

The Effects of a Dynamic Spectrum Access Overlay in LTE-Advanced Networks

International Dynamic Spectrum Access Networks (DySPAN) Symposium

Juan D. Deaton
Ryan E. Irwin
Luiz DaSilva

May 2011

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance



This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint should not be cited or reproduced without permission of the author. This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this paper are not necessarily those of the United States Government or the sponsoring agency.

The Effects of a Dynamic Spectrum Access Overlay in LTE-Advanced Networks

Juan D. Deaton^{*†}, Ryan E. Irwin[†], Luiz DaSilva^{‡†}

^{*}N&HS Directorate
Idaho National Lab
Idaho Falls, Idaho USA

[†] Wireless@VT
Bradley Dept. of Electrical and Computer Engineering
Virginia Tech
Blacksburg, Virginia USA

[‡] CTVR
Trinity College
Dublin, Ireland

Abstract—As early as 2014, wireless network operators spectral capacity will be overwhelmed by a data tsunami brought on by new devices and applications. To augment spectral capacity, operators could deploy a Dynamic Spectrum Access (DSA) overlay. In the light of the many planned Long Term Evolution Advanced (LTE+) network deployments, the affects of a DSA overlay have not been fully considered into the existing LTE+ standards. Coalescing many different aspects of DSA, this paper develops the Spectrum Accountability (SA) framework. The SA framework defines specific network element functionality, protocol interfaces, and signaling flow diagrams for LTE+ as a means to enforce the rights of responsibilities of primary and secondary users. We also include a network simulation to quantify the benefits of using DSA channels to augment capacity. Based on our simulation we show that overall throughput can increase by as much as 40% when operators share a DSA band to augment spectral capacity. With our framework, this paper could serve as a guide in developing future LTE+ network standards that include DSA.

I. INTRODUCTION

The next decade will bring accelerated growth in smart phone devices and applications. Although these new devices and mobile applications provide a welcome source of new revenue to the wireless network operators, they will also create a data tsunami so massive it could exceed current operator spectrum capacity as early as 2014 [1]. As a result, operators must find new ways to increase their spectrum capacity. One option is to use spectrum opportunistically as a secondary user, e.g. use underutilized TV channels. By deploying a Dynamic Spectrum Access (DSA) overlay, capacity constrained operators could capture potential revenue by augmenting their licensed spectrum capacity. To determine the operational effects of a DSA overlay in Long Term Evolution

Advanced (LTE+) networks, our study considers a scenario in which competitive LTE+ network operators opportunistically use spectrum as secondary users to augment their spectrum holdings.

While a DSA overlay can increase spectral capacity, it also brings significant challenges. The problem of identifying hidden receivers remains an issue [2], resulting in strict Federal Communications Commission (FCC) regulations for secondary spectrum use [3]. Additionally, because of the possibility of many secondary competitive operators, detecting rule violations is of vital importance in resolving spectrum feuding and enforcing judicious spectrum usage [4]. Our work presents an architectural and operational framework to support DSA overlay, called Spectrum Accountability (SA), as a means to address the challenges of deploying a DSA overlay in next generation wireless networks. With our framework, this paper could serve as a guide in developing future LTE+ network standards that fully account for DSA.

In our SA framework, secondary competitive base stations issue spectrum lease requests using spectrum access rules. These lease requests are sent 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, secondary competitive base stations report usage metrics. These usage metrics can be used by regulators for monitoring use of spectrum leases, detecting violations, resolving conflicts, and modifying spectrum usage policies. In summary, SA is a framework by which regulators can define, enforce, and manage spectrum access rules for competitive secondary operators and primary operators.

Our paper makes the following contributions. Our first contribution is to analyze how DSA operational procedures and architecture can be incorporated into future LTE+ standards. We argue that many parallels can be drawn to alternative network architectures such as WiMax. Our second contribution in this work is our SA framework. The SA framework focuses on the operational signaling scenarios to support cooperative sensing techniques [5], coordination and monitoring of spectrum access rules through a spectrum server [6, 7], and alarming scenarios for rule adjustment. Our SA framework provides the mechanism to coalesce many different

This work supported by the Idaho National Laboratory (INL) Ph.D. Candidate Program and Virginia Tech Bradley Fellowship. Work supported through the INL is supported through the Laboratory Directed Research & Development (LDRD) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Department of Energy or the U.S. Government.

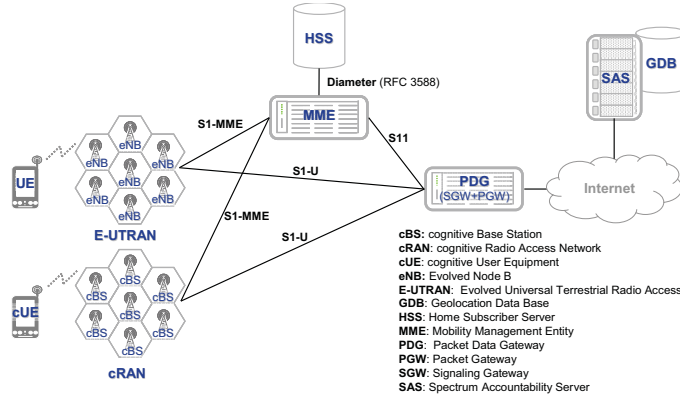


Fig. 1. DSA overlay in an LTE+ architecture is supported through the introduction of the SAS, cBS and the cUE.

aspects of DSA into specific network element functionality, protocol interfaces, and signaling flow diagrams, which could be agnostic to the spectrum access rule set. In our final contribution, we illustrate through simulation the quantifiable benefits for LTE+ network operators to use DSA spectrum to increase their spectral capacity.

Our paper is organized as follows: in Section II, we briefly outline the LTE+ network elements affected by the DSA overlay. Additionally, we examine the affected LTE+ control planes and introduce new network elements and functionality required to support DSA. The remainder of the paper describes the operational procedures that comprise the SA framework. In Section III, we present the operational procedures used to support service requests. Specifically, we describe the following procedures: cognitive Base Station (cBS) Registration and Discovery, Periodic Cooperative Sense, Spectrum Request and Reporting, Spectrum Sharing, and Service Request. In Section IV, we present the role of SA in terms of the spectrum management through the following procedures: New Primary User Alert, Integrated Receiver (IR) Interference Alarm, High Interference Spectrum Lease, Spectrum Unavailable Alarm, and Rogue Transmitter Detection. In Section V, we illustrate the potential benefits of augmenting LTE+ networks with a DSA overlay. We conclude in Section VI with a summary of the paper and discuss how our contributions can shape future work in this area.

II. EFFECTS OF A DSA OVERLAY IN LTE+

In this section, we provide an operational and architectural overview of the effects of a DSA overlay in LTE+ networks. This section first presents a brief overview of the LTE+ architecture, followed by an introduction of the new DSA network elements. We then introduce the concept of a DSA carrier, which is used to augment the licensed spectral capacity of the network. The section closes by presenting the reference architecture, which illustrates the logical signaling endpoints and introduces a basic scenario for our operational procedures presented in Section III and IV.

A. Affected LTE+ Network Elements

Figure 1 shows our proposed modified LTE+ architecture with new network elements to support a DSA overlay (it also includes an acronym list for convenience). In LTE+, the User Equipment (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 Evolved Node B (eNB), where the eNB has the important function of Radio Resource Control (RRC). RRC has responsibility for the establishment, configuration, maintenance and release of radio bearers. Authentication, Authorization and Accounting (AAA) is performed by a combination of functionality in the Mobility Management Entity (MME) and Home Subscriber Server (HSS). The MME uses a signaling protocol called non-access stratum for the UE to register for network services and to support encryption. HSS houses the access database, similar to a Home Location Register, which contains a record of the UE and the corresponding supported service capabilities. In addition to supporting access and security services, the MME also provides the mechanisms for coordinating data bearers for the UE through the eNB and Packet Data Gateway (PDG). The PDG provides the connections for the UE to external packet networks. (For ease of discussion, we consider the SGW and PGW LTE+ network elements together as the PDG.) While this brief introduction of LTE+ is sufficient to support further discussion in this paper, the reader is encouraged to consult [8] and [9] for more detailed information.

B. DSA Elements and Functions

We propose that the DSA overlay be supported through the introduction of the Spectrum Accountability Server (SAS), cognitive Base Station (cBS) and cognitive User Equipment (cUE). Management of spectrum access policies and monitoring of spectrum leases are performed by the SAS. Policies are distilled into rule sets, which the cBS uses to create spectrum lease requests. Additionally, the SAS maintains a geolocation database that contains the IP addresses of all primary and secondary operators. The database also maintains spectrum lease and usage information for spectrum management. Spectrum management is performed by monitoring usage metrics from cBS, Key Performance Indicators (KPI), and alarms from IRs. The IR is an IP-connected device, capable of detecting and sending interference alarms to the SAS. For example, the IR could be an IP-connected TV or other device with similar functionality. The SAS functions of maintaining spectrum-leasing policies, coordinating spectrum leases, monitoring spectrum usage, and managing spectrum access rules are supported through the Spectrum Accounting Protocol (SAP). The registration and reporting control plane to support SAP is shown in Figure 2.

The cBS calculates spectrum lease requests by using the spectrum access rules and sharing cooperative sensing information with geographic neighbors, where neighbors are either external or internal to the home network. Cooperative techniques may be adopted for accurate sensing [5] and to help

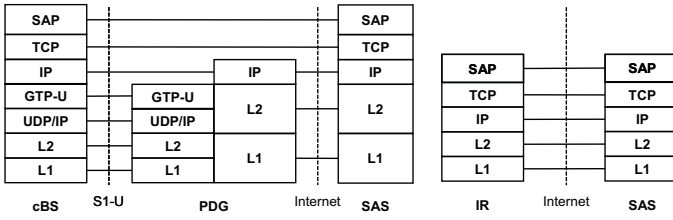


Fig. 2. SAP control plane for cBS registration and reporting functions.

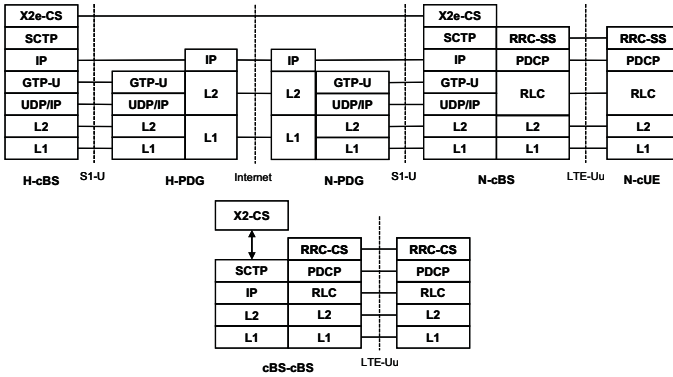


Fig. 3. Cooperative sense control planes for external (top) and internal networks (bottom).

abate the hidden user problem [2]. To support communication with external network entities, the cBS must have an external IP address and a default bearer through the 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 spectrum request lease use.

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). As part of the sensing, we also presuppose that the cUE contains some cognitive functions, which improves the accuracy of sensing information over time. The cUE uses a cBS for network service. Like the cUE, the cBS is also capable of spectrum sensing and learning for determining 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 the cooperative sensing are shown in Figure 3.

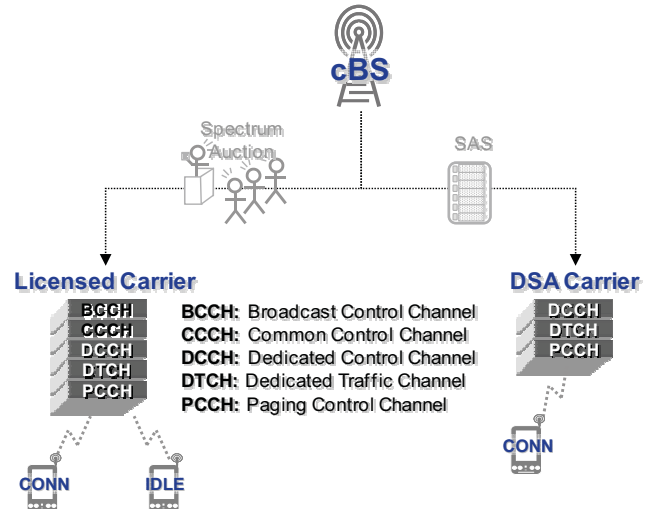


Fig. 4. cBS Carrier Channel Anatomy: The licensed carrier channels shown in black are not supported by the DSA carrier. IDLE mobiles always request access on the licensed carrier. After connected (CONN), cUEs use the DSA carrier to support the radio bearer.

C. DSA Carriers

From the perspective of spectrum leases, LTE+ deploys spectrum segments as carriers on the eNBs which can be used to support a limited amount of traffic; e.g., an LTE carrier size of 3 MHz consists of 15 resource blocks used for radio bearers. In our model, a cBS supports two different types of carriers: licensed carriers through a spectrum license and DSA carriers through a spectrum lease. Figure 4 shows a pictorial representation of these carriers. The licensed carrier supports all logical channels whereas the DSA carriers support only data bearers and channels used to support those data bearers. In Figure 4 IDLE cUE are shown requesting a radio bearer on the licensed carrier, i.e. using the Common Control Channel for an RRC connection request. When the cUE establishes a radio bearer, it becomes connected (CONN) on the DSA carrier if there is no capacity on the licensed carrier. In summary, licensed carriers are used to bootstrap DSA carriers for tasks like cUE synchronization and access, while DSA carriers are used to increase cBS operating capacity by adding more traffic channels.

D. Reference Architecture and Interfaces

In Figure 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 5 also captures the protocol and signaling endpoints of SAP, X2e: Cooperative Sense, and X2e: Spectrum Trading. In addition to showing signaling interfaces, Figure 5 introduces a new network element, the Integrated Receiver (IR).

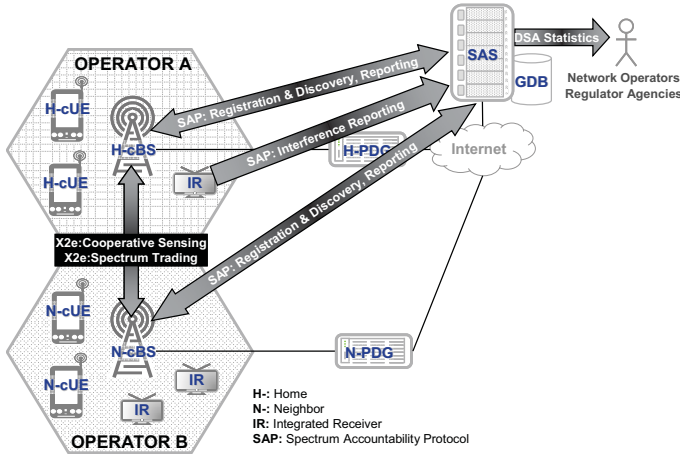


Fig. 5. Reference Architecture and Logical Signaling Endpoints

Figure 5 also introduces the Spectrum Accounting Protocol (SAP). SAP enables cBS registration, 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.

III. SERVICE REQUEST SUPPORTING PROCEDURES

Throughout all our procedure descriptions we remain agnostic of how the SAS decides to allocate leases and when cBS make lease requests. These decisions could be the result of a specific policy and implementation, whereas our goal in our work is to provide the mechanisms to support a variety of policies. In our first section describing the Spectrum Accountability (SA) framework, 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 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 these operational procedures that support service requests using the DSA overlay as: cBS Registration and Discovery, Periodic Cooperative Sense, Spectrum Lease

Request, Spectrum Trade, and Service Request Procedure.

The cBS Registration and Discovery procedure is the genesis for 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 Sense Procedure is performed so neighboring cBSs can exchange sensing information to determine available spectrum channels. When spectral capacity is exceeded, the Spectrum Lease Request Procedure is triggered to send a spectrum lease request to the SAS. To formulate the spectrum lease request, the cBS uses periodic cooperative sensing information and traffic trending information to determine local spectrum needs. 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 from a neighbor cBS in similar manner. 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.

A. cBS Registration and Neighbor Discovery

The cBS Registration and Neighbor Discovery procedure is shown in Figure 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-cBSs IP addresses, the H-cBS then sends an X2e: Link setup request to support exchange of sensing information and spectrum trading with N-cBSs.

B. Periodic Cooperative Sensing Procedure

In the Periodic Cooperative Sensing Procedure, shown in Figure 7, sensing functions are contained 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 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.

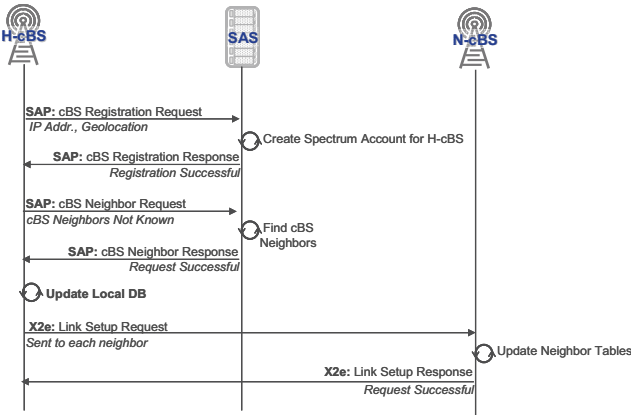


Fig. 6. Registration Reporting & Discovery Procedure.

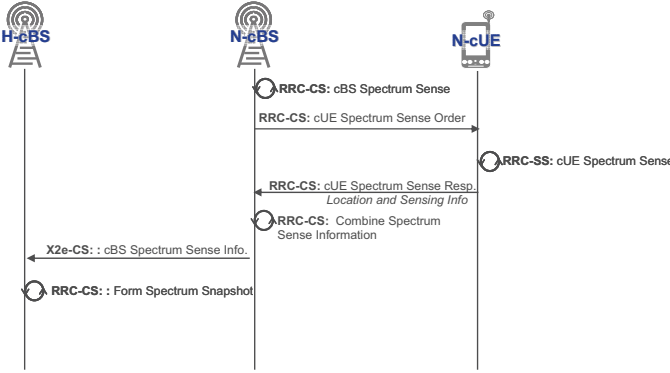


Fig. 7. Periodic Cooperative Sense Procedure

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.

C. Spectrum Lease Request Procedure

At the beginning of the spectrum lease procedure, shown in Figure 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 sense 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. In our example, the lease is considered valid if the cBS is following spectrum access rules. 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

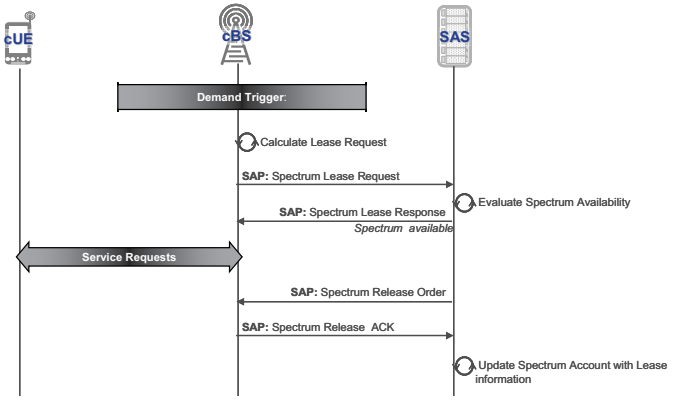


Fig. 8. Spectrum Lease Request Procedure

account of the cBS. Updating the spectrum account of the cBS is done to record 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 to support periodic load from commuter traffic at a roadside cBS while changes to existing leases would account for increase in overall demand. Additionally, spectrum negotiation could occur as a sub-procedure, where the cBS and SAS exchange information on 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.

D. 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 9). Like the Spectrum Lease Procedure, 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 through a spectrum lease request. The N-cBS examines the request and responds after examining current valid leases within the H-cBS's geographic area. The remaining procedure is similar to the Spectrum Lease Request Procedure, with the spectrum lease order and ACK being sent to the N-cBS from which the spectrum was obtained.

E. 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 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,

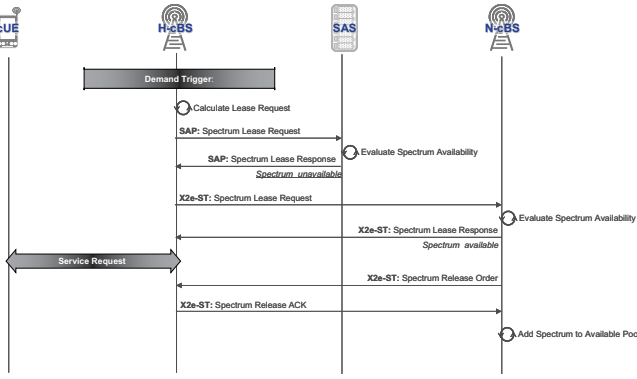


Fig. 9. Spectrum Sharing Procedure

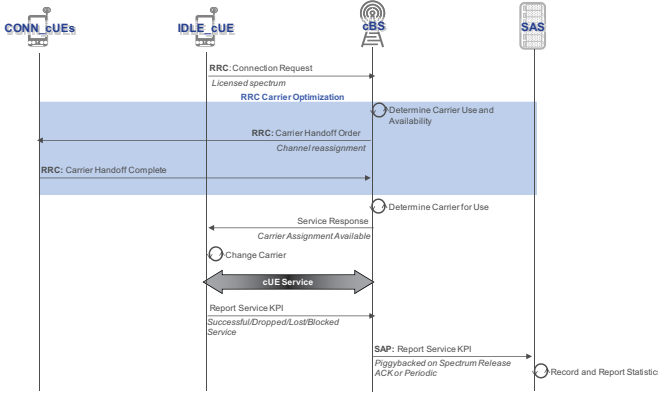


Fig. 10. Service Request Procedure and Reporting

messaging to move 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 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. Handoffs from neighboring cBS would also follow a similar procedure.

IV. 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. In this set of procedures, we have identified four new procedures to perform spectrum management: New Primary User Alert, IR Interference Alarm, High Interference Spectrum Lease, Spectrum Unavailable

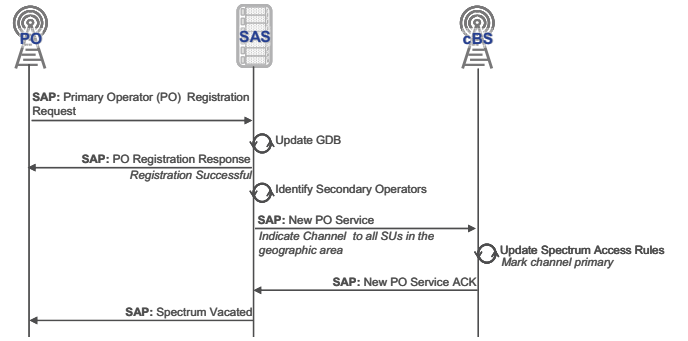


Fig. 11. New Primary User Alert Procedure

Alarm and Rogue Transmitter Detection.

A. New Primary User Alert

The purpose of this procedure is to notify secondary transmitters, cBSs, of a new primary operator so spectrum can be vacated. The procedure flow diagram is shown in Figure 11. Using SAP, the primary operator issues a registration request to the SAS. This request contains information about the spectrum licensed, 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 spectrum channel. The cBSs then update their spectrum access rules, mark the spectrum 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 completed vacating the spectrum, the SAS notifies the primary operator.

B. IR Interference Alarm

One problem with using DSA is the hidden receiver. In this 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 a loss of service and report the 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 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 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.

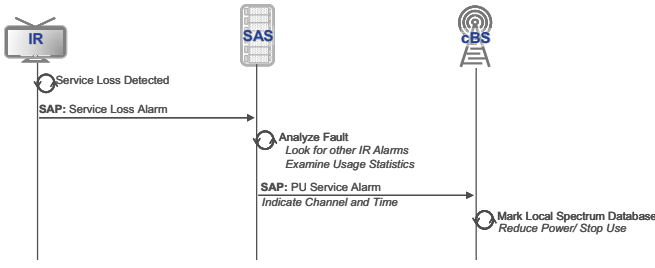


Fig. 12. IR Interference Alarm

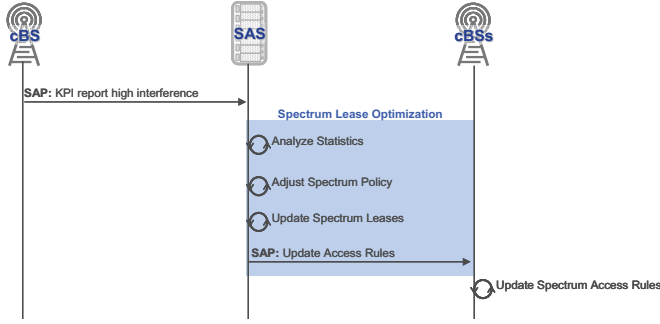


Fig. 13. High Interference Spectrum Lease

C. 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 13, begins with an H-cBS reporting KPI, which 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 this change, 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.

D. Rogue Transmitter Alarm Procedure

Another possible cause of high 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 14, instead of adjusting the set of spectrum leases the SAS determines the location of the rogue transmitter. After receiving KPI 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 the geolocation of the rogue transmitter. This information is then used by regulators to issue fines or take other appropriate measures.

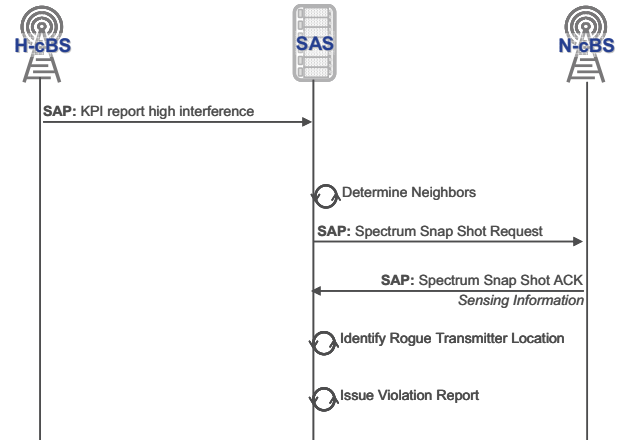


Fig. 14. Rogue Transmitter Alarm Procedure

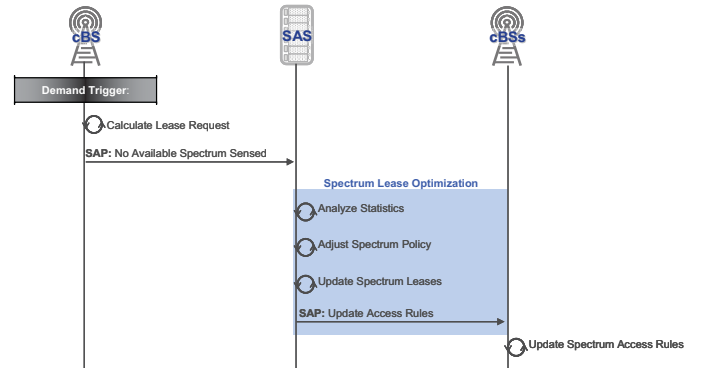


Fig. 15. Spectrum Unavailable Alarm Procedure

E. Spectrum Unavailable Alarm

In this final procedure, a cBS has detected that future demand 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 15. In the first message of the procedure, the cBS identifies 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.

V. DSA OVERLAY TO AUGMENT LTE+ CAPACITY

To illustrate the quantifiable benefits of using a DSA overlay in LTE+ networks, we consider a scenario in which multiple operators share the same site, tower or hilltop, to provide services. In our scenario, we assume the SA framework 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 [10]. The modified beta distribution probability density function is given by:

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

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:

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

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

$$\mathcal{B}(\alpha, \beta) = \int_0^1 t^{\alpha-1} (-t)^{\beta-1} dt. \quad (2)$$

The beta function is parameterized by α and β . Wellens, in [10], developed this model by using energy detection of 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 [10] 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 use of a DSA channel as long as the measured energy on the spectrum channel is below -107 dBm.

Arrivals are assumed Poisson and each arrival generates a demand for bandwidth. Following [11], we model the session demand using the Pareto distribution. The Pareto distribution probability density function is given by:

$$p(x) = \sigma k^{\sigma} x^{-\sigma-1}, \quad \sigma, k > 0, \quad x \geq k, \quad (3)$$

with parameters from [11], $\sigma = 1.06$ 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 service 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 S/N 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 cBSs 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

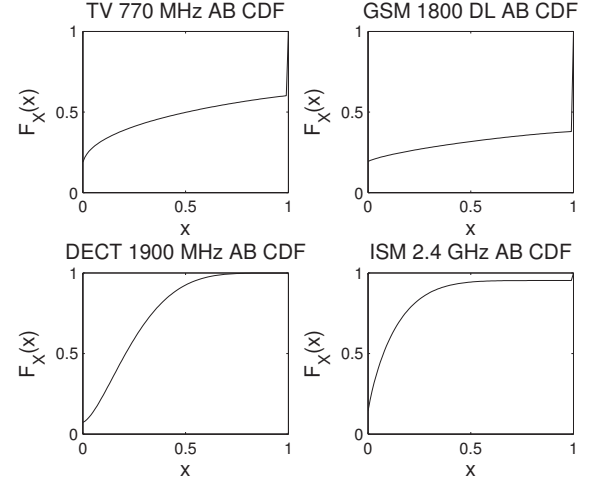


Fig. 16. Cumulative distribution functions for duty cycles of the four different DSA carrier types used in our simulation.

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 I
BAND PARAMETERS USED TO DETERMINE DSA CHANNEL DUTY CYCLE FROM [10]

compare the blocking probability of the three cBSs using 10 MHz licensed carrier with a shared 10 MHz DSA carrier against the case without.

From [10], we used four different parameter sets to model the DSA channel availability. The parameter set is shown in Table I. Figure 16 shows different cumulative distribution functions for the duty cycles of the four different DSA band types. Using these four different band types, we 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 17 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 [12]. Figure 17 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.

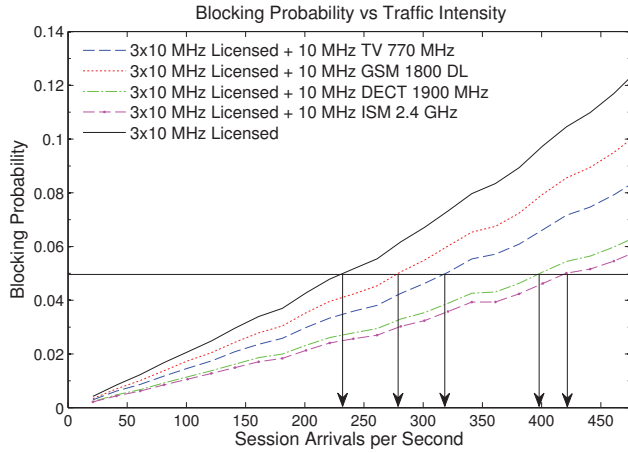


Fig. 17. Comparison of the blocking probability of the three cBS using licensed channels only with blocking probability of the three cBS with the shared DSA carrier for overflow traffic.

VI. FUTURE RESEARCH AREAS AND CONCLUSION

While studying the effects of DSA on next generation wireless networks, we have noted some potential open research areas, which we believe are of particular interest to network operators. The first area where we believe there is broad opportunity for research is specifically related to the cBS. In our work, we assumed that the cBS was able to assess traffic and spectrum trends to be able to calculate the amount of bandwidth required to accommodate future load and determine spectrum channels for use in the spectrum lease request. Analytical work is needed in this area to evaluate predictive algorithms that can be used for this purpose. Using machine learning, is it possible to have a cBS predict future traffic patterns and spectral conditions to determine the spectrum lease? Which learning techniques will be useful in this regard? Periodic sensing also plays an important role in determining spectrum conditions with respect to time. How often should spectrum sensing be performed and how fast? There are a myriad of issues regarding the formulation of a spectrum lease.

The second research area is related to the local policies used to dictate which traffic should be placed on DSA carriers. As highlighted in the Service Request Procedure, policies could be simple, only requiring overflow traffic to move to the DSA carriers. Another potential policy would be moving lower tiered users onto DSA carriers and higher tiered users onto licensed carriers. For this area, we pose the question: are there some types of traffic that are more suited for DSA carriers than licensed? These tradeoffs and the decisions for moving traffic onto different resources should be investigated. An additional twist to this area is evaluating the effects of different SAS spectrum access rules. Could different types of rules support specific local policies for DSA carriers? Additionally, what are the associated overhead costs of supporting a specific policy? Local policies for placing traffic on DSA carriers could affect service quality and throughput.

While there has been some work in mathematical modeling

spectrum leases [6], we believe that further investigation is needed to understand how the SAS should manage the spectrum leases through spectrum access rules. Of course, this work is also dependent on the previous open issues with the cBSs. Analytical work and large-scale simulations are needed for understanding how increasing traffic loads will determine spectrum demands and how these demands will be coordinated with the SAS in prudent manner. Realistic network topologies as well as traffic loads are needed to produce these large-scale simulations. One conundrum in most of this future research is to understand how to accommodate traffic loads that do not yet exist.

Our work has examined and proposed future methods by which DSA will be used in LTE+ wireless networks. In the first part of our paper, we examined the affected control planes and network elements from using a DSA overlay. Through the SA framework, we examined the 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. In the final section of the paper, we created a simulation model to illustrate, quantitatively, the benefits of using DSA. In conclusion, this paper presented the operational effects of a DSA overlay in LTE+ networks through an SA framework. 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.

REFERENCES

- [1] Rysavy Research, "HSPA to LTE-Advanced," September 2010.
- [2] M. Nekovee, "Cognitive radio access to TV white spaces: Spectrum opportunities, commercial applications and remaining technology challenges," in *New Frontiers in Dynamic Spectrum Access Networks, (DySPAN 2010) 2010 IEEE Symposium on*, 2010.
- [3] Federal Communications Commission, 08-260: Unlicensed Operation in the TV Broadcast Bands Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band, November 2008.
- [4] M. Buddhikot, "Understanding dynamic spectrum access: Models, taxonomy and challenges," in *New Frontiers in Dynamic Spectrum Access Networks, 2007. (DySPAN 2007). 2nd IEEE International Symposium on*, 2007, pp. 649–663.
- [5] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Communications Surveys Tutorials, IEEE*, vol. 11, no. 1, pp. 116–130, 2009.
- [6] M. Buddhikot and K. Ryan, "Spectrum management in coordinated dynamic spectrum access based cellular

networks,” in *New Frontiers in Dynamic Spectrum Access Networks, 2005. (DySPAN 2005) 1st IEEE International Symposium on*, 2005, pp. 299–307.

- [7] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey,” *Computer Networks*, vol. 50, no. 13, pp. 2127 – 2159, 2006.
- [8] TS 123 401 V9.4.0, March 2010, LTE; General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access version 9.4.0 Release 9.
- [9] TS 136 300 V9.3.0, March 2010, LTE; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2.
- [10] M. Wellens and P. Mahanen, “Lessons learned from an extensive spectrum occupancy measurement campaign and a stochastic duty cycle model,” *Mobile Networks and Applications*, vol. 15, no. 3, pp. 461–474, 2010.
- [11] B. Mah, “An empirical model of HTTP network traffic,” in *Sixteenth Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM’97)*, vol. 2, April 1997, pp. 592–600.
- [12] W. Lee, *Wireless and Cellular Communications*. McGraw-Hill Professional, 2005.