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Distributed resource allocation in cognitive and cooperative ad hoc networks through joint routing, relay selection and spectrum allocation ☆

Lei Ding [a,*], Tommaso Melodia [b], Stella N. Batalama [a], John D. Matyjas [c]

[a] *Department of Electrical Engineering, The State University of New York at Buffalo, NY 14260, USA*
[b] *Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115, USA*
[c] *The U.S. Air Force Research Laboratory, RIGF, Rome, NY 13441, USA*

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ABSTRACT

Cooperative relaying and dynamic-spectrum-access/cognitive techniques are promising solutions to increase the capacity and reliability of wireless links by exploiting the spatial and frequency diversity of the wireless channel. Yet, the combined use of cooperative relaying and dynamic spectrum access in multi-hop networks with decentralized control is far from being well understood.

We study the problem of network throughput maximization in cognitive and cooperative ad hoc networks through joint optimization of routing, relay assignment and spectrum allocation. We derive a decentralized algorithm that solves the power and spectrum allocation problem for two common cooperative transmission schemes, decode-and-forward (DF) and amplify-and-forward (AF), based on convex optimization and arithmetic–geometric mean approximation techniques. We then propose and design a practical medium access control protocol in which the probability of accessing the channel for a given node depends on a local utility function determined as the solution of the joint routing, relay selection, and dynamic spectrum allocation problem. Therefore, the algorithm aims at maximizing the network throughput through local control actions and with localized information only.

Through discrete-event network simulations, we finally demonstrate that the protocol provides significant throughput gains with respect to baseline solutions.

1. Introduction

The need to wirelessly share high-quality multimedia content is driving the need for ever-increasing wireless transport capacity, which is however limited by the scarcity of the available spectrum. Cognitive radio networks [2,3] have recently emerged as a promising technology to improve the utilization efficiency of the existing radio spectrum. Based on the reported evidence that static licensed spectrum allocation results in highly inefficient and unbalanced resource utilization, the cognitive radio paradigm prescribes the coexistence of licensed (or primary) and unlicensed (secondary or cognitive) radio users on the same portion of the spectrum. A key challenge in the design of cognitive radio networks is then dynamic spectrum allocation, which enables wireless devices to

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* Corresponding author.

E-mail addresses: leiding@buffalo.edu (L. Ding), melodia@ece.neu.edu (T. Melodia), batalama@buffalo.edu (S.N. Batalama), john.matyjas@rl.af.mil (J.D. Matyjas).

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opportunistically access portions of the spectrum as they become available. Consequently, techniques for dynamic spectrum allocation have received significant attention in the last few years, e.g., [4–7].

However, mainstream cognitive radio research has mostly been focused on infrastructure-based networks, while the underlying root challenge of devising *decentralized spectrum management* mechanisms for infrastru cture-less cognitive ad hoc networks is still substantially unaddressed. In cognitive networks with multi-hop communication requirements the dynamic nature of the radio spectrum calls for a new approach to spectrum management, where the key networking functionalities such as routing and medium access control, closely interact and are jointly optimized with the spectrum management functionality. Since in a spatially distributed ad hoc network spectrum occupancy is location-dependent the available spectrum bands may be different at each hop. Hence, controlling the interaction between the routing, medium access, and the spectrum management functionalities is of fundamental importance.

Within this context, we additionally consider techniques to leverage the *spatial diversity* that characterizes the wireless channel. Spatial diversity is traditionally exploited by using multiple transceiver antennas to effectively cope with channel fading. However, equipping a mobile device with multiple antennas may not be practical. The concept of *cooperative communications* has been hence proposed to achieve spatial diversity without requiring multiple transceiver antennas on the same node [8–10]. In cooperative communications, in their *virtual multiple-input single-output* (VMISO) variant, each node is equipped with a single antenna, and relies on the antennas of neighboring devices to achieve spatial diversity. There is a vast and growing literature on information and communication theoretic problems in cooperative communications. The reader is referred to [11,12] and references therein for excellent surveys of the main results in this area. However, the common theme of most research in this field is to optimize physical layer performance measures (i.e., bit error rate and link outage probability) from a broad system perspective, without modeling in detail how cooperation interacts with higher layers of the protocol stack to improve network performance metrics. For example, [13–16] investigate the achievable rates and diversity gains of given cooperative schemes focusing on a single source and destination pair. Some initial promising work on networking aspects of cooperative communications includes studies on medium access control protocols to leverage cooperation [17,10], cooperative routing [18–22], optimal network-wide relay selection [23,24], and optimal stochastic control [25]. However, decentralized spectrum management with cooperative devices is a substantially unexplored area.

In this paper, we consider an infrastructure-less ad hoc network (illustrated in Fig. 1) of devices endowed with wideband reconfigurable transceivers that communicate without an infrastructure and can potentially coexist with (i) legacy narrowband unlicensed devices (e.g., IEEE 802.11, IEEE 802.15.4, Bluetooth transceivers), and (ii) primary users operating on licensed portions of the spectrum. We make the following contributions:

- *Uncoordinated spectrum management.* Unlike mainstream work on cognitive ad hoc networks, we consider a distributed and dynamic environment, and study the interactions between cooperation and spectrum management.
- *Distributed joint routing, relay selection, and dynamic spectrum allocation.* We formulate a joint routing, relay selection, and dynamic spectrum allocation problem, with the objective of maximizing the network throughput. Given the centralized nature and computational intractability of the problem, we study decentralized and localized algorithms for joint dynamic routing, relay assignment, and spectrum allocation that are designed to maximize the global objective function of the centralized problem.
- *Spectrum and power allocation algorithms for two common cooperative schemes.* We propose spectrum and power allocation algorithms for two alternative cooperative relaying schemes, decode-and-forward (DF) and amplify-and-forward (AF), which are building blocks of the distributed resource allocation algorithm. We compare the link capacity achievable by the two cooperative schemes, and show that DF outperforms AF in general.
- *Mapping local to global objectives through stochastic channel access.* We propose a practical implementation of the proposed algorithm based on a medium access control protocol that relies on a common control channel and a frequency-agile data channel. In the proposed medium access control protocol, the probability of accessing the channel, and therefore of having priority in reserving spectrum resources and relays, depends on a utility function determined as the local solution, for each individual node, of the joint routing, relay selection, and dynamic spectrum allocation problem. The protocol can be seen as a hybrid between traditional contention-based protocols and utility-based scheduled channel access schemes.

The rest of the paper is organized as follows. In Section 2, we review related work. In Section 3, we introduce the system model. In Section 4 we formulate the cross-layer optimization problem. In Section 5, we discuss link capacity maximization with and without cooperative relays. In Section 6, we introduce the decentralized algorithm for joint routing, relay selection and dynamic spectrum allocation. Section 7 discusses the cooperative MAC/routing protocol design and addresses implementation details. In Section 8 we evaluate the performance of the proposed protocol. Finally, Section 9 concludes the paper.

2. Related work

Cooperative transmission has mainly been addressed at the physical-layer, i.e., by studying the achievable rates or