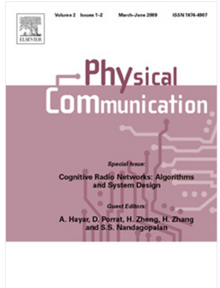
# Accepted Manuscript




Energy-efficient cooperative cognitive relaying schemes for cognitive radio networks

Ahmed El Shafie, Tamer Khattab, Amr El-Keyi

PII: S1874-4907(18)30217-9
DOI: https://doi.org/10.1016/j.phycom.2018.08.006
Reference: PHYCOM 589

To appear in: *Physical Communication*

Received date : 29 April 2018
Revised date : 15 July 2018
Accepted date : 18 August 2018

Please cite this article as: A.E. Shafie, et al., Energy-efficient cooperative cognitive relaying schemes for cognitive radio networks, *Physical Communication* (2018), https://doi.org/10.1016/j.phycom.2018.08.006

# Energy-Efficient Cooperative Cognitive Relaying Schemes for Cognitive Radio Networks

Ahmed El Shafie, *Senior Member, IEEE,* Tamer Khattab, *Senior Member, IEEE,* Amr El-Keyi, *Member, IEEE*

***Abstract*—We investigate a cognitive radio network in which a primary user (PU) may cooperate with a cognitive radio user (i.e., a secondary user (SU)) for transmissions of its data packets. The PU is assumed to be a buffered node operating in a time-slotted fashion where the time is partitioned into equal-length slots. We develop two schemes which involve cooperation between primary and secondary users. To satisfy certain quality of service (QoS) requirements, users share time slot duration and channel frequency bandwidth. Moreover, the SU may leverage the primary feedback message to further increase both its data rate and satisfy the PU QoS requirements. The proposed cooperative schemes are designed such that the SU data rate is maximized under the constraint that the PU average queueing delay is maintained less than the average queueing delay in case of non-cooperative PU. In addition, the proposed schemes guarantee the stability of the PU queue and maintain the average energy emitted by the SU below a certain value. The proposed schemes also provide more robust and potentially continuous service for SUs compared to the conventional practice in cognitive networks where SUs transmit in the spectrum holes and silence sessions of the PUs. We include primary source burstiness, sensing errors, and feedback decoding errors to the analysis of our proposed cooperative schemes. The optimization problems are solved offline and require a simple 2-dimensional grid-based search over the optimization variables. Numerical results show the beneficial gains of the cooperative schemes in terms of SU data rate and PU throughput, average PU queueing delay, and average PU energy savings.**

***Index Terms*—Cognitive radio, rate, queue stability, optimization problems.**

## I. Introduction

Secondary utilization of the licensed frequency bands can efficiently improve the spectral density of the under-utilized licensed spectrum. Cognitive radio (secondary) users are intelligent devices that use cognitive technologies to adapt with variations, and exploit methodologies of learning and reasoning to dynamically reconfigure their communication parameters [2]–[4]. This allows the secondary users (SUs) to utilize the spectrum whenever it is free to use and with the maximum possible data rates.

Cooperative diversity is a recently emerging technique for wireless communications that has gained wide interest [5]–[8] where multiple channels are used to communicate the same information symbol. Recently, cooperation in cognitive radio networks, referred to as the cooperative cognitive relaying, where the SU helps in relaying some of the undelivered primary user (PU) packets, has got extensive attention [9]–[16]. In particular, the SU functions as a relay node for the PU whenever the PU packet cannot be decoded at its destination. The authors of [9] showed that the maximum achievable rate can be achieved by simultaneous transmissions of PU and SU data signals over the same frequency band. The SU data signals are jointly encoded with PU data signals via dirty-paper coding techniques. Hence, the SUs know perfectly the PU's data. In [10], the authors assumed that the SU decodes-and-forwards the undelivered PU packets during the idle periods of the PU. The SU maximizes its throughput by adjusting its transmit power level.

### A. Related Work

In [12], the authors investigated the scenario of deploying a *dumb* relay node in cognitive radio networks to increase network spectrum efficiency. The relay node aids both the PU and the SU. The proposed scheme is investigated for a network consisting of a pair of PUs and a pair of SUs. In [13], the authors considered a network with one buffered PU and one buffered SU where the SU is allowed to access the channel when the PU's queue is empty. The SU has a relaying queue to store a fraction of the undelivered PU packets controlled through an adjustable admittance factor. A priority of transmission is given to the relayed PU packets over the SU own packets. The SU aims at minimizing its average queueing delay subject to a power budget for the relayed primary packets. In [15], the authors characterized some fundamental issues for a wireless shared channel composed of one PU and one SU. The authors considered a general multi-packet reception model, where concurrent packet transmission could be correctly decoded at receivers with a certain probability that is characterized by the system's parameters (e.g., packet length, data rates, time slot duration, bandwidth, etc.). The PU has unconditional channel access, whereas the SU accesses the channel based on the activity state of the PU, i.e., active or inactive, during a time slot. The spectrum sensing process is impractically assumed to be perfect. The SU is assumed to be capable of relaying the undelivered PU packets as in [13]. If the PU is sensed to be inactive during a time slot, the SU accesses the channel with probability one, and if the PU is active, the SU randomly accesses the channel simultaneously with the PU or attempts to decode the primary packet with

Part of this paper was published in the IEEE International Conference on Computing, Networking and Communications (ICNC), 2015 [1].

A. El Shafie (corresponding author) is with Qualcomm Inc., USA (e-mail: aelshafi@qti.qualcomm.com).

T. Khattab is with Electrical Engineering, Qatar University, Doha, Qatar (email: tkhattab@ieee.org).

A. El-Keyi is with Wireless Intelligent Networks Center (WINC), Nile University, Giza, Egypt (aelkeyi@nileuniversity.edu.eg).

The work of T. Khattab is supported by Qatar National Research Fund (QNRF) under grant number NPRP 7-923-2-344. The statements made herein are solely the responsibility of the authors.