Estimating the Use of Spectrum for Defining and Enforcing the Spectrum Access Rights

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Abstract—**In the static and exclusive spectrum allocation paradigm, the spectrum-access parameters for a service are chosen to mitigate potential harmful-interference and ensure minimum performance under worst-case conditions. The new dynamic spectrum-sharing paradigm necessitates dynamically defining and enforcing the spectrum-access rights while accommodating the dynamics of the RF environment and the spectrum-access scenarios. To enforce spectrum-access rights, we emphasize capturing the use of spectrum by an individual transceiver. We propose to articulate the spectrum-access rights in terms of the characterization of the spectrum used by an individual transceiver in the space, time, and frequency dimensions. In order to estimate the use of spectrum in real time, we employ a dedicated RF-sensor network that uses interference-tolerant algorithms to estimate the transceiver spectrum-access parameters and to characterize the propagation environment. We illustrate defining and enforcing a spectrum-access policy and we bring out its advantages for dynamic spectrum sharing.**

I. Introduction

In the conventional static and exclusive spectrum allocation paradigm, there is not much desirable radio frequency (RF) spectrum left to meet the ever-increasing demand from the existing and upcoming wireless services. It has been found that a significant amount of RF spectrum is underutilized in the space, time, and frequency dimensions [1], [2]. The new dynamic spectrum-sharing paradigm enables efficient use of the underutilized spectrum by enabling a shared access to the spectrum.

In the past decade, several spectrum-sharing models have been investigated [3–5]. Depending on the degree of sharing, the various spectrum-sharing approaches fall into exclusive spectrum use, static spectrum sharing, dynamic spectrum sharing, and pure spectrum sharing categories [5]. A key challenge for the spectrum-sharing models is defining and enforcing the spectrum-access rights under unknown RF-environment conditions and spectrum-access scenarios. Defining spectrum-sharing constraints to ensure *minimum* performance under the *worst-case* propagation conditions severely limits the opportunities to exploit the underutilized spectrum [6–8].

In this paper, we seek to address the problem of defining and enforcing spectrum-access rights based on real-time RF-environment conditions and realistic spectrum-access scenarios. Our approach is based on articulating the spectrum-access rights in terms of actual spectrum use in the space, time, and frequency dimensions by an individual transceiver. We divide the spectrum-space into discrete unit-spectrum spaces and estimate the use of spectrum by an individual transceiver in the space, time, and frequency dimensions. The estimation of used spectrum enables estimating the amount of spectrum that is potentially available for sharing with further RF users. A spectrum-access mechanism (SAM) can then define the spectrum-access rights for future spectrum-access requests in terms of the allowed quantified use of spectrum by each of the transceivers. The defined spectrum-access rights can be enforced with estimation of the actual use of spectrum.

In order to estimate the use of spectrum in real time, we employ an external dedicated RF-sensor network. The RF-sensors learn the fine-grained RF-environment and estimate the spectrum-access attributes of the transmitters. To passively estimate the spectrum-access attributes in the presence of cochannel interference, we employ detection, location estimation, and transmit-power estimation algorithms that exploit signal cyclostationarity [22]. The estimates of the spectrum-access parameters by multiple RF-sensors are fused to *estimate the use of spectrum*[1] in the unit-spectrum-spaces within a geographical region.

The remainder of the paper is organized as follows. In Section II, we discuss the limitations of the existing approaches to define and enforce the spectrum-access rights and underscore the need for characterizing the use of spectrum by an individual transceiver in the space, time, and frequency dimensions. In Section III, we provide a brief overview of the methodology to characterize the use of spectrum by individual transceivers within a geographical region. In Section IV, we describe characterization of the propagation environment and the estimation the transmitter attributes, and address estimating the use of spectrum in the space, time, and frequency dimensions. In Section V, we illustrate estimating the spectrum consumed by a single transmitter and the available spectrum under the dynamic spectrum-sharing paradigm. In Section VI, we explain the concept of defining and enforcing spectrum-access rights based on the estimated use of the spectrum. Finally, in Section VII, we draw conclusions and outline the future work.

II. Motivation

A. Defining and Enforcing a Dynamic Spectrum-Access Policy

Most of the work in the identification and exploitation of the underutilized spectrum focuses on the detection of the

[1] As described here, the problem of spectrum-estimation use involves several sub-problems. In the interest of illustrating how these sub-components come together to accomplish real-time characterization of the use of spectrum, we do not discuss the individual sub-problems in detail. In [9], we presented cochannel interference-tolerant algorithms for the purpose of signal detection, received power estimation, and TDOA estimation and provided illustrations of these algorithms.

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primary transmitter signal [10]. A simplistic approach for detecting a transmitter signal is to employ some form of energy detection. The transmitter-signal detection approach implies identifying a spatio-temporal spectrum-access opportunity and its performance is driven by the detection sensitivity. A multi-sensor cooperative approach helps to improve the performance of transmitter-signal detection [11–13]. However, the primary weakness of energy detection approaches is their well-known degradation under unknown or time-varying noise and cochannel interference conditions. Therefore, the transmitter signals are detected by exploiting signal cyclostationarity [14–17] in this work.

If the primary transmitter is far away from the secondary users, it is possible to access the underutilized spectrum while ensuring non-harmful interference to the primary receivers. In this regard, localization of transmitters based on the received signal strength is explored in [18].

The approach in this paper focuses on estimating the use of spectrum by the individual transmitters *and* receivers and thereby characterizing the spectrum-access opportunity in the space, time, and frequency dimensions. This provides two advantages. The first is that estimating the use of spectrum reveals the fine-grained spectrum-access opportunities and improves the recovery of underutilized spectrum. Thus, the spectrum available for the secondary users is increased. With estimation of real-time use, the *spectrum-access parameters could be dynamically and efficiently chosen* while protecting the existing spectrum users. Thus, estimation of the use of spectrum enables defining a spectrum-access policy.

The second advantage is the enabling of spectrum-access policy enforcement. As the use of spectrum by an individual transceiver is estimated, violations of the assigned spectrum-access policy can be detected. Thus, estimating the use of spectrum *enables automation* of the spectrum-access regulation under dynamic spectrum sharing.

B. A Dynamic RF Environment

For the past several decades, spectrum management has been centered around handcrafting allocation of the spectrum and imposing spatio-temporal boundaries to ensure minimum performance under worst-case conditions. Dynamic spectrum sharing requires the ability to characterize the unknown propagation conditions and spectrum-access scenarios in real-time and *adapt the use of spectrum* in response to the changes in the RF-environment.

III. Characterization of the Use of Spectrum

In order to characterize the use of spectrum in the space, time, and frequency dimensions, we first determine what constitutes *spectrum use*.

A. How is Spectrum Consumed?

Traditionally, it is assumed that spectrum is consumed by the transmitters only; however, the receivers *also* consume spectrum by constraining the RF power from other transmitters [19]. We note that for guaranteeing successful reception, protection is traditionally accomplished in terms of guard-bands, separation distances, and constraints on operational hours. Thus, the presence of receivers enforces limits on the interference-power in the space, time, and frequency dimensions. When the access to spectrum is exclusive in the space, time, and frequency dimensions, the spectrum consumed by receivers need not be separately considered [20].

The dynamic spectrum-sharing paradigm enables multiple spatially-overlapping wireless networks to share the spectrum. For characterizing the use of spectrum under the new paradigm, we argue that the spectrum consumed by the *individual* transmitters and receivers needs to be considered. While the RF power received from a transmitter decreases with increasing distance from the transmitter, the constraint imposed by a receiver on the tolerable interference power increases with increasing distance from the receiver. In the next subsection, we summarize the MUSE[2] methodology for characterizing and quantifying the use of spectrum [21].

B. Summary of MUSE

We consider a generic system of multiple spatially-overlapping wireless networks. The spectrum consumed by a transmitter is quantified in terms of the power received from the transmitter at points 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 the 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 defined as *interference opportunity*. The effective interference opportunity at a point in space due to all the cochannel receivers is defined as *spectrum opportunity*.

Next, we discretize the spectrum-occupancy and spectrum-opportunity based on the granularity of usage in the space, time, and frequency dimensions. This is accomplished by dividing the spectrum space into multiple unit-spectrum-spaces and quantifying spectrum-occupancy and spectrum-opportunity *at a sample point* in each of the unit spectrum-spaces. The aggregate use of the spectrum within a geographical region is computed by summing the spectrum consumed in the unit-spectrum-spaces; for example, the available spectrum is computed by summing the spectrum-opportunity in the unit-spectrum-spaces within the geographical region. Refer to [21] for more details.

C. Illustration

1) Use of the Spectrum at a Point: The methodology identifies the following five basic attributes that characterize the use of spectrum at a point in the system.

1) the *maximum permissible power* at any point in the system, P_{MAX}. This is usually driven by human safety considerations.

[2] A **M**ethodology for Characterizing and Quantifying the **USE** of Spectrum.

2) the *minimum power* at any point in the system, P_{MIN}. This could be an arbitrary low value below the noise-floor.
3) *spectrum occupancy* representing the spectrum consumed by all the transmitters.
4) *spectrum liability* representing the spectrum consumed by all the receivers in terms of constraining the interference power and thereby the occupiable RF power with respect to P_{MAX}.
5) *spectrum opportunity* representing the remainder of the RF-power, that is, opportunity for using the spectrum by existing or future transceivers.

Figure 1 illustrates the use of spectrum at a point.

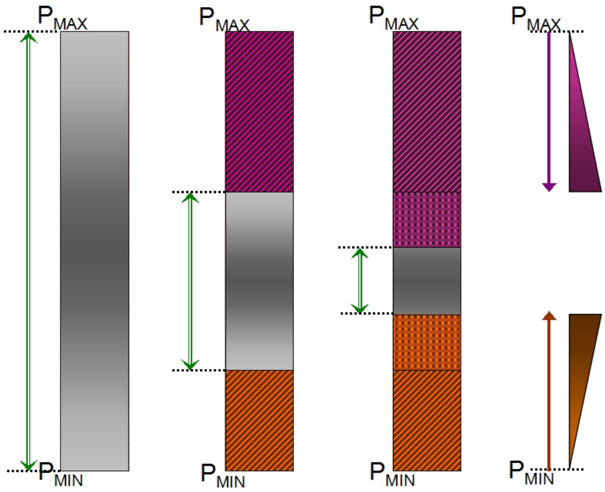

Fig. 1. Use of the spectrum at a point. The leftmost bar captures the maximum ($P_{MAX} - P_{MIN}$) spectrum-opportunity (shown with green double arrow) at a point when no transceivers are present. The middle bar shows the spectrum consumed by a transmitter and its receiver. The rightmost bar shows the spectrum consumed by two pairs of transceivers. Here, we note that the spectrum-occupancy grows from P_{MIN} towards P_{MAX} while spectrum-liability representing a constraint on the occupiable RF-power grows from P_{MAX} towards P_{MIN}. The spectrum opportunity continues decreasing as the transceivers consume more and more of the spectrum at a point.

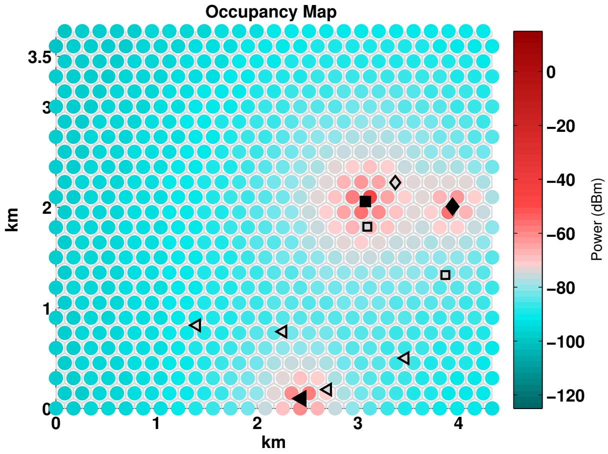

Fig. 2. Single-band spectrum-occupancy map showing the aggregate RF power across the unit-regions within a geographical region. Transmitters and receivers in a single network have the same shape; transmitter is solid.

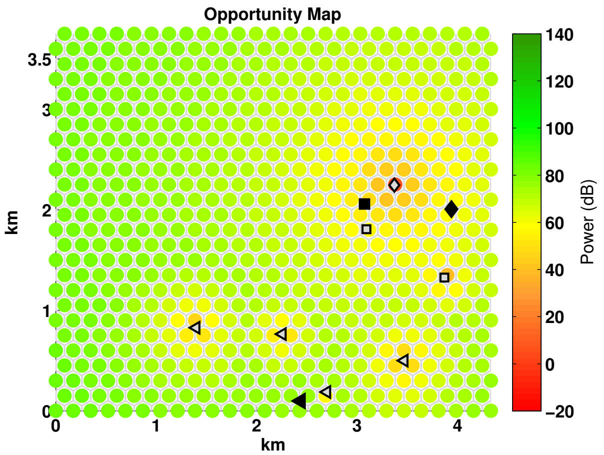

Fig. 3. Single-band spectrum-opportunity map showing the RF power that each unit-region can tolerate given the presence of the shown networks. High-opportunity regions are green; low are red. The spectrum opportunity is relative to -125 dBm (P_{MIN}).

2) Use of the Spectrum in a Geographical Region: By characterizing the *spectrum-occupancy* across the unit-spectrum-spaces within a geographical region, we can identify the *utilized spectrum*. Similarly, by characterizing the *spectrum-opportunity* across the unit-spectrum-spaces, we can identify the *available spectrum*. Figures 2 and 3 capture the spatial distribution of spectrum occupancy and spectrum opportunity respectively.

IV. Estimating the Use of the Spectrum

Using MUSE to characterize the use of the spectrum, the spectrum consumed by individual transceivers and the spectrum available for new users can be estimated.

A. Sub-problems

The spectrum consumed by transmitters in the space, time, and frequency dimensions is dependent on the actual (as against the maximum) transmit power and the antenna directionality employed during transmission. Similarly, the spectrum consumption by receivers in the space, time, and frequency dimensions is dependent on the minimum signal to interference and noise ratio (SINR) required for successful reception and the antenna directionality employed during reception.

In order to passively estimate the spectrum used by a transmitter, it is necessary to

- detect the active transmitters.
- estimate the position of the transmitters.
- estimate the transmit power and the radiation pattern.
- estimate the transmitter occupancy *at a sample point* across all the unit-spectrum spaces. Refer to (4) and (5) from [21].

We assume the receiver parameters are specified during the spectrum-access request to the spectrum-access management infrastructure. This is to avoid worst-case assumptions regarding the receiver positions and spectrum-access parameters. In order to estimate the available spectrum, it is necessary to

- estimate the received-power from all the cochannel transmitters at all the cochannel receivers.
- estimate the SINR at each of the cochannel receivers.
- estimate the spectrum-opportunity *at a sample point* across all the unit-spectrum-spaces. Refer to (9) and (10) from [21].

B. Estimating the Transmitter Spectrum-Access Attributes

The enforcement of the spectrum-access rights requires a passive technique for estimating use of the spectrum. The techniques exploiting signal cyclostationarity do not require coherency, are tolerant to noise and cochannel interference, and provide good performance under low SINR conditions [9], [15], [22].

In our earlier work [9], we presented algorithms exploiting signal cyclostationarity for the purpose of signal detection, received power estimation, and TDOA estimation. Here, we briefly describe the approach in the context of estimation of the location and transmit-power of the transmitter.

Detecting a Transmitter Signal: For signal detection, we exploit the second-order statistics of each signal through the spectral correlation function (SCF) [9]. The technique only requires the knowledge of the cyclic frequency of the transmitted signal.

Estimating the Received Signal Power: Exploiting the knowledge of SCF for the unit-power version of the transmitter-signal, a least-squares estimation problem is formulated in order to estimate the received signal power.

Estimating the Transmit-Power: In order to estimate the transmit power, each RF sensor estimates the received power from the transmitter. Using the estimated position of the transmitter, the estimated mean path-loss exponent (PLE), and the estimated shadowing loss, the transmit-power is then estimated.

Estimating the Position of a Transmitter We employ a method of maximizing the measured SCF by phase alignment for obtaining a TDOA estimate [23]. The method requires knowledge of the transmitter cycle frequency and synchronization between the involved pairs of RF-sensors. For the purposes of TDOA estimation, we choose the candidate RF-sensors based on their *estimated* received power at the RF-sensors. We employ a least-squares position estimation technique in order to estimate position of the transmitter based on the TDOAs. TDOA estimation is sensitive to multipath and hence it is subject to errors. Due to an overdetermined system of equations, with least squares solution, the error in the location estimation is minimized [25].

C. Characterizing the Propagation Environment

Estimating the transmit-power from the received-power estimate requires the knowledge of the propagation environment. Since the transmit-power estimation is very much sensitive to the path-loss exponent and shadowing, real-time enforcement of a dynamic spectrum-access policy cannot rely on the assumed propagation parameters. In this regard, we estimate the mean path-loss and shadowing variance at a fine granularity using a dense RF-sensor network.

We divide the geographical region into multiple fine-grained unit-sections and consider a log-normal shadow fading environment within each unit-section. To facilitate real-time characterization in the presence of cochannel interference, the path-loss and shadowing variance within *each* of the unit-sections are estimated using monitoring signals with known transmit-power and exploiting signal-cyclostationarity [25].

D. Estimating Spectrum Occupancy and Spectrum Opportunity

The fusion center uses the estimated spectrum-access parameters of all the cochannel transmitters and estimates the spectrum-occupancy and spectrum-opportunity at the sample-points in each of unit-regions in the geographical area under interest.

Censoring: The spectrum-occupancy estimate quality depends on the performance of the detection, received-power estimation, and geolocation subalgorithms. In this regard, the RF-sensors that are far away from a certain transmitter or the RF-sensors that are very close to the cochannel interference source cannot accurately estimate the transmitter spectrum-access parameters and therefore introduce errors in the estimation of spectrum-occupancy and spectrum-opportunity [25]. To improve the estimation performance, we employ *estimated-SINR*-based censoring of the position estimates and the received-power estimates from each of the RF-sensors.

Incorporating Directionality: Using the shadowing profile information, the estimated transmitter spectrum-access parameters from an RF-sensor, and the known receiver spectrum-access parameters, the fusion center estimates spectrum-occupancy and spectrum-opportunity perceived by *each* of the non-censored RF-sensors. This is especially helpful considering directional transmission. In this case, the received power from a directional transmitter at the individual RF-sensors is different and the spectrum-consumption footprint for the directional transmitter can be accordingly estimated. The directionality of the receiver antennas is considered while estimating the spectrum-opportunity within the unit-regions.

Fusion: For each unit-region, we have multiple spectrum-occupancy and spectrum-opportunity estimates from each of the RF-sensors. In order to facilitate choosing a conservative or an aggressive estimate, we define a *guard-margin factor* and choose a single value from the distribution. The value of the guard-margin factor ranges from -1 to 1. The lower boundary represents the most conservative behavior (selecting the minimum spectrum-opportunity estimate from the distribution) and the upper boundary represents the most aggressive behavior (selecting the maximum spectrum-opportunity estimate from the distribution).

V. Illustration

A. Setup

We consider a 4.3 km $\times$ 3.7 km geographical region. We estimate the utilized and available spectrum in a single 6 MHz wide frequency band at a given instant of time (single unit-time-quanta). The maximum power at any point P_{MAX} is considered 30 dBm or 1 W. The minimum power at any point P_{MIN} is considered to be -125 dBm. The minimum desired SINR for successful reception is considered to be 3 dBm. The thermal noise floor is -106 dBm considering channel bandwidth of 6 MHz. The geographical region is divided into 676 hexagonal cells with each side of 100 m. Thus, the total spectrum in the geographical region is 676 Wm^2.

Within each Monte Carlo trial, a network topology with multiple transmitters and receivers is generated. We simulate the large-scale fading effects and the transmitter signals at the physical layer. We implement the algorithms for detection, location estimation, and transmit-power estimation exploiting cyclostationarity in software.

The errors in estimation of the use of spectrum can be captured at various levels. For example, detection errors in terms of missed detections and false positives, TDOA-estimation errors, position-estimation errors, received-power estimation errors, transmit-power estimation errors, and finally the spectrum-occupancy and spectrum-opportunity estimation errors. In the scope of this paper, we illustrate the resulting spectrum-occupancy and spectrum-opportunity errors.

We note that a positive error in spectrum opportunity implies loss of the available spectrum while a negative error may lead to potential harmful interference at some of the receivers in the system. We capture these two effects in terms of the *lost-available spectrum* and *potentially-degraded spectrum*.

B. Estimating the Spectrum-Access Footprint of a Single Transmitter

Figure 4 illustrates the spectrum consumed by a transmitter within a geographical region. The transmitter is located at (1000, 2000) and is exercising omnidirectional transmission with transmit power of 15 dBm. We can estimate the RF-power from the transmitter at any of the unit-regions in accordance with the estimated fine-grained shadowing profile. For example, at (1000, 2400), the power received from this transmitter is estimated to be -66 dBm. We note that exploiting signal cyclostationarity enables us to estimate the RF power at a point when multiple transmitters are simultaneously exercising spectrum-access in the same frequency band within a geographical region. The estimated use of spectrum by a specific transmitter can be applied for validating a spectrum-access policy.

C. Estimating the Available Spectrum

Next, we estimate the available spectrum in case of multiple cochannel transmitters. We note that the SINR at the RF-sensors can be poor with respect to many of the transmitters due to proximity with other cochannel transmitters; therefore, when there are a large number cochannel transmitters, accurate spectrum consumption estimation requires a large number of RF sensors.

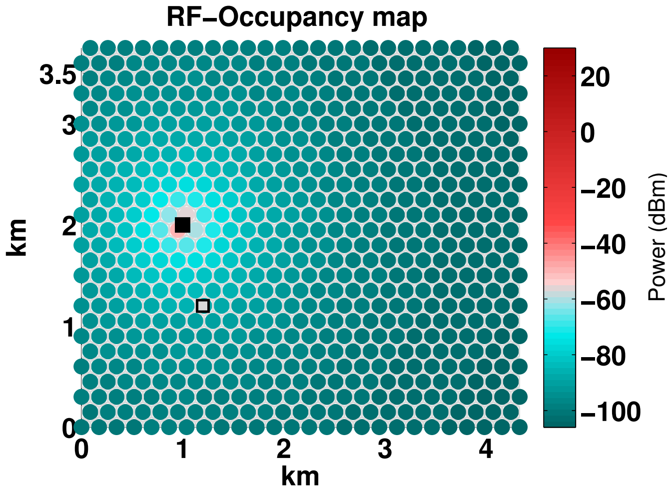

Fig. 4. Spectrum-consumption space of an individual transmitter. The figure shows spatial distribution of the transmitter-occupancy in the unit-spectrum-spaces within a geographical region. Thus, it captures the spectrum consumed by a transmitter within the geographical region. The transmitter is shown by a solid square and the receiver is shown by a non-solid square.

Figure 5 shows the estimation performance with 16 transceiver-pairs and 169 RF-sensors. As the accuracy of spectrum-opportunity estimation depends on the receiver-SINR, we vary SINR at a receiver by varying the receiver's distance from its transmitter. In Figure 5, range refers to the distance between a receiver and its transmitter. The 16 transmitters employ distinct cyclostationary signatures, which is achieved through signal design [16]. We observe that 169 RF-sensors used with 16 cochannel networks accomplish reasonable spectrum consumption estimation performance assuming no shadowing. Shadow fading introduces significant errors into estimation of the transmit-power and consequently in the estimation of spectrum occupancy and spectrum opportunity. Therefore, we characterize the shadowing profile at a fine granularity.

D. Characterizing the Shadowing Profile

With a dense RF-sensor network, we characterize the shadowing losses in the fine-grained unit-sections of the geographical region as shown in Fig. 6. We incorporate the mean PLE and the fine-grained shadowing losses while estimating transmit-power for all the transmitters. The shadowing profile is also used in the estimation of spectrum-occupancy and spectrum-opportunity in each of the unit-regions of the geographical region.

From Figure 7, we observe significant errors in the transmit-power estimation while not employing characterization of the shadowing profile (refer to legend, '*with PLE estimation only*'). In this case, we deployed a RF sensor network with 36 sensors to estimate mean PLE across the geographical region. With the learning approach (refer to legend, '*Learning with 676 RF-sensors*'), the spatial variations in the shadowing loss are estimated with reasonable accuracy and it lowers the errors in transmit power estimation at the RF-sensors.

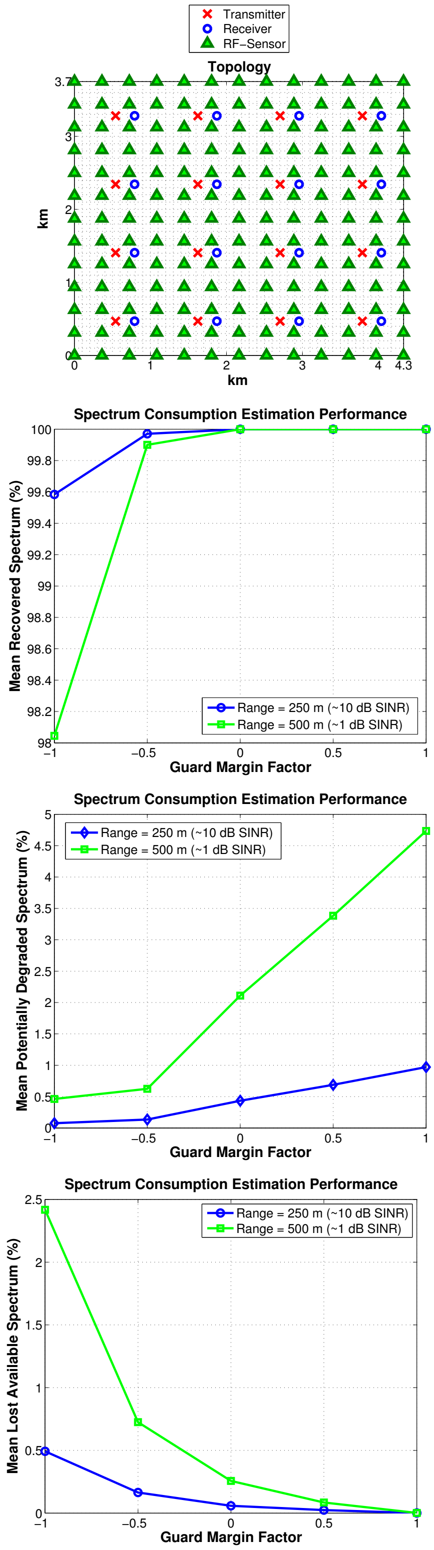

Fig. 5. Estimation of the available spectrum. The RF-sensors estimate the spectrum-access parameters of all cochannel transmitters and estimate spectrum opportunity in the unit regions within the geographical region. The lost-available spectrum and potentially-degraded spectrum capture the positive and negative errors in the estimation of spectrum opportunity, respectively. The 16 cochannel transmitters have distinct cyclostationary signatures. When the SINR at the receivers is lower, the spatial footprint of the receiver-consumed spectrum is larger and the spectrum-opportunity estimation errors are pronounced.

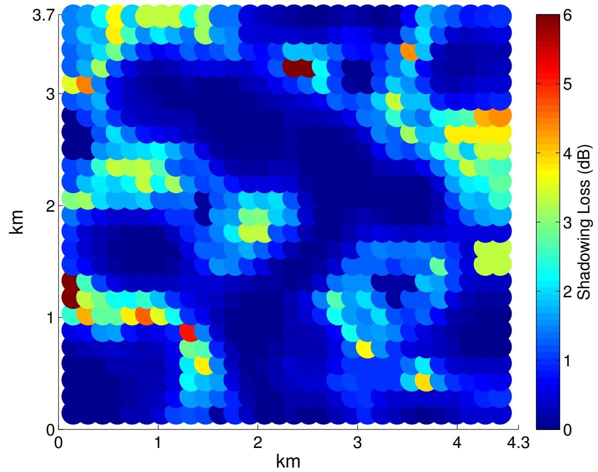

Fig. 6. Fine-grained characterization of shadowing. A dense RF-sensor network is applied for estimating mean path-loss index and shadowing variance within the fine-grained sections of a geographical region. The characterization of fine-grained shadowing loss helps to accurately estimate use of the spectrum in the unit-spectrum spaces.

In comparison with the proposed approach to estimating the use of spectrum, the simplistic primary user transmitter-signal-detection approach identifies much less underutilized spectrum due to constraints on the minimum sensitivity and maximum secondary user transmit-power defined to statically handle the worst-case RF-environment conditions and spectrum-access scenarios [8], [24].

We acknowledge that the number of RF-sensors required to characterize the propagation environment increases with terrain complexity. In order to reduce the number of RF-sensors, the terrain information from contour and/or satellite maps may be helpful. We pursue this in future work.

VI. Defining and Enforcing a Quantified Spectrum Access Policy

Fine-grained estimation of the use of spectrum in the space, time, and frequency dimension enables spectrum sharing with dynamic spectrum-access rights. Figure 8 describes the overall approach for defining a policy with quantified spectrum-access rights in real time. A spectrum-sharing model may choose to add a guard-margin to the estimated spectrum-opportunity. A spectrum-access mechanism (SAM) may further control the spectrum consumed by the to-be-added transceivers and thereby increase the overall number of spectrum accesses. Thus, the spectrum-access rights for the transceivers are defined based on the real-time spectrum-access opportunity, spectrum-sharing constraints, and spectrum-access etiquette. The rights are articulated in terms of allowed use of the spectrum in the space, time, and frequency dimensions and accordingly spectrum-access parameters for the transceivers can be inferred.

We describe an example spectrum manager for defining and enforcing quantified spectrum-access rights in real time. The key elements of such a framework are:

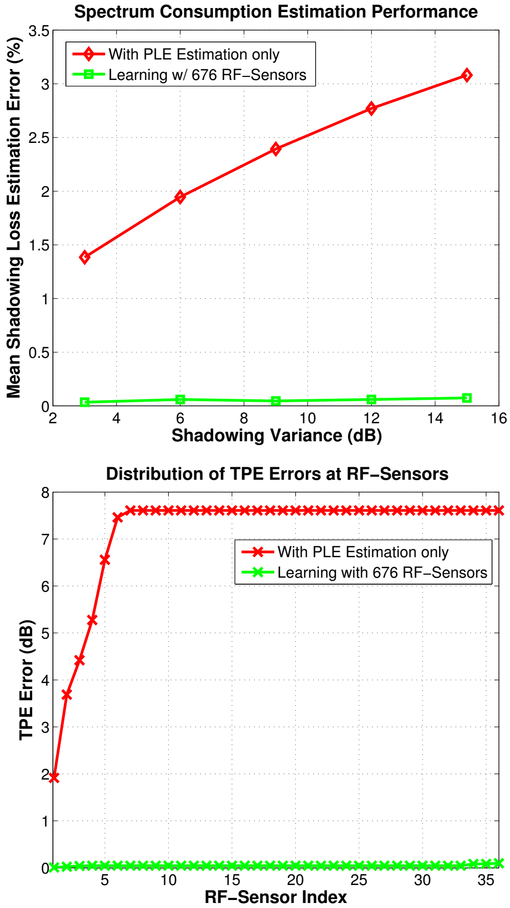

Fig. 7. Characterizing the shadowing losses within a geographical region helps to improve the transmit-power estimation performance. Transmit-power is estimated from the received-power using the estimated mean path-loss exponent (PLE) and the shadowing loss. When shadowing losses are not characterized at a fine granularity (case: 'with PLE estimation only'), it impacts the performance of transmit-power estimation and consequently that of estimating spectrum occupancy and spectrum opportunity. When a dense RF-sensor network is employed (case:'Learning with 676 RF-sensors'), the transmit-power estimation (TPE) performance is improved.

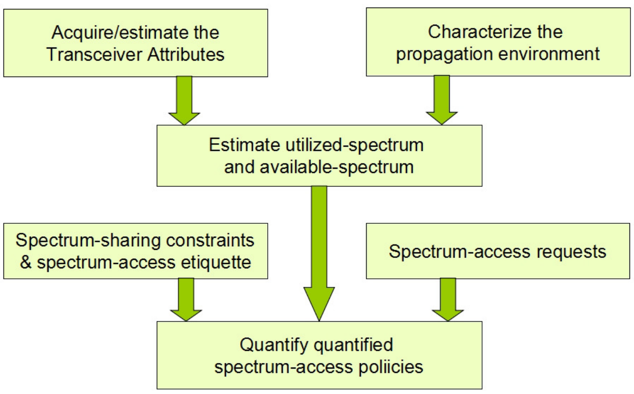

Fig. 8. Illustration of defining spectrum-access rights based on real-time use of the spectrum. By passively estimating the spectrum-access attributes of the transmitters and by characterizing the propagation environment, the use of spectrum by transmitters and the available spectrum can be estimated. Based on spectrum-sharing constraints and etiquette, quantified spectrum-access rights can be defined and enforced in real time.

- **Spectrum Sensing Infrastructure (SSI)** that learns the fine-grained propagation conditions and estimates the transceiver spectrum-access parameters.
- **Spectrum-consumption Analysis Infrastructure (SAI)** uses the known and estimated transceiver spectrum-access parameters and learned fine-grained propagation model parameters to estimate spectrum-consumption spaces for individual transceivers.
- **Spectrum-Access Policy Infrastructure (SPI)** that manages spectrum-access requests from transceivers. It receives the desired spectrum-access parameters for transceivers of a given spectrum-access request and assigns a spectrum-consumption policy that ensures non-harmful interference with current RF-entities while satisfying the minimum desired spectrum-access attributes. SPI also detects violations of the policy based on information from SAI.
- **Spectrum-Access Management Infrastructure (SMI)** uses the available spectrum-consumption space information in order to schedule and assign spectrum-consumption footprints to the individual transceivers of a spectrum-access request.

Fig. 9 illustrates a scenario of defining and enforcing a dynamic spectrum-access policy wherein the spectrum management infrastructure estimates the use of spectrum by a transmitter and detects violation of the assigned spectrum-access policy.

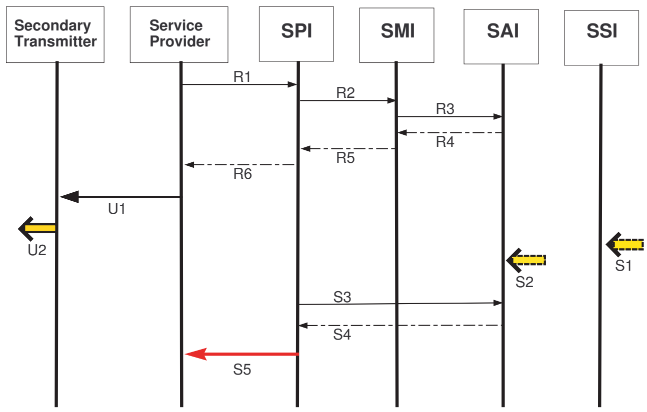

Fig. 9. A scenario of defining and enforcing a spectrum-access policy. A service-provider requests a spectrum-access footprint from SPI along with the information about position and capabilities of the transceivers. This is shown with arrows R1-R6. A service-provider assigns a partial time to one of the secondary transmitters (Arrow U1). The secondary transmitter fails to conform to the assigned quantified spectrum-access policy (Arrow U2). This scenario is detected with transmitter spectrum consumption estimation (Arrows S1-S4) and a regulatory action is taken (Arrow S5).

Using the estimation of the spectrum-opportunity across the unit-regions in a geographical region:

- we can choose the best frequency band based on the spectrum opportunity at the potential transmitter location across multiple bands.
- we can define the transmit power based on the spectrum opportunity at the transmitter location and make more

efficient use of spectrum while ensuring non-harmful interference to all the receivers in the system.

- we can precisely control sharing of the spectrum among multiple networks. For example, let us consider spectrum opportunity at an arbitrary point to be -20 dBm. We can allow spectrum access to a single transmitter such that the RF power from this transmitter at this location is -20 dBm or we can allow two or more transmitters (with lower power levels) access to the spectrum while ensuring the same constraint.

Thus, estimating the spectrum-opportunity enables efficient allocation and scheduling options for spectrum management.

Finally, though the proposed approach to dynamic spectrum sharing depends on a dedicated spectrum management infrastructure, it potentially brings in new business models along with flexible and efficient use of the spectrum and an ability for automated regulation of the dynamic spectrum-accesses.

VII. Conclusions and Future Research Avenues

In this paper, we investigated estimating the use of spectrum in the space, time, and frequency dimensions using a dedicated RF-sensor network and exploiting signal cyclostationarity. We argue that for making an efficient use of the underutilized spectrum, the transmitter-detection based approach is not sufficient. As demand for the spectrum increases, it is necessary to estimate the real-time use of the spectrum in order to exploit the fine-grained spectrum-reuse opportunities.

We emphasize that enforcing the spectrum-access rights under the new dynamic spectrum-sharing paradigm is feasible with estimation of spectrum use in the space, time, and frequency dimensions. We have shown that exploiting signal cyclostationarity can provide the necessary noise-and-interference-tolerant sensing functions.

We acknowledge that the dynamics of the RF-environment is the main challenge for spectrum management under the new dynamic spectrum-sharing paradigm. In this regard, the proposed approach to discretize the spectrum-space is helpful in bringing in adaptation into the spectrum management functions.

We suggest a need for research in developing fine-grained characterization of the propagation environment using auxiliary techniques such as contour maps and satellite maps in order to assist the spectrum sensing infrastructure in the real-time characterization of the RF-environment and reduce the number of dedicated RF sensors.

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