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Dynamic Markov-Chain Monte Carlo Channel Negotiation for Cognitive Radio

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***Abstract*—In ad hoc cognitive radio (CR) networks, channel negotiation and access have been raised as challenging issues due to its highly dynamic nature and strong user diversity, particularly in situations where a dedicated common control channel is not reserved among the distributed CR nodes. In this paper, a novel stochastic channel negotiation algorithm is proposed for improving spectrum sharing efficiency in the CR networks. The paper first formulates the problem of channel selection for negotiation, aiming to maximize the probability of successful channel negotiation. The formulated optimization problem is then solved using a dynamic Markov-Chain Monte-Carlo (MCMC) scheme. Simulation is conducted to examine the performance of the proposed approach and demonstrate its merits. We have witnessed that the proposed approach can serve as an excellent complementary to the CR networks in which dedicated control channels are not defined.**

I. Introduction

Cognitive radio (CR) has been envisioned as a promising approach to solving the scarce resources problem by opportunistically accessing the spatiotemporally available spectrum from other networks for the purpose of ubiquitous wireless communications anytime and anywhere. In the context of channel access, the CR nodes must deal with the dynamic and opportunistic nature of media access, as well as situations where dedicated common control channels may not always be available. In this case, an important issue associated with channel access for the distributed CR nodes is how to efficiently reach an agreement on a set of available channels upon which data transmission can take place. The negotiation process has to be fast while considering network states in order to achieve high efficiency and accuracy.

The presence of a dedicated common control channel in multi-channel networks has been a general assumption employed by the research community, even in most recently reported media access control (MAC) protocols for CR networks [1]- [5]. The dedicated control channel can be in a form of reserved resources, such as frequency bands and time slots. The most popular class of channel negotiation approaches are those that use particular frequency bands as dedicated control channels [6]- [8]. Channel negotiation is performed on the pre-defined control channels before media access and data transmission take place. Another type of algorithms with dedicated control channels are those which utilize reserved time slots [9]- [11], where time is sub-divided into beacon intervals such that channel negotiation is performed at the beginning of each beacon interval. The exchanged channel selection information during the beacon intervals are then used to aid in the channel negotiation process between the transmission pairs. Variations of this approach have been proposed to improve the efficiency of time usage by adapting time window sizes based on network traffic [10] and signal-to-interference plus noise ratio (SINR) at the receiver [11].

To handle the scenario without any dedicated control channel, channel hopping [12], [13] has been proposed as an alternative approach, where each node follows a set of multi-channel hopping sequences in an attempt to select a common channel with the intended receiver without the need for a dedicated control channel. While such approaches hold great potential in alleviating the need to reserve resources for dedicated control channels in the channel negotiation process, current approaches exhibit important drawbacks when being applied to CR networks - they rely on fixed hopping sequences generated from simple hashing functions [12] or pseudo-random hopping sequences [13]. However, such hopping sequences do not consider the underlying channel availabilities of the network environment, and as such do not account for the highly dynamic nature of CR networks. This will certainly lead to poor performance in the channel negotiation process of CR systems as transmission pairs are unable to negotiate with each other in a timely manner due to poor hopping sequences.

We envision that the static and blind assignment of common control channels or channel sequences will not meet the design premise of highly dynamic CR networks. It may not only limit the prevalence and ubiquitousness of CR network development, but also degrade the system performance due to possibly long latency in channel access. Note that future heterogeneous wireless networks may accommodate devices of different vendors and even protocol stacks, such that the pre-defined common control channels will significantly reduce flexibility and interoperability of such systems. Thus in this work, we take the assumption that dedicated control channels are not available, and propose a novel channel negotiation scheme via a dynamic stochastic sequencing approach. With the proposed scheme, channels used for negotiation between CR peers are dynamically determined according to the network environment. In specific, the proposed scheme manipulates a dynamic Markov-Chain Monte Carlo (MCMC) method for selecting channels to negotiate and access in order to achieve high success rates in channel negotiation. We will demonstrate via extensive simulation that the proposed scheme can achieve comparable performance with that by the channel negotiation

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approaches with dedicated control channels, while achieving noticeably improved performance when compared with existing channel hopping approaches. Finally, we conclude that the proposed scheme is positioned as a value-added complement to the state-of-the-art multi-channel CR systems.

The rest of this paper is organized as follows. The problem statement is presented in Section II. The proposed channel negotiation method is described in Section III. The numerical performance evaluation is presented in Section IV. Finally, conclusions are drawn and future work are discussed in Section V.

II. Problem Statement

A. System Model

In the study, users with CR capabilities (i.e., secondary users) can utilize spatially and/or temporally available spectrum resources from other networks to communicate with other CR nodes when their own network does not have sufficient spectrum resources. The secondary users then form an ad-hoc network without using reserved dedicated control channels.

Consider a set of M non-overlapping channels $\{\mathbf{CH}|CH_i, i = 1, 2, ..., M\}$ over the spectrum that can be accessed by N_s secondary users who may seek the spectrum opportunities. Let $\mathcal{T}$ be a sequence of time instances, where each element $t \in \mathcal{T}$ stands for a time instance at which a negotiation takes place. Let $\mathcal{S} = \{S_t|t \in \mathcal{T}\}$ be a sequence of channels, which is a random field on $\mathcal{T}$, where S_t is a random variable. Let $s = \{s_t|t \in \mathcal{T}\}$ denote the realization of $\mathcal{S}$, which is the channel that is actually selected for negotiation at t. Spectrum sensing is performed over the M channels by way of energy detection. With a Rayleigh fading channel model, given a certain probability of false alarm, P_f, the average detection probability can be approximated as [14]

$$\bar{P}_d(S_t) = \frac{1}{\bar{\omega}} \int_0^\infty \int_{N_0 B(1+\frac{Q^{-1}(P_f)}{\sqrt{M}})}^\infty f(u_{s_t}) \exp(-\frac{\omega}{\bar{\omega}}) du_{s_t} d\omega, \quad (1)$$

where ω and $\bar{\omega}$ are the instantaneous signal-to-noise ratio (SNR) and average SNR, respectively; N_0 denotes the one-sided noise power spectral density (PSD), B is the signal bandwidth, $Q(\cdot)$ is the Q function, M is the number of samples, and $f(u_{s_t})$ is the probability density function (PDF) of test statistics u_{s_t}.

In order to mitigate the vicious effect due to imperfect channel availability information obtained through the spectrum sensing process, the goal of channel negotiation is to efficiently identify and establish commonly available channels between a pair of CR nodes. With the commonly available channels, channel access can be subsequently initiated between the CR pair.

B. Problem formulation

In the scenario without pre-defined common control channels, a fundamental question is how to dynamically and adaptively find common available channels between communication pairs. Specifically, our target is to identify the optimal channel sequence for a secondary transmitter to negotiate with the intended secondary receivers given the channel negotiation time limitation t_{max}, such that the probability of successful channel negotiation of the selected channels is maximized.

Let $\mathcal{Y} = \{Y_s|s \in \mathcal{S}\}$ be a random field on $\mathcal{S}$, where Y_s is a binary indicator on the result of channel negotiation s such that $Y_s = 0$ and $Y_s = 1$ indicates a failed and successful channel negotiation, respectively. The problem of selecting channels for negotiation can be formulated as the determination of an optimal sequence of channels, denoted as $s_{t_1}, s_{t_2}, \cdots, s_{t_j}$, for channel negotiation at time λ, such that the joint probability of successful negotiations on the selected channels is maximized given the channel negotiation time limitation t_{max}. Therefore, the problem of determining the optimal sequence of channels for channel negotiation can be formulated as

$$\{\hat{s}_{t_1}, \cdots, \hat{s}_{t_j}\}_\lambda = \underset{s_{t_1}, \cdots, s_{t_j}}{\arg\max} \left\{ P(Y_{s_{t_1}} = 1, \cdots, Y_{s_{t_j}} = 1) \right\}, \quad (2)$$

where $\lambda \leq t_1 <, ..., < t_j \leq \lambda + t_{\max}$.

A straightforward approach to solving this optimization problem is to identify a sequence of channels sorted according to their channel availabilities, and have the system negotiate on the channel with a higher availability first in order to increase the likelihood of successful channel negotiation. However, it is extremely hard, sometimes even impossible, to have sufficient knowledge on the availability of each channel in order to determine an optimal sequence of channels due to the highly dynamic environment of CR networks and imprecision of the sensing process. As such, a close-form solution to this problem is not possible. In this study, we propose a novel method in solving the above problem via a Markov-Chain Monte-Carlo (MCMC) method, given the partial knowledge of channel availability such as imperfect energy detection results. MCMC is a meta-heuristic approach designed to draw a sequence of samples that follows a target distribution in a stochastic manner. While this approach does not provide perfect accuracy, it is very efficient and can provide feasible solutions in a highly dynamic environment such as CR networks.

III. Proposed Channel Negotiation Method

A. Dynamic Markov-Chain Monte-Carlo Channel Negotiation

Let the average detection probability at time $t = \lambda$ be denoted as $\bar{P}_d(S_\lambda)$, as given by Eq. (1). Let $P(S_\lambda)$ denote the probability of channel availability at time $t = \lambda$ relative to the channel availabilities of all M channels across the spectrum being considered. $P(S_\lambda)$ can be taken as the best approximation of probability mass function (PMF) for the channel availability, which follows the following relationship:

$$P(S_\lambda) = \bar{P}_d(S_\lambda)/K, \quad (3)$$

where K is a normalizing constant.

In the proposed scheme, the sequence of channels for negotiation can be formed by simply sampling on the random field based on $P(S_\lambda)$. However, this will be a big challenge in a dynamic environment where network state changes rapidly. To achieve a fast yet precise sampling on $P(S_\lambda)$, we propose to use the Metropolis-Hastings algorithm [15], which takes advantage of an acceptance-rejection sampling approach according to a proposal density function $Q(S_\lambda)$. Specifically, $P(S_\lambda)$ is taken as a dominating function over the target density, and a sequence of channels $\{s_{t_1}, s_{t_2}, \cdots, s_{t_j}\}_\lambda$ is randomly drawn at time λ from the proposal probability distribution $Q(S_\lambda)$. Such an indirect sampling was proved to be able to achieve the best approximation of the sampling directly from $P(S_\lambda)$.

To determine the k^{th} channel for negotiation, a proposal channel s'_{t_k} is first drawn from a proposal probability distribution $Q(S'_{t_k}|S_{t_{k-1}})$. Furthermore, a random number u is drawn from a uniform distribution U(0,1). The probability of proposal channel s'_{t_k} being selected for channel negotiation based on the previous selected channel $S_{t_{k-1}}$, denoted as $\alpha(S'_{t_k}|S_{t_{k-1}})$, can be defined as

$$\alpha\left(S'_{t_k}|S_{t_{k-1}}\right) = \min\left\{1, \frac{\bar{P}_d(S'_{t_k}) \cdot Q(S_{t_{k-1}}|S'_{t_k})}{\bar{P}_d(S_{t_{k-1}}) \cdot Q(S'_{t_k}|S_{t_{k-1}})}\right\}. \quad (4)$$

Using a symmetric proposal probability distribution such as a Gaussian distribution, where $Q(S'_{t_k}|S_{t_{k-1}}) = Q(S_{t_{k-1}}|S'_{t_k})$, Eq. (4) can be rewritten as

$$\alpha\left(S'_{t_k}|S_{t_{k-1}}\right) = \min\left\{1, \frac{\bar{P}_d(S'_{t_k})}{\bar{P}_d(S_{t_{k-1}})}\right\}. \quad (5)$$

Based on Eq. (5), the proposal channel s'_{t_k} is accepted as a channel for negotiation, denoted as s_{t_k} if the following criteria are satisfied:

$$\alpha\left(S'_{t_k}|S_{t_{k-1}}\right) \geq u, \quad (6)$$

and,

$$s'_{t_k} \notin \{s_{t_1}, \cdots, s_{t_{k-1}}\}. \quad (7)$$

This channel selection process is repeated until the desired sequence of channels to negotiate on $\{s_{t_1}, s_{t_2}, \cdots, s_{t_j}\}_\lambda$ is determined. Finally, channel negotiation is performed between the transmission pairs based on the above sequence of channels and terminated when either the requested number of mutually available channels, denoted as n_{req}, is identified or the maximum number of channel negotiations that can be performed within time limitation t_{max}, denoted as n_{max}, has been reached. The pseudo code of the proposed dynamic MCMC channel negotiation method is shown in Algorithm. 1.

Algorithm 1 Dynamic MCMC Channel Negotiation

```
(Upon a data transmission request at time instance λ)
Set an initial channel s_{t_0} as the channel recently negotiated;
for k = 1; k < n_max; k++ do
    Generate a candidate channel s'_{t_k} from q(·) and a value u from U(0,1);
    while u > α(S'_{t_k} | S_{t_{k-1}}) and s'_{t_k} ∉ {s_{t_1}, ···, s_{t_{k-1}}} do
        Reject the candidate channel s'_{t_k};
        Generate a new candidate channel s'_{t_k} from q(·) and a new value u from U(0,1);
    end while
    Accept the candidate channel s_{t_k} ← s'_{t_k};
end for
Obtain the sequence of channels to negotiate on, denoted as {s_{t_1}, s_{t_2}, ···, s_{t_j}}_λ.
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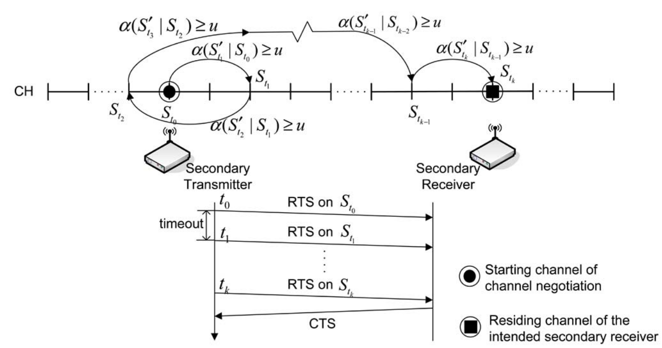

Fig. 1. Overview of the proposed channel negotiation.

B. Channel Negotiation Protocol

Based on the obtained channel negotiation sequence $\{s_{t_1}, s_{t_2}, \cdots, s_{t_j}\}_\lambda$, the secondary transmitter attempts to find the intended secondary receiver on the selected sequence of channels. In the proposed protocol, a secondary user currently without data for transmission performs a fast sensing on the channels and tunes itself to one of the possibly available channels to further identify the presence of faded primary signals. After identifying the availability of the channel, the secondary user stays on this available channel until it either detects primary user signals or any on-going transmission between other secondary users.

A secondary user with data to transmit serves as a secondary transmitter, and it attempts to find the channel to which the intended receiver is residing based on the following channel negotiation protocol. The secondary transmitter initiates channel negotiation by broadcasting a Ready-to-Send (RTS) message on s_{t_0}, which is the channel that has recently been used for negotiation successfully. The RTS message not only includes the address of the secondary transmitter, intended secondary receiver, and the duration value required to transmit the pending data transmission, but also piggy-backs the channel negotiation sequence $\{s_{t_1}, s_{t_2}, \cdots, s_{t_j}\}_\lambda$. If the intended receiver is not on s_{t_0}, it is unable to capture the RTS message so that no CTS will be responded. Therefore, the secondary transmitter turns to s_{t_1}, s_{t_2},..., s_{t_j} one after the other after timeout and repeats sending the same RTS message. If the intended receiver is found on s_{t_i}, it responds with the commonly available channels for negotiation piggy-backed on a Clear-to-Send (CTS) message. An overview of the proposed channel negotiation procedure is shown in Fig. 1.

IV. Performance Evaluation

Simulation is conducted to evaluate the effectiveness of the proposed channel negotiation scheme, where comparison is made between the proposed method and a number of previously reported schemes, including the dedicated control channel approach and the channel hopping approach [13].

We develop an object-oriented modular discrete event driven simulation model using OMNeT++ by considering a $300m \times 300m$ network area uniformly distributed with N_p primary users and N_s secondary users. Each secondary user has a radio transmission range radius of $R = 200m$. For every transmission, the one-way propagation delay is set to $0.01\mu s$, and the transmission speed is 9600bps. All secondary users are considered to have the same MAC frame payload $L = 9520bits$. For each transmission, a source node is randomly chosen and then the intended receiver is selected randomly among its neighbors. The back-off mechanism is employed after every collision. We conducted the simulation for $t_{simu} = 50000s$ for each suite of tests.

For the first set of simulation, we compare the performance of the proposed method with the other approaches in terms of failure rate of channel negotiation R_f, which is defined as the ratio of the number of failed channel negotiation to the number of attempts of channel negotiation. The failure rate R_f of channel negotiation of each transmission event in the first 5000 seconds are shown in Fig. 2, with $M = 20$ channels, $N_p = 20$ primary users with arrival rate 0.1 arrivals/second, $N_p = 10$ secondary users with arrival rate 0.1 arrivals/second, and a maximum of $n_{max} = 5$ channel negotiations. It is observed that the proposed method yields similar performance compared with that of the dedicated control channel method. The failures associated with the dedicated control channel approach is mainly caused by collisions, which account for 74.9% of these failures. Moreover, as expected, the failure rate of the channel hopping approach is significantly higher than the other two approaches. The poor performance of the conventional channel hopping approach is due to the fact that it does not account for the dynamic channel usage nature of the the primary and secondary users.

The performance of the proposed method as well as the other two approaches is investigated under different primary user traffic conditions in terms of average failure rates $\bar{R}_f$, and the results are shown in Fig. 3 . The secondary user traffic is fixed at 0.1 arrivals/second. Under a light primary user traffic, i.e. $10^{-3} - 10^{-1}$, the proposed method outperforms the dedicated control channel method due to more frequent collisions on the dedicated control channel for the dedicated control channel method. Under medium primary user traffic, i.e. $10^{-1} - 10^{1}$, the proposed method performs comparably to the dedicated control channel method while significantly outperforming the channel hopping method. Finally, under heavy primary user traffic beyond 10^2, the proposed method is outperformed by the one with a dedicated control channel because of frequent changes of channel usage status in the case of using dedicated control channels. Fig. 4 shows the average failure rate with respect to secondary user traffic under medium primary user traffic (0.1 arrivals/second). The increase in the secondary user traffic significantly degrades the performance of the dedicated control channel approach due to the collisions

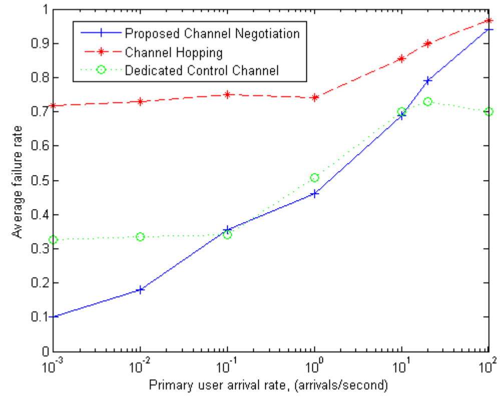

Fig. 3. Average failure rate with respect to primary user traffic.

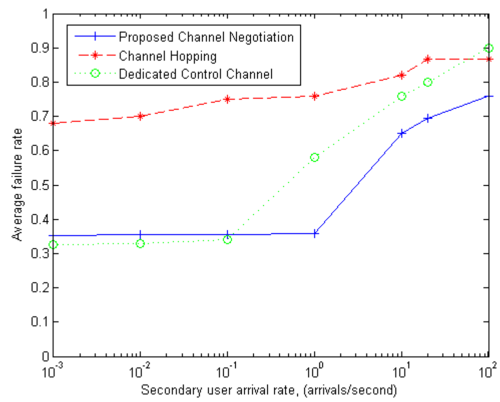

Fig. 4. Average failure rate with respect to secondary user traffic.

happening on the dedicated control channel. Therefore, the proposed method can provide smaller failure rates compared to that by the dedicated control channel approach.

Fig. 5 shows the failure rate with respect to the maximum number of channel negotiations n_{max}. The average failure rate of the proposed method decreases noticeably with increasing n_{max} due to the strong diversity gain obtained from using the proposed method. On the other hand, the average failure rate of the dedicated control channel method decreases more slowly primarily due to the collisions on the dedicated control channel. We also evaluate the failure rates of the proposed method and compare it with the channel hopping approach by changing the number of channels M, and the result is shown in Fig. 6. It is observed that the failure rate increases noticeably in the case of channel hopping when M is increasing due to the fact that it does not consider the highly dynamic nature of CR networks and as such the selection of channels for negotiation becomes less reliable as M increases. The proposed method, on the other hand, provides consistently lower failure rates irrespective of M.

V. Conclusions and Further Work

This paper has presented a novel approach for dynamic channel negotiation in CR networks without the use of dedi-

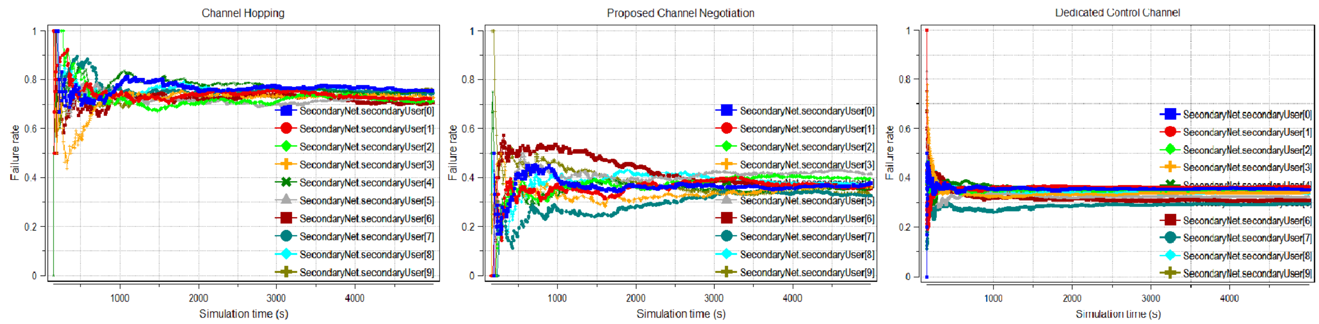

Fig. 2. Failure rate of the tested approaches in the first 5000 seconds.

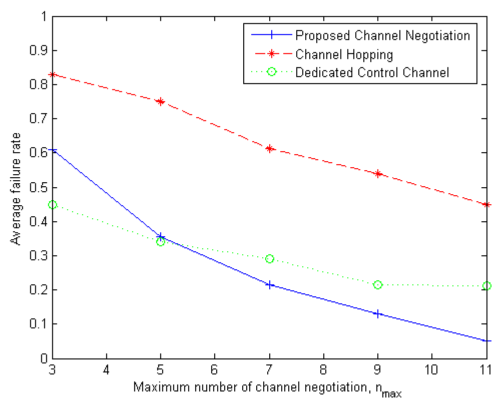

Fig. 5. Average failure rate with respect to maximum number of channel negotiations n_{max}.

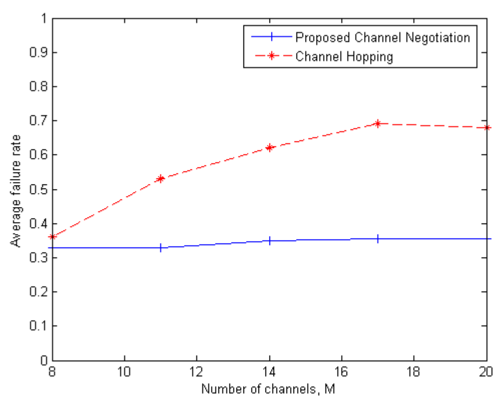

Fig. 6. Average failure rate with respect to number of channels M.

cated control channels. The proposed scheme is characterized by the employment of a Markov-Chain Monte Carlo method for identifying a sequence of channels for channel negotiation based on dynamic energy detection information, aiming to improve the probability of successful channel negotiations. Simulations were conducted to evaluate the performance of the proposed method against several previously published counterparts. The results showed that to the proposed scheme much outperforms other methods that do not employ dedicated control channels. Future work involves further extensive empirical investigations and analytical studies into the performance of the proposed method..

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