Performance Evaluation of the Effect of Primary Users on the Rendezvous process for Cognitive Radios

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Abstract

The Rendezvous process is an essential process for establishing a communication link between two nodes in cognitive radio networks. A number of rendezvous protocols have been developed in the last few years. However, many protocols ignore one of the basic constraints of cognitive radio networks which is the impact of the primary users (PUs) on the performance of the rendezvous process. In this paper, we develop an analytical model to evaluate such impact. The ordinary residual time process is used to develop this model. The results, which are validated by the simulation results, show that the primary user activity cannot be ignored and it affects negatively the time to rendezvous (TTR) between two nodes.

Keywords: *Rendezvous, Cognitive radio, Analytical model.*

1. Introduction

The rendezvous process can be defined as the process by which two or more cognitive radios or so called Secondary Users (SUs) attempt to arrive on the same frequency to begin transferring data [1]. This process is also known previously as neighbor discovery [2]. The rendezvous process is a fundamental and essential process in cognitive radio networks for exchanging information and establishing data communications between SUs. Without this process, data communications is impossible. In [1], the authors have established taxonomy for the rendezvous process. This taxonomy is consisting of two branches: aided rendezvous systems and unaided rendezvous systems. Under an aided rendezvous system, a centralized controller is responsible for detecting the available channels, passing this information to SUs and may be setting up links. Under an unaided rendezvous system, SUs are responsible for finding the common channel in a distributed manner. The unaided rendezvous can be classified according to how SUs access the spectrum into three classes:

1) using a single channel,
2) using multiple channel and
3) without control channel.

The process of establishing a link without the benefit of a control channel is sometimes referred to as a blind rendezvous [3]. The blind rendezvous belongs to the last class of the rendezvous classification. In this paper, we focus on blind rendezvous. In blind rendezvous, all channels are available for exchanging information and establishing data communications. However, SUs should be aware of the activities of the primary users (PUs) to guarantee the rendezvous process in a reasonable amount of time. This time is called Time-To-Rendezvous (TTR). Different classifications for blind rendezvous have been proposed in the literature [1].

Most of the aforementioned approaches of blind rendezvous ignore the presence and the impact of the PUs and the impact of their activities on the TTR between SUs. In this paper, we develop an analytical model to evaluate this impact on the rendezvous process. The ordinary residual time process is used to develop this model [3]. We show that PUs' activities cannot be ignored and it affects negatively the time to rendezvous between SUs.

The rest of the paper is organized as follows. In Section 2, we outline the system model and assumptions. Section 3 presents the performance metrics. The simulation and results are shown in Section 4. Finally, Section 5 concludes the paper.

2. System Model

In this section, a detailed description about the system is presented.

2.1 Assumptions

We consider a network consisting of N SUs. The SUs share a region with $M$of PUs, such as primary base stations and primary user equipment. The PUs form a licensed primary network whereas the SUs form a secondary network. The SUs can access the primary channel (PC) only when the PUs is idle. We assume that the primary spectrum consists of C non-overlapping channels labeled as $ch_1,\ ch_2,\ ch_3,\ \cdots,\ ch_C$, where $C > 1$.

Each channel state is considered to be idle or busy (see the primary channel model below). The time axis t is divided into slots of equal length and numbered from 0 to L.

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Each slot is divided to three sub-slots with equal length, ω basic time units. The tree sub-slots are sense, transmit and listen as shown in Figure 1.

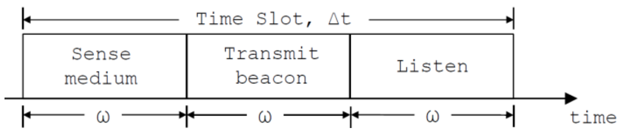

Fig. 1: The structure of a time slot

During the listen sub-slot, a SU begins by sensing the medium for the presence of a PU activity. If the sensing results shows that there is no PU, it will transmit a beacon during the transmit sub-slot. Afterwards, the listen sub-slot starts where the SU waits for a response from its communication partner. A SU wishing to join a network visits the potential communications channels in random order. The rendezvous will be successful if the following two conditions occur [4]:

1) the two SUs select the same channel and
2) one of the SUs is sensing the medium while the other is transmitting.

2.2 Primary Channel Model

The PUs are the owners of some licensed spectrum. Depending on the PU's activity pattern, a channel can be modeled as an ON-OFF source alternating between ON (busy) and OFF (idle) periods [5]. Since the arrivals of a PU at a PC changing its state from idle to busy and the inter-arrival times are assumed to be identically distributed with general distribution, then the PC usage can be modeled as an ordinary renewal process [3]. For mathematical tractability, we assume that the PUs on different channels exhibit independent random activity. Let X_k and Y_k, $K = 1, 2, 3, \ldots$, be random variables (RVs) denoting the respective ON and OFF times of the k^{th} renewal cycle with Probability Distribution Functions (PDF) given as $F(t) = Pr[X_k < t]$ and $G(t) = Pr[Y_k < t]$ respectively. Let $x_k(t)$ and $y_k(t)$ are the probability density functions (pdf) of X_k and Y_k with mean $\frac{1}{\gamma}$ and $\frac{1}{\beta}$ respectively. Let $\bar{G}(u) = 1 - G(u) = \lim_{t\to\infty} Pr[Y_k(t) > u] = \int_{\tau=u}^{\infty} y_k(\tau)\, d\tau$ be limiting cumulative probability distribution function (CPDF) of $G(u)$. Let $R_k(t)$ be a RV denoting the remaining or residual life time [6] at an arbitrary instant time t on a given channel when the channel is idle with the limiting pdf $r_k(u)$ and the limiting PDF given as $A_k(u) = \lim_{t\to\infty} Pr[R_k(t) \le u]$. From the renewal processes theory, the values of $A_k(u)$ and $r_k(u)$ can be written as the following:

$$A_k(u) = \beta \int_{\tau=0}^{u} \bar{G}(\tau)\, d\tau \qquad (1)$$

and

$$r_k(u) = \beta \int_{\tau=u}^{\infty} y_k(\tau)\, d\tau \qquad (2)$$

Let $P_i(t) = 0, 1, 2, 3, \ldots, C$ be a RV denoting the system occupancy of the PUs (i.e., the number of ongoing PUs) at a time slot t with the equilibrium probability distribution $p_i = \lim_{t\to\infty} Pr[P_i(t) = i]$. Since the inter-arrival times of the PUs at the system are assumed to be identically distributed with general distribution and mean $\frac{1}{\beta}$, then the PU system can be modelled as GI/GI/C queueing Model [6].

In random rendezvous algorithm, SUs randomly choose from the available PCs in an attempt to find each other. At the start of each slot, each SU can be in one of two modes: transmit mode with probability α or receive mode with probability $1 - \alpha$. During each time slot, the SU labeled as $l = 1, 2, 3, \ldots$ will select an available ch_k $(k = 1, 2, 3, \ldots, C - i)$ with probability $W_i^{l,k}$,where i denotes the number of ongoing PUs connections. The value of the probability $W_i^{l,k}$ can be written as:

$$W_i^{l,k} = Pr[l\ select\ ch_k] \cdot Pr[P = i] = \frac{p_i}{c - i} \qquad (3)$$

2.2 Multi-Channel, Synchronous

In the multi-channel synchronous scheme, rendezvous algorithms require at least some degree of time synchronization between the SUs in the networks. For two SUs following this procedure, rendezvous will be successful when two conditions occur:

1. The two SUs select the same channel.
2. AND one of the SUs is sensing the medium while the other is transmitting a beacon in such a way that the handshake required for rendezvous is possible.

Let us focus on a certain SU called the *tagged SU* and register the number of neighbor discoveries it makes with $N - 1$ SUs within the same transmission range. The other SUs are labeled as Y_1 through Y_{N-1} [7]. Let D be a RV denoting the number of discoveries that the *tagged SU* hears in a given time slot on an idle PC. By assumption, D cannot exceed 1, if more than one neighbor transmits in a slot using the same PC then the tagged SU could only hears a collision. Thus, the probability that $D = 1$ conditioned on the PUs system occupancy can be written as follows:

$$d_1 = \sum_{i=0}^{C-1} Pr[D = 1 | P = i] Pr[P = i] \qquad (4)$$

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The *tagged SU* discovers exactly one neighbor if the following events occur together on an idle PC k.

1. The *tagged SU* selects the idle channel k with probability $W_i^{tagged,k}$, which given in (3), and switches to the transmit mode with probability α.
2. The residual life time of the idle PC k is greater than or equal to ω slots.
3. One of the remaining $N-1$ SUs selects the same idle channel k with probability $W_i^{n,k}$ and switches to the receive mode with the probability $1-\alpha$ where $n = 1,2,3,\dots,N-1$ and $k = 1,2,3,\dots,C-1$.
4. The other remaining $N-2$ SUs do not select the idle channel k with probability $1-W_i^{n,k}$.

By combining the above listed events together, we get

$$Pr[D|P=i] = \alpha(1-\alpha)\sum_{k=1}^{C-i} W_i^{tagged,k} \cdot Pr[R_k \geq \omega]\sum_{n=1}^{N-1} W_i^{n,k} \prod_{m=1,m\neq n}^{N-1}\left(1-W_i^{m,k}\right) \quad (5)$$

Substituting for $W_i^{tagged,k}$, $W_i^{n,k}$ and $W_i^{m,k}$ from (3) into (5), yields:

$$Pr[D|P=i] = \alpha(1-\alpha)(N-1)\sum_{k=1}^{C-i}\left[\frac{1}{C-i}\right]^2\left[\frac{C-i-1}{C-i}\right]^{N-2} \cdot Pr[R_k \geq \omega] \quad (6)$$

Substituting for $Pr[D=1|P=i]$ from (6) into (4), yields

$$d_1 = \alpha(1-\alpha)(N-1)\sum_{k=1}^{C-i}\left[\frac{1}{C-i}\right]^2\left[\frac{C-i-1}{C-i}\right]^{N-2} \cdot Pr[R_k \geq \omega]Pr[P=i] \quad (7)$$

The expected number of discoveries per rendezvous slot can be computed using (7) as follows:

$$E[D] = 1\cdot d_1 + 0\cdot\{\dots\} = \alpha(1-\alpha)(N-1)\sum_{k=1}^{C-i}\left[\frac{1}{C-i}\right]^2\left[\frac{C-i-1}{C-i}\right]^{N-2} \cdot Pr[R_k \geq \omega]Pr[P=i] \quad (8)$$

3. Performance Metrics

The probability γ_1 that the tagged SU finds a specific SU Y_i on specific time slot on channel m is given as [4]:

$$\gamma_1 = \frac{E[D]}{N-1} \quad (9)$$

Let K be a RV denoting the number of times that node Y_i will be discovered by the tagged SU X during the duration of the rendezvous process across all L slots. Since each slot acts as Bernoulli trials with probability of success equal to γ_1, then the probability distribution of the RV K follows the Binomial distribution,

$$Pr[K=k] = \binom{L}{k}{\gamma_1}^k(1-\gamma_1)^{L-k} \quad (10)$$

Since L is typically large and the probability γ_1 is small, the Binomial distribution in (9) can be approximated using the Poison distribution as follows:

$$Pr[K=k] \approx \frac{(L\gamma_1)^k}{k!}\binom{}{k}e^{L\gamma_1} \quad (11)$$

The expected number of discovered links in L slots with T duration each is given as:

$$F[LT] = 1 - Pr[K=0] = 1 - e^{L\gamma_1}$$

Finally, let $R = 1,2,3,\dots$ be a RV denoting the number of slots elapsed until two or more SUs to rendezvous. The RV R represents the number of failures before the first success in a sequence of independent Bernoulli trials with probability γ_1. Thus, the RV R is geometrically distributed with probability distribution function given as:

$$Pr[K=k] = {\gamma_1}^k(1-\gamma_1)^{k-1}$$

The expected TTR is given as:

$$E[R] = \frac{1}{\gamma_1}$$

4. Simulation and Results

To validate the analytical model, we developed a discrete-event simulator using JAVA platform. The scenario used in our simulation can be described as follows: The SUs are varied from 10 to 50 nodes steps of 10. The transmission range of each node is set to 50 meter. The PUs arrive into the transmission range of the SUs according to Poisson process. Each SU in this network selects independently a PC to start the rendezvous process using a synchronous timing with the other SUs. We assume that the channel idle or busy period times due to PU activity are exponentially distributed. The total average cycle time of PU on each channel is set to 1000 sub-slots. Figure 2 shows the impact of different traffic loads of PUs on the number of discovered links among SUs. Obviously, when there is little PUs, the number of discovered links is high. Figure 3 shows the impact of PUs activities on the TTR. As depicted in the Figure, if the activities of the PUs are ignored, the TTR is very small. This result is not practical since the activities of the PUs cannot be ignored in CR networks. To measure the impact of the PUs, we increase the traffic load of the PUs. The results show that the expected TTR is negatively affected by the PUs activities.

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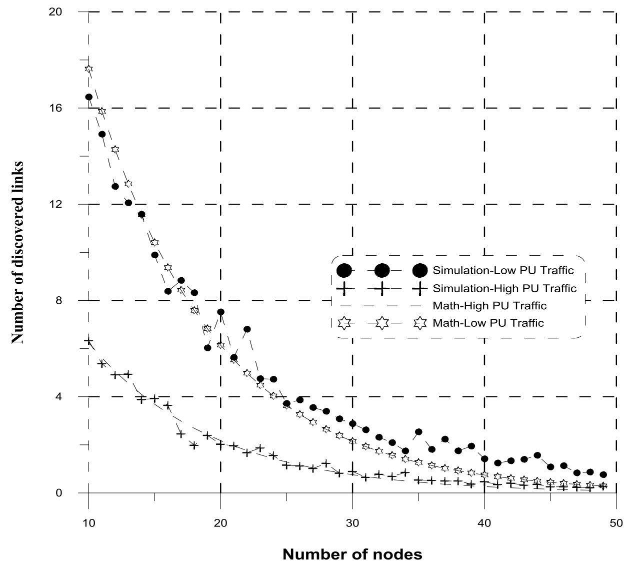

Fig. 2: The number of discovered links vs. the number of PUs.

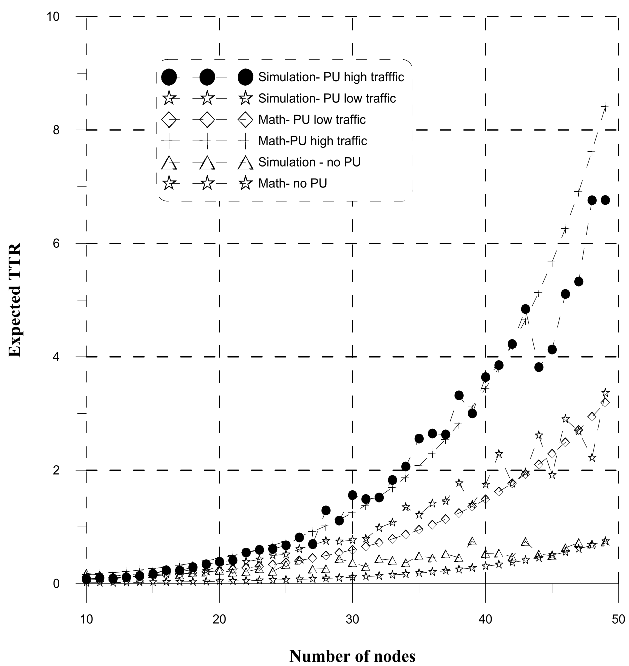

Fig. 3: The impact of PUs activities on TTR.

5. Conclusions

In this paper, we have developed an analytical model for evaluating the primary users' effects on the rendezvous process. The results show that such impact cannot be ignored. Thus, the protocols' developers should take this impact into consideration when designing a new rendezvous protocol for cognitive radio network.

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