A Spectrum Trading Scheme for Licensed User Incentives

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***Abstract*—Spectrum utility efficiency is key in designing systems that can meet the heavier demands of bandwidth and data rate of future communication technologies. Shared spectrum techniques and collaborative protocols have thus been studied, to better utilize already existing spectrum resources. In this paper, we present a spectrum trading approach that allows the licensed user's (LU) resources to be efficiently shared with the secondary user (SU) network in exchange for a monetary cost. The model is based on demand and supply economics, wherein the highest bidder for spectrum resource is awarded with transmission rights over licensed spectrum. The transmission opportunities for the SU consider every state of the licensed link, in the form of dynamic spectrum access (DSA), spectrum sharing, and relaying, each of which has an optimized cost that will maximize the returns for the LU. The numerical results backed by the analytical study done, shows that this spectrum trading scheme allows for significant improvements in data rate and spectrum transmission opportunities, than previous work conducted in either DSA or the spectrum sharing fields.**

***Index Terms*—Spectrum sharing, spectrum access, relaying, spectrum pricing, spectrum trading.**

I. Introduction

SPECTRUM resource has traditionally been allocated according to fixed leasing patterns, decided on, by spectrum regulation bodies worldwide. However, with the advancements made in communication, the need for higher operating bandwidths and a more flexible means of accessing spectrum are imminent. Spectrum surveys that were conducted [1] [2], bring to light the inefficiency of spectrum utilization, in that, more than 85% of the spectrum resource remains unutilized or underutilized across time and space. These temporospatial holes present opportunities for transmission across licensed spectrum. Through dynamic spectrum access (DSA) techniques [3]-[8], unlicensed secondary users (SU) could sense for unutilized spectrum and engage these windows of spectrum opportunity. Through work on dynamic spectrum hopping [9], these SUs could also enjoy uninterrupted transmissions, by switching their operating frequency to another available spectrum opportunity, as soon as the licensed user (LU) resumes use of its own spectrum resource. Not ignoring the bandwidth potential of underutilized spectrum, communications research has also looked at means of efficiently utilizing this resource through collaboration.

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Simultaneous spectrum sharing and relaying, were ideas that were birthed as a result of investigating this underutilized licensed resource. Spectrum sharing as a transmission opportunity [10]-[16], allows multiple users to transmit over licensed spectrum simultaneously, while regulating the impinged interference between them. Relaying on the other hand, involves a user broadcasting the signal of another, to either extend the communication range, or to provide path diversity to mitigate fading. Therefore, unlike spectrum sharing, the role of relaying as a solution to underutilized spectrum was not evident at first. Until recently, relaying was only seen implemented in collaborative SU networks [17]-[20]. The first idea of involving the LU with a SU relay was highlighted in [21], through a collaborative strategy that allowed both SU and relayed LU data to be transmitted simultaneously over the spectrum. Thus, the implementation of DSA, spectrum sharing, and relaying can be seen in improving the overall spectrum utility efficiency. However, what does the LU have to gain from all of this?

Models that have been designed to include one or more of these spectrally-efficient transmission schemes for a hybrid LU-SU network [11] [21]-[23], have all highlighted the need to mitigate interference to the LU or restrict it to an acceptable level. But from a practical standpoint, the LU must have an incentive to participate. Spectrum trading has taken the role in facilitating incentivized LU involvement, by allowing the LU to charge a spectrum fee for its shared resources. The general spectrum trading model features one LU with a network of competing or collaborative SUs, that wish to engage the unutilized or underutilized spectrum opportunities of the LU, in exchange for a cost. Most work carried out in spectrum trading follow either an economic model or a game theory model. An example of an economic model can be seen implemented in [24], to represent a monopoly market setting, wherein, the LU charges a channel quality-based price for spectrum that it wishes to lease. This provides the SU network with options to meet its specific throughput needs based on channel quality. This fixed cost bracket however, limits the returns the LU could get from a SU willing to pay more for said spectrum resource. Other work in spectrum trading take on the more popular game theory models [25] [26], with an optimal Nash equilibrium determining the strategy for pricing. As with Stackelberg games, the leader or initiator (in this case, the LU), is believed to have a competitive edge, in terms of the utility it can derive from the game. However if the follower (or the SU), wishes to pay less than the offered price, it can topple the LU out of its position of advantage, resulting in a non-optimal Nash equilibrium. Game theory models also associate decisions with intention, which can sometimes prove unrealistic. This can be seen, for example, when a SU is unwilling to access the spectrum resource due to unfavorable channel conditions, regardless of the cost, and associating this decision as its intention, lowers the average cost for the LU spectrum, and results in a non-optimal agreement.

The gap in research in the field of spectrum trading, is one which can maximize the returns to the LU, providing incentive for participation, and allowing the SU to decide if it sees positive utility in engaging these spectrum resources. Most spectrum trading work thus far, have focused on optimization of the throughput of the SU network, however, our work, maximizes the LU payoff. We base our spectrum trading scheme on an economic demand and supply model, that awards the highest bidder with the opportunity for transmission. Moreover, our scheme works on a hybrid access technology that allows the LU to engage the SU, regardless of the state of the LU link, i.e. strong or poor, busy or idle. Prior work in spectrum trading, considers only one avenue for transmission, either DSA, spectrum sharing or relaying. Though, the idea of a system that can switch between these three modes of operation, depending on the channel conditions, is a new concept, we wish to highlight through our work, the implications it can have on the average achievable rate of the SU network and LU spectrum utility efficiency.

The organization of the paper begins with the system model and the framework behind the procedure of spectrum trading in Section II. From here, we move on to Section III to discuss the three modes of collaboration, through which a SU can gain transmission rights over licensed spectrum. It is here, that we also discuss the goal of LU payoff maximization and study its formulation. We then propose an analytical model in Section IV, that can arrive at the theoretical closed-form solutions to cost optimization, that maximize the LU payoff. Finally, we present numerical results to corroborate our analytical model, and demonstrate the gains that can be expected from a hybrid LU-SU network for our spectrum trading model in Section V. The notations and acronyms used in this paper are summarized in Table I.

TABLE I

NOTATION TABLE

Symbol	Definition
k	Number of SUs in the network
h_j	j^{th} fading channel, $j = \{l, si, 1i, 2i, 3i\}$, $i \in [1, k]$
γ_j	Power gain of j^{th} fading channel
αi	Percentage of i^{th} SU's transmission power towards relaying LU data
R_d	Instantaneous LU data rate in absence of interference/SU involvement
P_p	LU's transmission power
N_0	Noise variance or noise power spectral density
R_t	LU target rate requirement
R_b^c	Achievable instantaneous rate for: $c = \{s, r, a\}$, s-sharing, r-relaying, a-access $b = \{p, si\}$, p-LU, si-i^{th} SU
P_s	SUs' transmission power
ν	Peak interference power constraint for sharing LU spectrum
x^+	Positive-semidefinite of x
P_{ci}	Spectrum sharing power constraint on i^{th} SU transmission
P	Maximum available transmission power for all k SUs
x_b	Transmission signal of $b = \{p, si, sti\}$, p-LU, si-i^{th} SU, sti-i^{th} ST relay
y_b	Received signal at $b = \{sti, lr_1, lr_2, sri_1, sri_2\}$, sti-i^{th} ST relay, lr-LR, sri-i^{th} SR, in the 1-first transmission phase, 2-second transmission phase
n_b	AWGN at b, represented above
z_i	Normalization factor in AF relay at i^{th} ST
C_c	Spectrum cost for $c = \{s, r, a\}$, s-sharing, r-relaying, a-access
U	LU Payoff
$\mathcal{P}(x)$	Probability of event x
$\mathcal{W}(x)$	Product log function of x
Acronym	**Definition**
LU, LT, LR	Licensed User, Transmitter, Receiver
SU, ST, SR	Secondary User, Transmitter, Receiver
RTA, RTR	Request To Access, Relay
PTS	Permit To Share
CTS, CTR	Confirm To Share, Relay
ATR	Acknowledgment To Relay
FTR	Fail To Relay
CSI	Channel state information
SNR	Signal-to-noise ratio
AWGN	Additive white gaussian noise

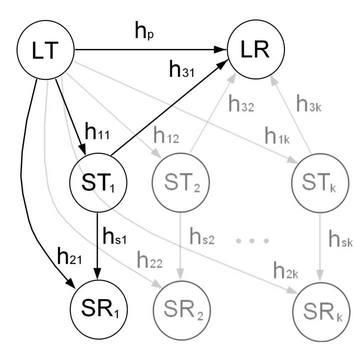

Fig. 1: System Model.

II. SYSTEM DESCRIPTION

The spectrum trading system model that we consider, consists of one LU and k SU transmitter-receiver pairs, with the channels between the respective nodes following flat slow Rayleigh fading. The transmitter-receiver pairs for the LU are referred to as LT-LR, and for the SU as ST-SR, for short. In this work, we consider a closed-access network, where the number of SUs, i.e. k, does not change. The reasoning behind this decision and the implications if this model is considered for an open access network, are discussed later in Section II-D. As seen in the system setup in Fig. 1, the channel gain between the LT and LR is denoted by h_p, between the k ST and SR pairs, by h_{si} for $i \in [1, k]$, and the cross-channels between LU and the k SUs, by h_{1i}, h_{2i}, and h_{3i}. The corresponding power gains for these channels are given by $\gamma_j = |h_j|^2$, where $j = \{l, si, 1i, 2i, 3i\}$.

The goal here, is to establish a protocol that allows the LU to interact with the network of k SUs, and determine the optimized spectrum costs that can maximize its payoff. The payoff of the LU is determined by its overall rate, and cost accorded it, from leasing its spectrum. The protocol is designed to work with every state of the licensed link, with opportunities for DSA and relaying in a poor channel, and spectrum sharing when the channel is strong. These modes of operation will be further elaborated in Section III. We will begin by investigating how the protocol is initiated.

A. Handshaking

The proposed protocol is initiated when the LU receives a Request To Access (RTA) message, sent out by any of the k SUs, as an indication that it wishes to trade resources to gain a transmission opportunity over licensed spectrum. The proposal of incentivized collaboration is then at the discretion of the LU, who can accept or reject this message. If the LU chooses to collaborate, then the LR can respond to this request with either of two messages: Request To Relay (RTR) or Permit To Share (PTS), based on its current channel condition. If the LR surpasses the instantaneous target rate for the underlying fading channel, and can accommodate additional interference from simultaneous SU transmissions, it uses this opportunity to lease this additional resource for a revenue stream. It does this by sending a PTS message to its LT, that acknowledges it by broadcasting a Confirm To Share (CTS) message to the SUs. This scenario can then be defined as the Sharing Mode, where the licensed link supports simultaneous LU and SU transmissions.

On the other hand, if the LU is in outage (i.e. a frame outage; where it cannot meet the target rate for the current transmission frame), and needs the relay support of a SU, the LR can inform the LT through a RTR message. This request is then backed up by an Acknowledgement To Relay (ATR) message broadcasted by the LT to the SU network. On receiving the RTR and ATR messages, the respective SU can determine if it can support the LU transmission, in preventing outage for the current channel realization. It does this by verifying if an α_i percentage of its power (less than 100%) dedicated to relaying the LU data, can prevent outage for LU communication. The calculation of this dedicated power percentage α_i, can be seen later in Section III-B. Therefore, if the respective ST can support LU communication, it broadcasts a Confirm To Relay (CTR) message. This scenario is defined as the Relaying Mode, and the LT and LR switch to accommodate a two-phase relaying scheme to prevent outage at the LR. In this scheme, the ST receives the LU data in the first phase, which it superimposes with its own signal and then broadcasts this over the next transmission phase to the LR, thus gaining an opportunity to transmit its data over licensed spectrum.

If however, the respective SU is not able to support the LU given its limited transmission power, it broadcasts a Fail To Relay (FTR) message, which informs the LU to stop transmission, and to preserve its power for a better channel. This then implies full spectrum access for that particular SU. This mode is appropriately named the Access Mode, as the given SU can have interference-free access to licensed spectrum. Here, the SU can transmit with maximum power, as the LU ceases to operate. These are all the handshaking messages involved, in establishing which mode of operation the LU is willing to lease its spectrum, and if the respective SU sees any utility in engaging these resources. So the question to answer now is, how is utility measured?

B. Utility Comparison

Utility or payoff is merely a term implying positive benefit or gain derived from an exchange. In spectrum trading, the LU is given incentives to lease spectrum, through payment of a spectrum cost. Each mode of operation has its own unique cost, optimized to maximize the LU's returns. Therefore, if the rate the particular SU derives, from utilizing the licensed resource is R, and the cost associated with this spectrum resource is C, the corresponding utility the SU would derive, is $R - C$. It is clear however, that the rate cannot be directly compared to a monetary cost, and therefore, we express this rate as $R = \mathcal{Q} \cdot \mathcal{B} \log_2(1 + SNR)$, where $\mathcal{B}$ represents the bandwidth, and $\mathcal{Q}$, the conversion coefficient, that allows the rate to be equated to a factor of cost. Here, without loss of generality, we make the assumption that both $\mathcal{B}$ and $\mathcal{Q}$ are 1, to represent the rate equations later.

Therefore, in comparing the rate against a particular cost, the given SU would only participate if it derives positive utility from the exchange. Also, the SU, could make the decision to choose one scheme of operation over another, say Access Mode over Relaying Mode, given that it derives greater utility from the former. These utility comparisons help the LU determine the demand for a particular mode of operation, and certainly affect the optimized cost values, that eventually decide the LU payoff. It is here we see the demand and supply nature of this economic spectrum trading model. To better understand how these handshaking messages and costs are communicated back and forth between the LU and SU network, we will now look at the frame design.

C. Frame Design

For the handshaking messages to be interpreted correctly, and for the utility comparisons to be made at the respective SUs, channel knowledge is essential. As with any spectrum trading approach, channel estimation is crucial for collaboration. We propose to use a common pilot signal, as part of the pilot sequence in every frame. As depicted in Fig. 2, we see that every symbol frame comprises of a pilot sequence, followed by transmission. This pilot sequence forms the overhead for each transmission frame, and must aim to be minimized for maximum transmission throughput. The pilot sequence comprises of the pilot signal, the handshaking message, and a user identifier (ID). The pilot signal has traditionally been used [27] [28] for work that relies on instantaneous channel state information (CSI). Depending on the fading of the channel, the level of computational complexity, and the error threshold, any standard estimator can be used in gauging the CSI; the most common ones being the minimum mean-square-error (MMSE) and least squares (LS) channel estimation techniques

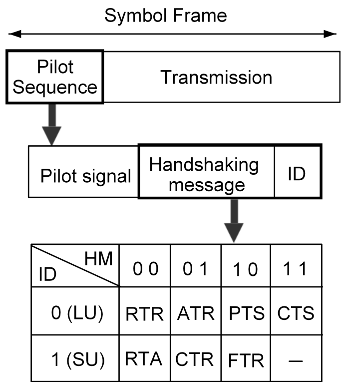

Fig. 2: Symbol Frame.

[29] [30]. After the pilot signal, the handshaking messages are exchanged between the LU and the k SUs. Here, we notice that only three of the messages (RTA, CTR, FTR) are sent by the SUs, and the remaining messages (RTR, PTS, CTS, ATR) are communicated by the LU. This can easily be digitized to a 2-bit message, with a single bit (0 - LU, 1 - SU) as the ID, as shown in Fig. 2. The ID helps a particular SU to ignore broadcasted pilot sequences from other SUs, and only look for the LU pilot sequence. To distinguish between each of the k SUs, the ID could take on more bits (i.e. $\log_2 k$), but as part of our training exercise, this is not a requirement at the LU, as we will see in the following subsection.

D. Channel Training

Channel training is generally used to make a system more robust to variations in the fading channel, or the surrounding noise. Here, we utilize this opportunity for the LU to also gauge the demand in the network for its spectrum resource. During the initial setup, the training exercise is carried out for a sufficient number of dynamic channel realizations, for the LU to optimize the costs for access, sharing and relaying. These optimized costs are then made public knowledge, for the SUs to make utility comparisons and determine if they wish to collaborate. As mentioned earlier, there is no need for separate IDs for each of the k SUs, as the LU does not need to distinguish between the users, but to ensure if and how many of the k SUs are interested in transmitting at the current price. Optimizing the costs, implies that there would be only one interested SU (usually the highest bidder) for a given set of channel realizations. Therefore, ensuring that this is a closed-access network (i.e. for a fixed SU network size) is crucial in determining that only one of k SUs will be engaging licensed resources at a given time. On the other hand, if the network follows an open-access topology, the optimized costs would be outdated information if new SUs enter the system after the training phase. In this scenario, the issue is that, for a given cost, there might be two or more SUs that are willing to enter into access, sharing or relaying modes based on this outdated cost information. This would result in unavoidable interference to the LU and reduced overall capacities for the SUs wishing to transmit. From a practical standpoint, if this open-access scheme were to be used, certain considerations must be made. The channels are assumed to follow slow fading, and the training exercise must be carried out as a function of the coherence time of the channel. Understandably, for an urban environment and for fast fading channels, only closed-access networks could be considered, and it is why we have adopted this access mechanism.

Alternatively, if the average received signal-to-noise ratio (SNR) of the given SU can be estimated, with closed-form theoretical costs, our simplified analytical model (demonstrated in Section IV) could be employed for a closed- or open-access network. We will now describe the formulation involved in our general model, before moving on to the aforementioned analytical model.

III. General Model

In this section, we discuss the formulation of the rates involved with each of the three modes of operation, i.e., sharing, relaying, and access, and how LU payoff is calculated. We begin by defining R_d as the instantaneous data rate the LU can support on its channel, in the absence of any collaboration/interference from the SUs. This rate is given by

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

where P_p is the LU's transmit power and N_0 is the noise variance at the LR. Throughout this paper, we assume unity noise variance (i.e. $N_0 = 1$) for all the noise terms involved. This instantaneous rate, R_d, is compared against a quality target rate, R_t, to determine the different modes in which the LU can lease its spectrum resource to the SUs. We will now look at these different modes of operation.

A. Sharing Mode

The sharing mode comes into play when R_d, surpasses the quality target rate, R_t, set by the LR. In this case, the LU experiences a surplus gain in terms of its transmission rate, which it can redirect to accommodating a SU on the same spectrum. In exchange for a spectrum cost, the SU gains an opportunity to transmit simultaneously over the same LU spectrum, within a margin of interference. The corresponding LU rate would now be

$$R_p^s = \log_2 \left(1 + \frac{P_p \cdot \gamma_p}{P_s \cdot \gamma_{3i} + 1} \right). \tag{2}$$

Here, P_s, is representative of the all the SU's transmit power, which for simplicity, has been considered equal across all SUs in the network. Now, this instantaneous LU sharing rate, must be maintained to the target quality rate, R_t, implying that P_s, must be limited by a power constraint, P_{ci}, to protect the LU from undesired interference. This can be calculated through the peak interference power (PIP) constraint made public by the LU. This PIP constraint, denoted by $\mathcal{V}$, is necessary to guarantee a cross-interference lower than the acceptable margin for an outage-free LU. It follows that

$$\mathcal{V} = \left[\frac{P_p \cdot \gamma_p}{2^{R_t} - 1} - 1 \right]^+ \tag{3}$$

$$P_{ci} = \frac{\mathcal{V}}{\gamma_{3i}} \tag{4}$$

where $[x]^+$ is the positive-semidefinite, which is equal to x when $x > 0$, and equal to 0 otherwise.

The corresponding sharing rate achieved by the i^{th} SU is given by

$$R^s_{si} = \log_2\left(1 + \frac{P_s \cdot \gamma_{si}}{P_p \cdot \gamma_{2i} + 1}\right) \tag{5}$$

where we recollect that the instantaneous transmission power must be limited as

$$P_s = \min(P_{ci}, P) \tag{6}$$

where P is the maximum available instantaneous transmission power for all k SUs.

B. Relaying Mode

Unlike spectrum sharing, the relaying mode is activated, when the instantaneous LU rate drops below the target rate (R_t), and the LU seeks for assistance from a SU in the form of relaying. Here, a SU can gain spectral rights to simultaneously transmit its own message, while helping the LU meet its target rate requirement. The LT and LR adopt a two-phase network with the given ST as a relay point. In the first transmission phase, the LU broadcasts its signal, x_p with power P_p. The signal received at the i^{th} ST and the LR in this first transmission phase can be given by y_{sti} and y_{lr_1} respectively,

$$y_{sti} = \sqrt{P_p} \cdot h_{1i} \cdot x_p + n_1^{sti} \tag{7}$$

$$y_{lr_1} = \sqrt{P_p} \cdot h_p \cdot x_p + n_1^{lr} \tag{8}$$

where n_1^{sti} and n_1^{lr} represent the additive white gaussian noise (AWGN) at the i^{th} ST and LR respectively, during the first transmission phase.

With amplify-and-forward relaying, the ST normalizes the received LU signal, and amplifies it with a percentage of its power given by α_i. It then is superimposed with the given ST's signal, x_{si} of power P_s, to be forwarded in the second transmission phase to the LR. This composite signal is given by

$$x_{sti} = \sqrt{\alpha_i \cdot z_i} \cdot y_{sti} + \sqrt{P_s \cdot (1 - \alpha_i)} \cdot x_{si} \tag{9}$$

where $z_i = \frac{P_s}{P_p \cdot \gamma_{1i} + 1}$ is the normalization factor. Thus, the signal received at the LR from the i^{th} SU in the second transmission phase then becomes

$$\begin{aligned} y_{lr_2} &= x_{sti} \cdot h_{3i} + n_2^{lr} \\ &= (\sqrt{P_p \cdot \alpha_i \cdot z_i} \cdot h_{1i} \cdot h_{3i}) x_p + (\sqrt{P_s (1 - \alpha_i)} \cdot h_{3i}) x_{si} \\ &\quad + \sqrt{\alpha_i \cdot z_i} \cdot h_{3i} \cdot n_1^{sti} + n_2^{lr} \end{aligned} \tag{10}$$

where n_2^{lr} represents the AWGN at the LR in phase two of transmission.

Therefore, from (8) and (10), the LU rate for a 2-phase relay system can be written as

$$R^r_p = \frac{1}{2}\log_2\left(1 + P_p \cdot \gamma_p + \frac{P_p \cdot \gamma_{1i} \cdot \gamma_{3i} \cdot z_i \cdot \alpha_i}{P_s \cdot (1 - \alpha_i) \cdot \gamma_{3i} + \alpha_i \cdot z_i \cdot \gamma_{3i} + 1}\right). \tag{11}$$

However, prior to accepting the relay opportunity, the given SU must check to ensure that it can sustain the instantaneous LU rate, R^r_p, to be no less than the target rate R_t. For this to happen, the ST can at most assign 100% (i.e. $\alpha_i = 1$) of its transmission power, acting as a pure relay to the LU in outage. With dynamic channel information made available through the pilot symbols, the given SU can calculate α_i as

$$\alpha_i = \left[\frac{(P_p \cdot \gamma_{1i} + 1)(P_s \cdot \gamma_{3i} + 1)(P_p \cdot \gamma_p - 4^{R_t} + 1)}{P_p \cdot P_s \cdot \gamma_{1i} \cdot \gamma_{3i} \cdot (P_p \cdot \gamma_p - 4^{R_t})}\right]^+. \tag{12}$$

During the broadcast of the LU's message to the i^{th} ST, its SR also eavesdrops on the transmitted signal, x_p, as

$$y_{sri_1} = \sqrt{P_p} \cdot h_{2i} \cdot x_p + n_1^{sri} \tag{13}$$

where n_1^{sri} is the AWGN at the i^{th} SR for the first transmission phase. With the received signal, y_{sri_1}, the given SR has a zero-forcing estimate of x_p, given by

$$\tilde{x}_p = x_p + \frac{n_1^{sri}}{\sqrt{P_p} \cdot h_{2i}}. \tag{14}$$

The i^{th} SR also receives the composite relayed signal from its ST, during the phase two broadcast transmission, as

$$\begin{aligned} y_{sri_2} &= x_{sti} \cdot h_{si} + n_2^{sri} \\ &= (\sqrt{P_p \cdot \alpha_i \cdot z_i} \cdot h_{1i} \cdot h_{si}) x_p + (\sqrt{P_s \cdot (1 - \alpha_i)} \cdot h_{si}) x_{si} \\ &\quad + \sqrt{\alpha_i \cdot z_i} \cdot h_{si} \cdot n_1^{sti} + n_2^{sri} \end{aligned} \tag{15}$$

where n_2^{sri} is the AWGN at the i^{th} SR for the second transmission phase. With the estimate of x_p from (14), the SR can cancel out the LU interference from the received signal to get

$$\begin{aligned} \tilde{y}_{sri_2} &= y_{sri_2} - (\sqrt{P_p \cdot \alpha_i \cdot z_i} \cdot h_{1i} \cdot h_{si}) \tilde{x}_p \\ &= (\sqrt{P_s \cdot (1 - \alpha_i)} \cdot h_{si}) x_{si} - \frac{\sqrt{\alpha_i \cdot z_i} \cdot h_{1i} \cdot h_{si} \cdot n_1^{sri}}{h_{2i}} \\ &\quad + \sqrt{\alpha_i \cdot z_i} \cdot h_{si} \cdot n_1^{sti} + n_2^{sri}. \end{aligned} \tag{16}$$

From (16), we can calculate the instantaneous rate for the i^{th} SU in relaying mode as

$$R^r_{si} = \frac{1}{2}\log_2\left(1 + \frac{P_s(1 - \alpha_i) \cdot \gamma_{2i} \cdot \gamma_{si}}{\alpha_i \cdot z_i(\gamma_{1i} + \gamma_{2i})\gamma_{si} + \gamma_{2i}}\right). \tag{17}$$

C. Access Mode

As we saw in relaying, the given SU can only support the LU in preventing an outage, only if $0 < \alpha_i \leq 1$. For the case where $\alpha_i = 0$ or $\alpha_i > 1$, the SU fails to support LU transmission even as a pure relay. The LU here, will face an outage, and does not benefit from transmitting. So instead, the LU leases out the spectrum to the given SU on an interference-free basis for a spectrum access cost. We term this opportunity for the SUs as the Access Mode. The maximum achievable rate for the i^{th} SU is given by

$$R^a_{si} = \log_2\left(1 + P \cdot \gamma_{si}\right). \tag{18}$$

D. Secondary User Rates

With the rate formulations for the three modes of operation above, the average achievable rate of each of k SUs, and consequently of the entire SU network can be computed. However, as we mentioned earlier in Section II-B, the SU will only enter into any of these modes of collaboration, only if it derives positive utility from the exchange. To each of the three modes the LU assigns a cost: a sharing cost, C_s, a relaying cost, C_r, and an access cost, C_a. On comparing the achievable rates against the set costs, the SU then makes the decision to collaborate. Also, the case may arise where, even though the SU has sufficient power to support LU communication during relaying (i.e. $\alpha_i \leq 1$), can choose to access the LU spectrum, by sending a FTR handshaking message, if it derives greater comparative utility in doing so (i.e. $R^a_{si} - Ca > R^r_{si} - Cr$). Thus this trading of resources becomes an interesting demand and supply model, as only the perfect balance between the spectrum costs, would entertain maximum returns for the LU while satisfying the price that a SU would be willing to pay for its spectrum needs. Thus, the overall average achievable rate over all the SUs in the network, and for all possible channel realizations, is given by

$$\begin{aligned}\overline{R}_s = \frac{1}{k}\sum_i \Big[&\overline{R}^s_{si} \cdot \mathcal{P}(R_d > R_t, R^s_{si} > C_s)\\ &+\overline{R}^a_{si} \cdot \mathcal{P}(R_d < R_t, \alpha_i > 1, R^a_{si} > C_a)\\ &+\overline{R}^a_{si} \cdot \mathcal{P}(R_d < R_t, \alpha_i \leq 1, R^r_{si} - C_r < R^a_{si} - C_a, R^a_{si} > C_a)\\ &+\overline{R}^r_{si} \cdot \mathcal{P}(R_d < R_t, \alpha_i \leq 1, R^r_{si} - C_r \geq R^a_{si} - C_a, R^r_{si} > C_r)\Big]\end{aligned} \tag{19}$$

where $\mathcal{P}(x)$ defines the probability of event x, and $\overline{R}^s_{si}$, $\overline{R}^r_{si}$, and $\overline{R}^a_{si}$ are the individual average rates of the i^{th} SU described in (5), (17), and (18), respectively.

E. Licensed User Payoff

The demand and supply trading model discussed thus far, has relied on the probability of the SUs finding utility in a particular LU spectrum resource. These utility measures are key in determining its involvement in trading for LU resources. For illustrative purposes, this is well described in Fig. 3. For this trading model, we choose LU payoff as the maximization goal. Contrary to popular spectrum trading papers, where average SU rate or throughput is the considered optimization parameter, we believe that since the LU is the one leasing out its spectrum resource, it must be the recipient of maximum gain from this exchange. The challenge here, is in optimizing the spectrum costs (C_s, C_r, C_a), to ensure maximum LU payoff while maintaining a demand (from the SUs) for the spectrum resource. The training for costs allows us to find the optimal tipping point, where there exists one of k SUs willing to engage in sharing, relaying or access for a particular channel realization. The corresponding LU payoff averaged over all possible channel realizations would then be given by

$$\begin{aligned}U = &\mathcal{P}(R_d > R_t, R^s_{si} > C_s) \cdot (R_t + C_s) +\\ &\mathcal{P}(R_d < R_t, \alpha_i > 1, R^a_{si} > C_a) \cdot C_a +\\ &\mathcal{P}(R_d < R_t, \alpha_i \leq 1, R^r_{si} - C_r < R^a_{si} - C_a, R^a_{si} > C_a) \cdot C_a +\\ &\mathcal{P}(R_d < R_t, \alpha_i \leq 1, R^r_{si} - C_r \geq R^a_{si} - C_a, R^r_{si} > C_r) \cdot (R_t + C_r).\end{aligned} \tag{20}$$

We now will look at achieving closed-form results for these costs with our analytical model in the following section.

IV. Analytical Model

In this section, we attempt to provide closed-form solutions for the different spectrum costs involved in maximizing the LU payoff. We propose an amendment to the general model to help create exclusivity between the modes of collaboration, in arriving at these optimized costs. This analytical model makes the assumption that the LT and the k SRs are geographically separated, and cannot interfere with each other. This implies that with no direct link between them, the given SR cannot overhear the LU's message in the first phase of transmissions during relaying (13). Therefore, it also cannot cancel out the LU's signal (14) from the superimposed composite message it receives from its ST. This would mean that the SU rate during relaying would be negligible, and it would not derive utility from this mode of operation. Eliminating relaying as an option for collaboration, would then leave only two modes of operation, i.e. sharing and access. The LU would entertain interference from the given SU, when it has a surplus instantaneous rate above the expected target rate R_t, in the form of spectrum sharing, and would alternatively lease out its spectrum to the SU, when in outage.

Therefore, by maximizing the LU payoff as a result of spectrum sharing and access alone, we can find the optimal theoretical costs that can be preset by the LU, and made available to the SUs that wish to collaborate. The updated instantaneous rate of the i^{th} SU in the sharing mode is given by

$$R^{s'}_{si} = \log_2\left(1 + P_s \cdot \gamma_{si}\right). \tag{21}$$

The corresponding average LU payoff can now be updated as

$$\begin{aligned}U' \;=\; &\mathcal{P}(R_d > R_t, R^{s'}_{si} > C_s) \cdot (R_t + C_s) +\\ &\mathcal{P}(R_d < R_t, R^a_{si} > C_a) \cdot C_a.\end{aligned} \tag{22}$$

This can also be expressed as

$$\begin{aligned}U' = &\exp\left(-\frac{2^{R_t}-1}{SNR_p}\right) \cdot \frac{\mathcal{V}}{2^{C_s} + \mathcal{V} - 1} \cdot (R_t + C_s)\\ &+\left(1 - \exp\left(-\frac{2^{R_t}-1}{SNR_p}\right)\right) \cdot \exp\left(-\frac{2^{C_a}-1}{SNR_{si}}\right) \cdot C_a\end{aligned} \tag{23}$$

where SNR_p and SNR_{si} refer to the average SNR of the LU link (h_p), and the i^{th} SU link (h_{si}), respectively. Given the exclusivity of access and sharing modes, the corresponding closed form solution for sharing and access costs are

$$C^*_s = \mathcal{I}\left[\frac{\mathcal{W}\left(\frac{2^{R_t}(\mathcal{V}-1)}{e}\right) - \ln 2 \cdot R_t + 1}{\ln 2}\right] \tag{24}$$

$$C^*_a = \frac{\mathcal{W}(SNR_{si})}{\ln 2} \tag{25}$$

where $\mathcal{W}$ is the product log function [31], [32], which is the inverse function of $f(\mathcal{W}) = \mathcal{W} \cdot \exp(\mathcal{W})$, and the indicator function $\mathcal{I}[x] = x; x \geq 0$, otherwise the optimal cost does not

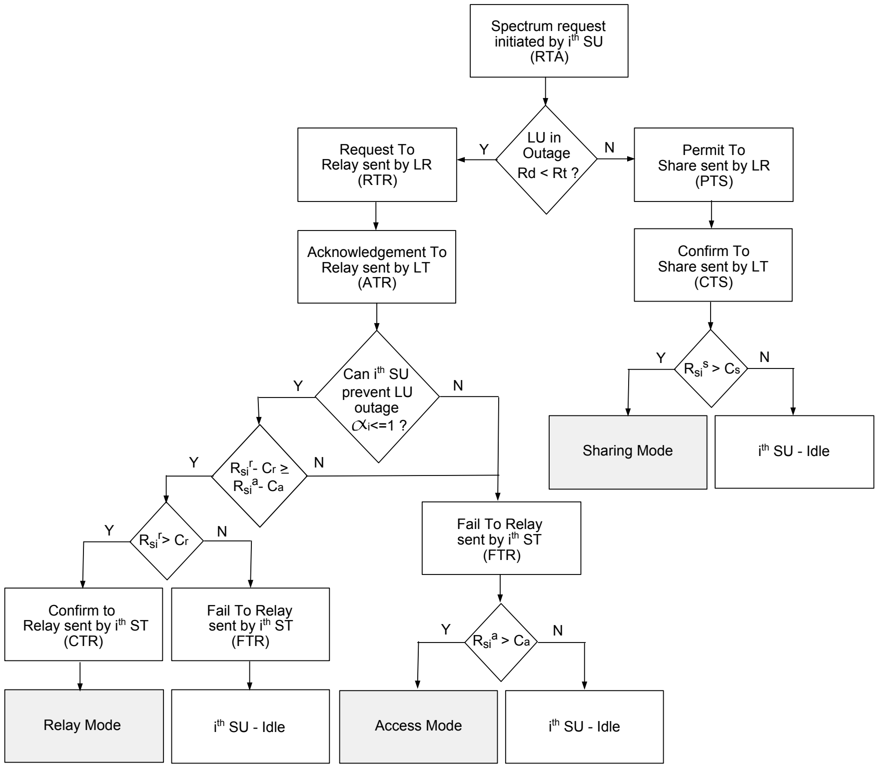

Fig. 3: Flowchart of Operations.

exist and sharing cannot take place. A detailed derivation of the optimal costs, and the discussion of their optimality can be found in the Appendix.

The optimized LU payoff for both the analytical and general models are compared and analyzed in the following results section.

V. Numerical Results

In this section, we plot the numerical results for the analytical and the general spectrum trading model, to demonstrate the achievable gains for the LU and SU network. For the simulations, we have assigned the transmission powers of the LU and the k SUs to be 10 dBW and 20 dBW, respectively (i.e. P_p=10 dBW, P_s=20 dBW), and the instantaneous target rate for the LU, R_t, to be 1 bps/Hz, unless otherwise specified.

We begin by corroborating the theoretically optimized closed-form results, obtained through our analytical model in Section IV, against simulations run for the same model, in plotting the LU payoff. We see in Fig. 4, the variation in the LU payoff against its own transmission power, being representative of the mode of operation, namely sharing or access. At lower LU transmission powers, when the LU is in outage, the LU payoff remains unchanged. It is here, that the probability of the given SU entering into access mode is high, but with the SU power fixed, there will be no increase in its achievable rate. Therefore, to maintain demand for this spectrum leasing opportunity, the LU cannot increase the associated cost, and consequently the LU payoff remains the same. After a certain point, we see a drop in LU payoff, which represents the phasing out of the access opportunities. With more power available for its own transmission, the LU becomes self-sufficient, and we see a greater probability of spectrum sharing opportunities come into play. The SU power though fixed (i.e 20 dBW), is still limited by a PIP constraint, determined by $\mathcal{V}$ (in (3)), and therefore the increase in LU payoff with further increase in LU transmission power, can be credited to the higher interference tolerance for spectrum sharing in the form of the PIP constraint. After a point however, the LU payoff will again saturate, when the given SU reaches its available transmission power limit.

We know that when the power available for SU transmission increases, so does its achievable rate (19). This allows the LU to set a higher cost for the particular spectrum opportunity, leading to an increase in the LU's payoff, as seen in Fig. 5. Here, we see a comparison made between the average LU payoff for the general and analytical models, with varying target rate requirements for the LU. For a lower target rate (like 1 bps/Hz), the LU is for the most part, self-sufficient, allowing the given SU to share its spectrum within the acceptable margin of interference. This constraint on the SU's power causes the LU's payoff to saturate for lower target rates, as evident from the graph. We notice a small deviation between the analytical and general models here, because on the off-chance that the LU cannot meet its target rate, the relaying and access modes come into play. However, with no relay mode available in our analytical model, the given SU has the opportunity to lease the LU's spectrum for interference-free transmission, and enjoys a higher achievable rate. This influences the optimized costs, and conversely the overall payoff to the LU. We observe the same divergence of the

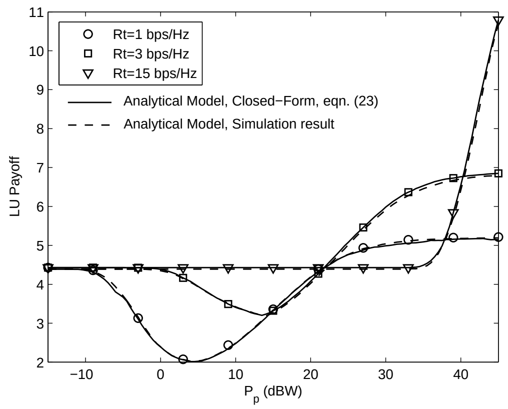

Fig. 4: LU payoff versus available LU transmission power for the Analytical Model.

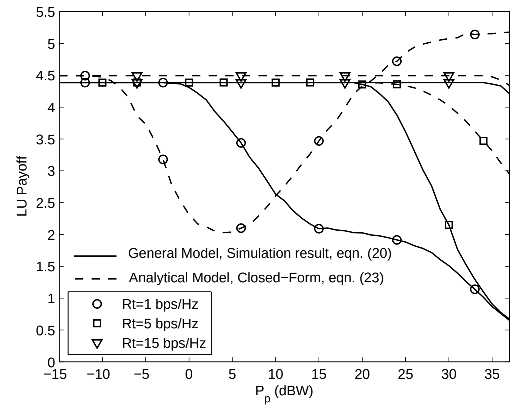

Fig. 6: LU payoff comparison against LU transmission power.

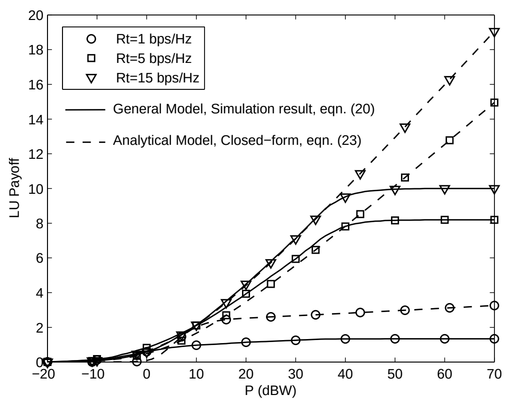

Fig. 5: LU payoff comparison against SU transmission power.

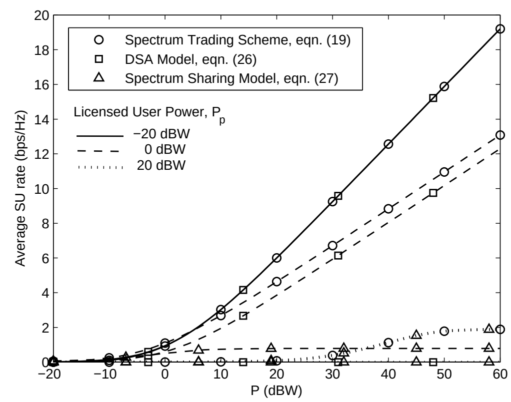

Fig. 7: SU Rate comparison against access and sharing protocols.

analytical model from the general model, at higher target rates, where the SU benefits from a higher achievable rate, while the LU gains a greater monetary return. Though this might seem like the general model is not beneficial to either LU or SU, that is far from the truth, as relaying allows the LU's transmission to be more reliable, with fewer outages over the fading channel, when the given SU steps in as a relay.

We now look at the comparison of the general and analytical models, for the change in their LU payoffs against an increase in the available LU transmission power in Fig. 6. The trend of a declining LU payoff with increasing LU transmission power, brings us to the conclusion that self-sufficiency for the LU, or the lack of collaboration with the SUs thereof, works against the idea of spectrum trading, thus limiting the payoff generated as a result. The non-uniform decline across the range of target rates, can be attributed to the different modes of operation with their corresponding costs, coming into play. But after a specific threshold value of the LU transmit power, all the payoff curves for the general model drop to a point of null LU payoff, indicating a lack of positive utility for SU participation. We also observe the points of similarity in the graph for the analytical and general models. We know that with no link between the LT and the k SRs in the analytical model, there would be no cross-interference, and hence this would liken it to the case where insignificant levels of interference are experienced in the general model. This can be observed at smaller LU transmission powers (given the target rate), that the payoff curves of the two models match up. Also, when the target rate set at the LU is very high, only access opportunities are available to the SUs, and therefore we see the similarity in the LU payoffs for the target rate of 15 bps/Hz.

Thus far, we have focused our attention on the gains the LU would derive from this collaborative exchange by sharing its resources. The SU network involved also benefits greatly through increased spectrum transmission opportunities and significant rate gains for its users. Given the utility comparisons made by each of the k SUs, the assignment of spectrum costs is optimized to meet the demand for the given spectrum resource. The average achievable rate for the SU network, as defined in (19), is plotted in Fig. 7. We first observe the change in the average SU rate for changing levels of LU transmission power for our spectrum trading scheme. As the LU transmission power increases, we notice a drop in the achievable rate for the SU. As described earlier in Fig. 6, with more power available for its transmission, the LU is self-sufficient, and there would be fewer opportunities for collaboration with the SUs. Therefore, this lack of transmission opportunities for the SU translates to an overall reduction in its achievable rate. More importantly, in this graph, we make a comparison between the rate gains achieved through our general spectrum trading model, with an example of DSA or spectrum sharing applied to a spectrum trading environment. The achievable rates for DSA and spectrum sharing can be given by (26) and (27) respectively. We can express them as

$$\overline{R}_{dsa} = \overline{R}_s^a \cdot \mathcal{P}(R_d < R_t) \tag{26}$$

$$\overline{R}_{ss} = \overline{R}_s^s \cdot \mathcal{P}(R_d > R_t) \tag{27}$$

where $\overline{R}_s^a$ and $\overline{R}_s^s$ are the average access and sharing rates described in (18) and (5) respectively.

From Fig. 7, we notice that the performance of our spectrum trading scheme is equivalent or better than both the current benchmarks used in spectrum trading literature. The achievable SU rate is higher because our scheme works for all states of the licensed link. We see for a weak LU (-20dBW power), the performance of our scheme is equivalent to the DSA approach to spectrum trading, but significantly outperforms the spectrum sharing technique. Conversely, when spectrum sharing is strong, that is when the LU link is self-sufficient (40dBW power), our scheme shows equal performance, but also outperforms the DSA scheme. Thereby using access, relaying and sharing techniques, we are able to utilize any spectrum opportunity, to maximize the SU network rate.

VI. Conclusion

The underlying focus of our paper is to emphasize the need for a LU incentive-based approach for spectrum trading environments. In this work, we look at a resource-sharing model established between a LU and a network of SUs, for three modes of collaboration, namely, spectrum sharing, spectrum access and relaying. Our model is designed after the demand and supply economics of a trading environment, to optimize the costs for each mode of operation, depending on the need for the spectrum resource. Utility measures implemented at the SU network level, allows each user to identify its need, and indicate their collaboration through handshaking messages embedded in the pilot sequence of each frame. Consequently, the optimized costs can be arrived at numerically through our general model, or theoretically from our analytical model, to demonstrate the achievable payoff gains for the LU. In terms of the LU's perspective, this model improves the overall spectral utility efficiency, and provides monetary returns for leased spectrum. And from a SU's perspective, this scheme allows for increased transmission opportunities and higher rate gains, than previously seen for a spectrum trading model. It is here that we conclude, that the idea of a spectrum trading scheme that celebrates collaboration for mutual gain, is realized and achieved through this work.

Appendix

Proof of Optimal Costs for LU Payoff

The probabilistic events in the average LU payoff function are independent, and therefore we can represent (22) as

$$\begin{aligned} U' &= \mathcal{P}(R_d > R_t) \cdot \mathcal{P}(R_{si}^{s'} > C_s) \cdot (R_t + C_s) + \\ &\quad \mathcal{P}(R_d < R_t) \cdot \mathcal{P}(R_{si}^{a} > C_a) \cdot C_a. \end{aligned} \tag{28}$$

To solve for these probabilistic events we need to know the pdf of the distribution function. With Rayleigh fading channels, the channel power gains would follow an exponential distribution, and with unity noise variance, we can arrive at

$$\begin{aligned} \mathcal{P}(R_d > R_t) &= \mathcal{P}(P_p \cdot \gamma_p > 2^{R_t} - 1) \\ &= \int_{2^{R_t}-1}^{\infty} \frac{1}{SNR_p} \exp\left(-\frac{x}{SNR_p}\right) dx \\ &= \exp\left(-\frac{2^{R_t}-1}{SNR_p}\right) \end{aligned} \tag{29}$$

and similarly,

$$\mathcal{P}(R_{si}^a > C_a) = \exp\left(-\frac{2^{C_a}-1}{SNR_{si}}\right) \tag{30}$$

For the spectrum sharing probability event $\mathcal{P}(R_{si}^{s'} > C_s)$, the power of the i^{th} SU must be bounded by the instantaneous interference constraint in PIP (4), giving us a log-logistic distribution [10],

$$\begin{aligned} \mathcal{P}(R_{si}^{s'} > C_s) &= \mathcal{P}\left(\frac{\gamma_{si}}{\gamma_{3i}} > \frac{2^{C_s}-1}{\mathcal{V}}\right) \\ &= \int_{\frac{2^{C_s}-1}{\mathcal{V}}}^{\infty} (x+1)^{-2} dx \\ &= \frac{\mathcal{V}}{2^{C_s} + \mathcal{V} - 1}. \end{aligned} \tag{31}$$

This gives us U' in (23), which is a sum of two univariate functions in C_s and C_a. Therefore, given the exclusivity of the sharing and access modes, we can differentiate U' against C_s and C_a respectively,

$$\begin{aligned} \frac{\partial U'}{\partial C_s} &= \exp\left(-\frac{2^{R_t}-1}{SNR_p}\right)\left[\frac{\mathcal{V}}{2^{C_s}+\mathcal{V}-1} - \right. \\ &\quad \left. \left(\frac{2^{C_s}\cdot\mathcal{V}\cdot\ln 2}{(2^{C_s}+\mathcal{V}-1)^2}\right)\cdot(R_t+C_s)\right] \end{aligned} \tag{32}$$

and,

$$\begin{aligned} \frac{\partial U'}{\partial C_a} &= \left(1-\exp\left(-\frac{2^{R_t}-1}{SNR_p}\right)\right)\left(\exp\left(-\frac{2^{C_a}-1}{SNR_{si}}\right)\right) \\ &\quad \left[1-\frac{2^{C_a}\cdot C_a\cdot\ln 2}{SNR_{si}}\right]. \end{aligned} \tag{33}$$

It is clear to see that the partial derivatives, $\frac{\partial U'}{\partial C_s}$ and $\frac{\partial U'}{\partial C_a}$, have only one solution on equating to zero, giving us the optimal sharing and access costs in (24) and (25), respectively. It can also be verified that these costs are local maxima, given that both $\frac{\partial^2 U'}{\partial {C_s}^2} < 0$ and $\frac{\partial^2 U'}{\partial {C_a}^2} < 0$, and can be confirmed to be global maxima by plotting the payoff function, which shows only one maximum at $U'(C_s^*, C_a^*)$ for the feasible range of $C_s > 0$ and $C_a > 0$.

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