Analysis of Channel Access Delay in CR-MAC Protocol for Ad Hoc Cognitive Radio Wireless Sensor Networks without a Common Control Channel

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Abstract

Ad hoc cognitive radio wireless sensor networks allow secondary wireless sensor nodes to recognize spectrum opportunities and transmit data. Most existing protocols proposed for ad hoc cognitive radio wireless sensor networks require a dedicated common control channel. Allocating one channel just for control packet exchange is a waste of resources for channel-constrained networks. There are very few protocols that do not rely on a common control channel and that exchange channel-negotiation control packets during a pre-allocated time on the data channels. This, however, can require a substantial amount of time to access the channel when an incumbent is present on the channel, where the nodes are intended to negotiate for the data channel. This study examined channel access delay on cognitive radio wireless sensor networks that have no dedicated common control channel.

Keywords: channel access delay, medium access control, cognitive radio networks, cognitive radio wireless sensor networks, common control channel

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1. Introduction

Many studies have examined several aspects of cognitive radio networks (CRNs). Because the radio spectrum resource is limited for wireless communication systems, inadequate resource management can restrict the development of next-generation wireless communication systems.

A wireless sensor with a cognitive radio (CR) is called a cognitive radio wireless sensor (CR-WS). Networks of these sensors collaborate for research or industrial and consumer applications, such as environmental monitoring, warfare, child education, surveillance, microsurgery, agriculture, wildlife monitoring and fire sensing. The CR-WS generates a packet burst whenever an event is detected, and might otherwise remain silent for a long time.

In CRNs, primary users (PUs) are the license holders; therefore, they have first priority when accessing the channels. Secondary users (SUs) are opportunistic and utilize a channel whenever the PUs are not using it. Because PUs and SUs have a different priority on the channel, CR wireless sensor networks (CR-WSNs) are very different than traditional wireless sensor networks. Therefore, media access control (MAC) layer protocols designed for traditional wireless sensor networks (WSNs) cannot be used directly in CR-WSNs.

To protect the right of the PUs to access the channel, SUs have to monitor PU activity on a regular basis. If a PU claims a channel currently used by SUs, the SUs have to immediately leave the channel and inform neighboring SUs about the PU's arrival on the channel. To flag PU activity and negotiate for the channel for data communications, most existing MAC protocols for CR-WSNs rely on a dedicated common control channel (CCC) [1]. The CCC is common among all nodes and, in most cases, it is assumed that this channel is not subject to PU intervention.

However, the CCC may get saturated, and can become a victim of a denial-of-service attack [2]. In addition, allocating just one channel for control packet exchange is a waste of resources for channel-constrained (e.g., 802.11b) networks [3]. Using the industrial, scientific and medical (ISM) band for a CCC is also a kind of violation of CRNs' original principle.

In this work, we analyze how long it takes to access the channel under a cognitive radio media access control (CR-MAC) protocol for ad hoc cognitive radio wireless sensor networks without a dedicated CCC.

2. Related Work

CR-WSNs are a specialized ad hoc network of distributed wireless sensors that are equipped with cognitive radio capabilities. In many ways, a CR-WSN is different from conventional WSNs and conventional distributed CRNs. The CR-WSN is an emerging research area, and research on them is still in its infancy. The detailed differences in various aspects among ad hoc CRNs, WSNs, and CR-WSNs were reported by Joshi et al. [4].

Although, several MAC layer protocols, both with and without a CCC, have been reported in the literature on CRNs [5-8], there are a few MAC protocols proposed for CR-WSNs with a dedicated CCC. There are even fewer protocols proposed in the literature for CR-WSNs without a CCC.

In the CR environment, it is not allowed to access a channel without proper information about PUs' existence in that channel. It is very important for SUs to leave the channel whenever a PU claims it. For these reasons, most of the protocols for CR-WSNs are

CCC-based. In our previous work, we analyzed channel access delay in a synchronized MAC protocol for CRNs [9]. To the best of our knowledge, this is the first work that analyzes channel access delay in ad hoc CR-WSNs without a CCC.

3. Protocol Description

This paper analyzes a MAC protocol for a CR-WSN that requires no dedicated CCC. A prototype of such a protocol is described briefly. Each CR-WS node was assumed to be equipped with two transceivers; one for data packets and another for control packets. In the beginning, we assumed each CR-WS node knows how many channels can be accessed opportunistically, which is denoted by κ. Whenever a node wakes up, it selects a channel to listen to and waits for a time period of length $\kappa \times BI$, where BI is a beacon interval fixed by a set design parameter. The BI was assumed to be a tolerable time period for PUs. If the wakened node does not receive any signal from other nodes within the $\kappa \times BI$ time, the node declares itself the first node in the network. The first node divides the channel into BIs, and each BI is divided further into the default timeslot (τ) and I_{data}, as shown in **Fig. 1**. τ is a default time period for a particular channel and is slotted into N_s number of mini-slots. I_{data} is a combination of the data transmission time (I'_{data}) and the channel switching time. The first node creates channel sensing sequence, senses the channel, and broadcasts a sync message at the beginning of the BI, and other nodes respond to the sync message, as reported by Sichitiu and Veerarittiphan [10].

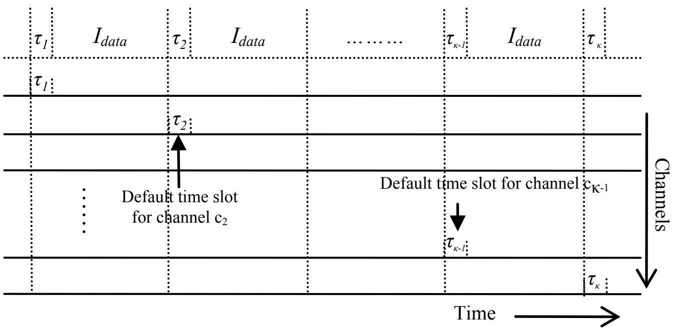

Fig. 1. Channels with their default timeslots.

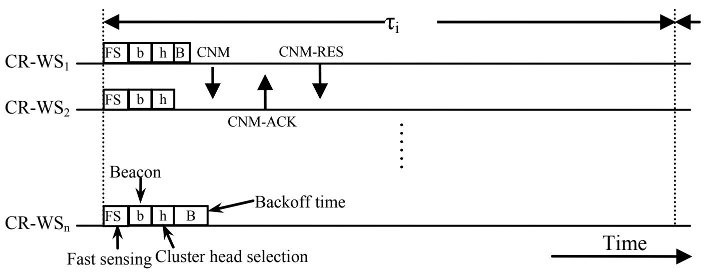

Fig. 2. Channel negotiation in the default timeslot.

After synchronization, the nodes sense the channel, contend for channel access, broadcast a beacon to inform the neighbors as to the BI and default time, and select the cluster head [11]. Subsequently, the nodes that have packets to send start the channel negotiation process by exchanging a channel negotiation message (CNM), along with channel negotiation acknowledge (CNM-ACK) and channel negotiation reservation (CNM-RES) packets, as shown in **Fig. 2**. All these packets are sent after the interframe spacing (IFS) time. Other nodes listen for the channel negotiation messages and update their channel status table.

After channel negotiation, the nodes begin sending data on the negotiated channel in the I_{data} period. After I_{data}, the nodes again rendezvous on another channel. This process continues in the same manner.

If a PU is sensed on the channel at the beginning of the default time, all the nodes hop to another channel without interfering with the PU, and they continue the process. In addition, if there are no control packets for a substantial period of time, the SUs assume the arrival of PUs on the channel. Because PUs can tolerate a unit of time up to one BI, a collision within the default time would be tolerable damage. In addition, before sending data packets in I_{data}, the nodes sense the channel, and if a PU detected, the SUs stop sending data packets.

4. Channel Access Delay Analysis

The channel access delay was analyzed by the control transceiver in default timeslot τ. **Table 1** lists the notation used throughout this work.

Table 1. Notations and their definitions.

Notations	Description
X	MAC layer access delay
I'_{data}	Data transmission time
I_{data}	Combination of channel switching delay and I'_{data}
m	Station short retry count, and maximum backoff stage
W_i	Contention window size in backoff stage i
W	Minimum contention window size
ς_i	Transmission succeeds in stage i
$E[X]$	Expectation of X
E_i	Event that the transmission succeeds in the i^{th} retrial
β	Primary users arrive rate
N	Number of primary users on the channel at an arbitrary time
p	Probability that a packet transmitted from an SU encounters a collision
p_1	Probability that a transmitted packet encounters a collision with any packet from a PU.
p_2	Probability that a transmitted packet encounters a collision with any packet from an SU.
p_{bp}	Probability that an SU senses a PU's presence on the channel during the fast-sensing period

Notations	**Description**
$\widetilde{W}_j$	Sojourn time in stage *j* measured in the number of mini-slots
W_i^*	Summation of $\widetilde{W}_j$ up to stage *i*
s_0	Time when stage 0 starts in the given channel's default time, i.e. when the MAC layer access attempt starts
N_s	Number of mini-slots in one default time
Δ	Width of one mini-slot
τ	Default timeslot
X_{add}	Delay from the time when a MAC layer receives data from the upper layer to the first available τ.

The contention model was considered, where the contention window size W_i in backoff stage *i* is determined to be

$$W_i = 2^i W, \qquad \text{if } i \le m, \tag{1}$$

where *W* is the minimum contention window size, *m* is the station short retry count and *m* is also the maximum backoff stage. The expectation of the MAC layer access delay *X* can be expressed as

$$\mathrm{E}[X] = \mathrm{E}[\mathrm{E}[X \mid E_i]] = \sum_{i=0}^{m} E[X \mid E_i] \times \Pr(\zeta_i). \tag{2}$$

Now, the behavior of the PUs on the channel was modeled. The primary users were assumed to arrive on the channel according to a Poisson process at a rate of β, and the sojourn time of each primary user on the channel is distributed exponentially with an average of $1/\alpha$. If *N* denotes the number of primary users on the channel at an arbitrary time, the process $\{N(t), t \ge 0\}$ can be modeled by a birth-death process, as shown in the state transition diagram in **Fig. 3**.

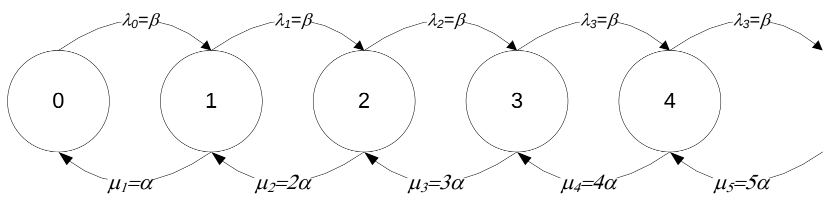

Fig. 3. State transition diagram of the birth-death process.

If P_n is defined as $P_n = \Pr(N = n)$ for $n \ge 0$, then the following set of balance equations can be obtained [12]:

$$\lambda_0 P_0 = \mu_1 P_1,$$

$$\lambda_n P_n = \mu_{n+1} P_{n+1} \qquad for\ n \ge 1.$$

The following can be obtained by solving the set of equations iteratively:

$$P_0 = \frac{1}{1+\sum_{n=1}^{\infty}\left(\frac{\prod_{i=0}^{n-1}\lambda_i}{\prod_{i=1}^{n}\mu_i}\right)} = \frac{1}{1+\sum_{n=1}^{\infty}\frac{1}{n!}\left(\frac{\beta}{\alpha}\right)^n} = \frac{1}{e^{\frac{\beta}{\alpha}}} = e^{-\frac{\beta}{\alpha}},$$

$$P_n = \frac{\prod_{i=0}^{n\text{-}1}\lambda_i}{\prod_{i=1}^{n}\mu_i}P_0 = \frac{1}{n!}\left(\frac{\beta}{\alpha}\right)^n P_0 = \frac{1}{n!}\left(\frac{\beta}{\alpha}\right)^n e^{\text{-}\frac{\beta}{\alpha}} \text{ for } n \geq 1. \tag{3}$$

Actually, Eq. (3) is also valid for $n \geq 0$.

Therefore, N has the following distribution:

$$\Pr(N=n) = \frac{1}{n!}\left(\frac{\beta}{\alpha}\right)^n e^{-\frac{\beta}{\alpha}}, \qquad (n \geq 0) \tag{4}$$

If p denotes the probability that a packet transmitted from an SU encounters a collision, then

$$1-p = (1-p_1)(1-p_2)$$

$$\text{i.e.,} \quad p = p_1 + p_2 - p_1 p_2, \tag{5}$$

where p_1 and p_2 are the probability that a transmitted packet encounters a collision with any packet from a PU, and the probability that a transmitted packet encounters a collision with any packet from an SU, respectively. p_2 can be obtained using the formulae described by Barowski and Biaz [13] (their Section III).

An SU will experience a collision if the channel is used by the PUs when the SU attempts to use the channel. Therefore, p_1 can be approximated by 1 – Pr(N=0) = $1-e^{-\frac{\beta}{\alpha}}$, of Eq. (4), if the mini-slot interval in the default time is negligibly short compared to the duration that the PU is active on the channel.

Let p_{bp} represent the probability that an SU senses the presence of a PU on the channel during the fast-sensing period (see **Fig. 2**). Assuming that the duration of the fast-sensing period is negligibly small compared to the duration of the data window, then p_{bp} can be approximated as

$$\widehat{p}_{bp} = 1-\Pr(N=0) = 1-e^{-\frac{\beta}{\alpha}},$$

i.e.

$$p_{bp} \cong 1-e^{-\frac{\beta}{\alpha}}, \tag{6}$$

Also,

$$\Pr(\zeta_i) = \frac{p^i(1-p)}{1-p^{m+1}}. \tag{7}$$

Combining Eq.(2) and Eq.(7) yields

$$\mathrm{E}[X] = \sum_{i=0}^{m} \frac{p^i(1-p)}{1-p^{m+1}} \mathrm{E}[X \mid E_i] \tag{8}$$

Let $\widetilde{W}_j$ denote the sojourn time in stage j measured in the number of mini-slots, and let W_i^* represent the summation of $\widetilde{W}_j$ up to stage i, i.e. $W_i^* = \sum_{j=0}^{i} \widetilde{W}_j$. s_0 denotes the time when stage 0 begins in the default time of the given channel, i.e. when the MAC layer access attempt begins. When N_s and Δ denote the number of mini-slots in a single default time and the width of one mini-slot, respectively, s_0 can be assumed to be distributed uniformly as follows:

$$\Pr(s_0 = i\Delta) = \frac{1}{N_s}, \quad 0 \le i \le N_s - 1. \tag{9}$$

If E_i represents the event that the transmission succeeds in stage i, then

$$\mathrm{E}[X \mid E_i] = \sum_j \mathrm{E}[X \mid W_i^* = j, E_i] \Pr(W_i^* = j \mid E_i) \tag{10}$$

By assuming independence between s_0 and W_i^*,$\mathrm{E}[X \mid W_i^* = j, E_i]$ can be expressed as

$$\begin{aligned}
\mathrm{E}[X \mid W_i^* = j, E_i] &= \sum_{k=0}^{N_s-1} \mathrm{E}[X \mid W_i^* = j, E_i, s_0 = k\Delta] \times Pr(s_0 = k\Delta \mid W_i^* = j, E_i) \\
&= \sum_{k=0}^{N_s-1} \mathrm{E}[X \mid W_i^* = j, E_i, s_0 = k\Delta] \Pr(s_0 = k\Delta) \\
&= \sum_{k=0}^{N_s-1} \mathrm{E}[X \mid W_i^* = j, E_i, s_0 = k\Delta] \frac{1}{N_s},
\end{aligned} \tag{11}$$

In cases where no PU is attempting to access the channel, then $E[X \mid W_i^* = j, E_i, s_0 = k\Delta]$ of Eq.(11) can be simplified as

$$E[X \mid W_i^* = j, E_i, s_0 = k\Delta] = \left\lfloor \frac{(k+j)\Delta}{N_s\Delta} \right\rfloor I_{data} + j\Delta \tag{12}$$

If a PU is sensed during the fast-sensing period, SUs do not attempt to access the channel during that BI. Therefore, when P_{bp} is not zero, $E[X \mid W_i^* = j, E_i, s_0 = k\Delta]$ can be expressed by the expectation of negative binomial distribution as

$$E[X \mid W_i^* = j, E_i, s_0 = k\Delta] = \left\lfloor \frac{(k+j)\Delta}{N_s\Delta} \right\rfloor \frac{I_{data}}{1-p_{bp}} + j\Delta \tag{13}$$

Combining Eqs. (11) and (13) yields

$$E[X \mid W_i^* = j, E_i] = \sum_{k=0}^{N_s-1}\left[\left\lfloor \frac{(k+j)}{N_s} \right\rfloor \frac{I_{data}}{1-p_{bp}} + j\Delta\right]\frac{1}{N_s},$$

$$= j\Delta + \frac{I_{data}}{N_s(1-p_{bp})}\sum_{k=0}^{N_s-1}\left\lfloor \frac{(k+j)}{N_s} \right\rfloor. \qquad (14)$$

Combining Eq.(10) and Eq.(14) yields

$$\mathrm{E}[X \mid E_i] = \sum_j E\left[X \mid W_i^* = j \mid E_i\right]\Pr(W_i^* = j \mid E_i),$$

$$= \sum_j \left[j\Delta + \frac{I_{data}}{n}\sum_{k=0}^{n-1}\left\lfloor \frac{(k+j)\Delta}{n\Delta} \right\rfloor\right]\Pr(W_i^* = j \mid E_i),$$

$$= \Delta E\left[W_i^* = j \mid E_i\right] + \sum_j \frac{I_{data}}{n}\sum_{k=0}^{n-1}\left\lfloor \frac{(k+j)}{n} \right\rfloor \Pr(W_i^* = j \mid E_i),$$

$$\mathrm{E}[X \mid E_i] = \Delta\sum_{j=0}^{i}\frac{W_j+1}{2} + \sum_{j=i+1}^{W_0+\cdots+W_i}\frac{I_{data}}{N_s - p_{bp}}\sum_{k=0}^{N_s-1}\left\lfloor \frac{k+j}{n} \right\rfloor \Pr(W_i^* = j \mid E_i). \qquad (15)$$

Here,

$$\Pr(W_i^* = i+1 \mid E_i) = \frac{1}{w_0}\cdot\frac{1}{w_1}\cdots\cdots\frac{1}{w_i} = \prod_{j=0}^{i}\frac{1}{w_j}$$

$$\Pr(W_i^* = i+2 \mid E_i) = \binom{i+1}{1}\frac{1}{w_0}\cdot\frac{1}{w_1}\cdots\cdots\frac{1}{w_i} = \prod_{j=0}^{i}\frac{1}{w_j}$$

$$\Pr(W_i^* = j \mid E_i) = \binom{j-1}{i}\prod_{k=0}^{i}\frac{1}{w_k}, \qquad if\ j \le w_0 + i,\ j \ge i+1$$

Therefore, $\Pr(W_i^* = j \mid E_i)$ can be expressed as follows:

$$\Pr(W_i^* = j \mid E_i) = A(j,i)\prod_{k=0}^{i}\frac{1}{W_k}, \qquad (16)$$

In Eq. (16), $A(n,i)$ counts the number of solutions for the integer indeterminate equation $X_0 + X_1 + X_2 + \dots + X_i = n$, when, $X_j \ge 1$ and $X_j \le W_j (0 \le j \le i)$

A closed-form formula for $A(n,i)$ is difficult to derive, but it is possible to evaluate the value of $A(n,i)$ numerically for given values of n, i and W_j using the following recursive formula and initial conditions:

$$A(n,i) = \sum_{j=1}^{W_i} A(n-j, i-1), \quad \text{for } i \geq 1,$$

$$A(n,0) = \begin{cases} 1, & 1 \leq n \leq W_n, \\ 0, & \text{otherwise.} \end{cases}$$

Assume that the MAC layer of a given node can receive data from the upper layer at an arbitrary time. Let X_{add} be the random variable denoting the delay from the time when a MAC layer receives data from the upper layer to the first available default time slot.

$$\begin{aligned} E[X_{add}] = & \left[E\left[X_{add} \mid packet\ arrival\ in\ I_{data}\ interval\right] \times Pr(packet\ arrival\ in\ I_{data}\ interval) \right] \\ & + \left[E\left[X_{add} \mid packet\ arrival\ in\ \tau\ interval\right] \times Pr(packet\ arrival\ in\ \tau\ interval) \right] \\ = & \left(\frac{I_{data}}{2} + \Delta \right) \cdot \frac{I_{data}}{I_{data} + N_s \Delta} + \left(\frac{\Delta}{2} \right) \cdot \frac{N_s \Delta}{I_{data} + N_s \Delta} \\ = & \frac{I_{data}^2 + 2\Delta I_{data} + N_s \Delta^2}{2\left(I_{data} + N_s \Delta\right)} \end{aligned} \tag{17}$$

The following can be obtained by combining Eqs. (8), (15), (16) and (17)

$$\begin{aligned} E[X] = & \sum_{i=0}^{m} \frac{p^i (1-p)}{1-p^{m+1}} \sum_{j=i+1}^{W_0+\cdots+W_i} \frac{I_{data}}{N_s (1-p_{pb})} \cdot A(j,i) \cdot \left(\prod_{l=0}^{i} \frac{1}{W_l} \right) \sum_{k=0}^{N_s-1} \left\lceil \frac{k+j}{N_s} \right\rceil \\ & + \Delta \sum_{j=0}^{m} \left(\frac{W_j + 1}{2} \right) \frac{p^j - p^{m+1}}{1-p^{m+1}} + \frac{I_{data}^2 + 2\Delta I_{data} + N_s \Delta^2}{2\left(I_{data} + N_s \Delta\right)}. \end{aligned}$$

The channel access delay was compared with the CCC-based protocol and the discussed protocol without CCC, with varying numbers of PUs from 4 to 55 nodes. This analysis was simulated using C++, and ns-2 [14] was extended for the simulation. The first part of **Table 2** lists the parameters and values used for the analysis. For the analysis, the collision probability was taken from the simulation results. The next part of **Table 2** presents the simulation parameters.

Fig. 4 presents the results of an evaluation of the proposed model and simulation results when the number of SUs is constant at 15 nodes. In the simulation, if a CR node loses contention for channel access, it attempts to regain it next time until it wins contention or reaches the maximum retry limit. The SU node can win contention in any subsequent BI. For simplicity, it is assumed that s_0 is distributed uniformly over a single default time slot in the analysis. The simulation results and the analysis results are closely matched. The small gap between the analysis and simulation results is due to the assumption of s_0 above.

Table 2. Simulation parameters.

Parameter	**Value**
Maximum retry limit	3
Minimum *CW* size	32
τ	20 ms
Δ	1.27 ms
I'_{data}	80 ms
κ	6
For simulations	
Channels' bit rate	2 Mbps
Traffic	CBR (100 packets/sec)
Channel switching delay	224 μs
Channel usage model	ON/OFF
Simulation runtime	40 seconds
Area	120 m × 120 m
Iterations	10

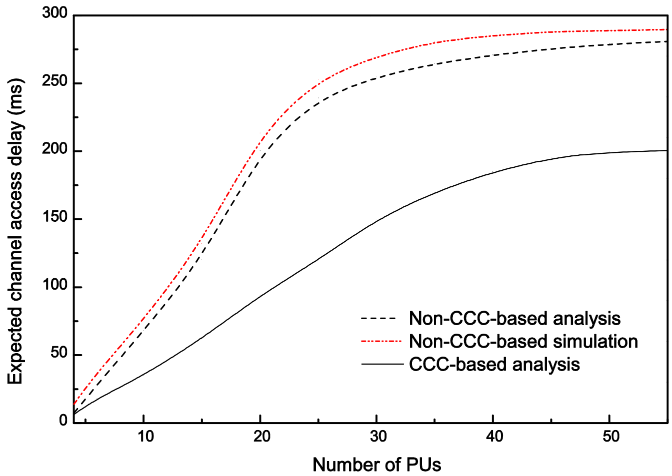

Fig. 4. Comparison of the channel access delay with the CCC-based protocol and non–CCC-based protocol.

Fig. 4 also compares the channel access delay in the CCC-based MAC protocol [15] and the discussed non–CCC-based protocol. The result shows that the non–CCC-based protocol has slightly more delay than the CCC-based protocol when the number of PUs increases. This is because in the CCC-based protocol, the nodes negotiate for the channel on a separate channel. On the other hand, in the discussed non–CCC-based protocol, SUs need to wait until the next default time if the channel is occupied by a PU in that channel's default time. In the worst case, some SUs may get a chance to access the channel after several BIs. In addition, there is a channel-switching delay, because at each time, the SUs negotiate for a channel during a different channel's default time.

Fig. 5 shows the delay due to the number of SUs, whereas the number of active PUs is constant at five. Here, active PUs means the PUs have a packet to send. The figure shows that if the number of PUs increases, the channel access delay is higher, and vice versa.

The results show that when the number of active PUs is small, the channel access delay is reasonable, even if there is no dedicated CCC for control packet exchange. However, when the number of active PUs is higher, it is better to use a dedicated CCC.

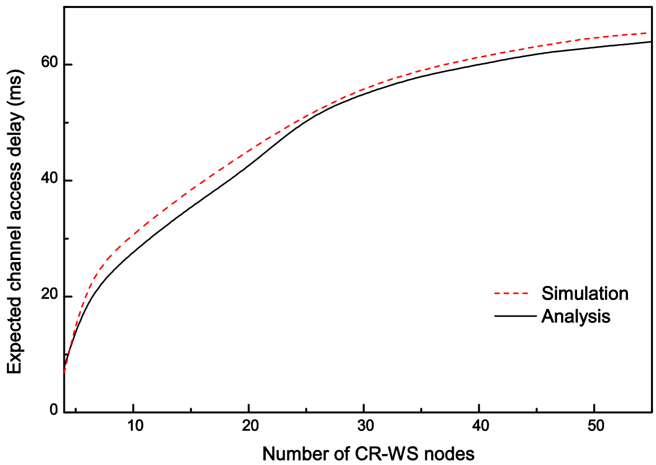

Fig. 5. Comparison of the channel access delay by analysis and simulation when the number of active PUs is 5.

5. Conclusion

This paper analyzed a non–CCC-based MAC protocol for CR-WSNs. The advantage of this protocol is that it does not require a dedicated CCC for control packet exchange. Therefore, it does not suffer from CCC bottleneck problems and saves bandwidth resources. On the other hand, this protocol requires tight time synchronization, which causes overhead. This protocol has a slightly higher channel access delay than the CCC-based protocol in the case of a dense network topology. The results suggest that CCC is necessary for dense CR-WSNs. The above-discussed non–CCC-based MAC protocol might be suitable for non–delay-sensitive applications and/or sparse-network scenarios.

The CCC-based MAC protocol has issues as to how to obtain a dedicated CCC channel to negotiate exclusively for control packets. The present study showed that it is possible to communicate opportunistically with no dedicated CCC channel. The tradeoff is that it incurs a delay in cases of dense SU deployment.

References

[1] Brandon F. Lo, "A survey of common control channel design in cognitive radio networks," *Physical Communication*, vol. 4, no. 1, pp. 26-39, March, 2011. Article (CrossRef Link).

[2] Kaigui Bian and Jung-Min Park, "MAC-layer misbehaviors in multi-hop cognitive radio networks," MAC-layer misbehaviors in multi-hop cognitive radio networks," in *Proc. of the 2006 US - Korea Conference on Science, Technology, and Entrepreneurship (UKC2006)*, August 2006.

[3] Gyanendra Prasad Joshi and Sung Won Kim "Mitigating the control channel bottleneck problem in dense cognitive radio networks," *International Journal of the Physical Sciences*, vol. 6, no. 20, pp. 4832–4837, September, 2011. Article (CrossRef Link).

[4] Gyanendra Prasad Joshi, Seung Yeob Nam, and Sung Won Kim, "Cognitive radio wireless sensor networks: Applications, challenges and research trends." *Sensors, vol.* 13, no. 9, pp. 11196-11228, August, 2013. Article (CrossRef Link).

[5] Brandon F. Lo, "*Design and analysis of common control channels in cognitive radio ad hoc networks.*" PhD Thesis, Georgia Institute of Technology, December, 2013.

[6] Yongli Sun, Bin Zhou, Zhenguo Wu, Qiufen Ni, and Rongbo Zhu, "Multi-channel MAC protocol in cognitive radio networks." *Journal of Networks*, vol. 8, no. 11, pp. 2478–2490, November, 2013. Article (CrossRef Link).

[7] Kaigui Bian, Jung-Min Park, and Ruiliang Chen, "Control channel establishment in cognitive radio networks using channel hopping." IEEE Journal on Selected Areas in Communications, vol. 29, no. 4, pp. 689-703, April, 2011. Article (CrossRef Link).

[8] De Domenico Antonio, Emilio Calvanese Strinati, and M-G. Di Benedetto, "A survey on MAC strategies for cognitive radio networks." *IEEE Communications Surveys & Tutorials,* vol. 14, no. 1, pp. 21-44, First Quarter 2012. Article (CrossRef Link).

[9] Gyanendra Prasad Joshi, Seung Yeob Nam, and Sung Won Kim, "An analysis of channel access delay in synchronized MAC protocol for cognitive radio networks," *Transactions on Emerging Telecommunications Technologies*, doi: 10.1002/ett.2589, September, 2012. Article (CrossRef Link).

[10] Mihail L. Sichitiu and Chanchai Veerarittiphan, "Simple, accurate time synchronization for wireless sensor networks," in *Proc. of the IEEE Wireless Communications and Networking (WCNC 2003)*, vol.2, pp.1266–1273, March 16-20, 2003.

[11] Gyanendra Prasad Joshi, Srijana Acharya and Sung Won Kim, "Decentralized cognitive radio medium access control protocol for cognitive radio wireless sensor networks," *INFORMATION*, in press.

[12] S.M. Ross, *Probability Models for Computer Science*. Academic Press, New York.

[13] Yawen Barowski and Saâd Biaz, *The performance analysis of IEEE 802.11 under unsaturated traffic conditions*, Technical Report, Auburn University, Alabama, USA, pp. 1–12, August 3, 2004.

[14] *The network simulator—ns-2*. Internet: http://www.isi.edu/nsnam/ns/. Accessed 17 June 2009.

[15] Michael Timmers, Sofie Pollin, Antoine Dejonghe, Liesbet Van der Perre, and Francky Catthoor, "A distributed multichannel MAC protocol for multihop cognitive radio networks," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 1, pp. 446–459, January, 2010. Article (CrossRef Link).

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