On Improving Serviceability With Quantified Dynamic Spectrum Access

Nilesh Khambekar
Department of Computer Science and Engineering
University at Buffalo, SUNY
Buffalo, New York 14260-2000

Chad M. Spooner
NorthWest Research Associates
cmspooner@nwra.com

Vipin Chaudhary
Department of Computer Science and Engineering
University at Buffalo, SUNY
Buffalo, New York 14260-2000

***Abstract*—Dynamic spectrum access is being investigated to meet the ever-increasing demand for wireless spectrum. We introduce a quantified dynamic spectrum access (QDSA) model for efficient sharing of spectrum among multiple heterogeneous networks. The QDSA paradigm enables us to define and enforce quantified spectrum-access footprints for the cochannel transceivers. By controlling the spectrum consumption by each of the individual transmitters and receivers, efficient spectrum sharing can be accomplished. In order to improve serviceability, we investigate the impact of the design choices for a spectrum access mechanism (SAM). The experiments demonstrate the significance of the active role by the incumbents, the impact of the granularity of spectrum access, and the need for transceiver standards for accomplishing efficient usage of the spectrum.**

I. INTRODUCTION

With exclusive and static allocation of spectrum, it has been observed that the spectrum is underutilized in the space, time, and frequency dimensions [1]. Dynamic spectrum access facilitates sharing of the spectrum by multiple heterogeneous networks in order to improve its utilization [2–4]. Dynamic spectrum access not only brings in potential for improving spectrum utilization, but also raises new technical and regulatory challenges in order to protect the spectrum-access rights of all spectrum users [5].

A spectrum access mechanism (SAM) defines how spectrum is accessed by the transceivers of multiple heterogeneous networks sharing the spectrum. Thus, a SAM plays a central role in accomplishing efficient spectrum sharing. There exist several uncertainties. In the case of non-cooperating networks, the spectrum-access parameters of cochannel networks may be unknown and can easily lead to harmful interference at the cochannel receivers. Even with the knowledge of the spectrum-access parameters of the transceivers, receivers may experience harmful interference due to random propagation conditions. To address these technical issues often the worst-case assumptions are made. This leads to potentially low exploitation of the available spectrum and makes it harder to develop attractive business models based on the dynamic spectrum sharing paradigm.

Under a secondary spectrum access mechanism, the underutilized spectrum can be opportunistically utilized on a secondary basis. In this case, the incumbents are concerned about disruption or degradation of their service due to harmful interference from secondary users. From the secondary-user perspective, the availability of the secondary spectrum is also a key concern in addition to throughput and lack of quality of service. These issues affect the business prospects and discourage secondary access to the underutilized spectrum.

Furthermore, with the advent of software-defined technology, the enforcement of the spectrum-access parameters poses difficulties for licensing and regulation [5]. The spectrum-access attributes of a transceiver could be modified and therefore it is difficult to detect violations and take regulatory action against nonconforming user devices. The lack of regulation may lead to severe interference incidents and disruptions to the wireless services. Hence, in order to promote dynamic spectrum sharing, there is a need for a model and an infrastructure that provide ability to enforce the spectrum-access policy in real time.

In this paper, we present a spectrum-access model to address the above mentioned technical and regulatory issues. Firstly, we investigate how spectrum is consumed when multiple wireless networks are operating simultaneously. Traditionally, the spectrum is assumed to be used by the transmitters. However, the receivers also consume spectrum by constraining the interference power in the space, time, and frequency dimensions. In the context of dynamic spectrum sharing, we need to separately quantify the spectrum consumed by the transmitters and the receivers. By discretizing the spectrum-space, the spectrum consumption quantification model proposed in [6] quantifies the spectrum consumed by the transmitters and receivers in a geographical region. Now, it is possible for a SAM to schedule multiple spectrum-access requests and define a spectrum-access policy with a *quantified* spectrum to each of transceivers. The quantified spectrum-access policy can be enforced in real time by estimating the spectrum-access footprint of transmitters with the aid of an external sensor-network as described in [7]. The spectrum consumption quantification approach is able to exploit the fine granular spectrum-access opportunities. In order to improve the number of concurrent spectrum-accesses, we illustrate the impact of several design choices for a SAM. We emphasize the coexistence between cochannel networks, fine granular spectrum access, and enforcing transceiver-performance standards. We present a secondary spectrum access model, *Primary Owned*

978-1-4799-2661-9/14/$31.00 ©2014 IEEE

Secondary Spectrum Access (POSSA), wherein the incumbents play an active role in managing the allocation of the spectrum for secondary purposes. POSSA helps to address the above mentioned technical and regulatory concerns, improves the performance of spectrum sharing, and encourages incumbents to extract more value out of their spectrum investments.

In related work, adopting the concept of usage of spectrum by receivers from [8], [9], we defined a spectrum usage quantification model based on the spectrum usage of the individual transmitters and the receivers [6] when multiple, spatially overlapping networks are sharing the spectrum in the time, space, and frequency dimensions. The proposed approach of quantified access to spectrum is inspired by the *spectrum consumption modeling* concept put forth by Stine [10]. Instead of defining spectrum rights based on the transceiver attributes, we defined a spectrum consumption quantification model that quantifies spectrum consumption by transmitters and receivers separately [6]. Thus, the spectrum rights for a spectrum-access request are driven by the actual spectrum consumption by the transmitter and receivers of the specific spectrum-access request. Similar to ‘Sensing as a Service’ [11], we separate the sensing function from the secondary user radio and apply an external sensor network based infrastructure for estimating of spectrum consumption in real time [7], [12]. In the proposed approach, the secondary users are provided the transceiver parameters for exercising spectrum access.

The paper is organized as follows. In Section 2, we describe the spectrum consumption quantification model that enables us to quantify the spectrum consumed by the transmitters and receivers. Next, we describe the QDSA model that facilitates spectrum access regulation with quantified spectrum-footprints in Section 3. In this regard, we discuss defining and enforcing spectrum-access policy and the infrastructure requirements. In Section 4, we illustrate several design choices for SAMs based on the QDSA paradigm. Here, we develop a baseline experiment and illustrate incremental performance improvement with modifications to the baseline experiments. Based on this, we emphasize network-coexistence with non-harmful interference, fine granular spectrum-access, and active role by the incumbents. Finally, we draw conclusions in Section 5.

II. Spectrum Consumption Quantification Model

Traditionally, we assume that spectrum is consumed by transmitters. This is because in the static spectrum allocation paradigm, a service could exclusively exercise the spectrum in the assigned time, space, and frequency dimensions.

The spectrum is consumed by receivers by constraining spectrum access by other transmitters. For guaranteeing successful reception, protection is traditionally accomplished in term of guard-bands, separation distance, and constraints on operational hours. Thus, the presence of receivers enforces limits on the interference-power in the space, time, and frequency dimensions. Since traditionally spectrum access is exclusive in the time, space, frequency dimensions, spectrum consumption by receivers need not be separately considered [13].

Dynamic spectrum sharing approach is a paradigm shift from the conventional static and exclusive approach to spectrum allocation. The networks could be *spatially overlapping* and the spectrum access is *shared* in the time, space, and frequency dimensions. The traditional metrics like Spectrum Utilization factor (SUF) and Spectrum Utilization Efficiency (SUE) are suited for measuring the usage of the spectrum by a single network. When multiple heterogeneous networks operate simultaneously, we need the ability to quantify how much spectrum used by the transceivers from each of the networks, how much harmful interference is is caused by and to each of the transceivers. Some of the recently proposed metrics [14–16] that can be applied have applications in specific cases and cannot be used for quantifying the utilization, availability, and degradation of spectrum under generic spectrum sharing scenarios.

Under the spectrum sharing paradigm, the spectrum consumption by each transceiver in the system needs to be individually considered as against the traditional approach of considering the spectrum consumption on a network basis. In the proposed spectrum consumption quantification model [6], the spectrum consumption by a network is determined based on the spectrum consumption of each of the transmitters and receivers. Here, we briefly describe quantification of spectrum consumption when multiple networks are sharing the spectrum in the space, time, and frequency dimensions.

We consider a generic system of multiple cochannel wireless networks in two-dimensional geometric space. A network is assumed to exercise one or more spectrum accesses. A spectrum access is carried out by a transmitter and one or more receivers. The spectrum consumed by a transmitter is quantified in terms of the power received from the transmitter in the space, time, and frequency dimensions. The amount of power received from a transmitter at a point is defined as *transmitter-occupancy*. The aggregate power received at a point from all cochannel transmitters is defined as *spectrum-occupancy* at the specified point. Receivers consume spectrum by imposing constraints on spectrum-access parameters of the cochannel transmitters in the space, time, and frequency dimensions. The limit imposed on the interference-power at a specific point in space is termed as *interference-opportunity*. The effective interference-opportunity due to all cochannel receivers at a point in space is termed as *spectrum-opportunity*. We note that the transmitter-occupancy decreases with increasing distance from the transmitter while interference-opportunity increases with distance from the receiver under physical interference model.

Next, we discretize the spectrum-occupancy and spectrum-opportunity based on the granularity of usage in the time, space, and frequency dimensions. This is accomplished by dividing the spectrum space into multiple unit spaces and quantifying spectrum-occupancy and spectrum-opportunity at a sample point in each of the unit spectrum-spaces. The total spectrum consumption is computed by summing up the spectrum consumed in the unit spectrum-spaces in the geographical region. Refer to [6] for more details.

The spectrum consumption quantification model can be applied to quantify, estimate, analyze, and optimize spectrum consumption under generic spectrum sharing scenarios.

III. Quantified Dynamic Spectrum Access Paradigm

In this Section, we apply the spectrum consumption quantification model for provisioning quantified spectrum access to multiple heterogeneous networks and manage the spectrum consumption in a geographical region.

We note that the spectrum consumption by transmitters is dependent on

1) the actual (as against the maximum) transmit power.
2) the antenna directionality employed during transmission.
3) the location of the transmitter. In case of transmitter mobility, the spectrum-access policy needs to be periodically updated.

*In order to **control** the spectrum consumption by **transmitters**, these transmitter parameters should be part of the spectrum access footprint.*

Similarly, the spectrum consumption by receivers is dependent on

1) the minimum SINR required for successful reception.
2) the antenna directionality employed during reception.
3) the location of the receiver. In case of receiver mobility, the spectrum-access policy needs to be periodically updated.

*In order to **control** the spectrum consumption by the **receivers**, these receiver parameters should be part of the spectrum access footprint.*

Under quantified dynamic spectrum access paradigm, the spectrum-consumption is quantified in terms of unit-regions in the spatial dimension, spectral-band in the frequency dimension, and time-quanta in the temporal dimension. A spectrum-access footprint represents the spectrum resource quantified in the space, time and frequency dimensions.

A spectrum-access policy represents the spectrum access attributes for a spectrum resource, given the transmitter and receiver positions, propagation medium, and expected link quality. Similar to [10], a spectrum-access policy is expressed in terms of

- Maximum transmit power
- Radiation pattern
- Spectral mask
- Start time and end time
- Location boundaries
- Modulation and coding parameters

A service provider, a spectrum broker, or a proprietary network can request for spectrum-access to spectrum-Access Policy Infrastructure (SPI). SPI assigns and enforces allocated spectrum-access-policies. Spectrum management infrastructure (SMI) schedules spectrum-access requests and defines spectrum-access parameters in order to manage spectrum consumption. Spectrum Analysis Infrastructure (SAI) estimates the spectrum-access footprints and the available spectrum in real time using the RF environment data acquired by Spectrum Sensing Infrastructure (SSI).

A. Enforcement of spectrum-access policy

When transceiver devices do not conform to the spectrum-access constraints imposed by the spectrum-access policy, it may lead to degradation of link-throughput and service-disruption for the cochannel networks.

Conformance to spectrum-access policy can be enforced via estimation of the spectrum consumption by the transmitters [7]. By exploiting the cyclostationarity of signals, a grid of uniformly distributed sensors can detect, geolocate the transmitters, and estimate the transmit-power of the transmitters. A fusion-center can combine the estimates to estimate spectrum consumption by each of the cochannel transmitters. SPI can determine if the actual spectrum consumed by a transmitter is unacceptable, and initiate a regulatory action. We illustrate this scenario in Figure 1. Here, we note that when receivers do not comply with the receiver parameters specified in the spectrum access footprint, the receiver spectrum consumption gets incorrectly quantified and it may result into harmful interference experienced at the receiver. As non-conformance by receivers does not cause any harm to other services, no regulatory action is needed.

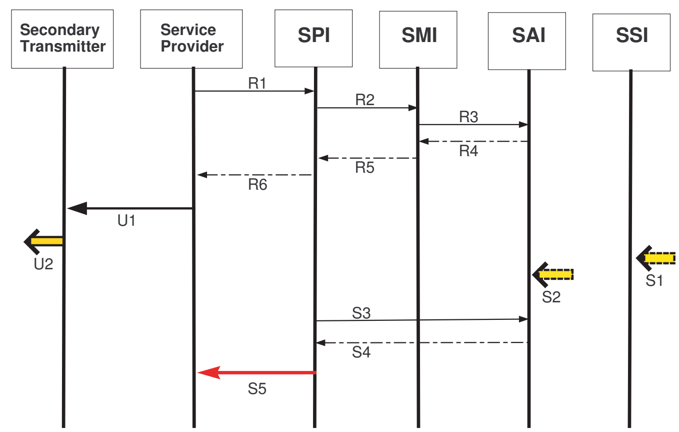

Fig. 1. Illustration of defining and enforcing a spectrum-access policy. A service-provider requests a spectrum-access footprint from SPI along with the information about position and capabilities of the transceivers (Arrows R1-R6). A service-provider assigns a partial time to one of the secondary transmitters (Arrow U1). The secondary transmitter fails to conform to the assigned quantified spectrum-access policy (Arrow U2). This scenario is detected by transmitter footprint estimation (Arrows S1-S4) and regulatory action is taken (Arrow S5).

IV. Improving Spectrum Serviceability

In order to extract more value from spectrum, we need to

- maximize the number of scheduled spectrum-access requests
- minimize the number of harmfully interfered receivers

In order to maximize the number of the scheduled requests, the *available spectrum* needs to be maximized. We note that spectrum consumption by receivers depends on the SINR at the receivers. The SINR at the receivers could be improved by increasing the signal power and minimizing interference power. This necessitates a SAM to schedule spectrum-access requests and assign spectrum-access parameters so as to optimize SINR at all the scheduled receivers. Here, we note that the problem of optimal scheduling and power allocation is NP-hard [17].

With regards to the coexistence strategy, different SAMs have different interference management strategies.

1) The SAM Candidates: Per the **Underlay** spectrum access mechanism [2], the secondary users (SUs) exploit the spectrum with a very low transmit power in order to not cause severe interference at the primary user (PU) receivers. We consider the secondary transmit power to be 30 dB above the thermal noise floor (-106 dBm for 6 MHz band). The underlay approach does not require to check whether the primary network is active at this time and location.

The second approach to spectrum access is the **Overlay** approach which requires secondary user devices to confirm that the primary transmitter signal is not present and it can access the spectrum with constrained transmit power only if the signal is not detected [2]. The key concern with this approach is the sensitivity required for PU detection maps to a large spatial range [18]. Thus, in most of the spatial locations, the spectrum could not be exercised when the primary network is active.

The third approach we investigate is an enhancement to the previous overlay approach exercising fixed constrained transmit power. It uses dynamic transmit power in order to ensure high SINR for its receivers and protect from cochannel interference from other secondary user networks. It however cannot ensure non-harmful interference to the primary network users that are just beyond the sensing range of the secondary user network due to interference aggregation effect. We term this approach as Secondary Throughput-oriented OVerlay SAM **(STOV DSA)**.

The last approach assumes the knowledge of the locations of the primary receivers and thus can correctly infer the interference margin imposed by the primary receivers. However, when multiple secondary networks are exercising secondary access with transmit power implied by the interference margin, the primary receiver may still experience aggregate interference. To avoid this interference aggregation scenario, a guard margin is used when inferring the transmit power for the secondary network. We term this approach as Secondary Throughput and Primary Protection oriented OVerlay SAM **(STPPOV DSA)**.

Table IV-1 shows the summary of spectrum access strategies of the SAM candidates.

TABLE I
SUMMARY OF THE SAM PROPERTIES

SAM	Potential Interference	Constraint on P_{SU-MAX}
Underlay DSA	to PU and SU	Fixed and low
Overlay DSA	to PU and SU	Fixed and high
STOV DSA	to PU and SU	Dynamic and high
STPPOV DSA	to SU only	Dynamic and high

Next, we perform experiments to improve the number of scheduled requests and compare the performance of different SAM candidates.

We consider a geographical region with a primary transmitter at the center. The secondary users do not have knowledge of the positions of the primary receivers which are assumed to be at the worst case positions. The SU networks are scattered in the geographical region. The mean path-loss exponent is 3.5. The initial parameter settings are as follows.

- The minimum desired SINR for the worst case PU receivers is 20 dB and the SINR experienced is equal to the minimum desired SINR, i.e. 20 dB. The minimum desired SINR for secondary receivers is 3 dB.
- The range of the PU networks is 500 m and the range of the SU networks is 100 m.
- All the PU and SU transceivers are employing omnidirectional spectrum access.

In a series of following experiments, we *incrementally* change these parameters in order to improve on the *available* spectrum. This helps us study how the available spectrum gets exploited by the candidate SAMs.

A. The Base Case Experiment

The performance of the four SAMs for this base setup is shown in Figure 2. We can see that:

1) In case of underlay spectrum access, all the SU networks are exercising spectrum, thus the number of scheduled requests is same as the number of SU networks. However, since the transmit power is constrained, the signal power at the secondary receivers is very low. Also, these receivers experience interference from the PU transmitter and the transmitters of the cochannel SU networks.
2) In case of overlay spectrum access, when PUs are not within the sensing range of the SU network transceivers, spectrum access is exercised. The SU sensitivity is considered to be -80 dBm and the PLE of 3.5 which implies 1390 m of sensing range. Thus, very often, with overlay spectrum-access policy, access is not performed and the spectrum consumption performance is poor when PU is present. When it can exercise access, the SU transmit power is constrained and the signal power at the SU receivers may not be high and those receivers need to tolerate interference from the cochannel PU and SU transmissions.
3) The dynamic overlay (STOV) with unconstrained SU transmit power faces similar issues and shows low spectrum consumption performance when PU is present. Because it employs high transmit power, the SINR at the SU receivers is high and receiver spectrum consumption is low and the available spectrum remains high.
4) The dynamic overlay with protection of PU receivers from aggregate interference (STPPOV) shows better performance as compared to overlay and dynamic overlay in the cases SUs can detect the presence of the PU

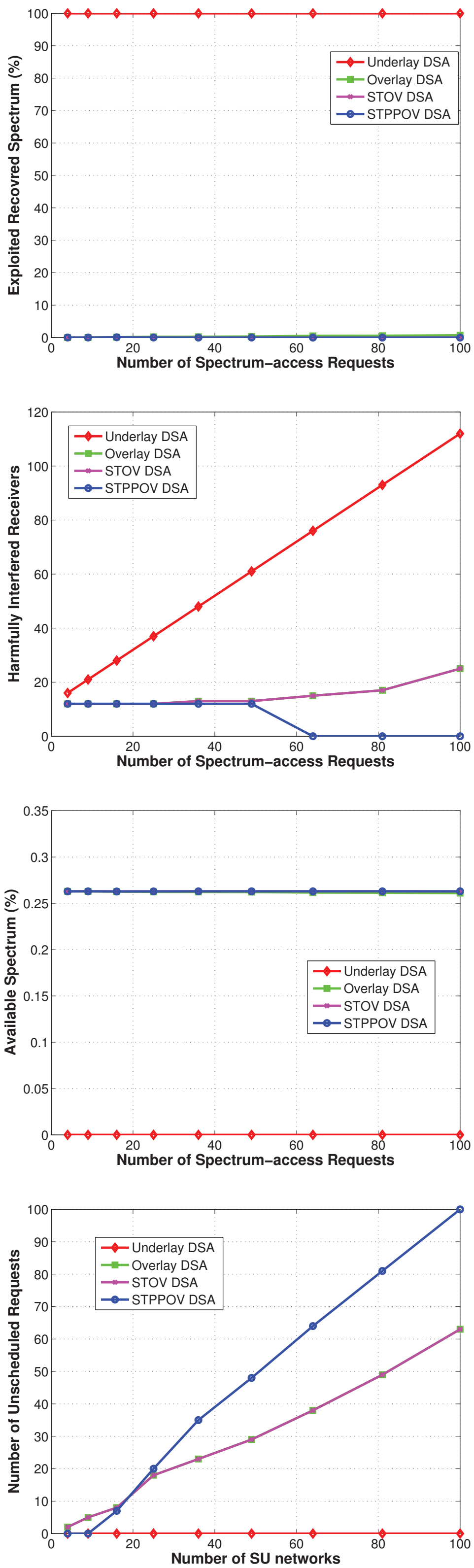

Fig. 2. The baseline performance of four SAMs with varying number of the secondary networks when the PU is active (**The base experiment**). A SAM with lower number of unscheduled requests, lower number of harmfully interfered receivers, and lower spectrum consumption by transceivers (that is, higher amount of available spectrum) makes more efficient use of spectrum.

transmitter but their transmissions do not cause harmful interference to the PU receivers. It, however, suffers with lower performance in general because of the guard margin to protect the PU receivers from the aggregate interference effect.

1) A Case for Better PU Receivers (Experiment-1): In this experiment, the PU receivers are assumed to be of better quality. The SINR experienced at the PU receivers is same as 20 dB; however, the minimum desired SINR is considered to be 10 dB. Thus, the interference margin at the receivers is higher and the available spectrum, in turn, is higher. Figure 3 shows the results for this experiment.

Following are the observations from this experiment.

- The available spectrum in case of STOV DSA and STPPOV DSA is higher due to their ability to provision higher SINR to the SU receivers and thus the spectrum consumption by the SU receivers is deterring the available spectrum. The plot with the exploited recovered spectrum shows the same effect from spectrum consumption perspective. Here, we see that the the exploited recovered spectrum by overlay DSA as higher as compared to the STOV DSA and STPPOV DSA mechanisms.
- Similar to the base experiment, the number of unscheduled requests in case of STPPOV DSA is lower as as compared to STOV DSA when PU transmitter lies within the sensing range of the SU network transceivers; however the effect is more pronounced due to higher interference margin at the PU receivers.
- In case of STPPOV DSA, even though the PU receivers are not experiencing harmful interference, the number of harmfully interfered receivers is nonzero due to secondary networks causing harmful interference to other cochannel SU networks. In case of Overlay DSA and STOV DSA as well, there is no protection to SU receivers and the number of harmfully interfered receivers is quite high. *The lack of **network coexistence with non-harmful interference** could be considered as a serious limiting factor in actual practice when the secondary spectrum access is employed for services requiring good link quality.*

We argue that directionality increases SINR at the receivers and reduces the consumption of spectrum by receivers. Directional transmission by SU transmitters helps to reduce interference and further improve SINR at the PU and SU receivers. *In order to improve spectrum consumption performance, it is desired to have directional transmission whenever possible.*

2) A Case for Directional Transceivers (Experiment-2): In the next experiment, the PU and SU receivers are assumed to employ directional reception. Also, the SU transmitters are assumed to employ directional transmission. The directional antenna beamwidth is assumed to be 60°. With directional transmission at the SU transmitters, the interference probability is reduced and SINR is improved. This results in lower spectrum consumption by the receivers and a smaller number of harmfully interfered SU receivers.

Firstly, we observe that *the available spectrum has increased from close to 3% to close to 15%.* With directional

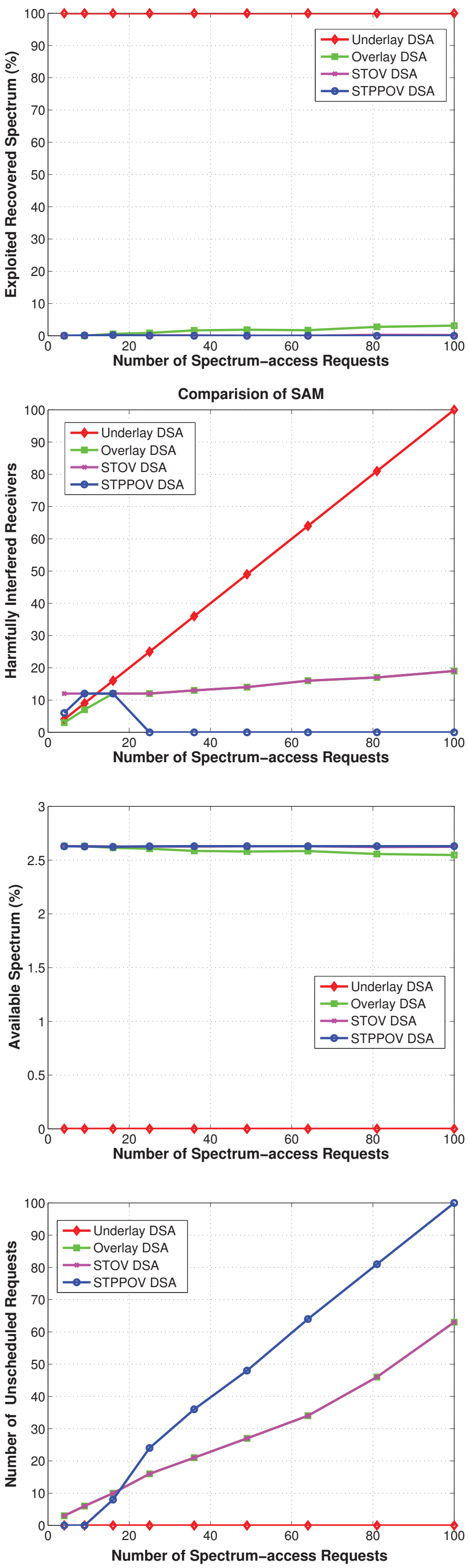

Fig. 3. The performance comparison of four SAMs with varying number of the secondary networks when the PU is active (**Experiment-1**). In this experiment, the PU receivers are assumed to be of better quality and the spectrum consumption by PU receivers is low yielding higher amount of the available spectrum than the base experiment.

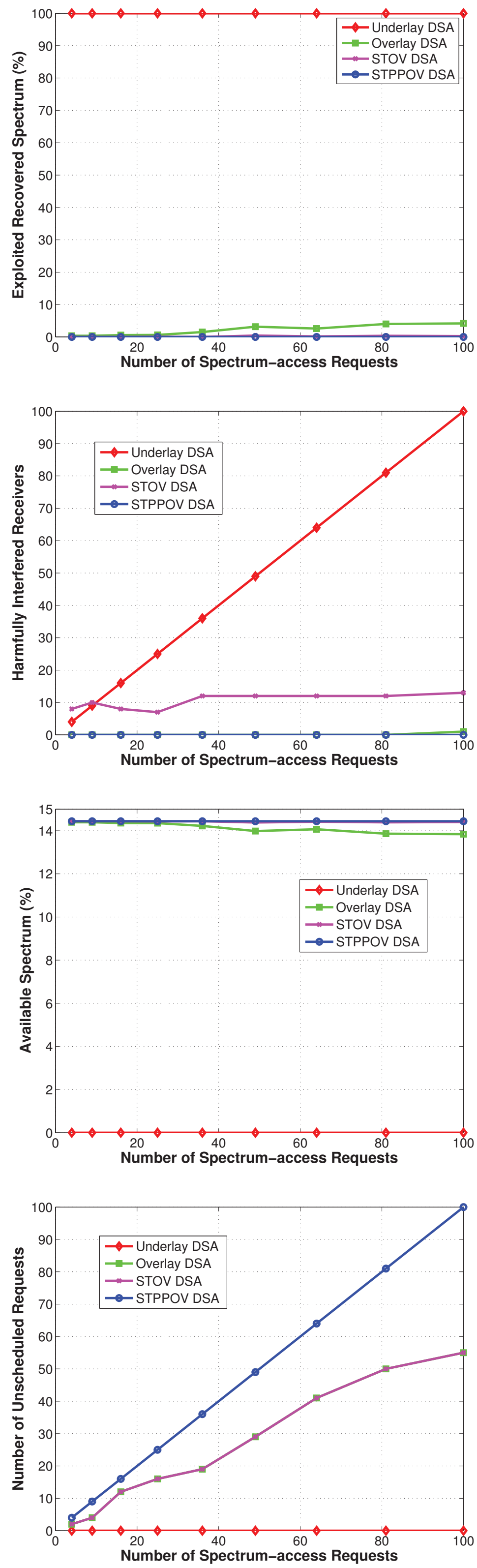

Fig. 4. The performance comparison of four SAMs with varying number of the secondary networks when the PU is active (**Experiment-2**). In this experiment, the SU and PU receivers are employing directional reception with 60° beamwidth antenna and the SU transmitters are employing direction transmission in addition to the assumptions from Experiment-1.

reception at the PU receivers, the spectrum consumption by the PU receivers is reduced and higher spectrum is available.

We see that the there is not much impact on the SAM performance as Overlay and STOV DSA mechanisms would exploit the higher available spectrum only if the PU transmitter is not detected within their sensing range.

3) A Case for Higher PU Transmit Power (Experiment-3): So far, we tried to improve the spectrum consumption performance of transceivers by improving the receiver quality and using directionality. Next, we consider the ***Primary Owned Secondary Spectrum Access (POSSA)*** scenario wherein the secondary spectrum access in a licensed band is managed by the spectrum-access policy defined by the incumbent owners of the spectrum.

From the perspective of incumbents, letting the purchased spectrum be underutilized over most times and locations undermines the financial investment. It would be in the business interests of incumbents to draw out more value from the spectrum they owned. In order to make secondary spectrum access feasible while not affecting the primary service is the very same problem of improving spectrum consumption performance in the restricted context of a single frequency band. In the next experiment, we focus on the POSSA scenario wherein the owner of the spectrum plays an active role in order to improve the spectrum consumption performance.

In this experiment, in addition to the assumptions from Experiment-2, the incumbent network is assumed to be using *higher transmit power to boost the SINR at the primary receivers*. As we have seen previously, the spectrum consumption by the receivers is reduced with increasing SINR and higher amount of spectrum would be available for exercising secondary spectrum access. **We argue that for improving spectrum consumption performance, it is necessary for the owners of the spectrum to play an active role.** From Figure 5, we observe that **the available spectrum has increased from close to** 15% **to close to** 100%. This is because the interference margin implied by the SINR at the PU receiver is much higher with increase in the PU signal power. Note that Figure 5 shows the number of scheduled connections instead of the number of unscheduled connections to emphasize the poor numbers of the scheduled connections even when the available spectrum is close to 100%.

The secondary access scenario is not encouraging. The performance of STPPOV DSA mechanism which ensures protection of PU receivers while opportunistically improving the throughput for secondary networks is found to be not able to exploit a substantial portion of the available spectrum even when nearly 100% of the spectrum is available.

With the transition to dynamic spectrum sharing, the cochannel networks would be spatially overlapping and the access to the spectrum is overlapping in the spatial, spectral, and temporal dimensions. Thus, we need to separately consider the spectrum consumption by a network transmitter and the spectrum consumption by receivers while improving the spectrum consumption performance.

When we consider scheduling of the spectrum-access re-

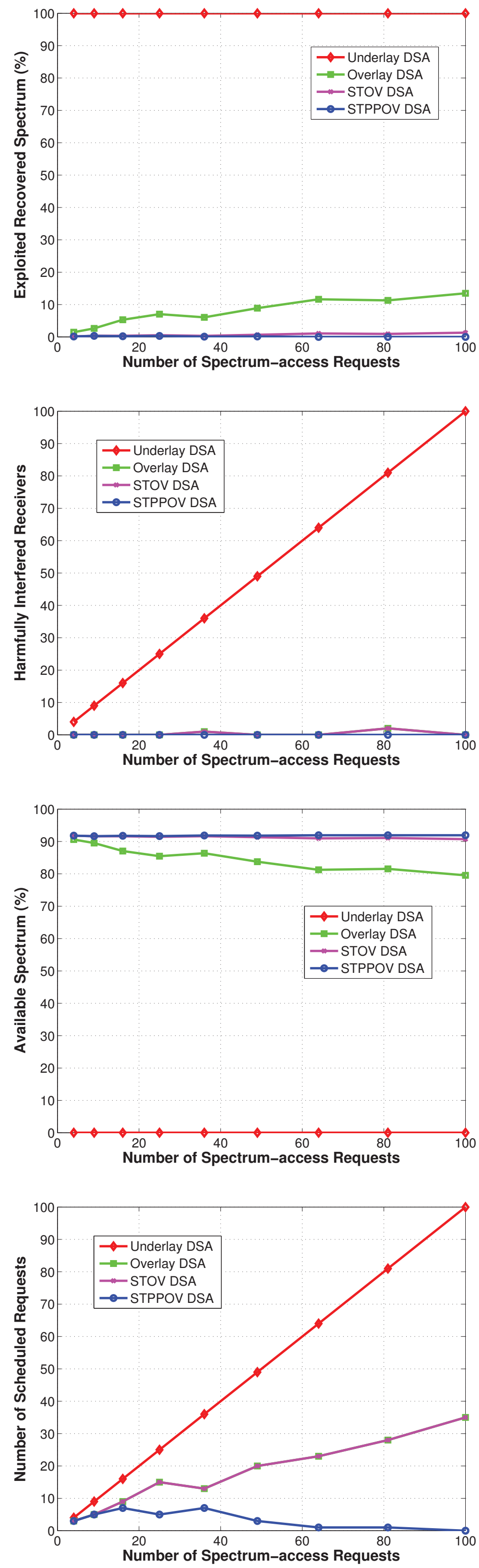

Fig. 5. The performance comparison of four SAMs with varying number of the secondary networks when the PU is active (**Experiment-3**). In this experiment, the incumbent network is assumed to be using higher transmit power to boost the SINR at the primary receivers in addition to the assumptions from Experiment-2.

quests, we need to consider transmitters and receivers together. The aggregate consumption of spectrum by network transceivers, ***network spectrum consumption***, plays an important role in efficient scheduling of the spectrum-access requests and improving the spectrum consumption performance.

4) The Case for Favoring the Requests with Lower Network Spectrum Consumption (Experiment-4): This poor performance of STPPOV DSA mechanism is discouraging for POSSA. In this experiment, we focus on improving the spectrum allocation in order to improve spectrum consumption performance.

The four SAMs used in comparison allow the networks to access the spectrum as long as their minimum SINR is met. To realize fairness to all the cochannel SU networks, the SU transmit power is proportionately increased until the transmit power reaches the upper limit.

With the resource management perspective elevated by spectrum discretization, the role of SAM can be viewed as allocating a quantified amount of spectrum to networks (i.e. network transmitters and receivers). *To improve the spectrum consumption performance, SAM needs to design spectrum-access policy in such a fashion that the spectrum consumed by the networks is minimized and in turn the available spectrum is maximized.*

Thus, our objective for designing spectrum allocation algorithm is to maximize the availability of the spectrum and the number of scheduled connections subject to the constraint that no (primary or secondary) receiver experiences SINR lower than the minimum desired SINR for that receiver.

In this experiment, we add a candidate mechanism that emphasizes on coexistence and favors maximizing the available spectrum in scheduling. Each SU network is allowed to exercise the maximum transmit power and the spectrum-access requests are ordered based on the network spectrum consumption weights. The SAM attempts to schedule the request by a network with the lowest network spectrum consumption (NSC). If it does not cause harmful interference to *any (PU or SU)* of the cochannel networks, only then it is scheduled. The SAM evaluates all the secondary-access requests for coexistence favoring the networks with lower network spectrum consumption.

Here, we note that the spectrum-access requests with

- a smaller network-range are favored as the receivers would experience higher SINR and their network spectrum consumption weight would be lower.
- directional transmission and reception are favored as it helps to improve SINR and reduces the network spectrum consumption.

The setup for the experiment is kept the same as Experiment-3. The incumbent network is assumed to be using higher transmit power to boost the SINR at the primary receivers and the available spectrum would be close to 100%. The performance of SAMs is shown in Figure 6. The performance of 'NSC-CX DSA' in terms of the number of scheduled requests seems very much promising as most of the secondary spectrum-access requests are serviced.

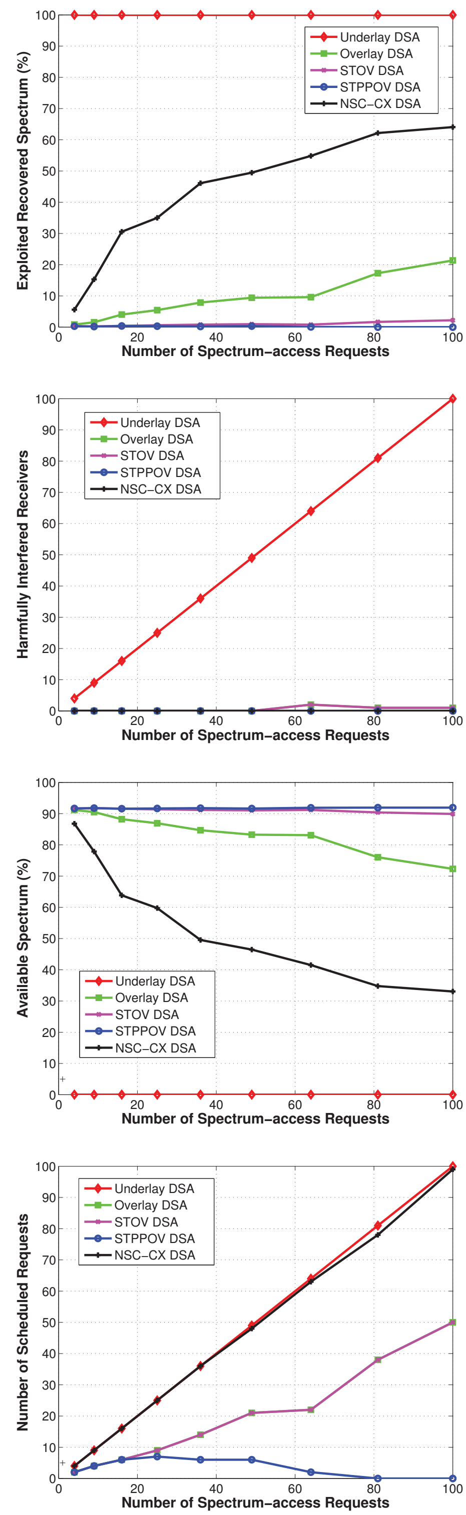

Fig. 6. The performance comparison of SAMs with varying number of the secondary networks when the PU is active **(Experiment-4)**. In this experiment, the incumbent network is assumed to be using higher transmit power to boost the SINR at the primary receivers in addition to the assumptions from Experiment-3. The 'NSC-CX DSA' mechanism favors spectrum-access requests with lower network spectrum consumption and also ensures coexistence with cochannel primary and secondary networks.

A few more observations on the performance of ‘NSC-CX DSA’.

- We note a salient feature of the algorithm is that it allows each network to perform the best in terms of minimizing the spectrum consumption [18]. This makes it possible to independently consider each request and then define the order for scheduling.
- As mentioned earlier the objective of ‘NSC-CX DSA’ is to minimize the network spectrum consumption and and maximize the number of the scheduled connections. Thus, it may not have optimal performance in terms of scheduling and power allocation in which case the network spectrum consumption need not be low enough.
- As expected, the number of harmfully interfered receivers with ‘NSC-CX DSA’ is zero.
- The exploited recovered spectrum is higher due to the higher number of scheduled connections and it is the same reason why the available spectrum is lower with ‘NSC-CX DSA’.

5) A Case for the Knowledge of the PU receiver positions (Experiment-5): The obvious next question is can we do better? In all the experiments from the base case to experiment-4, we had assumed the primary receivers are located at the worst case positions. This is mainly because, traditionally the primary receivers are assumed to passive receivers. POSSA makes a reasonable case to exploit the knowledge of the *active* receiver positions to extract more value from the existing spectrum. Without the knowledge of the receiver positions, the secondary spectrum access would be only possible outside the range of the primary service network and this would not be appealing from business perspective.

In this experiment, we position the primary receivers at half the range i.e. 250 m. We assume the knowledge of the actual receiver positions is available in case of the ‘NSC-CX DSA’ and evaluate the improvement in the performance of the algorithm. From Figure 7, we observe that the available spectrum has increased as PU receivers are positioned at a distance of half the range of the service networks reducing the spectrum-consumption by receivers. This improves the performance of the STPPOV DSA and it is higher than the performance of Overlay DSA and STOV DSA in all cases for the number of secondary networks.

We observe that the number of scheduled requests for ‘NSC-CX DSA’ performance has also slightly improved because the networks within the primary service coverage area and that are not close to any of the primary receivers are able to exercise the secondary spectrum access.

6) The Case for Small Cell Secondary Networks (Experiment-6): The next question is how far could we go with scheduling of the secondary spectrum-access requests? As we can see from the previous experiment, the available spectrum is close to 40% when the number of requests is 100. As we are scheduling higher number of the secondary spectrum-access requests, the SINR at the receivers is reduced (The SINR is still above the minimum desired SINR threshold in order to ensure successful reception) and

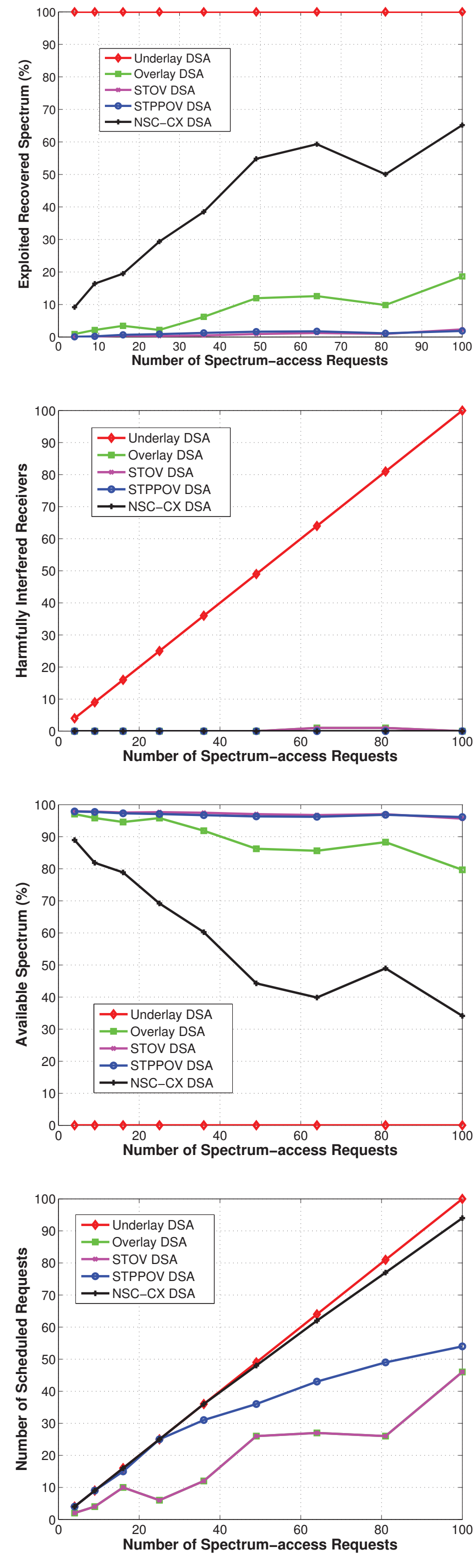

Fig. 7. The performance comparison of SAMs with the varying number of the secondary networks when the PU is active **(Experiment-5)**. In this experiment, the primary receivers are not positioned at the worst case locations but at a distance of half the range of the service networks. It results into higher amount of the available spectrum improving SAM performance.

the interference margin is lower at the receivers. As the number of scheduled connections goes close to 100, the available spectrum may decrease to nearly 0%.

An alternate question to ask is how would it be possible to accommodate higher number of secondary spectrum-access requests? In this experiment, we reduce the range of the secondary networks to 40 m and evaluate the performance of the DSA mechanisms. We observe that

- the performance of 'NSC-CX DSA' and 'STPPOV DSA' in terms of the number of connections has increased significantly.
- the available spectrum with 'STPPOV DSA' is higher than 'NSC-CX DSA'. This is due to fairness-favoring behavior of 'STPPOV DSA' able to choose transmit powers that are not very high as is the case with 'NSC-CX DSA' thus limiting interference power but not low enough to significantly increase the receiver consumed spectrum. The same fairness algorithm is used by the 'Overlay DSA' and 'STOV DSA' and the available spectrum is high in case of those mechanisms as well.

The high spectrum consumption performance with this experiment setup is attributed to the fine granular spectrum opportunities getting exercised. **We argue that for realizing the potential of dynamic spectrum sharing paradigm, the spectrum access granularity needs to be much finer.**

7) The Case for Dynamic Spectrum Sharing (Experiment-7): Now, we consider a more generic case wherein there is no PU, i.e. the spectrum rights with all the networks are equal. In the context of POSSA, this case could also be seen the case when the primary service network is not active.

In this experiment, all the networks are randomly positioned. The range of all the networks is 40 m. The minimum desired SINR at the receivers is 3 dB. The transmitters and receivers are directional with 60° antenna beamwidth. We observe that

- Except for 'STPPOV DSA' mechanism, for all candidate mechanisms, all the spectrum-access requests have been serviced. The 'STPPOV DSA' is not able to support 100% of the requests because of the guard margin setting to avoid the aggregate interference effect.
- There are no harmfully interfered receivers for all candidate mechanisms other than the Underlay mechanism. One reason for this is we consider fine granular spectrum access (the network ranges are small). In the next experiment, we characterize the behavior of SAM with the varying range for spectrum access.

8) Characterizing the Effect of Range in Open Dynamic Spectrum Sharing Model (Experiment-8): In this experiment, the performance of various SAMs is characterized with the varying range of the networks in the dynamic spectrum sharing scenario. All the networks are randomly positioned. The minimum desired SINR at the receivers is 3 dB. The transmitters and receivers are directional with 60° antenna beamwidth.

We observe that

- The fine granular access leads to higher spectrum access

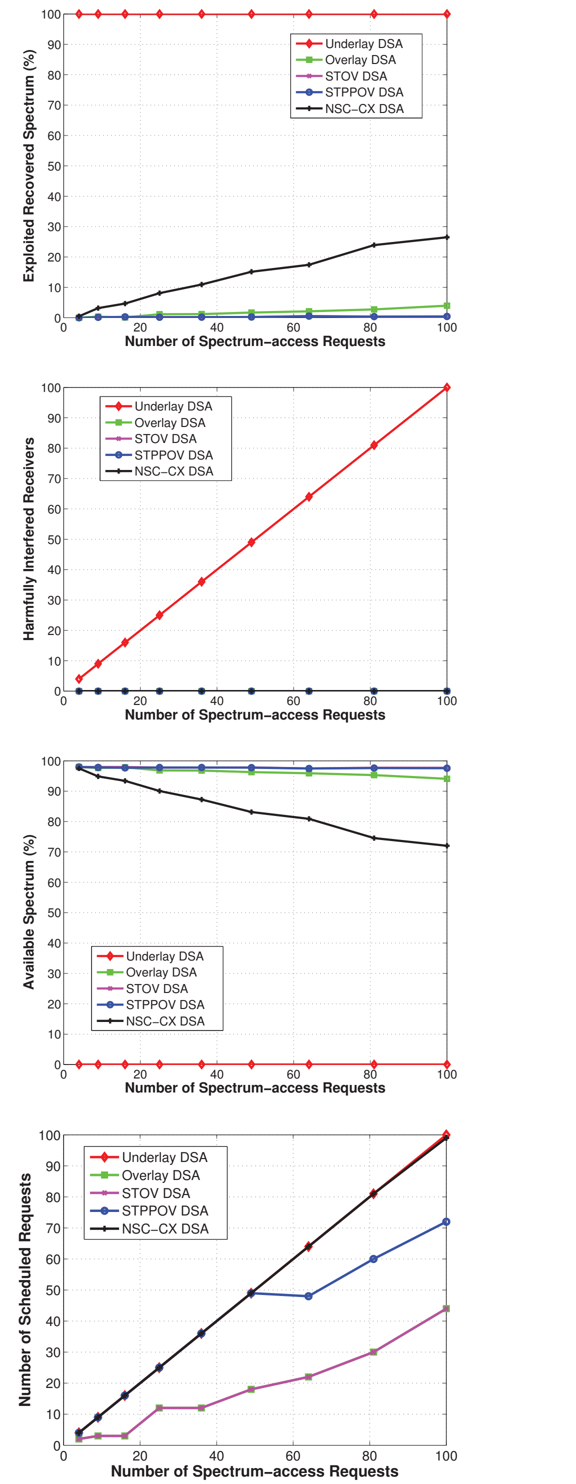

Fig. 8. The performance comparison of SAMs with the varying number of the secondary networks when the PU is active (**Experiment-6**). In this experiment, the the secondary networks are assumed to exercise spectrum-access with a small network-range. With secondary receivers being closer to the respective secondary transmitters resulting in better SINR and higher number of scheduled spectrum-access requests.

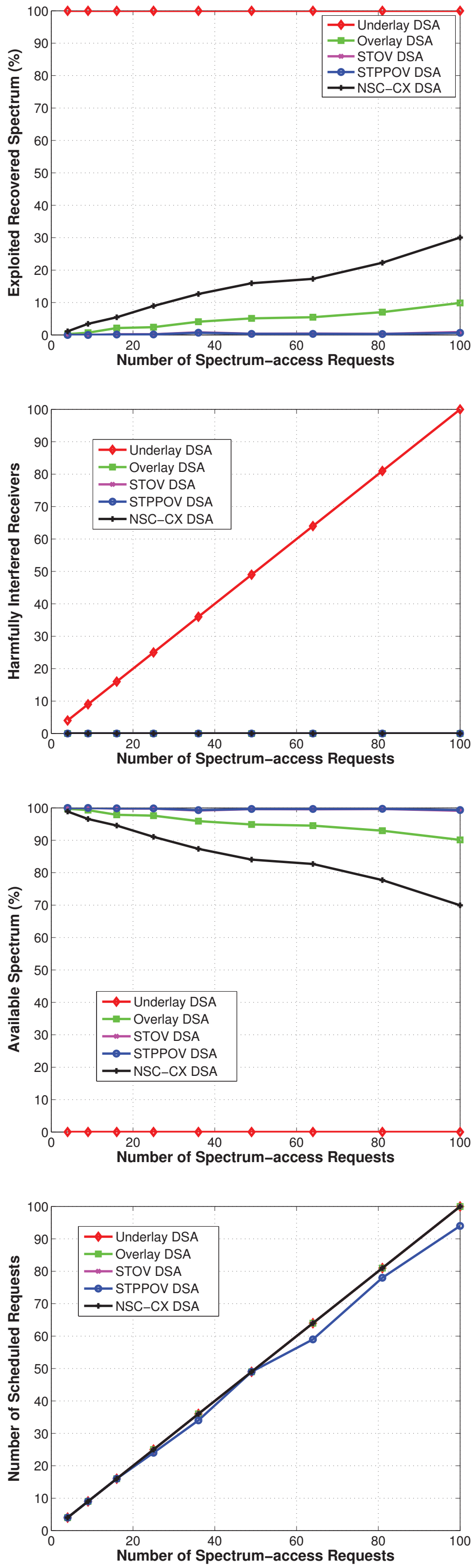

Fig. 9. The performance comparison of SAMs with the varying number of the secondary networks (**Experiment-7**). In this experiment, the primary network is assumed to be inactive. The performance of SAMs is higher with much higher availability of the spectrum.

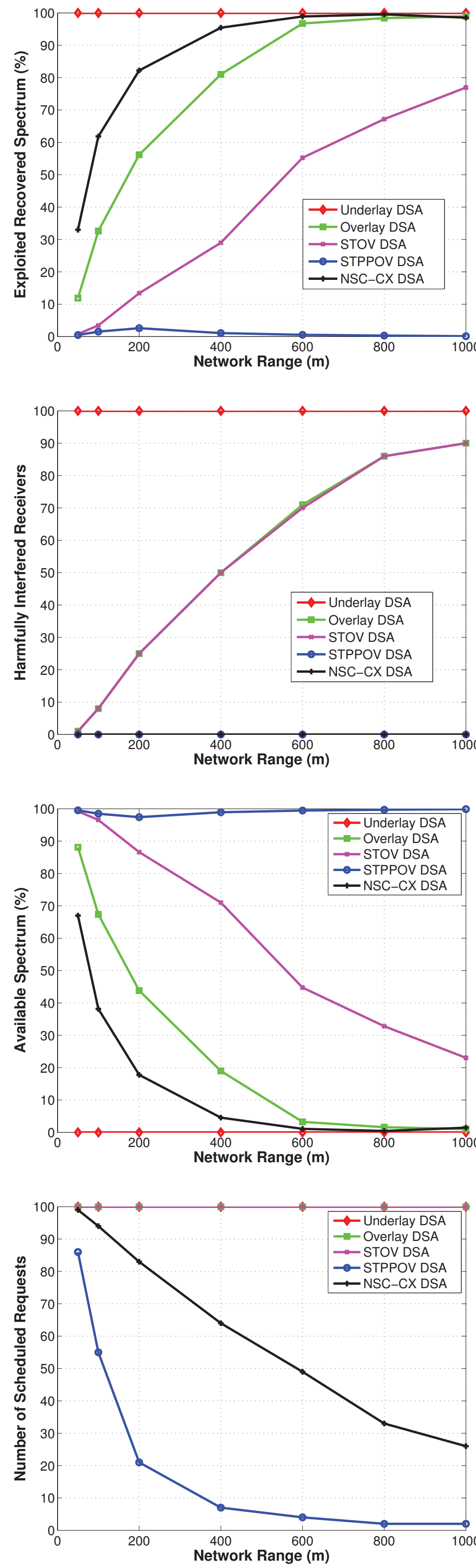

Fig. 10. The performance comparison of SAMs with the varying network range (**Experiment-8**). In this experiment, we observe that fine granular access with smaller network-ranges leads to higher spectrum-access requests being satisfied.

requests being satisfied. We argue that the fine granular spectrum access needs to be adopted whenever possible.
- The performance of 'NSC-CX DSA' mechanism is reasonably good for all network ranges. Especially for the larger network ranges, 'NSC-CX DSA' mechanism schedules a higher number of the spectrum-access requests as compared to other SAMs. This scenario helps us to understand expected performance in terms of how many spectrum-access requests would be scheduled when larger network ranges are desired.

V. Conclusions

In order to realize dynamic spectrum access, several technical and regulatory issues need to be addressed. Also, in order to improve revenue potential and make dynamic spectrum access appealing for businesses, it is also necessary to improve the serviceability of the spectrum. In this paper, we presented quantified spectrum access model that facilitates defining and enforcing the spectrum-access policy in real time. To improve serviceability, we investigated the design choices for spectrum access mechanism that would improve the throughput for spectrum sharing networks as well as the number of scheduled spectrum-access requests. Our findings suggest the need for

- **Quantified spectrum-access footprints.** The available spectrum can be precisely controlled with allocation of the quantified spectrum-access footprints. This helps to improve the schedulability of the spectrum-access requests.
- **Network-coexistence with non-harmful interference.** Ensuring non-harmful interference among ***all*** spectrum sharing networks, helps to improve the throughput and reliability of dynamic spectrum access.
- **Fine granular spectrum access**. As large portion of the spectrum-access opportunities are fine granular in the space, time, and frequency dimensions, the granularity of spectrum access plays a crucial role. The throughput and schedulability is significantly improved with the fine granular spectrum access.
- **Active role by incumbents**. With active role by incumbents, the available spectrum pool can be enhanced by altering the primary spectrum-access attributes and incorporating the knowledge of spectrum-access attributes of the primary transceivers.
- **Adopting interference tolerant signal model and transceiver technology** The minimum SINR for successful reception of the signal under cochannel interference conditions implies higher consumption of spectrum by the receivers. Adopting interference tolerant signal model and transceiver technology helps to improve the available spectrum. Also, directional transmission and reception is desired in order to further reduce the spectrum consumption.

With POSSA, we illustrated that secondary spectrum access could be attractive for the incumbents. The potential business opportunities should be able to justify the cost of the infrastructure necessary for spectrum consumption management.

References

[1] Federal Communications Commission, "Spectrum Policy Task Force Report," *ET Docket no. 02-135, Nov 2002*, Nov 2002.

[2] Qing Zhao; Swami, A, "A Survey of Dynamic Spectrum Access: Signal Processing and Networking Perspectives," *Acoustics, Speech and Signal Processing*, April 2007.

[3] I. Akyildiz, Won-Yeol Lee, K. Chowdhury, "Spectrum management in cognitive radio ad hoc networks," *Network, IEEE*, Jul. 2009.

[4] R. Menon, R.M. Buehrer, J.H. Reed, "Outage probability based comparison of underlay and overlay spectrum sharing techniques," *IEEE DySPAN 2005*, Nov. 2005.

[5] J.M. Peha, "Sharing Spectrum Through Spectrum Policy Reform and Cognitive Radio," *Proc. IEEE, vol. 97, no. 4, pp. 708719*, April 2009.

[6] N. Khambekar, C. M. Spooner and V. Chaudhary, "Extended Report: Spectrum Consumption Quantification," *Available: www.cse.buffalo.edu/ nvk3/scq.pdf*, 2013.

[7] ——, "Extended Report: Spectrum Consumption Estimation," *Available: www.cse.buffalo.edu/ nvk3/sce.pdf*, 2013.

[8] International Telecommunication Union Radiocommunication Sector (ITU-R), "Definition of Spectrum Use and Efficiency of a Radio System," *ITU-R Recommendation SM-1046-2*.

[9] M. Gastpar, "On capacity under received-signal constraints," *Allerton Conf. Communications, Control, Computing., Monticello, IL, Oct. 2004, pp. 13221331*, Oct 2004.

[10] J. A. Stine, "Spectrum-Consumption Models," *Chapter 20 in Cognitive Radio Technology, Second Edition, B. Fette, Ed., Academic Press*, 2009.

[11] M. Weiss, S. Delaere, and W. Lehr, "Sensing as a Service: An Exploration into Practical Implementations of DSA," *IEEE DySPAN, Singapore*, 2010.

[12] C. M. Spooner and N. Khambekar,, "A Signal-Processing Perspective on Signal-Statistics Exploitation in Cognitive Radio," *IEEE ICNC*, 2012.

[13] International Telecommunication Union Radiocommunication Sector (ITU-R), "Definition of Spectrum Use and Efficiency of a Radio System," *ITU-R Recommendation SM-1046-1*.

[14] FCC Notice of Inquiry and Notice of Proposed Rule Making, "In the matter of establishment of an interference temperature metric to quantify and manage interference and to expand available unlicensed operation in certain fixed, mobile and satellite frequency bands," *ET Docket No. 03-237*, Nov 13 2003.

[15] M. McHenry, E. Livsics, T. Nguyen, and N. Majumdar, "XG Dynamic Spectrum Access Field Test Results," *IEEE Communications, pp.5157*, June 2007.

[16] R. Tandra, A. Sahai, V. Veeravalli, "Space-time Metrics for Spectrum Sensing," *in Proceedings of the 2010 IEEE Symposium on Dynamic Spectrum Access Networks, Singapore*, April 2010.

[17] Matthew Andrews and Michael Dinitz, "Maximizing capacity in arbitrary wireless networks in the SINR model: Complexity and game theory," *In Proceedings of the 28th Conference of the IEEE Communications Society (INFOCOM)*, 2009.

[18] N. Khambekar, C. M. Spooner and V. Chaudhary, "Extended Report: Spectrum Consumption Analysis," *Available: www.cse.buffalo.edu/ nvk3/sca.pdf*, 2013.