This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2016.2615626, IEEE Transactions on Communications

Outage-Constrained Sensing Threshold Design for Decentralized Decision-making in Cognitive Radio Networks

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***Abstract*—Efficiency in spectrum utility has been a concern in wireless communications for a long time. Cognitive radios have been seen as a solution to occupy the gaps in the licensed spectrum through opportunistic spectrum access and simultaneous spectrum sharing techniques. For this purpose, spectrum sensing has been vital in providing accurate statistical information regarding licensed or primary user (PU) activity on its spectrum. In this paper, we design new sensing thresholds that take into account the outage caused to the PU as a consequence of cognitive or secondary users (SU) accessing or sharing the said spectrum. With these new thresholds, we can see more protection to the PU from SU spectrum access transmissions based on missed detections, and eliminate most common assumptions made with spectrum sharing systems. Our thresholds also work with a dynamic decision-making algorithm that allows the SUs to use only the statistical sensing information to understand the network dynamics, and determine its transmission opportunities and corresponding power consumption, in a decentralized and uncooperative cross-layer network.**

***Index Terms*—Spectrum sensing, spectrum access, spectrum sharing, threshold design, energy detection, decentralized network.**

I. INTRODUCTION

WITH the move towards more efficient means of communication, spectrum utility has often been addressed [1] [2] as an ongoing issue, where resources are going unused. Utilizing these resources requires a dynamic means of spectrum allocation and transmission, that cognitive radio programming was able to provide [3] [4]. These white spaces in the licensed spectrum are often categorized into unutilized and underutilized spectrum. The former representative of the absence (temporal) or inactivity (spatial) of a licensed or primary user (PU) on its spectrum. These can be seen as opportunities to allow cognitive or secondary users (SU) uninterfered spectrum access rights [5] [6] for as long as the PU is not transmitting. In this context, dynamic spectrum hopping techniques [7] [8] along with fast spectrum sensing [9] [10] have been studied, in finding and allocating these space-time sensitive windows of spectrum opportunity to SUs. On the other hand, underutilized spectrum can be seen as an opportunity to share the licensed resources of a PU [11] [12] with a SU as long as the cross-interference from SU transmissions is controlled. This classification of spectrum transmission opportunities into access or sharing corresponds to, what in spectrum sensing is called hypothesis testing.

In hypothesis testing, any sensing result that falls under an idle PU test case would be classified as a spectrum access opportunity for the SU, and conversely a busy PU hypothesis would correspond with spectrum sharing opportunities. An idle or busy primary link is based entirely on the detection probability, or ideally the activity probability of a PU on its spectrum. It is common therefore to see, spectrum sensing research plots on the probability of PU detection for a range of operating signal-to-noise ratios (SNR). However, ensuring a good detection rate does not translate to safety or accuracy in SU transmissions when measuring the interference felt at the primary receiver. Similar concerns [13] are highlighted with spectrum sharing systems when the SUs transmit simultaneously on PU spectrum. Spectrum sharing researchers [14]-[16] tackle this problem by enforcing a peak or average power constraint on SU transmission power, that is tied to the maximum perceived interference that can be accepted at the PU without disrupting the PU transmission. This generally involves estimating the cross-channel between the two parties (i.e. the respective secondary transmitter and the corresponding primary receiver), an area that has garnered attention in finding blind or semi-blind estimation techniques [17] [18] to defend the practicality of a spectrum sharing network. Research on interference alignment [19] also finds its root in the idea of better spectral utilization.

Therefore, as it stands, the quality of spectrum sensing work for the most part, has been weighed against the results from the front-end statistical sensing data, i.e., the probability of PU detection or false alarms, and the sensing time, for the purposes of SU spectrum access. Conversely, those opportunities that cannot be utilized for spectrum access are classified as busy PU spectrum and are seen as spectrum sharing opportunities, where research work is mainly involved in improving the accuracy of the back-end interference mitigation results at the primary receiver. The disconnect between these two transmission opportunities that originate from the same statistical data, is what motivated the work in this paper.

In this paper, we propose to utilize the statistical sensing data to give an advantage to both spectrum access and spectrum sharing fields, by bringing the back-end PU outage-constraints into the front-end design of the spectrum sensing thresholds that primarily govern spectrum allocation decisions. We thus design two thresholds, and therefore three decision regions for SU spectrum allocation, namely, spectrum access,

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2016.2615626, IEEE Transactions on Communications

spectrum sharing, and idle or no transmission opportunity. Consequently, SUs that utilize these thresholds while sensing, would automatically be in compliance with outage standards needed to share or access the PU spectrum. The proposal of this hybrid underlay-overlay topology that allows dynamic switching between spectrum access and spectrum sharing opportunities has been suggested before [20]-[23], and acknowledged for the achievable gain in SU throughput that can be derived across the range of transmission SNRs. Given this hybrid model, we also aim to eliminate more theoretical assumptions or considerations made for such a topology and replace them with practical means to achieving the same objective. For example, authors in [24] discuss a similar model that utilizes the bandwidth and power allocation for each user as a utility measure for optimization, constrained by certain PU interference constraints. The main distinguishing factor here is the assumption of channel knowledge between the nodes and a centralized architecture for spectrum allocation. On the other hand, our work has been developed with decentralized and uncooperative decision-making in mind, where the statistical sensing data is the only information that is needed for a SU to make dynamic allocation decisions and power adjustments that consequently determine the SU network rate while still guaranteeing a PU outage-constrained spectrum sharing space.

The organization of the rest of the paper begins with the system model and description of the hybrid network topology in Section II. We then highlight the importance of spectrum sensing in Section III. Here, both the traditional and the new outage-constrained threshold designs for spectrum sensing are discussed, and their corresponding optimal closed-form solutions are provided. In Section IV, we list some common assumptions made in the field, and propose practical measures to allow our thresholds to work without having any side information. We then demonstrate the workings of our algorithm in Section V, that would allow the SUs to recognize patterns and make cognitive spectrum allocation decisions, based on the practical outage-constrained thresholds provided. The corresponding achievable network gains can be seen in our simulation results in Section VI, followed by concluding remarks in Section VII.

II. SYSTEM DESCRIPTION

For this hybrid topology we consider one PU and k SUs in the vicinity of sensing and utilizing this PU's resources. Though it should be understood, that each SU will have the ability to sense and utilize the statistical information from all the PUs in its vicinity, and correspondingly make a utility decision as to which spectrum to use. Here, we are interested in understanding the workings of the decision-making algorithm and in optimizing the sensing thresholds to constrain the outage to the PU while achieving the highest utility (or rate) for each SU that transmits on this PU's spectrum. The corresponding transmitter-receiver pairs for the PU and the k SUs, will be referred to as PT-PR, and STi-SRi, respectively, where $i \in [1, k]$, as depicted in the general topology in Fig. 1. We see that for a general network model (Fig. 1(a)), path loss as a function of distance is key in determining the nodes that interfere with each other, represented by the region of interference (ROI). An algorithm for spectrum allocation that is designed after such a model will not effectively represent close-proximity nodes or dense networks. Therefore for our setup, we consider an equidistant channel model, where $\forall d_k = d$. This then represents the worst-case scenario, where each node will equally interfere with all other nodes in the network. The corresponding results shown later in Section VI are a representation of this strong interference model, and therefore more optimistic results can be expected from a relaxed network model.

The representative channel model in Fig. 1(b) depict the channel gains between the PT-PR pair as h_p, between the k ST-SR pairs, by h_{si}, and the cross-channels originating from the primary transmitter (PT) to the i^{th} secondary transmitter (ST) and secondary receiver (SR), as h_{pti}, and h_{pri}, respectively, and similarly those originating from the i^{th} ST to the primary receiver (PR), and other j^{th} STs and SRs, as h_{sip} , h_{stij}, and h_{srij}, respectively for $j \neq i$, $i \in [1, k]$. We have modelled these channels to follow Rayleigh block-fading with additive gaussian noise at the receivers. The corresponding channel power gains can be given by $\gamma_m = |h_m|^2$, where $m = \{p, si, pti, pri, sip, stij, srij\}$. The PU setup we consider, is one which is QOS-constrained and has its own power control to maintain a specified target rate. The focus of our work is in designing the thresholds for sensing, and establishing an adaptive algorithm for the SUs to carry out its own power control and decision making. We will now look at the spectrum sensing threshold design.

III. SPECTRUM SENSING

The importance of spectrum sensing cannot be emphasized enough, as it is the first step towards efficient spectrum utilization decision-making. An error in the sensing result will often be propagated over the phases of spectrum allocation and transmission, and is expected to reflect as a system outage at the PR or a reduced achievable rate for the SU network. Varied approaches for spectrum sensing have been carried out [25] [26] to provide more information regarding the PU activity, based on varying degrees of PU channel or signal information available to the SU. These approaches range from energy detection (ED) to matched filtering, as well as, cyclostationary feature detection, and waveform based sensing. ED is most commonly used in literature given its ease of implementation, and the need for no prior information. Given that the network model we have considered is decentralized and uncooperative, ED also happens to be the most appropriate sensing detector. The traditional threshold design for an ED depends solely on the number of samples used in sensing and on the noise variance. Given the fading characteristics of the channel, the corresponding probability of detection ($\mathcal{P}_d$, true positives) or false alarm ($\mathcal{P}_f$, false positives) can be calculated as a Q-function of these factors. From [27] [28], we can see that for a PU signal and noise modeled after a circularly symmetric complex gaussian random variable, we can expect a $\mathcal{P}_d$ and

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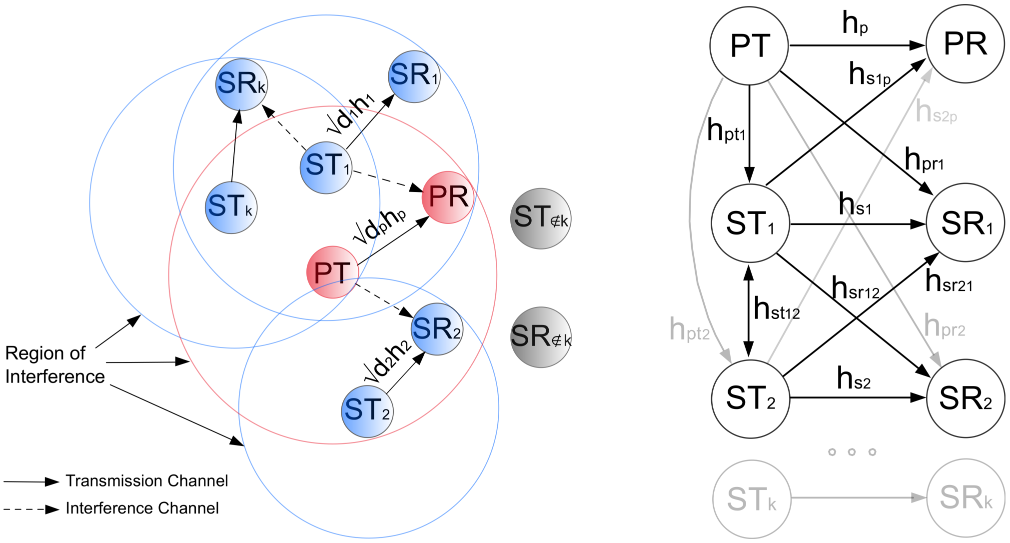

(a) Network Model (b) Channel Model

Fig. 1: General Topology

$\mathcal{P}_f$ as follows,

$$\mathcal{P}_d = Q\left(\frac{\lambda_i - (1+\rho_i)\cdot N_0}{\sqrt{\frac{1}{M}(1+\rho_i)^2 \cdot N_0^2}}\right) \tag{1}$$

$$\mathcal{P}_f = Q\left(\frac{\lambda_i - N_0}{\sqrt{\frac{1}{M}\cdot N_0^2}}\right) \tag{2}$$

where, $Q(x)$ is the Q-function, λ_i, the sensing threshold, ρ_i, the received SNR (signal-to-noise ratio) at the i^{th} ST, N_0, the noise power, and M, the number of samples used for sensing. For a PU transmission power of P_p, the received SNR at STi can be represented as

$$\rho_i = \frac{P_p \cdot \gamma_{pti}}{N_0}. \tag{3}$$

Therefore, conversely we can represent the traditional ED sensing threshold as a function of $\mathcal{P}_d$ by

$$\lambda_i = Q^{-1}(\mathcal{P}_d)\sqrt{\frac{1}{M}(1+\rho_i)^2 \cdot N_0^2} + (1+\rho_i)\cdot N_0. \tag{4}$$

It is clear to see here, that the sensing threshold will guarantee a certain level of detection for PU activity, and conversely limit the number of missed detections $(1-\mathcal{P}_d)$. However, we cannot directly equate these missed detections to a PU's outage, which is measured at the receiver-end. Therefore, in designing the threshold, a conservative approach would result in a lower achievable SU rate, while a more lenient threshold will probably result in higher outages seen at the PR. We recognize this gap in spectrum sensing research, in designing sensing thresholds that are linked to the consequence of transmitting on these spectrum opportunities. We refer to this as outage-constrained threshold design and through this paper, we propose practical means of being able to utilize these thresholds for spectrum allocation for SUs.

Another area that has not been discussed in spectrum sensing research is what we define as the ”safe zone” for PU communication.

Definition 1. *Safe Zone.* Spatial-temporal periods of non-accessability for a SU, guaranteeing QOS-secure frames for PU communication. To understand where this safe zone lies on the ED sensing threshold axis, let us first look at the traditional ED design in Fig. 2. Here, the hypothesis testing is either H_B, a busy PU, or H_I, an idle PU spectrum. If the received SNR at the respective ST happened to fall below the sensing threshold, $\rho_i < \lambda_i$, we would categorize this as an idle PU, and proceed with SU spectrum access. Conversely, if $\rho_i \geq \lambda_i$, the SU would be asked to remain silent for an overlay topology, or asked to utilize this opportunity to share spectrum with the PU under certain back-end interference mitigation constraints for a hybrid underlay-overlay topology.

Proposition 3.1. *Given an instantaneous PU target rate, R_t, for a given PU transmission power of P_p, and a channel realization, h_p, there exists an intermediate hypothesis region or safe zone, H_0, that if the i^{th} SU were to transmit over, even with power, $P_{s_i} \to 0$, the average outage constraint at the PU will be violated.*

This becomes clearer when we see how our outage-constrained thresholds are formulated giving us these three distinct hypothesis, namely H_I (the idle hypothesis representing spectrum access opportunities), H_0 (the safe zone or silent period for SU communication), and H_B (the busy hypothesis representing spectrum sharing opportunities for the SU).

A. *Outage-Constrained Threshold Design*

In designing these new thresholds, we must first establish our outage limiting constraint. For spectrum access transmissions, the sensing error is usually a false positive (or false alarm), i.e. sensing PU activity when the spectrum is idle, or a false negative (or missed detection), i.e. sensing idle spectrum

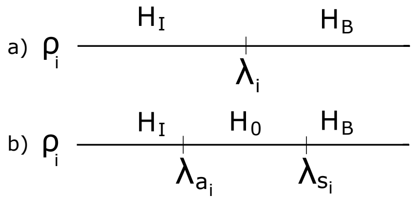

Fig. 2: Threshold Design for a) Traditional ED, b) Outage-constrained ED.

when the PU is transmitting. For a pure overlay topology, the SU would miss an opportunity to transmit during a false alarm, and would cause outage to the PU if it were to transmit for every missed detection. Therefore we aim to design our access threshold by limiting this error as

$$\mathcal{P}_r\left(\rho_i \geq \lambda_{a_i} \mid H_I\right) + \mathcal{P}_r\left(\rho_i < \lambda_{a_i} \mid H_B\right) = \varepsilon. \tag{5}$$

Here, ρ_i represents the received SNR at the respective STi, which is compared against our new spectrum access sensing threshold, λ_{a_i}, and constrained by a quantitative outage measure, ε. We can classify the PU as truly busy (H_B), when its instantaneous rate R_l surpasses a quality target rate, R_t, set at the PR. For a PU transmission power of P_p, R_l represents the achievable PU rate in the absence of SU interference, and can be defined as

$$R_l = \log_2\left(1 + \frac{P_p \cdot \gamma_p}{N_0}\right) \tag{6}$$

where, N_0 is noise variance at the PR. Conversely if $R_l < R_t$ for a given channel realization, we can classify this as idle spectrum, as the PU would already be in outage without any SU involvement. Therefore, our constraint in (5) can be written as

$$\begin{aligned}&\mathcal{P}_r\left(\frac{P_p \cdot \gamma_{pti}}{N_0} \geq \lambda_{a_i}\right) \cdot \mathcal{P}_r\left(\log_2\left(1 + \frac{P_p \cdot \gamma_p}{N_0}\right) < R_t\right) + \\ &\mathcal{P}_r\left(\frac{P_p \cdot \gamma_{pti}}{N_0} < \lambda_{a_i}\right) \cdot \mathcal{P}_r\left(\log_2\left(1 + \frac{P_p \cdot \gamma_p}{N_0}\right) \geq R_t\right) = \varepsilon.\end{aligned} \tag{7}$$

For rayleigh fading channels, these probabilities can be calculated, and expressed as

$$\begin{aligned}&\exp\left(-\frac{\lambda_{a_i} \cdot N_0}{\overline{P_p \cdot \gamma_{pti}}}\right) \cdot \left(1 - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right)\right) + \\ &\left(1 - \exp\left(-\frac{\lambda_{a_i} \cdot N_0}{\overline{P_p \cdot \gamma_{pti}}}\right)\right) \cdot \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right) = \varepsilon.\end{aligned} \tag{8}$$

Therefore, we can obtain the outage-constrained spectrum access threshold as

$$\lambda^*_{a_i} = \ln\left(\frac{1 - 2\exp\left(-\dfrac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right)}{\varepsilon - \exp\left(-\dfrac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right)}\right) \cdot \overline{\rho_i} \tag{9}$$

where $\overline{\rho_i} = \frac{\overline{P_p \cdot \gamma_{pti}}}{N_0}$ is the average received SNR at STi from sensing, and $\overline{x}$ represents the ergodic average of x.

Now in designing the spectrum sharing threshold, we first define the PU rate with SU interferers as

$$R^{'}_l = \log_2\left(1 + \frac{P_p \cdot \gamma_p}{\sum_{i=1}^{k} P_{si} \cdot \gamma_{sip} + N_0}\right) \tag{10}$$

where P_{si} is the transmission power of the i^{th} ST. When this PU rate does not meet the quality target of R_t, sharing PU spectrum would result in outage, which we can term as an error hypothesis, H_E. Therefore, the outage constraint for the design of the spectrum sharing threshold can be defined as

$$\mathcal{P}_r\left(\rho_i > \lambda_{s_i} \mid H_E\right) = \varepsilon. \tag{11}$$

This can be written as

$$\mathcal{P}_r\left(\rho_i > \lambda_{s_i}\right) \cdot \mathcal{P}_r\left(R^{'}_l < R_t\right) = \varepsilon \tag{12}$$

or,

$$\begin{aligned}&\mathcal{P}_r\left(\rho_i > \lambda_{s_i}\right) \cdot \Bigg(1 - \mathcal{P}_r\Bigg(\gamma_p \geq (2^{R_t} - 1) \\ &\qquad \cdot \left[\frac{N_0}{P_p} + \sum_{i=1}^{k} \frac{P_{si}}{P_p} \cdot \gamma_{sip}\right]\Bigg)\Bigg) = \varepsilon.\end{aligned} \tag{13}$$

For rayleigh fading channels, we can express this as

$$\begin{aligned}&\exp\left(-\frac{\lambda_{s_i}}{\overline{\rho_i}}\right) \cdot \Bigg(1 - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right) \\ &\qquad \cdot \prod_{i=1}^{k}\left(\frac{\overline{P_p}}{\overline{P_p} + (2^{R_t} - 1) \cdot \overline{P_{si}}}\right)\Bigg) = \varepsilon.\end{aligned} \tag{14}$$

This give us a sharing threshold of

$$\lambda^*_{s_i} = \ln\left(\frac{1 - \exp\left(-\frac{(2^{R_t} - 1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right) \cdot \prod_{i=1}^{k}\left(\frac{\overline{P_p}}{\overline{P_p} + (2^{R_t} - 1) \cdot \overline{P_{si}}}\right)}{\varepsilon}\right) \cdot \overline{\rho_i}. \tag{15}$$

A detailed simplification of these closed-form derivations can be found in the Appendix. We will now discuss how we can tackle some of the common assumptions made with this network topology.

IV. PRACTICAL OUTAGE-CONSTRAINED SENSING

With the hybrid underlay-overlay topology, a lot of common assumptions have been made in literature to allow researchers to focus on specific open problems in the model. We aim to make our spectrum learning scheme as practical as possible, by eliminating most of these concerns and implementing our own decision-making algorithm. Some of the common assumptions are:

1) Weak or absent PT-SRi and STi-SRj ($j \neq i$) communication links - The assumption that the PT cannot communicate or has negligible interference towards a respective SR has generally been made [29] to attain

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good achievable SU rates to warrant sharing PU spectrum. If the PU transmits with high power, the corresponding achievable SU sharing rate maybe too insignificant to justify the resources used. Similarly, assumptions have been made so that SRs can neglect interference from other STs, for the same justification.

In our model, we retain these communication links, allowing the channels to act as interference channels, and plot the corresponding achievable SU rates in our simulations. When working decentralized, and with no cooperation, it is mathematically impossible to cancel out interference. However, with SU cooperation, an open area of research exists in utilizing the sensing statistics to estimate the received signal at the SR and consequently cancel out the interference.

2) Neglecting other SU's transmissions while sensing - This is to allow the SUs to accurately sense PU activity on the link without interference from other SU's transmission signals in the received sensing metric. Much of the research work that has made this assumption [30]-[32], have designed their models around cooperative sensing, where SUs can collectively make weighted sensing decisions through a central controller. Consequentially, a lot of the corresponding formulations in these research papers rely on isolating the PU's signal to provide closed-form results for sensing.

   With decentralized decision-making, we see this interference as added information from the network. Not only do we include all transmitting users in the sensing metric, but we design our algorithm to function around the changes in received SNR at the sensing ST. This level of cognition translates to recognizing patterns and determining the state of the PU link amidst all the dynamic changes in channels and SU transmissions in the network. We will describe the algorithm in more detail in Section V.

3) Cross-channel knowledge for spectrum sharing - For the purposes of interference mitigation, many spectrum sharing or overlay papers [14]-[18] discuss having some knowledge to limit the SU's cross-interference felt at the PR. Though there is a lot of work on blind and semi-blind techniques for channel estimation between a transmitter and receiver pair, when talking about the cross-channel between two different users, i.e. SU and PU, few works exist that discuss estimation techniques, but are still reliant on some form of knowledge.

   Therefore to avoid any assumptions regarding the cross-channel knowledge, we incorporate the outage constraints at the PR into the design of the sharing threshold (15), so that any SU that utilizes this threshold will already be in compliance with the outage standard. However, the perfect closed-form thresholds in (9) and (15), still require some knowledge, and we will tackle how we can work around it with the limited sensing statistic information we have in the following subsection.

A. Practical Considerations

We aim to make our thresholds practical, by allowing some simplifications to the closed-form solutions provided. The impracticalities we wish to remove are:

1) Assumption of unknown channel power gains - It is fair to make the assumption that each transmitter and receiver pair, know its own transmission channel through simple pilot training sequences [33] [34]. We must also understand that we are dealing with close-proximity nodes that cause significant interference to each other. Otherwise, the assumption that papers make regarding weak PT-SR channels can hold, if the users are distant. Therefore, for our model, we assume the same unit distance between all nodes in the network, i.e. SUs and PU. Because of their close proximity, it is fair to say that these interference channels experience the same fading, and for a large number of samples will have equivalent average power gains. We can then replace the average unknown channel power gains with known primary channel information to re-construct our sensing thresholds in (9) and (15) as

$$\lambda_{a_i} = \ln\left(\frac{1-2\exp\left(-\frac{(2^{R_t}-1)\cdot N_0}{\overline{P_p\cdot\gamma_{pti}}}\right)}{\varepsilon-\exp\left(-\frac{(2^{R_t}-1)\cdot N_0}{\overline{P_p\cdot\gamma_{pti}}}\right)}\right)\cdot\overline{\rho_i} \quad (16)$$

or,

$$\lambda_{a_i} = \ln\left(\frac{1-2\exp\left(-\frac{2^{R_t}-1}{\overline{\rho_i}}\right)}{\varepsilon-\exp\left(-\frac{2^{R_t}-1}{\overline{\rho_i}}\right)}\right)\cdot\overline{\rho_i}. \quad (17)$$

and,

$$\lambda_{s_i} = \ln\left(\frac{1-\exp\left(-\frac{(2^{R_t}-1)\cdot N_0}{\overline{P_p\cdot\gamma_{pti}}}\right)\cdot\prod_{i=1}^{k}\left(\frac{\overline{P_p\cdot\gamma_{pti}}}{\overline{\overline{P_p\cdot\gamma_{pti}}+(2^{R_t}-1)\cdot\overline{P_{si}\cdot\gamma_{pti}}}}\right)}{\varepsilon}\right)\cdot\overline{\rho_i} \quad (18)$$

or,

$$\lambda_{s_i} = \ln\left(\frac{1-\exp\left(-\frac{2^{R_t}-1}{\overline{\rho_i}}\right)\cdot\prod_{i=1}^{k}\left(\frac{\overline{P_p\cdot\gamma_{pti}}}{\overline{\overline{P_p\cdot\gamma_{pti}}+(2^{R_t}-1)\cdot\overline{P_{si}\cdot\gamma_{si}}}}\right)}{\varepsilon}\right)\cdot\overline{\rho_i}. \quad (19)$$

2) Number of users in the network (or within a PU's ROI), k - Without any cooperation, each of the SUs has no shared information regarding other SU activity in the network. Though our decision-making algorithm can tackle understanding of the network dynamics despite this knowledge, we still need to know k, to guarantee an accurate sharing threshold. We know that, with similar fading, the corresponding average mean and variances of all the interference channels will be the same, and therefore we can employ a variance check on the received SNR, to determine when a SU begins or stops transmission on the spectrum. However, each new SU in the network has less information that the one before it and so its estimate of k will be off by 1 for every new user. Therefore, the network size estimate will be $k-N$ for the $(N+1)^{th}$ SU that enters the network, which can

result in sub-optimal sharing rates for the SU network. However, each individual SU is aware of its achievable sharing rate and can improve its estimate of the network size through feedback from its receiver.

Another concern is the actual power levels of the k users. Without cooperation, there is no means to knowing this information, and each i^{th} SU can only assume $\overline{P_{sj}} = \overline{P_{si}}, j \neq i$, re-defining the practical sharing threshold to be

$$\lambda_{s_i} = \ln\left(\frac{1-\exp\left(-\frac{2^{R_t}-1}{\overline{\rho_i}}\right)\cdot\left(\frac{\overline{\rho_i}}{\overline{\rho_i}+(2^{R_t}-1)\cdot\overline{SNR_{ci}}}\right)^k}{\varepsilon}\right)\cdot\overline{\rho_i} \tag{20}$$

where $\overline{SNR_{ci}}$ is the average SNR of the i^{th} SU channel. It is to be noted that these spectrum sharing and access thresholds are not the optimal thresholds presented earlier in (9) and (15), but are practical and can guarantee a certain level of protection to the PU and overall rate to the SU network to validate its significance. We will see the simulation results with these practical thresholds later in Section VI.

3) Knowledge of the PU QOS target, R_t - For safe coexistence on PU spectrum, this quality measure is essential for SU's to maintain a level of interference control. It is almost always an unstated assumption in literature, that this knowledge is available to SUs for spectrum sharing purposes, to design cross-channel estimates or maintain a peak power limit for transmissions. This is not a problem that we aim to tackle here, but in designing a completely blind system, we believe this to be an open area of research, where ideally, SUs will be able to estimate R_t through supervised probing and feedback. Although this might result in higher outages at the PU, the application can definitely be seen, where anonymity is desired.

V. DECISION-MAKING ALGORITHM

With the optimized outage-constrained thresholds, the SU still needs to process the received sensing statistics to understand the network dynamics, and correspondingly adapt its power for transmission opportunities over PU spectrum. This is where our decision-making algorithm comes into play. This algorithm is heuristic, in the sense that it improves over time, which is the best that can be done for a pure interference channel with no cooperation. We will now explain each stage of the algorithm presented in the flowchart in Fig. 3. The first obvious decision to be made is whether the PU spectrum opportunity is suitable for access or sharing. As discussed earlier, a SU makes this decision by comparing the sensing metric ρ_i to the optimized sensing thresholds presented. Generally, if $\rho_i < \lambda_{a_i}$, the SU can access the spectrum, if $\rho_i > \lambda_{s_i}$, it can share the spectrum, and otherwise it remains silent. However, The PU can also default to an idle hypothesis (i.e. $\rho_i < \lambda_{a_i}$) when:

1) The PU is silent (activity probability),
2) The PU is in outage because of channel fading, or,
3) The PU experiences forced outage because of excessive SU interference.

From the SU's standpoint, distinguishing between the first 2 cases is not important, but it is essential for the SU to realize when it is transmitting with excessive power. To eliminate the chance of a forced outage, we first verify if the SU had been sharing the PU spectrum in the previous frame, through a mode counter, mc. If so, we attribute the last SU transmission power increment to the forced outage, and ensure the SU reduces its power by two incremental states to when the network was stable. If it so happens that ρ_i is still less than λ_{a_i}, it implies that the PU is idle or silent and the i^{th} SU can access the spectrum freely. Finally, to ensure that only one user accesses the spectrum at a time, we introduce a check threshold in the form of λ_{chk_i}, to ensure that the other SUs remain silent even though the primary user statistics indicate inactivity. We define this new threshold for the occupied idle case hypothesis, H_{I_0}.

Definition 2. *Occupied Idle Case Hypothesis,* H_{I_0}. This represents the idle spectrum opportunity, H_I, that has been occupied by the i^{th} SU, making it unavailable for the other $k-1$ SUs that sense the same opportunity. We now define the check threshold as

$$\mathcal{P}_r\left(\rho_i < \lambda_{chk_i} \mid H_{I_0}\right) = \varepsilon \tag{21}$$

$$\mathcal{P}_r\left(\rho_i < \lambda_{chk_i}\right)\cdot\mathcal{P}_r\left(\log_2\left(1+\frac{P_p\cdot\gamma_p}{P_{s_{max}}\cdot\gamma_{sip}+N_0}\right) < R_t\right) = \varepsilon. \tag{22}$$

where $P_{s_{max}}$ is the maximum available instantaneous power for SU transmission. We can solve for λ_{chk_i} as

$$\left(1-\exp\left(-\frac{\lambda_{chk_i}}{\overline{\rho_i}}\right)\right)\cdot\left(1-\exp\left(-\frac{(2^{R_t}-1)\cdot N_0}{\overline{P_p\cdot\gamma_p}}\right)\right.$$
$$\left.\cdot\left(\frac{\overline{P_p}}{\overline{P_p}+(2^{R_t}-1)\cdot P_{s_{max}}}\right)\right) = \varepsilon. \tag{23}$$

This give us the optimal threshold check of

$$\lambda^*_{chk_i} = \ln\left(\frac{1-\exp\left(-\frac{(2^{R_t}-1)\cdot N_0}{\overline{P_p\cdot\gamma_p}}\right)\cdot\left(\frac{\overline{P_p}}{\overline{P_p}+(2^{R_t}-1)\cdot P_{s_{max}}}\right)}{1-\varepsilon-\exp\left(-\frac{(2^{R_t}-1)\cdot N_0}{\overline{P_p\cdot\gamma_p}}\right)\cdot\left(\frac{\overline{P_p}}{\overline{P_p}+(2^{R_t}-1)\cdot P_{s_{max}}}\right)}\right)\cdot\overline{\rho_i} \tag{24}$$

or with the simplifications discussed before, we have a practical check threshold of

$$\lambda_{chk_i} = \ln\left(\frac{1-\exp\left(-\frac{2^{R_t}-1}{\overline{\rho_i}}\right)\cdot\left(\frac{\overline{\rho_i}}{\overline{\rho_i}+(2^{R_t}-1)\cdot P_{s_{max}}\cdot\overline{\gamma_{si}}}\right)}{1-\varepsilon-\exp\left(-\frac{2^{R_t}-1}{\overline{\rho_i}}\right)\cdot\left(\frac{\overline{\rho_i}}{\overline{\rho_i}+(2^{R_t}-1)\cdot P_{s_{max}}\cdot\overline{\gamma_{si}}}\right)}\right)\cdot\overline{\rho_i}. \tag{25}$$

where $\overline{\gamma_{si}}$ is the average power gain of the i^{th} SU channel.

Now, when looking at spectrum sharing side of the algorithm (i.e. $\rho_i > \lambda_{s_i}$), we ideally want our adaptive algorithm to best utilize the available resources with all the SUs present. Through our coding, we try and emulate a water-filling idea in terms of the capacity the PU spectrum

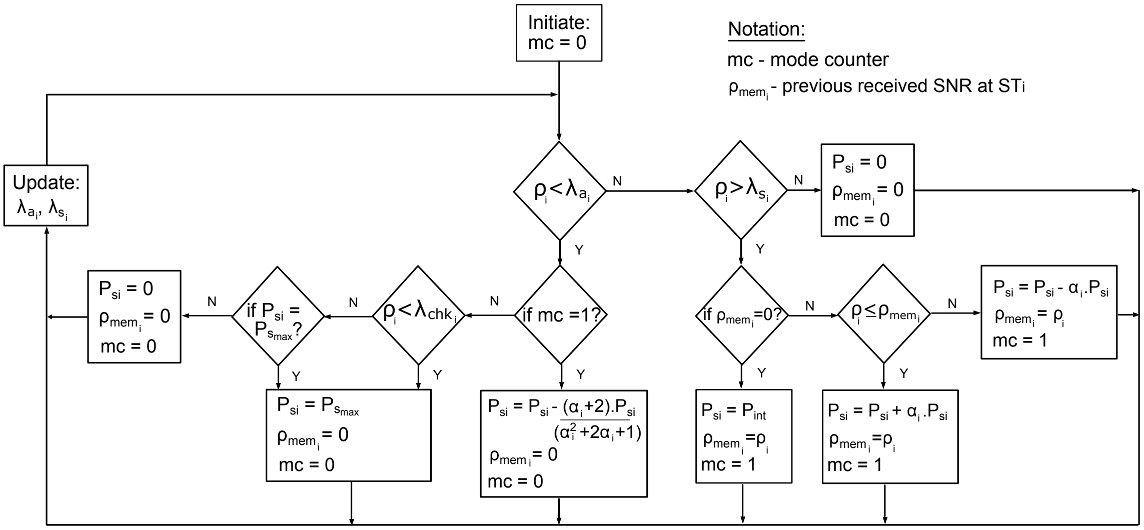

Fig. 3: Decision-making Algorithm.

can handle, as depicted in Fig. 4. Here, SUs that enter the network, accommodate underutilized spectrum resources, by adaptively increasing their transmission power. If the PU's instantaneous rate falls below the QOS target, they reduce their transmission power realizing the capacity of the network has been reached. We formulate this idea by comparing ρ_i, with the stored SNR, ρ_{mem_i}, from the previous transmission frame. The initialization phase is where the SU's transmission power is set to a pre-defined initial starting power of P_{int}. If in the consequent frames, the SU senses a $\rho_i > \rho_{mem_i}$, we understand this event to be the PU increasing its power to compensate for interference, and accordingly reduce the SU transmission power by a percentage, α_i. Conversely, the SU can increase its transmission power by an incremental state, α_i, if $\rho_i < \rho_{mem_i}$. This value of α_i can be practically optimized through a number of repeated iterations to satisfy a particular objective. In our model, we carry m Monte Carlo simulations, to arrive at the optimized alpha representing the maximum overall SU rate in the network as

$$\begin{aligned} \alpha_i^* = \max_{P_{si}} \quad & R_c \\ \text{s.t.} \quad & 0 \leq P_{si} \leq P_{s_{max}} \end{aligned}$$

where R_c is the overall average SU network rate given by

$$R_c = \frac{1}{m} \cdot \frac{1}{k} \cdot \sum_m \sum_i \log_2 \left(1 + \frac{P_{si} \cdot \gamma_{si}}{P_p \cdot \gamma_{pri} + \sum_{j,j \neq i} P_{sj} \cdot \gamma_{srji} + N_0} \right). \tag{26}$$

This optimization of α_i need only be calculated by a SU once on entering a new network. This is because the changes in the optimized α_i^* can be attributed to network size and density. To understand this, we look again at the water-filling idea for capacity maximization in Fig. 4. It can be seen, that with more users in the network, for example, a dense urban environment, power increment has to be more conservative to maintain network stability, and therefore we can expect a smaller α_i^*. Conversely, when there are fewer users or a sparse network arrangement similar to networks setup in a rural environment, aggressive power increments will help converge faster to the network capacity, and therefore a higher α_i^* can be expected. We will now demonstrate these achievable network rates along with the the corresponding PU outage in the following Simulation Results section.

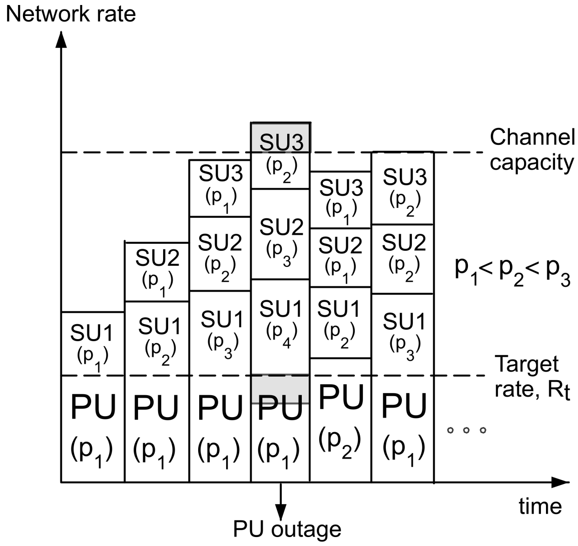

Fig. 4: Water-Filling Power adaptation.

VI. Simulation Results

In this section, we plot the average achievable SU network rate and corresponding PU outage, comparing our practical-outage constrained thresholds in (17), (20), and (25), against the traditional ED threshold design in (4). To plot our results, Monte Carlo simulations for 2×10^6 channel realizations have been carried out, with every 20 consecutive frames coherent. For this we consider a system bandwidth of 40MHz, and a channel coherence time of 5.28ms, which allows for as much as 10^4 symbols per frame. It is to be understood, that for fewer symbols per frame, we could allow for greater number of coherent transmission frames, and more precision in the decision-making algorithm. Since the PU system we

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2016.2615626, IEEE Transactions on Communications

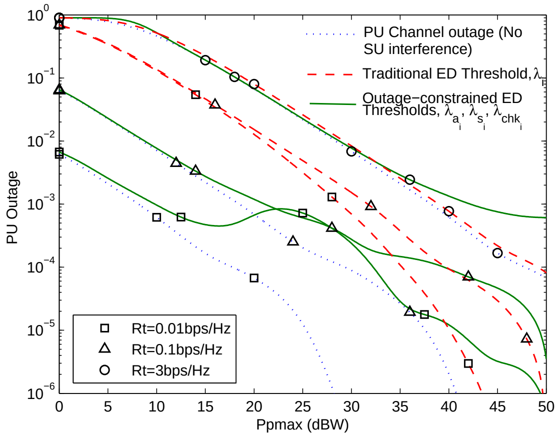

Fig. 5: PU Outage against maximum PU transmission power.

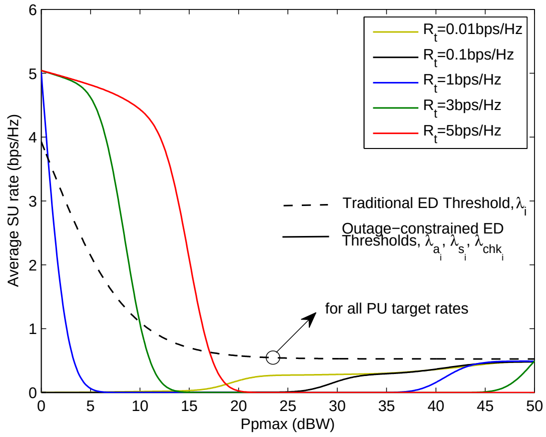

Fig. 6: Average achievable SU network rate for varying PU target rates.

are considering is QOS-centric and can update its transmission power based of its own feedback loop, we utilize the maximum available power to the PU, $P_{p_{max}}$, as the variable to plot our graphs. Here, we have set the maximum transmission power of the SU, $P_{s_{max}}$, to be 50dBW, the noise variance at the receivers, N_0, to unity, and the probability of PU activity as 0.9 (i.e. the PU is present 90% of the time on its channel). With 30 samples per frame (M), we plot the results for an error measure, $\epsilon = 10^{-3}$, and therefore correspondingly we use a probability of detection, $\mathcal{P}_d = 0.999$ for the traditional threshold design.

In these simulations, we compare our thresholds against two benchmarks: one being the aforementioned traditional threshold design in (4), and the second is the PU channel outage, void of any SU involvement. In Fig. 5, we demonstrate the corresponding PU outage for SU transmissions using these thresholds. It is to be noted that the graphs will not be representative of the traditional rayleigh fading BER (bit-error rate) vs SNR curves, as we plot the PU outage against $P_{p_{max}}$, its maximum available transmission power. Therefore, the information that this graph provides is the maximum interference compensation available to a QOS-sensitive PU. But what is obvious to note is the substantial performance improvement using outage-constrained thresholds. When a higher PU target rate like 3 bps/Hz is considered, we expect spectrum access opportunities to be aplenty, and we notice that our outage-constrained curve (solid green) defaults to the PU's own channel outage curve (dotted blue), until sufficient transmission power allows for spectrum sharing opportunities, which conform to the acceptable outage limit of 10^{-3}. Now when we observe the trend for lower target rates ($R_t = 0.01, 0.1$ bps/Hz), we see a clear distinction between our outage-constrained curve and the traditional ED threshold curve (dashed red), as part of our hybrid design involves utilizing spectrum sharing opportunities, which can be seen here. At the low SNR regime, our outage-constrained curve demonstrates the spectrum access opportunities within an error of ϵ, while the more erratic behavior at higher SNRs can be attributed to freedom in SU transmission power control for spectrum sharing opportunities within the limitations (below 10^{-3} mark) of the predesigned outage constraint. It is clear to see that with these thresholds we can guarantee an error floor for PU communication, something that has not been addressed in a decentralized manner in spectrum sensing research before.

When considering the benefit to the SUs, Fig. 6 demonstrates the average achievable network rate for our decentralized scheme. While being outage-constrained, we can still see comparable rate gains at higher QOS margins using our approach. It is to be understood, that these rate curves for the outage-constrained thresholds represent a stable and uncooperative hybrid network topology, i.e. the PU is QOS-secure while being unaware of the SUs in the network. In comparison, the average SU rate for the traditional threshold design (black dotted line) remains unchanged for a varying range of QOS margins in R_t, being oblivious to the state of PU transmissions. Therefore, a threshold design that is independent of the PU target rate will provides lesser protection to the PU, and also lesser flexibility in spectrum sharing opportunities for the SU. The reported higher average achievable rate for the traditional threshold is only a misrepresentation of how detection measures, like missed detection probability or probability of detection cannot be used as an effective outage measure for threshold design. We also observe that though our outage-constrained threshold design provides spectrum sharing opportunities at higher PU SNRs, with no shared information between the SUs themselves, the spectrum sharing rate shown is the best achievable rate for a pure interference network under the strong interference model. Ideally, with a less stringent model or with the introduction of cooperation, the SUs can carry out interference alignment or simple mitigation techniques, to achieve better spectrum sharing rates using these thresholds. This idea of cooperation however, does not fall within the framework of this network model, and so we reserve that research as a future direction for outage-constrained threshold design.

VII. CONCLUSION

In this paper, we discuss the need for outage-constrained threshold design for spectrum sensing in a decentralized network of SUs. Prior work in spectrum sensing has prioritized sensing PU activity, over the consequence of SU transmissions over the sensed spectrum. In this work, we bring the power-limiting constraints from the primary receiver end to the front end of threshold design, so that any SU in the network that carries out spectrum sensing with these thresholds, would already be in compliance with the QOS requirements of the PU when they transmit over the sensed spectrum. The paper also discusses a QOS-secure region for the PU in threshold design, through the introduction of a spectrum sharing threshold, for simultaneous SU transmissions over PU spectrum. This helps bring spectrum efficient design into spectrum sensing decisions made by the SUs in a network. Moreover, the SUs in the network do not cooperate, and operate decentralized with a decision-making algorithm that utilizes only the sensed channel statistics to make spectrum allocation and smart utility decisions. We have demonstrated that with these thresholds, we can guarantee an error-floor for PU communication at high SNRs and cause no interference at the lower SNR regime with a user-specified error control measure. Also the achievable SU rates for an interference network have been plotted, demonstrating an open area of research in cooperative SU outage-constrained threshold design that still remains incognito to the PU network. Convergence studies on this model can also be done by investigating the effect that the optimized percentage power increment has on the speed of this distributed network. Other open areas for future work, can be seen in predicting SU network dynamics or estimating PU's QOS margins using adaptive threshold design, an area of research that will greatly benefit SU spectrum sharing research.

APPENDIX

PROOF OF CLOSED FORM SOLUTIONS FOR OUTAGE-CONSTRAINED THRESHOLDS

These are well established closed-form results for Rayleigh fading channels, but for completeness we will elaborate them below. With Rayleigh fading, the channel power gains would follow an exponential distribution, therefore we represent the probability, $\mathcal{P}_r\left(\frac{P_p \cdot \gamma_{pti}}{N_0} \geq \lambda_{a_i}\right)$ in (7) as

$$\begin{aligned}\mathcal{P}_r\left(\frac{P_p \cdot \gamma_{pti}}{N_0} \geq \lambda_{a_i}\right) &= \mathcal{P}_r\left(\gamma_{pti} \geq \frac{\lambda_{a_i} \cdot N_0}{P_p}\right)\\ &= \int_{\frac{\lambda_{a_i} N_0}{P_p}}^{\infty} \frac{1}{\gamma_{pti}} \exp\left(-\frac{x}{\gamma_{pti}}\right) dx\\ &= \exp\left(-\frac{\lambda_{a_i} \cdot N_0}{\overline{\overline{P_p \cdot \gamma_{pti}}}}\right)\end{aligned} \tag{27}$$

and similarly, we get $\mathcal{P}_r\left(\log_2\left(1+\frac{P_p \cdot \gamma_p}{N_0}\right) \geq R_t\right) = \exp\left(-\frac{(2^{R_t}-1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right)$.

In solving the spectrum sharing threshold, the probability, $\mathcal{P}_r\left(R_l^{'} < R_t\right)$ in (12) can be written as

$$\begin{aligned}&\mathcal{P}_r\left(R_l^{'} < R_t\right)\\ &= \mathcal{P}_r\left(\log_2\left(1+\frac{P_p \cdot \gamma_p}{\sum_{i=1}^{k} P_{si} \cdot \gamma_{sip} + N_0}\right) < R_t\right)\\ &= 1 - \mathcal{P}_r\left(\gamma_p \geq (2^{R_t}-1) \cdot \left[\frac{N_0}{P_p} + \sum_{i=1}^{k} \frac{P_{si}}{P_p} \cdot \gamma_{sip}\right]\right)\\ &= 1 - E\left[\exp\left(-(2^{R_t}-1)\left[\frac{N_0}{P_p} + \sum_{i=1}^{k} \frac{P_{si}}{P_p} \cdot \gamma_{sip}\right]\right)\right]\\ &= 1 - \exp\left(-\frac{(2^{R_t}-1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right) \cdot E\left[\exp\left(-\sum_{i=1}^{k} \frac{P_{si}}{P_p} \cdot \gamma_{sip}\right)\right]\\ &= 1 - \exp\left(-\frac{(2^{R_t}-1) \cdot N_0}{\overline{P_p \cdot \gamma_p}}\right) \cdot \prod_{i=1}^{k}\left(\frac{\overline{P_p}}{\overline{P_p} + (2^{R_t}-1) \cdot \overline{P_{si}}}\right).\end{aligned} \tag{28}$$

We can arrive at this because for a single SU interferer, P_{s_j}, the distribution follows a log-logistic distribution [11] as

$$\begin{aligned}\mathcal{P}_r\left(\frac{\gamma_p}{\gamma_{sjp}} \geq (2^{R_t}-1)\left(\frac{\overline{P_{sj}}}{\overline{P_p}}\right)\right) &= \int_{(2^{R_t}-1)\left(\frac{\overline{P_{sj}}}{\overline{P_p}}\right)}^{\infty} (x+1)^{-2} dx\\ &= \frac{\overline{P_p}}{\overline{P_p} + (2^{R_t}-1) \cdot \overline{P_{sj}}}.\end{aligned} \tag{29}$$

We can thus solve for (22) in a similar fashion.

REFERENCES

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

[2] M. H. Islam, C. L. Koh, S. W. Oh, X. Qing; Y. Y. Lai, C. Wang; Y. -C. Liang; B. E. Toh, F. Chin, G. L. Tan, and W. Toh, "Spectrum survey in singapore: occupancy measurements and analyses," *3rd Intl. Conf. on Cognitive Radio Oriented Wireless Netw. and Commun., 2008*, Jul. 2008, pp. 1-7.

[3] M. Song, C. Xin, Y. Zhao and X. Cheng, "Dynamic spectrum access: from cognitive radio to network radio," *IEEE Trans. Wireless Commun.*, vol. 19, no. 1, pp. 23-29, Feb. 2012.

[4] M. Fitch, M. Nekovee, S. Kawade, K. Briggs and R. MacKenzie, "Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience," *IEEE Commun. Magazine*, vol. 49, no. 3, pp. 64-73, Mar. 2011.

[5] A. T. Hoang, Y. C. Liang, D. Wong, Y. Zeng, and R. Zhang, "Opportunistic spectrum access for energy-constrained cognitive radios," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1206-1211, Mar. 2009.

[6] S. W. Boyd, J. M. Frye, M. B. Pursley, and T. C. Royster, "Spectrum monitoring during reception in dynamic spectrum access cognitive radio networks," *IEEE Trans. on Commun.*, vol. 60, no. 2, pp. 547-558, Dec. 2011.

[7] W. Hu, D. Willkomm, M. Abusubaih, J. Gross, G. Vlantis, M. Gerla, and A. Wolisz, "Dynamic frequency hopping communities for efficient IEEE 802.22 operation," *IEEE Communications Magazine*, vol. 45, no. 5, pp. 80-87, May 2007.

[8] F. Marino, L. Paura, and R. Savoia, "On spectrum sensing optimal design in spatial-temporal domain for cognitive radio networks," *IEEE Trans. on Veh. Tech.*, vol. PP, no. 99, pp.1-1, Dec. 2015.

[9] G. Zhang, X. Wang, Y. C. Liang, and J. Liu, "Fast and robust spectrum sensing via kolmogorov-smirnov test," *IEEE Trans. on Commun.*, vol. 58, no. 12, pp. 3410-3416, Dec. 2010.

[10] J. Font-Segura and X. Wang, "GLRT-Based Spectrum Sensing for Cognitive Radio with Prior Information," *IEEE Trans. on Commun.*, vol. 58, no. 7, pp.2137-2146, Jul. 2010.

[11] A. Ghasemi and E. S. Sousa, "Fundamental limits of spectrum-sharing in fading environments ," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 649 - 658, Feb. 2007.

[12] S. Stotas and A. Nallanathan, "On the throughput maximization of spectrum sharing cognitive radio networks," *IEEE Global Telecomm. Conf. (GLOBECOMM 2010)*, Dec. 2010, pp. 1-5.

[13] S. Stotas and A. Nallanathan, "On the outage capacity of sensing-enhanced spectrum sharing cognitive radio systems in fading channels," *IEEE Trans. on Commun.*, vol. 59, no. 10, pp. 2871 - 2882, Oct. 2011.

[14] J. C. F. Li, W. Zhang, and J. Yuan, "Opportunistic spectrum sharing in cognitive radio networks based on primary limited feedback," *IEEE Trans. on Commun.*, vol. 59, no. 12, pp. 3272 - 3277, Dec. 2011.

[15] R. Zhang, "On active learning and supervised transmission of spectrum sharing based cognitive radios by exploiting hidden primary radio feedback," *IEEE Trans. on Commun.*, vol. 58, no. 10, pp. 2960 - 2970, Oct. 2010.

[16] H. YuanYuan and S. Dey, "Power allocation in spectrum sharing cognitive radio networks with quantized channel information," *IEEE Trans. on Commun.*, vol. 59, no. 6, pp. 1644 - 1656, Jun. 2011.

[17] I. Bajaj and Y. Gong, "Cross-channel estimation using supervised probing and sensing in cognitive radio networks," in *IEEE Intl. Conf. on Commun. (ICC 2011)*, Jun. 2011, pp. 1-5.

[18] L. Zhang, G. Zhao, G. Wu, and Z. Chen, "Proactive channel gain estimation for coexistence between cognitive and primary users," in *Global Commun. Conf. (GLOBECOM 2012)*, Dec. 2012, pp. 1410-1415.

[19] J. Tang, and S. Lambotharan, "Interference alignment techniques for MIMO multi-cell interfering broadcast channels," in *IEEE Trans. on Commun.*, vol. 61, no. 1, pp. 164-175, Jan. 2013.

[20] Y. Han, A. Pandharipande, and S. H. Ting, "Cooperative spectrum sharing via controlled amplify-and-forward relaying," *IEEE 19th Int. Symp. on Personal, Indoor and Mobile Radio Comm., 2008*, Sep. 2008, pp. 1-5.

[21] Y. Zou, Y. -D. Yao, and B. Zheng, "Cooperative relay techniques for cognitive radio systems: spectrum sensing and secondary user transmissions," *IEEE Commun. Magazine*, vol. 50, no. 4, pp. 98-103, Apr. 2012.

[22] Y. Zou, Y. -D. Yao, and B. Zheng, "Diversity-multiplexing tradeoff in selective cooperation for cognitive Radio," *IEEE Trans. on Commun.*, vol. 60, no. 9, pp. 2467-2481, Jul. 2012.

[23] I. Bajaj, Y. H. Lee, and Y. Gong, "A spectrum trading scheme for licensed user incentives," *IEEE Trans. on Commun.*, vol. 63, no. 11, pp. 4026-4036, Nov. 2015.

[24] Y. Tachwali, B. F. Lo, I. F. Akyildiz, and R. Agusti, "Multiuser resource allocation optimization using bandwidth-power product in cognitive radio networks," *IEEE Jour. on Sel. Areas in Commun.*, vol. 31, no. 3, pp. 451-463, Mar. 2013.

[25] I. F. Akyildiz, W. -Y. Lee, M. C. Vuran, and Mohanty S., "A survey on spectrum management in cognitive radio networks," *IEEE Commun. Magazine*, vol. 46, no. 4, pp. 40-48, Apr. 2008.

[26] R. Wang and M. Tao, "Blind spectrum sensing by information theoretic criteria for cognitive radios," *IEEE Trans. on Veh. Tech.*, vol. 59, no. 8, pp. 3806-3817, Oct. 2010.

[27] G. Zhao, G. Y. Li, and C. Yang, "Proactive detection of spectrum opportunities in primary systems with power control," in *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, pp. 4815-4823, Sep. 2009.

[28] I. Bajaj, Y. Gong, and X. J. Zhang, "Proactive spectrum sensing with probing power control in cognitive radio," in *4th Int. Conf. on Sig. Proc. and Commun. Sys. (ICSPCS 2010)*, Dec. 2010, pp. 1-5.

[29] L. Sboui, Z. Rezki, and M. -S. Alouini, "Achievable rate of spectrum sharing cognitive radio systems over fading channels at low-power regime," in *IEEE Trans. Wireless Commun.*, vol. 13, no. 11, pp. 6461-6473, Nov. 2014.

[30] A. S. Kannan and E. M. Manuel, "Performance analysis of blind spectrum sensing in cooperative environment," in *Intl. Conf. on Control Commun. and Computing (ICCC 2013)*, Dec. 2013, pp. 277-280.

[31] D. -J. Lee, "Adaptive cooperative spectrum sensing using random access in cognitive radio networks," in *IEEE 24th Intl. Symp. on Pers. Indoor and Mob. Radio Commun (PIMRC 2013)*, Sep. 2013, pp. 1835-1839.

[32] J. Zhu, Z. Xu, F. Wang, B. Huang, and B. Zhang, "Double threshold energy detection of cooperative spectrum sensing in cognitive radio," *3rd Intl. Conf. on Cog. Radio Oriented Wir. Netw. and Commun. (CROWNCOM 2008)*, May 2008, pp. 1-5.

[33] B. Gedik, O. Amin, and M. Uysal, "Power allocation for cooperative systems with training-aided channel estimation," *IEEE Trans. on Wireless Commun.*, vol. 8, no. 9, pp. 4773-4783, Sep. 2009.

[34] M. Morelli and U. Mengali, "A comparison of pilot-aided channel estimation methods for OFDM systems," *IEEE Trans. on Sig. Proc.*, vol. 49, no. 12, pp. 3065-3073, Dec. 2001.

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