similar assignment rules. Through an adjacency matrix $\mathbf{M}$, we define neighbor relationships between cHeNBs, where $m_{h,g} = 1$ indicates cHeNB h is a neighbor to cHeNB g. To manage inter-tier interference (i.e., interference between a cHeNB and a cBS) cHeNBs within a cell-center or cell-edge cannot use channels contained in those respective carriers. Let $u_{h,c} = 1$ to indicate when cHeNB h uses channel c. Through an interference matrix $\mathbf{Q}$, we define inter-tier relationships, where $q_{i,h,k} = 1$ indicates cBS i, carrier k overlaps with the coverage of cHeNB h. Here we introduce our first formulation, $\mathcal{F}_1$, which uses only licensed channels to satisfy the demands of the network given the constraints as described.

Maximize:

$$\sum_{i=1}^{B}\sum_{c=1}^{W}\sum_{k=1}^{2} x_{i,c,k} + \sum_{h=1}^{H}\sum_{c=1}^{W} u_{h,c} \tag{6.1}$$

Subject to:

$$\sum_{c=1}^{W} x_{i,c,k} \le d_{i,k} \qquad \forall\ i,k \tag{6.2}$$

$$\sum_{c=1}^{W} u_{h,c} \le d_h \qquad \forall\ h \tag{6.3}$$

$$\sum_{k=1}^{2} x_{i,c,k} \le 1 \qquad \forall\ i,c \tag{6.4}$$

$$n_{i,j}(x_{i,c,2} + x_{j,c,2}) \le 1 \qquad \forall\ i,j,c \tag{6.5}$$

$$m_{g,h}(u_{h,c} + u_{g,c}) \le 1 \qquad \forall\ g,h,c \tag{6.6}$$

$$q_{i,h,k}(x_{i,c,k} + u_{h,c}) \le 1 \qquad \forall\ i,h,k,c \tag{6.7}$$

$$\tag{6.8}$$

$$x_{i,c,k}, u_{h,c} \in \{0,1\} \qquad \forall\ i,c,k$$

Our objective function is to maximize the number of channels assigned to each cBS and cHeNB in Function (6.1) using only licensed channels. In Constraints (6.2) and (6.3), channels are only assigned as required to meet demand. Constraint (6.4) enforces that channels should only be used once within the cBS cell (i.e., cell-edge and cell center carriers cannot have the same channel). To prevent inter-cell interference, Constraints (6.5) and (6.6) prevent neighboring cBS cell-edges and cHeNB cells from using the same channels. Constraint 6.7 is used to prevent inter-tier interference.

To develop our second formulation, we extend formulation $\mathcal{F}_1$ by considering a HetNet that can use

DSA and licensed spectrum. Specifically, we consider DSA of TV white spaces and unused GSM channels, which can only be used when the cHeNBs will not interfere with primary transmissions. Therefore, we define an interference matrix **P**, where $p_{i,l} = 1$ if cBS i is not within interfering distance of TV station l. We further denote $y_{i,l,c,k} = 1$ to indicate when cBS i uses TV station l's channel c on carrier k, where there are P TV stations, each with V channels available. GSM channels available at the local cell can also be used when unoccupied. Thus, we denote matrix **A**, where $a_{i,c} = 1$ if the base station i's channel c, from the GSM spectrum, is available for secondary use. We further denote $z_{i,c,k} = 1$ to indicate when cBS i uses channel c, from the GSM spectrum, on carrier k, where each base station has U potential channels available.

Similarly, for the cHeNB, we define an interference matrix **S**, where $s_{h,l} = 1$ if cHeNB h is not within interfering range of TV station l. We further denote $v_{i,l,c} = 1$ to indicate when cHeNB i uses TV station l's channel c. GSM channels available at the local cell can also be used when unoccupied. Further denote $w_{h,i,c} = 1$ to indicate when cHeNB h uses channel c, from the GSM cell i, where each base station has U potential channels available. We assume that GSM frequencies are previously deployed to minimize inter-cell interference, and therefore, GSM channels can only be opportunistically used within the same cell. We also assume that the GSM and LTE+ base stations are collocated within the same cell and share the same coverage area. Given our described constraints we present our second formulation, $\mathcal{F}_2$.

Maximize:

$$\sum_{i=1}^{B}\sum_{c=1}^{W}\sum_{k=1}^{2} x_{i,c,k} + \sum_{i=1}^{B}\sum_{l=1}^{P}\sum_{c=1}^{V}\sum_{k=1}^{2} y_{i,l,c,k} + \sum_{i=1}^{B}\sum_{c=1}^{U}\sum_{k=1}^{2} z_{i,c,k} + \sum_{h=1}^{H}\sum_{c=1}^{W} u_{h,c} + \sum_{h=1}^{H}\sum_{l=1}^{P}\sum_{c=1}^{V} v_{h,l,c} + \sum_{h=1}^{H}\sum_{c=1}^{U} w_{h,i,c} \tag{6.9}$$

Subject to:

$$\sum_{c=1}^{W} x_{i,c,k} + \sum_{c=1}^{V}\sum_{l=1}^{P} y_{i,l,c,k} + \sum_{c=1}^{U} z_{i,c,k} \leq d_{i,k} \qquad \forall\, i,k \tag{6.10}$$

$$\sum_{c=1}^{W} u_{h,c} + \sum_{l=1}^{P}\sum_{c=1}^{V} v_{h,l,c} + \sum_{c=1}^{U} w_{h,i,c} \leq d_h \qquad \forall\, h \tag{6.11}$$

$$\sum_{k=1}^{2} x_{i,c,k} \leq 1 \qquad \forall\, i,c \tag{6.4}$$

$$\sum_{k=1}^{2} y_{i,l,c,k} \leq p_{i,l} \qquad \forall\, i,l,c \tag{6.12}$$

$$\sum_{k=1}^{2} z_{i,c,k} \leq a_{i,c} \qquad \forall\, i,c \tag{6.13}$$

$$v_{h,l,c} \leq s_{h,l} \qquad \forall\ h, l, c \tag{6.14}$$

$$w_{h,i,c} \leq a_{i,c} \sum_{k=1}^{2} q_{i,h,k} \qquad \forall\ h, c, i \tag{6.15}$$

$$n_{i,j}(x_{i,c,2} + x_{j,c,2}) \leq 1 \qquad \forall\ i, j, c \tag{6.5}$$

$$n_{i,j}(y_{i,l,c,2} + y_{j,l,c,2}) \leq 1 \qquad \forall\ i, j, l, c \tag{6.16}$$

$$m_{g,h}(u_{h,c} + u_{g,c}) \leq 1 \qquad \forall\ g, h, c \tag{6.6}$$

$$m_{g,h}(v_{h,l,c} + v_{g,l,c}) \leq 1 \qquad \forall\ g, h, l, c \tag{6.17}$$

$$m_{g,h}(w_{h,i,c} + w_{g,i,c}) \leq 1 \qquad \forall\ g, h, i, c \tag{6.18}$$

$$q_{i,h,k}(x_{i,c,k} + w_{h,i,c}) \leq 1 \qquad \forall\ i, h, k, c \tag{6.7}$$

$$q_{i,h,k}(y_{i,l,c,2} + v_{h,l,c}) \leq 1 \qquad \forall\ i, h, k, c \tag{6.19}$$

$$q_{i,h,k}(z_{i,c,k} + v_{h,l,c}) \leq 1 \qquad \forall\ i, h, k, c \tag{6.20}$$

$$\sum_{l=1}^{P} \sum_{c=1}^{V} \sum_{k=1}^{2} y_{i,l,c,k} \leq \sum_{l=1}^{P} p_{i,l} V \qquad \forall\ i \tag{6.21}$$

$$\sum_{l=1}^{P} \sum_{c=1}^{V} v_{h,l,c} \leq \sum_{l=1}^{P} s_{h,l} V \qquad \forall\ h \tag{6.22}$$

$$\sum_{c=1}^{U} \sum_{k=1}^{2} z_{i,c,k} \leq U \qquad \forall\ i \tag{6.23}$$

$$x_{i,c,k}, y_{i,l,c,k}, z_{i,c,k}, u_{h,c}, v_{h,l,c}, w_{h,i,c} \in \{0, 1\} \qquad \forall\ i, l, h, c, k$$

In $\mathcal{F}_2$, we carry the constraints introduced in $\mathcal{F}_1$ and introduce the new equivalent constraints for inter-cell interference, which consider DSA. The objective function in Equation (6.9) maximizes the assignment of licensed and DSA channels for the entire HetNet. Constraints (6.10) and (6.11) prevent the assignments of spectrum channels beyond the associated demand for the cBS and cHeNB, respectively. Similar to Constraint (6.4), the assignment of the same TV white space and GSM channels to different cBS carriers within the same cell is prevented through Constraints (6.12) and (6.13), respectively. For defining permitted assignments of TV white space and GSM spectrum for cHeNB, we use Constraints (6.14) and (6.15), respectively. To prevent the inter-cell and inter-femto-cell interference of DSA channels, we use Constraints (6.16) - (6.18) to define additional neighbor relationships. Inter-tier interference of DSA channels is similarly addressed with Constraints (6.19) and (6.20). Finally, Constraints (6.21)-(6.23) define the limits of available DSA channels for the cBS and cHeNB. Next, we discuss our input scenarios in which we can solve and compare optimal solutions to understand the quantitative benefits of using DSA in LTE+ HetNets.

6.2 Simulated Scenarios and Results

Our primary goal in creating our scenarios was to create the most realistic input possible for our performance analysis. We selected the Blacksburg-Christiansburg, VA metro-area as the basis for our study and began the arduous task of gathering and processing the necessary GIS data from many different sources. We gathered data from the FCC transmitter databases, building footprints from the city of Blacksburg and Christiansburg, and population data from Oak Ridge National Lab's LandScan [80]. Using this GIS data, we create a HetNet topology and an associated representative user population for inputs to our mathematical formulations. To create hybrid carriers, we consider dynamic 200kHz LTE+ channels from licensed and opportunistic spectrum (i.e.,GSM and TV white spaces) and use FCC allocated bandwidths for determining total available spectrum.

6.2.1 Topology

Our HetNet comprises two tiers, the macro-cell layer, supported by the cBS, and the femto-cell layer supported by the cHeNB. We model the macro-cell layer of our HetNet using real locations of cellular base stations within our study area. We retrieved a list from the FCC's Antenna Structure Registration (ASR) database [81] and identified registrations to known cellular network providers and tower management companies. Additionally, we checked our list against satellite imagery to determine whether the site contained cellular equipment. We also visually identified additional sites, not registered in the (ASR), and added them to our list. Determining coverage areas of these sites is problematic, because this information is proprietary. Therefore, we use Voronoi cells [1] to approximate macro-cell coverage areas [82]. Using Voronoi cells also allows us to determine adjacency information for our constraints in the mixed integer linear programs discussed in the previous section. For cell-center coverage areas, we consider a maximal circular coverage area within each Voronoi macro-cell. A rendered view of our macro-cell layer and study area is shown in Figure 6.1.

To create a realistic femto-cell layer for our HetNet, we overlay population information, from LandScan, with building footprints. LandScan provides the finest resolution of population distribution available by providing an ambient population count[2] in square kilometer pixels. Through our overlay, we identify edifices which lie in areas where the ambient population count exceeds 200. For each these buildings, we estimate the number of femto-cells required for each building by dividing the building area the approximate coverage area of a femto-cell ($\pi(100ft)^2 = 31kft^2$), then place femto-cells in these buildings according to a random distribution. As with the macro-cells, femto-cell coverage areas and adjacency relationships are determined through Voronoi cells. The entire femto-cell layer is two-dimensional, i.e., at the moment we do not consider the effects of femto-cell deployments in edifices with multiple floors. An example of a femto-cell deployment with an example edifice is shown in Figure 6.2.

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[1] Each facet of the Voronoi cells represents a set of equidistant points between base station sites.

[2] The ambient population count is a metric that incorporates both diurnal movements and collective travel habits.

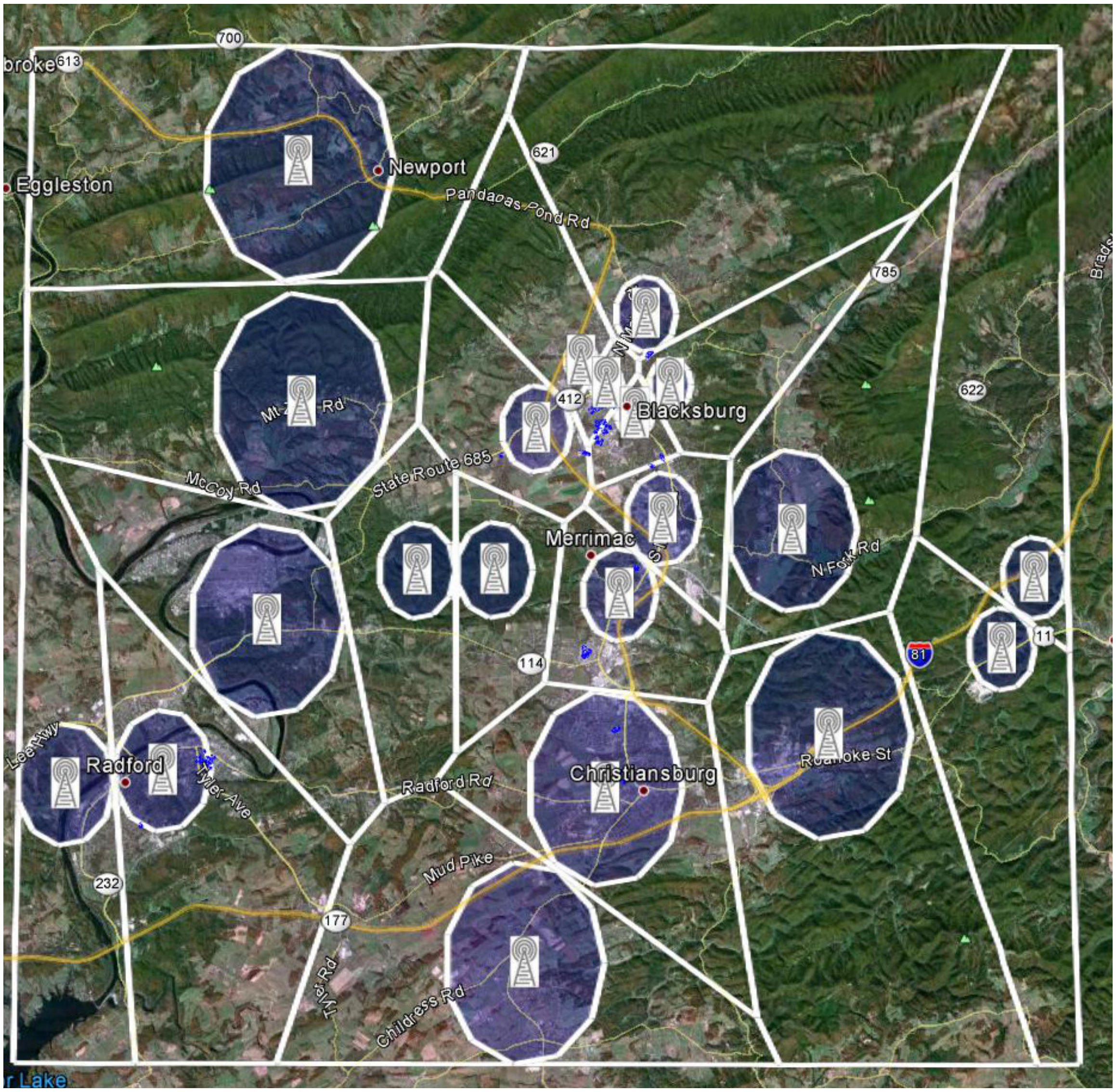

Figure 6.1: Rendered view of our study area using Google Earth. Cell-edge coverage areas are approximated through use of Voronoi cells and cell-center coverage is determined by a maximal circumference within the Voronoi macro-cell.

Figure 6.2: An example of an in-building deployment of our femto-cell layer. Polygons represent femto-cell coverage within a building. Locations of cHeNBs placement are indicated by the icons.

6.2.2 Channel Demand

Channel demand for the cBS $d_{i,k}$ and the cHeNB d_h is calculated by:

$$d = \left\lceil \frac{1}{1000\tau} \sum_{i}^{P} \left\lceil 1000 \frac{\Delta_i}{\theta(\gamma_i)} \right\rceil \right\rceil. \tag{6.24}$$

By Equation (6.24), each individual user i of cell population P, demands Δ_i bits. The LTE+ channel throughput mapping function θ translates user i's Signal to Interference and Noise Ratio (SINR) γ_i into a data rate for a single LTE+ channel. The quotient of Δ_i and θ yields the number of seconds the a single channel will be required by user i. Furthermore, in LTE+ a single channel is broken into 1ms scheduling blocks [73]. Thus, we convert the argument within the summation from seconds into scheduling blocks by multiplying by 1000. To convert the sum into the total number of channels, we bound the amount of time a channel can provide resources by a time period τ, e.g., if the channel is bounded by 2 seconds it can provide 2000 resource blocks.

P for the cell is determined through a count of users placed within the service area of the respective polygon. We place 90% of the pixel population in buildings and randomly place the remaining population within the pixel. Cell populations are determined by counting the number of placements within the respective polygons. To model Δ_i, we consider HyperText Transfer Protocol (HTTP) responses, i.e., a user downloading a web page. Following [77], we model the length HTTP responses using the Pareto distribution. The Pareto distribution probability density function is given by:

$$p(x) = \sigma k^{\sigma} x^{-\sigma-1}, \quad \sigma, k > 0, \quad x \geq k, \tag{6.25}$$

with parameters from [77], $\sigma = 1.06$ and $k = 8000$ bits.

SINRmin	Modulation	ECR	θ
-8.93	4QAM	0.08	27432
-6.87	4QAM	0.12	42192
-4.80	4QAM	0.19	67860
-2.73	4QAM	0.30	108288
-0.67	4QAM	0.44	157860
1.40	4QAM	0.59	211644
3.47	16QAM	0.37	265752
5.53	16QAM	0.48	344520
7.60	16QAM	0.60	433152
9.67	64QAM	0.46	491508
11.73	64QAM	0.55	597996
13.80	64QAM	0.65	702432
15.87	64QAM	0.75	814212
17.93	64QAM	0.85	920700
20.00	64QAM	0.93	999864

Table 6.1: SINR to throughput mapping function θ

The channel throughput mapping function θ is given in Table 6.1. We derived θ using the SINR to Channel Quality Indicator (CQI) mapping function from [83], and use the CQI to determine and modulation and coding rates using [84]. Using the modulation and coding rates, we calculate θ to represent the throughput for a single LTE+ channel. The SINR user i γ_i is modeled using a lognormal random variable.

6.2.3 Spectrum and DSA

In our scenario, cBSs and cHeNBs are allowed to aggregate spectrum channels to form carriers in the network. LTE+ channels can be dynamically assigned to any cBS or cHeNB using licensed, GSM, or TV white space spectrum. The FCC bands outlined in Table 6.2 are considered for use in the network. The GSM spectrum availability for LTE+ channels is modeled by the modified beta distribution, as used in [21] and we consider a frequency reuse factor of 4. For TV white spaces, we retrieved TV contour areas from the FCC's Consolidated Database System (CDBS) [85]. From the CDBS, we identified 12 stations which overlapped our area. In our scenario, any cell which overlaps a TV contour is not permitted to operate in the associated TV spectrum. Additionally, we also consider frequency division duplexing, i.e. paired frequencies in the up-link and down-link.

Band	Net	Freq Bands(MHz)	BW(MHz)
Cellular	GSM	824-849,869-894	25
AWS	GSM	1710-1755,2110-2155	45
PCS	GSM	1850-1910,1930-1990	60
700MHz	LTE	698-716,775-788,805-806	32
TV	TV	512-608, 614-698	84

Table 6.2: Assumed licensed spectrum allocation for GSM and LTE+ networks.

6.2.4 Results

Using our scenarios as input to our formulations, we assume $\tau = 1s$, vary the probability of active users and allow the LTE+ network to experience increasing demand. To solve our maximization problems we used the Matlab Parallel Computing Toobox [86], CPLEX [79], and used the multi-core (8-32) Advanced Research Computing servers at Virginia Tech [87] (Ithaca) to run 1000 simulations per data point. We used both MacroNets and HetNet topologies for our simulations. Additionally, we examine how the use of different spectrum bands increase the proportion of traffic served. Our results are shown in Figure 6.3. The most salient feature of this figure is the difference between traffic served for the MarcoNet and the HetNet. When comparing the *Licensed Only* curves of the MarcoNet and HetNet there is an average increase of 41% over the performance of the MacroNet. We further examine the differences when adding additional spectrum using Figure 6.4.

In Figure 6.4, we illustrate the average benefits of the baseline (*Licensed Only*) curves for the MacroNet (Figure 6.4 left) and the HetNet (Figure 6.4 right). When comparing the total benefits of additional spectrum, using DSA spectrum benefits the MacroNet more than the HetNet by over a factor of 3. Since HetNets can leverages frequency reuse more heavily than the MacroNet, additional spectrum provides less benefit. Additionally, we observe TV white spectrum provides the largest gain in performance for both Nets: 27% for MacroNet and 10% increase for the HetNet. Although the gains in using opportunistic use of GSM is modest, 10% and 2% for the Macro and HetNet, respectively, we believe that these gains will significantly increase as operators continue to migrate users to LTE+. We conclude by emphasizing that although spectrum availability varies by geography, opportunistic spectrum may provide substantial performance gains in cellular markets.

6.3 Comparison of Spectrum Management Frameworks in LTE+ HetNet

In the previous section, we presented a performance comparison of Macro and HetNet using DSA. In this section, we formulate mathematical programs to illustrate the differences in performance

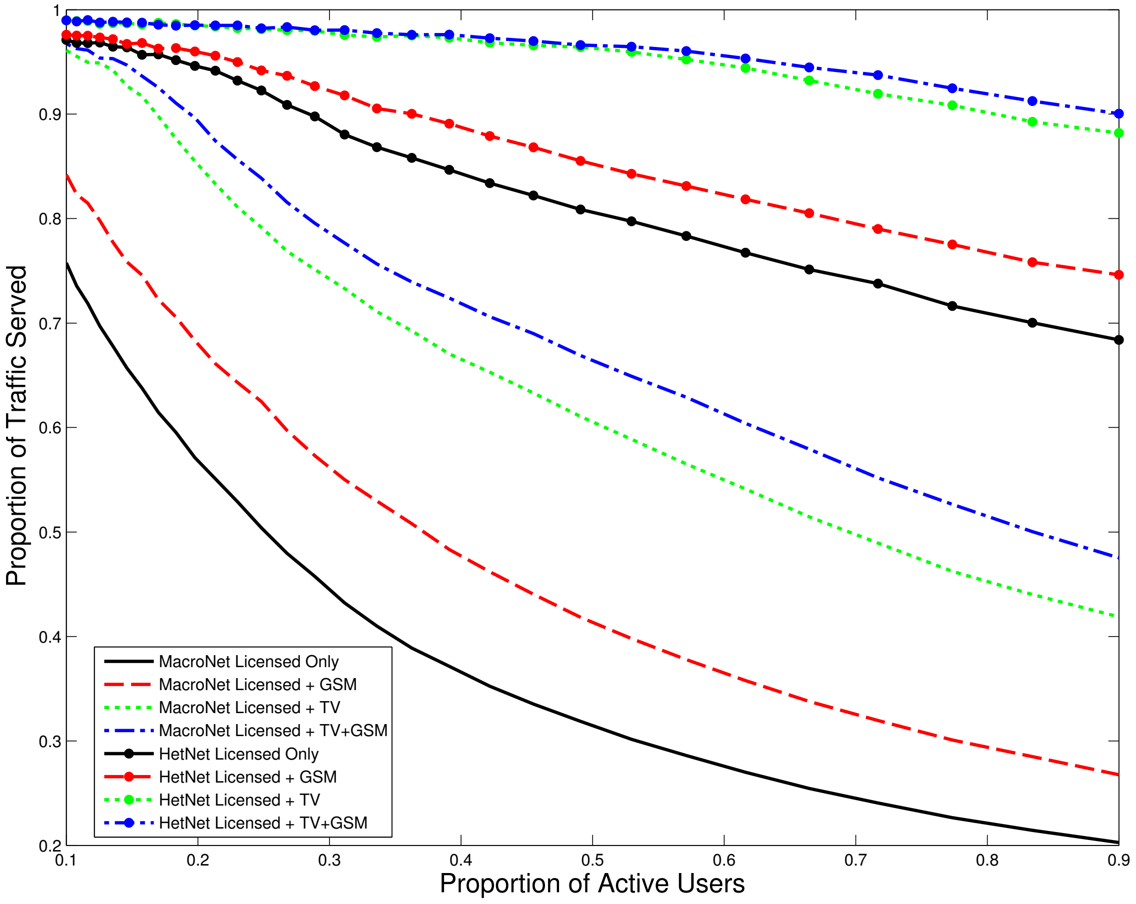

Figure 6.3: HetNets show 41% average increases in performance over MacroNets in the measured ranges. Additionally, using of GSM and TV spectrum also shows increases in performance.

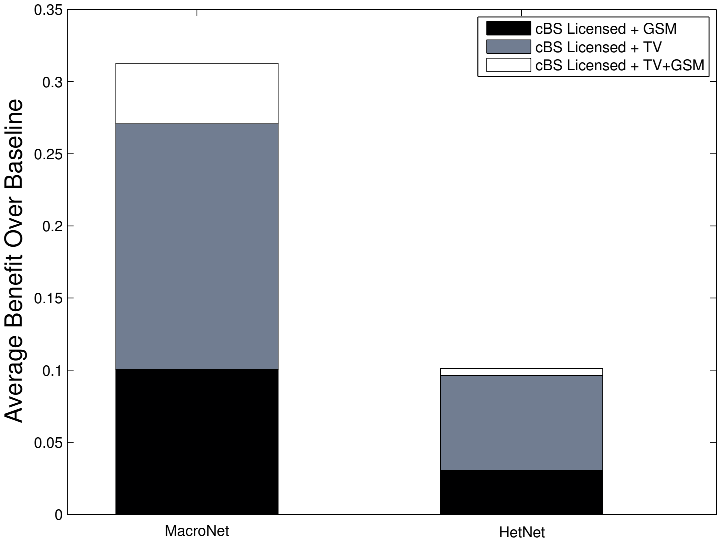

Figure 6.4: MarcoNets benefit from DSA spectrum by a factor of 3, when compared to the benefits of DSA in a HetNet. TV white spectrum provides the largest gain in performance for both Nets: 27% for MacroNet and 10% increase for the HetNet.

among the DSA HetNet management frameworks introduced in Section 5.1.3 (i.e., SAC, CSM, and DSM). These programs are based on an LTE+ HetNet, where the cBSs and cHeNBs aggregate licensed and TV white-space spectrum channels to service the traffic demand. Through spectrum leases, the SAS coordinates the assignment of TV-white space spectrum among the cBSs and cHeNBs. For each service interval, spectrum lease requests are sent to the SAS and periodically processed in batches. Using this scenario, we develop sets of mathematical programs to represent the demand served during the service period for each spectrum management framework. We solve these mathematical programs using CPLEX and present a performance comparison under changing demand.

For each management framework, the mathematical program sets generally comprise the following steps: (1) initial assignment of operators' licensed frequencies, (2) spectrum lease requests for additional spectrum, (3) calculation and assignment of spectrum leases, and (4) local assignment of spectral resources. In each program set, the first formulation represents network operator assigning licensed spectrum channels throughout the network. If there is unserved demand, spectrum lease requests are sent to the SAS for additional spectrum to serve remaining demand for spectrum. How spectrum lease requests are calculated and sent to the SAS differ according to each spectrum management framework. Using the SAC framework, lease requests from each cBS and cHeNB are sent directly to the SAS, which globally calculates assignments for the entire network.

For DSM and CSM, determining the spectrum assignment is performed through spectrum lease requests from local managers, spectrum lease assignment from the SAS to local managers, and assignment of spectrum lease resources by those local managers. In our envisioned spectrum lease request scenario, the cHeNBs first send resource requests to their local manager (i.e., DSMgr, CSMgr), which calculates the minimum number of spectral resources needed for the local demand. After the local managers have determined the needed spectral resources, lease requests are sent to the SAS. After lease requests are received at the SAS, the SAS calculates and assigns the spectrum leases to the local managers. In this step, the SAS maximizes the total number of channel assignments to serve the spectrum lease requests and assigns leases. After receiving their spectrum leases, the local resource managers then maximize the assignment of spectral resources at the cHeNBs. Using the optimal assignment as a basis for performance comparison, we develop these program sets for each spectrum management framework.

6.3.1 Optimal Assignment Formulation

We begin by considering an LTE+ HetNet with W licensed channels, which can be deployed throughout a network with B cBSs and H cHeNBs. To manage inter-cell interference between cBS, channels are aggregated into a cell-edge or cell-center carrier [73], where channels in the cell-edge carriers must be different among neighboring base stations. Denote $d_{i,k}$ as the demand in number of channels at cBS i on carrier k, where $k = 1$ and $k = 2$ indicate a cell-center and a cell-edge carrier, respectively. Additionally, denote and d_h as the demand, in number of channels, at cHeNB h. For convenience, we also define the set $\mathbb{D} = \{\{d_{i,k}\}, \{d_h\}\} \ \forall i, k, h$ as the set of all demands for the network.

Let $x_{i,c,k} = 1$ when cBS i assigns licensed channel c to carrier k. We further denote $u_{h,c} = 1$ to indicate when cHeNB h uses licensed channel c. Through an adjacency matrix $\mathbf{N}$, we define neighbor relationships between cBSs, where $n_{i,j} = 1$ indicates cBS i is a neighbor to cBS j. Similarly, through an adjacency matrix $\mathbf{M}$, we define neighbor relationships between cHeNBs, where $m_{h,g} = 1$ indicates cHeNB h is a neighbor to cHeNB g. We prevent inter-tier interference by assuming orthogonal channel assignment of LTE+ channels between cHeNB and cBS. Through an interference matrix $\mathbf{Q}$, we define inter-tier interference relationships, where $q_{i,h,k} = 1$ indicates cBS i, carrier k interferes with cHeNB h.

cBSs and cHeNB are allowed to use TV white-spaces spectrum. Therefore, we define an interference matrix $\mathbf{P}$, where $p_{i,l} = 1$ if cBS i is not within interfering distance of TV station l. We further denote $y_{i,l,c,k} = 1$ to indicate when cBS i uses TV station l's channel c on carrier k, where there are P TV stations, each with V channels available. For cHeNBs, we provide similar notation. We denote an interference matrix $\mathbf{S}$, where $s_{h,l} = 1$ if cHeNB h is not within interfering distance of TV station l. We further denote $v_{i,l,c} = 1$ to indicate when cHeNB i uses TV station l's channel c.

Here we introduce our the formulation, $\mathcal{O}$, for optimal assignment of licensed and TV white-space spectrum to satisfy the demands of the network given the constraints described above.

Maximize:

$$Z_{opt} = \sum_{i=1}^{B}\sum_{c=1}^{W}\sum_{k=1}^{2} x_{i,c,k} + \sum_{i=1}^{B}\sum_{l=1}^{P}\sum_{c=1}^{V}\sum_{k=1}^{2} y_{i,l,c,k} + \sum_{h=1}^{H}\sum_{c=1}^{W} u_{h,c} + \sum_{h=1}^{H}\sum_{l=1}^{P}\sum_{c=1}^{V} v_{h,l,c} \tag{6.26}$$

Subject to:

$$\sum_{c=1}^{W} x_{i,c,k} + \sum_{l=1}^{P}\sum_{c=1}^{V} y_{i,l,c,k} \leq d_{i,k} \qquad \forall\, i,k \tag{6.27}$$

$$\sum_{c=1}^{W} u_{h,c} + \sum_{l=1}^{P}\sum_{c=1}^{V} v_{h,l,c} \leq d_{h} \qquad \forall\, h \tag{6.28}$$

$$\sum_{k=1}^{2} x_{i,c,k} \leq 1 \qquad \forall\, i,c \tag{6.29}$$

$$\sum_{k=1}^{2} y_{i,l,c,k} \leq 1 \qquad \forall\, i,l,c \tag{6.12}$$

$$y_{i,l,c,k} \leq p_{i,l} \qquad \forall\, i,l,c,k \tag{6.30}$$

$$v_{h,l,c} \leq s_{h,l} \qquad \forall\, h,l,c \tag{6.31}$$

$$n_{i,j}(x_{i,c,2} + x_{j,c,2}) \leq 1 \qquad \forall\, i,j,c \tag{6.32}$$

$$n_{i,j}(y_{i,l,c,2} + y_{j,l,c,2}) \leq 1 \qquad \forall\, i,j,l,c \tag{6.33}$$

$$m_{g,h}(u_{h,c} + u_{g,c}) \leq 1 \qquad \forall\, g,h,c \tag{6.34}$$

$$m_{g,h}(v_{h,l,c} + v_{g,l,c}) \leq 1 \qquad \forall\, g,h,l,c \tag{6.17}$$

$$q_{i,h,k}(x_{i,c,k} + u_{h,c}) \leq 1 \qquad \forall\, i,h,k,c \tag{6.35}$$

$$q_{i,h,k}(y_{i,l,c,k} + v_{h,l,c}) \leq 1 \qquad \forall\, i,h,l,k,c \tag{6.19}$$

$$\sum_{l=1}^{P}\sum_{c=1}^{V}\sum_{k=1}^{2} y_{i,l,c,k} \leq \sum_{l=1}^{P} s_{h,l}V \qquad \forall\, i \tag{6.36}$$

$$\sum_{l=1}^{P}\sum_{c=1}^{V} v_{h,l,c} \leq \sum_{l=1}^{P} s_{h,l}V \qquad \forall\, h \tag{6.37}$$

$$x_{i,c,k}, y_{i,l,c,k}, u_{h,c}, v_{h,l,c} \in \{0,1\} \qquad \forall\, i,l,h,c,k$$

Function (6.26) maximizes the number of channels assigned to each cBS and cHeNB using licensed and TV white-space channels. In Constraints (6.27) and (6.28), channels are only assigned as required to meet demand. Constraint (6.29) and (6.12) enforces that channels should only be used once within the cBS cell (i.e., cell-edge and cell center carriers cannot have the same channel). Constraints (6.30) and (6.31) allow the cBS and cHeNB to use TV white-space channels only when they are available, respectively. To prevent inter-cell interference, Constraints (6.32) and (6.33) prevent neighboring cBS cell-edges from using the same licensed and TV white-space channels, respectively. Equivalent constraints to avoid inter-femto-cell interference are captured in Constraints (6.34) and (6.17). Inter-tier interference is captured in Constraints (6.35) and (6.19) for licensed and TV white-space channels, respectively. The Constraints (6.36) and (6.37) prevent an individual cBS and cHeNB from assigning more TV white space spectrum than available. Through program $\mathcal{O}$, denote $\mathbb{D} \xrightarrow{\mathcal{O}} Z_{opt}$ as optimal solution used for our performance baseline.

6.3.2 Assignment of Licensed Spectrum

Although the optimal solution can be obtained from $\mathcal{O}$, network operators will likely first assign all licensed spectrum to the LTE+ HetNet. To represent this first step, we provide formulation $\mathcal{L}$ through removing the TV white-space assignment variables from $\mathcal{O}$.

Maximize:

$$Z^{LIC} = \sum_{i=1}^{B} \sum_{c=1}^{W} \sum_{k=1}^{2} x_{i,c,k} + \sum_{h=1}^{H} \sum_{c=1}^{W} u_{h,c} \tag{6.38}$$

Subject to:

$$\sum_{c=1}^{W} x_{i,c,k} \le d_{i,k} \qquad \forall\ i, c, k \tag{6.39}$$

$$\sum_{c=1}^{W} u_{h,c} \le d_h \qquad \forall\ h \tag{6.40}$$

$$\sum_{k=1}^{2} x_{i,c,k} \le 1 \qquad \forall\ i, c \tag{6.29}$$

$$n_{i,j}(x_{i,c,2} + x_{j,c,2}) \le 1 \qquad \forall\ i, j, c \tag{6.32}$$

$$m_{g,h}(u_{h,c} + u_{g,c}) \le 1 \qquad \forall\ g, h, c \tag{6.34}$$

$$q_{i,h,k}(x_{i,c,k} + u_{h,c}) \le 1 \qquad \forall\ i, h, k, c \tag{6.35}$$

$$x_{i,c,k}, u_{h,c} \in \{0, 1\} \qquad \forall\ i, l, h, c, k$$

Thus, the Objective (6.38) maximizes the assignment of licensed channels. In Constraints (6.39) and (6.40), channels are only assigned as required to meet demand of the cBS and cHeNB using licensed channels, respectively.

6.3.3 SAC Program Set

When considering the SAC framework, after the network operators assign licensed spectrum, modeled through formulation $\mathcal{L}$, requests from each cBS and cHeNB are sent to the directly SAS. Denote $d^*_{i,k}$ and d^*_h as the remaining demand unserved by the licensed assignment from formulation $\mathcal{L}$, and denote $\mathbb{D}^* = \{\{d^*_{i,k}\}, \{d^*_h\}\}\ \forall i, k, h$. From the received lease requests, the SAS calculates lease assignments, which we model through formulation $\mathcal{S}$.

Maximize:

$$Z^{SAC} = \sum_{i=1}^{B}\sum_{l=1}^{P}\sum_{c=1}^{V}\sum_{k=1}^{2} y_{i,l,c,k} + \sum_{h=1}^{H}\sum_{l=1}^{P}\sum_{c=1}^{V} v_{h,l,c} + Z^{LIC} \tag{6.41}$$

Subject to:

$$\sum_{l=1}^{P}\sum_{c=1}^{V} y_{i,l,c,k} \leq d^*_{i,k} \qquad \forall\ i, k \tag{6.42}$$

$$\sum_{l=1}^{P}\sum_{c=1}^{V} v_{h,l,c} \leq d^*_{h} \qquad \forall\ h \tag{6.43}$$

$$\sum_{k=1}^{2} y_{i,l,c,k} \leq 1 \qquad \forall\ i, l, c \tag{6.12}$$

$$y_{i,l,c,k} \leq p_{i,l} \qquad \forall\ i, l, c, k \tag{6.30}$$

$$v_{h,l,c} \leq s_{h,l} \qquad \forall\ h, l, c \tag{6.31}$$

$$n_{i,j}(y_{i,l,c,2} + y_{j,l,c,2}) \leq 1 \qquad \forall\ i, j, l, c \tag{6.33}$$

$$m_{g,h}(v_{h,l,c} + v_{g,l,c}) \leq 1 \qquad \forall\ g, h, l, c \tag{6.17}$$

$$q_{i,h,k}(y_{i,l,c,k} + v_{h,l,c}) \leq 1 \qquad \forall\ i, h, l, k, c \tag{6.19}$$

$$\sum_{l=1}^{P}\sum_{c=1}^{V}\sum_{k=1}^{2} y_{i,l,c,k} \leq \sum_{l=1}^{P} s_{h,l}V \qquad \forall\ i \tag{6.36}$$

$$\sum_{l=1}^{P}\sum_{c=1}^{V} v_{h,l,c} \leq \sum_{l=1}^{P} s_{h,l}V \qquad \forall\ h \tag{6.37}$$

$$y_{i,l,c,k}, v_{h,l,c} \in \{0, 1\} \qquad \forall\ i, l, h, c, k$$

In formulation $\mathcal{S}$, the assignment of additional TV white-spaces is maximized through Function 6.41. Constraints (6.42) and (6.43) prevent assignments from exceeding the remaining demand. Denote $\mathbb{D} \xrightarrow{\mathcal{L}} \mathbb{D}^* \xrightarrow{\mathcal{S}} Z^{SAC}$ as the demand served by the SAC spectrum management framework.

6.3.4 CSM Program Set

For the CSM framework, after the licensed assignment from $\mathcal{L}$, three additional steps are required for the final assignment. In the first step, each CSMgr calculates spectrum lease requests based on the needs of the cell and any femto-cell domains that lie within the coverage area of the cell. These requests are sent to the SAS, which, in the second step, calculates the assignment for each cell. In the third step, the spectrum resources allocated through each lease are locally assigned to serve the traffic of the cell. These three steps are each modeled through separate formulations.

In the first step, each local CSMgr i calculates the minimum number of channels required to meet its local demand. Specifically, the carriers of cBS i $k = \{1, 2\}$ and the set of cHeNB $\mathbb{H}_i = \{1..H_i\}$ in the domain of cBS i. Denote $\gamma_{i,c,k} = 1$ to indicate that cBS i channel c is assigned to carrier k of the cell. Further denote $\upsilon_{h,c} = 1$ to indicate that channel c is assigned to cHeNB h. Thus, we present formulation $\mathcal{C}_1$, to model the first step in the CSM assignment program set, where $\mathcal{C}_1$ is performed for each cBS i.

Minimize:

$$\hat{C}_i \tag{6.44}$$

Subject to:

$$\sum_{c}^{\hat{C}_i} \gamma_{i,c,k} = d^*_{i,k} \qquad \forall\ k \tag{6.45}$$

$$\sum_{c}^{\hat{C}_i} \upsilon_{h,c} = d^*_{h} \qquad \forall\ h \in \mathbb{H}_i \tag{6.46}$$

$$\sum_{k=1}^{2} \gamma_{i,c,k} \leq 1 \qquad \forall\ c \in \hat{C}_i \tag{6.47}$$

$$m_{g,h}(\upsilon_{h,c} + \upsilon_{g,c}) \leq 1 \qquad \forall\ g \in \mathbb{H}_i, h \in \mathbb{H}_i, c \tag{6.48}$$

$$q_{i,h,k}(\gamma_{i,c,k} + \upsilon_{h,c}) \leq 1 \qquad \forall\ h \in \mathbb{H}_i, k, c \tag{6.49}$$

$$\gamma_{i,c,k}, \upsilon_{h,c} \in \{0, 1\} \qquad \forall\ h \in \mathbb{H}_i, c, k$$

The Function (6.44) represents the minimum number of channels required to serve the remaining demand of CSMgr i, not met with formulation $\mathcal{L}$. Constraints (6.45) and (6.46) require that the number of channels for each cBS cell-carrier and cHeNB meet the unserved demand, respectively. Unique channel assignment between cell-edge and cell-center carriers is modeled through Constraint (6.47). Constraints (6.48) and (6.49) prevent the inter-femto-cell and inter-tier interference for the local cell, respectively.

The demand calculation, in this first step, uses only local constraints that consider inter-tier and inter-femto-cell interference. Consequently, the second formulation in the CSM program set must enforce network level constraints such as inter-cell interference. Therefore, spectrum lease requests received from the cBS should indicate if the spectrum must be coordinated between macro-cell neighbors to prevent inter-cell interference (i.e., neighboring cell-edge channels) or not (i.e., cell-center) and possibly neighboring cHeNB of associated with different CSMgrs. Thus, in the second step, the SAS receives the spectrum lease requests and must assign the spectrum accordingly. To this end, we denote demand set $\hat{\mathbb{D}}$ by:

$$\hat{d}_{i,1} = \sum_{c}^{\hat{C}_i} \gamma_{i,c,1} + \sum_{c}^{\hat{C}_i} g_1(c, \boldsymbol{\upsilon}). \tag{6.50}$$

and

$$\hat{d}_{i,2} = \sum_{c}^{\hat{C}_i} \gamma_{i,c,2} + \sum_{c}^{\hat{C}_i} g_2(c, \boldsymbol{\upsilon}) \tag{6.51}$$

as the demand for non-coordinated and coordinated channels requested from CSMgr i, respectively, where the $g_k(c, \boldsymbol{\upsilon}) = 1$ if channel c is used at least once (as indicated from $\boldsymbol{\upsilon}$) by a femtocell in carrier k. Using $\hat{\mathbb{D}}$, the SAS should maximize the assignment of available spectrum while satisfying inter-cell and TV broadcast interference constraints. Thus, we present formulation C_2, to model the second step in the CSM assignment program set, where C_2 is performed at the SAS to determine spectrum lease assignments.

Maximize:

$$\sum_{i=1}^{B} \sum_{l=1}^{P} \sum_{c=1}^{V} \sum_{k=1}^{2} y_{i,l,c,k} \tag{6.52}$$

Subject to:

$$\sum_{l=1}^{P} \sum_{c=1}^{V} y_{i,l,c,k} \le \hat{d}_{i,k} \qquad \forall\ i, k \tag{6.53}$$

$$\sum_{k=1}^{2} y_{i,l,c,k} \le 1 \qquad \forall\ i, l, c \tag{6.12}$$

$$y_{i,l,c,k} \le p_{i,l} \qquad \forall\ i, l, c, k \tag{6.30}$$

$$n_{i,j}(y_{i,l,c,2} + y_{j,l,c,2}) \le 1 \qquad \forall\ i, j, l, c \tag{6.33}$$

$$\sum_{l=1}^{P} \sum_{c=1}^{V} \sum_{k=1}^{2} y_{i,l,c,k} \le \sum_{l=1}^{P} s_{h,l} V \qquad \forall\ i \tag{6.36}$$

$$y_{i,l,c,k} \in \{0, 1\} \qquad \forall\ i, l, h, c, k$$

In Function (6.52), we seek to maximize the possible assignments of TV white-space spectrum among the CSMgrs. These assignments are not to exceed to the request demand as indicated in Constraint (6.53).

After the SAS returns the spectrum leases to each cBS i, the spectrum assignment is used to maximize the service of traffic of its carriers and of cHeNB within the service area of cBS i. Denote

$\bar{\gamma}_{i,c,k} = 1$ to indicate that at cBS i channel c is assigned to carrier k of the cell using the spectrum lease. Further denote $\bar{\upsilon}_{h,c} = 1$ to indicate that channel c is assigned to cHeNB h from the spectrum lease. From the perspective of each cBS in the final step, the total channels assigned for each coordinated and non-coordinated spectrum assignment are considered for the final assignment. To this end, we denote assignment matrix $\bar{\mathbb{D}}$, where

$$\bar{d}_{i,2} = \sum_{l=1}^{P} \sum_{c=1}^{V} y_{i,l,c,2} \tag{6.54}$$

is the assignment of coordinated channels for cBS i and where

$$\bar{d}_{i,1} = \sum_{l=1}^{P} \sum_{c=1}^{V} y_{i,l,c,1} \tag{6.55}$$

is the assignment for non-coordinated cBS i. Furthermore, let

$$\bar{C}_i = \bar{d}_{i,2} + \bar{d}_{i,1} \tag{6.56}$$

to represent the total number of channels available to the cBS i. Thus, we present formulation C_3, to model the final step in the CSM assignment program set, where C_3 is performed for each cBS i.

Maximize:

$$\psi_i^{CSM} = \sum_{c}^{C_i} \bar{\gamma}_{i,c,1} + \sum_{h=1}^{H_i} \sum_{c}^{C_i} \bar{\upsilon}_{h,c} \tag{6.57}$$

Subject to:

$$\sum_{c=1}^{C_i} \bar{\gamma}_{i,c,1} \leq \bar{d}_{i,1} \tag{6.58}$$

$$\sum_{c=1}^{C_i} \bar{\gamma}_{i,c,2} \leq \bar{d}_{i,2} \tag{6.59}$$

$$\sum_{c=1}^{C_i} \bar{\gamma}_{i,c,k} \leq d^*_{i,k} \qquad \forall\ k \tag{6.60}$$

$$\sum_{k=1}^{2} \bar{\gamma}_{i,c,k} \leq 1 \qquad \forall\ c \tag{6.61}$$

$$\sum_{c=1}^{C_i} \bar{\upsilon}_{h,c} q_{i,h,1} \leq \bar{d}_{i,1} \qquad \forall\ h \tag{6.62}$$

$$\sum_{c=1}^{C_i} \bar{\upsilon}_{h,c} q_{i,h,2} \leq \bar{d}_{i,2} \qquad \forall\ h \tag{6.63}$$

$$\sum_{c=1}^{C_i} \bar{\upsilon}_{h,c} \leq d_h^* \qquad \forall\ h \tag{6.64}$$

$$\bar{\upsilon}_{h,c} q_{i,h,1} + \bar{\upsilon}_{g,c} q_{i,g,2} \leq 1 \qquad \forall\ c, g, h \tag{6.65}$$

$$m_{g,h}(\bar{\upsilon}_{h,c} + \bar{\upsilon}_{g,c}) \leq 1 \qquad \forall\ g, h, c \tag{6.66}$$

$$q_{i,h,k}(\bar{\gamma}_{i,c,k} + \bar{\upsilon}_{h,c}) \leq 1 \qquad \forall\ h, k, c \tag{6.67}$$

$$\bar{\gamma}_{i,c,k}, \bar{\upsilon}_{h,c} \in \{0, 1\} \qquad \forall\ h, c, k$$

In C_3, Function (6.57) maximizes the total assignment of channels to meet the required demand for cBS i. Constraints (6.58) and (6.59) limit the number channels assigned to the to the total number of assigned uncoordinated and coordinated channels, respectively. Unique channel assignment between cell-edge and cell-center carriers is modeled through Constraint (6.61). Additionally, uncoordinated and coordinated assignment limits also apply to the cHeNB through Constraints (6.62) and (6.63), respectively. Furthermore, Constraint (6.64) prevents assignment of channels for each cHeNB from exceeding its respective demand. Like cell-center and cell-edge cBS carriers, cHeNB which lie in the within the cell-edge or cell-center carriers must not share channels through Constraint (6.65). Constraints (6.66) and (6.67) prevent the inter-femto-cell and inter-tier interference for the local cell respectively.

To complete our program set, we introduce a final summing function to tally the number of channels served TV white-spaces and licensed spectrum channels by the following equation:

$$f_{sc}(\mathbf{\Psi}^{CSM}) = \sum_{i=1}^{B} \psi_i^{CSM} + Z^{LIC}. \tag{6.68}$$

Thus, obtaining the total number of traffic channels served through the program set for CSM is denoted by: $\mathbb{D} \xrightarrow{\mathcal{L}} \mathbb{D}^* \xrightarrow{C_1 \forall i} \hat{\mathbb{D}} \xrightarrow{C_2} \{\bar{\mathbb{D}}, \mathbb{D}^*\} \xrightarrow{C_3 \forall i} \mathbf{\Psi}^{\mathbf{CSM}} \xrightarrow{f_{sc}} Z^{CSM}$.

6.3.5 DSM Program Set

For the DSM framework, after the licensed assignment from $\mathcal{L}$, three additional steps are required for the final assignment. In the first step, each cBS and DSMgr calculate spectrum lease requests based on the needs of the cell and femto-cell domains, respectively. These requests are sent to the SAS, which in the second step, calculates the spectrum leases for each cell and femto-cell domain. In the third step, the spectrum resources allocated through leases and are locally assigned to serve the traffic of the cell and femto-cell domains. These three steps are each modeled through separate formulations.

In the first step, each local cBS i and DSMgr calculate the minimum number of channels required for the spectrum lease request. In the DSM, each cBS sends a spectrum lease request for $\hat{d}_{i,k} = d_{i,k}^*$, the remaining demand on the cell-carrier after the licensed assignment. For the femto-cell domains, we consider G DSMgrs, where each DSMgr g manages a set of H_g cHeNBs. The DSMgr calculates the minimum number of required channels for the spectrum lease request based on the needs of each femto-cell. This calculation is performed using $\mathcal{D}_1$ for each DSMgr g.

Minimize:

$$\hat{C}_i \tag{6.69}$$

Subject to:

$$\sum_{c}^{\hat{C}_i} \upsilon_{h,c} = d_h^* \qquad \forall\ h \tag{6.46}$$

$$m_{g,h}(\upsilon_{h,c} + \upsilon_{g,c}) \leq 1 \qquad \forall\ g, h, c \tag{6.48}$$

$$\upsilon_{h,c} \in \{0, 1\} \qquad \forall\ h, c$$

In the second step, each cBS and DSMgr sends spectrum lease requests for their associated demand to the SAS. Denote $\hat{\mathbf{D}}_D = \{\{\hat{d}_{i,k}\}, \{\hat{d}_g\}\}\ \forall i, k, g$ to represent the set of lease requests received by the SAS for the cBS cell-carriers and DSMgr. Let $z_{g,l,c} = 1$ to indicate that DSMgr g uses channel c of TV station l, and let $r_{g,l} = 1$ to indicate that femto-cell domain managed by DSMgr g is not within interfering distance of TV station l . Each DSMgr should also report conflicts with existing cBS cell-carriers. Therefore, denote interference matrix $\mathbf{T}$, where $t_{i,k,g} = 1$ indicates when cBS i, carrier k, interferes with DSMgr domain g.

Maximize:

$$\sum_{i=1}^{B} \sum_{l=1}^{P} \sum_{c=1}^{V} \sum_{k=1}^{2} y_{i,l,c,k} + \sum_{i=1}^{B} \sum_{l=1}^{P} \sum_{c=1}^{V} z_{g,l,c} \tag{6.70}$$

Subject to:

$$\sum_{l=1}^{P} \sum_{c=1}^{V} y_{i,l,c,k} \leq d_{i,k}^* \qquad \forall\ i, k \tag{6.71}$$

$$\sum_{l=1}^{P} \sum_{c=1}^{V} z_{g,l,c} \leq \hat{d}_g \qquad \forall\ g \tag{6.72}$$

$$\sum_{k=1}^{2} y_{i,l,c,k} \leq 1 \qquad \forall\ i, l, c \tag{6.12}$$

$$y_{i,l,c,k} \leq p_{i,l} \qquad \forall\ i, l, c, k \tag{6.30}$$

$$z_{g,l,c} \leq r_{g,l} \qquad \forall\ g, l, c \tag{6.73}$$

$$n_{i,j}(y_{i,l,c,2} + y_{j,l,c,2}) \leq 1 \qquad \forall\ i, j, l, c \tag{6.33}$$

$$t_{i,k,g}(y_{i,l,c,k} + z_{g,l,c}) \leq 1 \qquad \forall\ i, l, c, k, g \tag{6.74}$$

$$\sum_{l=1}^{P} \sum_{c=1}^{V} \sum_{k=1}^{2} y_{i,l,c,k} \leq \sum_{l=1}^{P} s_{h,l} V \qquad \forall\ i \tag{6.36}$$

$$\sum_{l=1}^{P}\sum_{c=1}^{V} z_{g,l,c} \leq \sum_{l=1}^{P} s_{h,l}V \qquad \forall\ g \tag{6.75}$$

$$y_{i,l,c,k} \in \{0,1\} \qquad \forall\ i,l,h,c,k$$

The Function (6.70) maximizes the assignment of the channels to the base stations and also the domains managed by the DSMgr. Constraints (6.71) and (6.72) prevent the assignment of channels to exceed the number of channels required in the spectrum lease request from the cBS and the DSMgr, respectively. Femto-cell domains are prevented from interfering with TV stations through Constraint (6.73), and spectrum channel caps for domains are captured in Constraint (6.75).

When the SAS returns leases to each cBS i and DSMgr g the spectrum lease is then used to serve the demand. For each cBS, the lease is directly assigned to each cell-carrier. To capture this lease end, we denote lease assignments for each cBS as

$$\bar{d}_{i,k} = \sum_{l=1}^{P}\sum_{c=1}^{V} y_{i,l,c,k}, \tag{6.76}$$

and the assignments to for each DSMgr g as

$$\bar{d}_{g} = \sum_{l=1}^{P}\sum_{c=1}^{V} z_{g,l,c}. \tag{6.77}$$

For convenience we denote $\bar{\mathbb{D}}_D = \{\{\bar{d}_{i,k}\},\{\bar{d}_g\}\}\ \forall i,k,g$, as the set of spectrum leases assigned by the SAS. For each DSMgr g the channels from the spectrum lease are then used to maximize the local traffic with $\mathcal{D}_3$.

Maximize:

$$\psi_g^{DSM} = \sum_{h=1}^{H_g}\sum_{c=1}^{\bar{d}_g} \bar{\upsilon}_{h,c} \tag{6.78}$$

Subject to:

$$\sum_{c=1}^{d_g} \bar{\upsilon}_{h,c} \leq d_h^* \qquad \forall\ h \tag{6.79}$$

$$m_{g,h}(\bar{\upsilon}_{h,c} + \bar{\upsilon}_{g,c}) \leq 1 \qquad \forall\ g,h,c \tag{6.80}$$

$$\upsilon_{h,c} \in \{0,1\} \qquad \forall\ h,c$$

Similar to the CSM framework, the final objective function (6.78) maximizes the number of channel assignments for each domain. Constraint (6.79) limits the number of assigned channels from exceeding the required demand, and Constraint (6.80) prevents inter-femto interference. To complete the DSM program set, we introduce the DSM final summing function to tally the number of

SAC	$\mathbb{D} \xrightarrow{\mathcal{L}} \mathbb{D}^* \xrightarrow{\mathcal{S}} Z^{SAC}$
CSM	$\mathbb{D} \xrightarrow{\mathcal{L}} \mathbb{D}^* \xrightarrow{C_1 \forall i} \hat{\mathbb{D}} \xrightarrow{C_2} \{\bar{\mathbb{D}}, \mathbb{D}^*\} \xrightarrow{C_3 \forall i} \mathbf{\Psi}^{\mathbf{CSM}} \xrightarrow{f_{sc}} Z^{CSM}$
DSM	$\mathbb{D} \xrightarrow{\mathcal{L}} \mathbb{D}^* \xrightarrow{\mathcal{D}_1 \forall g} \hat{\mathbb{D}}_D \xrightarrow{\mathcal{D}_2} \{\bar{\mathbb{D}}_D, \mathbb{D}^*\} \xrightarrow{\mathcal{D}_3 \forall g} \mathbf{\Psi}^{\mathbf{DSM}} \xrightarrow{f_{sd}} Z^{DSM}.$

Table 6.3: A comparison of the program sets that model each spectrum management framework.

channels served from TV white-spaces and licensed spectrum channels by the following equation:

$$f_{sd}(\mathbf{\Psi}^{DSM}) = \sum_{i=g}^{G} \psi_g^{DSM} + \sum_{i=1}^{B} \sum_{k=1}^{2} \bar{d}_{i,k} + Z^{LIC}. \tag{6.81}$$

Thus, obtaining the total number of traffic channels served through the program set for DSM is denoted by: $\mathbb{D} \xrightarrow{\mathcal{L}} \mathbb{D}^* \xrightarrow{\mathcal{D}_1 \forall g} \hat{\mathbb{D}}_D \xrightarrow{\mathcal{D}_2} \{\bar{\mathbb{D}}_D, \mathbb{D}^*\} \xrightarrow{\mathcal{D}_3 \forall g} \mathbf{\Psi}^{\mathbf{DSM}} \xrightarrow{f_{sd}} Z^{DSM}$.

6.3.6 Program Set Summary

In this section, we have developed three program sets, one for each spectrum management framework: SAC-only, CSM, and DSM. The SAC set compromised two different programs, the first for assigning licensed channels and the second to assign the TV white space channels. In SAC-only, global knowledge is used for the assignment since SACs all send spectrum lease requests to the SAS. In CSM and DSM spectrum lease requests are sent for the network elements that are managed by the domain managers: CSMgr and DSMgr. In these program sets, the spectrum lease requests only consider information relative to the domain manager and constraints are considered with a much coarser granularity than with SAC. Table 6.3 compares the program set of each framework.

6.4 Simulations Scenarios and Results

In this section we present a performance comparison of our proposed management frameworks. We use the same simulation model as in Section 6.2. This includes the same topology, demand, and spectrum resources. Using this topology and programs sets show in Table 6.3, we compare the performance of each management framework.

6.4.1 Domain Formation

In real femto-cell deployments, domain formations may be dependent on available wireline infrastructure. Additionally, domain managers may have other limitations on the number of supported cHeNBs. In this study, accounting for these considerations may be impractical, since wireline infrastructure could be different for each edifice and different equipment vendors may support varying capabilities and configurations. Therefore, we approximate domain formulations by grouping edifices together by their relative proximity. We do this by first forming a directed graph using the relative distance between edifice centroids and form domains through identifying strongly connected components of the graph.

The directed graph is formed by first calculating the matrix **C** by

$$c_{i,j} = \frac{1}{b_{i,j}^{\alpha}}, \tag{6.82}$$

where $b_{i,j}$ is the distance between edifice centroids i and j, and where α is a parameter called the proximity index. The adjacency matrix, **A** of the directed graph is then determined by

$$a_{i,j} = \begin{cases} 1 & \text{if } c_{i,j} \geq \frac{\sum_{i}^{E} c_{i,j}}{E} \\ 0 & \text{if } c_{i,j} < \frac{\sum_{i}^{E} c_{i,j}}{E} \end{cases}, \tag{6.83}$$

where E is the total number of edifices. Using **A** with Tarjan's algorithm [88], strongly connected components of the graph, each of which comprises a set of edifices, are identified. Thus, each component of the graph is considered a unique domain. The results of this method are shown in Figure 6.5 using $\alpha = 7$.

6.4.2 Results

Using the same assumptions and tools as Section 6.2, we simulated each of the spectrum management frameworks. The results are captured in Figure 6.6. Our results show the performance of the integer programs are relatively equivalent. We attribute this close performance to the urban-rural nature of the topology. In our topology, not all macro-cells have femto-cells within the coverage area. Additionally, the availability of TV white spaces is almost constant across the coverage area, causing little difference in performance. We speculate that there would be more differences in performance in urban environments, since the likely hood of femto-cell deployments would be more widely distributed, and have more interference constraints with neighboring macro-cells. Additionally, we also suspect that heterogeneous opportunistic spectrum would produced differing results.

6.5 Summary

In this chapter, we formulate integer programs to assess the benefits of using DSA in an LTE+ HetNet and compare our spectrum management frameworks (i.e., SAC, CSM, or DSM). We use

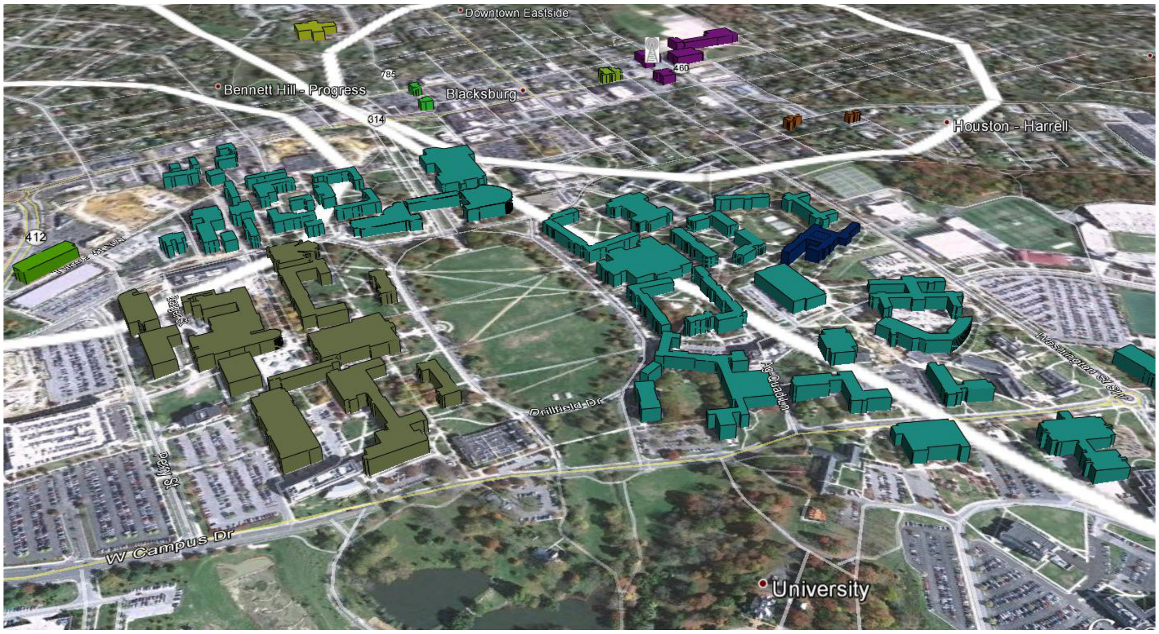

Figure 6.5: Rendered view of edifices identified by domain, shown through color with $\alpha = 7$.

a GIS data to form realistic topologies using Blacksburg,VA . These topologies are used as input to our integer programs to create results based on realistic assumptions. In summary, this chapter quantified the benefits of an SA framework through an optimization model using integer programs. In our future work, we plan to extend this work to an urban area to verify consistency with our existing results. Through this work, future LTE+ standards, infrastructure vendors, and network operators can gain a better understanding of the benefits of using DSA in HetNets.

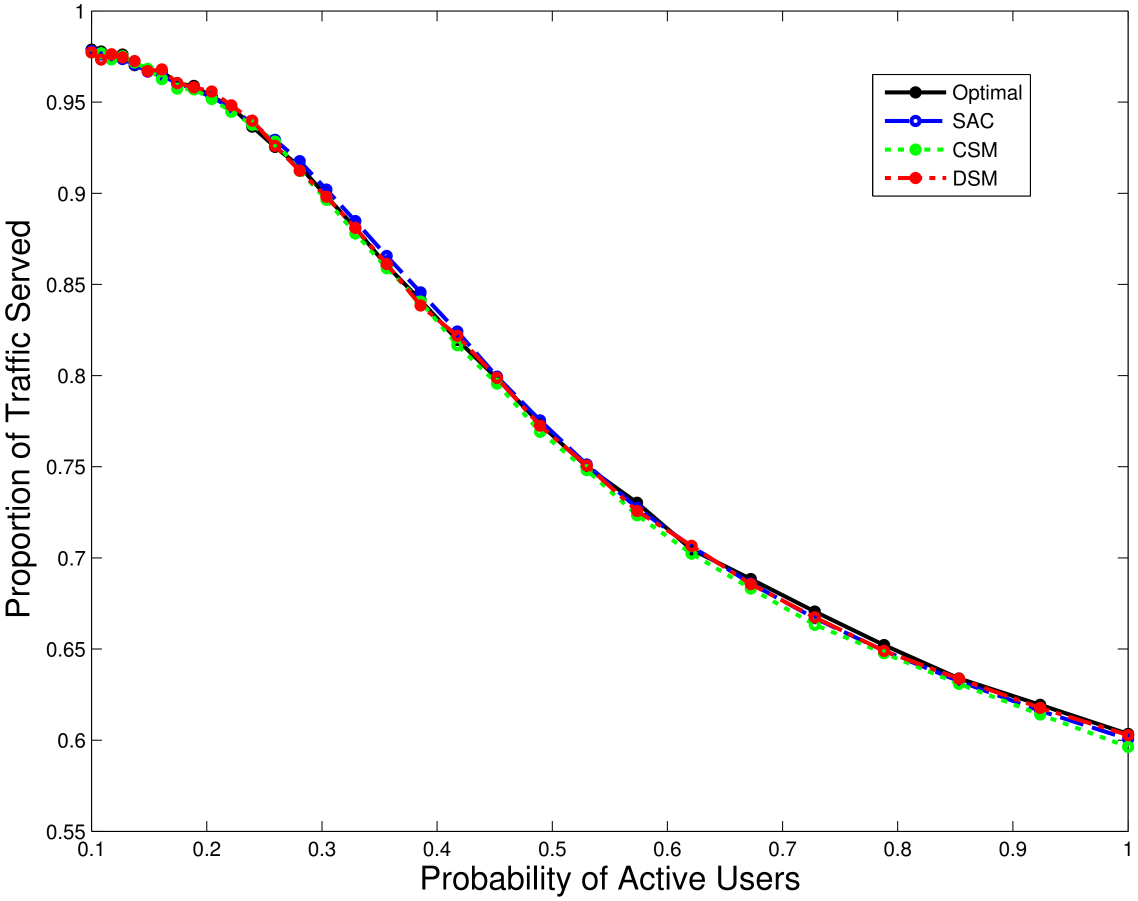

Figure 6.6: All frameworks show performance close to that of the optimal.

Chapter 7

Decision Analysis of Spectrum Access Rules

Previous chapters examined the functional and architectual aspects of implementing DSA in LTE+ networks. In this chapter, we examine the spectrum policy aspect, examining current trends in DSA regulation through decision theory. This chapter develops a utility model and decision framework for regulators to measure the utility of a particular spectrum access rule or policy. We propose and evaluate nine spectrum access rules based on spectrum sensing and geolocation databases.

7.1 Introduction

Recent trends in regulatory paradigms have been shifting from the traditional command and control model of spectrum management to one of shared use through Dynamic Spectrum Access (DSA) [27–29]. Both the FCC and OFCOM have released initial regulation for unlicensed used of TV white space devices, and the FCC, in a recent NOI, is requesting information on the viability of DSA techniques [29]. In this effort, the FCC seeks to understand how spectrum access rules based on spectrum sensing and geolocation databases can be useful in providing secondary operators with opportunistic access while protecting primary users from harmful interference.

This chapter applies decision theory to analyze the impact of different shared use spectrum access rules. This decision analysis provides regulators with a methodology to evaluate spectrum access rules based on the resulting utility to the various constituencies that are vying for spectrum. Our first contribution in this study is a multi-attribute utility model for evaluating spectrum access rules. This multi-attribute utility model is based on the fundamental objectives of primary and secondary operators deploying DSA. Through the AHP [30], we weight the relative importance between objectives, using input from experts in network performance. In our second contribution, we propose and evaluate nine spectrum access rules based on spectrum sensing and geolocation databases. Here, we simulate a scenario in which a primary operator shares spectrum with a secondary operator. The results of the simulation are then evaluated through our multi-attribute utility model and we calculate the utility of each rule.

This chapter is organized as follows. Section 7.2 defines the anatomy of a spectrum access rule $\mathcal{R}$. Section 7.3, describes the decision analytic framework. In this section, we propose an objective hierarchy, develop the multi-attribute utility model, and identify nine spectrum access rules that we set out to evaluate in the ensuing analysis. Section 7.4 presents our system model, simulation scenario and the specific implementation of our utility model. In Section 7.5, we present the resulting utilities from our simulation using the multi-attribute utility model. We conclude this chapter, in Section 7.6, with the summary of our results and a discussion of future work.

7.2 Spectrum Access Rules

Recent regulations, in [27] and [28], for DSA describe the set of underlying behaviors (sub-rules) that DSA radios use to opportunistically access primary spectrum. These regulations can be categorized into three sub-rules: exclusion ($\mathcal{E}$), channel assignment ($\mathcal{A}$), and power and transmission control ($\mathcal{P}$). Thus, when a DSA radio accesses the spectral medium it uses the spectrum access rule defined by the triplet $\mathcal{R} = \{\mathcal{E}, \mathcal{A}, \mathcal{P}\}$.

The exclusion sub-rule $\mathcal{E}$ dictates which channels are available. This sub-rule has the objective of preventing harmful interference to primary users. Exclusion sub-rules determine that channels currently occupied by primary users must be avoided by secondary users. They also determine how this interference avoidance is to be accomplished, e.g., through spectrum sensing, or geolocation databases. A thorough survey on spectrum sensing is presented in [26]. Additional rules for exclusion also considered by regulators support the adoption of cooperative sensing for determining channel availability [28, 29]. A survey of cooperative sensing techniques and their tradeoffs have been captured in [39].

The channel assignment sub-rule $\mathcal{A}$ determines which channels can be used for opportunistic communications, a subset of the channels not excluded by $\mathcal{E}$. Regulation in [27] and [28] does not specify channel selection algorithms; however, it suggests that device manufactures could use sensing information to select the best channel. If multiple secondary operators or devices seek to simultaneously use common spectra, efficient channel assignment will be important for maximizing channel reuse. A comparison of different channel assignment techniques for DSA has been examined in [47].

The power and transmission control sub-rule $\mathcal{P}$ dictates the maximum allowable power limits, transmit mask and techniques for minimizing power and interference. Power control is necessary in DSA applications to minimize interference among co-channel and adjacent channel users. These rules include maximum transmit power and Out of Band Emission (OOBE) requirements such as adjacent channel attenuation or Block Edge Mask (BEM) specifications. Power and transmission sub-rules can also work in tandem with exclusion sub-rules. For instance, the transmit power limits set by a BEM may take into account what systems currently operate in adjacent bands. Additionally, the maximum power limits of the secondary transmitters can also be reduced depending on the proximity to exclusion areas. Power control etiquette schemes have been proposed in [89, 90].

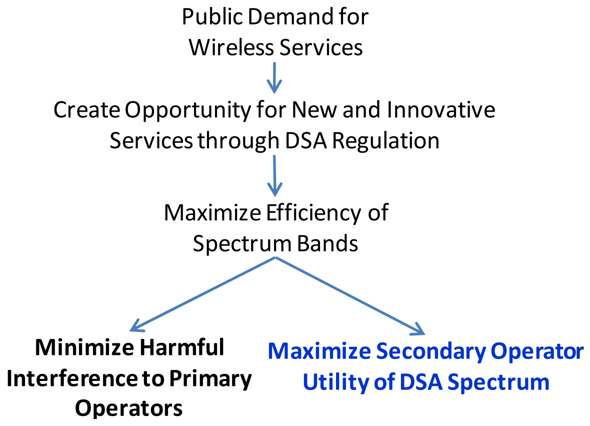

Figure 7.1: Pictorial representation of the objective hierarchy.

7.3 Decision Analysis

In this section, we apply techniques from decision theory to explore regulators' objectives in setting spectrum access rules. In any decision process, there are objectives that the decision maker wishes to accomplish when selecting among alternatives. These objectives can be expressed as utility functions, which are used to evaluate the alternatives and make the final decision. In our formulation, distinct spectrum access rules are represented as alternatives available to the regulator, the decision maker, who must select the set of rules that maximizes a defined measure of social welfare.

7.3.1 Objective Hierarchy

The first and most fundamental objective of regulators is to enable telecommunications that are in the best interest of the public [27, 28]. In the context we consider here, this goal implies that regulators seek to create spectrum access rules as a means to support new and improved wireless services. Through spectrum access rules, regulators seek to maximize the spectrum efficiency of underutilized bands by accomplishing two sub-objectives: (1) minimizing harmful interference to primary operators' service; and (2) maximizing the utility of DSA spectrum for secondary operators. Managing the tradeoffs between these two sub-objectives is the main challenge regulators face in evaluating spectrum access rules. Ideally, spectrum access rules would allow for maximum secondary usage without creating any harmful interference to primary users. Figure 7.1 illustrates this objective hierarchy. We equate maximizing secondary operator utility with maximizing service revenue. This perspective is intuitive because customers demonstrate utility by paying for services. If secondary operators cannot provide suitable services with DSA spectrum, customers will not use these services. Maximizing revenue is captured in two sub-objectives: (1) maximizing service volume; and (2) minimizing customer churn. Maximizing service volume equates to supporting the highest volume of calls or data as possible. Customer churn is defined as the percentage of the customer base that leaves the service provider annually, usually as a result of service issues such as dropped or blocked calls [91–93]. When several secondary competitive operators share the DSA spectrum simultaneously, competition for resources could result in dropping existing service requests or blocking future attempts. Therefore, we express customer churn as a function of dropped or blocked services.

7.3.2 Utility Model

Generically, a multi-attribute utility model can be expressed as:

$$u(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} w_i u_i(x_i), \tag{7.1}$$

where x_i is the measure for attribute $i = 1, \ldots, n$, $u_i(\cdot)$ is a single-attribute utility measure for attribute i scaled in the interval [0,1], and w_i is the weight for measure i, with $\sum_i w_i = 1$ [94]. Weights represent the perceived importance of a specific utility attribute.

Our multi-attribute utility model for evaluating spectrum access rules, derived from the objective hierarchy, is given by the following equation:

$$\begin{aligned} u_{regulator} = {} & \overbrace{w_1 u_{p-drop}}^{\text{Primary Operator Utility}} \\ & + \overbrace{w_2[\underbrace{v_1 u_{s-bits}}_{\text{Service Volume}} + \underbrace{v_2(z_1 u_{s-drop} + z_2 u_{s-block})}_{\text{Customer Churn}}]}^{\text{Secondary Operator Utility}}. \end{aligned} \tag{7.2}$$

The utility u_{p-drop} represents the total utility for primary operators and is based on the service losses due to harmful secondary interference. The secondary operator utility is based on service volume and customer churn. Service volume is represented through the utility u_{s-bits}. Customer churn is represented through the two utility functions u_{s-drop} and $u_{s-block}$, which consider the proportions of dropped and blocked service attempts, respectively. Weights w_i, v_i, and z_i represent the relative importance between primary and secondary operators' utilities, service volume and customer churn, and drops and blocks, respectively. Weights can be subjective, however stakeholders should have input to determine appropriate values for the application.

The values of the w_i reflect the relative importance the regulator attaches to services provided by primary and secondary operators. As primary user protection and prioritization is already reflected in the spectrum access rules (Section 7.2), our study is agnostic on the type of service provided by primary and secondary operators and thus we set $w_i = w = 0.5$. This value selection reflects that secondary service and primary service are equally valued. In other applications, the service value between primary and secondary service could be examined from a monetary or social benefit point of view to determine weights.

Expert	Compare		More Important	Factor
A	Blocks	Drops	Drops	6.00
	Max Service	Min Churn	Min Churn	5.00
B	Blocks	Drops	Equal	1.00
	Max Service	Min Churn	Max Service	7.00

Table 7.1: Pairwise comparison results from interviews.

Determining the value of v_i and z_i should be driven by network operator perspectives who provide secondary services. We obtain values of v_i and z_i through a technique known as Analytical Hierarchy Process (AHP) [30]. Using AHP, we interviewed two experts to perform pairwise comparisons between attributes of relevance to secondary operator performance in a DSA environment[1]. After determining which attribute is more important, the more important attribute receives a score from 1-9, with 1 indicating that the two attributes are equally important. These pairwise comparisons are placed in matrix **A**, with $a_{ji} = 1/a_{ij}$, where each row and column represents a specific attribute. Using the following equation:

$$\mathbf{A}\mathbf{w} = \lambda_{\max}\mathbf{w}, \tag{7.3}$$

and solving for $\lambda_{\max}$, the principal eigenvalue of **A**, and **w**, the principal right eigenvector of **A**, we can normalize the entries of **w** by dividing by their sum and recover the weighted values for our utility function.

We repeated the above process twice, with inputs from our interviews with two experts in cellular network performance and obtained two perspectives for the weights v_i and z_i. We asked each expert to compare the relative importance of minimizing customer churn versus maximizing service volume and minimizing session blocks versus minimizing session drops. The resulting matrices and relative importance scores are shown in Table 7.1. The results of the interview are placed in a comparison matrix, from which the principal eigenvector is calculated. The results from this calculation and resulting weight values are shown in Table 7.2. From Table 7.2, we note that Expert A views existing service requests as more important than new service requests, whereas Expert B views new and existing service requests as equivalent.

7.3.3 Evaluated Spectrum Access Rules

In this study, we consider the intent of the FCC rules in [27, 68] and focus on channel exclusion techniques that consider energy detection thresholds and a geolocation database that defines exclusion areas. For power control, we propose an adaptive power control algorithm to minimize co-channel interference and conserve transmit power based on [97].

While more sophisticated spectrum sensing techniques exist, our evaluation considers spectrum sensing based on energy detection. Through energy detection, a channel c is deemed available if

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[1] While in this chapter we only examine only two viewpoints, we also note that group decision making and viewpoint aggregation has also been studied in [95, 96].

Expert A	Blocks	Drops	z_i
Blocks	1.00	1/6	0.14
Drops	6.00	1.00	0.86

Expert A	Max Service	Min Churn	v_i
Max Service	1.00	1/5	0.17
Min Churn	5.00	1.00	0.83

Expert B	Max Service	Min Churn	v_i
Max Service	1.00	1/7	0.12
Min Churn	7.00	1.00	0.88

Table 7.2: Pairwise comparison matrices derived from expert interviews and utility model weights for z_i and v_i. Blocks and drops for Expert B are not captured since $z_i = z = 0.5$.

the receiver of link i measures the received power to be below the detection threshold α, denoted as $I_i^{(c)} < \alpha$. Our study uses a detection threshold of α = -107 dBm as indicated in [27]. Using sensing information, our work considers the channel assignment sub-rule through Least Interfering Channel (LIC) assignment, where the LIC is determined by the $\min_c I_i^{(c)}$. We also consider additional exclusion rules using cooperative sensing with hard combining. In hard combining, a channel is determined to be available if a certain proportion of the receivers detect power on the channel to be below the detection threshold.

Like the ruling in [27], we define channel exclusion through exclusion areas to protect primary operators from secondary interference. Secondary links in this exclusion model are not provided with protection areas and accept interference from one another. We consider exclusion areas surrounding primary links as disks of radius $d_{i,i}$, where $d_{i,j}$ is the Euclidean distance between the transmitter of link i and receiver of link j. If primary link i is using channel c, secondary link j is permitted to use channel c if $d_{j,i} > d_{i,i}$ and $d_{i,j} > d_{i,i}$. The distance $d_{i,i}$, can also be extended by additional factors. In our study, we define the exclusion areas such that $d_{j,i} > \kappa d_{i,i}$, with $\kappa \geq 1$ and we explore values $\kappa \in \{1, 1.5, 2, 2.5\}$.

Power control is necessary in DSA applications to minimize interference among co-channel links. Additionally, changing network conditions require adjusting transmit power to maintain the requisite link SINR. Thus, we consider dynamic power control for primary and secondary users such that all links on channel c, $\mathcal{L}_c$, iteratively adjust their transmit power according to:

$$p_i(k+1) = \min\left(p_{\max}, \frac{\beta}{\gamma_i} p_i(k)\right), \tag{7.4}$$

where k is the iteration number, p_i is the power of transmitter i, and γ_i is the SINR of link i. Foschini in [97] demonstrated that when transmitters use equation (7.4) to adjust their power levels, the transmit powers of the links will converge exponentially to an optimal power assignment. In our case, optimal power assignment means using only the amount of power necessary to maintain requisite link SINR. If the link cannot maintain an SINR of at least β without the transmit power

	Sensing	**Additional Channel Exclusion**
Rule 1	Receiver Only	None
Rule 2	Receiver and Transmitter	None
Rule 3	Cooperative	Hard Combining Ratio = .25
Rule 4	Cooperative	Hard Combining Ratio = .5
Rule 5	Cooperative	Hard Combining Ratio = 1
Rule 6	Receiver Only	Exclusion space factor = 1
Rule 7	Receiver Only	Exclusion space factor= 1.5
Rule 8	Receiver Only	Exclusion space factor= 2
Rule 9	Receiver Only	Exclusion space factor= 2.5

Table 7.3: Spectrum access rules for simulations. Rules use $\alpha = -107$ dBm and Least Interfering Channel for channel assignment

of the link exceeding maximum transmit power, $p_{\max}$, the link is infeasible and the power of the link is set to zero. Table 7.3 summarizes the list of the spectrum access rules that we consider in this study.

7.4 System Model and Simulation Scenario

In this section we introduce our system model, our simulation scenario and also our derivations of the utility functions. We adopt the SINR model for defining interference between co-channel links and determine which links are feasible. The simulation scenario defines how primary and secondary users share spectrum. This section closes with a description of how the utilities defined in Equation (7.2) are calculated from the simulation scenarios.

7.4.1 System Model

We define a set of frequency channels $\mathcal{C}$ and a set of communication links $\mathcal{L}$. Each link $i \in \mathcal{L}$ comprises a transmitter and receiver, which seek to establish a wireless communications link using a channel $c \in \mathcal{C}$. All $c \in \mathcal{C}$ have a bandwidth of W. Given a set of communications links operating on a channel c, $\mathcal{L}_c$, the SINR of the receiver of link $i \in \mathcal{L}_c$, $\gamma_i^{(c)}$, is determined by:

$$\gamma_i^{(c)} = \frac{g_{ii} p_i}{N_o + I_i^{(c)}}, \tag{7.5}$$

where g_{ji} is the gain between the transmitter of link j and the receiver of link i. The variable p_i denotes the power of the transmitting node of link i, and N_o the thermal noise. $I_i^{(c)}$ is the interference power at the receiver of link i, expressed as:

$$I_i^{(c)} = \sum_{j \in \mathcal{L}_c, j \neq i} g_{ji} p_j. \tag{7.6}$$

In this system model, a feasible link is a link whose receiver SINR, γ_i, is above a threshold β. We define a session as a pair of unidirectional links between communicating nodes and denote γ_i as the SINR of the uplink and $\hat{\gamma}_i$ as the SINR of the downlink. A session is feasible if and only if the pair of links are both feasible, i.e., $\gamma_i \geq \beta$ and $\hat{\gamma}_i \geq \beta$.

7.4.2 Simulation Scenario

In our simulation, we consider a scenario in which a set of primary and secondary operators share a set of channels, $\mathcal{C}$. Each operator comprises a set of access points and corresponding users associated with each access point. Access points are assumed to have established a control channel to coordinate channel assignment with the users. The simulation randomly places four primary and four secondary operator access points, each with twenty users surrounding the associated access points, in a square simulation area (1000m x 1000m). After placement of the access points, users for each access point are randomly and uniformly placed within a distance D_{max} = 700m from their respective access point. We assume a noise floor (N_o) of -110 dBm, $p_{ref} = p_{max} = 1W$, path loss factor of 4, and independent Rayleigh fading. To show a lower bound in our given scenario, our simulation considers a worst case scenario, where every link carries traffic and attempts to be in service simultaneously.

Initially, primary users are allowed to establish sessions with their corresponding access points using non-interfering channels $c \in \mathcal{C}$, without secondary users. Following primary users, secondary sessions attempt to be admitted into the network individually and at random. Admission of secondary links begins by determining channel availability using exclusion sub-rule $\mathcal{E}$, followed by the channel assignment sub-rule $\mathcal{A}$, and then the power control and transmission sub-rule $\mathcal{P}$. In our scenario, we use each of the exclusion rules defined in Table 7.3 followed by LIC for channel assignment. We also assume that nodes are capable of perfect spectrum sensing and there exists a common control channel for exchange of sensing information. After channel assignment of link i to channel c (the LIC of the receiver) power control is initiated by the transmitter of secondary link i with initial power parameter p_{ref}. Links in $\mathcal{L}_c$ then adjust their transmit power using equation (7.4), until the power settings of $\mathcal{L}_c$ converge. The simulation time, T is determined by using the simulation time step when link admission converges (no more links can be admitted) or when all links are attempted at least once, whichever comes last. Determining T in this manner was done to allow every link to be attempted and simulations to converge.

7.4.3 Utility Derivations

The utility u_{p-drop} is used to measure the primary service losses from harmful secondary interference. When secondary links are admitted, they may cause other sessions to become infeasible (harmful interference) through lowering the SINR of the co-channel links below β. If the transmitters of those links cannot maintain an SINR of β without exceeding p_{max}, those links will drop.

Thus, u_{p-drop} is a linear utility function that is zero if all sessions are dropped during T and reaches a value of 1 if no primary sessions are dropped.

Similarly, the utility function u_{s-drop}, is based on the number dropped sessions for the secondary operators in the same manner. However, in this case the linearly decreasing function reaches zero when the percentage of secondary session drops reaches 4.5% [98]. We use 4.5% as an expected worst case. Thus, u_{s-drop} is a linear utility function that is one if no secondary sessions are dropped and zero if more than 4.5% links are dropped.

To develop u_{s-bits}, the utility for the attribute bit volume , we examine secondary link feasibility over a time period T. This is a linear utility function that is zero if no secondary sessions are feasible and reaches a value of 1 if all possible secondary session are feasible during time period T.

The utility $u_{s-block}$ represents the measure of blocked secondary session admissions. During admission, secondary users can be blocked for two reasons. First, the channel could be unavailable because of exclusion, i.e., the spectrum access sub-rule $\mathcal{E}$ prevents the channel from being used. Second, the requisite SINR of the link may not be reached because of excessive co-channel interference. This linear utility function is zero if all secondary links are blocked and reaches a value of 1 if no links are blocked.

7.5 Results

Figures 7.2 and 7.3 show the resulting utility for attribute weights from Expert A and Expert B, respectively. Rule 10 represents the utopia point, the maximum utility due to each attribute if there were no conflicts between primary and secondary user objectives. The most salient feature in both Figures 7.2 and 7.3 is the poorest performing rule, Rule 1. Placing this in context, Rule 1's exclusion sub-rules are based only on receiver sensing, i.e. channels are available if the measured power is below a detection threshold. The poor performance is due to two reasons. First, Rule 1 provides insufficient protection for primary users, causing a relatively large proportion of primary sessions to drop, i.e. low utility for u_{p-drop} . Second, Rule 1 also causes many secondary links to drop, i.e. low utility for u_{s-drop}. Thus, Rule 1, the receiver-only sensing exclusion sub-rule, provides the least amount of utility for primary and secondary operators, at the expense of admitting a large number of new sessions.

Figures 7.2 and 7.3 show that Rules 2, 5, and 9 result in the highest overall utilities. Rule 2 and Rule 5 both use cooperative sensing by hard combining. Rule 2 requires the transmitter of the link to sense the LIC of the receiver to be below the detection threshold. Compared to receiver-only sensing, this is a dramatic improvement in providing protection from harmful interference to both primary and secondary users, i.e. high u_{s-drop} and u_{p-drop}. Rule 5 only allows channels to be available if all users associated to the same access point sense the LIC of the receiver to be below the detection threshold, providing the best protection for primary and secondary users, i.e.

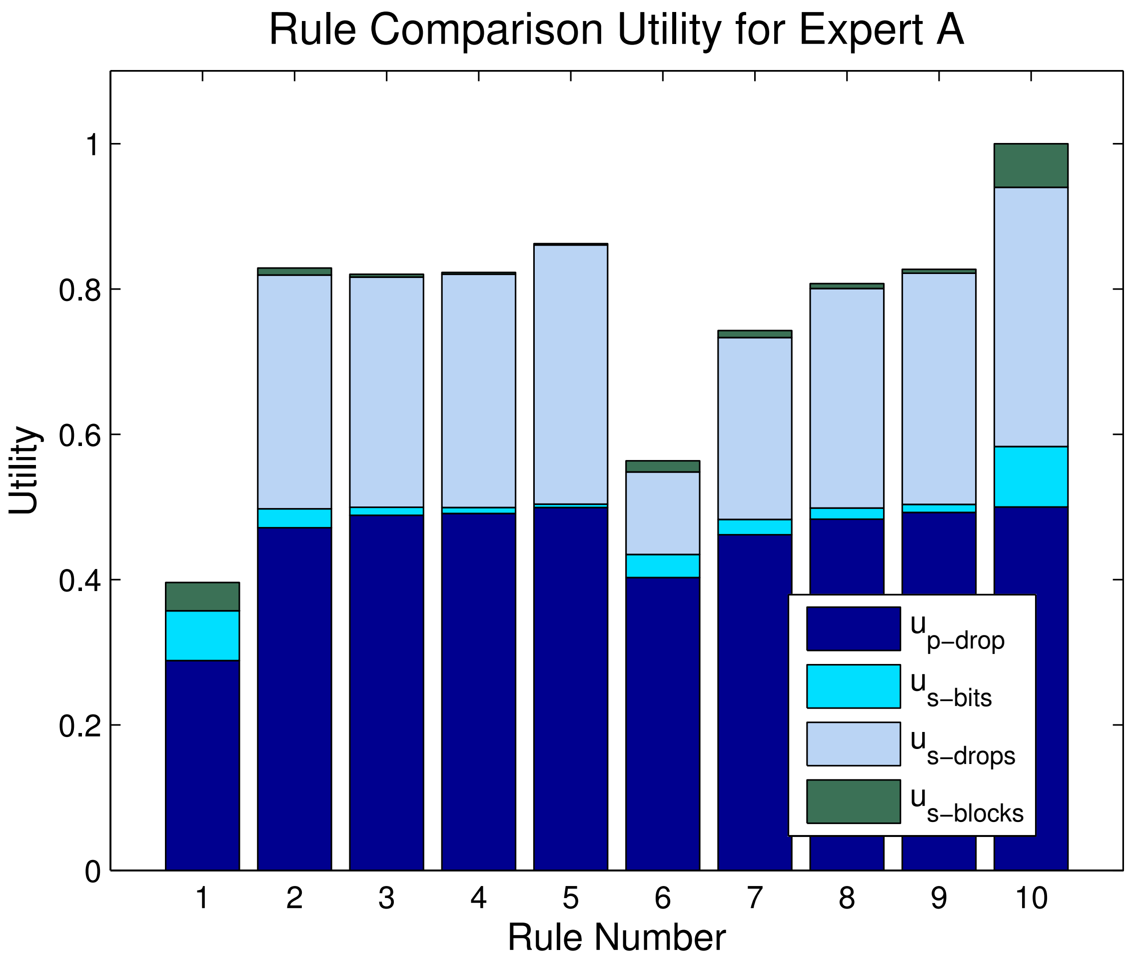

Figure 7.2: Utility comparison of spectrum access rules using attribute weights from Expert A. Rule 10 shows the utopia point.

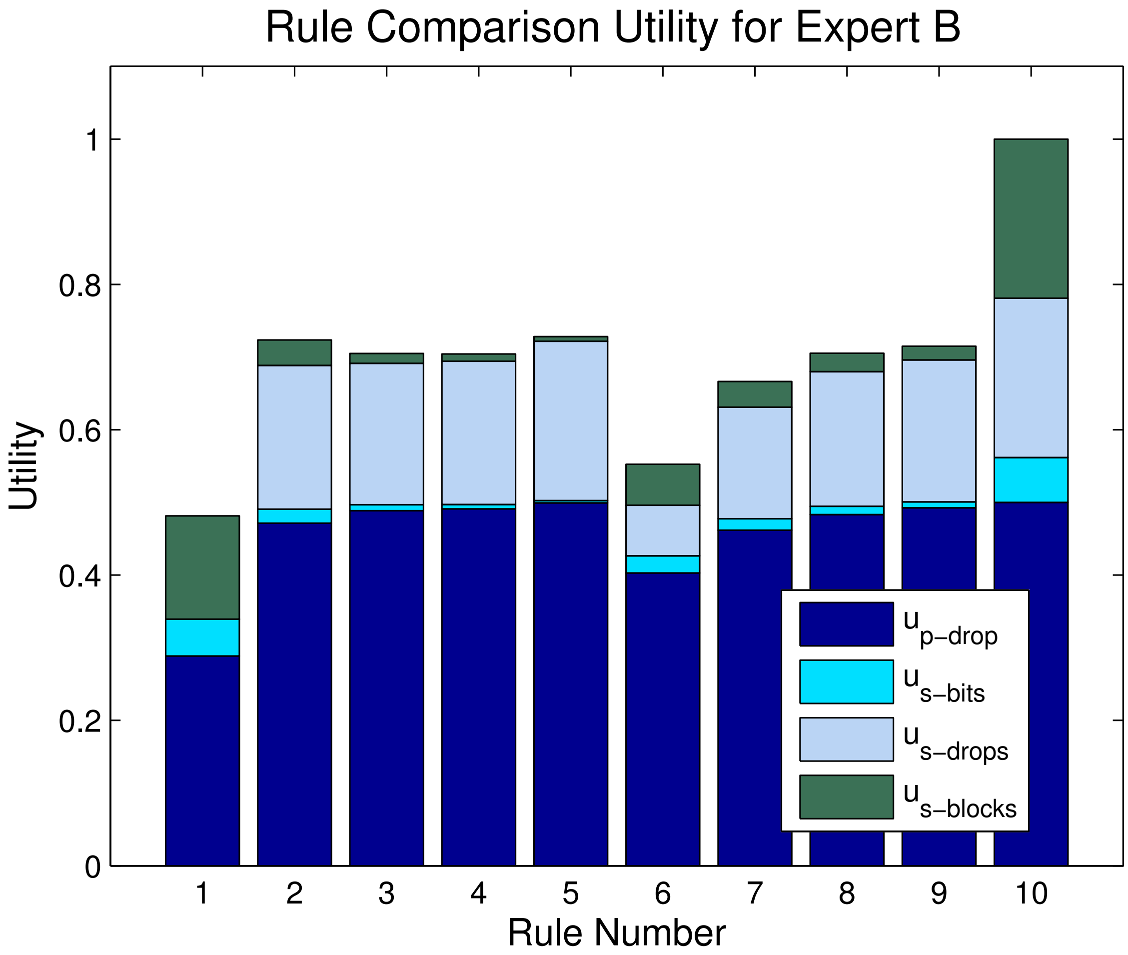

Figure 7.3: Utility comparison of spectrum access rules using attribute weights from Expert B. Rule 10 shows the utopia point.

u_{s-drop} and u_{p-drop}. However, Rule 5 provides very little throughput for secondary users, i.e. low u_{s-bits} and low $u_{s-block}$, by being overly conservative about opportunistic use. Rule 9 provides the largest exclusion regions, allowing for significant amount of protection for primary users through preventing secondary use. In summary, based on the two weighted values from Experts A and B, Rules 2, 5, and 9 have relatively equivalent overall utilities. It is also evident that as secondary users are less restricted, and achieve higher u_{s-bits} and $u_{s-block}$, they can cause more service drops to both primary and secondary users and thus lower overall utilities. This phenomenon is magnified in the utility function since throughput, u_{s-bits} is less important in the perspective of both experts.

We next examine the causes of blocking. Figure 7.4 shows the cumulative number of blocks for each rule during the simulation and classify them according to the cause of session blocking. An SINR Block is a session block caused because the SINR of the link cannot be reached. SINR Blocks are a result of limited transmitter power or high levels of interference. Channel Access Blocks are due to the exclusion sub-rule, preventing access to the spectrum. From Figure 7.4, the rules with the highest utilities also have the highest proportions of channel access blocks. One could also argue that Channel Access Blocks are less expensive than SINR Blocks, in that on the latter the transmitter must use energy and time to attempt to access the channel.

7.6 Summary

Applying decision theory, this study created a multi-attribute utility model for evaluating different dynamic spectrum access rules. Using this utility model, we developed a scenario for evaluating network performance of both secondary and primary operators and evaluated different spectrum access rules. We considered rules based on sensing and exclusion spaces. Our results show that as secondary users are less restricted, they can cause service drops to both primary and secondary users and thus overall lower utilities. Additionally, rules with higher proportion of channel access blocks result in the largest overall utilities.

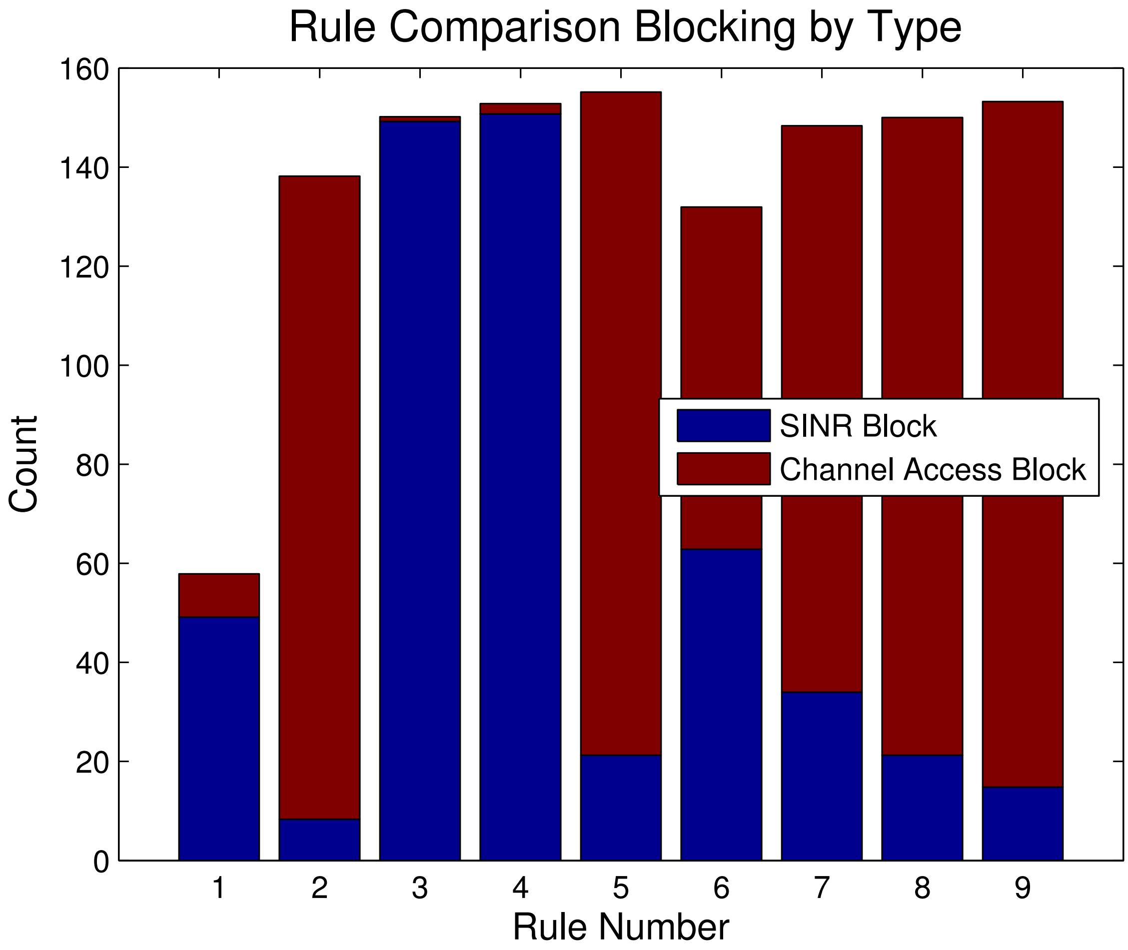

Figure 7.4: Blocking by type of rules. Rules 2, 5, and 9 have the highest proportions of channel access blocks.

Appendix A

Acronyms

3GPP 3rd Generation Partnership Project

ACK Acknowledgment

AHP Analytical Hierarchy Process

BEM Block Edge Mask

BS Base Station

CAB Coordinated Access Band

CDMA Code Division Multiple Access

CPE Customer Premise Equipment

CQI Channel Quality Indicator

CSM Cell Spectrum Management

CSMgr Cell Spectrum Manager

CBP Coexistence Beacon Protocol

cBS cognitive Base Station

cHeNB cognitive Home evolved Node B

cRN cognitive Relay Node

CSM Cell Spectrum Management

CFBS Cognitive Femtocell Base Station

cUE cognitive User Equipment

DcBS Donor cognitive Base Station

DeNB Donor Evolved Node B

DcBS Donor cognitive Base Station (cBS)

DHCP Dynamic Host Configuration Protocol

DSA Dynamic Spectrum Access

DSMgr Domain Spectrum Manager

DSAP Dynamic Spectrum Access Protocol

DSM Domain Spectrum Management

eNB Evolved Node B

EPC Evolved Packet Core

E-UTRAN Evolved Universal Terrestrial Radio Access

FBS Femtocell Base Station

FCC Federal Communications Commission

GDB Geolocation DataBase

GIS Geographic Information System

GSM Global System for Mobile Communications

HetNet Heterogeneous Network

HeNB Home Evolved Node B

HLR Home Location Register

HTTP HyperText Transfer Protocol

HSS Home Subscriber Server

IGDB Incumbent Geolocation Data Base

IR Integrated Receiver

KPI Key Performance Indicators

LIC Least Interfering Channel

LTE Long Term Evolution

LTE+ Long Term Evolution Advanced

MAC Medium Access Control

MANET Mobile Ad Hoc Network

MILP Mixed Integer Linear Program

MME Mobility Management Entity

N-cBS Neighboring-cognitive Base Station

NAS Non-Access Stratum

NOI Notice of Inquiry

OFDM Orthogonal Frequency Division Multiplexing

OFCOM Office of Communications

OOBE Out of Band Emission

PCS Personal Communications Service

PDG Packet Data Gateway

PGW Packet Gateway

RN Relay Node

RNC Radio Network Controller

RRC Radio Resource Control

RRC-SS Radio Resource Control-Spectrum Sensing

RRC-CS Radio Resource Control-Cooperative Sensing

RRC-CSM Radio Resource Control-Cell Spectrum Management

SA Spectrum Accountability

SAC Spectrum Accountability Client

SAP Spectrum Accounting Protocol

SAS Spectrum Accountability Server

SB Spectrum Broker

SBA Spectrum Broker Architecture

SGW Signaling Gateway

SINR Signal to Interference and Noise Ratio

UE User Equipment

WNaN Wireless Network after Next

WRAN Wireless Regional Area Network

WSD White Space Device

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