Exploring the Impact of Node Cooperation Level on Routing in Cognitive Radio Networks

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***Abstract*—In this paper, we analyze the effect of different degrees of node cooperation on the performance of routing protocols for cognitive radio networks. We first present an analytical model of the routing performance in terms of expected end-to-end packet delivery ratio (PDR) for cognitive radio networks with uncooperative node behaviors. We also performed extensive simulations to evaluate the analytical model. The simulation results show that Optimal Primary-Aware Route Quality Protocol (OPERA) could provide better PDR performance under higher degrees of network cooperation and Shortest Path First routing protocol (SPF) works better under lower cooperation degrees. Finally, our results suggest that even a modest level of node cooperation is sufficient to achieve significant performance improvement with respect to the fully non-cooperative network in which all secondary users are selfish.**

Keywords- node selfishness; cognitive radio; routing.

I. INTRODUCTION

The cognitive radio paradigm [1][2] has attracted much attention in the research and industrial community in recent years. Different from conventional spectrum regulation paradigms in which the spectrum is allocated to fixed licensed users (or primary users) for exclusive use, a cognitive radio system permits unlicensed users (or secondary users) to utilize idle spectrum in a dynamic manner. In cognitive radio networks (CRNs), the secondary users (SUs) should sense the spectrum environment, find available spectrum channels and utilize them without interfering the transmission of primary users (PUs) [3].

Communication is opportunistic in CRNs because SUs can transmit in the spectrum channels if PUs are not using them. Meanwhile, connectivity is intermittent due to the unpredictable node mobility. Therefore, to ensure routing services, nodes are requested not only to act as packet forwarders but also to perform spectrum sensing. That means, both energy and computing resources, which are very limited in a typical mobile node, have to be sacrificed for the other nodes' good. Hence, some SUs show lower degree of node cooperation with a selfish motivation to save their own resources [4][5][6]. It will lead to the failure of most existing routing protocols. This is because most existing routing protocols operate under the assumption that all SUs are fully cooperative in the routing operations [6].

Since routing is the most important network functionality in CRNs, in this paper we focus our attention on evaluating the impact of node cooperation level on routing performance in terms of end-to-end packet delivery ratio (PDR). First, we present a theoretical framework for studying the effects of different node cooperation levels for proactive routing protocols. Then, we perform extensive simulations to evaluate the theoretical analysis model. More specifically, we consider three common CRN routing protocols, including Shortest Path First (SPF) [7], Spectrum Aware Mesh Routing Protocol (SAMER) [8], and Optimal Primary-Aware Route Quality Protocol (OPERA) [9]. The main findings of this evaluation are: i) OPERA has the potential to provide the best packet delivery ratio in presence of reduced node cooperation levels; and ii) even a modest level of node cooperation is sufficient to achieve a considerable performance improvement over the fully non-cooperative scenarios.

The rest of this paper is organized as follows. Section II describes the system model. In Section III, we give the analysis framework, and derive the expected Packet Delivery Ratio (PDR) of routing under different degrees of cooperation. In Section IV, we validate the accuracy of our system model by simulation. Finally, we conclude this paper in Section V.

II. SYSTEM MODEL

We consider a CRN with a set of SUs, which is denoted by V. There exist M primary users, which are indexed by 1, 2, … , M. Each PU n holds a licensed frequency channel n and the probability that PU n is active on its channel is denoted by λ_n. And each PU n has a interference range R_n. A SU could utilize channel n, if the SU is not in the interference boundary of PU n or PU n is not active. Then, the CRN could be modeled as a direct graph:

$$G(t) = (V, E), \quad (1)$$

where a vertex $v_i \in V$ denotes a SU, and an edge $e_{ij} \in E$ denotes the presence of at least one communication link e_{ij}^n from SU v_i to SU v_j through the channel n:

$$e_{ij} = 1 \Leftrightarrow \exists n \in \{1,2,\dots,M\}, s.t.\ e_{ij}^n = 1 .$$

Considering the uncooperative behaviors we study in this paper, we cluster the SUs into two groups respectively denoted by V_1 and V_2, where V_1 denote the selfish SUs and V_2 denote the selfless SUs. Let $\gamma = |V_1| / |V|$ denote selfish SU intensity in the CRN where $|V_1|$ means the number of SUs in V_1 and $|V|$ means the total number of nodes in the network.

To model cooperation level of SUs in this paper, we define a cooperation value for each SU by the probability with which it would forward packets from other SUs. Let ρ_i denote the cooperation value of a SU v_i, where $v_i \in V$. In this paper, we assume that SUs in V_2 will always forward packets from other nodes. Therefore, for $v_i \in V_2$, $\rho_i = 1$.

III. PERFORMANCE ANALYSIS

In this section, we characterize the expected Packet Delivery Ratio (PDR) of routing under different degrees of cooperation. For mathematical tractability, we only consider the routing protocols with which routes are determined in proactive manner. Let $D_{i,j}$ denote the event that a packet is generated for a source-destination (v_i, v_j). Denote the route determined for the source-destination (v_i, v_j) by the ordered set $L = \{l_1, l_2, \ldots, l_{|L|}\}$, where $l_k \in L$ denote the index of the k[th] SU along the route, $l_1 = i$, and $l_{|L|} = j$. For simplicity, we also use l_k to denote the SU v_{l_k}.

In the CRN, whether a packet could be successfully delivered to the destination is dependent on the effect of the PU, SU mobility and/or SU cooperation level. Therefore, we measure the expected end-to-end PDR by explicitly accounting for the effect of the relative movement between two SUs, the relative movement between SU and PU, and the cooperation value of SU.

A. Packet Delivery Ratio over a Link

Let D_{l_k} denote the event that a packet sucessfully arrives at SU l_k. Now we consider the next hop from SU l_k to SU l_{k+1}. Evaluating the expected PDR over the link from SU l_k to SU l_{k+1} is equivalent to computing the conditional probability of the event "the packet is sucessfully received at SU l_{k+1}". Given D_{l_k}, then whether the packet could be successfully transmitted to SU l_{k+1} is totally dependent on the state of the communication link between SU l_k to SU l_{k+1}. If the link is connected and not affected by PU activity, then the packet could be transmitted to SU l_{k+1}. But whether SU l_{k+1} would like to accept the packet and forward it to the next hop is totally dependent on its cooperation value.

We denote the probability that the link between SU l_k and SU l_{k+1} being connected by $\alpha_{k,k+1}$. The calculation of $\alpha_{k,k+1}$ is similar to that in wireless networks, which has been extensively studied by considering the relative movement between two mobile nodes. In this paper, we adopt the approach introduced in [10] to calculate $\alpha_{k,k+1}$. Since the calculation procedure is complex, we do not give an explicit expression of $\alpha_{k,k+1}$. Please refer to [10] to learn more.

Let δ_k^n denote the probability that a SU l_k enters into the interference boundary of PU n. A SU entering into the interference boundary of a PU means that the relative distance between the SU and the PU is less than the interference range of the PU. Similarly to the calculation of $\alpha_{k,k+1}$, we can obtain the probability δ_k^n. The activity of PU n can interfere with the communications between SU l_k and SU l_{k+1} if either SU l_k or SU l_{k+1} enters into the interference boundary of PU n. We use $\delta_{k,k+1}^n$ to denote the probablity that the activity of PU n can interfere with the communications between SU l_k and SU l_{k+1}. Then, the probability $\delta_{k,k+1}^n$ can be calculated by:

$$\delta_{k,k+1}^n = 1 - (1 - \delta_k^n)(1 - \delta_{k+1}^n) \quad (2)$$

Channel n is not available for communication between SU l_k and SU l_{k+1}, if the activity of PU n can interfere with the communications between them and PU is active on channel n. We use spectrum availability $\beta_{k,k+1}^n$ to denote the probability that channel n is available for communication link between SU l_k and SU l_{k+1} to use. Therefore, spectrum availability $\beta_{k,k+1}^n$ could be given as:

$$\beta_{k,k+1}^n = 1 - \delta_{k,k+1}^n \lambda_n , \quad (3)$$

where, $\delta_{k,k+1}^n$ is given in (2), and λ_n is the activity probablity of PU n on channel n. And if no channel is avaialble for communication between SU l_k and SU l_{k+1}, then the transmission would be blocked. Let $\beta_{k,k+1}$ denote the block probability due to spectrum unavailability. Then, the block probability $\beta_{k,k+1}$ can be calculated by:

$$\beta_{k,k+1} = \prod_{n=1}^{M} (1 - \beta_{k,k+1}^n) . \quad (4)$$

For simplicity, we assume that the relative movement between SU l_k to SU l_{k+1}, the spectrum availability and the cooperative levels of SU l_{k+1} are independent. Therefore, the expected packet delivery ratio over a link from SU l_k to SU l_{k+1} is given by (5), where $\rho_{l_{k+1}}$ is the cooperation value of SU l_{k+1}.

Remark. The expected packet delivery ratio (5) allows us to estimate the packet delivery ratio sent over a link by accounting for three main factors that affect the transmission of this link: (1) the SU movement, via the probability $\alpha_{k,k+1}$; (2) the PU characteristics, via the probability $\beta_{k,k+1}$; (3) the cooperation level of next hop, via cooperation value $\rho_{l_{k+1}}$. Notice that at the last hop, since the receiver of the last hop is the destination, it will always be willing to receive the packet. From (5), we can notice that the smaller is $\rho_{l_{k+1}}$, the smaller is the packet delivery ratio. Thus, the coopeartion value of the SUs should be considered into the route selection.

$$\theta_{k,k+1} = P(D_{l_{k+1}}|D_{l_k}) = \begin{cases} \alpha_{k,k+1}\,(1-\beta_{k,k+1})\,\rho_{l_{k+1}}, if\ k < |L|-1 \\ \alpha_{k,k+1}\,(1-\beta_{k,k+1})\,, if\ k = |L|-1 \end{cases} \quad (5)$$

B. End-to-End Packet Delivery Ratio

Based on the aforementioned work, we now derive the analytical expression of end-to-end packet delivery ratio. Evaluating the end-to-end PDR for the source-destination (v_i, v_j) is equivalent to computing the probability of the event "a packet generated at an SU v_i is successfully delivered to destination v_j". Thus, we have

$$PDR_{i,j} = P(D_j|D_{i,j}) = \prod_{k=1}^{|L|} P(D_{l_{k+1}}|D_{l_k}) \quad (6)$$

Then the expected end-to-end delay over the whole network is calculated as:

$$\overline{PDR} = \sum_{v_i, v_j \in V} P(D_{i,j})\, PDR_{i,j} \quad (7)$$

where $P(D_{i,j})$ is the probability that a message is generated for the source-destination (v_i, v_j). It could be estimated based on the number of packets generated between v_i and v_j in the past. In this paper, we assume that the source-destination pairs are randomly selected among all SUs. Then, $P(D_{i,j}) = 1/|V|(|V|-1)$.

IV. MODEL VALIDATION

In this section, we evaluate our analysis by comparing the theoretical results obtained based on our model with the simulation results, which are obtained by simulating the packet dissemination under three different routing protocols for CRNs (i.e., SPF, SAMER, and OPERA) with different cooperation levels.

A. Simulaiton Setting

In our simulation, the network topology consists of 50 SUs randomly distributed in a square area of the side of 500 m. All the SUs are mobile and follow the random walk mobility (RWM) model [11], in which each SU's movement consists of a sequence of random length intervals called mobility epochs. During an epoch, a SU moves in a constant direction at a constant speed. The speed and direction of mobile during each epoch is uniformly distributed over (0, 20m/s) and (0, 2π) respectively. The transmission ranges of SUs are set to be 30m.

In the simulated area, there are 10 PUs and each PU possesses a licensed channel. Each channel n is utilized by a PU with a probability $\lambda_n \in [0.05, 0.95]$. And the interference ranges of PUs are all set to be 50m.

We vary the selfish SU intensity γ from 0.0 to 1.0 with step of 0.1. We will also vary the cooperation value ρ_i of selfish SUs with two different values: 0 and 0.5. For each value of γ and ρ_i, we run the simulation for 1000 times.

B. Simulation Results

Simulation results are shown as below. Figure 1 shows the expected end-to-end packet delivery ratio vs. γ for SPF protocol with values of γ from 0.0 to 1.0. Figure 2 shows the results for SAMER protocol and Figure 3 shows the results for OPERA protocol.

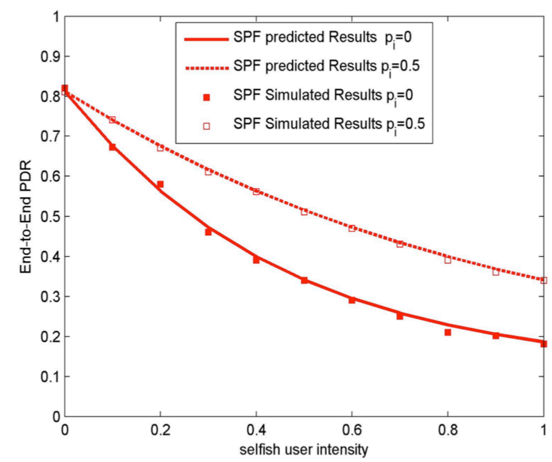

Figure 1. End-to-end PDR with SPF routing v.s. selfish user intensity.

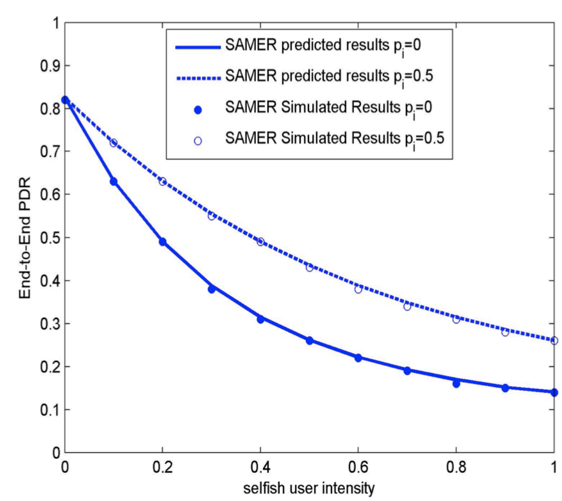

Figure 2. End-to-end PDR with SAMER routing v.s. selfish user intensity.

From the results, we first note that there is a very good agreement between the theoretical and the experimental results for two different cooperation values under SPF, SAMER and OPERA protocols.

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Second, we could find that for all three protocols, the expected end-to-end PDR decreases as the number of selfish nodes increases. Thus, to provide efficient routing performance for CRNs, it is necessary to incorporate selfish node detection mechanisms into routing protocol.

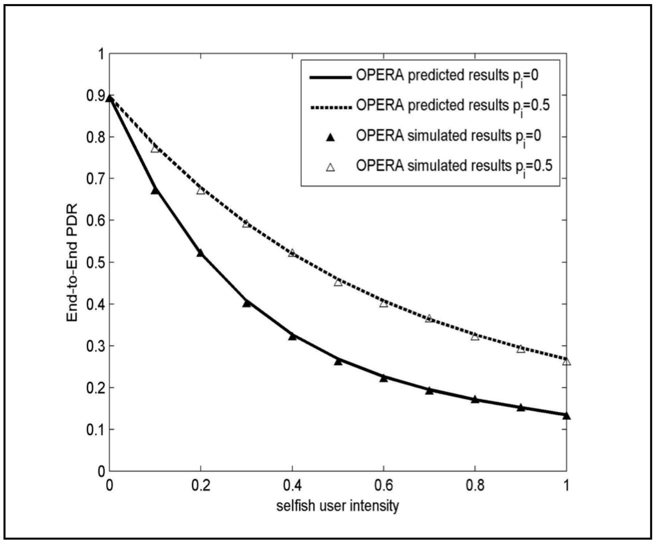

Figure 3. End-to-end PDR with OPERA routing v.s. selfish user intensity.

Moreover, through comparison between results of different routing protocols, we can find that OPERA is able to provide the best packet delivery ratio in cases with higher cooperative level (lower selfish SU intensity γ and higher cooperation value). But when the selfish SU intensity γ increase to almost 1 and the cooperation value becomes 0, SPF protocol performs better than OPERA.

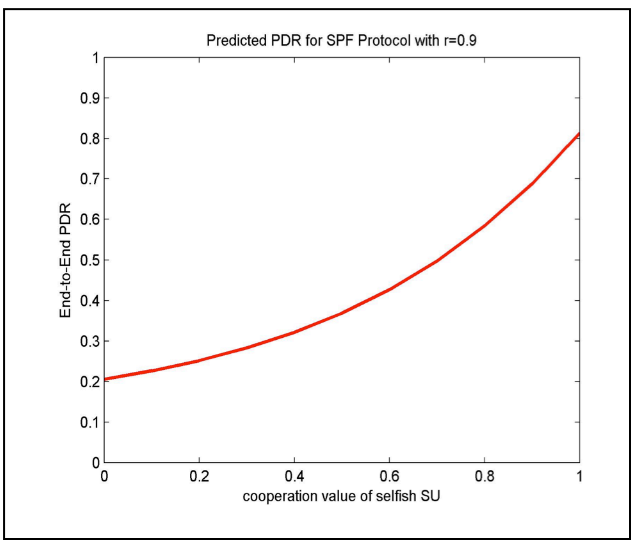

Figure 4. End-to-end PDR with OPERA routing v.s. coperation value.

We also give the results for SPF protocol with different values of ρ_i from 0.0 to 1.0 in Figure 4. From Figure 4, we also find that a modest level of increase in node cooperation is sufficient to achieve a considerable performance improvement in packet delivery ratio. Thus, it is essential to enhance the cooperation willingness of SUs in order to provide efficient routing performance, such as introduce some reward-and-penalty mechanism.

V. CONCLUSISON

In this paper, we characterized the performance of proactive routing protocols for CRNs under different levels of node cooperation. We also perform extensive simulations to validate our analysis. The simulation results give some insights into future routing protocol designs for CRNs, such as incorporate selfish node detection mechanisms and reward-and-penalty mechanism into routing protocols. In the future work, we will focus on applying our conclusions to CRNs.

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