IEICE TRANS. COMMUN., VOL.E98–B, NO.2 FEBRUARY 2015

PAPER

Optimization of Learning Time for Learning-Assisted Rendezvous Channel in Cognitive Radio System

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SUMMARY This paper derives the optimal learning time for the learning-assisted rendezvous channel. One problem with the dynamic spectrum access system of cognitive radio is access channel mismatch between two wireless terminals. In the learning-assisted rendezvous channel, before exchanging packets for link connection, the rate of channel occupancy by the other system is estimated within the learning time; it is referred to as the channel occupancy rate (COR). High speed packet exchange is made possible by selecting a low COR channel. However, the optimal learning time and the impact of COR estimation errors have not been clarified yet. This paper analyzes the time to rendezvous channel (TTR), where TTR is the time needed to complete the rendezvous with a certain probability. The results indicate that the learning time and TTR have a concave relationship which means that the optimal learning time can be determined.
key words: *cognitive radio, rendezvous channel, Channel Occupancy Rate (COR)*

1. Introduction

The problem of frequency spectrum exhaustion has become a much more serious problem but cognitive radio (CR) is a powerful solution. CR is aware of the wireless communication environment and then adjusts the wireless communication parameters for exploiting the frequency spectrum [1]. The CR can be categorized into two: heterogeneous type and spectrum sharing one [2]. In heterogeneous type, the user selects the existing wireless communication systems in accordance with the achieved user throughput and the required communication quality. In spectrum sharing type, the CR bundles or selects the vacant partial frequency bands and time slots. This paper pays attention to the spectrum sharing type of CR.

In the spectrum sharing type of CR, there are two systems, primary system (PS) and secondary system (SS). PS has the priority to access the frequency spectrum and SS can access it while the PS does not use it, where the temporal vacant of frequency spectrum without PS access is white space [3]. Since the white spaces appear over various channels and time slots, the SS exploits the white space by changing the accessing channel in each time slot. Therefore, the spectrum sharing type of CR is a dynamic spectrum access (DSA) system [4]. In DSA systems, when the wireless terminal (master) attempts to establish a new communication link, the other terminal (slave) may not catch the signal from the master due to access channel mismatch [5]. The rendezvous channel scheme can be used to eliminate this mismatch. The rendezvous channel scheme is the initial connection protocol for finding one another in multiple frequency channels [5].

Various kinds of rendezvous channel schemes have been considered so far. There are mainly two types: Centralized type and Distributed one. In centralized type, the central controller, such as base station, informs all the terminals about the channel number for rendezvous channel [6]. In distributed type, the master and the slave exchange the control signal for rendezvous channel [5]. The distributed type does not need the other accessing channel to the central controller and has the easy implementation owing to the low dependency to the other system. The distributed type is categorized into single rendezvous and parallel one [7]. In single rendezvous, the steady time period [5], [8], the steady frequency channel [5], [8], and the steady hopping pattern [9], [10] are used for the rendezvous channel. If the steady resources for rendezvous channel are used by PS, the construction of rendezvous channel is difficult. Since the steady resources are exclusive use for rendezvous channel, the single rendezvous channel suffers from the low efficiency of frequency spectrum [5]. In the parallel rendezvous, the plural resources for the rendezvous channel are adaptively selected. In [11], the terminal constructs the hopping sequence, independently and informs each other terminal about its own hopping sequence. However, the signaling overhead required for informing is huge. Reference [12]–[14] constructs the flexible hopping sequence by removing the channel numbers where the PS's access is sensed. However, Refs. [12]–[14] does not obviously show the rule for excluding the channel number. The CR exploits the frequency channel during the temporal vacant period of PS. Even if the carrier sensing detects the PS's access, the SS could wait the next vacant period. As a result, it is possible for SS to have the opportunity to use the channel. However, Refs. [12]–[14] does not consider this possibility.

In Ref. [15], before exchanging the control packet for rendezvous channel, a sensing period is set to recognize the

Manuscript received August 31, 2014.
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DOI: 10.1587/transcom.E98.B.360

PS's average accessing rate, where the PS's average accessing rate is the channel occupancy rate (COR). The hopping sequence is then modified to access the channel of the low COR. Since SS has a large enough sensor range, a common view of the COR is easily obtained by the SS. The resulting hopping sequence provides a lot of meeting times between master and slave and thus achieves a high speed rendezvous channel. The additional merit of this technique is the realization of high throughput performance due to the many access opportunities. Therefore, the scheme of rendezvous in Ref. [15] may be suitable for the spectrum sharing type of the CR but its availability is only shown by computer simulation under a simplified system model. The optimal time, in terms of minimizing the time to rendezvous, taken to estimate the COR has not been derived yet.

This paper derives the optimal learning time for creating high speed rendezvous channels. In the scheme of Ref. [15], the sensing period is referred to as the learning time. Increasing the learning time increases the accuracy with which the low COR channel can be determined. Since using a low COR channel gives the SS more opportunities to access the channel, the PS is quiescent more often and thus the time to exchange the packets for link connection is reduced. We determine the optimal learning time for minimizing the time to rendezvous channel (TTR), where TTR includes the time to exchange the packets between the master and the slave, unlike Ref. [15]. Our analysis confirms that selecting a low COR channel yields high speed packet exchange. This is a heretofore unknown advantage of [15]'s rendezvous scheme. This paper also assumes that actual sensing techniques will have some detection errors. We clarify the impact of the misdetection to the rendezvous channel.

This paper is constructed as follows. Section 2 describes the wireless communication system considered here. Section 3 details the learning-assisted rendezvous channel. Section 4 derives TTR by a theoretical analysis. In Sect. 5, numerical results are shown and our conclusion is given in Sect. 6.

2. Overview of Wireless Communication System

Figures 1(a) and (b) show the field and time environments of the wireless communication system assumed here, respectively. In this environment, there are three types of wireless terminals, the first one belongs to the PS and is active intermittently, the second and third belong to the SS, where the second terminal has just joined this wireless communication system and tries to construct the wireless communication link to the third terminal, where the second and third terminals are referred to as master and slave, respectively. This paper considers the rendezvous channel between master and slave.

Figure 1(b) shows the status of PS access rate for each channel. In the wireless communication system assumed here, a time slot is defined as the minimum time duration and the slot-by-slot synchronization among all terminals is assumed to be ideal. The PS decides to access a channel in each slot, independently. The channel access decision is considered to be a stochastic process. The rate at which the PS accesses the ith channel is ρ_i, where ρ_i is referred to as the ideal COR. The master and the slave detect PS activity by carrier sensing. This paper assumes that carrier sensing is realized by energy detection [16]. In carrier sensing, there are two types of error, false alarm and misdetection. To simplify the analysis, we assume the decision threshold is set so high that the false alarm rate is negligible [16]. The sensing result of each slot is recorded in the master and the slave in a first-in first-out (FIFO) memory. If the memory becomes full, the oldest result is popped to allow the latest one to be pushed. From the memory entries, each terminal calculates the COR for each channel. Each channel has one memory. To avoid PS/SS collision, SS confirms PS quiescence before attempting channel access. Therefore, SS must be a carrier sense multiple access system.

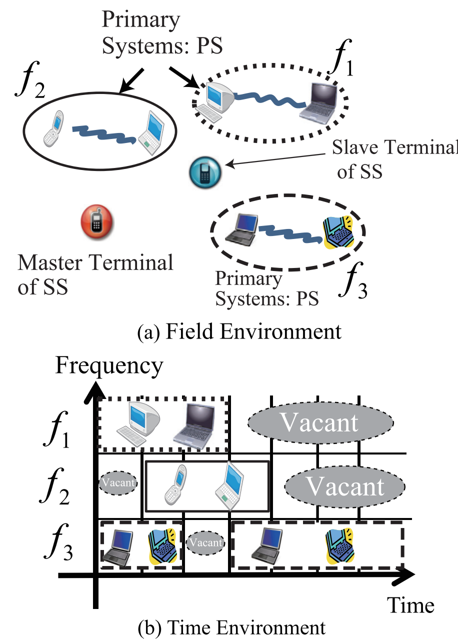

Fig. 1 Wireless communication environment.

3. Learning-Assisted Rendezvous Channel

3.1 Measurement Method of COR

The carrier sensing process places a one bit result, occupied or vacant, in the memory for each channel. Therefore, the COR of a channel is calculated by each terminal as the total number of occupied results normalized by the total number of results in that channel's memory. The master and the slave switch between channels so as to evaluate the CORs of all channels. Figure 2(a) shows the image of COR measurement for each channel. This technique is referred to as the uniform measurement because the connection probabilities of each channel are equal. Figure 2(b) shows the image of learning measurements. At the commencement of learning measurement, the connection probabilities to each channel

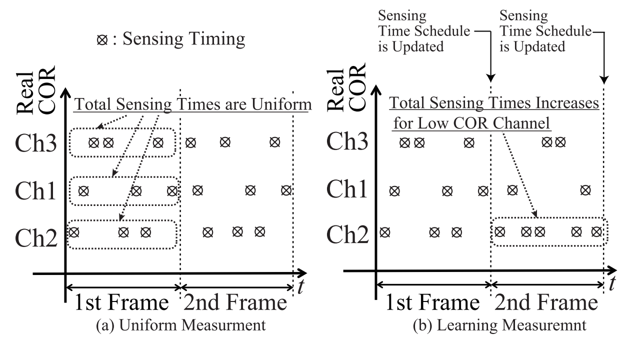

Fig. 2 COR measurement method.

are equal and the CORs in all channels are roughly estimated during one frame time period. As a result, the channel with minimum COR is found, where it is referred to as the superior channel. This is because it gives the more opportunities to find the vacant of the channel and thus it is more suitable for the rendezvous channel than any other channel. The COR of the superior channel, $\bar{\rho}_{\min}$, is defined as

$$\bar{\rho}_{\min} = \min_{j \in 1,2,\ldots,N} \bar{\rho}_j, \tag{1}$$

where N is the number of channels and $\bar{\rho}_j$ is the estimated COR of the jth channel. The learning measurement sets the larger connection probability to the superior channel than that to the other channel. The connection probability to the ith channel is derived as

$$\begin{cases} \alpha, & \bar{\rho}_i = \bar{\rho}_{\min} \\ \frac{1-\alpha}{N-1} & \bar{\rho}_i \neq \bar{\rho}_{\min} \end{cases}, \tag{2}$$

where α is the priority factor ($0 \leq \alpha \leq 1$). As α becomes large, the connection probability to the superior channel becomes high. For example, in $N = 3$ and $\alpha = 0.7$, the connection probabilities of the superior channel and the other channel are 70% and 15%, respectively. Switching from uniform measurement to learning measurement is possible by controlling α. If $\alpha = 1/N$, the measurement scheme becomes uniform measurement, otherwise it is learning measurement. The connection probabilities are updated by the past estimated COR every frame time period.

3.2 Rendezvous Process

We consider the situation in which the master joins the wireless communication system and tries to establish a link connection to the slave. The handshaking type of rendezvous channel is used [5]. The master sends the request signal to the slave. If the slave successfully receives it, it sends the reply packet to the master. If the master successfully receive it, the rendezvous channel is completed. Therefore, the handshaking type of rendezvous channel is established by the packet exchange between the master and the slave.

Since the master has no prior information of each channel's COR, its COR memories are null before starting COR estimation. We assume that the slave has full COR memory. In the learning-assisted rendezvous channel, the master uses the uniform measurement, whereas the slave uses learning measurement as determined by the connection probability to each channel. Before sending its request packet, the master needs some time to estimate COR. This is the learning time. After the learning time, the master selects the superior channel for sending the request packet. Before sending the request packet, carrier sensing is used to confirm PS quiescence. This paper assumes that carrier sensing and packet transmission take one slot to perform. When the slave receives the packet from the master, it also confirms PS quiescence before sending the reply packet to the master.

If the slave is connected to a different channel, it fails to receive the request packet. The master discovers this failure from the absence of a reply packet. After the confirmation of failure to receive, the master sends the request packet again. If PS occupies the channel after the master sends the request packet, the slave has to wait to send the reply packet. Since the master also detects the PS's accessing, it also recognizes that the slave intends to wait to send its reply packet. This paper considers that the time to rendezvous channel (TTR) includes the time needed to confirm "failure to receive reply packet". Once the master selects the superior channel, it continues to use the same channel for subsequent attempts. One option is to change the selected channel for subsequent connection attempts. This paper considers an important future task is to determine the desirability of switching the selected channel after failure to connect.

3.3 Impact of Misdetection

In carrier sensing, misdetection triggers COR misunderstanding and collision between PS accessing signal and the request and reply packets. Collision causes the miss reception of the packet, where the miss reception of the packet means that not only the slave does not receive the request packet from the master, but also the master does not receive the reply packet from the slave. To compensate the miss reception of the packet, retransmission is necessary. As a result, TTR becomes large. Note that this paper ignores false alarms; if the channel is vacant, the terminal surely sends the packet to the partner.

4. Theoretical Analysis of TTR

4.1 Selection Probability of Minimum COR's Channel

The COR of ith channel is defined as

$$\bar{\rho}_i = k_i / l_i, \tag{3}$$

where l_i and k_i are the number of slots taken for estimating the COR of the ith channel and the number of slots occupied by PS in the ith channel, respectively. From the definition, the real COR of ith channel, ρ_i, is derived as

$$\rho_i = \lim_{l_i \to \infty} \bar{\rho}_i. \tag{4}$$

The real COR is equal to the average PS's accessing probability in a slot. When the PS's access is modeled as the random variable, the recognition of PS's access by the master or the slave is also the random variable. Therefore, the probability that the master or the slave recognizes the occupancy of the ith channel by PS's access in the slot, $\hat{\rho}_i$, is

$$\hat{\rho}_i = \rho_i(1-\varepsilon), \tag{5}$$

where ε is the miss detection probability of carrier sensing ($0 \le \varepsilon \le 1$). The miss detection probability depends on the location of PS and the channel propagation between sensor and PS. For simple analysis, this paper assumes the accuracy of carrier sensing is uniform and thus the miss detection probability of carrier sensing is also uniform for all the channels. Note that this paper assumes the false alarm is ignored. Therefore, it does not occur that the sensor decides the occupancy of the channel even in no PS's accessing. Since the $\bar{\rho}_i$ defined by Eq. (3) is composed of some decision results of PS's access, it is stochastic process. Therefore, the occurrence probability of $\bar{\rho}_i$, $f(\hat{\rho}_i, l_i, k_i)$, is defined as

$$f(\hat{\rho}_i, l_i, k_i) = {}_{l_i}C_{k_i}\hat{\rho}_i^{k_i}(1-\hat{\rho}_i)^{l_i-k_i}, \tag{6}$$

where ${}_aC_b$ is the number of combination patterns possible in selecting b from a. This paper assumes the time for estimating each channel's COR is uniform. Therefore, $l = l_1 = l_2 = \ldots = l_N$.

In the proposed learning assisted rendezvous channel, the channel of the smaller COR is more superior for rendezvous channel and that of the smallest COR among all the channels is the superior channel. When the estimated COR of the ith channel is smaller than that of jth channel, the master or the slave selects the ith channel as the more superior channel. If the former is as large as the latter, it decides the ith channel as the more superior channel by flipping coin. Therefore, the probability that the master or the slave chooses the ith channel as the more superior channel than the jth channel is

$$g_{i,j}(l) = \sum_{k_i=0}^{l}\sum_{k_j=k_i+1}^{l} f(\hat{\rho}_i, l, k_i) f(\hat{\rho}_j, l, k_j) + \frac{1}{2}\{f(\hat{\rho}_i, l, k_i)\}^2. \tag{7}$$

Therefore, the probability that the master or the slave chooses the ith channel as the more superior channel than any other channel, that is a superior channel, is

$$g_i(l) = \prod_{j=1, j\neq i}^{N} g_{i,j}(l). \tag{8}$$

The normalized probability that the master or the slave chooses the ith channel as the superior channel from the learning time of l slots is

$$G_i(l) = g_i(l) / \sum_{j=1}^{N} g_j(l). \tag{9}$$

4.2 Time to Exchange the Request Packet and the Reply Packet

In the packet exchange of the rendezvous channel, after the master emits the request packet, it hears the request packet. If the request packet is received, the rendezvous channel is completed, otherwise the master emits the request packet, again. In this section, the consecutive protocol of emitting the request packet and hearing the reply packet is defined as a one trial.

4.2.1 0th Trial

We consider that the master selects the ith channel as the superior channel for sending the request packet. We also consider that the master must wait for m_0 slots ($m_0 = 0, 1, \ldots$) until the PS releases the ith channel. After m_0 slots, the probability that the master can transmit the request packet through the ith channel is

$$h_i(m_0) = (1-\hat{\rho}_i)\hat{\rho}_i^{m_0-1}. \tag{10}$$

Similarly, after the slave must wait for n_0, ($n_0 = 0, 1, \ldots$) slots, the probability that the slave obtains the opportunity of transmitting the reply packet in the ith channel is

$$I_i(n_0) = (1-\hat{\rho}_i)\hat{\rho}_i^{n_0-1}. \tag{11}$$

From Eqs. (10) and (11), the probability that it takes $m_0 + n_0$ slots to exchange them, $J_i(m_0, n_0)$, is

$$J_i(m_0, n_0) = (1-\hat{\rho}_i)^2\hat{\rho}_i^{m_0+n_0-2}. \tag{12}$$

We derive the probability of avoiding the collision between the PS's access and the request packet or the reply packet. We consider the two events. Event A: The master or the slave decides that the channel is vacant. Event B: The channel is truly vacancy because of no PS's access. The probability of Event B under the Event A is that of avoiding the collision between the PS's access and the request packet or the reply one. This is the conditional probability $P(B|A)$ and is defined as

$$P(B|A) = \frac{P(B, A)}{P(A)}, \tag{13}$$

where $P(B, A)$ and $P(A)$ are the joint probability of Events B and A, and the probability of Event A, respectively. We can consider Event A is the sum event between the following two events. In first event, when the PS is accessing to the channel, the master or the slave decides that it is vacant due to the misdetection. In second event, when the PS is not accessing to the channel, it does. Note that we assume the false alarm is ignored. When PS is not accessing to the channel, the master or the slave can perfectly detect that the channel is vacant. Therefore, the probability of Event A to the ith channel, $P_i(A)$ is

$$P_i(A) = \rho_i\varepsilon + (1-\rho_i). \tag{14}$$

In addition, since Event A includes Event B, $B \subset A$, $P_i(B, A) = P_i(B) = 1 - \rho_i$ [17]. Therefore, the probability of avoiding the collision between PS and the request packet or the reply packet in the ith channel is

$$P_i(B|A) = \frac{1-\rho_i}{\rho_i\varepsilon + (1-\rho_i)} = \frac{1-\rho_i}{1-\hat{\rho}_i}. \quad (15)$$

Next, when the master and the slave decide the ith channel and the jth one as superior channels, respectively, the successful probability of exchanging the request and reply packets between the master and the slave, $V(i, j)$, is derived from Eq. (2) as

$$V(i,j) = \begin{cases} \alpha\left(\frac{1-\rho_i}{1-\hat{\rho}_i}\right)^2 = \alpha\beta_i, & j = i \\ \frac{1-\alpha}{N-1}\left(\frac{1-\rho_i}{1-\hat{\rho}_i}\right)^2 = \frac{1-\alpha}{N-1}\beta_i, & j \neq i \end{cases} \quad (16)$$

$$\beta_i = \left(\frac{1-\rho_i}{1-\hat{\rho}_i}\right)^2. \quad (17)$$

Therefore, in 0th trail, the probability of completing the packet exchange within $m_0 + n_0$ slots, $K_{i,j}(0, m_0, n_0)$, is

$$\begin{aligned} K_{i,j}(0, m_0, n_0) &= J_{i,j}(m_0, n_0)V(i, j) \\ &= (1-\hat{\rho}_i)^2\hat{\rho}_i^{m_0+n_0-2}V(i, j). \end{aligned} \quad (18)$$

When the total slots for the packet exchange are $p_0 (= m_0 + n_0 = 2, 3, \ldots)$, the number of combinations of m_0, n_0 for satisfying $p_0 = m_0 + n_0$ is ${}_{p_0-1}C_1$. Therefore, $K_{i,j}(0, m_0, n_0)$ is reformed as

$$K_{i,j}(0, p_0) = {}_{p_0-1}C_1(1-\hat{\rho}_i)^2\hat{\rho}_i^{p_0-2}V(i, j). \quad (19)$$

4.2.2 1st Trial

In the 1st trial, we assume that it takes m_1 slots and n_1 slots to send the request packet to the slave and the reply packet to the master, respectively. The cumulative required slots for completing the packet exchange in the 1st trial is $r = p_0 + p_1 = m_0 + n_0 + m_1 + n_1$. Therefore, the probability of completing the packet exchange within r slots, $K_{i,j}(1, r)$, is derived as follows.

$$\begin{aligned} &K_{i,j}(1, r) \\ &= {}_{p_0+p_1-1}C_3 \cdot J_{i,j}(p_0)\{1 - V(i, j)\} \cdot J_{i,j}(p_1)V(i, j) \\ &= {}_{r-1}C_3 \cdot (1-\hat{\rho}_i)^4\hat{\rho}_i^{r-4} \cdot V(i, j)\{1 - V(i, j)\}. \end{aligned} \quad (20)$$

4.2.3 Sth Trial

Similarly, we can derive the probability of successfully completing the exchange of the request packet and the reply one, when the master and the slave fail to exchange the packet in $S - 1$ attempts but do so at the Sth attempt, where $S = 0, 1, \ldots$. The total number of time slots, r, is defined as follows.

$$r = \sum_{s=0}^{S} p_s = \sum_{s=0}^{S}(m_s + n_s), \quad (21)$$

where m_s and n_s are the number of slots for sending the request packet and the reply packet at the sth attempt, respectively. The number of combinations of $m_0, n_0, \ldots, m_S, n_S$ is ${}_{r-1}C_{2S+1}$. Therefore, we derive the probability of completing the packet exchanging within r slots, $K_{i,j}(S, r)$, as

$$\begin{aligned} K_{i,j}(S, r) &= (1-\hat{\rho}_i)^{2(S+1)}\hat{\rho}_i^{r-2(S+1)} \\ &\quad V(i, j)\{1 - V(i, j)\}^S\ {}_{r-1}C_{2S+1}. \end{aligned} \quad (22)$$

In $i = j$, we can rewrite $K_{i,j}(S, r)$ as

$$\begin{aligned} P_i(S, r) &= (1-\hat{\rho}_i)^{2(S+1)}\hat{\rho}_i^{r-2(S+1)} \\ &\quad \alpha\beta_i(1 - \alpha\beta_i)^S\ {}_{r-1}C_{2S+1}. \end{aligned} \quad (23)$$

Similarly, in $i \neq j$, we can rewrite $K_{i,j}(S, r)$ as

$$\begin{aligned} Q_i(S, r) &= (1-\hat{\rho}_i)^{2(S+1)}\hat{\rho}_i^{r-2(S+1)} \\ &\quad \frac{1-\alpha}{N-1}\beta_i\left(1 - \frac{1-\alpha}{N-1}\beta_i\right)^S\ {}_{r-1}C_{2S+1}. \end{aligned} \quad (24)$$

4.3 Success Probability of Rendezvous Channel

If the master and the slave select the same channel as the superior channel, the probability of successfully exchanging packets is Eq. (23).

Each trial needs at least two slots. Therefore, when the total slots for completing the packet exchange are $u = (2, 3, \ldots)$, the maximal number of trials is $\lfloor u/2 - 1 \rfloor$, where $\lfloor \cdot \rfloor$ is the floor function. The probability of completing the packet exchange within u slots in the ith channel, $C_i(u)$, is

$$C_i(u) = \sum_{r=2}^{u}\sum_{S=0}^{\lfloor r/2-1 \rfloor} P_i(S, r). \quad (25)$$

Similarly, if the master and the slave select different superior channels, the probability of successfully exchanging packets is given by Eq. (24). Therefore, the probability of successfully completing packet exchange within u slots in the ith channel, $D_i(u)$, is

$$D_i(u) = \sum_{r=2}^{u}\sum_{S=0}^{\lfloor r/2-1 \rfloor} Q_i(S, r). \quad (26)$$

We assume that the slave has been active long enough to have filled its COR memories before the master starts estimating COR. In addition, for simplicity, we assume that COR remains constant. Therefore, the probability that the slave considers the ith channel as the superior channel is given by Eq. (9) with $l = M$, where M is memory size for each channel.

If the master and the slave decide the ith channel as the superior channel, the probability of completing the packet exchange within u slots is

$$C_i(u)G_i(l)G_i(M), \quad (27)$$

where l is the time for estimating the COR per one channel and thus lN is referred to as Learning time.

If the master decides the ith channel as the superior channel but the slave decides the other channel as it, the probability of completing the packet exchange within u slots is

$$D_i(u)G_i(l)\,(1 - G_i(M))\,. \tag{28}$$

When we take the probabilities of the packet exchange for all the channels, finally, the probability of completing the packet exchange, in other words the probability of successfully establishing the rendezvous channel, within u slots is

$$R(u) = \sum_{i=1}^{N} [C_i(u)G_i(l)G_i(M) + D_i(u)G_i(l)\{1 - G_i(M)\}]\,. \tag{29}$$

5. Numerical Results

Table 1 shows the channel model, where the numbers of channels, N, are 3 for Cases 1, 2, 3, 4 and 8 for Case 5, respectively. In Cases 1, 2, and 3, the COR of each channel is fixed. Since the COR of the 1st channel is minimum, the 1st channel is considered as the superior channel. In Cases 2 and 3, the differences in CORs between 1st and 2nd channels and between 2nd and 3rd ones are both 0.1. The CORs of Case 2 are much larger than those of Case 3. In Cases 4 and 5, for confirming the effect of the constructed rendezvous channel scheme in various channel model, the COR of each channel follows an independent uniform distribution with range of [0.0,0.8].

The misdetection probabilities, ε, are 0.0 and 0.1 for all figures except Fig. 8. The priority factor, α, is 0.7 for all figures except Figs. 5 and 6. Memory size, M, is 50 slots.

Table 1 Channel model.

Name	Number of Channels N	COR for Each Channel
Case 1	3	$\rho_1 = 0.2, \rho_2 = 0.6, \rho_3 = 0.8$
Case 2	3	$\rho_1 = 0.7, \rho_2 = 0.8, \rho_3 = 0.9$
Case 3	3	$\rho_1 = 0.1, \rho_2 = 0.2, \rho_3 = 0.3$
Case 4	3	Random Model of Uniform Distribution $\rho = 0 \sim 0.8$
Case 5	8	Random Model of Uniform Distribution $\rho = 0 \sim 0.8$

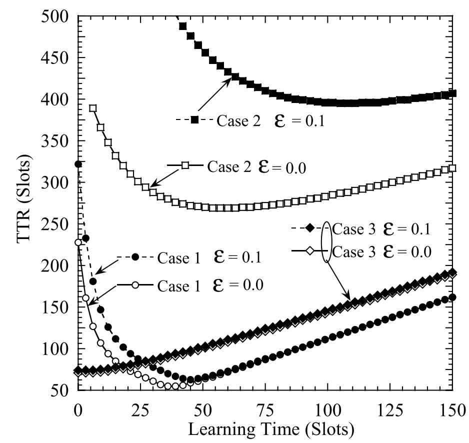

Fig. 3 Impact of learning time on TTR in Cases 1 to 3.

5.1 TTR in Fixed COR Channel Environment

5.1.1 Ideal Carrier Sensing

Figure 3 shows the learning time versus the TTR, where TTR is defined as the time, u, taken to satisfy $R(u) = 0.99$ in Eq. (29) plus the learning time. Therefore, TTR means the time taken to successfully establish the rendezvous channel in 99% of all attempts. The channel models are Cases 1 to 3. From this figure, in Cases 1 and 2, the performance exhibits a concave tendency. As the learning time becomes large, the accuracy of COR estimation is improved and thus the high speed exchange of request and reply packets through the superior channel is achieved. However, as the learning time increases further, it, rather than packet exchange, becomes the dominant component of TTR. When the learning time exceeds a certain value, TTR increases.

With $\varepsilon = 0.0$, the minimum TTRs are achieved for Cases 1 and 2 when the learning times are 38 and 80 slots, respectively. To clarify the reason for this, Fig. 4 shows the impact of learning time on the selection probability for each channel. In Case 1, when the learning time is 38 slots, the selection probabilities of $\rho = 0.8$ and $\rho = 0.6$ channels are approximately 0.0 and $1.4 \cdot 10^{-2}$, respectively. Therefore, in Case 1, the superior channel is certainly selected and a high speed rendezvous channel is thus formed. In Case 2, when the learning time is 60 slots, the selection probabilities of $\rho = 0.9$ channel is $1.0 \cdot 10^{-2}$. However, that of $\rho = 0.8$ is 0.25. Since the difference in COR between $\rho = 0.8$ and $\rho = 0.7$ is not so large, the channels cannot be distinguished by the roughly estimated COR. In addition, TTR is not significantly reduced because of the slight difference in COR between the superior channel and $\rho = 0.8$ channel. In Case 2, the worst channel is excluded by COR estimation and then the master starts packet exchange through the superior channel or the second superior channel. This is a suitable strategy for forming the high speed rendezvous channel.

In Case 3, Fig. 3 shows TTR is smallest with 0 learning time. There are a lot of access opportunities for any channel in Case 3, so the packets are quickly exchanged. In addition, as indicated, the difference in COR between the superior channel and the others is so small that the superior channel cannot be distinguished from the others by the roughly estimated COR. To form the high speed rendezvous channel, the “zero learning time” strategy is suitable.

5.1.2 Carrier Sensing with Misdetection Event

In cases 1 and 2 of Fig. 3, the optimal learning times with $\varepsilon = 0.1$ are larger than that with $\varepsilon = 0.0$. From Fig. 4, when misdetection may occur, the required time for selecting the superior channel at the certain probability becomes large. In other words, the degradation of selection probability to the superior channel can be compensated by enlarging the learning time. However, in Case 2, when ε becomes large, the

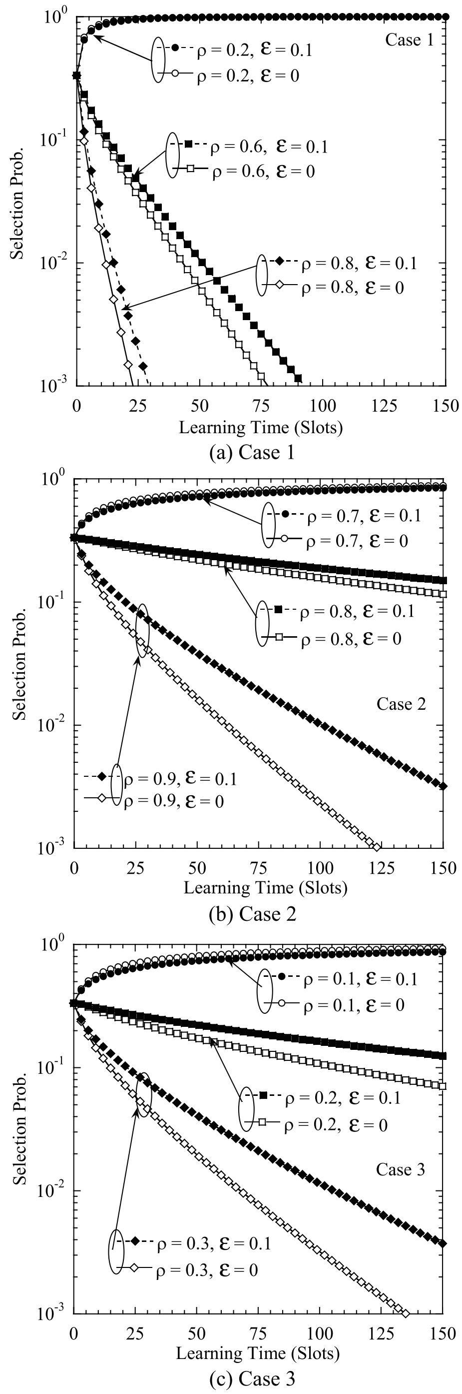

Fig. 4 Impact of learning time on channel selection probability in Cases 1 to 3.

TTR achieved by the optimal learning time is significantly increased. Since the CORs of all the channels are large, the collisions between the PS and the reply or request packets caused by the misdetection frequently occur. Therefore, a lot of retrials consume time.

5.1.3 Effect of Priority Factor, α

Figure 5 shows the impact of priority factor, α, on TTR,

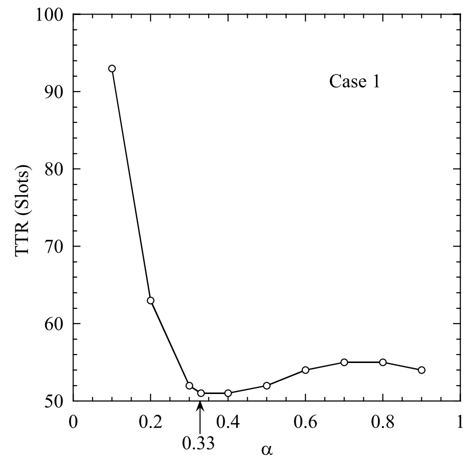

Fig. 5 Impact of priority factor α on TTR in Case 1.

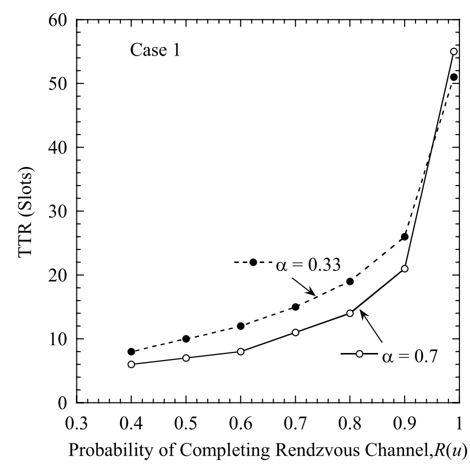

Fig. 6 Impact of the probability of completing rendezvous on TTR in Case 1.

where the channel model is Case 1, $\varepsilon = 0.0$, and TTR is obtained by the $R(u) = 0.99$ of Eq. (29). The priority factor decides the access probability of the slave to the superior channel. From this figure, the TTR of $\alpha = 0.33$ is 4 slots smaller than that of $\alpha = 0.7$. Since $\alpha = 0.33$ means uniform measurement is used, the advantage of learning measurement is not obvious.

For understanding this effect, Fig. 6 shows the impact of the probability of completing rendezvous, $R(u)$, in Eq. (29) on TTR, where $\alpha = 0.33$ and 0.7. The learning time is optimized for each probability. From this figure, when the probability lies in the range 0.4 to 0.9, the TTR with $\alpha = 0.7$ is 2 to 5 slots smaller than that with $\alpha = 0.33$. Reference [15] indicates that the average TTR with learning measurement is smaller than that with random hopping, where the random hopping scheme is the same as uniform measurement. Therefore, our results match those of Ref. [15]. However, in $R(u) = 0.99$, the TTR with $\alpha = 0.33$ is 4 slots smaller than that with $\alpha = 0.7$. As we explained in Fig. 4(a), the access probability of $\rho = 0.6$ is $1.4 \cdot 10^{-2}$. In $R(u) = 0.99$, it is not negligible that the slave selects the channel with

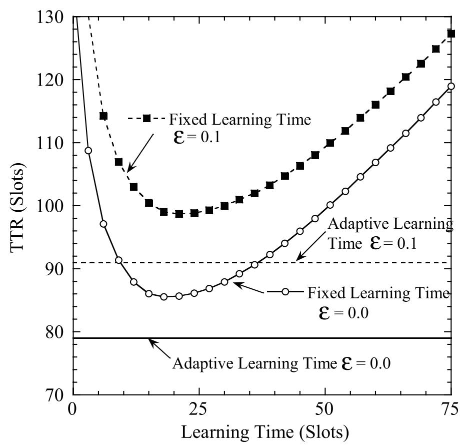

Fig. 7 Impact of learning time on TTR in Case 4 - part 1.

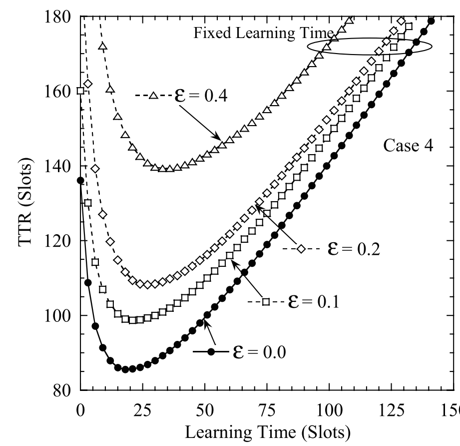

Fig. 8 Impact of learning time on TTR in Case 4 - part 2.

$\rho = 0.6$. In $\alpha = 0.7$, the probability of accessing the channel with $\rho = 0.6$ is 0.15. Therefore, the master has more difficulty in reaching the slaves with $\alpha = 0.7$ than with $\alpha = 0.3$. It takes more time to complete rendezvous. Nevertheless, if it is accepted that the rendezvous channel is completed with long TTR at 1%, we admit $\alpha = 0.7$ is slightly superior to $\alpha = 0.33$. Since the weak point of learning measurement is found in the worst cases, in the following evaluation, the TTR for $R(u) = 0.99$ is also evaluated.

5.2 TTR in Uniform Model of COR

Figure 7 shows the impact of the learning time on TTR in Case 4, where the COR of each channel is modeled by a random variable with uniform distribution. There are two variants, fixed and adaptive learning time. In fixed learning time, the learning time is fixed regardless of the actual COR. In adaptive learning time, as the minimum TTR is achieved, the learning time for each COR is adaptively, and ideally, changed. This figure indicates that TTR with adaptive learning time is constant.

From this figure, when $\varepsilon = 0.0$ and the learning time is 18 slots, the minimum TTR with fixed learning time is achieved. The difference in minimum TTR between fixed learning time and adaptive learning time is 7 slots. If the slight degradation in TTR is accepted, it is not necessary to adaptively change the learning time following the actual COR.

When $\varepsilon = 0.1$, the TTRs with fixed and adaptive learning times become larger than those when $\varepsilon = 0.0$. In addition, Fig. 8 shows the impact of learning time on TTR for various misdetection rates. From this figure, as ε becomes large, the optimal learning time for minimum TTR becomes large. This is because a longer learning time is necessary to compensate the misdetection. However, as ε becomes large from 0.0 to 0.4, the optimal learning time becomes large from 20 slots to 35 slots but the minimum TTR significantly becomes large from 85 slots to 140 slots. Therefore, the longer learning time does not compensate the misdetection, perfectly. This is because as we described in Case2, the longer learning time is not effective for avoiding the packet collision between PS and SS caused by the misdetection. In Fig. 7, the difference in TTR between fixed and adaptive learning times at $\varepsilon = 0.0$ is as large as that at $\varepsilon = 0.1$. If the constant degradation in TTR is accepted, it is also not necessary to adaptively change the learning time to suit the actual COR even with practical carrier sensing.

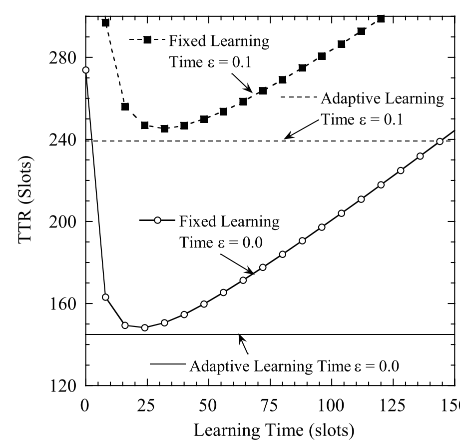

Fig. 9 Impact of learning time on TTR in Case 5.

Figure 9 shows the performance between learning time and TTR in Case5. The difference between Cases 4 and 5 is the number of channels, where the number of channels is 8. The model of COR is the same as that of Case 4. In Fig. 9, we can see the performance tendency and the performance gap between fixed learning time and the adaptive one are similar to those of Case 4. However, when ε is changed from 0.0 to 0.1, the TTR is significantly degraded. The TTRs in $\varepsilon = 0.1$ is about 95 slots larger than that in $\varepsilon = 0.0$. This reason is as follows. From Eq. (2), the connection probabilities of the superior channel and the other one are 0.7 and 0.15 in $N = 3$ but 0.7 and 0.0428 in $N = 8$, respectively. If the master does not select the channel which the slave selects as the superior channel, the slave can hardly receive the request packet, so a lot of trials are necessary for completing the rendezvous channel. As we described, the misdetection causes the packet collision between PS and SS, so a lot of retrials consumes TTR.

6. Conclusion

This paper introduced a theoretical analysis to derive the optimal learning time for the learning-assisted rendezvous channel. The analysis took the impact of carrier sensing errors into account. The numerical results indicate that if the difference in COR among channels is large, the optimal learning time for minimum rendezvous exists and can be found from the convex plot of TTR versus learning time. However, if it is not, it is difficult to distinguish among the low COR channels, and a small learning time is the most suitable strategy for high speed rendezvous. In the uniform random model environment of COR, the TTR achieved with the certain learning time is near to that with the optimal learning time for actual COR.

In addition, the impact of misdetection to the rendezvous channel is evaluated. As the number of channels becomes large, it becomes harder. The causes of this are the difficulty of finding the superior channel and the packet collision between primary system and secondary one. It is important future work to recover these problems.

In practical wireless environment, the propagation models, such as fading, shadowing, and propagation loss, are necessary for determining the model of misdetection. Reference [18] clarifies the impact of the propagation loss to the rendezvous channel, where the problem of missing PS's access is referred to as hidden node terminal. The analysis of the hidden node terminal problem in practical wireless environment is also important future work.

Acknowledgement

A part of this research project is sponsored by Ministry of Internal Affairs and Communications in Japan under the project name of Strategic Information and Communications R&D Promotion Programme (SCOPE 135003005) and KAKENHI (24760293).

References

[1] J. Mitola and G.Q. Maguire, "Cognitive radio: Making software radios more personal," IEEE Pers. Commun., vol.6, no.4, pp.13–18, Aug. 1999

[2] H. Harada, T. Baykas, S. Chin-Sean, H. Murakami, K. Ishizu, S. Filin, Y. Alemseged, T. Ha Nguyen, S. Chen, M. Azizur Rahman, W. Junyi, L. Zhou, P. Chang-Woo, G. Villardi, S. Chunyi, R. Funada, and F. Kojima, "Research, development, and standards related activities on dynamic spectrum access and cognitive radio," Proc. IEEE DYSPAN 2010, pp.1–12, April 2010

[3] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," IEEE J. Sel. Areas Commun., vol.23, pp.201–220, Feb. 2005.

[4] E. Hossain, D. Niyato, and Z. Han, Dynamic spectrum access and management in cognitive radio networks, Cambridge university press 2009.

[5] K.C. Chen and R. Prasad, Cognitive radio networks, Wiley, 2009.

[6] J.J. Pil and Y. Myungsik, "Resource-aware rendezvous algorithm for cognitive radio networks," Proc. IEEE The 9th International Conference on Advanced Communication Technology, vol.3, pp.1673–1678, Feb. 2007.

[7] J. Lei and F.Y. Li, "A single radio based channel data rate-aware parallel rendezvous MAC protocol for cognitive radio networks," Proc. IEEE Conference on Local Computer Networks, 2009, pp.392–399, Oct. 2009.

[8] M. Jeonghoon, H.-S.W. So, and J. Walrand, "Comparison of multichannel MAC protocols," IEEE Trans. Mobile Comput., vol.7, no.1, pp.50–65, Jan. 2008.

[9] S. Jongmin, Y. Dongmin, and K. Cheeha, "A channel rendezvous scheme for cognitive radio networks," IEEE Commun. Lett., vol.14, no.10, pp.954–956, Oct. 2010.

[10] D. Yang, J. Shin, and C. Kim, "Deterministic rendezvous scheme in multichannel access networks," Electron. Lett., vol.46, no.20, pp.1402–1404, Sept. 2010.

[11] S. Hang and Z. Xi, "Channel-hopping based single transceiver MAC for cognitive radio networks," Proc. IEEE Conference on Information Sciences and Systems, 2008, pp.197–202, March 2008.

[12] N.C. Theis, R.W. Thomas, and L.A. DaSilva, "Rendezvous for cognitive radios," IEEE Trans. Mobile Comput., vol.10, no.2, pp.216–227, Feb. 2011.

[13] L.A. DaSilva and I. Guerreiro, "Sequence-based rendezvous for dynamic spectrum access," Proc. IEEE DySPAN 2008, p.7, Oct. 2008.

[14] S. Hoi, W. So, J. Walrand, and M. Jeonghoon, "McMAC: A parallel rendezvous multi-channel MAC protocol," Proc. IEEE, Wireless Communications and Networking Conference, 2007, pp.334–339, March 2007.

[15] C. Cormio and K.R. Chowdhury, "An adaptive multiple rendezvous control channel for cognitive radio wireless ad hoc networks," Proc. IEEE International Conference on Pervasive Computing and Communications Workshops, pp.346–351, March-April 2010.

[16] S.M. Kay, Fundamentals of statistical signal processing, Prentice hall, 1998.

[17] A. Papoulis, Probability, random variables, and stochastic process, McGraw-Hill, 2nd edition, 1984.

[18] O. Takyu, K. Kinoshita, T. Fujii, and Y. Umeda, "A study of channel identification method based on channel occupancy ratio for multichannel wireless access," IEICE Technical Report, SR2010-14, May 2010. (in Japanese)

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