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SHORT RESEARCH LETTER

An analysis of channel access delay in synchronized MAC protocol for cognitive radio networks

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ABSTRACT

The spectrum scarcity issue due to a fixed radio spectrum allocation system has become an obstacle to future wireless communications. In cognitive radio, the idea of an open spectrum was devised, which allows unlicensed users to utilise these underutilised licensed spectrum bands opportunistically. Several synchronisation-based, Medium Access Control protocols for cognitive radio networks have been reported. This study examines how these protocols suffer from the common control channel bottleneck problem in a dense network. The analysis shows that control messages exchanging in a fixed channel negotiation window in the control channel is not efficient in dense cognitive radio networks. This increases the channel access delay and limits the network performance. This study develops an analytical model to calculate the expected channel access delay and analyse the impact of the number of nodes on the channel access. The analysis is verified with simulations. Copyright © 2012 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The next-generation wireless network will most likely suffer from spectrum-scarcity problems because of the increasing number of wireless consumer electronics devices. This creates a new challenge to researchers. Cognitive radio (CR) networks came up with the idea to mitigate this spectrum-scarcity problem by utilising licensed spectra opportunistically. Several protocols to access channels opportunistically have been reported [1–3].

Some of the synchronisation-based Medium Access Control (MAC) protocols for CR networks divide time into beacon intervals (BIs), and the BIs are divided further into a channel negotiation (CN) window and a data window [4, 5]. This study examined the channel access delay of those synchronisation-based MAC protocols.

Figure 1 shows the structure of the BI, CN window and data window. At the start of each CN window, all nodes in the network are synchronised by periodic beacon transmission. After synchronisation, all nodes tune their transceivers into the common control channel (CCC) for the CN window. Nodes with data to send compete for channel access. The contention winner sends the CN message with the available channel list to the receiver. The receiver node selects a common channel from its own available channel list and sends back an acknowledgement (CN-ACK), along with the selected channel. After receiving a CN-ACK, the sender sends a confirmation message for channel reservations (CN-RES) to inform the neighbour nodes about channel selection, as shown in Figure 1(b). The contention winner nodes initiate negotiations for the channel in the CN window. The sender sends the CN message and then sends CN-RES after receiving CN-ACK from the intended receiver.

The synchronised MAC protocols for CR networks are less prone to the CCC bottleneck problem. However, they cannot perform well in dense CR networks because CN messages are sent only in the CN window, which is (in general) around one quarter of the total data window. The CN window can be overcrowded and cannot negotiate for all available channels when the number of communicating pairs exceeds the available time slots in the CN window. This may lead to some of the data channels being underutilised or completely unused.

Although this problem can be solved with a large CN window, the bandwidth of all the data channels is wasted if the CN window is too large because the nodes do not

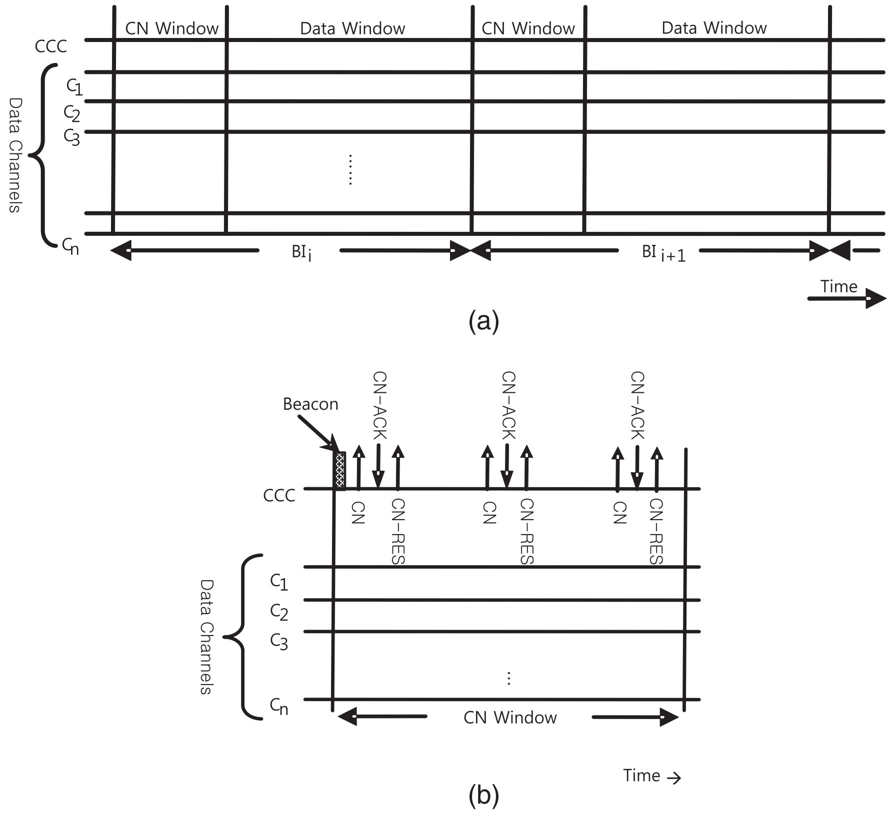

Figure 1. Channel negotiation in synchronisation-based cognitive radio Medium Access Control protocols. (a) Beacon intervals (BIs), channel negotiation (CN) window and data window. (b) CN in CN window.

send or receive data packets at the CN window. In addition, increasing the CN window also decreases the data window, which obviously decreases the overall network throughput. The duration of the BIs cannot be increased because licensed users have a limited tolerable interference time. On the other hand, if the CN window is too short, the contention loser nodes have to wait until the next BI. In the worst case, there may be several BIs if the number of nodes is very high. Therefore, they might have to wait a long time to access the idle channels. Because the data window is much larger than the CN window, waiting for more than one BI is more costly in terms of delay and bandwidth utilisation.

The remainder of this paper is organised as follows. Section 2 reviews some of the related papers. Section 3 discusses the consequences of the number of nodes in a channel access delay in CN-window-based CR MAC protocols. Section 3 also discusses the analysis and simulation results. Section 4 reports conclusions and future work.

2. RELATED WORK

Several researchers are working in this area, and a number of papers have been published. The IEEE 802.22 working group [6] already standardised a MAC layer based on CR for reusing the spectrum allocated to a TV broadcast service. IEEE 802.22 specifies that the network should operate point to multipoint. The architecture of the 802.22 MAC layer is centralised and relies on base stations. Many locations where licensed spectrum bands are underutilised lack infrastructure. Therefore, a decentralised approach can be the solution to utilise those spectrum holes because ad hoc networks do not require any central infrastructure.

A multichannel MAC protocol (MMAC-CR) is proposed in [4] for CR networks. This is a synchronisation-based protocol. As described in the introduction, in this protocol, time is divided into an ad hoc traffic indication message (ATIM) window and a data window. In the ATIM window, secondary users exchange control packets for CN and channel reservation. After CN, secondary users hop into the selected data channels in the data window and transfer data packets in the respective channels. In this protocol, data packet transmission begins only after the ATIM window. In the ATIM window, nodes cannot send or receive any data packets; hence, the channel bandwidth of all data channels in the ATIM window are wasted. Similar to MMAC-CR, an energy-efficient CR MAC protocol for quality-of-service provisioning (ECRQ-MAC) [5] is proposed. Some other synchronisation-based protocols are discussed in [1–3].

3. CONSEQUENCES OF THE NUMBER OF NODES IN CHANNEL ACCESS DELAY IN CHANNEL NEGOTIATION WINDOW-BASED COGNITIVE RADIO MEDIUM ACCESS CONTROL PROTOCOLS

Once the number of nodes with packets to send reaches more than the number of mini-slots available in a CN window, the probability of collisions increase. The existing protocols use similar channel access techniques to the 802.11 basic access. This study develops a model and analyses how the expected channel access delay increases when the number of active secondary CR nodes increases.

Let X denote the MAC layer access delay. m represents the station short retry count, and m is also the maximum backoff stage. In this paper, a contention model is considered, where the contention window size W_i in the backoff stage i is determined to be

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

where W is the minimum contention window size. The expectation of X can then be expressed as follows

$$\begin{aligned} E[X] &= E[E[X|\text{trans. succeeds in stage } i]] \\ &= \sum_{i=0}^{m} E[X|\text{trans succeeds in stage } i] \\ &\quad \times \Pr(\text{trans. succeeds in stage } i) \end{aligned} \tag{2}$$

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

$$\Pr(\text{trans. succeeds in stage } i) = \frac{p^i(1-p)}{1-p^{m+1}} \tag{3}$$

Combining Equations (2) and (3) yields

$$\begin{aligned} E[X] = &\sum_{i=0}^{m} \frac{p^i(1-p)}{1-p^{m+1}} \\ &\times E[X|\text{trans. succeeds in stage } i] \end{aligned} \tag{4}$$

Let $\tilde{W}_j$ denote the sojourn time in stage j measured in the number of mini-slots and W_i^* denote the summation of $\tilde{W}_j$ up to stage i, that is, $W_i^* = \sum_{j=0}^{i} \tilde{W}_j$. s_0 denotes the time when stage 0 starts in the given CN window, that is, when the MAC layer access attempt begins. N_s and Δ denote the number of mini-slots in one CN window and the width of one mini-slot, respectively. For simplicity, it is assumed that s_0 is distributed uniformly as follows:

$$\Pr(s_0 = i\Delta) = \frac{1}{N_s}, \quad 0 \leqslant i \leqslant N_\text{s} - 1 \tag{5}$$

If E_i represents the event that the transmission succeeds in stage i, the following can be obtained:

$$E[X|E_i] = \sum_j E\left[X|W_i^* = j, E_i\right] \Pr\left(W_i^* = j|E_i\right) \tag{6}$$

Assuming independence between s_0 and W_i^*, $E\left[X|W_i^* = j, E_i\right]$ can be expressed as follows:

$$\begin{aligned} &E\left[X|W_i^* = j, E_i\right] \\ &\quad = \sum_{k=0}^{N_\text{s}-1} E\left[X|W_i^* = j, E_i, s_0 = k\Delta\right] \\ &\qquad \times \Pr\left(s_0 = k\Delta|W_i^* = j, E_i\right) \\ &\quad = \sum_{k=0}^{N_s-1} E\left[X|W_i^* = j, E_i, s_0 = k\Delta\right] \Pr(s_0 = k\Delta) \\ &\quad = \sum_{k=0}^{N_s-1} E\left[X|W_i^* = j, E_i, s_0 = k\Delta\right] \frac{1}{N_\text{s}} \\ &\quad = \sum_{k=0}^{N_\text{s}-1} \left(\left\lfloor \frac{(k+j)\Delta}{N_s\Delta} \right\rfloor I_\text{data} + j\Delta\right) \frac{1}{N_s} \\ &\quad = j\Delta + \frac{I_\text{data}}{N_\text{s}} \sum_{k=0}^{N_s-1} \left\lfloor \frac{(k+j)}{N_s} \right\rfloor \end{aligned} \tag{7}$$

where I_data is the data window time. Because $E\left[W_i^*|E_i\right] = \sum_{l=0}^{i} (W_l+1)/2$ by the random selection of backoff values in each backoff stage, combining (6) and (7) yields

$$\begin{aligned} E[X|E_i] &= \sum_j E\left[X|W_i^* = j, E_i\right] \Pr\left(W_i^* = j|E_i\right) \\ &= \sum_j \left\{ j\Delta + \frac{I_\text{data}}{N_\text{s}} \sum_{k=0}^{n-1} \left\lfloor \frac{k+j}{N_\text{s}} \right\rfloor \right\} \\ &\quad \times \Pr\left(W_i^* = j|E_i\right) \\ &= \Delta \sum_j j \Pr\left(W_i^* = j|E_i\right) \\ &\quad + \sum_j \frac{I_\text{data}}{N_\text{s}} \sum_{k=0}^{n-1} \left\lfloor \frac{k+j}{N_\text{s}} \right\rfloor \Pr\left(W_i^* = j|E_i\right) \\ &= \Delta E\left[W_i^*|E_i\right] + \sum_j \frac{I_\text{data}}{N_\text{s}} \sum_{k=0}^{n-1} \left\lfloor \frac{k+j}{N_\text{s}} \right\rfloor \\ &\quad \times \Pr\left(W_i^* = j|E_i\right) \\ &= \Delta \sum_{l=0}^{i} \frac{W_l+1}{2} \\ &\quad + \sum_{j=i+1}^{W_0+\cdots+W_i} \frac{I_\text{data}}{N_\text{s}} \sum_{k=0}^{N_\text{s}-1} \left\lfloor \frac{k+j}{N_\text{s}} \right\rfloor \\ &\quad \times \Pr\left(W_i^* = j|E_i\right) \end{aligned} \tag{8}$$

$\Pr\left(W_i^* = j \,|\, E_i\right)$ can be expressed as

$$\Pr(W_i^* = j \,|\, E_i) = A(j,i) \prod_{k=0}^{i} \frac{1}{W_k} \tag{9}$$

where $A(n,i)$ counts the number of solutions for the indeterminate integer equation below under the condition that $X_j \geqslant 1$ and $X_j \leqslant W_j \, (0 \leqslant j \leqslant i)$.

$$X_0 + X_1 + \ldots + X_i = n.$$

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.

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

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

By combining Equations (4), (8) and (9),

$$E[X] = \Delta \sum_{j=0}^{m} \left(\frac{W_j + 1}{2}\right) \frac{p^j - p^{m+1}}{1 - p^{m+1}} + \left[\sum_{i=0}^{m} \frac{p^i (1-p)}{1 - p^{m+1}} \sum_{j=i+1}^{W_0 + \cdots + W_i} \frac{I_{\text{data}}}{N_s} \right. \\ \left. .\ A(j,i) \cdot \left(\prod_{l=0}^{i} \frac{1}{W_l} \right) \sum_{k=0}^{N_s - 1} \left\lfloor \frac{k+j}{N_s} \right\rfloor \right],$$

where the collision probability p can be obtained using the formulae described in Section 3 of [7].

In Figure 2, the model and simulation results are closely matched, where the maximum retry limit is 3, Δ is 1.27 ms, I_{data} is 80 ms and the minimum CW size is 16. ns-2 [8] is used for the simulation. The number of CR nodes varies from four to 25 nodes and is distributed in a 400-m^2 area. The BI is set to 100 ms, and the CN window size is one-fourth of the data window size. The results are reported as an average of 10 iterations.

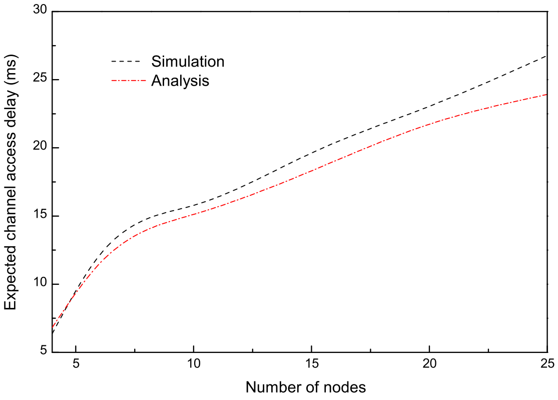

Figure 2. Comparison of the channel access delay by analysis and simulation.

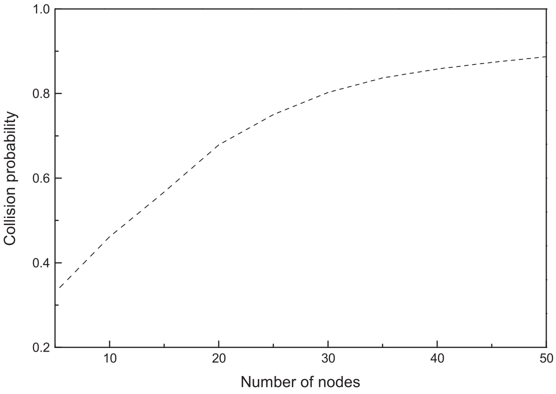

Figure 3. Collision probability.

The graph shows that the channel access delay increases drastically whenever the number of nodes increases. This creates a channel bottleneck problem and decreases the network throughput. Therefore, some measures are needed to solve this problem. This is an open issue to researchers.

In a simulation, if a CR node loses contention for channel access, it tries next time until it wins the contention or reaches the maximum retry limit. The CR node can win the contention in any subsequent BI. On the other hand, for simplicity, it is assumed that s_0 is distributed uniformly over one CN window in the analysis. In Figure 2, the gap between the analysis and simulation results is due to these assumptions. Furthermore, in the analysis, the *beacon time* is not considered, as shown in the beginning of the CN window in Figure 1(b). The CR nodes synchronise with other CR nodes. They sense the channel status and report during this time. This also helps increase the gap between the analysis and simulation results.

Figure 3 shows the collision probability observed by the simulation using the same parameters. The graph shows that the collision probability increases drastically after six to eight nodes. This is because Δ takes 1.27 ms and the CN window size is just 20 ms. Even in the best case, less than 16 nodes have an opportunity to access the channel.

4. CONCLUSION

This study examined how synchronisation-based MAC protocols for CR networks suffer from the CCC bottleneck problem. The analysis shows that in dense CR networks, the control messages exchange during a limited time and only if the control channel is insufficient. This increases the channel access delay and limits the performance of the network. Therefore, other measures that allow multiple negotiation messages in a distributed manner are required.

Two possible solutions are as follows: (i) distribute the CN packets in multiple channels; and (ii) estimate the number of nodes and adjust the CN window. These possible solutions will be examined in a future study.

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REFERENCES

1. Cormio C, Chowdhury KR. A survey on MAC protocols for cognitive radio networks. *Ad Hoc Networks* 2009; **7**: 1315–1329.
2. De Domenico A, Calvanese Strinati E, Di Benedetto MG. A survey on MAC strategies for cognitive radio networks. *IEEE Communications, Surveys and Tutorials* 2012; **14**(1): 21–44.
3. Wang H, Qin H, Zhu L. A survey on MAC protocols for opportunistic spectrum access in cognitive radio networks. *International Conference on Computer Science and Software Engineering* 2008; **1**: 214–218.
4. Timmers M, Pollin S, Dejonghe A, Van der Perre L, Catthoor F. A distributed multichannel MAC protocol for multihop cognitive radio networks. *IEEE Transactions on Vehicular Technology* 2010; **59**(1): 446–459.
5. Kamruzzaman SM, Hamid MA, Abdullah-Al-Wadud M. An energy-efficient MAC protocol for QoS provisioning in cognitive radio ad hoc networks. *Radioengineering* 2010; **19**(4): 567–578.
6. LAN/MAN Standards Committee of the IEEE Computer Society. IEEE Std 802.22-2011: IEEE Standard for Information Technology: Telecommunications and information exchange between systems. Wireless regional area networks (WRAN): specific requirements. Part 22: cognitive wireless RAN Medium Access Control (MAC) and physical layer (PHY) specifications: policies and procedures for operation in the TV bands., Approved 16 June (2011).
7. Chatzimisios P, Boucouvalas AC, Vitsas V. IEEE 802.11 packet delay: a finite retry limit analysis, In *IEEE GLOBECOM,* Vol. 2, San Francisco, CA, USA, 2003; 950–954.
8. The network simulator—ns-2. (Available from: http://www.isi.edu/nsnam/ns/. [Accessed on 17 June 2009]).