Hindawi Publishing Corporation
Journal of Computer Networks and Communications
Volume 2012, Article ID 851204, 12 pages
doi:10.1155/2012/851204

Research Article

The SS-SCR Scheme for Dynamic Spectrum Access

Vinay Thumar,[1] Taskeen Nadkar,[1] U. B. Desai,[2] and S. N. Merchant[1]

[1] *Department of Electrical Engineering, Indian Institute of Technology, Bombay 400076, India*
[2] *Indian Institute of Technology Hyderabad, Yeddumailaram 502205, India*

Correspondence should be addressed to Vinay Thumar, vinay_thumar@ee.iitb.ac.in

Received 16 December 2011; Revised 24 April 2012; Accepted 1 May 2012

Academic Editor: Torleiv Maseng

We integrate the two models of *Cognitive Radio (CR)*, namely, the conventional *Sense-and-Scavenge (SS) Model and Symbiotic Cooperative Relaying (SCR)*. The resultant scheme, called *SS-SCR*, improves the efficiency of spectrum usage and reliability of the transmission links. *SS-SCR* is enabled by a suitable cross-layer optimization problem in a multihop multichannel CR network. Its performance is compared for different PU activity patterns with those schemes which consider *SS* and *SCR* separately and perform disjoint resource allocation. Simulation results depict the effectiveness of the proposed *SS-SCR* scheme. We also indicate the usefulness of cloud computing for a practical deployment of the scheme.

1. Introduction

1.1. Cognitive Radio/Dynamic Spectrum Access. The emerging *Cognitive Radio (CR)* technology is an attempt to alleviate the inefficient utilization of the spectrum, created by the current *Command-and-Control* spectrum access policy. It temporarily allows unused portions of the spectrum (*spectrum holes* or *white-spaces*), owned by the licensed users, known as *primary users (PUs)*, to be accessed by unlicensed users, known as *secondary users (SUs)*, without causing intrusive interference to the former's communication [1]. This is the *Sense-and-Scavenge (SS)* Model of conventional CR. A CR node is characterized by an adaptive, multi-dimensionally aware, autonomous radio system empowered by advanced intelligent functionality, which interacts with its operating environment and learns from its experiences to *reason*, *plan*, and *decide* future actions to meet various needs [2].

In the *SS* model of CR, the temporal PU activity patterns have a significant influence on the opportunities for the SUs. The source traffic for the PU alternates between ON (busy) and OFF (idle) periods. The ON/OFF activity is characterized by suitable statistical models, for predictive estimation of the patterns. Exponential [3–6] and log-normal [3–5] distributions are popularly used in the literature to model the ON (and OFF) times of the PU activity. Measurements have also revealed that successive ON and OFF periods are independent, though in some cases long-term correlations exist [4].

1.2. Symbiotic Cooperative Relaying. An interesting paradigm that has surfaced in the research surrounding CR is a symbiotic architecture, which improves the efficiency of spectrum usage and reliability of the transmission links [7–12]. According to this model, which we refer to as *Symbiotic Cooperative Relaying (SCR)*, the PU seeks to enhance its own communication by leveraging other users in its vicinity, having better channel conditions, as cooperative relays for its transmission and in return provides suitable remuneration to them. The SU nodes, being scavengers of the licensed PU spectrum, are potential candidates as relays, since they are idling when the PU transmission is in progress. Besides, they have cognitive capabilities, which give a large amount of flexibility of reconfiguration and resource allocation during the cooperative relaying process. The cooperation from the SU network results in enhanced transmission rate of the PU, which translates into reduced transmission time for the same amount of information bits of the PU as that transmitted on its direct link. Then, the time saved can be offered to the SUs for their own communication as a reward for cooperating with the PU (with a fixed rate demand). The SUs can achieve their communication in the *time incentive* without the need for spectrum sensing. In our previous work, we have formulated a cross-layer design to enable the *SCR* scheme, called *Cognitive Relaying with Time Incentive (CRTI)*, for an Orthogonal Frequency Division Multiplexing-(OFDM-) based multi-hop CR network, with special emphasis on the MAC layer coordination protocol [13]. We have also proposed that it is possible to reward the SUs with incentive frequency bands, that is, *Cognitive Relaying with Frequency Incentive (CRFI)* [12, 14]. Some unique challenges are faced when the *SCR* scheme is enabled on the spectra of multiple PUs; we have addressed these in prior work as well [15, 16].

In case of *SCR*, the PU is assumed to have a constant occupancy state throughout the frame duration (in a frame-based communication); that is, it does not exhibit intermittent ON/OFF periods. During those frames when *SCR* is enabled, the PU should definitely be ON.

1.3. The SS-SCR Scheme. In this paper, we integrate the two aforementioned models of CR, namely, the *Sense-and-Scavenge (SS)* model of conventional CR and *Symbiotic Cooperative Relaying (SCR)*. We refer to this composite scheme as *SS-SCR*. *SS-SCR* entails a multiple PU scenario, with each PU having its own distinct bandwidth of operation. On the PUs' spectra having a weak direct link, *SCR* is enabled, while, on the rest of the PUs' bands, *SS* is enabled. Since most present day wireless technologies such as IEEE 802.16 [17] and 802.22 [18] are based on OFDM, the multichannel multi-hop networks, thus created, pose a more challenging environment for deployment of the *SS-SCR* scheme, as opposed to simplistic two-hop or single-channel scenarios addressed in the literature (discussed in *Related Literature*). Optimum resource (time, bandwidth, power) allocation, which can be achieved by leveraging the channel diversity abundantly available in a multichannel network, will improve spectral efficiency and in turn maximize the transmission opportunities for both the PUs and SUs. With this objective, we present our original contributions in this paper, which are summarized as follows.

(1) We propose a scheme for enabling *SS-SCR* by means of a suitable cross-layer optimization problem which addresses power control, scheduling, and routing. Though the work can readily be extended to any number of PUs, currently a simple scenario with two PUs is assumed—on the spectrum of one we enable *SS*, while on the other we enable *SCR*. The *SS-SCR* scheme jointly considers the resource allocation on both the PUs' bands to maximize the overall spectral efficiency and mutual benefits of both entities under concern, namely, the PU and SU.

(2) For comparison, we also describe two schemes which consider the *SS* and *SCR* separately, and the resource allocation on each of the PUs' bands is disjoint. All the schemes are investigated under various PU ON/OFF traffic models.

(3) We propose the use of cloud computing to enhance the performance of *SS-SCR* in practical CR networks.

To detail our work, the paper has been organized as follows. Section 2 presents related background literature. Section 3 describes the system model and communication scenario. Section 4 methodically explains the generalized cross-layer optimization problem. In Section 5 we propose the *SS-SCR* scheme, while in Section 6 we describe the problems for the *SS* and *SCR* schemes separately considered. Section 7 provides a note on the practical implementation. Section 8 illustrates the use of *cloud computing* for *SS-SCR*. In Section 9, we present simulation results and their detailed analysis. Section 10 concludes the paper.

2. Related Literature

Conventionally, there are two approaches to spectrum sharing in CR [19]: *underlay approach*, in which the SUs and the PU access the same frequency band by the use of sophisticated spread spectrum techniques, and *overlay approach*, in which the SUs access the licensed spectra when the PU is not using it. The *SS* model pertains to the *overlay approach*—the SUs sense the spectrum to detect a white space and utilize it for their own communication.

Surrounding the concept of *SCR* for CR, many schools of thought have evolved to accommodate substantially different technologies and solutions. Simeone et al. [7, 8] have used game theoretic tools to analyze the performance of cooperation in a CR network, wherein the PU leases the owned spectrum to an ad hoc network of SUs in exchange for cooperation in the form of transmission power from the SUs. The model proposed by J. Zhang and Q. Zhang [9] is more rational; when the PU's demand is satisfied, it is willing to enhance its benefit in any other format, for instance, by collecting a higher revenue from the SU. Xue et al. [10] have considered a single full-duplex amplify-and-forward (AF) SU relay to assist the PU transmission. Gong et al. [11] have analyzed the power and diversity gains obtained by AF relaying of the PU's data by multiple cooperating SUs. All of the aforementioned works in the literature have considered either a single-relay node or single-channel CR networks. The authors have also contributed significantly towards *SCR* schemes for multichannel multi-hop networks [12–16]. The cross-layer formulations in this work are inspired by those of Shi and Hou [20], Zhang et al. [21], and some references therein. While Shi et al. aim at maximizing the sum throughput of the SUs in a multi-hop multichannel CR network, in the proposed *SS-SCR* scheme, the objective is to perform a joint resource allocation on both the PUs band (*SS* and *SCR*) for maximizing the net spectral efficiency. As far as the previous works of the authors are concerned, the concept of *CRTI* [13] involves a cross-layer optimization problem for a single source, that is, PU Tx, for throughput maximization. The approaches to *CRFI* [13, 14] are totally different in their objective—that of achieving a specified throughput for the PU while using the least number of frequency bands. Techniques for *CRTI* for multiple PUs [15, 16] describe the maximization of the time incentive for the SUs, while utilizing multiple PUs spectra optimally. Two methods have been proposed for the same, the formulations for which are distinct, and different from those in the literature [20, 21].

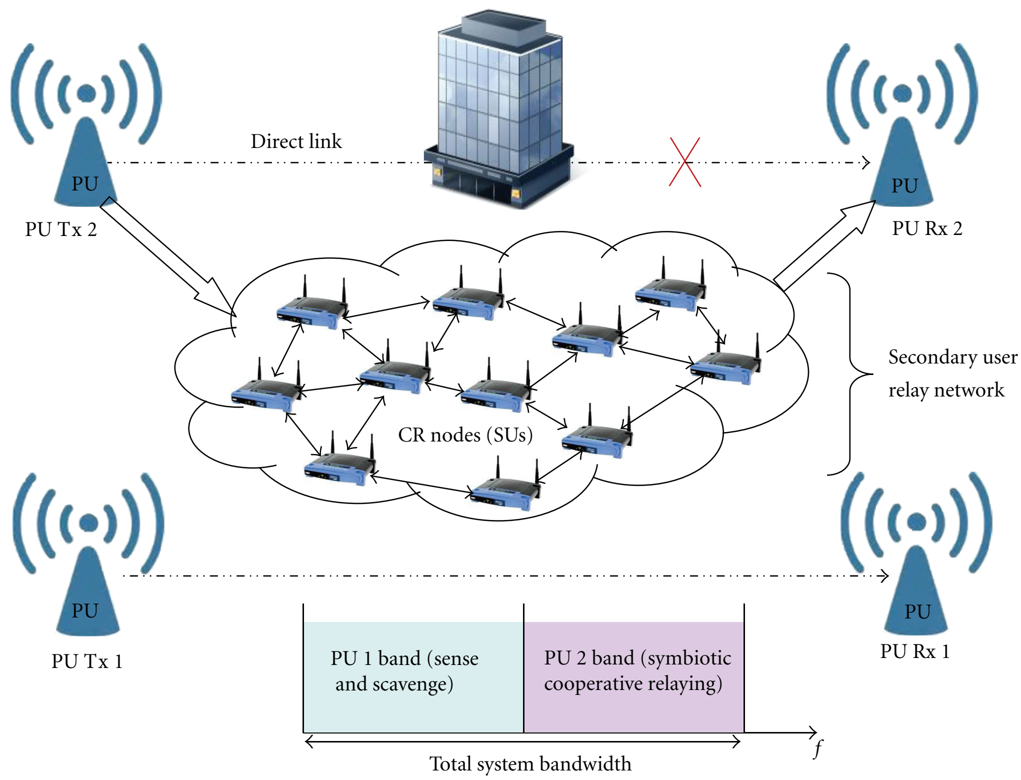

Figure 1: System model.

This work differs from the above in the fact that it is a *hybrid* architecture: it integrates the conventional *SS* model with *SCR*, for a multiple PU scenario.

3. System Description

We consider a CR system with a network of cognitive SUs and two PU transceivers (Figure 1). Each PU has its own distinct bandwidth of operation. The available bandwidth is divided into frequency flat subchannels by deploying OFDM. The band-sets of the two PUs are denoted by $\mathbb{M}_1$ and $\mathbb{M}_2$, respectively. On the band-set of PU 1, conventional CR mode of operation, that is, *SS*, is enabled. The SUs are continuously sensing the spectrum for a transmission opportunity; when PU 1 is OFF, the SUs use its spectrum for their own communication. The activity of PU Tx 1 is detected by all the SU nodes by cooperative spectrum sensing [22]. Band-set $\mathbb{M}_1$ is also referred to as the *SS* band.

On the other hand, on the band-set of PU 2, *SCR* is enabled. Rather than using the direct link, the PU Tx 2 relays its data through the SU network and in return rewards them with a *time incentive* λ_t for their own communication. If C_{dir} is the throughput (bits/sec/Hz) obtained on the direct link, C_{rel} is the maximized throughput (bits/sec/Hz) obtained through the SU relay network, then the incentive in a time frame normalized to unity is $\lambda_t = 1 - C_{\text{dir}}/C_{\text{rel}}$, $0 \le \lambda_t \le 1$. On band-set $\mathbb{M}_2$ (also referred to as the *SCR* band), PU Tx 2 acts as the source, PU Rx 2 as the destination, and the SU nodes act as the relays in the multi-hop relay network (Figure 1). Decode-and-forward multihopping is assumed at each node.

The fading gains for various links are mutually independent and are modeled as zero mean complex circular Gaussian random variables. The protocol interference model is assumed [20]. The channel gains are invariant within a frame but vary over frames (i.e., block-fading channels). We assume that the channel gains from the PU Tx 2 to SUs, the SUs to the PU Rx 2, and those among the SUs are good enough to provide a significantly higher end-to-end throughput as compared to the direct link of PU 2, resulting in performance gains for both the PU and the SUs on band-set $\mathbb{M}_2$.

4. Problem Formulation: Cross-Layer Optimization

In the subsequent sections we will be describing the proposed *SS-SCR* scheme which considers joint resource allocation on both PUs' bands, as well as the schemes which are disjoint in their resource allocation on the two bands. Each scheme will involve solving a sequence of optimization problems, their objective being maximization of the sum throughput of the users under consideration (PU or SUs or both) within the given resources (time slot, frequency bands, power). To efficiently exploit the channel diversities available in the multi-hop multichannel SU network, we allow flow splitting and spatial reuse of frequencies outside the interference range of nodes. Each optimization problem involves a cross-layer view for power allocation, frequency band scheduling, and routing. A relay with poor channel conditions on all its links will be eliminated from the routes which strive to achieve maximum throughput; thus relay selection is automatically achieved by the problem. We describe the basic structure of such a cross-layer optimization problem which will be suitably adapted for the various schemes to be described subsequently.

Optimization Problem (P1):

$$\max_{\left(x_{ij}^{(m)}, P_{ij}^{(m)}, f_{ij}(l)\right)} \sum_{l\in\mathbb{L}} \sum_{j\in T_i} f_{ij}(l) \quad i = s(l). \tag{1}$$

It is subject to the constraints which are described as follows.

Flow Constraints:

$$\sum_{j\in T_i}^{j\neq s(l)} f_{ij}(l) = \sum_{k\in T_i}^{k\neq d(l)} f_{ki}(l) \quad \forall i \in \mathbb{N},\ l \in \mathbb{L},\ i \neq s(l),\ i \neq d(l), \tag{2}$$

$$f_{ij}(l) \geq 0 \quad \forall (i,j) \in \mathbb{E},\ l \in \mathbb{L}, \tag{3}$$

$$\sum_{l\in\mathbb{L}} f_{ij}(l) - \sum_{m\in M} \log_2\left(1 + \frac{h_{ij}^{(m)} P_{ij}^{(m)}}{\sigma^2}\right) \leq 0 \quad \forall (i,j) \in \mathbb{E}. \tag{4}$$

Frequency Domain Scheduling Constraints:

$$\sum_{j\in T_i} x_{ij}^{(m)} + \sum_{k\in T_i} x_{ki}^{(m)} \leq 1 \quad \forall i \in \mathbb{N},\ m \in \mathbb{M}, \tag{5}$$

$$x_{ij}^{(m)} = \{0,1\} \quad \forall (i,j) \in \mathbb{E},\ m \in \mathbb{M}. \tag{6}$$

Power Constraints:

$$\begin{aligned} &P_{ij}^{(m)} - P_{T_{ij}}^{(m)} x_{ij}^{(m)} \geq 0 \quad \forall (i,j) \in \mathbb{E},\ m \in \mathbb{M}, \\ &P_{ij}^{(m)} - P_{\text{peak}} x_{ij}^{(m)} \leq 0 \quad \forall (i,j) \in \mathbb{E},\ m \in \mathbb{M}, \end{aligned} \tag{7}$$

$$\sum_{j\in T_i, m\in\mathbb{M}} P_{ij}^{(m)} \leq P_{\text{avl}_i} \quad \forall i \in \mathbb{N}. \tag{8}$$

Interference Constraints:

$$\begin{gathered} P_{kh}^{(m)} + \left(\sum_{k\in I_j^m} P_{kh}^{(m)} h_{kj}^{(m)} - P_I + P_{\text{peak}} - P_{kh}^{(m)}\right) x_{ij}^{(m)} \leq P_{\text{peak}}, \\ \forall i \in \mathbb{N},\ m \in \mathbb{M},\ j \in T_i,\ k \in I_j^m,\ k \neq i. \end{gathered} \tag{9}$$

Since our objective (1) is to maximize the throughput, it is sufficient to maximize the sum of outgoing flows from the source node [23]. We denote the communication between each unique transmitter-receiver pair as a session. $s(l)$ and $d(l)$ represent the source and destination of the session l, $l \in \mathbb{L}$, where $\mathbb{L}$ denotes the set of the sessions.

Bidirectional links are assumed; that is, in the network graph each node i has an transmit/receive set of nodes T_i. $f_{ij}(l)$ is the data flow (bits/sec) from node i to node j for session l. Equation (2) indicates that, except for the source and destination nodes, the inflow into a node is equal to the outflow. Equation (3) ensures that all the flows are non-negative. Equation (4) refers to the fact that the sum of the flows on a link cannot exceed the capacity of a link according to Shannon's channel capacity theorem [24]. Each link has $|\mathbb{M}|$ orthogonal frequency bands, and the net achievable throughput is the sum throughput of the individual bands. $h_{ij}^{(m)}$ denotes the channel power gain on band m, and $P_{ij}^{(m)}$ denotes the corresponding power allocation. We have assumed unit bandwidth of each band. In (4), the log function contains only σ^2 in the denominator due to the use of an interference model, which ensures that when node i is transmitting to node j on band m, the interference from all other nodes in this band must remain negligible due to the frequency domain scheduling and interference constraints. $\mathbb{N}$ denotes the node set of the network and $\mathbb{E}$ denotes the edge set.

Equation (5) suggests that if a node i has used a band m for transmission or reception, it cannot be used by node i again for any other transmission or reception. Note that $x_{ij}^{(m)}$ is a binary variable which takes the value 1 if and only if band m is active on link (i, j).

Equation (7) ensure that $P_{ij}^{(m)} \in [P_{T_{ij}}^{(m)}, P_{\text{peak}}]$ if the band m is selected and $P_{ij}^{(m)} = 0$ if the band is not selected. The data transmission from node i to node j is successful only if the received transmission power exceeds a power threshold P_T, from which we can calculate the minimum required transmission power on a band m at node i as $P_{T_{ij}}^{(m)} = P_T/h_{ij}^{(m)}$. P_{peak} denotes the maximum power that can be allocated to any band m, under which we compute the interference set I_j^m of a receiving node j. Equation (8) is to ensure that the total power transmitted on all the active bands at node i does not exceed the power available at the node P_{avl_i}.

Equation (9) ensures that for a successful transmission on link i to j, on an interfering link k to h, the transmit power on any band m cannot exceed a threshold P_{peak} if $x_{ij}^{(m)} = 0$, and if $x_{ij}^{(m)} = 1$, then $\sum_{k\in I_j^m} P_{kh}^{(m)} h_{kj}^{(m)} \leq P_I$. The complete list of symbols with their description is given in Table 1.

In the above optimization problem $h_{ij}^{(m)}$, σ^2, P_T, P_I, P_{peak}, and P_{avl_i} are all constants, while $x_{ij}^{(m)}$, $P_{ij}^{(m)}$, and $f_{ij}(l)$ are the optimization variables. The formulation is a *mixed integer nonlinear programming problem (MINLP)*. Based on the discussion on similar problems in [20, 21] and the references therein, we conjecture that the given problem is NP-hard. We are thus motivated to investigate a linear formulation, which will greatly simplify the problem (which is observed in terms of reduced computation time during simulation). This entails employing three tangential supports to the log term in (4), as its approximation [20]. The tangential supports are drawn at points 1, 2, and 3 on the *log* curve (Figure 2), namely, $(0,0)$, $(\beta, f(\beta))$, and $(P_{\text{peak}}, f(P_{\text{peak}}))$. β denotes the x-coordinate of the point of intersection of the tangents drawn at points 1 and 3. The solution to the log relaxed

Table 1: Notations.

Symbol	Definition
PU Tx, PU Rx	PU transmitter, PU receiver
(i, j)	Edge between nodes i and j
T_i	The set of nodes that node i can transmit to and receive from
$h_{ij}^{(m)}$	Channel gain on edge (i, j) and band m
$x_{ij}^{(m)}$	Band assignment on edge (i, j) and band m
$P_{ij}^{(m)}$	Power allocation on edge (i, j) and band m (W)
$P_{T_{i,j}}^{(m)}$	Detection threshold of band m on edge (i, j) (W)
P_I	Interference threshold of a node (W)
P_{peak}	Maximum power that can be transmitted on a frequency band (W)
$P_{\text{node}_i}/P_{\text{avl}_i}$	Power available at node i (W)
I_j^m	Set of nodes that can interfere with node j on band m
σ^2	Additive white Gaussian noise (AWGN) variance (W)
$\mathbb{N}$	Node set of the entire network
$\mathbb{M}$	Band set of the entire network
$\mathbb{E}$	Edge set of the entire network
$\mathbb{L}$	Set of SU sessions in the entire network
$s(l)$, $d(l)$	Source of session l, destination of session l
$f_{ij}(l)$	Flow on edge (i, j) and band m for session l (bps)

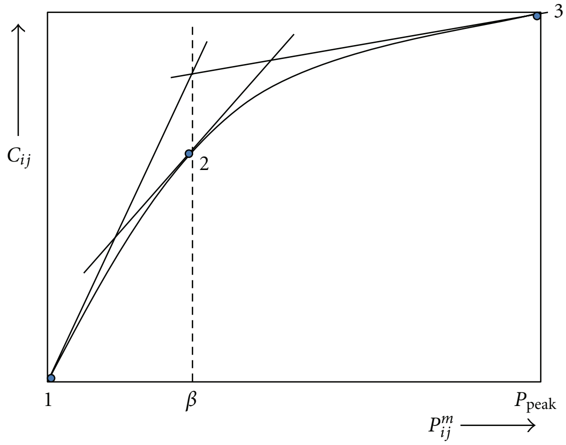

Figure 2: Approximating the log function.

problem provides an upper bound to the original maximization problem P1.

A Feasible Centralized Solution. We suggest an approach to obtain a feasible suboptimum solution to the original problem by decoupling the operations of power allocation and band scheduling and that of flow computation. The solution consists of two steps.

(1) The power allocation and band scheduling (P_{ij}^m, x_{ij}^m) are obtained from the log relaxed problem with tangential supports. This solution, however, may violate the flow constraints.

(2) The above (P_{ij}^m, x_{ij}^m) are substituted in the original problem, which is then solved only with respect to f_{ij} as the optimization variable. The overall result represents a feasible solution to the original problem P1.

5. The SS-SCR Scheme

As described earlier, PU 1's activity is changing on band-set $\mathbb{M}_1$ (*SS* band), providing intermittent periods for the SUs to communicate; on band-set $\mathbb{M}_2$ (*SCR* band), PU 2 is ON and relaying its data through the SU network. It is on this band that a *time incentive* will be offered to the SUs in return for their cooperation. In *SS-SCR*, we solve a joint resource allocation problem on both the PUs' bands; that is, $\mathbb{M}_1 \cup \mathbb{M}_2$, in every such time interval that PU 1's activity changes. There are totally four possibilities (Figure 3): PU 1 is OFF and PU 2 is relaying on $\mathbb{M}_2$, PU 1 is ON and PU 2 is relaying on $\mathbb{M}_2$, PU 1 is OFF and SUs are using the *time incentive* on $\mathbb{M}_2$, and PU 1 is ON and SUs are using the *time incentive* on $\mathbb{M}_2$. Cross-layer optimization problems are formulated for the aforementioned possibilities, as follows.

(Ia) PU 1 is OFF and PU 2 is relaying on $\mathbb{M}_2$. In this case, the joint problem entails maximizing the sum throughput of the SUs and PU 2; the SUs want to make the best utilization of the OFF time of PU 1, while PU 2 wants to maximize its throughput through the SU network so that in turn it can maximize the *time incentive* offered to the cooperating SUs. The complete band-set $\mathbb{M}_1 \cup \mathbb{M}_2$ and the total node power budget P_{node_i} are available for the problem.

(Ib) PU 1 is ON and PU 2 is relaying on $\mathbb{M}_2$. PU 2 can maximize its throughput through the SU network only on $\mathbb{M}_2$ with the total node power budget P_{node_i}.

(Ic) PU 1 is OFF and SUs are using the *time incentive* on $\mathbb{M}_2$. The SUs can now use the complete band-set $\mathbb{M}_1 \cup \mathbb{M}_2$ with the total node power budget P_{node_i} to maximize their sum throughput.

(Id) PU 1 is ON and SUs are using the *time incentive* on $\mathbb{M}_2$. The SUs can only use $\mathbb{M}_2$ with the total node power budget P_{node_i} to maximize their sum throughput.

To enable *SS-SCR*, the following parameters should be set in problem P1 (Table 2).

6. Disjoint Resource Allocation for SS and SCR

In this section, we describe schemes based on disjoint resource allocation on the *SS* and *SCR* bands, considering them as separate problems.

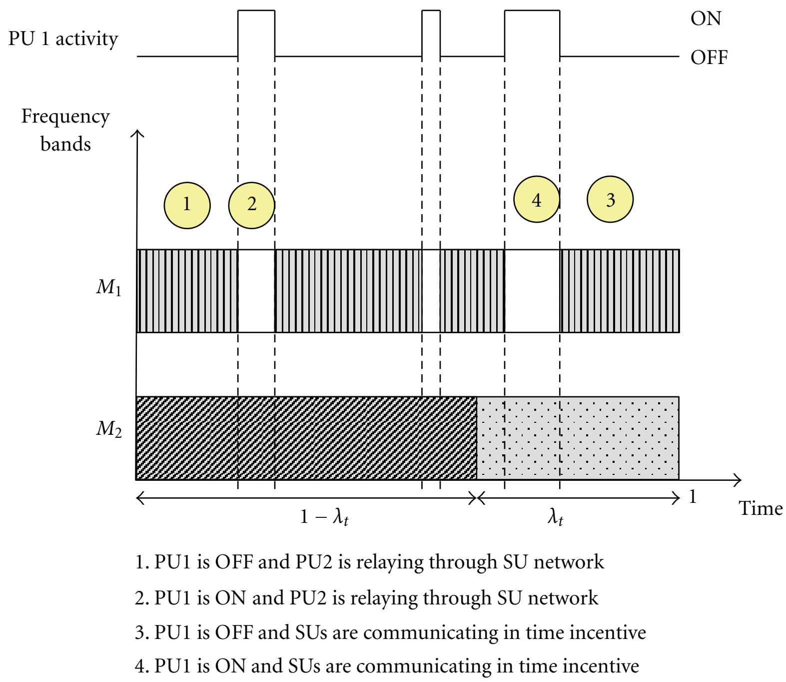

FIGURE 3: SS-SCR scheme.

TABLE 2: SS-SCR.

	Node set ($\mathbb{N}$)	Band-set ($\mathbb{M}$)	Session set ($\mathbb{L}$)	P_{avl_i} (W)
(Ia)*	All SUs PU Tx 2, PU Rx 2	$\mathbb{M}_1 \bigcup \mathbb{M}_2$	SUs, PU 2	P_{node_i}
(Ib)	All SUs PU Tx 2, PU Rx 2	$\mathbb{M}_2$	PU 2	P_{node_i}
(Ic)	All SUs	$\mathbb{M}_1 \bigcup \mathbb{M}_2$	SUs	P_{node_i}
(Id)	All SUs	$\mathbb{M}_2$	SUs	P_{node_i}

*Note: A provision should be made to prevent the SUs from relaying their data through PU Tx 2 and PU Rx 2 by means of additional constraints: $x_{ij}^{(m)} = 0$, $j =$ PU Tx 2 and $x_{ij}^{(m)} = 0$, $i =$ PU Rx 2.

TABLE 3: Scheme A.

	Node set ($\mathbb{N}$)	Band-set ($\mathbb{M}$)	Session set ($\mathbb{L}$)	P_{avl_i} (W)
(IIa)	All SUs	$\mathbb{M}_1$	SUs	P_{node_i}
(IIb)	All SUs, PU Tx 2, PU Rx 2,	$\mathbb{M}_2$	PU 2	$P_{\text{node}_i} - P_{\text{cons}_i}$
(IIc)	All SUs	$\mathbb{M}_3$	SUs	$P_{\text{node}_i} - P_{\text{cons}_i}$

6.1. Scheme A. This scheme gives priority to the activity on the *SS* band and second preference to the *SCR* band. It is devised for that situation in which the OFF periods of PU 1 are high. The following steps are adopted (Figure 4(a)).

(IIa) First, the SUs' sum throughput maximization problem is solved on band-set $\mathbb{M}_1$ (*SS* band). The SUs will be sensing for a spectrum opportunity on this band. In the OFF time of PU 1, they will utilize this band for their own communication. The total node power budget P_{node_i} is available for them at each node i.

(IIb) Secondly, on band-set $\mathbb{M}_2$ (*SCR* band), PU Tx 2 will relay its data through the SU network with maximized throughput. Since the communication happens concurrently with the SU's communication on $\mathbb{M}_1$, now the power available at each node i is the node power budget minus the power consumed in step (IIa), that is, $P_{\text{node}_i} - P_{\text{cons}_i}$. The channel diversity and consequently the higher throughput obtained from the SU network will diminish the transmission time for the same number of bits as those transmitted on the direct link of PU 2. The time saved is offered as an incentive to the SUs for their own communication.

(IIc) In the *time incentive* obtained from PU 2, the SUs maximize their sum throughput on $\mathbb{M}_2$. The power available at each node i is $P_{\text{node}_i} - P_{\text{cons}_i}$.

To enable Scheme A, the following parameters should be set in problem *P1* (Table 3).

6.2. Scheme B. This scheme gives priority to the activity on the *SCR* band and second preference to the *SS* band. It is devised for that situation in which the ON periods of PU 1 are high. The following steps are adopted (Figure 4(b)).

(IIIa) First, on band-set $\mathbb{M}_2$ (*SCR* band), PU Tx 2 will relay its data through the SU network with maximized throughput. The total node power budget P_{node_i} is available for its communication. The higher throughput achieved, as compared to the direct link of PU 2, will generate a *time incentive* for the SUs on $\mathbb{M}_2$.

(IIIb) Next, in the *time incentive* obtained from PU 2, the SUs maximize their sum throughput on band-set $\mathbb{M}_2$. The power available at each node i is P_{node_i}.

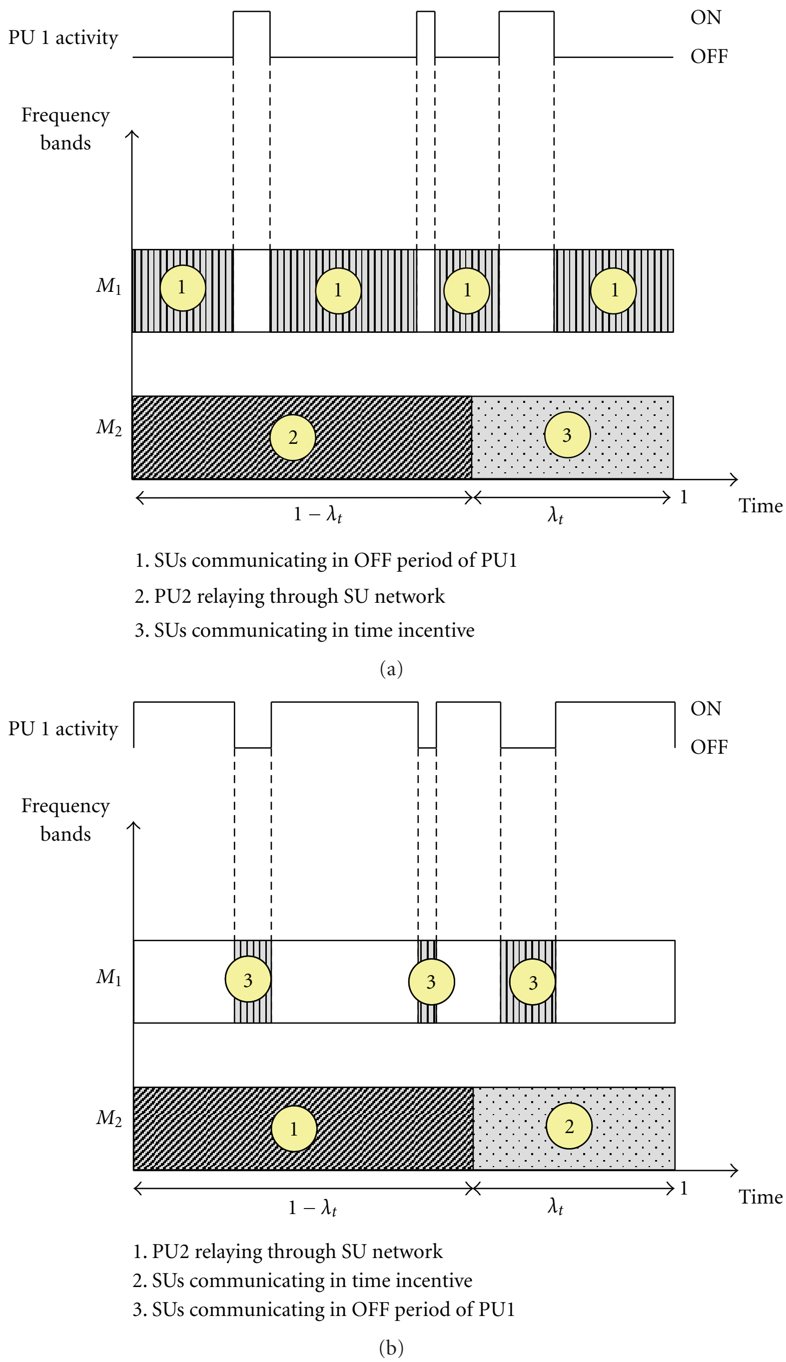

FIGURE 4: Separate SS and SCR: (a) Scheme A (b) Scheme B.

(IIIc) Lastly, the SUs' sum throughput maximization problem is solved on band-set $\mathbb{M}_1$ (*SS* band). The SUs will be sensing for a spectrum opportunity on this band. In the OFF time of the PU, they will utilize this band for their own communication. Since this transmission is concurrent with that on $\mathbb{M}_2$, the power available for them at each node i is minimum of that left after consumption in the relaying interval and the incentive period, that is, $\min(P_{\text{node}_i} - P_{\text{cons}_{\text{III}ai}}, P_{\text{node}_i} - P_{\text{cons}_{\text{III}bi}})$.

To enable Scheme B, the following parameters should be set in problem P1 (Table 4).

7. A Note on the Practical Implementation

To make the *SS-SCR* scheme a practical reality, a MAC schedule is needed to coordinate all the operations. The MAC frame consists of a control interval in which estimation of the channel states, prediction of PU activity, solving the optimization problems at a centralized controller, and

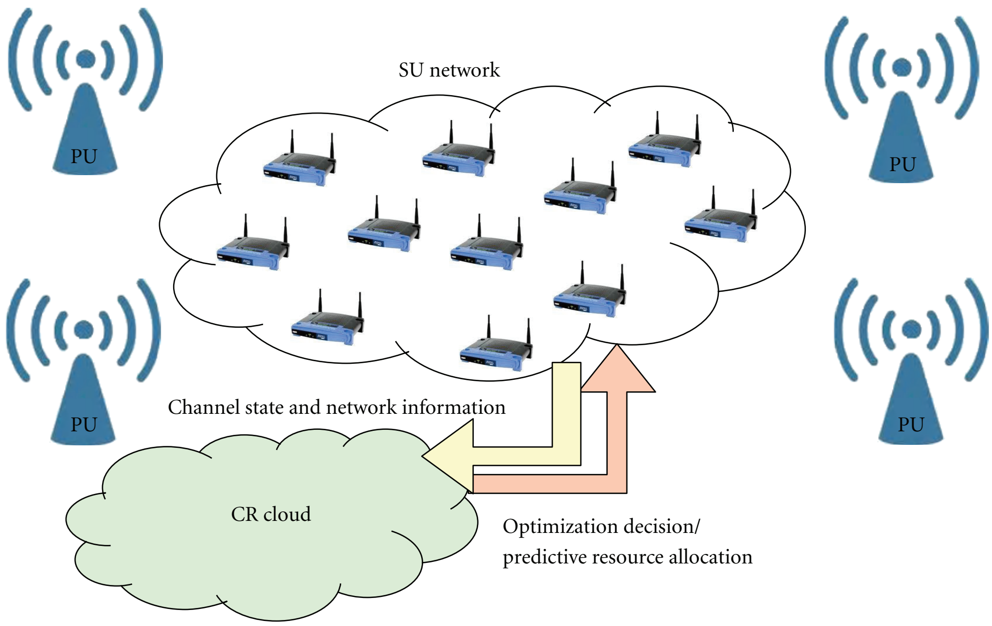

Figure 5: Cloud computing for SS-SCR.

Table 4: Scheme B.

	Node set ($\mathbb{N}$)	Band-set ($\mathbb{M}$)	Session set ($\mathbb{L}$)	P_{avl_i} (W)
(IIIa)	All SUs, PU Tx 2, PU Rx 2	$\mathbb{M}_2$	PU 2	P_{node_i}
(IIIb)	All SUs	$\mathbb{M}_2$	SUs	P_{node_i}
(IIIc)	All SUs	$\mathbb{M}_1$	SUs	Min $P_{\mathrm{node}_i} - P_{\mathrm{cons}_{\mathrm{IIIa}i}}$, $P_{\mathrm{node}_i} - P_{\mathrm{cons}_{\mathrm{IIIb}i}}$

dissemination of the decision throughout the network, are conducted [13]. It is followed by the data interval in which the PUs and SUs communicate using the designated resources. Based on the predicted PU activity, it can be decided when the different solutions of the joint resource allocation are to be applied. The prediction may be corroborated with spectrum sensing to protect the PU 1 from the SU's interference. The *time incentive* can be computed in the control interval itself, to determine when the SUs can access the *SCR* band. An important underlying assumption for the successful execution of the SS-SCR scheme, as well as Schemes A and B (included for comparison), is that the solution time for the optimization problem on the available spectrum is less than the spectrum hole created by the inactivity of PU 1.

Discontiguous OFDM (D-OFDM) is used at the physical layer, which allows the relays to decode only a fraction of the total subcarriers. A control channel is dedicated for all the signalling that enables and coordinates the entire SS-SCR scheme.

8. Cloud Computing for SS-SCR

In *SS-SCR*, the SU nodes are involved with the following tasks, (i) spectrum sensing, (ii) collaborative spectrum sensing decision algorithms, (iii) machine learning algorithms for PU activity prediction based on recorded history, (iv) solving the cross-layer optimization problems for resource allocation and (v) software defined radio (SDR) technologies for reconfiguration. Most of these operations involve both processing vast volume of data (depending on the network size and parameters) and processing it fast. The cognitive SU nodes may have limited computing and storage capability, which may prevent them from realizing their full potential. In such a situation, shifting some of the operations to the *cloud* may drastically improve the performance of the system [25–27]. *Cloud computing* is a recent technology revolution that is shaping the world. However, the decision to exploit the vast computational resources of the *cloud* should be governed by the volume of data and computational complexity, as well as time sensitivity. Primarily for the tasks of PU activity prediction and solving the cross-layer optimization (especially in a large network), the *cloud* may be of great use in *SS-SCR* (Figure 5). A low latency, high-bandwidth, reliable link is needed between the SU network and the *cloud*; else the connectivity may become a performance bottleneck.

9. Simulation Results and Discussion

We have simulated a network with the nodes randomly distributed in an area of 10 square units (Figure 8). Nodes 1 and 9 represent PU Tx 1-PU Rx 1, on the band-set of which *Sense-and-Scavenge (SS)* takes place. Nodes 10 and 11 represent PU Tx 2-PU Rx 2, on the band-set of which

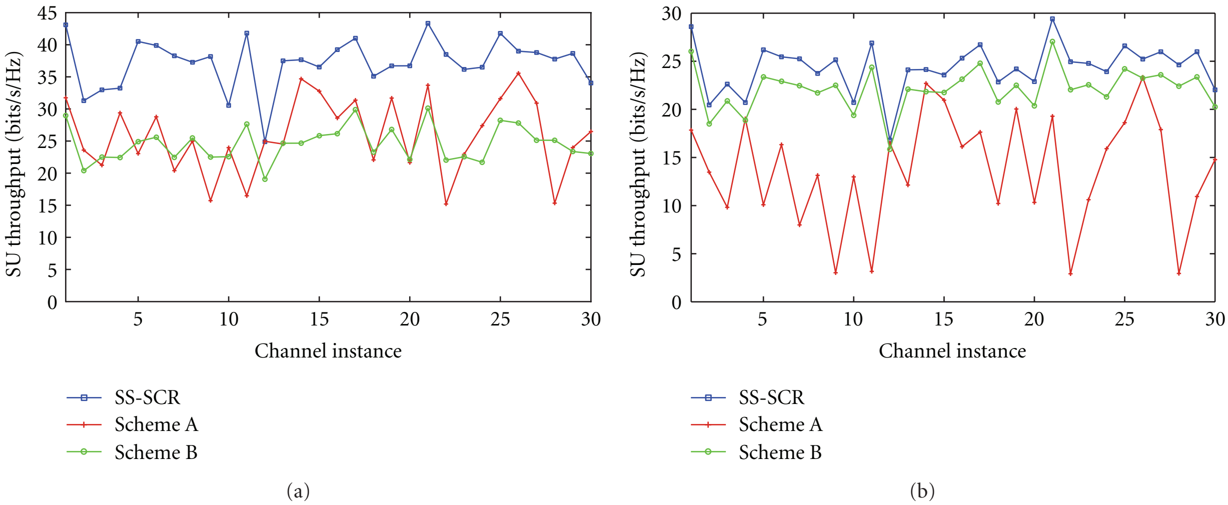

Figure 6: SU throughput versus channel instance (log-normal): (a) high mean OFF time, (b) high mean ON time.

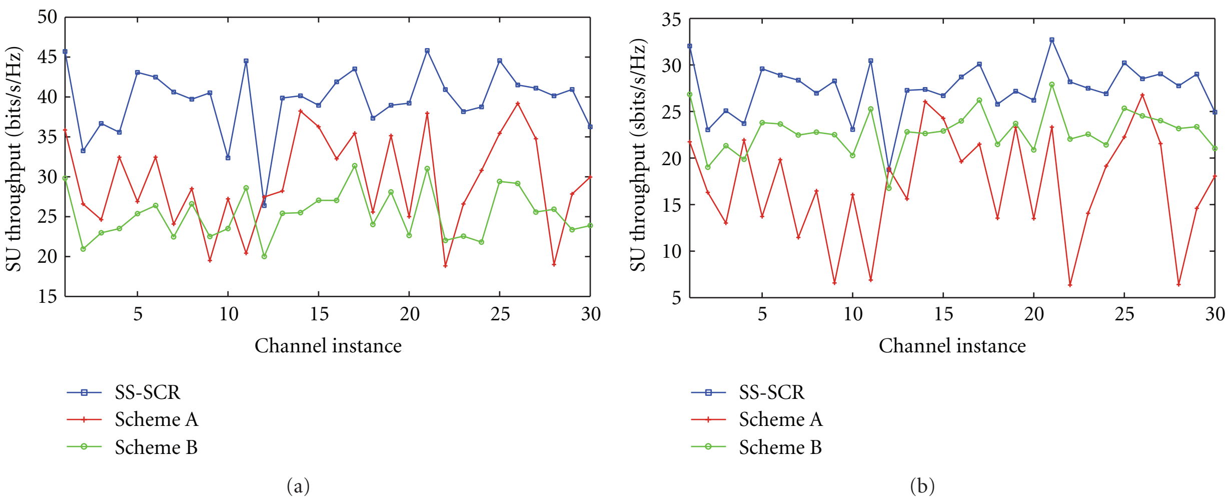

Figure 7: SU throughput versus channel instance (exponential): (a) high mean OFF time, (b) high mean ON time.

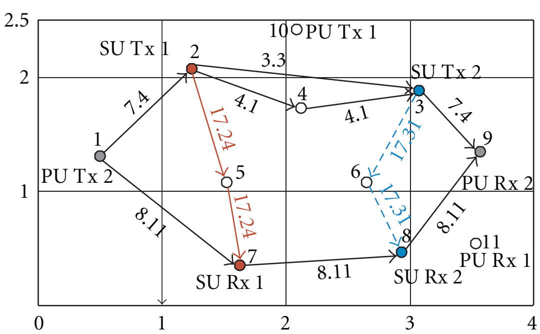

Figure 8: Flow allocation.

Symbiotic Cooperative Relaying (SCR) takes place. Nodes 2 to 8 represent the SU relay nodes.

All the links undergo the Rayleigh multipath fading, defined in the time domain by $\sum_{l=0}^{L-1} h_l \delta(t - lT)$ where h_l is the complex amplitude of path l and L is the number of channel taps. The lth channel coefficient between two nodes with a distance d between them is distributed as $N(0, 1/d^{\eta})$, and the frequency domain channel is given by its Fourier transform. The path loss exponent $\eta = 2.5$. The AWGN variance $\sigma^2 = 1e-4$. A 16 band OFDM system is considered on each link. Bands 1–8 are the *SS* bands, while 9–16 are the *SCR* bands. The OFDM subcarrier bandwidth is unit Hz.

The detection threshold is $P_T = 0.01$ W, the interference threshold is $P_I = 0.001$ W, the peak power constraint on each frequency band is $P_{\text{peak}} = 0.5$ W, and the node power constraint is $P_{\text{node}_i} = 3$ W (it is the same on each node i).

The environment has been simulated in MATLAB, while the LINGO [28] software has been used to solve the MINLP problem.

Figures 6(a) and 6(b) depict the sum SU throughput (bits/sec/Hz) for the proposed *SS-SCR* scheme with respect to 30 independent channel instances. It is compared with Schemes A and B, which consider *SS* and *SCR* separately, on

Table 5: Results for SS-SCR.

Edge (i, j)	Frequency band $*$ power (W) $x_{ij}^{(m)} * P_{ij}^{(m)}$
(1,2)	[0 0 0 0 0 0 0 0 0 0.08 0.5 0.5 0 0 0 0]
(1,7)	[0 0 0 0 0 0 0 0 0 0 0 0 0.5 0.412 0.5 0.5]
(2,3)	[0 0 0 0 0 0.5 0.486 0 0 0 0 0 0 0 0 0]
(2,4)	[0 0 0 0 0 0 0 0 0.380 0 0 0 0.5 0 0 0]
(2,5)	[0 0.017 0.023 0.053 0.073 0 0 0 0 0 0 0 0.053 0.023 0.389]
(3,6)	[0.495 0.240 0.028 0.021 0 0 0 0 0 0 0 0.081 0.029 0.5 0.028 0.075]
(3,9)	[0 0 0 0 0 0 0 0 0.5 0.5 0.5 0 0 0 0 0]
(4,3)	[0 0 0 0 0.5 0 0 0.5 0 0 0 0 0 0 0 0]
(5,7)	[0 0 0 0 0 0.0522 0.5 0.5 0.5 0.5 0.5 0.447 0 0 0 0]
(6,8)	[0 0 0 0 0.5 0.5 0.5 0.471 0.028 0.5 0.5 0 0 0 0 0]
(8,9)	[0 0 0 0 0 0 0 0 0 0 0 0.215 0.5 0.5 0.5 0.5]

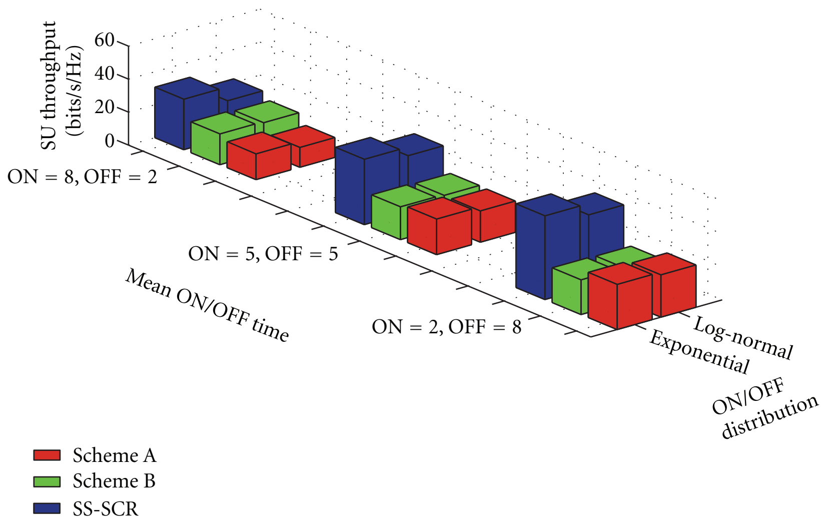

Figure 9: SU throughput versus mean ON/OFF time: log-normal and exponential.

their respective bands. Each of the values are averaged over 100 time frames, each of 10 sec duration. Two SU sessions are assumed, with nodes 2–7 forming the first pair and nodes 3–8 forming the second pair. The ON and OFF periods of PU 1 are each assumed to follow a log-normal distribution. In Figure 6(a), the mean ON time of PU 1 (μ_{ON}) is 2 and the mean OFF time (μ_{OFF}) is 8, while the variance of each distribution ($\sigma_{\mathrm{ON}}^2 = \sigma_{\mathrm{OFF}}^2$) is 10. It is observed that Scheme A performs better (on an average) than Scheme B since it gives preference to the SUs to communicate on the *SS* band, which is free most of the time (mean OFF time of PU 1 is higher). In Figure 6(b), the mean ON time of PU 1 (μ_{ON}) is 8 and the mean OFF time (μ_{OFF}) is 2, while the variance of each distribution ($\sigma_{\mathrm{ON}}^2 = \sigma_{\mathrm{OFF}}^2$) is 10. It is observed that Scheme B performs better (on an average) than Scheme A because it gives preference to PU 2's relaying and consequently creates a higher *time incentive* for the SUs to communicate, while PU 1 provides few opportunities for the SUs to communicate on its band (mean OFF time of PU 1 is lower). *SS-SCR* consistently performs better than the disjoint *SS* and *SCR* schemes, since the complete band-set, $\mathbb{M}_1 \cup \mathbb{M}_2$, is available in every time interval for the SU's communication with the total node power budget. Figures 7(a) and 7(b) depict a similar trend for the exponential distribution of PU 1. In Figure 7(a), $\mu_{\mathrm{OFF}} = \sigma_{\mathrm{OFF}} = 8$ and $\mu_{\mathrm{ON}} = \sigma_{\mathrm{ON}} = 2$, while in Figure 7(b), $\mu_{\mathrm{OFF}} = \sigma_{\mathrm{OFF}} = 2$ and $\mu_{\mathrm{ON}} = \sigma_{\mathrm{ON}} = 8$.

To illustrate the results of the cross-layer optimization problems, the band assignment and power allocation for a particular channel instance for *SS-SCR* (Case Ia) are shown in Table 5. The corresponding flow (bits/sec/Hz) is shown in Figure 8.

Figure 9 demonstrates the average sum SU throughput with different mean ON and OFF times of the log-normal and exponential distributions (fixed variance $\sigma_{\mathrm{ON}}^2 = \sigma_{\mathrm{OFF}}^2 = 10$). It is observed that when the mean OFF time is higher and ON time is lower, Scheme A performs better than Scheme B, for reasons described earlier. But as the OFF time reduces and the ON time increases, the trend reverses. For equal mean ON and OFF times, both Schemes A and B perform similarly. *SS-SCR* is consistently better than the previous two schemes, but its performance degrades and approaches that of Scheme B as the mean ON time increases. This is because the band-set of PU 1 is available for too short a duration for it to exploit the channel diversity. The above discussion holds true for log-normal and exponentially distributed ON/OFF periods of PU 1.

10. Conclusion

We have proposed a novel *SS-SCR* scheme to be deployed in CR networks with multiple PUs, some of which have weak direct links. On the spectra of such licensed users *SCR* is enabled, while on the other PUs' spectra conventional *SS* is implemented. The hybrid *SS-SCR* scheme results in a better utilization of the available resources (time, bandwidth, power) by means of the formulated cross-layer optimization problems. Its performance is compared, for different PU activity patterns on the *SS* bands, with those schemes which consider *SS* and *SCR* separately and perform disjoint resource allocation. Simulation results depict that the *SS-SCR* scheme with joint resource allocation gives a higher net SU throughput as compared to the other schemes. Further, the usefulness of *cloud computing* is illustrated to realize the full potential of *SS-SCR*.

Appendix

If D_{off} is the random variable which describes the OFF period of the PU activity and if it follows the log-normal distribution, its probability density function (PDF) is given by

$$f_{\text{off}}(t;\mu,\sigma) = \frac{1}{t\sigma\sqrt{2\pi}} e^{-(\ln t-\mu)^2/2\sigma^2}, \quad t > 0. \tag{A.1}$$

μ and σ denote the mean and standard deviation, respectively.

In case of the exponential distribution,

$$f_{\text{off}}(t;\lambda) = \lambda e^{-\lambda t}, \quad t \geq 0. \tag{A.2}$$

The mean and standard deviation are both given by $1/\lambda$.

Acknowledgments

This work has been supported in part by the Ministry of Communication and Information Technology, Government of India, New Delhi. The work has also been supported by Microsoft Corporation and Microsoft Research India under the Microsoft Research India PhD Fellowship Award 2009.

References

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, 2005.

[2] H. Zhang, "Cognitive Radio Networking for Green Communications and Green Spectrum," http://www.comnets.org/keynote.html.

[3] K. W. Sung, S. L. Kim, and J. Zander, "Temporal spectrum sharing based on primary user activity prediction," *IEEE Transactions on Wireless Communications*, vol. 9, no. 12, pp. 3848–3855, 2010.

[4] J. Riihijärvi, J. Nasreddine, and P. Mähönen, "Impact of primary user activity patterns on spatial spectrum reuse opportunities," in *Proceedings of the European Wireless Conference (EW '10)*, pp. 962–968, ita, April 2010.

[5] M. Wellens, J. Riihijärvi, and P. Mähönen, "Empirical time and frequency domain models of spectrum use," *Physical Communication*, vol. 2, no. 1-2, pp. 10–32, 2009.

[6] F. Bouali, O. Sallent, J. Pérez-Romero, and R. Agustí, "Strengthening radio environment maps with primary-user statistical patterns for enhancing cognitive radio operation," in *Proceedings of the 6th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM '11)*, pp. 256–260, 2011.

[7] O. Simeone, Y. Bar-Ness, and U. Spagnolini, "Cooperative cognitive radio," in *Cooperative Wireless Communications*, Y. Zhang, H. Chen, and M. Guizani, Eds., pp. 209–230, Auerbach, CRC Press, 2009.

[8] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 203–213, 2008.

[9] J. Zhang and Q. Zhang, "Stackelberg game for utility-based cooperative cognitive radio networks," in *Proceedings of the 10th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc '09)*, pp. 23–31, May 2009.

[10] P. Xue, P. Gong, N. Cao, and D. K. Kim, "Symbiotic Architecture for the cognitive radio networks with amplify-and-forward relaying cooperation," in *Proceedings of the 18th Joint Conference on Communications and Information (JCCI '09)*, pp. 49–54, Jeju, Korea, 2009.

[11] P. Gong, J. H. Park, J. M. Yoo, B. S. Yu, and D. K. Kim, "Throughput maximization with multiuser non-selfish cognitive relaying in CR networks," in *Proceedings of the 4th International Symposium on Wireless and Pervasive Computing (ISWPC '09)*, February 2009.

[12] T. Nadkar, V. Thumar, U. B. Desai, and S. N. Merchant, "Symbiotic cooperative relaying in cognitive radio networks with time and frequency incentive," *Springer Telecommunications System Journal*.

[13] T. Nadkar, V. Thumar, G. Shenoy, A. Mehta, U. B. Desai, and S. N. Merchant, "A cross-layer framework for symbiotic relaying in cognitive radio networks," in *Proceedings of the IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN '11)*, pp. 498–509, deu, May 2011.

[14] T. Nadkar, V. Thumar, G. Shenoy, U. B. Desai, and S. N. Merchant, "Cognitive relaying with frequency incentive," in *Proceedings of the 54th Annual IEEE Global Telecommunications Conference (GLOBECOM '11)*, 2011.

[15] T. Nadkar, V. Thumar, G. Shenoy, U. B. Desai, and S. N. Merchant, "Cognitive relaying with time incentive: protocol design for multiple primary users," in *Proceedings of the IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '11)*, pp. 577–582, 2011.

[16] V. Thumar, T. Nadkar, G. Shenoy, U. B. Desai, and S. N. Merchant, "Cognitive relaying with time incentive: multiple primary users," in *Proceedings of the IEEE 74th Vehicular Technology Conference (VTC '11)*, 2011.

[17] IEEE 802.16 WiMax, http://www.ieee802.org/16/.

[18] IEEE 802.22 WRAN, http://www.ieee802.org/22/.

[19] I. F. Akyildiz, W. Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey," *Computer Networks*, vol. 50, no. 13, pp. 2127–2159, 2006.

[20] Y. Shi and Y. T. Hou, "A distributed optimization algorithm for multi-hop cognitive radio networks," in *Proceedings of the 27th IEEE Communications Society Conference on Computer Communications (INFOCOM '08)*, pp. 1966–1974, April 2008.

[21] J. Zhang, Z. Zhang, H. Luo, and A. Huang, "A column generation approach for spectrum allocation in cognitive wireless mesh network," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '08)*, pp. 3091–3095, December 2008.

[22] Y. Zeng, Y. C. Liang, A. T. Hoang, and R. Zhang, "A review on spectrumsensing for cognitive radio: challenges and solutions," *Eurasip Journal on Advances in Signal Processing*, vol. 2010, Article ID 381465, 2010.

[23] P. Dimitri Bertsekas, *Network Optimization—Continuous and Discrete Models*, Athena Scientific, Belmont, Mass, USA, 1998.

[24] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, Wiley-Interscie, New York, NY, USA, 2nd edition, 2006.

[25] F. Ge, H. Lin, A. Khajeh et al., "Cognitive radio rides on the cloud," in *Proceedings of the IEEE Military Communications Conference (MILCOM '10)*, pp. 1448–1453, November 2010.

[26] C. H. Ko, D. H. Huang, and S. H. Wu, "Cooperative spectrum sensing in TV white spaces: when cognitive radio meets cloud," in *Proceedings of the IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS '11)*, pp. 672–677, April 2011.

[27] H. Harada, H. Murakami, K. Ishizu et al., "A software defined cognitive radio system cognitive wireless clouds," in *Proceedings of the 50th Annual IEEE Global Telecommunications Conference (GLOBECOM '07)*, pp. 294–299, November 2007.

[28] "LINGO: User's guide," LINDO Systems Inc., 2006.