Throughput-optimal Cross-layer Design for Cognitive Radio Ad Hoc Networks

Alessandro Cammarano[†], Francesco Lo Presti[‡], Gaia Maselli[†],
Loreto Pescosolido[†], *Member, IEEE,* and Chiara Petrioli[†], *Senior Member, IEEE*

Abstract—We present a distributed, integrated medium access control, scheduling, routing and congestion/rate control protocol stack for Cognitive Radio Ad Hoc Networks (CRAHNs) that dynamically exploits the available spectrum resources left unused by primary licensed users, maximizing the throughput of a set of multi-hop flows between peer nodes. Using a Network Utility Maximization (NUM) formulation, we devise a distributed solution consisting of a set of sub-algorithms for the different layers of the protocol stack (MAC, flow scheduling and routing), which result from a natural decomposition of the problem into sub-problems. Specifically, we show that: 1) The NUM optimization problem can be solved via duality theory in a distributed way, and 2) the resulting algorithms can be regarded as the CRAHN protocols. These protocols combine back-pressure scheduling with a CSMA-based random access with exponential backoffs. Our theoretical findings are exploited to provide a practical implementation of our algorithms using a common control channel for node coordination and a wireless spectrum sensor network for spectrum sensing. We evaluate our solutions through ns-2 MIRACLE-based simulations. Our results show that the proposed protocol stack effectively enables multiple flows among cognitive radio nodes to coexist with primary communications. The CRAHN achieves high utilization of the spectrum left unused by the licensed users, while the impact on their communications is limited to an increase of their packet error rate that is below 1%.

Index Terms—Cognitive radio networks, spectrum sensor network, Dynamic Spectrum Access (DSA), cross-layer optimization, backpressure methods.

1 Introduction

The last decade has witnessed an explosion of wireless applications that created an ever-increasing demand for radio frequency resources. The government traditional allocation of the radio spectrum has been based on licensing. The lack of flexibility of this allocation policy has resulted in spectrum assignment saturation, without actual exhaustion of available frequencies [1], which leads to a high degree of spectrum underutilization.

One of the most promising approaches to a more efficient, intelligent, and dynamic spectrum utilization is provided by Cognitive Radios (CRs) [2]–[4]. According to the CR paradigm, allocated portions of spectrum are used by both *primary users* (PUs), which are nodes of a primary network (PNet) licensed to use a given band, and by *secondary users* (SUs) that can use the licensed band or some of its sub-channels only when/where they are not used by PUs.

Implementing the Cognitive Radio paradigm through Cognitive Radio Ad Hoc Networks (CRAHNs) has to overcome significant challenges in the design and integration of fundamental functions such as determining spectrum availability, spectrum decision, spectrum sharing (MAC) and cognitive routing [5]–[8].

In this paper, we address the problem of joint MAC, flow scheduling, and routing in CRAHNs, with the objective of maximizing the throughput of coexisting end-to-end flows among peer nodes.

We describe and evaluate a novel *fully decentralized* cross-layer solution derived by exploiting the well known Network Utility Maximization (NUM) approach [9]–[13]. The NUM approach has been widely acknowledged to be a systematic methodology to study, design and optimize network protocols as distributed solutions to global optimization problems [13].

Using standard duality theory, the optimization problem can be decomposed into sub-problems. In particular, by properly choosing the decomposition, the solutions to the sub-problems specify a set of distributed protocols each corresponding to a different layer of the protocol stack, *i.e.*, routing, scheduling, and MAC. It is important to observe that the nodes do not perform any explicit optimization and/or computation. Rather, by locally executing protocols combining the well-known *backpressure scheduler* [14] with a modified version of the CSMA algorithm [15], the CRAHN converges to a distributed solution that is provably optimal and fully scalable.

[†]*Alessandro Cammarano, Gaia Maselli, Loreto Pescosolido, and Chiara Petrioli are with the Computer Science Department, University of Rome "La Sapienza," via Salaria 113, I-00198 Rome, Italy. Email:* {cammarano, maselli, petrioli}@di.uniroma1.it, loreto.pescosolido@uniroma1.it.
[‡]*Francesco Lo Presti is with the "Dipartimento di Ingegneria Civile e Ingegneria Informatica," University of Rome "Tor Vergata," via del Politecnico 1, I-00133 Rome, Italy. Email:* lopresti@info.uniroma2.it.

The protocols so derived assume that the SUs have knowledge of the *average* PU channel occupation in their area, across the set of available channels[1] and periodically exchange their queue length over a common control channel (CCC).

We evaluate our solution via extensive simulations, using a complete simulation environment that we have implemented using the ns2-Miracle simulator [23]. Our implementation includes the CRAHN, or Secondary Network (SNet), the SU protocol stack, a PNet, and spectrum sensors. Our simulation results show that the proposed implementation validates the gains determined by the theoretically optimal scheme. In particular, we evaluate (i) the impact of SNet operations on the performance of the PNet, considering the additional interference to the PU receivers, the bit errors and the PU packet error rate (PER) induced by the SNet activities, and (ii) the performance of the SNet in terms of achievable flow rates.

The performance of our protocols are also benchmarked against that of baseline SU protocol stacks, demonstrating that our cross layer approach significantly outperforms the benchmarks both in terms of resulting PU performance degradation, and in terms of sustainable achievable SNet flow rates.

The remainder of this paper is organized as follows. Section 2 describes the considered scenario and introduces our theoretical framework. Section 3 details the proposed protocol stack that solves the NUM problem. Section 4 describes the practical protocol implementation and simulation environment, and presents the simulations results showing the performance gain achievable through our protocols. Section 5 positions our work with respect to existing research on CRAHNs. Finally, Section 6 concludes the paper.

This paper is supplemented by a document including three appendices: Appendix A details the formal derivation of the distributed solution to the NUM problem presented in Section 2; Appendix B gives additional details on the simulation environment; Appendix C contains additional simulation results.

2 Model and Problem Formulation

2.1 Secondary Network Model

We consider a CRAHN composed of a set of SUs $\mathcal{N} \triangleq \{1, \ldots, N\}$ deployed in the same region of the PNet (Figure 1). The PNet uses a set of K frequency channels $\mathcal{C} = \{c_1, \ldots, c_K\}$, each of bandwidth B and capacity C. By capacity, we indicate the *nominal* transmission rate on a channel if a node uses it 100% of the time, without considering bit errors due to channel noise, fading, interference. Table 1 summarizes the notation used in the paper.

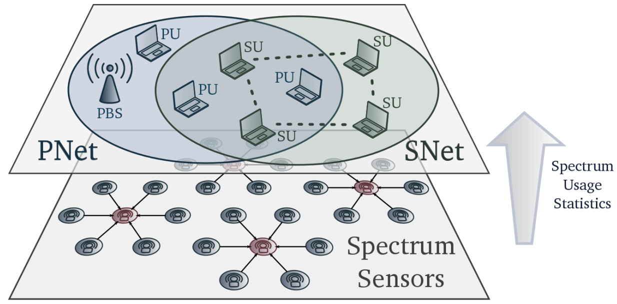


Figure 1. Considered Scenario: Coexisting SNet, PNet, and spectrum sensors for spectrum usage statistics.

Table 1
Notation

n, m	network nodes
(n,m)	link between n and m
$(n,m;c)$	channel c of link (n,m)
$\alpha_{(n,m;c)}$	availability of channel c on link (n,m)
C	channel capacity
f	traffic flow
$s(f)$, $d(f)$	source and destination node of flow f
T	epoch duration
Q_{nf}	queue length at node n of flow f
q_{nf}	normalized queue length at node n for flow f
x_f	normalized traffic transmission rate of flow f
s_{fl}	flow transmission rate across sublink l
$w_{(n,m;c)}$	sublink $(n,m;c)$ unused capacity measure
ϵ	unused capacity threshold
$R_{(n,m)}$	link (n,m) exponential backoff rate
$p_{(n,m;c)}$	probability of transmitting on link (n,m) channel c

We model the SNet with a static multigraph[2] $(\mathcal{N}, \mathcal{L})$, where $\mathcal{L}$ is the set of sublinks, defined as triples of the form $(n,m;c)$, $n,m \in \mathcal{N}$, $c \in \mathcal{C}$. We will refer to $n = h(l)$, $m = t(l)$ and $c = c(l)$ as the head, tail and channel of the sublink, respectively . The existence of a sublink $(n,m;c)$ means that node n can communicate with node m using channel c. We then define the link (n,m) as the set of sublinks connecting node n to node m. For each node n,

1. Interference monitoring and mapping have been recently recognized as a key feature for enabling Licensed Shared Access (LSA) [16] or LTE-U [17]. In our scenario, the needed spectrum monitoring can be provided by CRAHN nodes themselves or by a supporting *wireless spectrum sensor network* (WSSN), whose monitoring capabilities have been shown to be remarkably accurate [19]. WSSN-based solution can be deployed by co-locating their nodes within the cellular network infrastructures, such as those made up of large numbers of "small cells" [18] used by operators for covering dense urban areas. The WSSN nodes located within such cells can act as "spectrum sensors" that disseminate spatially tagged, pre-processed and temporally filtered information on the availability of each channel. A business model for WSSN-aided cognitive radio networks has been proposed in [21].

2. In the problem formulation we consider static multigraphs. To be consistent with a time selective fading scenario, the existence of a sublink is defined either considering the average SNR or an instantaneous SNR outage probability. In the former case, transmission is conventionally assumed to be possible when the distance between transmitter and receiver is such that the average SNR experienced on that radio link (obtained averaging out the fluctuations due to fading) is above a predefined threshold. In the latter, the existence of the sublink is defined by the requirement that the instantaneous SNR be above a given threshold for at least a predefined percentage of time.

we denote by $Li(n) \triangleq \{l = (m, n'; c) \in \mathcal{L} : n' = n\}$ and $Lo(n) \triangleq \{l = (n', m; c) \in \mathcal{L} : n' = n\}$, the set of incoming and outgoing sublinks, respectively.

The SUs exploit the same set of channels of the PNet following a Dynamic Spectrum Access (DSA) approach by utilizing the idle primary spectrum. Periodically updated information on PU channel use is made available to SUs by spectrum sensors, see Appendix B in the supplemental document. Based on such information, each SU n computes, for each of its outgoing link (n, m), a set of channel availability coefficients $\alpha_{(n,m;c_1)}, \ldots, \alpha_{(n,m;c_K)}$, where $\alpha_{(n,m;c)}$ combines the probability that the channel c is free in an area surrounding the node n, which we call *nominal interference region*, and the availability of m to receive on that channel. Without loss of generality, we assume that SU n selects the channel for transmission to SU m from a set of channels $\mathcal{C}_{nm}(\alpha_{min})$ with availability larger than a minimum threshold α_{min}.

2.2 Traffic Model

We denote by $\mathcal{F}$ the set of end-to-end packet flows in the CRAHN. Each flow is characterized by a source-destination pair $(s(f), d(f)) \in \mathcal{N}^2$. For each flow $f \in \mathcal{F}$ we define the flow rate x_f as the average number of bits per second transmitted by the flow source node $s(f)$. We assume that x_f is bounded in the interval $[0, x_M]$, where x_M is the maximum flow traffic rate. In the rest of the paper, without loss of generality, we assume that rates are normalized with respect to the channel capacity C, *i.e.*, $x_f = 1$ means that source f transmits at rate C.

We denote by s_{fl} the rate of flow f along link l. The flow conservation law implies that for flow f and node n:

$$x_f + \sum_{l \in Li(n)} s_{fl} = \sum_{l \in Lo(n)} s_{fl} \quad n = s(f), f \in \mathcal{F} \tag{1}$$

$$\sum_{l \in Li(n)} s_{fl} = \sum_{l \in Lo(n)} s_{fl} \quad n \neq s(f), d(f), f \in \mathcal{F} \tag{2}$$

which simply states that for any node traversed by the flow f, except for the destination node $d(f)$, the flow entering the node must be equal to the flow exiting it.

Each flow is associated with a utility function $U_f(x_f)$ which reflects the "utility" for flow f when it can transmit at rate x_f. We assume that $U_f(.)$ is differentiable, strictly concave and non decreasing. There are several classes of functions satisfying this condition, *e.g.*, $\log(1 + x_f)$ and $\beta_f x_f^{1-\eta_f}/(1 - \eta_f)$ which are used to characterize a large class of fairness concepts, including weighted proportional and max-min fairness [24].

2.3 Interference/Conflicts Model

Interference/Conflicts among links limit the transmissions opportunities. We need to consider different types of conflicts. First, the wireless nature of channels cause interference when the sender of one sublink is within the interference range of the sender or the receiver of another sublink and the two sublinks share the same channel. Second, we need to account for the physical limitation that one node can transmit over only one single channel at a given time. Thus, for any node $n \in \mathcal{N}$, sublink l also conflicts with all links $l' \in Lo(n)$, $l' \neq l$, $c(l) \neq c(l')$.

We use a conflict graph to capture scheduling constraints among different sublinks. A conflict graph is a graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of vertexes, each of them representing a sublink, and $\mathcal{E}$ is the set of edges, representing sublinks conflicts, *i.e.*, two links cannot transmit at the same time if and only if there is an edge between them.

Definition: An independent set of the conflict graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ is a subset $I \subseteq \mathcal{V}$ such that no two elements are adjacent, *i.e.*, $i, j \in I \Rightarrow (i, j) \notin \mathcal{E}$. Only sublinks within the same independent set can transmit simultaneously without interference/conflict with each other.

Let $\mathcal{I}$ denote the set of independent sets of $\mathcal{G}$. We denote by $a_I = (a_{Il})_{l \in \mathcal{L}}$, $I \in \mathcal{I}$, a binary vector that indicates which link belongs to I. In particular, $a_{Il} = 1$ if $l \in i$ and $a_{Il} = 0$ otherwise. We denote by $\mathcal{X} = \{a_I | I \in \mathcal{I}\}$ the set of all characteristics vectors a_I. We indicate with p_I the frequency which transmission over the independent set $I \in \mathcal{I}$ occurs. Since only independent sets can be simultaneously scheduled, $\sum_{I \in \mathcal{I}} p_I = 1$. From these frequencies, we directly obtain an expression for the average transmission rate over sublink l as $\sum_{f \in \mathcal{F}} s_{fl} = \sum_{I \in \mathcal{I}} p_I a_{Il}$ under the assumption of unit capacity.

2.4 Problem Formulation

We formalize the optimal congestion control, routing and flow scheduling in a CRAHN problem as a NUM problem with the aggregate traffic utility $U(x) = \sum_{f \in \mathcal{F}} U_f(x_f)$ as objective function, as follows:

Optimization Problem P

$$\mathbf{P}: \max \sum_{f \in \mathcal{F}} U_f(x_f) \tag{3a}$$

$$\text{s.t.} \quad x_f + \sum_{l \in Li(n)} s_{fl} = \sum_{l \in Lo(n)} s_{fl} \quad n = s(f), f \in \mathcal{F} \tag{3b}$$

$$\sum_{l \in Li(n)} s_{fl} = \sum_{l \in Lo(n)} s_{fl} \quad n \neq s(f), d(f), f \in \mathcal{F} \tag{3c}$$

$$\sum_{f \in \mathcal{F}} s_{fl} = \sum_{I \in \mathcal{I}} p_I a_{Il} \quad l \in \mathcal{L} \tag{3d}$$

$$\sum_{I \in \mathcal{I}} p_I a_{Il} \leq \alpha_l \quad l \in \mathcal{L} \tag{3e}$$

$$\sum_{I \in \mathcal{I}} p_I = 1, \quad p_I \geq 0 \quad I \in \mathcal{I}\ . \tag{3f}$$

Constraints (3b)-(3c) are the flow constraints. Constraints (3d) state that the aggregate flow rate traversing a sublink l, $\sum_{f \in \mathcal{F}} s_{fl}$, is equal to the average link l transmission rate, that is, the fraction of time link l is scheduled which corresponds to $\sum_{I \in \mathcal{I}} p_I a_{Il} = \sum_{I \in \mathcal{I}: l \in I} p_I$. The average link l transmission rate, in turn, is limited by α_l, the fraction of time the sublink is not occupied by primary transmissions (3e).

3 SU Protocol Stack: Joint Rate, Scheduling and MAC Control

In this section we present the proposed CRAHN protocol stack derived from the solution of the network utility maximization problem $\mathbf{P}$ via Lagrangian duality. The solution implicitly defines an *ideal* distributed cross-layer scheme for joint rate control, scheduling and MAC. For its length, the formal derivation is provided in the supplemental document. Below we provide a sketch of it. For mathematical tractability, the derivation of the protocols requires assuming instantaneous propagation, resulting in no collisions among SU packets, and the optimal scheduling and channel assignment to SU flows refers to a given average PU channel occupancy. However, in Section 4, we remove such assumptions and, by taking suitable countermeasures to the presence of collisions, show that the framework performs very well even in the realistic case. The goal of using a complete simulation environment, including a highly dynamic PNet, is exactly to show that the proposed solution works even when the above assumptions are relaxed, as it is the case of any realistic scenario where propagation delays, collisions, and dynamic PU activity (in time and frequency) are considered.

3.1 Summary of the formal derivation

In this subsection we present a sketch of the derivation of the distributed solution via Lagrangian duality to the problem $\mathbf{P}$. The detailed derivation can be found in the supplemental material.

We consider a slightly different problem $\mathbf{P}'$ obtained from $\mathbf{P}$ by adding the term $-\frac{1}{\beta}\sum_{I\in\mathcal{I}} p_I \log p_I$ to the objective function where β is a large constant and replacing constraint (3d) with $\sum_{I\in\mathcal{I}} p_I a_{Il} + \epsilon \le \alpha_l$ where $\epsilon > 0$ is a small constant. Since $\mathbf{P}'$ cannot be solved directly without complete knowledge of the network, we resort to dual decomposition [44]. We form the dual problem by relaxing the constraints (3b)-(3c) and (3e). The resulting dual problem $\mathbf{D}'$ is

Dual Problem $\mathbf{D}'$

$$\mathbf{D}' \text{: min } D(\boldsymbol{q},\boldsymbol{w}) \tag{4}$$

$$\text{s.t. } q_{nf} \ge 0,\ n\in N, f\in\mathcal{F} \tag{5}$$

$$w_l \ge 0,\ l\in\mathcal{L}$$

with partial dual function given by

$$D(\boldsymbol{q},\boldsymbol{w}) = \max_{\boldsymbol{p},\boldsymbol{s},\boldsymbol{x}} L(\boldsymbol{p},\boldsymbol{s},\boldsymbol{x},\boldsymbol{q},\boldsymbol{w})$$

$$= \max_{\boldsymbol{p},\boldsymbol{s},\boldsymbol{x}} \sum_{f\in\mathcal{F}}\sum_{f\in\mathcal{F}} \left(U_f(x_f) - q_{s(f)f}x_f\right) - \frac{1}{\beta}\sum_{I\in\mathcal{I}} p_I \log(p_I) \tag{6}$$

$$+\sum_{l\in\mathcal{L}}\sum_{f\in\mathcal{F}} s_{fl}\left(q_{h(l)f} - q_{t(l)f}\right) - \sum_{l\in\mathcal{L}} w_l \left(\sum_{I\in\mathcal{I}} p_I a_{Il} + \epsilon - \alpha_l\right)$$

$$\text{s.t. } \sum_{f\in\mathcal{F}} s_{fl} \le \sum_{I\in\mathcal{I}} p_I a_{Il} \qquad l\in\mathcal{L} \tag{7}$$

$$\sum_{I\in\mathcal{I}} p_I = 1, \quad p_I \ge 0 \qquad I\in\mathcal{I}$$

$$s_{fl} \ge 0 \quad f\in\mathcal{F}, l\in\mathcal{L}\ .$$

where $\boldsymbol{q} = (q_{nf})_{n\in N, f\in\mathcal{F}}$ and $\boldsymbol{w} = (w_l)_{l\in\mathcal{L}}$ are the vectors of Lagrangian multipliers associated to the flow constraints (3b)-(3c) and to the available capacity constraints (3e), respectively. For the solution of $\mathbf{D}'$, since $D(\boldsymbol{q},\boldsymbol{w})$ is only piecewise differentiable, we use the subgradient method for its possibility to implement it in a distributed way. Starting with an initial value of the dual function variables, $(\boldsymbol{q},\boldsymbol{w}) = (\boldsymbol{q}^{(0)},\boldsymbol{w}^{(0)})$, iteratively, until convergence, the subgradient method boils down to: 1) Compute $D(\boldsymbol{q},\boldsymbol{w})$; and 2) Update $\boldsymbol{q},\boldsymbol{w}$ using the subgradient.

Dual Function Evaluation: Computation of $D(\boldsymbol{q},\boldsymbol{w})$ entails finding $\boldsymbol{p}^*$ (the MAC layer probabilities), $\boldsymbol{s}^*$ (the routing and scheduling) and $\boldsymbol{x}^*$ (the rate control) that maximize the Lagrangian. First, we fix $\boldsymbol{p}$ and $\boldsymbol{x}$ and solve (6) for $\boldsymbol{s}$. Then we plug the optimizer $\boldsymbol{s}^*(\boldsymbol{q},\boldsymbol{w})$ back into (6) and determine the optimal $\boldsymbol{p}^*$ and $\boldsymbol{x}^*$.

First Step: Fix $\boldsymbol{p}$ and $\boldsymbol{x}$ and solve (6) for $\boldsymbol{s}$. It suffices to observe that $\sum_{l\in\mathcal{L}}\sum_{f\in\mathcal{F}} s_{fl}\left(q_{h(l)f} - q_{t(l)f}\right)$ is the only term of the Lagrangian $L(\boldsymbol{p},\boldsymbol{s},\boldsymbol{x},\boldsymbol{q},\boldsymbol{w})$ which is function of $\boldsymbol{s}$. The solution is straightforward: we simply assign all the bandwidth $\sum_{I\in\mathcal{I}} p_I a_{Il}$ to the flow with the largest queue differential $z_{nm} = \max_{f\in\mathcal{F}} q_{nf} - q_{mf}$. As shown in the supplemental document, this step corresponds to the back-pressure scheduling implemented by the nodes.

Second Step: Plugging $\boldsymbol{s}^*(\boldsymbol{q},\boldsymbol{w})$ back into (6), we obtain:

$$D(\boldsymbol{q},\boldsymbol{w}) = \max_{\boldsymbol{p},\boldsymbol{x}} \sum_{f\in\mathcal{F}} \left(U_f(x_f) - q_{s(f)f}x_f\right) - \frac{1}{\beta}\sum_{I\in\mathcal{I}} p_I \log(p_I)$$

$$+\sum_{I\in\mathcal{I}} p_I \sum_{l\in\mathcal{L}} (z_{nm} - w_l)a_{Il} + \sum_{l\in\mathcal{L}} w_l(\alpha_l - \epsilon)$$

$$\text{s.t. } \sum_{I\in\mathcal{I}} p_I = 1, \quad p_I \ge 0,\ \forall I\in\mathcal{I} \tag{8}$$

$$s_{fl} \ge 0, \quad \forall f\in\mathcal{F}, l\in\mathcal{L}\ ,$$

which is now separable in $\boldsymbol{p}$ and $\boldsymbol{x}$. Hence, $\boldsymbol{x}_f^*(\boldsymbol{q},\boldsymbol{w})$ and $\boldsymbol{p}_I^*(\boldsymbol{q},\boldsymbol{w})$ can be computed independently. For $x_f^*(\boldsymbol{q},\boldsymbol{w})$, under the assumption that U_f is differentially invertible, it follows that $x_f^*(\boldsymbol{q},\boldsymbol{w})$ is the maximizer of $U_f(x_f) - q_{s(f)f}x_f$ which yields $x_f^*(\boldsymbol{q},\boldsymbol{w}) = x^*(q_{s(f),f}) = U_f'^{-1}(q_{s(f)f})$ the rate value of each $f\in\mathcal{F}$. This provides the flow rate control expression. For, $\boldsymbol{p}^*(\boldsymbol{q})$, applying the techniques of Walrand [15] to our problem, it is possible to show that they represent the stationary distribution of the link transmission probabilities under the MAC backoff timers defined in (15). In other words, $p^*(\boldsymbol{q},\boldsymbol{w})$ is obtained by simply having the secondary network running the SU MAC protocols.

Iteration: Dual variable $\boldsymbol{w},\boldsymbol{q}$ update: After evaluating the dual function, we update the dual variables using the subgradient algorithm [45]. The dual variables updating equations are of the form

$$q_{nf}^{(k+1)} = q_{nf}^{(k)} + \gamma^{(k)}\frac{\partial D(\boldsymbol{q},\boldsymbol{w})}{q_{nf}} \tag{9}$$

$$w_l^{(k+1)} = w_l^{(k)} + \gamma^{(k)}\frac{\partial D(\boldsymbol{q},\boldsymbol{w})}{w_l}, \tag{10}$$

where the derivatives represent the subgradients. These two equations represents the queue (9) and the available bandwidth control variables dynamics (10).

3.2 Protocol Stack

The proposed protocol stack follows from the formal derivation of the optimal distributed solution, completed by the needed mechanisms to make it work in a realistic setting.

The protocol stack is a combination of *backpressure scheduler* [14] and of a modified version of the distributed adaptive CSMA algorithm in [15], where backlogged SUs access the network according to a CSMA-based protocol with exponential backoff function of the differential queue lengths across different links.

The SNet relies on the channel availability information provided by the spectrum sensors (or by their own sensing, depending on the specific use-case) and on the network flows queues sizes. Moreover, we assume the availability of a dedicated CCC outside the band of cognitive operation, *i.e.*, free from interference, for information exchange and CSMA handshaking.

Time is divided into epochs of equal length T. System variables are updated in each epoch. We write $y^{(k)}$ to denote the value of the variable y at the beginning of epoch k.

- Flow Scheduling: Each node n keeps a separate queue for each flow f passing through it. We let $Q_{nf}^{(k)}$ denote this queue length at time kT. We find it convenient to define a normalized queue length $q_{nf}^{(k)} = \frac{Q_{nf}^{(k)}}{C}\frac{\gamma}{T}$, where $\gamma > 0$ is a positive system-wide constant.

At the beginning of epoch k, each node $n \in \mathcal{N}$ schedules for transmission the flow $f_{nm}^* = \text{argmax}_{f\in F}\left(q_{nf}^{(k)} - q_{mf}^{(k)}\right)$, *i.e.*, the flow with maximal differential backpressure on the link. The flow f_{nm}^* packets are then transmitted by node n for the entire duration of the epoch, unless the queue empties first, in which case transmission is suspended until new packets of flow f_{nm}^* are enqueued at node n.

- Rate Control: Outgoing traffic from each traffic source node is constant during each epoch: at the beginning of epoch k, for each flow f, the source node $s(f)$ recomputes the outgoing traffic rate x_f as the maximizer of the function $U_f(x_f) - q_{s(f)f}x_f$ in the interval $[0, x_M]$, where $q_{s(f)f}$ is the normalized queue length of flow f at its source node. $q_{s(f)f}$ represents the traffic incoming (from the application layer) on node $s(f)$ for flow f but not yet injected into the network. We obtain $x_f^{(k)} = \left[U_f'^{-1}(q_{s(f)f}^{(k)})\right]_0^{x_M}$. For instance, considering the log utility function $U(x_f) = \log(1 + x_f)$, which ensures proportional fairness, we readily obtain:

$$x_f = \begin{cases} x_M & q_{s(f)f} \le \frac{1}{x_M+1} \\ \frac{1}{q_{s(f)f}} - 1 & \frac{1}{x_M+1} < q_{s(f)f} \le 1 \\ 0 & q_{s(f)f} > 1 \end{cases} . \qquad (11)$$

- Queue Length dynamics: Let $s_{fl}^{(k)}$ denote the average (normalized) transmission rate of flow f over sublink l during the k-th epoch. The queue dynamics obey to:

$$Q_{nf}^{(k+1)} = \begin{cases} \left[Q_{nf}^{(k)} + TC\left(\sum_{l\in Li(n)} s_{fl}^{(k)} - \sum_{l\in Lo(n)} s_{fl}^{(k)}\right)\right]^+ \\ \quad \text{if } f\in\mathcal{F}, n \ne s(f) \\ \left[Q_{nf}^{(k)} + TC\left(x_f - \sum_{l\in Lo(n)} s_{fl}^{(k)}\right)\right]^+ \\ \quad \text{if } f\in\mathcal{F}, n = s(f). \end{cases} \qquad (12)$$

- MAC protocol: The SUs MAC protocol is a distributed CSMA-based protocol which accounts for the presence of PUs and the existence of multiple sublinks per transmitter-receiver pair. The design is inspired by the results in [15], where a fully distributed CSMA-based protocol with close to optimal performance is presented for a single-channel wireless network.

When a node $n \in \mathcal{N}$ has backlogged traffic to send over one of its outgoing links, say (n, m), it randomly selects a channel within the set $\{c_1, \ldots, c_K\}$ according to a probability vector $\mathbf{p_{(n,m)}} = [p_{(n,m;c_1)}, \ldots, p_{(n,m;c_K)}]$ whose k-th element $p_{(n,m;c_k)}$ is nonzero if and only if $c_k \in \mathcal{C}_{n,m}(\alpha_{min})$. The node then waits for an exponential backoff with mean L/CR_{nm}, where L is the average packet length and the R_{nm} values are node and link dependent quantities function of both the link backpressure and the channels availability. Expressions for setting the values of the R_{nm} values and of $\mathbf{p_{(n,m)}}$ are given below. When the backoff timer expires, if the node senses the channel as free it starts transmission; otherwise, it backs off again. When performing carrier sensing, a SU can find the channel busy either because a conflicting link started transmission, or because a PU is using the same channel.

To compute the R_{nm} values and the vector $\mathbf{p_{(n,m)}}$, each node keeps track of the control variables $\left\{w_{(n,m;c)}, c \in \mathcal{C}_{n,m}(\alpha_{min})\right\}$, representing the scarcity of available capacity of channel c for link (n, m). For each link and each channel, $w_{(n,m;c)}$ is updated at the beginning of each epoch as follows:

$$w_{(n,m;c)}^{(k)} = \left[w_{(n,m;c)}^{(k-1)} + \gamma\left(r_{(n,m;c)}^{(k-1)} - (\alpha_{(n,m;c)} - \epsilon)\right)\right]^+ \qquad (13)$$
$$c \in \mathcal{C}_{n,m}(\alpha_{min}),$$

where $r_{(n,m;c)}^{(k-1)}$ is the (normalized) average transmission rate over channel c during epoch $k-1$ and $\epsilon > 0$ is a small constant whose introduction will be justified in Appendix A of the supplemental document. $w_{(n,m;c)}$ increases when $r_{(n,m;c)} > \alpha_{(n,m;c)} - \epsilon$, *i.e.*, when the fraction of unused (by both PUs and SUs) channel c bandwidth $\alpha_{(n,m;c)} - r_{(n,m;c)}$ is smaller than ϵ, and decreases when $\alpha_{(n,m;c)} - r_{(n,m;c)} > \epsilon$. For instance, if $\alpha_{(n,m;c)} = 0.8$ and $\epsilon = 0.1$, $w_{(n,m;c)}$ increases when the (normalized) transmission rate $r_{(n,m;c)} > 0.7$ (*i.e.*, when less than 10% of the channel capacity is not used by PUs or SUs) and decreases when $r_{(n,m;c)} \le 0.7$ (*i.e.*, when more than 10% of the channel capacity is unused). $w_{(n,m;c)}$ can be thus regarded as a measure of the *lack* of spare capacity on channel c with respect to the threshold ϵ. It is easy to realize that $w_{(n,m;c)} = 0$ for channels with high availability, which are are best suited for secondary transmissions. On the other hand, $w_{(n,m;c)}$ takes positive and progressively larger values for channels with progressively lower availability, *i.e.*, those less suited for secondary transmissions.

We indicate with $z_{nm} = \max_{f\in F}(q_{nf} - q_{mf}) = q_{nf^*} - q_{mf^*}$ the maximal backpressure along link (n,m), and define

$$R_{(n,m;c)} = \frac{e^{\beta(z_{nm} - w_{(n,m;c)})}}{\alpha_{(n,m;c)}}\ , \tag{14}$$

where β is a tunable positive constant. Given $R_{(n,m;c)}$, we compute the rate of the exponential backoff timer R_{nm} and the channel probability vector $\mathbf{p_{(n,m)}}$ as follows:

$$R_{nm} = \sum_{c\in\mathcal{C}_{(n,m)}(\alpha_{min})} R_{(n,m;c)} \tag{15}$$

$$p_{(n,m;c)} = \frac{R_{(n,m;c)}}{R_{nm}} \quad c \in \mathcal{C}_{(n,m)}(\alpha_{min})\ . \tag{16}$$

$R_{(n,m;c)}$ can be regarded as the transmission aggressiveness on sublink $(n,m;c)$: the larger its value, the more likely node n will attempt to transmit over channel c on link (n,m).

From (14) and (15), we can observe that R_{nm} grows exponentially with z_{nm}. Moreover, it can be seen that larger values of R_{nm} translate into shorter backoffs, which implies that the protocol gives priority to links with higher queue differential. If we look at the different channels of a given link, we can observe that $R_{(n,m;c)}$, and thus $p_{(n,m;c)}$, is *inversely* proportional to $\alpha_{(n,m;c)}e^{\beta w_{(n,m;c)}}$. This term is dominated by the exponent: the smaller $\alpha_{(n,m;c)}$, the larger $w_{(n,m;c)}$; whereas, for larger $\alpha_{(n,m;c)}$, $w_{(n,m;c)}$ decreases towards 0 (and $\alpha_{(n,m;c)}e^{\beta w_{(n,m;c)}} \approx 1$). As a result, $R_{(n,m;c)}$ is an increasing function of $\alpha_{(n,m;c)}$: channels with low availability (less than ϵ) are in practice not utilized. The rest of the links are used for a fraction of time proportional to $\alpha_{(n,m;c)} - \epsilon$.

- Implementation issues: The implementation of the proposed solution requires peer nodes to exchange control messages for (i) communicating the values of the queue sizes required by the backpressure scheduler, and (ii) making the receiver of each data packet aware of the channel on which the packet will be transmitted. For exchanging control packets we assume a CCC on a dedicated band.[3] The channel is divided into two subchannels, one for queue information exchange and one for RTS-CTSs related to data packets. In particular:

- *Queue length information exchange:* At the beginning of each epoch, each SU broadcasts a packet containing the queue size of each flow passing through it. To avoid collisions, an initial random jitter is used before the first transmission attempt, followed by a CSMA scheme with binary exponential backoff in case the CCC is sensed busy. The exchanged queue values are used to schedule traffic in the next epoch. In case a node does not succeed in sending the queue size updates, its neighbors will use their last available stored values of queues size.[4]

- *RTS/CTS and communication channel synchronization:* RTS/CTS packets are exchanged on the dedicated control channel to synchronize sender/ receiver pairs on the channel to use for data transmission. To this end, the sender piggybacks in the RTS packet the identifier of the communication channel it has selected. The RTS/CTS mechanisms also mitigates the effect of collisions due to propagation delays or hidden terminals. Upon receiving the RTS, the destination node senses the channel specified in the packet and answers with a CTS packet if that channel is free.

Further details on the implementation of the control operations are provided in the supplemental material.

4 Implementation, Simulation Environment, and Performance Evaluation

In this section we detail the ns2-Miracle-based [23] simulation environment, and we evaluate our solution through simulations.

4.1 Simulation Environment

To evaluate the performance of our solution we have implemented it on an extension of the ns2-Miracle simulator [23]. Our simulation environment accurately models PUs, SUs and spectrum sensors. We consider reception errors due to noise, interference, and channel fading, as well as collisions. Besides communication of data packets, we implement: (i) The control plane communication among SUs; (ii) a set of spectrum sensors that probe the channels occupancy (taking into account spectrum sensing errors) and communicate their readings to the SUs, and (iii) a complete multi-channel PNet that includes base stations and mobile terminals and uses a realistic channel adaptive scheduling for its transmissions, thus resulting in a dynamic channel occupation across time, space and frequency. The PNet MAC is organized in time-frequency frames, similar to LTE. Each frame is a grid of Physical Resource Blocks (PRBs). A detailed description of all the components of our simulation environment is provided in Appendix B of the supplemental document.

4.2 Benchmarks

We have implemented benchmark SNet protocol stacks that include MAC, scheduling and routing. Channel access follows a CSMA scheme. Channel selection is performed according to three different "genie aided" schemes. The schemes are assumed to have direct access to the PNet MAC scheduling frame from the nearby PNet base stations (BS), and use it to classify channel availability. The derived channel availability coefficients are then used to assign weights to each channel for a

3. The design of a CCC implementation tailored to CRAHNs is outside of the scope of this paper. See, for instance [25].

4. We have verified that the proposed solution is robust to occasional loss of queue size information.

probabilistic channel selection. The three schemes assign weights in different ways: The first scheme selects the channel randomly and uniformly among the least used available K channels, where K is a pre-defined parameter. The second scheme is similar to the first. However, to consider a channel it requires its availability to be above a pre-defined percentage threshold ϕ. Finally, the third scheme considers the whole sets of channels as eligible, and uses probability weights that are proportional to each channel availability. In all three schemes packets are enqueued and forwarded at each node following a FIFO scheme, regardless of the flow they belong to, and routes for each flow are precomputed shortest paths.

In Section 4.3 we display only results for the best performing benchmarks. Further results are shown in the supplemental document where we vary the benchmarks and we evaluate them in many different scenarios.

4.3 Experimental Results

We have performed simulations to demonstrate that the proposed integrated flow scheduling, MAC, and routing protocols, allow the coexistence of the SNet with the PNet, limiting the performance degradation of PUs within a tolerable level. We consider the following metrics.

M1: **Probability Density Function (PDF) of the interference plus noise power**, measured on a time-slot basis at primary receivers.

M2: **PDF of the PU corrupted bits**, per fragment. A fragment is defined as the set of bits transmitted in a primary PRB. In our simulations, 192 bits can be transmitted in each PRB.

M3: **PU PER:** Packet error rate of the primary user, for different PU traffic loads. We did not consider the implementation of FEC, so as to quantify the direct impact of SU transmissions on the bit errors of PUs.

M4: **SU flow rate:** This is the throughput achieved by the different flows in the secondary CRAHN. This metric is useful to evaluate the data rate achieved by the CRAHN with our scheme, as well as its fairness when considering multiple SU flows.

Metrics M1–M3 are useful to quantify the impact of the CRAHN operation on the performance of PNet communications, whereas M4 allows to evaluate the effectiveness of our scheme in terms of CRAHN throughput. Table 2 summarizes our simulation parameters.

Our simulation scenario includes 1) spectrum sensors organized in a single cluster made up of 37 elements deployed on a regular triangular grid, 2) a cell of the PNet with one BS and 50 mobile PUs and 3) an SNet with 10 SUs. PUs are deployed randomly, whereas SUs are placed according to the topology showed in Figure 2. The SNet transmits 3 multi-hop flows, with source-destination pairs $\langle 5,4\rangle$, $\langle 6,9\rangle$, and $\langle 7,8\rangle$. The routes used by the benchmark system for the three flows are 5-3-2-1-4, 6-2-1-9, and 7-2-3-8. Routes are instead not fixed in our proposed solution, as flows can exploit multiple paths (not showed in Figure 2).

Table 2
Scenario Settings

Parameter	Value
Simulation Duration	60 s
Bandwidth per channel	200 kHz
Number of channels	20
PU Timeframe Duration	10 ms
Slots per Timeframe	20
Allocation Time Interval	0.1 s
PU Packet Size	768 Bytes
Bits per Primary PRB	192 bits
Received data fragments per PU	$\approx 10^6$
Control Channels Rate	600 Kbps
SU Packet Size	32 Bytes
β	10
γ	5
T	0.1
Benchmark protocol exponential backoff window range	$[0,4]$ ms – $[0,64]$ ms

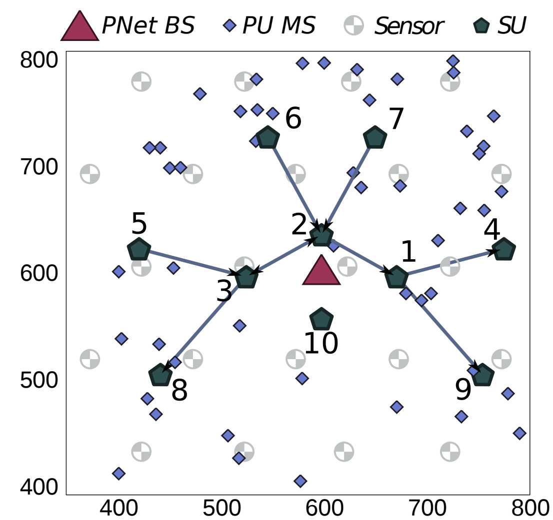


Figure 2. Simulation Topology. Active flows are 5-to-4, 6-to-9, 7-to-8.

Traffic in the SNet is saturated, i.e., every SU tries to fully utilize the available communication resources. Traffic in the PNet is made up of fixed-length packets generated according to a Poisson process. Packet size has been set to 768 Bytes corresponding to the maximum code block size used in the data link layer of LTE. Rather than displaying results as a function of the arrival rate, we show results in terms of PU resource usage (%) with respect to the overall channels capacity. We have varied PU resource usage between 5% and 30%.

In the following, we compare the performance of our solutions to those of the benchmark protocols described in Section 4.2, with the following parameter setting:

Benchmark A: In each epoch, all the SUs contend on the channel that is less utilized by PUs.

Benchmark B: Probabilistic channel selection among the best available $K = 10$ channels, with the further requirement that the availability be above $\phi = 30\%$.

We consider these two benchmarks because among all possible benchmark protocol configurations (listed in the supplemental document), Benchmark A achieves the lowest PU PER, and Benchmark B achieves the best end-to-end throughput.

Figure 3 shows the impact of the SNet on primary communications. In particular, Figure 3a shows the percentage of times that the noise plus interference at a PU is equal to the values on the horizontal axis (expressed in dBW). It can be seen that the tail of the curve of our scheme is lower than the corresponding tail of the benchmark protocols. This means that SUs disrupt primary communications much less frequently when using our scheme than when using the benchmarks, as the disruption happens when interference power exceeds a given threshold. Figure 3b depicts the number of corrupted bits in a MAC fragment, showing how interference turns into corrupted bits. In particular, we display the percentage of fragments whose corrupted bits are exactly equal to the value on the horizontal axis. The figure shows that our scheme is effective in significantly reducing the number of corrupted bits per fragment. Only $0,05\%$ of the fragments experience 10 or more corrupted bits, 20 or more bits are corrupted in $0,027\%$ of the fragments, and 30 or more bits are corrupted in $0,01\%$ of the fragments when running our scheme. These percentages increase to $0,1\%$, $0,07\%$, $0,05\%$ and to $0,2\%$, $0,15\%$, $0,1\%$ for Benchmark A and Benchmark B, respectively.

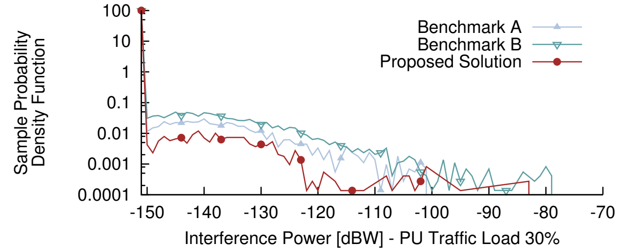
Figure 4 shows the impact of the CRAHN operation on the PNet performance, represented by the PU PER averaged over all the PUs[5]. The curves show PER values in scenarios with: 1) The sole PNet, 2) the PNet and an SNet running our protocol stack, and 3) the PNet and an SNet running the benchmark protocols A and B.

Finally, Figure 5 shows the CRAHN performance in terms of per-flow throughput, measured in Bytes/s.

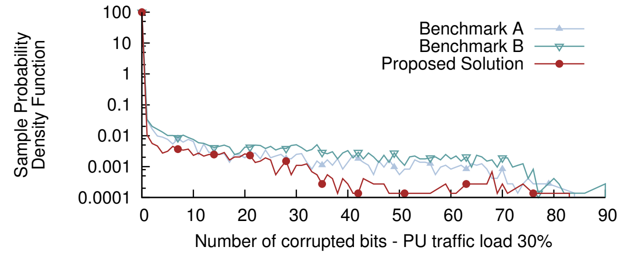
These results confirm that our approach achieves a very good tradeoff between PU performance and CRAHN throughput. Benchmark A has a limited impact on PU performance, interfering only on 0.47% of the PU fragments (Figure 3a) and corrupting at least one bit in 0.2% of the fragments. This results in a 1.5% and 2% PU PER (Figure 4). This limited impact is however paid in terms of very low SU end-to-end throughput, which stabilizes around 150 Bytes per second per flow (Figure 5). Benchmark B has a higher SU average per-flow throughput of 360 Bytes per second (Figure 5). However, it causes a significant PU performance degradation. It interferes with 0.93% of the PU fragments, corrupting at least one bit in 0.32% of the fragments, and results in a PU PER ranging between 4% and 6%.

Our solution outperforms both benchmarks on all relevant metrics: The SU end-to-end throughput converges to around 1200 Bytes per second per flow (three times larger than that of Benchmark A). Interference is limited to 0.15% of PU fragments, resulting in only 0.09% fragments with a corrupted bit. Irrespective of the PU traffic load, the PU PER is always less than 0.95% (0.8% on average) when SUs estimate channel availability coefficients based on their own measurements, and to less then 0.75% (0.69% on average) when they do so with the aid of spectrum sensors.

5. Since a PU packet is composed of 32 fragments, and a corrupted fragment will prevent a correct packet detection, the PU PER is typically much larger than the percentage of disruptive interference or corrupted bits showed in Figure 3b.



(a) Distribution of the interference power realizations - 30% primary traffic load.



(b) Distribution of the number of corrupted bits per PU fragment - 30% primary traffic load.

Figure 3. Interference to PNet (a), and PU bit errors (b).

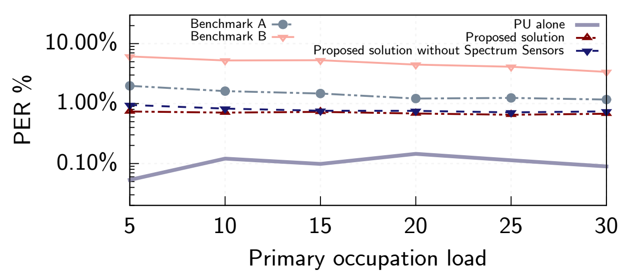


Figure 4. PNet packet error rate vs. PU traffic.

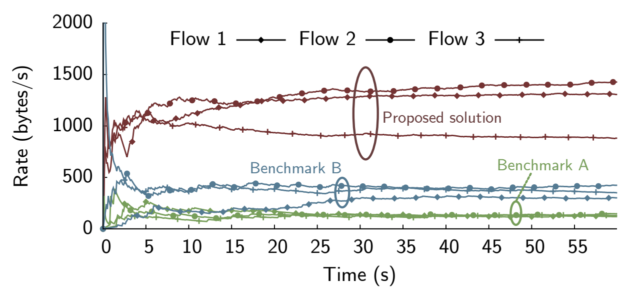


Figure 5. SNet flow rates with 30% PNet traffic load.

These results show that, even in a highly dynamic PU channel occupation regime, our distributed scheme is able to effectively exploit the bandwidth left unused by PUs, induces a limited performance loss on the PUs, and ensures fairness among CRAHN flows.

The average overhead computed as the ratio between the amount of queue-size update packets and data traffic transmitted in network in this case is only 7%.

5 Related Work

A classification of the solutions proposed in the literature for cognitive radio networks can be found in several recent surveys [5]–[8]. While there is a wide range of CR solutions targeting specific aspects of these networks, works that take into account the interplay among the different functions in a cognitive radio system and their implementation are rare.

The combined design of sensing and channel access has been addressed by Zhao et al. [26], [27]. Node collaboration through cooperative sensing is introduced to increase the accuracy in the identification of spectral opportunities and to coordinate channel access. Similar interplay has been recently considered also in [28]–[31]. None of these works, however, considers routing.

Spectrum sharing and decisions are jointly considered in DDMAC [32], a CSMA-like protocol focusing on spectrum and power allocation to CR nodes subject to interference. DDMAC considers the signal attenuation model and the interference conditions to maximize the number of simultaneous CR transmission by optimal channel assignment. To achieve this goal the scheme assigns channels with lower average Signal to Noise plus Interference Ratio (SNIR) to nodes transmitting over shorter distances.

In [33], based on the observed channel usage statistics, Song and Xie propose to use a probability-based PU behavior prediction method to select the transmission channel distributively. An important feature of this method is the absence of CCC.

Cognitive channel access and routing in CRAHNs have been jointly investigated in [34]–[43]. Feng et al. present a heuristic decentralized handoff procedure through which the SUs change the transmission channel before PUs start using it [34]. SUs are assumed to be able to predict incoming PUs without errors, and have the time to complete the channel migration procedure. In this way, the operations of the SUs do not have an impact on PU performance. Such an assumption would require a collaboration between PUs and SUs. As such, it differs from our setup, where the primary detection is performed through spectrum sensing. Chowdhury et al. propose a routing algorithm in which each relay node locally chooses the channel for transmitting to the next hop relay, based on a local objective function expressing the probability of interfering with PU receivers [35]. Such probability is computed using the knowledge of the position of PU transmitters and of the nominal interference region. Similarly to our approach, the technique in [35] allows bypass areas in which the presence of active PU receivers is expected. The work, however, does not deal with the coexistence of multiple flows, and follows the traditional approach of requiring a route selection phase before the establishment of each flow, as opposed to our approach, which does not require a specific route setup. In [36], Xin et al. use CRAHN technology for extending the coverage of an infrastructure-based SNet and propose an admission control scheme to keep the overall amount of interference on PUs under a tolerable level. Differently from our approach, the authors assume an underlay CDMA-based channel access. The SU signal occupies all the primary system bandwidth, but with a very low level of interference per single channel. We instead consider overlay access where the SUs access the wireless channel with the same granularity of the Pus, in the frequency domain. Huang et al. present a routing algorithm for CRAHNs aiming at minimizing the probability that the route will be dropped because of a PU using resources (channel) allocated to one link in the route [37]. The route selection requires a central entity with global knowledge. Coexistence of multiple parallel multi-hop links in the network is not considered.

Multiple flow scheduling in multi-hop multi-channel cognitive radio networks is addressed in [38]–[42]. In these works, under different assumptions and constraints, throughput optimization problems are formulated and optimal or suboptimal algorithms are presented. With respect to our solution, such works do not take advantage of the results of [15] that allows us to derive a fully distributed throughput cross layer design, thus needing to resort to centralized solutions or (suboptimal) heuristics. Finally, all works mentioned so far assume an idealistic spectrum sensing, able to provide timely and error-free information to the cognitive users. When, as in realistic scenarios, this is not the case, the performance of these protocols is likely to significantly degrade.

The dynamics of PU activity are considered in a NUM framework by Ruan and Lau [43]. This work assumes a single frequency channel. In this paper, we evaluate our solution taking into account all system dynamics in a multi-channel scenario.

6 Conclusion

In this paper we have presented a distributed cross-layer framework for the joint optimization of MAC, scheduling, routing and rate control in CRAHNs. The proposed protocols have been devised by first studying a distributed theoretical optimal solution of a suitable NUM problem and then implementing practical MAC and routing mechanisms that allow to handle the non-idealities of practical systems with respect to the assumptions of the theoretical solution. We have evaluated the proposed protocols through extensive simulations, using an extension of the ns2-Miracle simulator that we have developed, including an implementation at the packet level of the PNet, SNet and the supporting WSSN. The results show that our proposed protocols significantly outperform benchmark solutions reducing the performance degradation imposed on the PNet, measured in terms of interference and PER, by one or two order of magnitudes. In presence of up to 30% PU activity the SNet is still able to achieved throughput similar to that obtained with no PU activity at all. In other words, the proposed protocols take full advantage of the unused channels.

Acknowledgement

Part of this work was funded by the "Lazio Region" Italian research project “Design of Spectrum Sensor Networks in support of Cognitive Radio Networks”.

References

[1] NTIA, “United States Frequency Allocation - The Radio Spectrum,” Online available http://www.ntia.doc.gov/osmhome/allochrt.pdf, 2003.

[2] J. Mitola, III and G. Q. Maguire, Jr, “Cognitive radio: Making software radios more personal,” *IEEE Personal Commun. Mag.*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[3] S. Haykin, “Cognitive radio: Brain empowered wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[4] FCC Spectrum Policy Task Force, “Notice of Proposed Rule Making, WT Docket no 00-230, FCC 00-402,” Nov. 2000.

[5] I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury, “CRAHNs: Cognitive Radio Ad Hoc Networks,” *Elsevier Ad Hoc Networks*, vol. 7, no. 5, pp. 810—836, Jul. 2009.

[6] C. Cormio and K. R. Chowdhury, “A survey on MAC protocols for cognitive radio networks,” *Elsevier Ad Hoc Networks*, vol. 7, no. 7, pp. 1315–1329, Sep. 2009.

[7] M. Cesana, F. Cuomo, and E. Ekici, “Routing in cognitive radio networks: Challenges and solutions,” *Elsevier Ad Hoc Networks*, vol. 9, no. 3, pp. 228–248, May 2011.

[8] A. De Domenico, E. Calvanese Strinati, and M.-G. Di Benedetto, “A survey on MAC strategies for cognitive radio networks,” *IEEE Commun. Surveys Tuts.*, vol. 14, no. 1, pp. 21–44, 2012.

[9] F. Kelly, “Charging and rate control for elastic traffic,” 1997.

[10] F. Kelly, A. Maulloo, and D. Tan, “Rate control in communication networks: shadow prices, proportional fairness and stability,” in *Journal of the Operational Research Society*, vol. 49, 1998.

[11] S. H. Low and D. E. Lapsley, “Optimization flow control i: basic algorithm and convergence,” *IEEE/ACM Trans. Netw.*, vol. 7, no. 6, pp. 861–874, Dec. 1999.

[12] S. Kunniyur and R. Srikant, “End-to-end congestion control schemes: utility functions, random losses and ecn marks,” *IEEE/ACM Trans. Netw.*, vol. 11, no. 5, pp. 689–702, Oct. 2003. [Online]. Available: http://dx.doi.org/10.1109/TNET.2003.818183

[13] M. Chiang, S. H. Low, A. R. Calderbank, and J. C. Doyle, “Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures,” *Proceedings of the IEEE*, vol. 95, no. 1, pp. 255–312, Jan. 2007.

[14] L. Tassiulas, “Scheduling and performance limits of networks with constantly changing topology,” *IEEE Trans. Inf. Theory*, vol. 43, no. 3, pp. 1067 – 1073, Mar. 1997.

[15] L. Jiang and J. Walrand, “A Distributed CSMA Algorithm for Throughput and Utility Maximization in Wireless Networks,” *IEEE/ACM Trans. Netw.*, vol. 18, no. 3, pp. 960–972, Jun. 2010.

[16] “Spectrum Sharing - fast-track capacity with Licensed Shared Access,” Ericsson white paper, Oct. 2013. [Online]. Available: http://www.ericsson.com/res/docs/whitepapers/wp-spectrum-sharing.pdf

[17] “U-LTE: Unlicensed Spectrum Utilization of LTE,” Huawei white paper, 2014. [Online]. Available: http://www.huawei.com/ilink/en/download/HW_327803

[18] The Small Cell Forum: http://www.smallcellforum.org.

[19] B. Mercier et al. , “Sensor networks for cognitive radio: Theory and system design,” in *Proc. of ICT Mobile Summit*, June 2008.

[20] S. Subramani, T. Farnham, and M. Sooriyabandara, “Deployment and interface design considerations for radio environment maps,” in *Proc. of IEEE WiMob 2012*, 2012, pp. 480–487.

[21] O. Grøndalen, M. Lättenoja, and P. Grønsund, “Evaluation of Business Cases for a Cognitive Radio Network based on Wireless Sensor Network,” in *Proc. of IEEE DySPAN 2011*, Aachen, Germany, May 3-6, 2011.

[22] L. Pescosolido and C. Petrioli, “Wireless Sensor Networks for Spectrum Sensing to Support Opportunistic Spectrum Access Networks: Protocol Design and Fundamental Trade-offs,” in *Proc. of IEEE WCNC 2011*, Cancun, Mexico, Mar. 31- Apr. 3, 2011.

[23] N. Baldo et Al., “ns2-miracle: a modular framework for multi-technology and cross-layer support in network simulator 2,” in *Proc. of ICST ValueTools 2007*, Brussels, Belgium, 2007, pp. 16:1–8. [Online]. Available: http://dl.acm.org/citation.cfm?id=1345263.1345284

[24] J. Mo and J. Walrand, “Fair End-to-End Window Based Congestion Control,” *IEEE/ACM Trans. Netw.*, vol. 8, no. 5, pp. 556–567, Oct. 2000.

[25] C. Cormio and K. R. Chowdhury, “Common control channel design for cognitive radio wireless ad hoc networks using adaptive frequency hopping,” *Elsevier Ad Hoc Networks*, vol. 8, no. 4, pp. 430–438, 2010.

[26] Q. Zhao, L. Tong, A. Swami, and Y. Chen, “Decentralized Cognitive MAC for Opporutnistic Spectrum Access in Ad Hoc Networks: A POMDP Framework,” *IEEE J. Sel. Areas Commun.*, vol. 25, no. 3, pp. 589–600, Apr. 2007.

[27] Y. Chen, Q. Zhao, and A. Swami, “Joint design and separation principle for opportunistic spectrum access in the presence of sensing errors,” *IEEE Trans. Inf. Theory*, vol. 54, no. 5, pp. 2053–2071, May 2008.

[28] S. Li, Z. Zheng, E. Ekici, and N. Shroff, “Maximizing System Throughput by Cooperative Sensing in Cognitive Radio Networks,” in *Proc. of IEEE INFOCOM 2012*, Orlando, FL, USA, Mar. 25-30, 2012.

[29] X. Sheng, J. Tang, and W. Zhang, “Energy-efficient collaborative sensing with mobile phones,” in *Proc. of IEEE INFOCOM 2012*, Orlando, FL, USA, Mar. 25-30, 2012.

[30] X. Sun, L. Chen, and D. H. K. Tsang, “Energy-efficient Cooperative Sensing Scheduling for Heterogeneous Channel Access in Cognitive Radio,” in *1st IEEE INFOCOM Workshop on Communications and Control for Sustainable Energy Systems: Green Networking and Smart Grids*, Orlando, FL, USA, Mar. 2012.

[31] W. S. Jeon, J. A. Han, and D. G. Jeong, “A Novel MAC Scheme for Multichannel Cognitive Radio Ad Hoc Networks,” *IEEE Trans. Mobile Comput.*, vol. 11, no. 6, pp. 922 –934, june 2012.

[32] H. A. Bany Salameh, M. Krunz, and O. Younis, “Cooperative Adaptive Spectrum Sharing in Cognitive Radio Networks,” *IEEE/ACM Trans. Netw.*, vol. 18, no. 4, pp. 1181–1194, Aug. 2010.

[33] Y. Song and J. Xie, “PROSPECT: A Proactive Spectrum Handoff Framework for Cognitive Radio Networks without Common Control Channel,” *IEEE Trans. Mobile Comput.*, vol. 11, no. 7, pp. 1127–1139, Jul. 2012.

[34] W. Feng, J. Cao, C. Zhang, and C. Liu, “Joint optimization of spectrum handoff scheduling and routing in multi-hop multi-radio cognitive networks,” in *Proc. of IEEE ICDCS 2009*, june 2009, pp. 85–92.

[35] K. R. Chowdhury and I. F. Akyldiz, “CRP: A Routing Protocol for Cognitive Radio Ad Hoc Networks,” *IEEE J. Sel. Areas Commun.*, vol. 29, no. 4, pp. 794–804, Apr. 2011.

[36] Q. Xin, X. Wang, J. Cao, and W. Feng, “Joint Admission Control, Channel Assignment and QoS Routing for Coverage Optimization in Multi-hop Cognitive Radio Cellular Networks,” in *Proc. of IEEE MASS 2011*, Valencia, Spain, Oct. 17-22, 2011.

[37] X. Huang, D. Lu, P. Li, and Y. Fang, “Coolest Path: Spectrum Mobility Aware Routing Metrics in Cognitive Ad Hoc Networks,” in *Proc. of IEEE ICDCS 2011*, Minneapolis, Minnesota, USA, Apr. 20-24, 2011.

[38] Y. T. Hou, Y. Shi, and H. D. Sherali, “Spectrum Sharing for Multi-hop Networking with Cognitive Radio,” *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 146–155, Jan. 2008.

[39] G. Cheng, W. Liu, Y. Li, and W. Cheng, “Joint On-Demand Routing and Spectrum Assignment in Cognitive Radio Networks,” in *Prof. of IEEE ICC 2007*, Glasgow, Scotland, Jun 24–28 2007.

[40] L. Ding, T. Melodia, S. Batalama, and M. Medley, “ROSA: Distributed Joint Routing and Dynamic Spectrum Allocation in Cognitive Radio Ad Hoc Networks,” in *Proc. of ACM MSWiM 2009)*, Tenerife, Canary Islands, Spain, Oct. 2009.

[41] D. Xue and E. Ekici, “Guaranteed Opportunistic Scheduling in Multi-Hop Cognitive Radio Networks,” in *Proc. of IEEE INFOCOM 2011*, Shangai, China, Apr. 10-15, 2011.

[42] M. Pan, C. Zhang, P. Li, and Y. Fang, “Joint Routing and Link Scheduling for Cognitive Radio Networks under Uncertain Spectrum Supply,” in *Proc. of IEEE INFOCOM 2011*, Shangai, China, Apr. 10–15, 2011.

[43] L. Ruan and V. K. N. Lau, “Decentralized Dynamic Hop Selection and Power Control in Cognitive Multi-Hop Relay Systems,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 10, pp. 3024–3030, Oct. 2010.

[44] D. L. Y. Ye, Ed., *Linear and Nonlinear Programming*, 3rd ed., Springer Verlag, 2008.

[45] D. Bertsekas, *Nonlinear Programming*, 2nd ed., Athena Scientific, 1999.

Alessandro Cammarano received the laurea degree with the highest honors in Computer Science in 2010 from the University of Rome La Sapienza. He is currently a PhD student at the Computer Science Department of the same University, and member of the SENSES laboratory. His research interests focus on wireless sensor networks design, cognitive radio networks, energy harvesting wireless sensor networks and energy prediction models.

Francesco Lo Presti is Associate Professor in the Department of Civil Engineering and Computer Science of the University of Roma "Tor Vergata". He received the Laurea degree in electrical engineering and the Doctorate degree in computer science from the University of Rome "Tor Vergata" in 1993 and 1997. His research interests include measurements, modeling and performance evaluation of computer and communications networks. He has more than 60 publications in international conferences and journals. He has served as TPC member of conferences on networking and performance areas, and as reviewer for various international journals.

Gaia Maselli is Assistant Professor in the Computer Science Department at the Sapienza University of Rome - Italy. She received the Laurea Degree in Computer Science and the Ph.D. in Computer Science both from University of Pisa, Italy. She was Postdoc researcher at Sapienza University of Rome. Prior to Rome University, she was junior researcher at Italian National Research Council (CNR) in Pisa. Her research interests focus on architectural and networking aspects of wireless networks. In particular, her current work focuses on the design and evaluation of networking protocols for RFID systems, sensor ad hoc networks, and cognitive radio networks.

Loreto Pescosolido (S'03, M'14) received the MS degree in 2003 and the Ph. D. degree from University of Rome "La Sapienza" in 2008. He currently holds a postdoc position at the Computer Science Department of the same university. His research focus on cognitive radio networks, wireless sensor networks, underwater acoustic communications, cooperative communications. He has been special-session co-chair for the CrownCom 2010 conference, TPC member for several conferences and workshops, and has served as a reviewer for different international scientific journals and conferences. He has worked in several research projects funded by the European Commission including ROMANTIK, SURFACE, FREEDOM, SENDORA, WINSOC, CLAM, GENESI, and SUNRISE.

Chiara Petrioli (S'96, M'98, SM'06) has received the Ph.D. in Computer Engineering from Rome University "La Sapienza," Italy, in 1998. She is currently on faculty at University of Rome La Sapienza Computer Science Department, where she leads the Sensor Networks and Embedded Systems laboratory (SENSES lab). She also leads the Cyber Physical System lab of "La Sapienza" center for Cyber Intelligence and Information Security, and is a founding partner of "La Sapienza" spinoff WSENSE S.r.l. Her research interests focus on the design and optimization of wireless, embedded and cyber physical systems. Prof. Petrioli is member of the steering committee of IEEE SECON and ACM SenSys, general chair of ACM SenSys 2013. She has been member of the steering committee and associate editor of IEEE Transactions on Mobile Computing, associate editor of IEEE Transactions on Vehicular Technology, member of the executive committee of ACM SIGMOBILE, and has been program co-chair of leading conferences in the field such as ACM MobiCom and IEEE SECON. Prof. Petrioli has published over a hundred papers in prominent international journals and conferences (h-index 27, over 3100 citations). She has also been PI of over twenty national and international research projects, and is serving as coordinator of two EC projects (FP7 projects GENESI and SUNRISE). Prof. Petrioli was a Fulbright scholar.