A CROSS-LAYER APPROACH TO COGNITIVE MAC FOR SPECTRUM AGILITY

Qing Zhao, Lang Tong, and Ananthram Swami

ABSTRACT

Opportunistic spectrum access aims to exploit the instantaneous spectrum availability using sophisticated signal processing and networking techniques. Cognitive MAC that enables instantaneous detection and efficient utilization of spectrum opportunities is one of the key components of opportunistic spectrum access. In this paper, we pursue a cross-layer approach that integrates opportunity assessment and opportunity allocation for optimal spectrum utilization. We develop optimal cognitive MAC protocols for multihop ad hoc networks.

1. INTRODUCTION

Sensor networks present new challenges ranging from physical layer communications to higher layer network protocols. There is a growing body of literature addressing these challenges. Perhaps one crucial issue that has not received enough attention is the integration of sensor networks into the existing communication infrastructure. For sensor networks deployed in an urban environment where the wireless medium is already crowded with cellular, WiFi and WiMAX, bluetooth, and the envisioned ultra wideband networks, can we find enough spectrum to host large sensor networks deployed for various applications?

The current state of spectrum allocation indicates that almost all usable frequencies have already been occupied. This makes one pessimistic about the feasibility of concepts such as sensors as smart dust interacting between the human and the natural world; there is simply not enough usable spectrum to host large sensor networks deployed for various applications. Furthermore, it is questionable whether allocating expensive bandwidth to sensors is economically justified. For certain applications in disaster relief and emergency response, sensors may need to be deployed rapidly without prior spectrum assignment. All these factors make the current static spectrum allotment policy inadequate for the seamless integration of large sensor networks.

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In contrast to the apparent spectrum scarcity is the pervasive existence of spectrum opportunity. Extensive measurements indicate that, at any given time and location, a large portion of licensed spectrum lies unused. For example, over % of white space exists in the spectrum below GHz [1]. These measurements of actual spectrum usage provide the key rationale for opportunistic spectrum access (OSA) envisioned by the DARPA XG program [2]. The idea is to exploit instantaneous spectrum availability by opening licensed spectrum to secondary users. This would allow secondary users (*e.g.,* sensors) to identify available spectrum resources and communicate in a manner that limits the level of interference perceived by the primary users.

While conceptually simple, OSA requires sophisticated MAC protocols coupled with advanced signal processing techniques for spectrum sensing and spectrum access. There have been several attempts on developing cognitive MAC for OSA networks [3–7]. These techniques, assuming continuous full-spectrum sensing, decompose OSA into two separate problems: opportunity identification and opportunity allocation among secondary users. The disadvantages of this approach are energy inefficiency and hardware requirement of continuous full-spectrum sensing, especially when the traffic of the secondary users is bursty.

Another approach to OSA is based on partial spectrum monitoring. Limited by hardware complexity and constrained by energy supply, a secondary user must decide which subset of possible channels to sense and which subset of available channels to access based on the sensing outcome. Under this formulation, optimal channel sensing and access strategies rely on intelligent sequential decision making that exploits the spectrum occupancy statistics and the decision and observation history. In [8], optimal and reduced-state suboptimal strategies are proposed by formulating OSA as a partially observable Markov decision process (POMDP). The focus of [8] is the theoretical formulation and characterization of decentralized OSA in fully connected networks. In this paper, we focus on the protocol implementations of the channel sensing and access strategies developed in [8] and address issues that are unique to multihop ad hoc OSA networks.

The rest of the paper is organized as follows. In Section 2 we state the network model and the design objective. A brief review of the channel sensing and access strategies developed in [8] is given in Section 3. In Section 4, we identify the MAC design issues arising in multihop ad hoc OSA networks and specify the protocol implementations. Concludes are provided in Section 5.

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14. ABSTRACT
Opportunistic spectrum access aims to exploit the instantaneous spectrum availability using sophisticated signal processing and networking techniques. Cognitive MAC that enables instantaneous detection and efficient utilization of spectrum opportunities is one of the key components of opportunistic spectrum access. In this paper, we pursue a crosslayer approach that integrates opportunity assessment and opportunity allocation for optimal spectrum utilization. We develop optimal cognitive MAC protocols for multihop ad hoc networks.

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2. PROBLEM STATEMENT

Consider N channels[1] each with bandwidth B_i (i $, \cdots, N$). These N channels are shared among primary users and a large number of secondary users seeking spectrum opportunities. The traffic statistics of the primary users are such that these N channels are synchronous and slotted. We also assume that the spectrum usage statistics remain unchanged for T slots. The energy and hardware constraints restrict the secondary users from monitoring more than one channel within one slot.

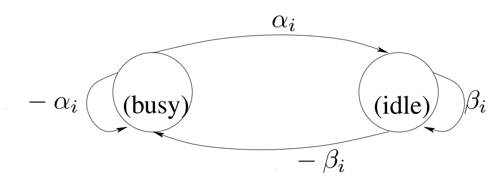

Fig. 1: The Markov channel model

We focus on a decentralized multihop ad hoc network where a large number of secondary users join/exit the network and sense/access the spectrum independently without exchanging local information. We assume that when the network reaches a steady-state, each channel presents itself as an opportunity to a secondary user according to a Markov process. As illustrated in Figure 1, channel states are represented by (busy) and (idle thus available to the secondary user). State transitions occur at the beginning of each slot with transition probabilities given by $\{\alpha_i, \beta_i\}$ (i $, \cdots, N$).

The design objective is to develop an optimal OSA strategy that maximizes the average number of bits transmitted by the secondary user in T slots. Specifically, we seek the optimal OSA protocol for the secondary user to determine in each slot which channel to monitor and subsequently access so that the average number of bits transmitted in T slots is maximized. We focus on specific protocol implementations under a multihop ad hoc setting.

3. OSA STRATEGIES FOR FULLY CONNECTED NETWORKS

In this section, we review the channel sensing and access strategies developed in [8].

3.1. The POMDP Formulation and The Optimal Strategy

The system of N channels given in Section 2 can be modelled by a discrete-time Markov chain with M ^{N} states where the state is defined as the availability of each channel. The transition probability $p_{i,j}$ can be readily obtained from $\{\alpha_i, \beta_i\}_{i=1}^N$. Since in each slot, the user can only select one channel to monitor, the state of the system is only partially observable. The problem of designing an OSA protocol that maximizes the transmission rate in T slots can then be formulated as a POMDP over a finite horizon. Specifically, at the beginning of a slot, the system state transits according to $p_{i,j}$. According to a chosen action a which specifies the channel to be sensed in this slot, the user senses the channel and transmits if it decides that the chosen channel is available. The result of channel sensing is given by $_{j,a} \in \{ \ , \ \}$ which indicates the availability of the chosen channel a when the network is at state j. A reward $w_{a,\theta}$ given by the number of transmitted bits when the observation is θ under action a is obtained at the end of this slot. Let R_a be the transmission rate over channel a when it is available. We then have $w_{a,\theta}$ θR_a. Under this formulation, the optimal OSA protocol is given by the optimal policy (in terms of maximizing the expected reward in T slots) of this POMDP.

Since the underlying Markov process is only partially observable, the internal state of the system is unknown. Our knowledge of the internal state of the system based on all the past decisions and observations can be encoded as an information vector π $\pi_1, \cdots, \pi_M$ where π_i is the conditional probability (given all the past sensing history) that the state of the system is i at the beginning of the current slot prior to the state transition.

It has been shown in [9] that at any time the information vector π is a sufficient statistic for the optimal policy. Let $V_n(\pi)$ denote the maximum expected reward that can be accrued in the remaining n slots when the current information vector is π. We can obtain the following Bellman's equation for $V_n(\pi)$.

$$V_n(\pi) \quad {}_{a=1,\cdots,N}\{\sum_{i=1}^{M} \pi_i \sum_{j=1}^{M} p_{i,j} \sum_{\theta=0}^{1} \quad {}_{j,a} \quad \theta$$

$$(\theta R_{j,a} + V_{n-1}(\mathcal{T}(\pi|a,\theta)))\}, \qquad (1)$$

where $\mathcal{T}(\pi|a,\theta)$ is the a posterior information vector based on observation θ and action a. The a posterior information vector $\mathcal{T}(\pi|a,\theta)$ can be easily obtained via Bayes' rule. It is shown in [9] that $V_n(\pi)$ is piecewise linear and convex, leading to a linear programming procedure for calculating the optimal policy and the corresponding expected reward.

3.2. A Sufficient Statistic with Reduced Dimension and A Suboptimal Strategy

The computational complexity of the optimal strategy presented above grows *exponentially* with the number N of channels. It is thus crucial to exploit the specific structure of the problem at hand. In [8], it is shown that when channels evolve independently, we can find a sufficient statistic for the optimal policy whose dimension grows *linearly* with

[1] Here we use the term channel broadly. A channel can be a frequency band with certain bandwidth. It can also be a collection of spreading codes in a CDMA network or a set of tones in an OFDM system.

N. Specifically, let $\lambda_1, \cdots, \lambda_N$ where λ_i is the probability that channel i is available to the secondary user. Then at any time, is a sufficient statistic for the optimal policy.

Based on the sufficient statistic , a suboptimal strategy using a greedy approach that maximizes per-slot throughput is developed in [8]. The optimal action a_* and the update of are given by

$$a_* \qquad {}_{a=1,\cdots,N}(\lambda_a\beta_a + (\;\; - \lambda_a)\alpha_a)R_a$$

$$\mathcal{T}_i(\; |a,\theta) \qquad \begin{cases} & \text{if } a \quad i, \theta \\ & \text{if } a \quad i, \theta \\ \lambda_i\beta_i + (\;\; - \lambda_i)\alpha_i & \text{if } a \; / \; i \end{cases} \qquad (2)$$

where $\mathcal{T}_i(\; |a,\theta)$ is the ith entry of the updated information on channel availability given observation θ under action a.

4. PROTOCOL RAMIFICATIONS FOR MULTIHOP AD HOC NETWORKS

In this section, we focus on the protocol implementations of the channel sensing and access strategies presented in Section 3. We first identify MAC issues unique to OSA in a multihop ad hoc network. A decentralized cognitive MAC protocol is then developed to address these issues.

4.1. Challenges in Multihop Ad Hoc OSA Networks

MAC design in multihop ad hoc networks is a complex issue, largely due to the presence of hidden and exposed terminals. While research in this area is extensive, OSA further complicates the problem. Since secondary users cannot exchange local information before agreeing on a communication channel, coordinating transmissions among secondary users becomes more challenging. Below we examine several key issues in MAC design for multihop ad hoc OSA networks.

Collision with Primary Users A central design constraint on OSA protocols is the interference perceived by the primary users. MAC and power control for OSA should ensure that the occurrence of collisions between primary and secondary users is bounded below a tolerable level specified by the primary network.

Initial Handshake and Transceiver Synchronization The transmitter and the receiver need to tune to the same channel in order to communicate, and they need to hop synchronously. The synchronization problem can be separated into two phases: the initial handshake between the transmitter and the receiver and the synchronous hopping in the spectrum after the initial establishment of communication.

Spectrum Opportunity Identification At the beginning of each slot, the transmitter and the receiver select a channel to sense in order to determine whether it is an opportunity for communication. In a multihop ad hoc network, a spectrum opportunity cannot be identified at the transmitter alone; a channel that is idle at the transmitter may not be idle at the receiver. As illustrated in Figure 2 where primary and secondary users are indicated by squares and dots, respectively, the state (busy or idle) of the selected channel at the transmitter A is determined by the transmission activities within A's receiving range r while the state of the channel at the receiver B is determined by nodes within B's receiving range. As a consequence, spectrum opportunities (channels available at both the transmitter and the receiver) need to be identified by the transmitter and the receiver jointly.

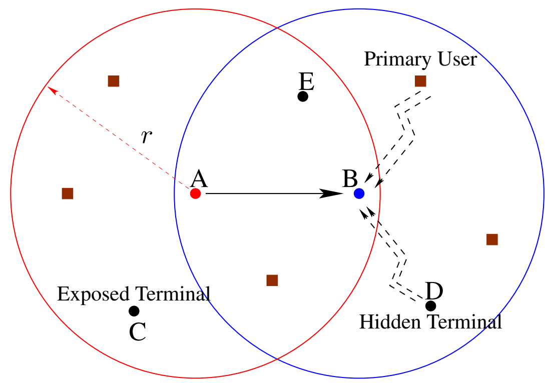

Fig. 2: A multihop ad hoc OSA network.

Hidden and Exposed Terminals The presence of hidden and exposed terminals is a classical problem in MAC design for multihop ad hoc networks. In an OSA network as illustrated in Figure 2, hidden terminals are secondary users within the receiver's range but outside the transmitter's range (for example, D) while exposed terminals are secondary users within the transmitter's range but outside the receiver's range (for example, C). Since hidden terminals can cause collision and exposed terminals may lead to wasted opportunities[2], the ability to deal with hidden and exposed terminals is crucial to the efficiency of OSA protocols.

4.2. A Decentralized Cognitive MAC Protocol

We propose here a CSMA-based cognitive MAC protocol to address the issues stated in Section 4.1. The basic structure of the protocol is first presented assuming perfect carrier sensing. We then discuss implementation details in the presence of collisions.

[2] If C chooses to sense the channel used by A, C concludes that the channel is not available thus refrains from transmitting. This leads to a wasted opportunity since C's transmission will not interfere with the communication between A and B.

4.2.1. *The Slot Structure*

We assume that channels are slotted, and the slot timing is broadcasted[3]. The beginning of each slot is dedicated for opportunity identification via channel sensing. If the channel is identified as an opportunity, the transmitter transmits data. At the end of the slot, the receiver acknowledges a successful data transmission. The basic slot structure is illustrated in Figure 3.

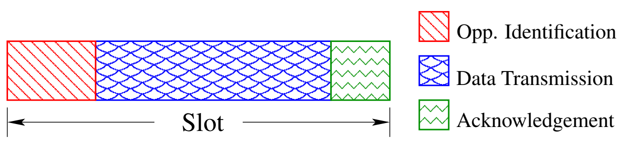

Fig. 3: The slot structure.

4.2.2. *The Protocol Structure*

Assuming perfect carrier sensing, we present here the basic protocol structure with the help of Figure 4. Suppose that the initial handshake has been established and the transceiver synchronization maintained. At the beginning of a slot, the transmitter and the receiver choose, according to the channel selection strategies presented in Section 3, the same channel to sense. Specifically, the transmitter generates a random backoff time and monitors the channel. If the channel remains idle when its backoff time expires, it transmits a short request-to-send (RTS) message to the receiver, indicating that the channel is available at the transmitter. The receiver, upon receiving the RTS, replies with a clear-to-send (CTS) message if the channel is also available at the receiver. A successful exchange of RTS-CTS completes the identification of a spectrum opportunity. A data packet is then transmitted. A successful data transmission is acknowledged at the end of the slot. Based on this basic protocol structure, we address below the major issues identified in Section 4.1.

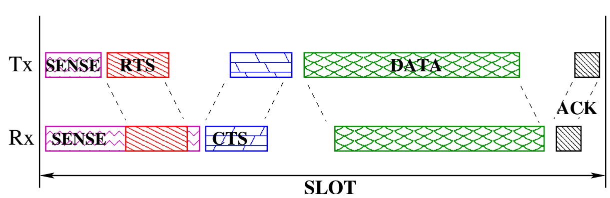

Fig. 4: The protocol structure.

Collision with Primary Users To give the primary users the highest priority in channel access, we impose a minimum value on the backoff time of secondary users. The primary users can claim the slot before the secondary users start sensing. The choice of the minimum backoff time for secondary users depends on the propagation delay among neighboring nodes and how much the network can tolerate interference from secondary users.

Furthermore, to ensure that a secondary user can sense the transmissions of the primary users with whom it may interfere, the transmission power of secondary users should be no larger than that of the primary users. In other words, the transmission range r of secondary users should be upper bounded by that of the primary users. We assume here that a secondary user (only) interferes with the primary users within its transmission range r and the transmissions of a primary user can only be accurately detected by nodes within the range of the primary user. We pointed out that this power control scheme may not guarantee accurate channel sensing in a severe fading environment. Discussions on channel sensing under fading can be found in [10].

Initial Handshake and Transceiver Synchronization There are a number of implementations to facilitate the initial handshake. Here we borrow the idea of receiver-oriented code assignment in CDMA ad hoc networks [11]. Specifically, each secondary user is assigned a set of channels (not necessarily unique) which it monitors regularly to check whether it is an intended receiver. A user with a message for, say, user B will transmit a handshake signal over one of the channels assigned to B. Once the initial communication is established, the transmitter and the receiver will implement the same channel sensing and access strategies presented in Section 3. Assuming perfect carrier sensing which eliminates collision among secondary users, the transmitter and the receiver obtain the same observation θ on the selected channel, which leads to the same updated information vector ($\mathcal{T}(\pi|a,\theta)$ or $\mathcal{T}(\_\,|a,\theta)$). The transmitter and the receiver are then synchronized.

Hidden and Exposed Terminals The RTS-CTS exchange has dual functions. Besides facilitating opportunity identification, it also mitigates the hidden and exposed terminal problem. Specifically, a hidden terminal refrains from transmission when it detects a transmission of CTS while an exposed terminal attempts to capture the channel if it detects RTS but not CTS. Under perfect carrier sensing, wasted spectrum opportunities and collisions among secondary users are avoided.

4.2.3. *In the Presence of Collisions*

Under significant propagation delay, carrier sensing cannot eliminate collision among secondary users. Several secondary users may attempt to capture the same idle channel by transmitting RTS or CTS simultaneously, leading to unsuccessful transmissions of RTS/CTS. Since opportunity identification is carried out through RTS-CTS exchange, our concern here is whether we can maintain the same information vector updates at the transmitter and the receiver (consequently the

[3] The slot information can be broadcasted by the primary users.

transceiver synchronization) in the presence of collisions.

Consider the impact of collision on the synchronization between nodes A and B (see Figure 2). Collisions may occur during the transmission of RTS, CTS, or data as a result of concurrent transmissions by a hidden node (for example, D), an exposed node (for example, C), or a node in the common coverage area of A and B (for example, E). In Table 1, we consider each possible scenario and list the resulted observation θ at both A and B. From Table 1 we see that collisions do not affect the synchronization between the transmitter and the receiver. Note that when a collision occurs during the data transmission, node A will not receive the acknowledgement. Both A and B use θ to update the information vector and maintain the synchronization.

	Hidden (D)	Exposed (C)	Common (E)
RTS	θ	RTS successful	θ
CTS	CTS successful	θ	will not occur
Data	θ	θ	will not occur

Table 1: In the presence of collisions

5. CONCLUSION

We have presented a protocol framework for decentralized cognitive MAC for opportunistic spectrum access. The protocol is based on carrier sensing that allows proper assignment of priorities among primary and secondary users.

The proposed approach can be extended in a number of areas. Existing MAC protocols for ad hoc networks can be easily incorporated into our framework. Opportunistic communication techniques based on channel realizations are also compatible with our framework.

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