A Cross-layer Framework for Symbiotic Relaying in Cognitive Radio Networks

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***Abstract*—The prime focus of this work is in developing a *Symbiotic Cooperative Relaying (SCR)* architecture for the *Commons model* of *Dynamic Spectrum Access*. The incumbent *Primary User (PU)* of the spectrum, with a weak transmission link, seeks cooperation from the cognitive *Secondary User (SU)* nodes in its vicinity, and in return rewards them with a suitable incentive. The incentive may be offered in terms of time (*Cognitive Relaying with Time Incentive*), frequency bands (*Cognitive Relaying with Frequency Incentive*), or both (*Cognitive Relaying with Time and Frequency Incentive*). Cross-layer optimization problems are formulated, which maximize the transmission opportunities for the *SUs* in the multi-hop multi-channel relay network, and offer a guaranteed throughput to the *PU*. To make the *SCR* scheme practically realizable, a MAC scheduling protocol is proposed within a unified framework for both the *PU* and *SUs*. Furthermore, cross-layer formulations are also proposed for multiple *SUs* to efficiently access the *Time* or *Frequency Incentive* for their own communication. Simulation results are furnished for each of the proposed *SCR* schemes to demonstrate their effectiveness from the perspective of both the *PU* and *SUs*.**

Keywords: Cognitive Radio; Dynamic Spectrum Access; Cross-layer; Symbiotic Cooperative Relaying; OFDM

I. INTRODUCTION

A. Dynamic Spectrum Access/Cognitive Radio

Extensive measurements of its actual usage has revealed the under-utilization of the radio spectrum [1]. This discovery has stimulated exciting activities in the engineering, economics and regulation communities in searching for better spectrum management policies [2]. The envisioned spectrum reform ideas have manifested in the technology solution called *Dynamic Spectrum Access (DSA)*, also referred to as *Cognitive Radio (CR)*. The emerging CR technology is an attempt to mitigate the imbalance between spectrum allocation and its use, created by the current *Command-and-Control* spectrum access policy, by temporarily allowing unused portions of the spectrum owned by the licensed users *(Primary Users)* to be accessed by unlicensed users *(Secondary Users)*. Cognitive Radio 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. This approach can lead to a significant increase in spectrum efficiency, networking efficiency as well as energy efficiency [3]. A CR node has the capability of sensing the spectrum for an opportunity referred to as a *spectrum hole* or a *white-space*. Besides sophisticated spectrum sensing, most of the current research in CR encompasses the following broad areas: (i) spectrum management (capturing the best available spectrum to meet user communication requirements), (ii) spectrum sharing (providing fair spectrum scheduling method among coexisting users), (iii) spectrum mobility and handoff (maintaining seamless communication requirements during the transition to a better spectrum); the latter being specifically relevant to mobile CR networks, and (iv) cross layer design (obtaining performance gains by actively exploiting the dependence between the layers of the network protocol stack) [4]. The potential of the technology has been recognized by the commercial sector (wireless internet, cellular service providers, wireless local area networks, etc.) as well as military and public safety emergency services [5]. Microsoft Research's project *White Fi* aims at creating the networking protocols to handle the challenges for operation in the lower frequencies left open by the transition from analog to digital TV broadcasting, which is being carried out in most parts of the world [6]. Standardization efforts of the working groups IEEE 802.22 [7] (wireless regional area network for secondary use), 802.11h [8] (dynamic frequency selection for wireless local area networks) and P1900/SCC41 [9] (technologies and techniques for next generation radio and advanced spectrum management) evince the great interest surrounding the CR paradigm.

B. Cooperation and Cognitive Radio

To satiate the ever increasing demand for high data rate wireless services, cooperative communication has evolved. Parallel to the developments in the field of CR, research in cooperative technologies has progressed significantly. In its basic definition, cooperative transmission refers to the information theoretic model of a three terminal relay channel in which the relay forwards the transmission from the source towards the destination. The processing at the relay may simply involve forwarding an amplified version of the received signal to the destination i.e. *amplify-and-forward (AF)*, or decoding the received signal completely and re-encoding it to forward it to the destination i.e. *decode-and-forward (DF)*. Performance advantages achievable from collaborating relays arise in two forms, both of which translate into enhancing overall network capacity: (i) power gains which can be achieved if the relay is suitable located, typically half way between the source and destination; (ii) diversity gains which arise due to the multiple paths taken by the signal to reach the destination [10].

The incorporation of cooperative communication in CR networks, creates a promising solution to efficient radio resource utilization, and forms the premise for next-generation wireless systems. Varied forms of cooperation have been investigated to suit different topologies and to meet various requirements of the CR network. Strategies that provide efficient usage of the spectrum opportunity and guarantee QoS constraints for both primary users (PUs) and secondary users (SUs) are suggested in [11]-[14]. The main focus of these works is to enhance the SU network throughput with multi-user cooperation. Cooperative sensing is an important area where cooperative technology can be deployed for robust detection of spectrum holes and estimation of channel conditions [15].

C. Symbiotic Cooperative Relaying in Cognitive Radio

A more recent paradigm in the research surrounding CR, is a symbiotic architecture, which improves the efficiency of spectrum usage and reliability of the transmission links [15], [18]- [24]. According to this model, 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 gives 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.

The performance of a CR network greatly depends on the success of its spectrum sensing module [25][26]. It involves cost and complexity of implementation, and accounts for significant sensing overheads (in terms of time, energy) in the CR cycle. The authors of [25] have proved the fundamental tradeoff between sensing capability and achievable throughput of the SU network. The aforementioned *Symbiotic Cooperative Relaying (SCR)* paradigm advocates that the SUs can access the licensed spectrum in the incentive time without the need for sensing, which will drastically improve the transmission opportunities of the SU, and consequently improve spectrum utilization.

It is evident from the above discussion that both entities of a CR network, viz. the PU and SU, will be motivated by the mutual benefit to participate in the SCR scheme. The need of the hour, is a practical communication protocol that will enable the cooperation and reimbursement architecture. Besides, most present day wireless technologies, such as IEEE 802.16 [27] and 802.22 [7] are based on Orthogonal Frequency Division Multiplexing (OFDM); the multi-channel multi-hop networks thus created, pose a more challenging environment for deployment of the PU-SU cooperative paradigm. Optimum resource allocation, which can be achieved by leveraging the channel diversity abundantly available in a multi-channel network, will improve spectral efficiency and in turn maximize the cooperation opportunities in the symbiotic architecture. With this objective, we present our original contributions towards symbiotic cooperative relaying in CR networks, which are summarized as under:

1) We formulate a cross-layer design to enable the SCR scheme for an OFDM-based multi-hop CR network, with special emphasis on the MAC layer co-ordination which will regulate the sequence of events. The analytical model captures aspects across multiple layers of the protocol stack, viz. physical (power control), MAC (scheduling) and network (routing) layers. The cross-layer optimization problem formulated with the objective of maximizing the PU throughput when relaying through the SU network, exploits the spectral and spatial dimensions for optimum resource allocation. The enhanced throughput (C_{rel}) significantly diminishes the transmission time of the PU for the same amount of information bits as those transmitted on the direct link; and for the remaining time the entire licensed bandwidth is made available to the SU network for its own communication. We call this scheme *Cognitive Relaying with Time Incentive (CRTI)*.
2) As opposed to the previous strategy, which can reward the SUs with an incentive time, it is also possible to reward the SUs with incentive frequency bands, i.e. *Cognitive Relaying with Frequency Incentive (CRFI)*. We explore this possibility by formulating a suitable optimization problem in which we strive to achieve only that PU throughput that can be obtained by the weak direct link between its transmitter and receiver (C_{dir}). The channel diversity in the multi-hop multi-channel SU network makes it possible to achieve C_{dir} by utilizing a few orthogonal frequency bands out of the complete OFDM bandwidth, thereby leaving the remaining bands free as *frequency incentive* for the SUs.
3) A *Maximum Time Incentive* can be obtained if throughput maximization (C_{rel}) is achieved when relaying through the SU network; a *Maximum Frequency Incentive* can be obtained if the minimum capacity (C_{dir}) is achieved from the SU network. It follows logically then, that it is possible to have both a time and frequency incentive for the SUs i.e. *Cognitive Relaying with Time and Frequency Incentive (CRTFI)*, if we achieve some capacity C from the SU network such that $C_{dir} < C < C_{rel}$. A few frequency bands will be freed for long time durations, and intermittently the entire spectrum will be

available for short durations.

4) Once the incentive time or frequency has been *created*, it is crucial to devise access mechanisms for the SUs to utilize the incentive in the best possible way. We develop the cross-layer model for the multiple contending SUs to optimally use the incentive to communicate their own data.
5) We compare and contrast the two major symbiotic schemes proposed i.e. *CRTI* and *CRFI* from the perspective of both the PU and SU, and provide potential application scenarios where each can be deployed.

To detail our work, the paper has been organized as follows: Section II presents related background literature. Section III describes the system model and communication scenario. Section IV methodically explains the cross-layer optimization problem for *CRTI*. Likewise, Sections V and VI present the problem formulations for the *CRFI* and *CRTFI* schemes respectively. In Section VII, we formulate problems for optimum usage of the incentive time and frequency by the SUs. Section VIII describes the complete unified protocol design which makes the SCR scheme possible. In Sections IX and X, we briefly discuss the two major schemes, i.e. *CRTI* and *CRFI*, and compare them. Section XI presents simulation results for each of the SCR schemes and their detailed analysis, while Section XII concludes the paper.

II. Related literature

Preserving the identifying features of CR i.e. coexistence of the PU and SU on the same spectral resource, two main frameworks that have emerged for dynamic spectrum access are [15][16][17] (i) the *Commons model*, and (ii) the *Property-rights model*. Spectrum sharing between the PU and SUs is fundamentally different in the two models in both technical and regulatory aspects. In the Commons model, the SUs sense the radio environment in search of spectrum holes and then exploit the detected transmission opportunities, while complying with the QoS requirements of the PU. The PU remains oblivious to the activity of the SUs. The main implementation challenges and overheads arise from accurate spectrum sensing and efficient utilization of the detected unused spectrum, the responsibility of which resides with the SUs. In the Property-rights model, the PUs own the spectral resource and possibly decide to lease part of it to the SUs in exchange for appropriate remuneration (i.e. secondary trading). Through explicit signaling, the PU informs the SUs when they can operate and when to interrupt service. This model may be accompanied by commercial hoarding of the spectrum rights, which could be detrimental to innovative flexible use of the spectrum.

In the Commons model, the decision-making authority is decentralized to the SUs, and is largely governed by the protocol in use, while in the Property-rights model the licensee (i.e. the PU) makes all substantive choices as to how the spectrum is used; in other words, the computational burden is shifted to the PU.

Surrounding the concept of symbiotic cooperative relaying for CR, many schools of thought have evolved to accommodate substantially different technologies and solutions. The authors of [15] have presented the advantages of cooperation in the Commons model of CR, in terms of cooperative sensing and cooperative transmission. They focus on that instance of cooperation, where a secondary node acts as a relay for the PU traffic. After modeling a cognitive interference channel, the conditions on the two-hop network topology, that make cognitive relaying effective in enhancing the transmission opportunities of the SU, are demonstrated. In the same work of literature (as also in [18]), the authors have used game theoretic tools to analyze the performance of cooperation in the Property-rights model of 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 PU aims at maximizing its transmission rate, while the SU nodes compete among themselves for transmission within the leased time-slot using a decentralized power control mechanism. The problem is cast in the framework of a Stackelberg game, in which the leader (the PU) optimizes its strategy based on the knowledge of its effects on the follower (the SU). It is demonstrated by simulation that both systems significantly gain from the cooperation. The work of [19] is similar to that of [18], except that the former's model 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. Also the access scheme of the SUs is different in [19] as compared to that of [18], in the fact that the former uses TDMA by allocating the incentive time slots to the SUs in proportion to their contribution towards relaying the PU's traffic, while the latter assumes an interference channel which all SUs can access at the same time, within an SNR constraint.

In [20], the symbiotic cooperative model corresponds to a single PU link and only one SU transceiver. For cooperation, the full-duplex AF relaying is considered at the SU to assist the PU transmission. The achievable transmission rate of the PU is analyzed, and the corresponding allocated channel time ratio for the SU link is computed. In [21], the symbiotic architecture considering a single PU and multiple SUs is modeled. The power and diversity gains obtained by AF relaying from multiple cooperating SUs result in enhanced PU throughput, yielding an incentive time for the SUs. Additionally, the utilization of the incentive time is discussed; instead of granting the incentive time directly to the SUs who participated in relaying (*selfish scheme*), it is possible that the PU gives it to the other SUs with a better channel (*non-selfish scheme*). Average overall capacities for both symbiotic relaying schemes, viz. selfish and non-selfish, are analyzed and compared.

Although motivated by the aforementioned works in literature, our work differs from them in view of the following facts: (i) All of the above models have considered a single channel CR network, which will be highly inefficient in exploiting cooperation opportunities in most present day wireless networks, which deploy multi-channel technologies such as OFDM. The prime objective of this paper, is in formulating a cooperative relaying strategy for the PU traffic through a multi-hop network of SUs, which necessitates a cross-layer view of the problem for optimum results (Cross-layer design formulations for multi-channel multi-hop networks can be found in [5],[28]-[31]). (ii) None of the above works have devised procedural rules for the complete operation of the scheme. Motivated by the need to make the symbiotic architecture a practical reality, we identify the roles of each of the entities of the network, and propose a robust MAC scheduling protocol which will coordinate the entire sequence of events. (iii) Most of the above works (part of [15], [18], [19], [21]) have assumed a Property-rights model. We surmise from the discussion on the two models of dynamic spectrum access, viz. the Commons model and the Property-rights model, that the Commons model, having protocol-centric decentralized control, is specially attractive for shared usage of the spectrum by multiple secondary devices with varied applications. Despite the overheads of spectrum sensing, it appears appealing in the realm of CR due to the flexibility and adaptability it offers by exploiting the *intelligence* of the SU devices. We, therefore, propose a SCR scheme for the Commons model, which provides enhanced transmission opportunities for the SU, while protecting the QoS of the PU. In the proposed architecture, when the PU transceiver is communicating on its direct link, the SUs are sensing and awaiting a spectrum opportunity from the PU (as in the Commons model); however, when the PU detects that the direct link is weak it request the SU network for cooperation. In a way, we do take the liberty of incorporating this modification in the Commons model (i.e. explicit signalling from the PU to the SUs, which happens in the Property-rights model and not in the Commons model), but the protocol is thus designed that, thereafter, the PU is oblivious to the activity of the SU. Furthermore, the SUs can now achieve their communication without the need for spectrum sensing (which is a significant saving in terms of computational overheads and time). The proposed model for SCR attempts to combine the appealing features of both the spectrum access models: accessing the leased spectrum without continuous sensing by the SUs as in the Property-rights model, and improved spectrum utilization by exploiting the cognition of the SU nodes as in the Commons model. (iv) Furthermore, two novel concepts of *Cognitive Relaying with Frequency Incentive (CRFI)* and *Cognitive Relaying with Time and Frequency Incentive (CRTFI)* have been proposed, as alternative formats in which the incentive for cooperation may be offered to the SUs.

We would also like to refer the readers to our own previous work on cooperative relaying in CR networks, in which low-complexity *decoupled* approaches have been proposed to achieve time and frequency incentive maximization [22] [24]. In the decoupled approach, the routing and resource allocation are computed at the network and MAC layers respectively. In [23], we have introduced a novel routing metric at the network layer for the purpose of end-to-end throughput maximization through the SU network. The *collaborative* cross-layer formulations for the proposed SCR schemes (*CRTI*,*CRFI*,*CRTFI*), the unified MAC schedule for the PU and SUs in view of the Commons model, and the cross-layer formulations for the SUs to utilize the time and frequency incentives, are the exclusive contributions to this paper.

III. System Description

Typically in CR, the SUs can access the licensed bandwidth when the PU is not communicating. Contrary to the typical CR scenario, in the SCR architecture, when the link between the PU transmitter and receiver is weak, the SUs assist the PU by relaying its data. This is *Phase I* of the communication (Figure 1a). In *Phase II*, the SUs use the time or frequency incentive *created*, for their own data transmission (Figure 1b).

We consider a CR system with a network of cognitive SUs

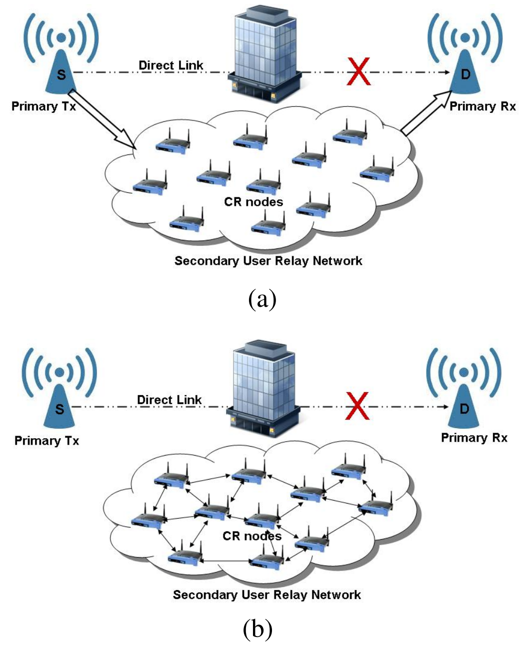


Fig. 1. Symbiotic Cooperative Relaying : (a) Phase I (b) Phase II

and a PU transceiver. The available bandwidth is divided into frequency flat sub-channels by deploying OFDM. The primary transmitter ($PU\ Tx$) acts as the source (S), the receiver ($PU\ Rx$) as the destination (D), and the secondary nodes act as the relays (R) in the multi-hop relay network (Figure 2). Decode-and-forward multi-hopping 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 interference protocol model is assumed [5]. 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 $PU\ Tx$ to SUs, the SUs to the $PU\ Rx$, and those among the SUs, are good enough to provide a significantly higher end-to-end throughput as compared to the direct link of the PU transceiver, resulting in performance gains for both the PU and SUs.

Remarks:

1) *Higher data rates may be achieved with more sophisticated coding-decoding schemes, but we assume decode-and-forward for simplicity of presentation. However, the SCR protocol proposed in this work can be readily applied to other schemes as well.*

2) *The symbiotic cooperative relaying will be achieved with an increase in the overall energy consumed by the SU network since it has to deliver not only its own packets but also those of the PU. We have considered only power constraints, and our work cannot be applied directly to an energy constrained scenario.*

IV. Problem formulation for *CRTI*

The objective in *Cognitive Relaying with Time Incentive (CRTI)* is to maximize the PU's throughput by relaying through the SU network, so that it results in diminished transmission time for the PU, and in turn maximizes the time incentive for the SUs. To efficiently exploit the channel diversities available in the multi-hop multi-channel SU network, we allow flow splitting, and spatial reuse of frequencies outside the interference range of nodes. The 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.

Since our objective is to maximize the throughput, it is sufficient to maximize the sum of outgoing flows from the source node, i.e. the $PU\ Tx$ [32].

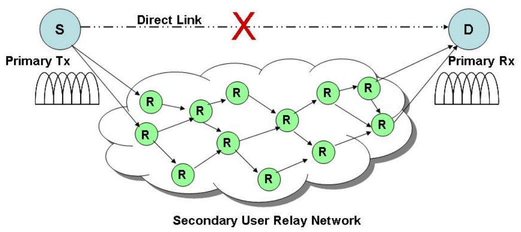


Fig. 2. Relay topology

Optimization Problem (P1):

$$\max_{(x_{ij}^{(m)}, P_{ij}^{(m)}, f_{ij})} \sum_{j \in T_i} f_{ij} \quad i = PU\ Tx \tag{1}$$

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

Flow constraints:

$$\sum_{j \in T_i}^{j \neq PU\ Tx} f_{ij} = \sum_{k \in R_i}^{k \neq PU\ Rx} f_{ki} \quad \forall i \in \mathbb{N}, i \neq PU\ Tx, PU\ Rx \tag{2}$$

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

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

We assume unidirectional links i.e. in the directed graph each node i has a transmit set of nodes T_i, and a receive set of nodes R_i. f_{ij} is the data flow (bits/sec) from node i to node j. Eqn. (2) indicates that, except for the source ($PU\ Tx$) and destination ($PU\ Rx$) nodes, the inflow into a node is equal to the outflow. Eqn. (3) ensures that all the flows are non-negative. Eqn. (4) refers to the fact that the flows on a link cannot exceed the capacity of a link according to Shannon's channel capacity theorem [33]. $h_{ij}^{(m)}$ denotes the channel power gain on band m and $P_{ij}^{(m)}$ denotes the corresponding power allocation. Each link has $\mathbb{M}$ orthogonal frequency bands, and the net achievable throughput is the sum throughput of the individual bands. We have assumed unit bandwidth of each band. In Eqn. (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 (including the $PU\ Tx$, $PU\ Rx$ and SUs), and $\mathbb{E}$ denotes the edge set.

Frequency Domain Scheduling Constraints:

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

Eqn. (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)*, i.e.

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

Power constraints:

$$P_{ij}^{(m)} - P_{T_{ij}}^{(m)} x_{ij}^{(m)} \geq 0 \quad \forall (i,j) \in \mathbb{E}, \quad \forall m \in \mathbb{M} \tag{7}$$

$$P_{ij}^{(m)} - P_{peak} x_{ij}^{(m)} \leq 0 \quad \forall (i,j) \in \mathbb{E}, \quad \forall m \in \mathbb{M} \tag{8}$$

$$\sum_{j \in T_i, m \in \mathbb{M}} P_{ij}^{(m)} x_{ij}^{(m)} \leq Q_i \quad \forall i \in \mathbb{N} \tag{9}$$

Eqns. (7) and (8) ensure that $P_{ij}^{(m)} \in [P_{T_{ij}}^{(m)}, P_{peak}]$ 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. Eqn. (9) is to ensure that the total power transmitted on all the active bands at node i does not exceed the node power budget Q_i.

Interference constraints:

$$\sum_{h \in T_k^m} P_{kh}^{(m)} + (P_{peak} - P_{I_{kj}}^{(m)}) x_{ij}^{(m)} \leq P_{peak} \tag{10}$$

$$\forall i \in \mathbb{N}, m \in \mathbb{M}, j \in T_i, k \in I_j^m, k \neq i$$

Eqn. (10) 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 $P_{kh}^{(m)}$ cannot exceed the interference threshold of node j, given by $P_{I_{kj}}^{(m)} = P_I / h_{kj}^{(m)}$.

The optimization problem can be summarized as

$$\max_{(x_{ij}^{(m)}, P_{ij}^{(m)}, f_{ij})} \sum_{j \in T_i} f_{ij} \quad i = PU\ Tx$$

subject to the constraints of Eqns. (2) to (10). $h_{ij}^{(m)}$, σ^2, P_T, P_I, P_{peak}, Q_i are all constants, while $x_{ij}^{(m)}$, $P_{ij}^{(m)}$, f_{ij} are the optimization variables. The formulation is a mixed integer non-linear programming problem (MINLP). Based on the discussion on similar problems in [5], [29] and the references therein, we conjecture that the given problem is NP-hard.

A Centralized Solution:

Generally, for such MINLP formulations, we employ the *branch-and-bound* framework [34] to develop a solution. Branch-and-bound obtains a linear relaxation on the integer variables in the original problem (The integer variables $x_{ij}^{(m)}$ are relaxed as continuous variables in the range [0,1]). The solution to this relaxed problem provides an upper bound (UB) to the objective function. With the relaxation as the starting point, branch-and-bound uses a *local search* to find a feasible solution to the original problem, which provides a lower bound (LB) to the objective. If the lower and upper bounds are in close proximity of each other, i.e. $(1-\epsilon)UB \leq LB \leq UB$, then the current feasible solution is $(1-\epsilon)$ optimal, where ϵ is a small positive constant.

V. Problem formulation for *CRFI*

The symbiosis between the PU and SU can also take an alternate form: the SUs relay the PU's traffic to guarantee the throughput that could be met with the weak direct link of the PU transceiver (C_{dir}). The direct link would use the complete bandwidth to achieve this rate. However by relaying through the multi-hop secondary network, due to the channel diversity, C_{dir} can be achieved by utilizing a few orthogonal frequency bands out of the complete OFDM bandwidth, thereby leaving the remaining bands as frequency incentive for the SUs, i.e. *Cognitive Relaying with Frequency Incentive (CRFI)* . The optimization problem will be posed such that it achieves C_{dir} while utilizing the least number of frequency bands.

Optimization Problem (P2):

$$\min_{(x_{ij}^{(m)}, P_{ij}^{(m)}, f_{ij})} \sum_{m \in \mathbb{M}} u_m \tag{11}$$

subject to

$$1 - \prod_{(i,j) \in \mathbb{E}} (1 - x_{ij}^{(m)}) = u_m \quad \forall m \in \mathbb{M} \tag{12}$$

$$\sum_{j \in T_i} f_{ij} = C_{dir} \quad i = PU\ Tx \tag{13}$$

Besides, the constraints of Eqns. (2) to (10) are also required for flow balancing, frequency band scheduling and power allocation.

The new variable u_m is an indicator which will represent the occupancy of frequency band $m \in \mathbb{M}$ in the entire network. Eqn. (13) indicates that the sum throughput to be achieved from the SU network should be C_{dir}, so that it leaves some bands free for the SUs as an incentive. The details of the formulation of Eqns. (11) and (12) are provided in the Appendix.

VI. Problem formulation for *CRTFI*

The symbiotic schemes proposed in the previous two sections have a logical extension in *CRTFI*. If we try to achieve a target throughput, C_{tar}, for the PU, through the multi-hop SU network, such that $C_{dir} \leq C_{tar} \leq C_{rel}$, then both a time and frequency incentive will be obtained for the SUs' own communication. Since the PU will finish its communication faster than it would on the direct link, the entire licensed spectrum is freed for a short while (as in *CRTI*). At the same time, the maximum capacity of the relay network is not fully exploited; consequently, a few frequency bands will be freed for all time (as in *CRFI*). The optimization problem will remain the same as *CRFI*, i.e.

Optimization Problem (P3):

$$\min_{(x_{ij}^{(m)}, P_{ij}^{(m)}, f_{ij})} \sum_{m \in \mathbb{M}} u_m$$

subject to the constraints of Eqns. (2) to (10), and (12) to (13); however, the constraint of Eqn. (13) is modified to

$$\sum_{j \in T_i} f_{ij} = C_{tar} \quad i = PU\ Tx \tag{14}$$

Both the problems *P2* and *P3* are MINLP problems, and can be solved using the centralized approach as that described for *CRTI*.

VII. Utilization of Time and Frequency Incentive

The transmission opportunity *created* by the SCR scheme, in terms of time ($CRTI$), or frequency ($CRFI$), or both ($CRTFI$), should be efficiently exploited by the SUs. This also calls for a cross-layer optimization, which determines the power allocation, frequency band assignment and route selection in the multi-channel, multi-hop network of CR nodes. However, since there are multiple SUs who may want to simultaneously communicate their own data, the problem now involves a sum throughput maximization. We would like to re-define the node set $\mathbb{N}$ to include the SU nodes only (it does not include the $PU\ Tx$ or $PU\ Rx$ anymore). We now assume bidirectional links to efficiently accommodate the communication from multiple SUs in the network.

We denote the communication between each unique SU transmitter-receiver pair, that wants to use the incentive time or frequency, as a (unicast) session. $s(l)$ and $d(l)$ represent the source and destination of the session l, $l \in \mathbb{L}$. The objective is to maximize the sum throughput of the session rates; the problem can be formulated as

Optimization Problem (P4):

$$\max_{(x_{ij}^{(m)}, P_{ij}^{(m)}, f_{ij})} \sum_{l \in \mathbb{L}} \sum_{j \in T_i} f_{ij}(l) \quad i = s(l) \tag{15}$$

subject to

$$\sum_{j \in T_i}^{j \neq s(l)} f_{ij}(l) = \sum_{k \in T_i}^{k \neq d(l)} f_{ki}(l) \tag{16}$$

$$\forall i \in \mathbb{N}, l \in \mathbb{L}, i \neq s(l), i \neq d(l)$$

$$f_{ij}(l) \geq 0 \quad \forall (i,j) \in \mathbb{E}, \quad l \in \mathbb{L} \tag{17}$$

$$\sum_{l \in \mathbb{L}} f_{ij}(l) - \sum_{m \in M_{ij}} log_2 \left(1 + \frac{h_{ij}^{(m)} P_{ij}^{(m)}}{\sigma^2}\right) \leq 0 \quad \forall (i,j) \in \mathbb{E} \tag{18}$$

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

$$P_{ij}^{(m)} - P_{T_{ij}}^{(m)} x_{ij}^{(m)} \geq 0 \quad \forall (i,j) \in \mathbb{E}, \quad \forall m \in \mathbb{M}$$

$$P_{ij}^{(m)} - P_{peak} x_{ij}^{(m)} \leq 0 \quad \forall (i,j) \in \mathbb{E}, \quad \forall m \in \mathbb{M}$$

$$\sum_{j \in T_i, m \in \mathbb{M}} P_{ij}^{(m)} x_{ij}^{(m)} \leq Q_i \quad \forall i \in \mathbb{N}$$

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

The flow constraints of Eqns. (16) to (18) are similar to Eqns. (2) to (4) respectively, but have been modified to include multiple sessions. The frequency domain scheduling constraints and the power constraints are the same as those posed earlier, but have been repeated for completeness.

The scheme described above is a non-selfish scheme, i.e.. the SUs will utilize the incentive time or frequency, irrespective of their contribution for relaying the PU's data. This scheme will allow SUs with better channel conditions to communicate. We would like to mention here that it is also possible to allow the SUs to access the time or frequency incentive in proportion to the cost incurred when relaying the PU's data, viz. a selfish scheme.

The above problem formulation (*P4*) holds true for utilization of the network in the *CRTI* scheme, since all the frequency bands are available for the SUs for the incentive time duration. However, when utilizing the network in the *CRFI* scheme, the communication of the PU and SU happens in the same epoch, but over exclusive frequency bands. Therefore, in the above problem formulation, the complete OFDM frequency band set $\mathbb{M}$ will be replaced by $\hat{\mathbb{M}}$, where $\hat{\mathbb{M}}$ the set of frequency bands which are unutilized after the PU has solved its *CRFI* problem i.e. *Problem P2*.

VIII. Protocol Design for the Symbiotic Relaying: A unified framework for the PU and SUs

The aforementioned cross-layer optimization problem formulations for the PU and the SUs address the power allocation, frequency band scheduling and routing, to achieve the various forms of the SCR paradigm, viz. *CRTI*, *CRFI* and *CRTFI*. Additionally, we need to consider some physical layer aspects, and MAC coordination which will make the schemes practically realizable.

A. Physical Layer Considerations

The cross-layer optimization problems assume the knowledge of accurate *Channel State Information (CSI)* at the nodes. The estimation of CSI is done by measuring the received power of the pilot signals. Discontiguous OFDM (D-OFDM) is used for data transmission, which allows the relays to decode only a fraction of the total sub-carriers. The authors of [13] have demonstrated the practicability of D-OFDM based relay system on a USRP and GNU radio test-bed. We assume that every node is equipped with two half duplex radios: one is cognitive for data transmission and the other is conventional for control signalling. The control channel is dedicated for all the signalling that enables and coordinates the entire SCR protocol.

B. MAC layer co-ordination

To make the SCR scheme for a CR network workable, a MAC layer schedule is needed to co-ordinate the cross-layer activities in the network. Under normal operation the PU is communicating on its direct link, and the SUs are monitoring the licensed spectrum to detect a transmission opportunity, like a typical Commons model. When the PU detects that the direct link is weak (based on high BER or delayed acknowledgements), it seeks cooperation from the SUs to relay its data. Consequently, the $PU\ Tx$ sends a Cooperation Request (*CREQ*) to the SU network. It is received by the SUs within its radio range. This explicit signalling between the PU and SU is akin to the Property-rights model. However, we design the relaying scheme considering the fact that the PU does not have any cognitive processing capability, and apart from the initial CREQ signalling, the PU should be oblivious to the relaying strategy adopted by the SU network.

As such, it is proposed that the nodes which are in the immediate radio range of the PU transmitter act as a *proxy source* for the SU network (Figure 3). Upon receiving the CREQ, the *proxy source* nodes send a frame initialization command which is propagated throughout the SU network to indicate the beginning of the symbiotic relaying. This is followed by local channel state estimation at each node. The information collected is used in the cross-layer optimization problem.

After a certain duration, that is reserved for channel state estimation, the *proxy source* nodes send an AODV (Ad-hoc On-demand Distance Vector) type of RREQ (Route Request) packet for route discovery ([35]). It is piggy-backed with the CSI. The RREQ also accumulates, along its path, every SU nodes communication request (if it has one), so that it can be served in the incentive time or on the incentive frequency bands. Every node appends its own address to the route path list of the RREQ packet and broadcasts the RREQ packet to its neighboring nodes. To decrease the broadcast overheads, a maximum hop count field is used at every node. This process will generate a group of paths, not exceeding a certain hop count, between the source and destination, from which *node-disjoint* paths ([36]) are selected. It is important to note that the routes generated are not used for data transmission, since that is already taken care of by the cross-layer optimization; rather they are used for efficiently conveying the optimization decision to each SU node on the control channel. We propose that the nodes of the last hop, which terminates in the PU receiver, form a cluster called the *proxy destination* to shield the $PU\ Rx$ from the operation of the SU network (Figure 3). Similar to cluster head selection in wireless sensor networks, the nodes in the cluster mutually designate the cluster head based on cost of conveying information to the other nodes in the cluster. The cluster head plays an important role in the process: it selects the node-disjoint paths for information disbursement on the control channel, and solves the optimization problem for data transmission for both the PU and SUs. The results are cooperatively conveyed to the other nodes in the cluster. The *proxy destination* nodes then generate a route reply (RREP) on all the reverse paths, piggy-backed with the optimization decision ($x_{ij}^{(m)}$, $P_{ij}^{(m)}$, f_{ij}). The node-disjoint paths, created for disbursement of information, will ensure that each *proxy destination* node forwards the information pertaining to its own path, rather than that of the entire network (Figure 3). This will significantly reduce transmission overheads, and consequently, the bandwidth requirement of the control channel. The SU nodes along the respective paths parse the information to determine their own resource allocation. The *proxy source* intercepts these RREPs, and in turn indicates to the PU transmitter to transmit its data using the allocated resources by means of a READY control signal. The entire process is depicted in the event diagram of Figure 4.

All of the above transactions take place in the control interval of the MAC frame (Figure 5). In the data transmission interval, communication takes place using the allocated resources in the multi-hop network. The total time for the control interval is acceptable, provided it is a small fraction of the channel coherence time, which is true in a slow fading environment as is assumed in this work.

The proposed MAC scheduling protocol indeed provides a unified framework for both the entities of the SCR scheme, viz. the PU and SU. As mentioned earlier in this section, if an SU has its own data to transmit, the RREQ captures this request and conveys it to the *proxy destination*. With this information, the cross-layer resource allocation problem for the SUs' transmission in the incentive time or frequency can be solved at the beginning of the frame (in the control interval) along with the PU's optimization problem. However, parallel processing can reduce timing overheads, i.e. if the SUs' problem is solved and its decision conveyed on the control channel, while the PU's data is already being relayed by the SU network.

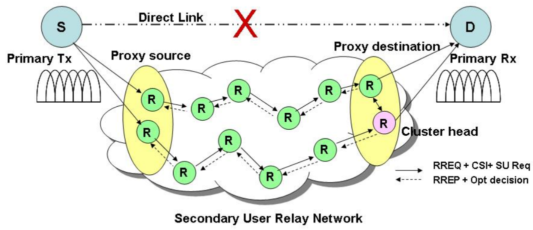


Fig. 3. Proxy source and destination, and information disbursement on node-disjoint paths

IX. A NOTE ON THE TIME AND FREQUENCY INCENTIVE

As discussed in the previous sections, the PU takes assistance from the multi-hop network of SUs to relay its data when the link between its transmitter and receiver is weak. In return, the PU rewards them with an incentive time in the *CRTI* scheme. If C_{dir} is the capacity obtained by using the weak PU link, and if C_{dir}= (1-λ_t) C_{rel}, $0 \leq \lambda_t \leq 1$, then λ_t is the time incentive in a unit time slot.

$$\lambda_t = 1 - \frac{C_{dir}}{C_{rel}} \tag{19}$$

In this time fraction, the SUs can use the network for their own communication. If the SUs provide more cooperation gain to the PU i.e $C_{rel} \gg C_{dir}$, the required time for the PU communication is reduced. Consequently, the SUs can have a greater transmission time (higher λ_t).

In *CRFI*, let $\mathbb{M}_{rel}$ be the number of frequency bands utilized to achieve the throughput C_{dir} via the SU relay network. In an $\mathbb{M}$ band OFDM system, the frequency incentive is computed as

$$\lambda_f = \mathbb{M} - \mathbb{M}_{rel} \tag{20}$$

The SUs will be able to achieve their own communication using these λ_f bands. If the SUs provide more cooperation gain to the PU, the throughput C_{dir} will be achieved with lesser frequency bands ($\mathbb{M}_{rel}$), and a larger set of bands (λ_f)

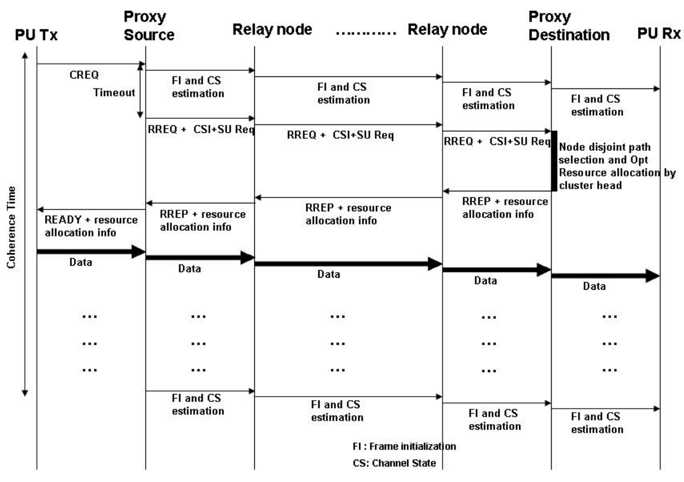


Fig. 4. Event diagram

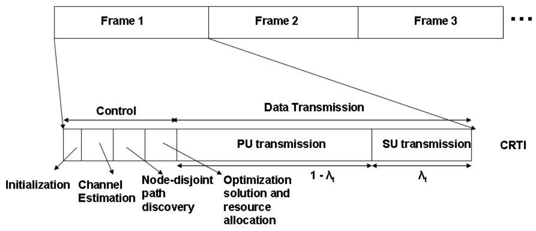
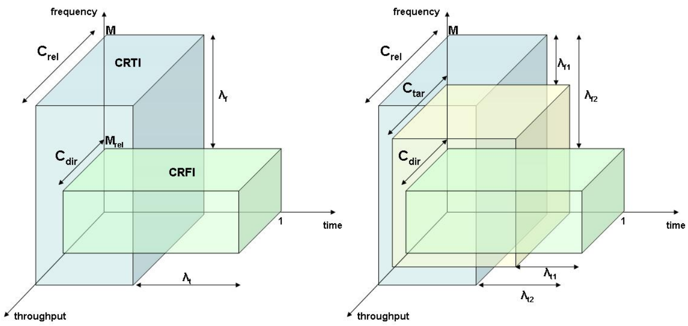


Fig. 5. MAC frame format

will be free for the SU's transmission. The relation between the time and frequency incentive, and the throughput, is presented in Figure 6a. In *CRTFI*, when a target capacity C_{tar} is posed, such that $C_{dir} \leq C_{tar} \leq C_{rel}$, both a time and frequency incentive will be obtained. It can be observed from Figure 6b, that in the unit slot, as the time incentive (λ_t) decreases, the frequency incentive (λ_f) increases, and vice versa.



(a) (b)

Fig. 6. Relation between Time and Frequency Incentive

X. Comparing the CRTI and CRFI schemes

The most important difference between the two major SCR schemes, viz. *CRTI* and *CRFI*, is the way in which the PU and SUs access the network resources. In the data transmission interval of the MAC frame, in the case of *CRTI*, the relaying of PU's data and the SUs' transmission take place in different epochs, i.e. resources are time-division multiplexed (TDM) by the two. However, in *CRFI*, the PU and SUs communicate simultaneously but on exclusive frequency bands, which means that frequency-division multiplexing (FDM) takes place between the two. We would also like to remark here, that while in our work, we have treated the optimization problem for *CRFI*, and the SUs' usage of the frequency incentive, as separate problems, it is very easy to incorporate the two into a unified optimization problem in which a single objective function achieves the target throughput C_{dir} for the PU, while the sum throughput of the remaining SU sessions is maximized on the available resources. The same cannot be said about the *CRTI* scheme, since the PU and SU communicate in different time intervals.

The choice of the symbiotic scheme will be largely dominated by the application requirement of the SUs. A *CRFI* scheme will be more suitable for telephony; being a real-time application it requires fixed frequency bands for continuous time. On the other hand, a packet data communication can be achieved by using the *CRTI* scheme, which will give the complete bandwidth for intermittent time durations. In *CRTFI* some frequency bands are available for continuous time, while others are available intermittently. Since the temporal and spatial availability of each frequency band can be identified at the beginning of the time frame (when the PU determines its' optimum resource allocation, scheduling and routing, and consequently the incentive is computed), it is possible for the SUs to plan their activity on the incentive time and/or frequency. Using frequency division multiple access (FDMA), the bands may be shared among SUs with heterogenous applications; for instance, those frequency bands which will be available for all time may be allocated, on a priority basis, to that application of the SU which demands so, while the intermittently available frequency bands may be given to other applications.

XI. Simulation Results and Discussion

A. Simulation Set-up

We have simulated a network with the nodes randomly distributed in an area of 10 sq. units as shown in Figure 7a. Nodes 1 and 9 represent the $PU\ Tx$ and $PU\ Rx$ respectively, while nodes 2 to 8 represent the SU relay nodes. All the links undergo Rayleigh multi-path 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 l^{th} channel coefficient between two nodes with a distance d between them is distributed as N(0,1/d^{η}) and the frequency domain channel is given by its Fourier Transform. The path loss exponent η = 2.5. The AWGN variance σ^2 = 1e-4. An 8 band OFDM system is considered on each link and the OFDM subcarrier bandwidth is unit Hz. The detection threshold is P_T=0.01W, the interference threshold is P_I=0.001W, the peak power constraint on each frequency band is P_{peak}=1W, and the node power constraint is Q_i=2W (it is the same on each node i).

The environment has been simulated in MATLAB; while the LINGO [37] software has been used to solve the MINLP problem. LINGO is an integrated package that includes a powerful language for expressing optimization models, and an environment for building and editing problems efficiently.

B. Cognitive Relaying with Time Incentive (CRTI)

The results of the cross-layer optimization problem for *CRTI* are reported in Figure 7b and Table I. The PU's transmission is relayed through the multi-hop multi-channel SU network. As indicated in Figure 7b, the flow originating from the $PU\ Tx$, i.e. node 1, is split at node 5 into three paths: (5,6), (5,7) and (5,8). These paths then converge at the $PU\ Rx$, i.e. node 9. The corresponding frequency band ($x_{ij}^{(m)}$) and power allocation ($P_{ij}^{(m)}$) on the used edge sets ($(i,j) \in \mathbb{E}$) are reported in Table I. The PU throughput obtained is C_{rel} = 44.00906 bits/sec. If the throughput obtained on the PU's direct link C_{dir} = 20 bits/sec, then the corresponding fractional time incentive λ_t obtained in a unit time slot is 0.5455 (from Eqn. 19), which is offered to the SUs in return for their resources in relaying the PU's traffic. As anticipated, the *CRTI* scheme yields no frequency incentive, but a maximum time incentive.

C. Cognitive Relaying with Frequency Incentive (CRFI)

Next, the *CRFI* scheme is simulated to obtain a maximum frequency incentive. When using the SU network to achieve a throughput C_{dir} = 20 bits/sec, only three frequency bands are utilized, i.e. $\sum_{m\in\mathbb{M}} u_m$=3, leaving 5 out of 8 OFDM bands free as the incentive (λ_f) for the SUs. As observed from Table II, frequency bands $\{1,2,8\}$ have been used. The corresponding power allocation is also indicated in Table II. The flow between the $PU\ Tx$ and the $PU\ Rx$ is as shown in Figure 7c.

D. Cognitive Relaying with Time and Frequency Incentive (CRTFI)

We simulate *CRTFI* with the target PU throughput as C_{tar}=33 bits/sec. This scheme achieves a frequency incentive (λ_f) of 2 bands, i.e. bands 4 and 5 have not been used (Table III) and a time incentive, λ_t= 0.25 (1-C_{tar}/C_{rel}). As expected, the *CRTFI* scheme gives a lesser time incentive than the *CRTI* scheme and a lesser frequency incentive than the *CRFI* scheme. The results of the flow, frequency band and power allocation are reported in Figure 7d and Table III respectively.

E. Utilization of the Time and Frequency Incentive

The time and frequency opportunity has to be efficiently utilized by the SUs. In *CRTI* the SUs use the complete frequency band set in a different time epoch from the PU; while in *CRFI* the SUs simultaneously communicate with the PUs, but only on the frequency incentive band set. We have assumed two SU pairs who want to communicate in the incentive time duration: nodes 2 to 6 form one session, and nodes 3 to 8 form the second session. The cross-layer optimization results for a non-selfish utilization are depicted in Table IV and Figure 7e. The sum throughput obtained as a result of the optimization is 103.1799 bits/sec. The throughput being much higher than that obtained in the *CRTI* case, may be attributed to the fact that there are flows originating from multiple sources, and possibly better channel conditions. The flows corresponding to the two sessions are shown in Figure 7e, while the frequency band and power allocation is shown in Table IV.

The results of the utilization of the incentive frequency bands, i.e. bands $\{3,4,5,6,7\}$, by the SUs are reported in Table V and Figure 7f. Here again we have assumed that nodes 2 to 6 form one session, and nodes 3 to 8 form the second session. It is evident from the frequency band and power allocation reported in Table V that only the incentive frequency bands have been used by the SUs for their own communication. The flows corresponding to the two sessions are shown in Figure 7f. Though they have not been included here, we would expect similar results for the utilization in the case of *CRTFI*.

TABLE I
RESULTS FOR *CRTI*

Edge (i,j)	Frequency Band $x_{ij}^{(m)}$	Power(W) $P_{ij}^{(m)}$
(1,5)	[0 1 1 0 0 0 1 1]	[0 0.2575 0.2574 0 0 0 0.2574 0.2575]
(5,6)	[1 0 0 0 0 0 0 0]	[0.3984 0 0 0 0 0 0 0]
(5,7)	[0 0 0 1 1 0 0 0]	[0 0 0 1.0 0.4686 0 0 0]
(5,8)	[0 0 0 0 0 1 0 0]	[0 0 0 0 0 0.1328 0 0]
(7,8)	[0 1 0 0 0 0 1 0]	[0 0.3666 0 0 0 0 0.7259 0]
(6,9)	[0 0 0 0 0 0 0 1]	[0 0 0 0 0 0 0 1.0]
(8,9)	[1 0 1 0 1 0 0 0]	[0.6788 0 0.1958 0 0.8845 0 0 0]

TABLE II
RESULTS FOR *CRFI*

Edge set (i,j)	Frequency Band $x_{ij}^{(m)}$	Power(W) $P_{ij}^{(m)}$
(1,5)	[1 0 0 0 0 0 0 0]	[0.2421 0 0 0 0 0 0 0]
(1,7)	[0 1 0 0 0 0 0 0]	[0 0.3 0 0 0 0 0 0]
(5,6)	[0 0 0 0 0 0 0 1]	[0 0 0 0 0 0 0 0.1645]
(6,9)	[0 1 0 0 0 0 0 0]	[0.1645 0 0 0 0 0 0 0]
(7,8)	[1 0 0 0 0 0 0 0]	[0.0927 0 0 0 0 0 0 0]
(8,9)	[0 0 0 0 0 0 0 1]	[0 0 0 0 0 0 0 0.1108]

TABLE III
RESULTS FOR *CRTFI*

Edge set (i,j)	Frequency Band $x_{ij}^{(m)}$	Power(W) $P_{ij}^{(m)}$
(1,2)	[0 0 1 0 0 0 1 0]	[0 0 0.5531 0 0 0 1.0 0]
(1,5)	[0 0 0 0 0 1 0 0]	[0 0 0 0 0 0.3750 0 0]
(2,3)	[0 0 0 0 0 0 0 1]	[0 0 0 0 0 0 0 1.0]
(2,4)	[0 1 0 0 0 0 0 0]	[0 0.9572 0 0 0 0 0 0]
(4,5)	[1 0 0 0 0 0 0 0]	[0.0259 0 0 0 0 0 0 0]
(4,6)	[0 0 0 0 0 0 1 0]	[0 0 0 0 0 0 0.1073 0]
(5,6)	[0 0 1 0 0 0 0 0]	[0 0 1.0 0 0 0 0 0]
(6,8)	[0 1 0 0 0 0 0 0]	[0 0.0111 0 0 0 0 0 0]
(3,9)	[0 0 0 0 0 1 0 0]	[0 0 0 0 0 0.1964 0 0]
(6,9)	[1 0 0 0 0 0 0 1]	[0.1128 0 0 0 0 0 0 0.0164]
(8,9)	[0 0 1 0 0 0 1 0]	[0 0 0.0802 0 0 0 0.0812 0]

TABLE IV
RESULTS FOR UTILIZATION OF THE TIME INCENTIVE

Edge set (i,j)	Frequency Band $x_{ij}^{(m)}$	Power(W) $P_{ij}^{(m)}$
(2,3)	[1 0 0 0 0 0 0 0]	[0.2130 0 0 0 0 0 0 0]
(2,4)	[0 0 0 1 0 1 0 0]	[0 0 0 0.3296 0 0.4625 0 0]
(2,5)	[0 0 1 0 0 0 1 0]	[0 0 0.3889 0 0 0 0.4389 0]
(3,4)	[0 1 0 0 0 0 0 0]	[0 1.0 0 0 0 0 0 0]
(3,6)	[0 0 1 0 0 0 1 0]	[0 0 0.0952 0 0 0 0.0952 0]
(4,5)	[0 0 0 0 1 0 0 0]	[0 0 0 0 0.1852 0 0 0]
(4,6)	[1 0 0 0 0 0 0 1]	[0.9073 0 0 0 0 0 0 0.9073]
(5,6)	[0 0 0 1 0 1 0 0]	[0 0 0 0.7153 0 0.7153 0 0]
(6,8)	[0 0 0 0 1 0 0 0]	[0 0 0 0 1.0 0 0 0]

TABLE V
RESULTS FOR UTILIZATION OF THE FREQUENCY INCENTIVE

Edge set (i,j)	Frequency Band $x_{ij}^{(m)}$	Power(W) $P_{ij}^{(m)}$
(2,3)	[0 0 0 0 1 0 0 0]	[0 0 0 0 0.1 0 0 0]
(2,4)	[0 0 0 0 0 0 1 0]	[0 0 0 0 0 0 0.1111 0]
(2,5)	[0 0 0 0 0 1 0 0]	[0 0 0 0 0 1.0 0 0]
(3,4)	[0 0 0 1 0 0 0 0]	[0 0 0 1.0 0 0 0 0]
(4,6)	[0 0 1 0 1 0 0 0]	[0 0 1.0 0 1.0 0 0 0]
(5,6)	[0 0 0 0 0 0 1 0]	[0 0 0 0 0 0 1.0 0]
(6,8)	[0 0 0 0 0 1 0 0]	[0 0 0 0 0 0.4629 0 0]

XII. CONCLUSION

In this paper we have developed a *Symbiotic Cooperative Relaying (SCR)* architecture for CR networks, in which an incumbent PU seeks cooperation from SUs in its vicinity for an enhanced throughput, and in return rewards them with an incentive time duration for their own communication (*CRTI*). The available channel diversity in the SU network also makes it possible to offer the incentive in terms of frequency bands (*CRFI*), and both time and frequency bands (*CRTFI*). Cross-layer optimization problems have been formulated for each of the three SCR schemes, viz. *CRTI*, *CRFI* and *CRTFI*. Furthermore, the role of each of the network participants is identified, including two intermediaries: the proxy source and destination. The MAC schedule, which will co-ordinate the entire SCR scheme, is devised. Cross-layer problems, that enable efficient utilization of the time and frequency incentive, are also formulated. The simulation results demonstrate that a significant time and frequency incentive is, indeed, *created* for the SUs, which is used by them for their own communication. We conclude that the proposed SCR paradigm is suggestive of the usefulness of cooperative technology to unleash the potential of CR networks.

XIII. ACKNOWLEDGEMENT

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APPENDIX

In order to model the *CRFI* problem, we need to introduce a new variable u_m which will indicate the occupancy of band $m \in \mathbb{M}$ in the entire network. Logically, this is modeled as

$$OR_{(i,j)\in\mathbb{E}} x_{ij}^{(m)} = u_m$$

Where OR() performs a logical OR on its arguments. We would prefer to write the above using arithmetic operations, as they are easier to work with. We use the following lemma:

Lemma: For binary variables (0 or 1), multiplication and logical AND operations are identical.

Proof: It can be verified using truth tables.

Therefore we have,

$$OR_{(i,j)\in\mathbb{E}} x_{ij}^{(m)} = u_m \tag{21}$$

$$\Rightarrow \left(\left(OR_{(i,j)\in\mathbb{E}} x_{ij}^{(m)}\right)^c\right)^c = u_m \tag{22}$$

$$\Rightarrow \left(AND_{(i,j)\in\mathbb{E}}(1 - x_{ij}^{(m)})\right)^c = u_m \quad ...De - Morgan'sRule \tag{23}$$

$$\Rightarrow \left(\prod_{(i,j)\in\mathbb{E}} (1 - x_{ij}^{(m)})\right)^c = u_m \quad ...Lemma \tag{24}$$

$$\Rightarrow 1 - \prod_{(i,j)\in\mathbb{E}} (1 - x_{ij}^{(m)}) = u_m \tag{25}$$

In the above expressions $()^c$ represents the binary complement operator. When we take the sum of all u_m, and seek to minimize it (as in Eqn. (11)), we are in effect minimizing the total number of bands used.

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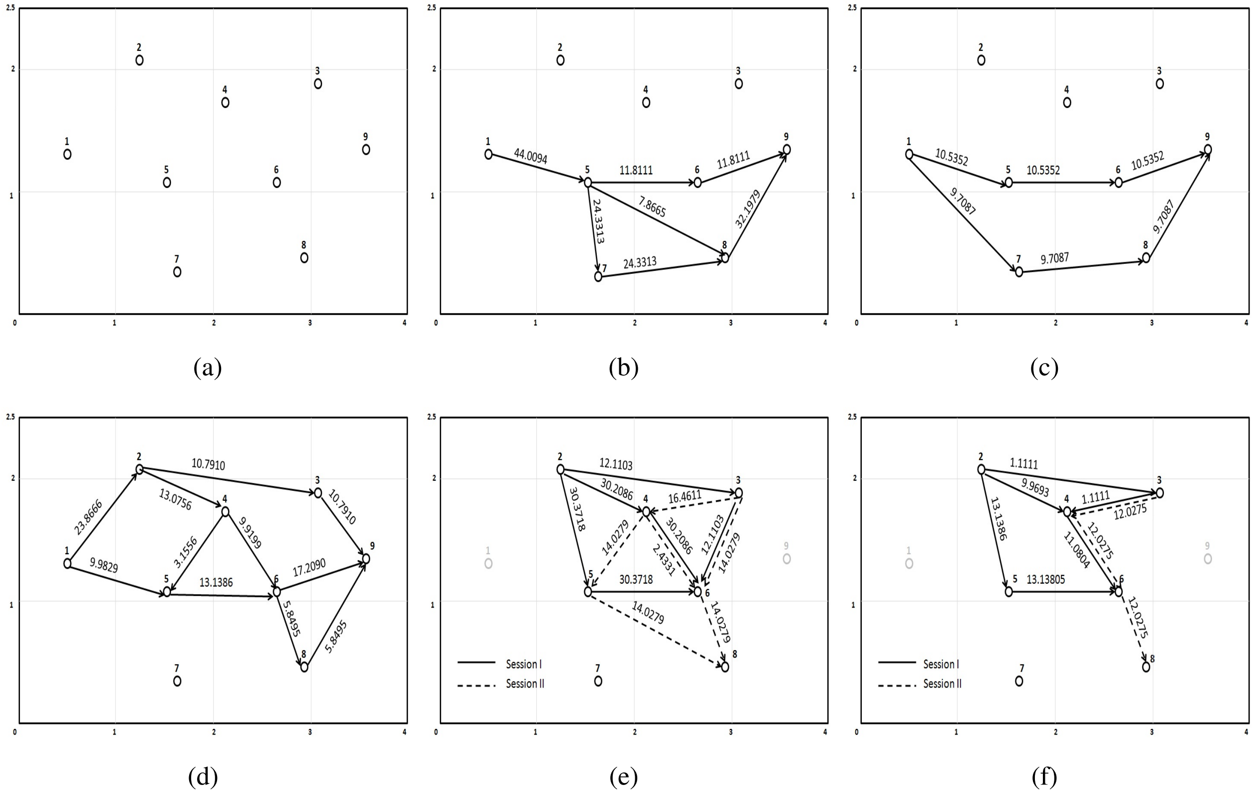

Fig. 7. Simulation Results: (a) Network topology (b) CRTI (c) CRFI (d) CRFI (e) Utilization of Time Incentive (f) Utilization of Frequency Incentive

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