科技部補助專題研究計畫成果報告
期末報告

多重通道感知無線隨意網路之具有能源效率與高輸出量媒介存取協定

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中文摘要：本計畫將提出一個在多重通道感知無線隨意網路環境中具能源效率與高輸出量之媒介存取協定。藉由考慮降低PU干擾及提升SU通道使用率達到提升系統輸出量的目的，為達到此目的及降低對隱藏節點PUs及SUs的干擾；並同時解決暴露節點SU問題，提出動態長度之競爭視窗大小及SU傳送端持續佔有多個資料時槽機制。此競爭視窗包含四個控制訊框，控制訊框時槽長度將由SU所感測到PU空閒的資料通道個數及SU競爭節點個數多寡所共同決定。如果所有控制訊框時槽長度都是固定時，當設定值太大時，在SU低負載的情況時，將導致系統浪費較長時間在等待競爭週期的結束；當設定值太小時，在SU高負載的情況時，將導致系統因競爭情況加劇，使碰撞所導致的隱藏節點問題更形嚴重而大大降低系統效能。而為了延長整個網路生命週期，藉由計算SU傳送端所剩餘的能量多寡來決定是否持續佔有多個資料通道時槽，並提升系統輸出量。

中文關鍵詞：感知無線隨意網路；媒介存取協定；隱藏節點；暴露節點；網路生命週期。

英文摘要：In this proposal, we propose an Energy Efficient and High Throughput MAC (EEHT-MAC) protocol in multichannel Cognitive Radio Ad Hoc Networks (CRAHNs), to solve the hidden and exposed terminal problems of multichannel PUs and SUs. To improve the system throughput by reduce the interference to PUs and increase the channel utilization of SUs. We propose the dynamic length of contention window and permit the SU sender to reserve multiple data slots to solve the hidden and exposed terminal problems between PUs and SUs. Too longer length in contention window, the SUs must wait more time on contention window under lower load. In contrast, too shorter length in contention window, the contention and hidden terminal problems will be serious under higher load. In order to increase the network life time and fairness, the low power of SU sender can reserve multiple data slots.

We also compare our proposed scheme to existing MAC protocols for CRAHNs. We will show that EEHT-MAC has higher power efficiency and system throughput than previous MAC protocols.

英文關鍵詞：cognitive radio ad hoc networks；MAC；hidden terminal problem； exposed terminal problem；network lifetime。

Energy Efficient and High Throughput MAC Protocol for Multichannel Cognitive Radio Ad Hoc Networks

Chien-Min Wu

***Abstract*—In cognitive radio ad hoc networks (CRAHNs), secondary users (SUs) can opportunistically utilize the spectrum that is available from primary users (PUs). SUs must hop from one spectrum band to another to obtain spectrum opportunities. The medium access control (MAC) protocol for CRAHNs plays an important role to exploit the spectrum opportunities, manage the interference to PUs, and coordinate the spectrum access amongst SUs. In this paper, we propose an energy efficient and high throughput MAC (ETMAC) protocol in multichannel CRAHNs to reduce the energy consumption and increase throughput in multichannel CRAHNs. The energy consumption will be reduced by the dynamic length of contention window and the selective sensing to PU channels according to the successful sensing probability. For the dynamic length of contention window, the ETMAC will save more idle slots and decrease energy consumption and MAC contention delay. The ETMAC using dynamic length scheme of contention window is also proposed to solve the hidden and exposed terminal problems between PUs and SUs. We compare our proposed scheme to existing MAC protocols for CRAHNs. We will show that ETMAC has higher channel spatial reuse and normalized throughput, lower energy consumption and MAC delay than previous MAC protocols.**

***Index Terms*—cognitive radio ad hoc networks (CRAHNs),medium access control (MAC), hidden terminal problem, exposed terminal problem, Markov chain model.**

I. INTRODUCTION

Today's wireless networks are regulated by a fixed spectrum assignment policy. According to the Federal Communications Commission (FCC), the variation range in the utilization of the assigned spectrum is about 15 % to 85 %, with a high variance in time. The spectrum is a limited available source. Inefficient spectrum usage necessitates a new communication technology to opportunistically exploit the existing wireless spectrum. This new access method for the wireless spectrum is referred to as NeXt Generation (xG) Network, as well as Dynamic Spectrum Access (DSA) and Cognitive Radio Network (CRN) [1], [2], [3].

In CRNs, secondary users (SUs) can opportunistically utilize the spectrum of primary users (PUs) when it is idle. In cognitive radio ad hoc networks (CRAHNs), the spectrum can be divided into several channels. A single-channel can be used by SUs when there is no interference with other SUs and no interference between SUs and PUs; this improves network performance. In multichannel CRAHNs, channels are unreliable owing to collisions between SUs and PUs. Therefore, medium access control (MAC) protocols are quite important for avoiding collisions between SUs and PUs and avoiding problems with hidden terminals and exposed terminals.

In cognitive radio (CR) networks, MAC protocols play an important role in exploiting spectrum opportunities, managing the interference with PUs, and coordinating the spectrum access among SUs. A single-channel MAC protocol contains a common channel shared by wireless mobile nodes. IEEE 802.11 is a widely used standard based on a single-channel model. When using such a protocol, system performance will decrease rapidly as the number of nodes increases because of increased contentions and collisions among nodes.

One scheme to reduce the contention and collision problems between SUs is to utilize multichannel. With the progress of wireless network technology, allowing one SU to access multiple channels is feasible at the same time. Thus, we can define a multichannel MAC protocol that has such capability. In addition, using multichannel also has three advantages. First, while the maximum throughput

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of a single-channel MAC protocol will be limited by the bandwidth of the channel, the throughput may be increased immediately if one SU is allowed to utilize multichannel. Second, using multichannel will experience less normalized propagation delay per channel than single-channel. Third, since using a single channel is difficult to support quality of service (QoS). And this is easier to do so by using multichannel [4].

The hardware limitations of practical cognitive radios are considered in [5]. The authors identify two hardware constraints of a cognitive radio. One is a sensing constraint, and the other is a transmission constraint. A decentralized cognitive MAC (DC-MAC) for opportunistic spectrum access in ad hoc networks is proposed in [6]. The authors developed an analytical framework for opportunistic spectrum access based on the theory of Partially Observable Markov Decision Process (POMDP). The POMDP scheme integrates the design of channel access protocols at the MAC layer with channel sensing at the physical layer.

An Opportunistic Spectrum MAC (OS-MAC) for wireless networks equipped with cognitive radios is proposed in [7]. The OS-MAC proposes a new protocol for cognitive wireless networks that empowers software-defined radios (SDRs) based wireless devices with following capabilities. First, OS-MAC can adaptively and dynamically seek and exploit opportunities in both licensed and unlicensed spectra and along both the time and frequency dimensions. Second, OS-MAC can access and share spectrum among different unlicensed and licensed users. Thirs, OS-MAC can coordinate with SUs for better spectrum utilization.

In [8], a novel cognitive MAC (C-MAC) protocol for distributed multichannel CRAHNs is proposed. C-MAC operates over multichannel, and hence is able to effectively deal with channel access among PUs and SUs. CMAC overcome the dynamics of resource availability due to PUs and mitigate the effects of distributed quiet periods utilized for PUs signal detection.

An efficient cognitive-radio-enabled multichannel MAC (CREAM-MAC) protocol for CRAHNs is proposed in [9], which integrates the spectrum sensing at physical layer and packet scheduling at MAC layer. Under the proposed CREAM-MAC protocol, each SU is equipped with a cognitive radio-enabled transceiver and multiple channel sensors. The proposed CREAM-MAC enables the SUs to best utilize the unused frequency spectrum while avoiding the collisions among SUs and between SUs and PUs.

A MAC protocol for opportunistic spectrum access (OSA-MAC) in CRAHNs is proposed by [10]. The OSA-MAC protocol works in a multichannel environment which is capable of performing channel sensing to discover spectrum opportunities. OSA-MAC also uses the Power Saving Mechanism (PSM) model from IEEE 802.11 DCF-based WLANs. It assumes that time is divided into beacon intervals, and that all SUs are synchronized by periodic beacon transmissions.

A novel MAC (N-MAC) scheme for multichannel CRAHNs considers the PU signal that may cover only part of the network. The proposed N-MAC scheme adjusts the sensing priorities of channels at each SU with the PU detection information of other SUs and also limits the transmission power of a SU to the maximum allowable power in order to guarantee the quality of the service requirements of the PU [11].

An energy-efficient distributed multichannel MAC protocol (MMAC) is proposed for CR networks [12]. MMAC can achieve energy-efficient communication, and the phases of its sensing algorithms include a low-power inaccurate scan and a high-power accurate scan.

The modeling and analytical delay analysis for a multichannel cognitive radio network is proposed [13]. The authors shown that a buffering MAC protocol outperforms a switching MAC protocol. The reason is that the delay bottleneck for both protocols is the time required to successfully access the control channel, which occurs more frequently for the switching MAC protocol.

A contention based distributed medium access control (CBMAC) protocol for the secondary users channel access is proposed in [14]. The CBMAC allows collision-free access to the available PU data channels and eventually their utilization by SUs. CBMAC also introduce the provision of reservation of free channels by SUs for extended periods to increase utilization without causing harmful interference to PUs. The contention window cycle size of CBMAC protocol is suitably chosen to keep the interference caused to primary within a tolerable range.

The primary motivation underlying almost all previous MAC protocols is throughput awareness due to the characteristics of CRAHNs, such as severe resource constraints, hidden terminal problems, exposed terminal problems and PU outage probability conditions. However, there is a rising need for efficient throughput and delay aware MAC protocols, proportional to the increasing number of the fields of their applications, such as TV white spaces, emergency and public safety applications, vehicular Communications, and novel applications of CRAHNs.

In this paper, we propose a energy efficient and high throughput MAC (ETMAC) protocol using for multichannel CRAHNs, to enable primary users (PUs) to efficiently use the available spectrum. In addition, frequencies reserved for PUs may experience periodic use and frequent quiet periods; thus, secondary users (SUs) may utilize these frequencies during these periods. However, in cases in which SUs use PU frequencies, PUs must not be subjected to performance degradation. The beacon interval of ETMAC is the sum of sensing window and contention window and is small than the CBMAC. Therefore, the ETMAC will keep the interference caused by PUs within a tolerable range.

These requirements motivated use to design a distributed MAC protocol for CRAHNs, to reduce the energy consumption and MAC delay due to the contention among SUs and the sensing to PUs in multichannel CRAHNs.

The main goal of this paper is to design a ETMAC protocol in multihop, multichannel CRAHNs. ETMAC resolves multichannel hidden terminal problems for PUs and SUs, as well as multichannel exposed terminal problems for SUs. The main contributions of this paper are the design of a multichannel MAC protocol for CRAHNs, and the development of a Markov chain model to characterize the normalized throughput and other performance metrics for the saturation CRAHNs. In this protocol, requiring two transceivers per node mitigates the hidden and exposed terminal problems in multichannel CRAHNs, unlike other multichannel MAC protocols that only mitigate the hidden terminal problem.

The remainder of this paper is organized as follows: ETMAC protocols are described in Section 2. Basic operation of the multichannel ETMAC and normalized throughput analysis for the saturation CRAHNs are described in Sections 3 and 4, respectively. We evaluate the performance of the proposed ETMAC with some numerical results obtained from a simulation in Section 5. Finally, the paper concludes in Section 6.

II. ENERGY EFFICIENT AND HIGH THROUGHPUT MAC (ETMAC) PROTOCOL

In this section, we introduce the ETMAC, which enables opportunistic spectrum sharing in CRAHNs. The ETMAC enables significant increases in throughput and channel spatial reuse, and reduces the energy consumption and MAC delay. This protocol is designed to protect PUs from SU interference and resolve the hidden and the exposed terminal problems for SUs. The time structure used is similar to the IEEE 802.11 power-saving mode.

A. System Model in Multichannel MAC Protocol CRAHNs

Several research groups [10], [11], [12], [15], [16], [17], [18] found the use of a common control channel (CCC) to guarantee reliable control information exchanges for CRAHNs to be an effective method.

We consider a multichannel environment in CRAHNs. There is one common control channel and N data channels within the CRAHNs. It is assumed that SUs will not be disturbed by PUs in accessing the control channel. The data channels are licensed to PUs and can be opportunistically used by the SUs. In the environment under consideration, the PU and SU signals can have influence not on the entire CRAHN but only on part of the CRAHN. That is, there exist SUs that cannot detect the PU activation within the CRAHN and this will create hidden and exposed terminal problems in CRAHNs. In addition, the data transmission model is in a multihop environment.

Each host has two transceivers to enable it to listen on both the control channel and the data channel simultaneously. Since one of the transceivers is always listening on the control channel, the multichannel hidden terminal problem does not occur. When the number of channels is small, the dedicated use of one channel for control messages can be costly. On the other hand, if the number of channels is large, the control channel can become a bottleneck and prevent the data channels from being fully utilized [4].

The frame length of RTS control frame is set as a power of 2. This method efficiently utilizes the channel bandwidth by assigning unused slots to SUs of new connections and enlarging the frame length when the number of slots in the frame is insufficient to support the SUs. This method also shrinks the frame length when the frame of RTS is half empty.

In the proposed ETMAC protocol, each SU is equipped with two transceivers: one to communicate with the control channel and one to communicate with data channels. The control transceiver will operate on the control channel to exchange control packets with other SUs and to obtain rights to access data channels. The data transceiver will dynamically switch to one of the data channels to transmit data packets and acknowledgements.

B. *ETMAC Protocol in Multichannel CRAHNs*

In this section, we propose the use of the ETMAC protocol in multichannel CRAHNs to resolve hidden and exposed terminal problems. Before describing the ETMAC in detail, we first summarize our assumptions. This protocol uses a scheme similar to [4] that provides throughput improvements using N channels, and all channels have the same bandwidth. None of the channels overlap, thus the packets transmitted on different channels do not interfere with each other. Nodes have prior knowledge regarding the number of available channels. Each node is equipped with two half-duplex transceivers. The transceiver is capable of switching channels dynamically. Nodes are synchronized, allowing them to begin their beacon intervals at the same time.

The time structure is divided into time intervals in CRAHNs, where each time interval has two phases. Fig. 1 shows the one control channel of the ETMAC protocol in multichannel CRAHNs. The first phase includes the sensing minislot window, which avoids PU interference on the same channel. Each SU node maintains a beacon table, which records the beacon's probability of success. The beacon's probability of success is the probability that none of the other nodes transmits in the same beacon slot. The beacon message will return to the backoff mechanism if a collision occurs. Each SU node will maintain a neighbor table. This table records its neighbors and includes PUs and SUs. Each SU also maintains a channel status table. This table records success probabilities of the borrowing channel status from the PU. The SU sender will sense and determine the usable channel according to the channel's probability of success. The channel's probability of success is the probability that none of the other nodes transmits on the same channel. The SU will sense that the channel's probability of success is larger than the threshold value, which decreases energy consumption. If the probability of success of all channels is lower than the threshold value, the SU will sense all of the channels and detect the PUs in a timely manner. In addition, each SU will adjust its threshold value by itself.

The second phase involves a contention window. In the first phase, the SU node avoids interference with the PU to some extent, but cannot completely avoid it. The second phase will contain the proposed mechanism to resolve the hidden and exposed terminal problems.

The following section contains detailed descriptions of these two phases in a ETMAC.

- Sensing minislot window phase: Each node sends itself a beacon control message, using the IEEE 802.11 Timer Synchronization Function (TSF) to perform the synchronization. This beacon records its local time in the sensing minislot window and refreshes its time when it receives a faster beacon time than itself. If a collision occurs between the beacon messages, the backoff mechanism is invoked. IEEE 802.11 and previous documents specify that the SU should change and sense each channel, which is a misuse of energy. In this study, channel sensing is performed according to success probability. Therefore, ETMAC will reduce transition time and further decrease energy consumption.
- Contention window phase: This phase contains the following control messages: RTS (Request-to-send), CTS (Clear-to-send), RCA (Reservation channel assignment). Each SU must perform this procedure completely in a control channel before obtaining a this channel.

C. *Contention Window Descriptions*

Fig. 1 shows all the fields of the control packet for data channel reservation in a ETMAC protocol of multichannel CRAHNs. The detailed descriptions are as follows:

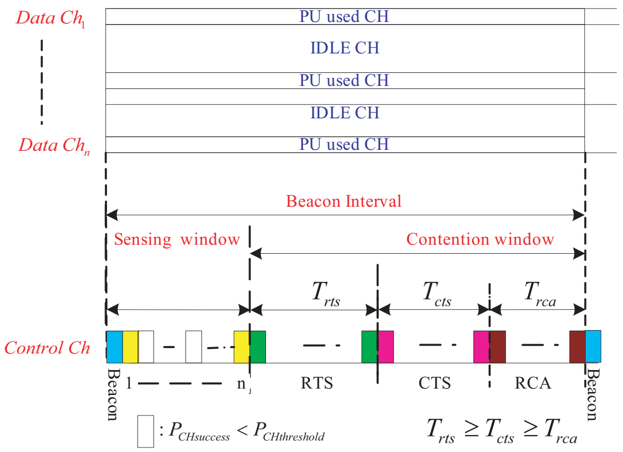

Fig. 1. Control packet for data channel reservation in ETMAC protocol of multichannel CRAHNs

- Beacon: Using IEEE 802.11 Timer Synchronization Function(TSF).
- INT: INT contains the following fields: CH_{id}, SU_{sender}, and PU_{sender}. CH_{id} denotes the interfered channel to PU, SU_{sender} denotes the SUs that sent the interrupt message, and PU_{sender} denotes the interfered PU.
- RTS: The following fields: CH_{id1}, CH_{id2}, CH_{id3}, SU_{sender}, $SU_{receiver}$, $Nbr_{ID1}, \cdots, Nbr_{IDn}$ and $Power_{max}$ were added to the fields in the CTS of IEEE 802.11. Channels CH_{id1}, CH_{id2}, and CH_{id3} have higher priority in the channel status of the SU sender. SU_{sender} denotes the SU sender, $SU_{receiver}$ denotes the SU receiver, $Nbr_{ID1}, \cdots, Nbr_{IDn}$ denotes the ID of the neighbors of SU_{sender}, and $Power_{max}$ denotes the maximum transmission power of the SU sender.
- CTS: The following fields: CH_{id}, SU_{sender}, $SU_{receiver}$, $Nbr_{ID1}, \cdots, Nbr_{IDn}$, $Power_{rcv}$ and $Power_{max}$ were added to the fields in the CTS of IEEE 802.11. CH_{id} denotes the channel selected according to the received RTS message. SU_{sender} denotes the SU sender, $SU_{receiver}$ denotes the SU receiver, $Nbr_{ID1}, \cdots, Nbr_{IDn}$ denotes the ID of the neighbors of $SU_{receiver}$, and $Power_{max}$ denotes the maximum transmission power of SU sender.
- RCA: RCA contains the following fields: CH_{id}, SU_{sender}, $SU_{receiver}$, and $Power_{snd}$. CH_{id} denotes the channel selected by the SU sender, SU_{sender} denotes the SU sender, $SU_{receiver}$ denotes the SU receiver.
- ACK: ACK contains the following fields: CH_{id}, SU_{sender}, and $SU_{receiver}$. CH_{id} denotes the channel selected by the SU sender, SU_{sender} denotes the SU sender, and $SU_{receiver}$ denotes SU receiver.

D. Buffering MAC Protocol and Switching MAC Protocol

In [13], the authors proposed two MAC protocols, one is buffering MAC protocol and another is switching buffering MAC protocol. The authors also observed that using an slotted time access scheme to the control channel, a buffering MAC protocol, where in case of interruption the SU waits for the PU to vacate the channel before resuming the transmission, outperforms a switching MAC protocol, where the SU vacates the channel in case of appearance of PUs and then compete again to access a new channel.

One SU stays on its reserved channel, even this channel becomes occupied by PUs in buffering MAC protocol. In buffering MAC protocol, the SU will keep silent while PU active ON and SU will transmit its packet while PU active OFF. The SU will occupied this channel as log as the packet is not transmitted completely. SU will release its occupied channel until the packet is entirely transmitted. For the buffering MAC protocol, the packet service time of SU consists of only one beacon interval and followed by a transmission time which consists of successful transmission, unsuccessful transmission and unavailable channels, until the entire packet is transmitted.

One SU that senses its channel occupied by PUs and then leaves the channel in switching MAC protocol. In switching MAC protocol, one SU will return to the idle state to participate the contention window and competes with other SUs in the next beacon interval. While one SU wins the rights of transmission from the competition among SUs, it will reserve a new channel in this timeslot. For the switching MAC protocol, the packet service time consists of several beacon intervals in order to switch to available channels and the successful transmission and unsuccessful transmission timeslots required to transmit the entire packet.

In this paper, we use buffering MAC protocol in our ETMAC protocol while its has higher performance than switching MAC protocol.

III. BASIC OPERATION IN MULTICHANNEL ETMAC

Each SU determines channel vacancy based only on its sensing outcomes. To efficiently sense all channels, the SU must assign a sensing success probability to each channel. The SU should perform sensing on an idle channel to facilitate reliable PU detection. Each SU maintains various state data for each channel.

A. Channel State Informations in Multichannel ETMAC

The data for channel i at node j is as follows:

- $CH_i(j)$: This denotes the state of channel i at $SU(j)$. Let $SU(i)$ denote a cognitive radio secondary user i, and $PU(j)$ denote a primary user j. If $SU(j)$ detects other SU signals on channel i in the contention window, it sets $CH_i(j) = 1$. Otherwise, $CH_i(j) = 0$. When $CH_i(j) = 0$, $SU(j)$ considers channel i to be empty.
- $PU_i(j)$: This indicates the $SU(j)$ that has detected the existence of a PU on channel i in the sensing minislot window. If $SU(j)$ detects the PU signal on channel i, it sets $PU_i(j) = 1$. Otherwise, $PU_i(j) = 0$. When $PU_i(j) = 0$, $SU(j)$ considers channel i to be empty.

B. Channel Sensing in Sensing Minislot Window

In ETMAC, periodically transmitted beacons divide time into beacon intervals. A small window on the control channel called the sensing minislot window is placed at the start of each beacon interval. During this window, each SU must sense each data channel according the success probability on the control channel; it must then record the status for sensed data channels. Each SU records sensed data channels, whether or not they are occupied by SUs or PUs.

C. Data Transmission Scheme in Multichannel ETMAC

In the sensing minislot window, each SU performs scans and obtains the status of sensed data channels that have higher success probability. The contention window is used for control packet exchanges and selects one idle channel. In the contention window, the transmission range of the SUs on the data channels cannot cover the entire network, because the SUs transmit data packets using power controlled by ETMAC. Thus, some SU_{sender} and $SU_{receiver}$ pairs in the CRAHNs will use multihop data transmissions. A multihop transmission is composed of several concatenated one-hop transmissions; a proposed data transmission scheme governs each one-hop transmission, where the $SU_{receiver}$ is located within the transmission range of the SU_{sender} [11]. An SU_{sender} that wants to transmit data packets should first reserve a data channel. Data channels are reserved by an exchange of control packets between an SU_{sender} and $SU_{receiver}$. In ETMAC, packet transmissions on the control channel are governed by a modified IEEE 802.11, referred to as energy efficient and high throughput MAC (ETMAC).

In CBMAC, each control frame will has same length in contention window, and select the time slots according to the sequence of time order. Therefore, there are some idle time slots will not be used and this will increase the MAC delay. In Fig. 2, there are two connections successfully by the RTS/CTS/RCA MAC protocol, and each control frame has four time slots. In addition, collision happens in two time slots in RTS control frame. So, we will see that has four time slots wasted in CTS/RCA field. The idle time slots in CTS/RCA will be shrunk while ETMAC is used.

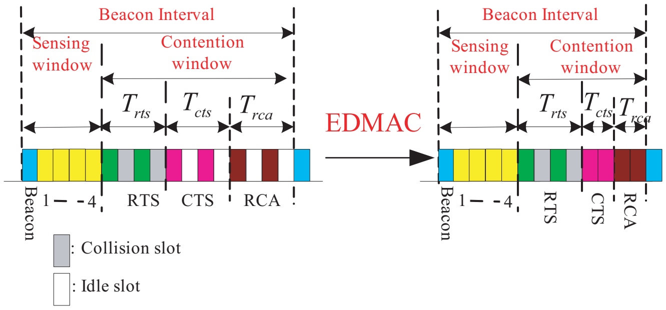

Fig. 2. The procedure of ETMAC protocol example 1 in multichannel CRAHNs

In Fig. 3, there are two connections successfully by the RTS/CTS/RCA MAC protocol initially, and each control frame has four time slots. Larter, collision happens in two time slots in RTS control frame field and one time slot in CTS control frame field. So, we will see that has six time slots wasted in CTS/RCA field. The idle time slots in CTS/RCA will be shrunk while ETMAC is used.

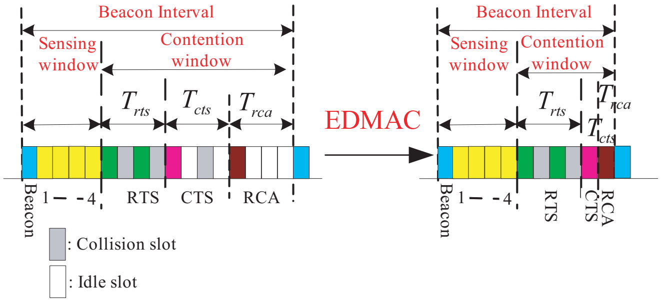

Fig. 3. The procedure of ETMAC protocol example 2 in multichannel CRAHNs

ETMAC is designed to reduce energy consumption and MAC contention delay in multichannel CRAHNs. The ETMAC procedures for reducing energy consumption and MAC contention delay are performed as follows.

1) Upon receiving a beacon at the sensing minislot window, each SU obtains the PUs' idle channel information from the sensing minislot window. If $SU(i)$ detects the PU signal on channel c, it sets $PU_c(i) = 1$. Otherwise, $PU_c(i) = 0$. The notation c denotes licensed channels. In this scenario, c ranges from 1 to 4.
2) If $SU(i)$ has a data packet to send to $SU(j)$, then $SU(j)$ is also a cognitive radio secondary user j. Initially, the frame length of RTS control frame is set to 4, and this is a power of 2. The frame length of RTS will be enlarged when the number of slots in the frame is insufficient to support the SUs. The frame length of RTS will be shrunk when the frame of RTS is half empty.
3) SU_i checks the status of $PU_c(i)$ for each licensed channel of the PU. SU_i selects the idle channels from $PU_c(i)$ and then selects three channels (CH_{id1}, CH_{id2}, CH_{id3}) that have higher probabilities of success from the channel status table. It then adds the selected channels, the ID of the one-hop neighbors of SU_i and the maximum transmission power information, $Power_{max}$, to the RTS control packet in the contention window, and sends it to SU_j. Here, it is assumed that all the SUs have the same maximum transmission power, $Power_{max}$.
4) Assume SU_j receives the RTS control message from SU_i, and then selects one channel, CH_{id}, according to the success probability data in its channel status table and whether the status $PU_{id}(j)$ is 0. SU_j then sends the CTS control message, including the selected channel CH_{id}, and the ID of the one-hop neighbors of SU_j to SU_i after waiting the SIFS (Short Inter Frame Space) time interval. The CTS also includes the receiving power, $Power_{rcv}$, of the SU_j to SU_i transmission, and the maximum transmission power $Power_{max}$, of SU_j. If SU_j has no suitable $PU_c(j)$ channel in its status stable, the channel field CH_{id} of CTS is set to empty. As a result, the connection cannot be established and $SU(i)$ must wait for the next frame; the above procedures are repeated if $SU(i)$ still wants to establish communication between $SU(i)$ and $SU(j)$.
5) SU_i selects one slot in the RTS field and sends RTS control packet, other SUs who want to create one connection also send RTS control packet in selected slot. SU_i and other destinations' SUs will receive RTS if no collision happens. The received RTS control packets will less than the total sent RTS control packets due to the collision in the contention region. Then, the SU_j will send CTS control packet, if received the RTS control packet.
6) The length of CTS field T_{cts} will less than the length of RTS field T_{rts} due to the collision in the contention region. And this will reduce the MAC delay and achieve the saving energy due to no idle slots in the CTS field. In CBMAC, the length of all the control frame field is same. So, if the collision happens in RTS field, then the the number of idle slots of other control fields in the contention window is remain as same as the RTS field. And then the consumption of idle slots will increase and the MAC delay alos increase in CBMAC. In ETMAC, the SUs will shrink down the contention window by deleting idle slots, then the system performance will increase.
7) The contention window will into RCA field when the handshake of RTS and CTS completed. In the RCA field, the length of RCA

field will shorter than the CBAMC protocol. So, the ETMAC will at least has less energy consumption while its has less sensing PU times in sensing window, and shorter length of RCA field. The ETMAC will remain saving energy per beacon interval and reducing MAC delay due to dynamic length of contention window.

8) Therefore, ETMAC will save more energy per beacon interval and reduce more MAC delay than CBMAC due to dynamic length of contention window and PU sensing in the sensing window according to the success probability.

D. Channel Assignment in Multichannel ETMAC

For overlapped channel assignment, a MAC protocol is needed to resolve the contention when several SUs attempt to access the same assigned channel. In addition, the channel spatial reuse of overlapped channel is needed to improve the network throughput [19], [20].

In ETMAC for CRAHNs, channel assignment addresses the hidden node problem. If two SUs can communicate directly, we say that these two SUs are neighbor nodes. When two SUs are not neighbor nodes but have a common neighbor node in between them, we say that these two SUs have the relationship of being potential hidden nodes.

Suppose there is a pool of *M* channels available to the network and they are numbered from 1 to *M*. Let

$$CH_{one}(i,j) = \begin{cases} 1 & \text{channel } i \text{ is used at node } j \\ 0 & \text{otherwise} \end{cases}$$

$$CH_{mul}(i) = \begin{cases} 1 & \text{channel } i \text{ is used at least one node} \\ 0 & \text{otherwise} \end{cases}$$

When a SU_{snd} requests to set up a connection with a destination SU_{rcv}, the SUs will run the MAC protocol of ETMAC to mitigate the multichannel hidden terminal problem and then access one usable channel by channel assignment of ETMAC. If a channel is available, the SU then updates its $CH_l(m)$. Other SUs can update their $CH_g(m)$ by exchange or receive the control packet $RTS/CTS/RCA$ of ETMAC. $CH_g^h(m,t)$ information is exchanged between neighbor SUs.

In order to increase channel spatial reuse, when there is no risk of violating the hidden terminal problem constraints, effort should be made to reuse assigned channel as often as possible. Since the usage status of each channel is kept track of by the exchange the control packet, ETMAC can approach a compact pattern for channel spatial reuse. The price, however, is that the SUs have to exchange the channel status information by exchange control packet, resulting in a higher control traffic load.

Although the SUs will not cause harmful interference to the existing users, they may choose the same channels in the same time slot independently, and thus co-channel interference may be introduced. In ETMAC, we allow multiple new SUs to share the same channels as long as their respective Signal-to-Interference-and- Noise-Ratio (SINR) is acceptable. This may be achieved by ETMAC, which converges very fast [21].

The channel spatial reuse (η) is defined as the average number of times that a channel is being used simultaneously. It is defined as follows.

Then

$$\eta = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N} CH_{one}(i,j)}{\sum_{i=1}^{M} CH_{mul}(i)} \tag{1}$$

In Fig. 4 shows that original channel spatial reuse is 1.0 for two existing SUs that use two different channels. Then, four new SUs want to create communication. The ETMAC with the energy efficient and high throughput spectrum access and resource allocation scheme will increased the channel spatial reuse from 1.0 to 1.5.

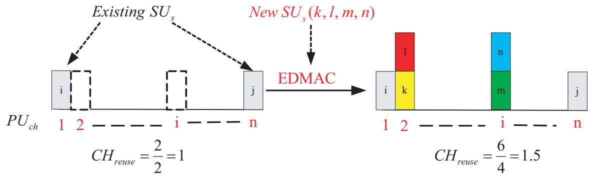

Fig. 4. The channel spatial reuse example of ETMAC in multichannel CRAHNs.

IV. PERFORMANCE ANALYSIS FOR THE SATURATION NETWORK

An interference model for one PU and multiple SUs under a primary signal-to-interference-plus-noise (SINR) constraint is proposed [17]. The desired signal (transmitted by PU_{snd}, and received by PU_{rcv}) and the interference signal (transmitted by SU_{snd}, and intended for SU_{rcv}) are subject to Rayleigh fading and path loss. The interference control scheme considered for dynamic spectrum access allows PU and SUs to share the same band, provided that the SINR required by the PU (denoted $SINR_{th}$) is attained. The arrival traffic rates of the PU and SUs are assumed to be Poisson processes denoted by λ_P and λ_S, respectively. The departure traffic rate of the PUs and SUs are modeled with Poisson processes with rates of μ_P and μ_S, respectively.

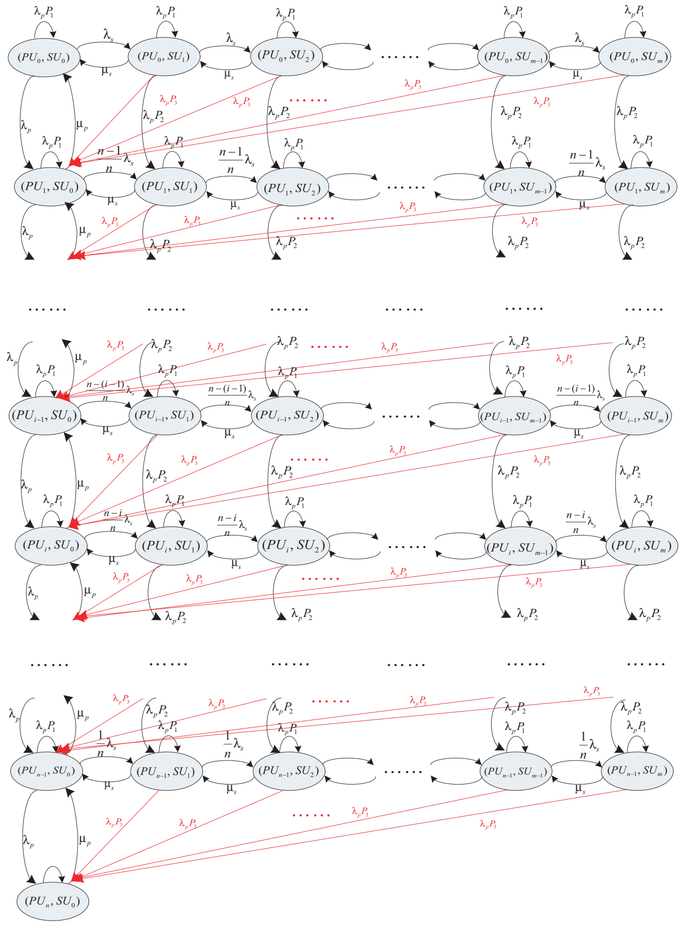

Fig. 5. Markov chain modeling interference control with multiple PUs and multiple SUs

The PU can transmit data packets when its SINR is greater than $SINR_{th}$. Otherwise, the SUs may transmit data packets on this band if this constraint cannot be satisfied. In addition, PUs and SUs can coexist if the primary SINR is greater than $SINR_{th}$. Finally, if a PU is able to transmit, and coexistence with an SU is not possible because of the SINR constraint, the SUs will be silent.

P_{fail} represents the probability that a PU sender is not able to transmit data packets because of poor channel quality, even in the absence of SUs. P_{share} represents the probability that a PU sender can transmit data packets and coexist with SUs to share a channel. P_{suc} represents the probability that a PU can use the channel and cannot share it with SUs [17].

$$P_{fail} = Prob(SINR_{PU_{interference=0}} < SINR_{th}) \quad (2)$$

$$P_{share} = Prob(SINR_{PU} > SINR_{th}) \quad (3)$$

$$P_{suc} = 1 - P_{share} = Prob(SINR_{PU} \leq SINR_{th}) \quad (4)$$

In Fig. 5, continuous-time Markov Chain models a ETMAC system containing multiple PUs and SUs [22]. ETMAC assumes that each PU channel is independent, and that the PU channels do not overlap. The different states are as follows.

- (PU_0, SU_0): There are no transmissions by any PUs or SUs. The number of PUs and SUs is 0.
- (PU_0, SU_j): Only the SUs are transmitting. The numbers of PUs and SUs are 0 and j, respectively.
- (PU_i, SU_0): Only the PUs are transmitting. The numbers of PUs and SUs are i and 0, respectively.
- (PU_i, SU_j): The numbers of PUs and SUs are i and j, respectively. The PUs and SUs can coexist to share the channel.

The analysis of the ETMAC system illustrated in Fig. 5 consists of the following equation systems.

$$\begin{cases} \pi_{0,0} + \cdots + \pi_{0,m} + \cdots + \pi_{n,0} + \cdots + \pi_{n,m} = 1 \\ \pi_{1,0}\mu_p + \pi_{0,1}\mu_s = \pi_{0,0}(\lambda_p + \lambda_s) \\ \pi_{0,j-1}\lambda_s + \pi_{0,j+1}\mu_s = \pi_{0,j}\alpha_1 \\ \pi_{0,m-1}\lambda_s = \pi_{0,m}\alpha_2 \\ \pi_{i-1,0}\lambda_p + \pi_{i+1,0}\mu_p + \pi_{i,1}\mu_s + \lambda_p P_{suc}\beta_1 = \pi_{i,0}\alpha_3 \\ \pi_{i-1,j}\lambda_p P_{share} + \pi_{i,j-1}\frac{n-i}{n}\lambda_s + \pi_{i,j+1}\mu_s = \pi_{i,j}\alpha_4 \\ \pi_{i-1,m}\lambda_p P_{share} + \pi_{i,m-1}\frac{n-i}{n}\lambda_s = \pi_{i,m}\alpha_2 \\ \pi_{n-2,0}\lambda_p + \pi_{n,0}\mu_p + \pi_{n-1,1}\mu_s + \lambda_p P_{suc}\beta_2 = \pi_{n-1,0}\alpha_5 \\ \pi_{n-2,j}\lambda_p P_{share} + \pi_{n-1,j-1}\frac{1}{n}\lambda_s + \pi_{n-1,j+1}\mu_s = \pi_{n-1,j}\alpha_6 \\ \pi_{n-2,m}\lambda_p P_{share} + \pi_{n-1,m-1}\frac{1}{n}\lambda_s = \pi_{n-1,m}\alpha_7 \\ \pi_{n-1,0}\lambda_p + \lambda_p P_{suc}\beta_3 = \pi_{n,0}\mu_p \\ i = 1, \cdots, n-2 \\ j = 1, \cdots, m-1 \end{cases} \quad (5)$$

with
$\beta_1 = \pi_{i-1,1} + \cdots + \pi_{i-1,m}$
$\beta_2 = \pi_{n-2,1} + \cdots + \pi_{n-2,m}$
$\beta_3 = \pi_{n-1,1} + \cdots + \pi_{n-1,m}$
$\alpha_1 = \lambda_p P_{share} + \lambda_p P_{suc} + \mu_s + \lambda_s$
$\alpha_2 = \lambda_p P_{share} + \lambda_p P_{suc} + \mu_s$
$\alpha_3 = \mu_p + \lambda_p + \frac{n-i}{n}\lambda_s$
$\alpha_4 = \lambda_p P_{share} + \lambda_p P_{suc} + \mu_s + \frac{n-i}{n}\lambda_s$
$\alpha_5 = \mu_p + \lambda_p + \frac{1}{n}\lambda_s$
$\alpha_6 = \lambda_p P_{suc} + \mu_s + \frac{1}{n}\lambda_s$
$\alpha_7 = \lambda_p P_{suc} + \mu_s$

The first equation in Eq. (5) represents the normalization equation that should satisfy a Markov Chain. The ten others represent the flow balance at each state, with the $\pi_{(i,j)}, (i,j) \in \{(0,0), \cdots, (n,m)\}$ being the steady probabilities of states $(PU_0, SU_0), \cdots, (PU_n, SU_m)$.

Denoting by

$$\pi = [\pi_{(0,0)}, \cdots, \pi_{(0,m)}, \cdots, \pi_{(n,0)}, \cdots, \pi_{(n,m)}] \quad (6)$$

the row vector with elements $\pi_{(i,j)}$, the previous equations system can be re-written as:

$$X\pi = Y, \quad (7)$$

with $Y = (1, 0, \cdots, 0)^T$. Matrix X is defined in Eq. (9).

Hence,

$$\pi = X^{-1}Y \quad (8)$$

The entries in each row of the matrix X in Eq. (5) represent the probabilities for the various kinds of the numbers of PUs and SUs. Such a square array is called the matrix of transition probabilities,or the transition matrix. The probabilities $\pi_{(i,j)}$ are called transition probabilities. The process can remain in the state it is in, and this occurs with probability $\pi_{(i,i)}$. An initial probability distribution, defined on π, specifies the starting state. Usually this is done by specifying a particular state as the starting state.

A performance analysis of the IEEE 802.11 DCF in wireless LAN is proposed in [23]. The saturation throughput by analyzing the licensed data channels has derived in [9] and the normalized saturation throughput by analyzing the licensed data channels has derived in [18].

The previous analytical throughput method in [23] for an IEEE 802.11-based network cannot be directly adopted because IEEE 802.11-based CRAHNs in beacon interval-based transmission mode owing to the periodic spectrum sensing [24].

A. Normalized Throughput Analysis

Suppose that each node can only try once time to send packet in each beacon interval. If collision happens due to multiple packets transmitted, then the SU_{sender} must go into next beacon interval to create connection.

For n licensed data channels, the probability that there will be i vacant PU channels is

$$P_{VC}(i) = \sum_{j=1}^{m} \pi_{(i,j)} = \binom{n}{i} (1-\gamma)^i \gamma^{n-i} \quad (10)$$

Let γ is defined as the channel utilization under PU ON and OFF states for all licensed channels. We assumed that all the licensed channels had the same channel utilization. The average number of vacant channels that can be used by SUs can be derived by

$$\begin{aligned} E[CH_{vacant}] &= \sum_{i=1}^{n}\sum_{j=1}^{m} i\pi_{(i,j)} = \sum_{i=1}^{n} iP_{VC}(i) \\ &= \sum_{i=1}^{n} i \binom{n}{i} (1-\gamma)^i \gamma^{n-i} = n(1-\gamma) \end{aligned} \quad (11)$$

The probability that a transmitted packet collides by p. The probability τ that a given SU transmits in a randomly selected slot time. In the stationary state, each station transmits a packet with probability τ. Let P_{tr} be the probability that there is at least one transmission in the considered slot time. Further, let P_s be the probability that a transmission occurring on the channel is successful is given by the probability that exactly one station transmit on the channel. Let p_{idle}, p_{succ}, and p_{coll} as the probability that the channel is idle , the probability that a node successfully transmits an RTS packet, and the probability that the collision occurs, respectively [22].

For ETMAC, each SU has two transceiver. Now we are able to express the average time that is required for the successful handshakes of $RTS/CTS/RCA$ of ETMAC, which can be derived as follows:

$$\begin{bmatrix} 1 & 1 & \cdots & 1 & 1 & 1 & \cdots & 1 & 1 & 1 & \cdots & 1 & 1 & 1 & \cdots & 1 & 1 & 1 \\ -\alpha_1 & \mu_s & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 & \mu_p & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & \cdots & -\lambda_s & -\alpha_1 & \mu_s & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & & & & \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & \lambda_s & -\alpha_2 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ \cdots & & \cdots & & & & \cdots & & & & \cdots & & & & & & & \cdots \\ \vdots & & \vdots & & & & \vdots & & & & \vdots & & \vdots & & & & & \vdots \\ \cdots & & \cdots & & & & \cdots & & & & \cdots & & \cdots & & & & & \cdots \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & \cdots & 0 & 0 & \cdots & 0 & \lambda_p & \lambda_p P_3 & \cdots & 0 & \lambda_p P_3 & -\mu_p \\ & & & & & & & & & & & & & & & & & \end{bmatrix} \tag{9}$$

$$E[T] = \frac{P_{succ}T_s + P_{coll}T_c}{P_{succ}} \tag{12}$$

$$= \frac{P_{tr}P_sT_s + P_{tr}(1-P_s)T_c}{P_sP_{tr}} \tag{13}$$

Let T_s and T_c be the average time in the ETMAC access scheme in which the channel is sensed busy because of a successful transmission or a collision, and T_{idle} be the average time for idle state. For the ETMAC access scheme, we obtain:

$$\begin{aligned} T_s = (RTS + CTS + RCA)/R_{control} \\ +2 \times SIFS + DIFS \end{aligned} \tag{14}$$

$$T_c = \frac{RTS}{R_{control}} + DIFS \tag{15}$$

where RTS is the time spent by sending a RTS packet, CTS is the time spent by sending a CTS packet, RCA is the time spent by sending a RCA packet, $SIFS$ is the time interval of short inter-frame space (SIFS), and $DIFS$ is the time interval DCF inter-frame space (DIFS).

CCC saturation problems occur when using a dedicated CCC [25], and the collision between packets will become more critical. Then the contending node of SUs will be into “backoff stage.” From the aforementioned equations, we infer that τ, p, P_{tr}, P_s, P_{idle}, P_{succ}, P_{coll} and $E[T]$ will be affected by W_k. This often degrades the following normalized throughput.

The normalized throughput under overload condition of the multichannel CRAHNs. In CRAHNs, PUs use licensed channels dynamically; the licensed channels used by SUs are alternated between ON and OFF states.

For n licensed data channels, the probability that there will be i vacant PU channels is

$$P_{VC}(i) = \sum_{j=1}^{m} \pi_{(i,j)} = \binom{n}{i}(1-\gamma)^i\gamma^{n-i} \tag{16}$$

Let γ is defined as the channel utilization under PU ON and OFF states for all licensed channels. We assumed that all the licensed channels had the same channel utilization.

The average number of vacant channels that can be used by SUs can be derived by

$$\begin{aligned} E[CH_{vacant}] &= \sum_{i=1}^{n}\sum_{j=1}^{m} i\pi_{(i,j)} = \sum_{i=1}^{n} iP_{VC}(i) \\ &= \sum_{i=1}^{n} i\binom{n}{i}(1-\gamma)^i\gamma^{n-i} = n(1-\gamma) \end{aligned} \tag{17}$$

The normalized throughput of the multichannel CRAHNs ζ (with n licensed data channels, and one control channel) is defined as follows:

$$\zeta = \frac{\eta R_{data} E[CH_{vacant}] E[T]}{(nR_{data} + R_{control})(E[T] + nT_{sensing})} \tag{18}$$

where R_{data} is the data rate of a licensed channel, $R_{control}$ is the data rate of a control channel, $T_{sensing}$ is the minislot time units in sensing window, $E[CH_{vacant}]$ is the average number of vacant channels, and $E[T]$ is the average MAC time slots that is required for the successful handshakes of $RTS/CTS/RCA$ of ETMAC.

B. Energy Consumption Analysis

In IEEE 802.11 PSM, each node will be stay in wake mode or go into sleep mode. Each node in wake mode performs the back-off mechanism of IEEE 802.11 DCF to transmit its power-save poll frame. Therfefore, the computations of energy consumption will consider three cases that are energy consumption for idling, energy consumption of successful transmission , and energy consumption of collision [24]. In this paper, we focus on that the energy consumption of creation process of any SUs pairs communication. Therefore, we only consider that the energy consumption during a period of the successful transmission (E_{succ}) and energy consumption during a period of the collision (E_{coll}). In addition, we assume that all SUs are always power on in our simulation.

- Energy consumption during a period of the successful transmission E_{succ} : When only one SU is transmitting in CRAHNs, the transmission is successfully performed. During this transmission period, the SU_{snd} energy consumes only the transmission power PW_{tx} and the reception power PW_{rx} for transmitting $RTS/CTS/RCA$ frames and receiving the data frame, respectively. Therefore, E_{succ} is computed as follows.

$$\begin{aligned} E_{succ} = T_{sensing}PW_{sensing} + T_{rts}PW_{rts} + \\ T_{cts}PW_{cts} + T_{rca}PW_{rca} + T_{data}PW_{data} \end{aligned} \tag{19}$$

- Energy consumption during a period of collision E_{coll}: When two or more SUs transmit their ETMAC control frames simultaneously, collisions occur. During this period, the transmitting nodes consume the transmission power to transmit the ETMAC control frames. Hence, E_{coll} is given as follows.

$$E_{coll} = T_{sensing}PW_{sensing} + T_{rts}PW_{rts} \tag{20}$$

where $E_{sensing}$ is the PU channel sensing energy consumption for SU in the sensing minislot window to a licensed channel, $T_{sensing}$ is the sensing time slots for SU in the sensing minislot window to a licensed channel. E_{idle} is the idle state energy consumption for SU in the contention window, T_{idle} is the idle state delay for SU in the contention window. E_{rts}, E_{cts}, E_{rca} are the energy consumption for SU of MAC contention window to a licensed channel in the RTS field, CTS field and RCA field, respectively. T_{rts}, T_{cts}, T_{rca} are the contention time slots for SU of MAC contention window to a licensed channel in the RTS field, the CTS field, the RCA field, respectively.

We now derive the average consumed power of ETMAC in CRAHNs (denoted by $E[P]$) as the ratio of the average amount of energy consumption for idle, successful transmission, and collision cases during a slot time to the average time duration of a slot time. Therefore, $E[P]$ can be computed as follows.

$$E[P] = \frac{P_{tr}P_sE_{succ} + P_{tr}(1-P_s)E_{coll}}{E[T]} \tag{21}$$

C. Outage Probability

Outage probability $Prob_{outage}$: the outage probability for PU due to the sensing error for SU to a licensed channel in the sensing minislot window. The ETMAC and CBMAC will keep the interference caused by PUs within a tolerable range. Therefore, we will not discuss the outage probability due to the interference to PUs, we discuss the outage probability due to sensing error to PUs. For the sensing error has two cases. One is that PU is ON state and SU is take it as OFF in the sensing window. Another is that PU is OFF state and SU is take it as ON. In first case, the PU will be interfered by SU. In the second case, the system throughput will be decreased. Here, we focus on first case.

The outage probability of the multichannel CRAHNs P_{outage} is redefined as follows:

$$P_{outage} = \frac{CONN_{error}}{CONN_{tal}} \tag{22}$$

where $CONN_{error}$ is the total number of connections for sensing error to a licensed channel, $CONN_{tal}$ is the total numbers of connection that are created in the simulation time.

D. MAC Delay

MAC delay per beacon interval T_{delay}: the MAC delay per beacon interval that is required for the sensing minislot window and the successful handshakes of $RTS/CTS/RCA$ of ETMAC. The MAC delay per beacon interval of attempting a handshake the multichannel CRAHNs is defined as follows:

$$T_{delay} = E[T] + nT_{sensing} \tag{23}$$

V. PERFORMANCE EVALUATION

In this section, we present the simulation results for the performance evaluation of the protocol. The simulation is based on event-driven programming, and implemented in the C programming language. The main different scenario between ETMAC and CBMAC is the traffic scenario. In the multihop scenario of CBMAC generate only two traffic streams that diagonally cross the network. In ETMAC, the traffic is assumed to be uniformly distributed among all nodes with various overall loads (or erlangs, the ratio of the arrival rate to the departure rate). Therefore, we compare ETMAC's performance with the CBMAC scheme, in which channels are assigned to a connection on demand.

The cognitive radio ad hoc network is simulated by placing 400 nodes randomly within a bounded region of $1200 \times 1200\ m^2$. It is assumed that nodes will be continuously powered on. Before the transmission range is adjusted for each node, the control message transmission range for SUs is fixed at 250 m; each simulation runs for 20,000 seconds. The transmission range for PUs is fixed at 300 m. There are four PUs, placed at (300, 300), (900, 300), (300, 900),and (900, 900). There are four data channels. Each PU has its own channel and not overlap in the transmission range. The transmission rates for each data channel is 2 $Mbps$ and the transmission rate for control channel is 1 $Mbps$. The sizes of RTS, CTS, and RCA are given as 125, 125, and 21 bytes, respectively. The energy consumption of sensing is given as 0.1. The energy consumption of transmission, and receiving for RTS, CTS, and RCA control frames are given as 1.35, and 0.9 W, respectively. The state of a channel alternates between the PU ON state where a PU is busy on the channel and the PU OFF state where the channel is idle for a PU. The PU ON duration of each channel are exponentially distributed with mean 300 sec. We do not consider mobility in this paper, and all nodes are assumed to be stationary to eliminate the effects of broken routes caused by mobility.

Each of our simulation results is the average of 10 randomly generated network topologies, each with a different seed. All reported results were averaged over 10 seeds. Furthermore, to generate a more uniform topology, we divided the topology into 100 regions and randomly dispersed the 400 SUs in the regions. This prevented the network from becoming disconnected when N (the average number of neighbors) was small. The distances between the source node and the destination node were also uniformly distributed. That is, we ensured that there were roughly equal numbers of short, medium, and long connections.

The arrival rate is the number of newly arriving connections per second. The departure rate is the number of terminated connections per second, and is also the inverse of the average lifetime of a connection. To obtain the desired traffic load, the departure rate was fixed at 0.05 and the arrival rate was 1, 2, 4, 8, and 16. Therefore, when the arrival rate was 16, the overall load was 320, indicating that there were 320 active connections in the network, on average. For a given traffic load (arrival rate), we first determine when a new connection request should arrive. Subsequently, its source and destination are determined independently from the uniform distributions. Therefore, the number of connection requests depends on the load, but not on the number of nodes.

Fig. 6 shows the channel spatial reuse index η for ETMAC and CBMAC versus the arrival rate for a channel in multichannel CRAHNs. For ETMAC, the channel spatial reuse index η can be higher than 1.0 because channels are reused if no interference problems can occur. ETMAC produces the highest channel spatial reuse at arrival rate = 16, because the system achieves the saturation. CBMAC produces the highest channel spatial reuse at arrival rate = 8, because the system achieves the saturation. When the arrival rate is larger than 16, then the channel reuse OF ETMAC is diminished. We observe that the channel spatial reuse of ETMAC ranged from 1.41 to 3.20 (PU sensing error = 10 %) for different arrival rate on a channel (for two channel active of PU ON). For CBMAC, the channel spatial reuse ranged from 1.40 to 2.20 (PU sensing error = 10 %) for different arrival rate on a channel (for two channel active of PU ON). The maximum improvements of channel spatial reuse for ETMAC compared to CBMAC is 45.5 %. For ETMAC, as the PU sensing error increases, the channel spatial reuse decreases.

Fig. 7 shows the normalized throughput index ζ for ETMAC and CBMAC versus the arrival rate for a channel in multichannel CRAHNs. We observe that the normalized throughput of ETMAC ranged from 1.00 to 2.75 (PU sensing error = 10 %) for different arrival rates on a channel (for two channel

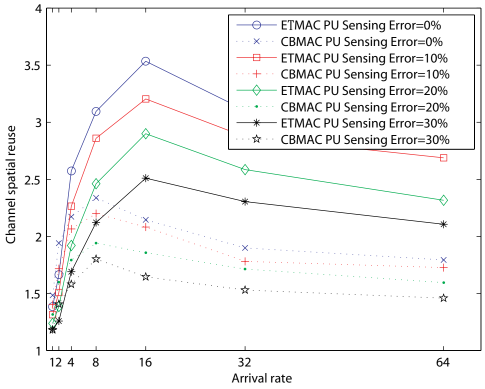

Fig. 6. The comparision of channel spatial reuse of ETMAC and CBMAC versus arrival rate a channel in multichannel CRAHNs.

active of PU ON). For CBMAC, the normalized throughput ranged from 0.49 to 1.34 (PU sensing error = 10 %) for different arrival rates on a channel (for two channel active of PU ON). The normalized throughput improvements for ETMAC compared to CBMAC raged from 104.1 % to 105.2 %. For ETMAC, as the PU sensing error increases, the normalized throughput decreases, but the required arrival rate on a channel increases to achieve the maximum normalized throughput.

In this paper, the normalized throughput of ETMAC is defined in Eq. (18) and the channel spatial reuse is included in the numerator of Eq. (18). From Fig. 6, the channel spatial reuse is higher than 1.0. Hence, the maximum normalized throughput is also greater than 1.0.

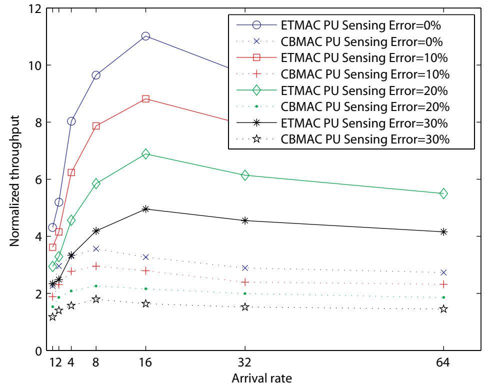

Fig. 7. The comparision of normalized throughput of ETMAC and CBMAC versus arrival rate on a channel in multichannel CRAHNs.

Fig. 8 shows the influence that PU sensing error has on the PU outage probability. In CBMAC, interference to a PU is avoided by suitable length of beacon interval. For ETMAC, interference to a PU is also avoided by shorter length of beacon interval than CBMAC, which will reduce the probability of an outage because of the PU sensing error. Despite reductions in channel spatial reuse and throughput in this method, ETMAC still provides higher spatial channel reuse and normalized throughput by the dynamic and shorter length of beacon interval than CBMAC. Fig. 8, shows that the outage probability of ETMAC ranges from 0.76 % to 0.32 % (PU sensing error = 10 %) for different arrival rates on a channel (for two channel active of PU ON). For CBMAC, the outage probability of CBMAC ranges from 0.77 % to 0.37 % (PU sensing error = 10 %) for different arrival rates on a channel (for two channel active of PU ON). The outage probability due to PU sensing error improvement provided by ETMAC compared to CBMAC ranged from 1.3 % to 13.5 %. In ETMAC, as the PU sensing error increases, the outage probability increases. From the simulation results, we see that the number of PU outage of ETMAC is larger than CBMAC, but the number of connections of ETMAC is also larger than CBMAC. From the definition of PU outage probability, the ETMAC has less PU outage probability than CBMAC.

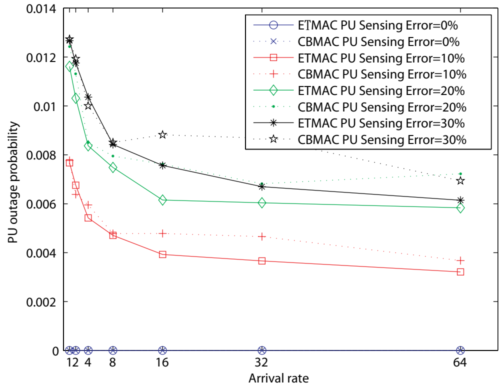

Fig. 8. The comparision of PU outage probability for PU sensing error of ETMAC and CBMAC versus arrival rate on a channel in multichannel CRAHNs.

Fig. 9 shows the MAC delay per beacon interval of SU for ETMAC and CBMAC versus the arrival rate for a channel in multichannel CRAHNs. We observe that the MAC delay per beacon interval of ETMAC ranged from 9.25 to 14.25 slots (PU sensing error = 10 %) for different arrival rates on a channel (for two channel active of PU ON). For CBMAC, the MAC delay per beacon interval ranged from 15.58 to 28.09 slots (PU sensing error = 10 %) for different arrival rates on a channel (for two channel active of PU ON). The MAC delay per beacon interval improvements for ETMAC compared to CBMAC raged from 40.6 % to 49.3 %. For ETMAC, as the PU sensing error increases, the MAC delay per beacon interval increases.

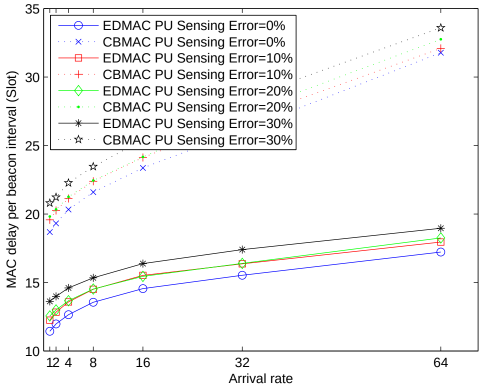

Fig. 9. The comparision of MAC delay per beacon interval of SU of ETMAC and CBMAC versus arrival rate on a channel in multichannel CRAHNs.

Fig. 10 shows the energy consumption per beacon interval of SU for ETMAC and CBMAC versus the arrival rate for a channel in multichannel CRAHNs. We observe that the energy consumption per beacon interval of ETMAC ranged from 23.51 to 36.34 W (PU sensing error = 10 %) for different arrival rates on a channel (for two channel active of PU ON). For CBMAC, the energy consumption per beacon interval ranged from 29.09 to 46.96 W (PU sensing error = 10 %) for different arrival rates on a channel (for two channel active of PU ON). The energy consumption per beacon interval improvements for ETMAC compared to CBMAC raged from 19.2 % to 22.6 %. For ETMAC, as the PU sensing error increases, the energy consumption per beacon interval increases.

In CBMAC, SU sender transmits a data packet using the fixed power, which is equal to the maximum allowable transmission power, and the interference to a PU is avoided by enabling SUs in the transmission range of the PU to notify the communication pairs that may interfere with the PU. For ETMAC, the SU in the transmission range will also inform the one-hop neighbors, which will reduce the probability of an outage, and the SUs having data packets first selects the data channels according to the channel's sensing probability of success and then it transmits the packets with the optimum transmission power. Therefore, ETMAC provides higher spatial channel reuse and normalized throughput by determining power control according to estimated distance, and also provides the lower PU outage probability.

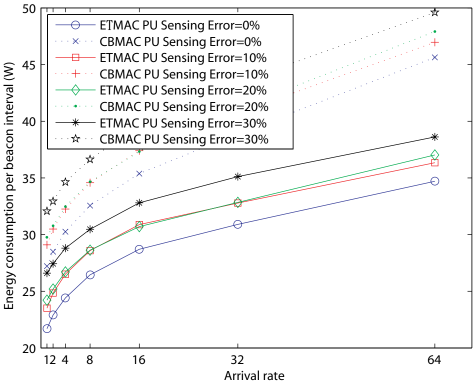

Fig. 10. The comparision of energy consumption per beacon interval of SU of ETMAC and CBMAC versus arrival rate on a channel in multichannel CRAHNs.

VI. CONCLUSION

We have proposed an energy efficient and high throughput MAC protocol based on opportunistic sensing for multichannel CRAHNs. We showed that a dynamic contention window results in significant improvements to energy efficient and high throughput. The proposed method, referred to as the energy efficient and high throughput MAC (ETMAC) protocol in multichannel CRAHNs, will save energy and reduce MAC delay by dynamic contention window. In a ETMAC, energy saving and delay deducing is more than CBMAC by dynamic contention window to save more idle slots. The proposed ETMAC scheme effectively saves not only the SUs energy but also reduces the MAC delay between SUs. Therefore, the ETMAC provides for higher spatial channel reuse, normalized throughput, and lower energy consumption and MAC delay. The simulation results show that the MAC delay reduced from 40.6 % to 49.3 % and the energy consumption reduced from 19.2 % to 22.6 % (for PU sensing error = 10 %). In addition, the ETMAC saves idle slots, to obtain improved channel spatial reuse and normalized throughput. As shown in the simulation results, channel spatial reuse maximum improved is 45.5 % and normalized throughput improved from 104.1 % to 105.2 % (for PU sensing error = 10 %).

APPENDIX

ACKNOWLEDGMENT

The authors would like to thank the editor and the reviewers for their valuable comments and suggestions. This work is supported by Ministry of Science and Technology, Taiwan, R.O.C. under grant MOST 106-2221-E-343-001 -.

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附件六

科技部補助專題研究計畫出席國際學術會議心得報告

日期：106 年 10 月 15 日

計畫編號	MOST 105－2221－E－343－002－		
計畫名稱	多重通道感知無線隨意網路之具有能源效率與高輸出量媒介存取協定		
出國人員姓名	吳建民	服務機構及職稱	南華大學資訊工程系副教授
會議時間	106 年 10 月 3 日至 106 年 10 月 11 日	會議地點	加拿大 BANFF
會議名稱	(中文)國際電機電子工程師協會 2017 系統、人、控制研討會 (英文)IEEE 2017 SMC		
發表題目	(中文)多重通道無線感知隨意網路之鄰居關係距離估測媒介存取協定 (英文) Neighbor-aware Distance Estimated MAC Protocol for Multichannel Cognitive Radio Ad Hoc Networks		

一、 參加會議經過

2017 IEEE International Conference on System, Man, Cybernetics（IEEE 2017 SMC）為 1 年舉辦一次的國際學術研討會，今年 2017 年 10 月 5 日至 10 月 8 日在加拿大班夫舉行。

感謝科技部的補助，讓我這次可以順利出行國際學術會議報告。參與這次研討會，同行的還有國立宜蘭大電機系系主任黃義盛教授。會議邀請了許多重量級的學者與會演講，每場演講後，各個與會學者均藉此機會提出意見交流。

此次大會的主要學術會程有邀請演講及口頭報告和壁報式論文呈現三

種。我發表了一篇口頭報告的論文，時間是 10 月 7 日，題目為" Neighbor-aware Distance Estimated MAC Protocol for Multichannel Cognitive Radio Ad Hoc Networks ".

二、 與會心得

首先感謝國科會計畫對於這次國際會議研究計畫的經費補助和支持，除了吸收世界各地優秀學者所提供的研究資訊之外，對於這種直接面對面交流與觀摩的機會，與會者提出的最新成果對提升無線感知隨意網路新技術的研究開發有極大的幫助。藉著參與國際研討會，我也能夠提升自己的研究水準，也藉著同行教授們的輪番上台報告，來提高台灣在國際學術研究上的能見度。

三、 發表論文全文或摘要

如附件

四、 建議

在此建議多致力補助大學部學生，讓年輕人有出國磨練的機會，不但在英文程度的提升有極大助益並能使學生更具有國際觀。

五、 攜回資料名稱及內容

1. 會議議程與投稿者之論文摘要一本。
2. 大會附贈環保袋一只。

六、其他

1. 與本次會議註冊主席台北科技大學電機系黃有評教授合影

2. 與本次會議台北大學資工系張玉山教授合影

3. 會議現場

4. 本人當日會議報告情形

Outline

- Background and Goal
- Neighbor-aware MAC Protocol
- Control channel in Neighbor-aware MAC Protocol
- Transmit-Power Estimation in Neighbor-aware MAC Protocol
- Performance Evaluation
- Conclusions

Neighbor-Aware Distance Estimated MAC Protocol for Multichannel Cognitive Radio Ad Hoc Networks

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***Abstract*—Cognitive radio (CR) is a promising method suitable for solving inefficiency spectrum policy by opportunistically identifying the vacant portions of the spectrum that are used by primary users (PUs). In cognitive radio ad hoc networks (CRAHNs), secondary users (SUs) can opportunistically utilize the spectrum that is available from PUs. In this paper, we propose a neighbor-aware distance estimated medium access control (NMAC) protocol for CRAHNs to mitigate the hidden and exposed terminal problems of multichannel CRAHNs. In this study, transmitter power control is based on the neighbor-aware estimated distance between SU communication pairs; this increases throughput, and reduces PU outage probability. We also compare our proposed scheme with existing MAC protocols for CRAHNs. We show that the NMAC will improve the channel spatial reuse, the normalized throughput, and reduce PU outage probability.**

***Index Terms*—cognitive radio ad hoc networks (CRAHNs), neighbor-aware distance estimated, medium access control (MAC), hidden terminal, exposed terminal problem.**

I. INTRODUCTION

Today's wireless networks are regulated by a fixed spectrum assignment policy. According to the Federal Communications Commission (FCC), the variation range in the utilization of the assigned spectrum is about 15 % to 85 %, with a high variance in time. The spectrum is a limited available source. Inefficient spectrum usage necessitates a new communication technology to opportunistically exploit the existing wireless spectrum. This new access method for the wireless spectrum is referred to as NeXt Generation (xG) Network, as well as Dynamic Spectrum Access (DSA) and Cognitive Radio Network (CRN) [1], [2], [3].

In CRNs, secondary users (SUs) can opportunistically utilize the spectrum of primary users (PUs) when it is idle. In cognitive radio ad hoc networks (CRAHNs), the spectrum can be divided into several channels. A single-channel can be used by SUs when there is no interference with other SUs and no interference between SUs and PUs; this improves network performance. In multichannel CRAHNs, channels are unreliable owing to collisions between SUs and PUs. Therefore, medium access control (MAC) protocols are quite important for avoiding collisions between SUs and PUs and avoiding problems with hidden terminals and exposed terminals.

The multichannel MAC protocols are an efficient method to solve the contention and collision problems among nodes. Multichannel MAC protocols can efficiently improve system throughput, while the maximum throughput of a single-channel MAC protocol is limited by the channel's bandwidth. In addition, multichannel protocols will create fewer propagation delays per channel than a single-channel [4].

The hard-ware limitations of practical cognitive radios are considered in [5]. The authors identify two hardware constraints of a cognitive radio. One is a sensing constraint, and the other is a transmission constraint. A decentralized cognitive MAC (DC-MAC) for opportunistic spectrum access in ad hoc networks is proposed in [6]. The authors proposed cognitive MAC protocols that optimize the performance of SUs and avoid the interference with PUs.

An Opportunistic Spectrum MAC (OS-MAC) for wireless networks equipped with cognitive radios is proposed in [7]. The OS-MAC can adaptively and dynamically seek and exploit opportunities in spectrum access along both the time and frequency dimensions. OS-MAC can efficiently access and share the spectrum among SUs and PUs. In [8], a novel cognitive MAC (C-MAC) protocol for distributed multichannel CRAHNs is proposed. C-MAC operates under multichannels, and hence is able to efficiently deal with spectrum access among PUs and SUs.

An efficient cognitive-radio-enabled multichannel MAC (CREAM-MAC) protocol for wireless networks is proposed in [9]. In CREAM-MAC, each SU is equipped with a cognitive radio transceiver and multiple channel sensors; as a result, collisions among SUs and between SUs and PUs can be resolved. A MAC protocol for opportunistic spectrum access (OSA-MAC) in cognitive radio networks is proposed by [10]. In OSA-MAC, each SU exchange controls information in a dedicated control channel. OSA-MAC uses the Power Saving Mechanism (PSM) model from IEEE 802.11 DCF-based WLANs.

A novel MAC (Novel-MAC) scheme for multichannel CRAHNs considers the PU signal that may cover only part of the network. The proposed Novel-MAC scheme adjusts the sensing priorities of channels at each SU with the PU detection information of other SUs and also limits the transmission power of a SU to the maximum allowable power in order to guarantee the quality of the service requirements of the PU [11].

A combined-MAC scheme for multichannel CRNs is proposed. The combined-MAC provided a comprehensive modeling and analytical delay analysis for a multichannel CRNs with both buffering and switching recovery policies [12].

An energy-efficient distributed multichannel MAC protocol (MMAC) is proposed for CR networks [13]. MMAC can achieve energy-efficient communication, and the phases of its sensing algorithms include a low-power inaccurate scan and a high-power accurate scan.

In this paper, we propose a neighbor-aware distance estimated MAC (NMAC) protocol for CRAHNs, to enable primary users (PUs) to efficiently use the available spectrum. In addition, frequencies reserved for PUs may experience periodic use and frequent quiet periods; thus, secondary users (SUs) may utilize these frequencies during these periods. However, in cases where SUs use PU frequencies, PUs must not be subjected to performance degradation. These requirements motivated us to design a Neighbor-Aware Distance Estimated MAC protocol for CRAHNs to overcome the hidden and exposed terminal problems in multichannel CRAHNs.

The main goal of this paper is to design a NMAC protocol in multihop, multichannel CRAHNs. NMAC resolves multichannel hidden terminal problems for PUs and SUs, as well as multichannel exposed terminal problems for SUs. The main contributions of this paper are the design of a multichannel MAC protocol for CRAHNs and other performance metrics for the saturation CRAHNs. In this protocol, requiring two transceivers per node mitigates the hidden and exposed terminal problems in multichannel CRAHNs, unlike other multichannel MAC protocols that only mitigate the hidden terminal problem.

The remainder of this paper is organized as follows: NMAC protocols are described in Section 2. Log-distance power-law path-loss model in ad hoc networks and transmit-power estimation in NMAC protocol are described in Sections 3, 4, respectively. We evaluate the performance of the proposed NMAC with some numerical results obtained from a simulation in Section 5. Finally, the paper concludes in Section 6.

II. NEIGHBOR-AWARE DISTANCE ESTIMATED MAC (NMAC) PROTOCOL

In this section, we introduce the NMAC, which enables opportunistic spectrum sharing in CRAHNs. The NMAC enables significant increases in throughput and reduces the probability of an outage for PUs. This protocol is designed to protect PUs from SU interference and resolve the hidden and the exposed terminal problems for SUs. The time structure used is similar to the IEEE 802.11 power-saving mode.

A. System Model in Multichannel MAC Protocol CRAHNs

We consider a multichannel environment in CRAHNs. There is one control channel and N data channels within the CRAHNs. It is assumed that SUs will not be disturbed by PUs in accessing the control channel. The data channels are licensed to PUs and can be opportunistically used by the SUs. In the environment under consideration, the PU and SU signals can have influence not on the entire CRAHN but only on part of the CRAHN. That is, there exist SUs that cannot detect the PU activation within the CRAHN and this will create hidden and exposed terminal problems in CRAHNs. In addition, the data transmission model is in a multihop environment.

On the other hand, SUs can transmit data traffic with the controlled power by a NMAC as low as possible to avoid influencing PUs. In addition, the SU sender should use minimum power by the NMAC to transmit data traffic to the SU receiver. This will mitigate the hidden and exposed terminal problems for SUs. When an SU does not detect the PU signal on a data channel, the SU is allowed to access the data channel, irrespective of the sensing results of other SUs.

In the proposed NMAC protocol, each SU is equipped with two transceivers: one to communicate with the control channel and one to communicate with data channels.

B. NMAC Protocol in Multichannel CRAHNs

In this section, we propose the use of the NMAC protocol in multichannel CRAHNs to resolve hidden and exposed terminal problems. Before describing the NMAC in detail, we first summarize our assumptions. This protocol uses a scheme similar to [4] that provides throughput improvements using N channels, and all channels have the same bandwidth. None of the channels overlap, thus the packets transmitted on different channels do not interfere with each other. Nodes have prior knowledge regarding the number of available channels. Each node is equipped with two half-duplex transceivers. The transceiver is capable of switching channels dynamically. Nodes are synchronized, allowing them to begin their beacon intervals at the same time.

The time structure is divided into time intervals in CRAHNs, where each time interval has two phases. Fig. 1 shows the one control channel of the NMAC protocol in multichannel CRAHNs.

The following section contains detailed descriptions of these two phases in a NMAC.

- Sensing minislot window phase: Each node sends itself a beacon control message, using the IEEE 802.11 Timer Synchronization Function (TSF) to perform the synchronization. This beacon records its local time in the sensing minislot window and refreshes its time when it receives a faster beacon time than itself. If a collision occurs between the beacon messages, the backoff mechanism is invoked. IEEE 802.11 and previous documents specify that the SU should change and sense each channel, which is a misuse of energy. In this study, channel sensing is performed according to success probability. Therefore, NMAC will reduce transition time and further decrease energy consumption.
- Contention window phase: This phase contains the following control messages: RTS (Request-to-send), CTS

(Clear-to-send), PCA (position confirm ACK), CCA (channel confirm assignment), TRC (transmission range confirm), data, and ACK (acknowledgement). Each SU must perform this procedure completely in a control channel before obtaining a this channel.

C. Contention Window Descriptions

All the fields of the control packet for data channel reservation in a NMAC protocol of multichannel CRAHNs are descriptions as follows:

- Beacon: Using IEEE 802.11 Timer Synchronization Function(TSF).
- INT: INT contains the following fields: CH_{id}, SU_{sender}, and PU_{sender}. CH_{id} denotes the interfered channel to PU, SU_{sender} denotes the SUs that sent the interrupt message, and PU_{sender} denotes the interfered PU.
- RTS: The following fields: CH_{id1}, CH_{id2}, CH_{id3}, SU_{sender}, $SU_{receiver}$, $Nbr_{ID1}, \cdots, Nbr_{IDn}$ and $Power_{max}$ were added to the fields in the CTS of IEEE 802.11. Channels CH_{id1}, CH_{id2} and CH_{id3} have higher priority in the channel status of the SU sender. SU_{sender} denotes the SU sender, $SU_{receiver}$ denotes the SU receiver, $Nbr_{ID1}, \cdots, Nbr_{IDn}$ denotes the ID of the neighbors of SU_{sender}, and $Power_{max}$ denotes the maximum transmission power of the SU sender.
- CTS: The following fields: CH_{id}, SU_{sender}, $SU_{receiver}$, $Nbr_{ID1}, \cdots, Nbr_{IDn}$, $Power_{rcv}$ and $Power_{max}$ were added to the fields in the CTS of IEEE 802.11. CH_{id} denotes the channel selected according to the received RTS message. $Nbr_{ID1}, \cdots, Nbr_{IDn}$ denotes the ID of the neighbors of $SU_{receiver}$, and $Power_{rcv}$ denotes the receiving power of the SU receiver, and $Power_{max}$ denotes the maximum transmission power of SU sender.
- CAS: CAS contains the following fields: CH_{id}, SU_{sender}, $SU_{receiver}$, and $Power_{snd}$. CH_{id} denotes the channel selected by the SU sender, $Power_{snd}$ denotes the sending power of the SU sender.
- CAC: CAC contains the following fields: CH_{id}, SU_{sender}, $SU_{receiver}$, and $Power_{rcv}$. CH_{id} denotes the channel selected by the SU receiver and $Power_{rcv}$ denotes the receiving power of the SU receiver.
- ACK: ACK contains the following fields: CH_{id}, SU_{sender}, and $SU_{receiver}$. CH_{id} denotes the channel selected by the SU sender.

Fig. 1 shows the exchange of control packets and the data channel reserved during the period from the start of the beacon interval to the completion of the contention window.

III. LOG-DISTANCE POWER-LAW PATH-LOSS MODEL IN AD HOC NETWORKS

In [14], the authors proposed a deterministic propagation model for wireless networks. In [15], a shadow fading model for vehicular ad hoc networks is proposed, and a realistic model takes shadowing effects into account with a reasonable amount of complexity. A simple log-distance power law is used to model the path loss that occurs when predicting a reliable communication range between a transmitter and receiver. The log-distance power law path loss model is derived as follows:

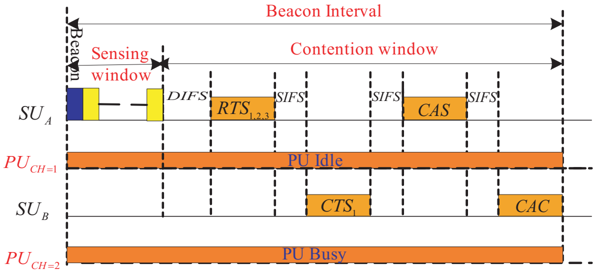

Fig. 1. One control channel in NMAC protocol of multichannel CRAHNs

$$PL(d) = PL_0 + 10n\log_{10}(\frac{d}{d_0}) + X_\sigma \tag{1}$$

where d is the distance between transmitter and receiver, n is the path loss exponent estimated and X_σ is zero-mean Gaussian distributed random variable with standard deviation σ. The PL_0 is the path loss at a reference distance d_0 in dB, and is based on either close-in measurements or a free space assumption from the transmitter to d_0.

IV. TRANSMIT-POWER ESTIMATION IN NMAC PROTOCOL

Distributed localization algorithms for SUs in cognitive radio ad hoc networks are essential for estimating distance. Neighbor-aware distance estimates rely on the number of shared communication neighbors and applies geometrical properties to the network structure. A neighbor-aware approach provides reliable estimates for the distances between any two adjacent SUs in CRAHNs [16].

The basic idea of neighbor-aware distance estimation is to approximately determine the common surface of two overlapping communication areas by the ratio of shared to total neighbors. Knowing the overlapping surface, the distance between the two communicating SUs can be derived. The distance can then be used as input for the power estimation [16].

Fig. 2 shows how to estimate the overlapping surface of the communication area of two adjacent SUs. The requirements for the neighbor-aware distance estimation algorithm are that each SU knows all its neighbors and can communicate with them.

For SU_A, the sector area (the sum of the red-dotted-line area and blue-solid-line area) of points $SU_A, A,$ and B, is

$$S_{SU_A AB} = \pi R^2 * \frac{\theta}{2\pi} = \frac{1}{2}R^2\theta \tag{2}$$

The triangular area (the-red-dotted line area) of points, $SU_A, A, and B$, is

$$\triangle_{SU_A AB} = \frac{1}{2} * \frac{d}{2} * 2R\sin\frac{\theta}{2} = \frac{1}{2}dR\sin\frac{\theta}{2} \tag{3}$$

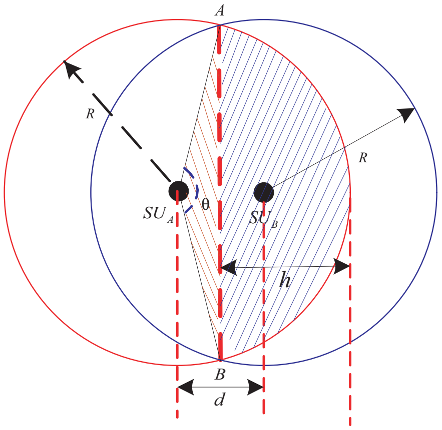

Fig. 2. Estimation of the overlapping surface of the communication area of two adjacent SUs.

The network structure of two adjacent SUs and their communication area can be mapped to the geometrical shape of two overlapping circles. The problem of determining the distance between the adjacent SUs becomes a computation of the distance between the corresponding circles' centers. The surface of the overlapping area OA can be estimated as follows:

$$\begin{aligned} OA &= 2*(S_{SU_AAB} - \triangle_{SU_AAB}) \\ &= 2*(\frac{1}{2}R^2\theta - \frac{1}{2}dR\sin\frac{\theta}{2}) = R^2\theta - dR\sin\frac{\theta}{2} \end{aligned} \quad (4)$$

For $\triangle_{SU_AAB}$, $\cos\frac{\theta}{2} = \frac{\frac{d}{2}}{R} = \frac{d}{2R}$,
therefore $\theta = 2\cos^{-1}(\frac{d}{2R})$, and $\sin\frac{\theta}{2} = \sqrt{1-\frac{d^2}{4R^2}}$,

$$OA = 2R^2\cos^{-1}(\frac{d}{2R}) - \frac{1}{2}d\sqrt{4R^2-d^2} \quad (5)$$

From the relations among d, h, and R, the distance between the two centers can be obtained by $d = 2(R-h)$,

Therefore the overlapping surface OA can be calculated from an unknown distance between SU_A and SU_B and a segment height h.

$$OA = 2R^2\cos^{-1}(1-\frac{h}{R}) - 2(R-h)\sqrt{2Rh-h^2} \quad (6)$$

As Eq. (6) depends on h and R, there is no two-dimensional representation that can be approximated by using regression. Nevertheless, the following considerations help to solve this problem. The height h of a segment can be described as a ratio α of the circle's radius R, and the segment area OA is a portion of half the circle's surface [16]:

$$\alpha = \frac{h}{R}, \beta = \frac{OA}{\pi R^2} \quad (7)$$

Here we show that α and β are independent of R, with the result that the relationship between α and β can be approximated using regression. Because $\cos\frac{\theta}{2} = \frac{\frac{d}{2}}{R} = \frac{1}{R} = 1 - \frac{h}{R}$, Therefore, $h = R(1-\cos\frac{\theta}{2})$, and we can get

$$\alpha = \frac{h}{R} = 1 - \cos\frac{\theta}{2} \quad (8)$$

$$\beta = \frac{OA}{\pi}R^2 = \frac{1}{\pi}R^2(R^2\theta - dR\sin\frac{\theta}{2}) = \frac{1}{\pi}(\theta - \frac{d}{R}\sin\frac{\theta}{2}) \quad (9)$$

So,

$$\beta = \frac{1}{\pi}(\theta - 2\frac{\frac{d}{2}}{R}\sin\frac{\theta}{2}) = \frac{1}{\pi}(\theta - 2\cos\frac{\theta}{2}\sin\frac{\theta}{2}) = \frac{1}{\pi}(\theta - \sin\theta) \quad (10)$$

From above, we show that α and β are independent of R. In [16], the authors showed that the optimal distance can be obtained by a third-degree polynomial function.

$$d_{AB} = R(a*(\frac{N_{AB}}{N_{SU_A}})^3 + b*(\frac{N_{AB}}{N_{SU_A}})^2 + c*(\frac{N_{AB}}{N_{SU_A}}) + e) \quad (11)$$

$$d_{BA} = R(a*(\frac{N_{BA}}{N_{SU_B}})^3 + b*(\frac{N_{BA}}{N_{SU_B}})^2 + c*(\frac{N_{BA}}{N_{SU_B}}) + e) \quad (12)$$

Then the estimated distance d between SU_A and SU_B is

$$d = \frac{1}{2}(d_{AB} + d_{BA}) \quad (13)$$

Using regression to determine the polynomials d_{AB} and d_{BA} and further computations, the coefficients of the above equation can be estimated as follows:
$a = -1.992, b = 4.394, c = -4.707$, and $e = 2.294$

V. PERFORMANCE EVALUATION

We compare NMAC's performance with the MMAC scheme, in which channels are assigned to a connection on demand.

The cognitive radio ad hoc network is simulated by placing 400 nodes randomly within a bounded region of 1200×1200 m^2. It is assumed that nodes will be continuously powered on. Before the transmission range is adjusted for each node, the control message transmission range for SUs is fixed at 250 m; each simulation runs for 20,000 seconds. The transmission range for PUs is fixed at 300 m. There are four PUs, placed at (300, 300), (900, 300), (300, 900),and (900, 900). There are four data channels. Each PU has its own channel and not overlap in the transmission range. The transmission rates for each data channel is 2 $Mbps$ and the transmission rate for control channel is 1 $Mbps$. The state of a channel alternates between the PU ON state where a PU is busy on the channel and the PU OFF state where the channel is idle for a PU. The PU ON duration of each channel are exponentially distributed with mean 10, 20, 30, 40, 60, 120, 180, 240, and 300 sec, respectively. We do not consider mobility in this paper, and all nodes are assumed to be stationary to eliminate the effects of broken routes caused by mobility.

Each of our simulation results is the average of 10 randomly generated network topologies. Furthermore, to generate a more uniform topology, we divided the topology into 100 regions and randomly dispersed the 400 SUs in the regions. This prevented the network from becoming disconnected when N (the average number of neighbors) was small. The distances between the source node and the destination node were also uniformly distributed. That is, we ensured that there were roughly equal numbers of short, medium, and long connections.

Traffic is assumed to be uniformly distributed among all nodes with various overall loads (or erlangs, the ratio of the arrival rate to the departure rate). The arrival rate is the number of newly arriving connections per second. The departure rate is the number of terminated connections per second, and is also the inverse of the average lifetime of a connection. To obtain the desired traffic load, the departure rate was fixed at 0.05 and the arrival rate was 16.

We evaluated NMACs performance in CRAHNs, based on the following metrics:

- Channel spatial reuse index η: The average number of times that a channel is being used simultaneously. It is defined as follows.

$$\eta = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} CH_{one}(i,j)}{\sum_{i=1}^{M} CH_{mul}(i)} \ . \tag{14}$$

- Normalized throughput ζ: the normalized throughput under overload condition of the multichannel CRAHNs. In CRAHNs, PUs use licensed channels dynamically; the licensed channels used by SUs are alternated between ON and OFF states. The normalized throughput of the multichannel CRAHNs ζ (with n licensed data channels, and one control channel) is defined as follows:

$$\zeta = \frac{\eta R_{data} E[CH_{vacant}] E[T]}{(nR_{data} + R_{control})(E[T] + nT_{ms})} \tag{15}$$

where R_{data} is the data rate of a licensed channel, $R_{control}$ is the data rate of a control channel, T_{ms} is the mini-slot time units in sensing window, $E[CH_{vacant}]$ is the average number of vacant channels, and $E[T]$ is the average time that is required for the successful handshakes of $RTS/CTS/CAS/CAC$ of NMAC.

Fig. 3 shows the channel spatial reuse index η for NMAC and MMAC versus the PU ON duration for a channel in multichannel CRAHNs. For NMAC, the channel spatial reuse index η can be higher than 1.0 because channels are reused if no interference problems can occur. NMAC produces the highest channel spatial reuse, because it adjusts the transmission range and reduces the interference range of PUs and SUs. We observe that the channel spatial reuse of NMAC ranged from 1.73 to 6.39 for different PU ON durations on a channel (for two channel active of PU ON). For MMAC, the channel spatial reuse of NMAC ranged from 1.00 to 3.34 for different PU ON durations on a channel (for two channel active of PU ON). The channel spatial reuse improvements for NMAC compared to MMAC raged from 73.0% to 91.4%. For NMAC, as the PU ON duration for a channel increases, the channel spatial reuse increases; as the PU activity ratio increases, the channel spatial reuse decreases.

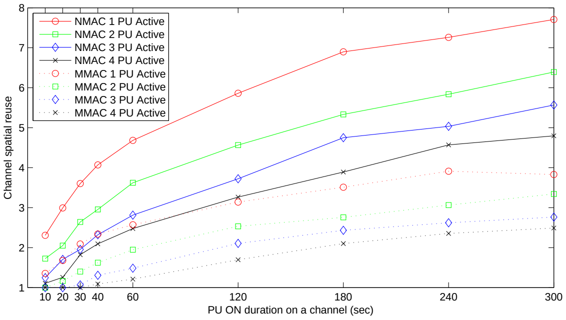

Fig. 3. The comparison of channel spatial reuse of NMAC and MMAC versus PU ON duration on a channel in multichannel CRAHNs.

Fig. 4 shows the normalized throughput index ζ for NMAC and MMAC versus the PU ON duration for a channel in multichannel CRAHNs. We observe that the normalized throughput of NMAC ranged from 0.074 to 1.663 for different PU ON durations on a channel (for two channel active of PU ON). For MMAC, the normalized throughput ranged from 0.043 to 0.918 for different PU ON durations on a channel (for two channel active of PU ON). The normalized throughput improvements for NMAC compared to MMAC raged from 72.1% to 81.2%. For NMAC, as the channel active of PU ON decreases, the normalized throughput increases, but the required PU ON durations on a channel increases to achieve the maximum normalized throughput. From Fig. 3, the channel spatial reuse is higher than 1.0. Hence, the maximum normalized throughput is also greater than 1.0.

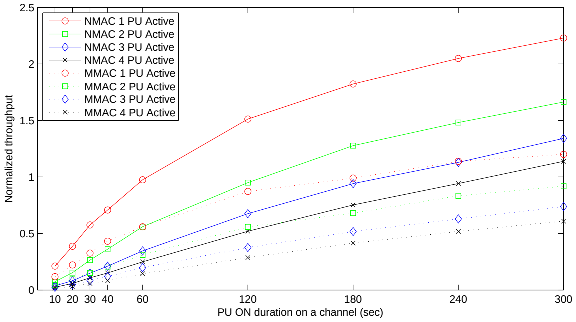

Fig. 4. The comparison of normalized throughput of NMAC and MMAC versus PU ON duration on a channel in multichannel CRAHNs.

Fig. 5 shows the influence that PU activation/deactivation frequency has on the PU outage probability. In MMAC, interference to a PU is avoided by enabling SUs in the transmission range of the PU to notify the communication pairs that may interfere with the PU. For NMAC, the SU in the transmission range will inform the one-hop neighbors, which will reduce the probability of an outage. Despite reductions in channel spatial reuse and throughput in this method, NMAC still provides higher spatial channel reuse and throughput by determining power control according to estimated distance. Fig. 5, shows that the outage probability of NMAC ranges from 13.86% to 1.34% for different PU ON durations on a channel (for two channel active of PU ON). For MMAC, the outage probability of MMAC ranges from 45.28% to 4.16% for different PU ON durations on a channel (for two channel active of PU ON). The outage probability improvement provided by NMAC compared to MMAC ranged from 69.4% to 67.8%. In NMAC, as the PU ON duration on a channel increases, the outage probability decreases; as the PU activity ratio increases, the outage probability increases.

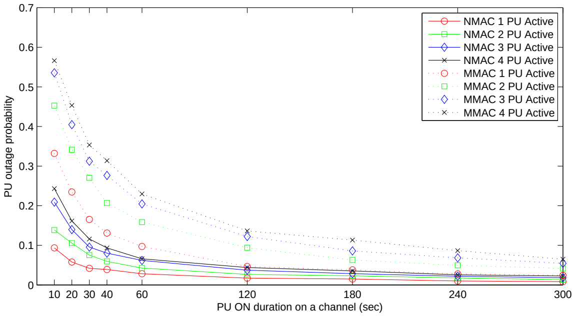

Fig. 5. The comparison of PU outage probability of NMAC and MMAC versus PU ON duration on a channel in multichannel CRAHNs.

In MMAC, SU sender transmits a data packet using the fixed power, which is equal to the maximum allowable transmission power, and the interference to a PU is avoided by enabling SUs in the transmission range of the PU to notify the communication pairs that may interfere with the PU. For NMAC, the SU in the transmission range will also inform the one-hop neighbors, which will reduce the probability of an outage, and the SUs having data packets first selects the data channels according to the channel's sensing probability of success and then it transmits the packets with the optimum transmission power. Therefore, NMAC provides higher channel spatial reuse, the higher normalized throughput by determining power control according to estimated distance, and also provides the lower PU outage probability.

VI. CONCLUSION

We showed that a neighbor-aware distance estimation results in significant improvements to transmission power estimation. The proposed method, referred to as the neighbor-aware distance estimated MAC (NMAC) protocol in multichannel CRAHNs, will mitigate the hidden and exposed terminal problems for PUs and SUs by estimating neighbor-aware distance to adjust the transmission range. In a NMAC, by estimating the distance between SUs and controlling the transmission power of packets to guarantee the quality of service requirements of PUs. The proposed NMAC scheme effectively protects not only the hidden terminal PUs and SUs but also mitigates the exposed terminal problems between SUs. Therefore, the NMAC provides for higher spatial channel reuse, normalized throughput, and lower PU outage probability. The simulation results show that the outage probability was reduced from 69.4% to 67.8% (for two channels active of PU ON). In addition, the NMAC determines power control according to estimated distance, to obtain improved channel spatial reuse and normalized throughput. As shown in the simulation results, channel spatial reuse improved from 73.0% to 91.4% and normalized throughput improved from 72.1% to 81.2% (for two channels active of PU ON).

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105年度專題研究計畫成果彙整表

計畫主持人：吳建民					**計畫編號：**105-2221-E-343-002-		
計畫名稱：多重通道感知無線隨意網路之具有能源效率與高輸出量媒介存取協定							
成果項目					量化	單位	質化 （說明：各成果項目請附佐證資料或細項說明，如期刊名稱、年份、卷期、起訖頁數、證號...等）
國內	學術性論文	期刊論文			0	篇	
		研討會論文			0		
		專書			0	本	
		專書論文			0	章	
		技術報告			0	篇	
		其他			0	篇	
	智慧財產權及成果	專利權	發明專利	申請中	0	件	
				已獲得	0		
			新型/設計專利		0		
		商標權			0		
		營業秘密			0		
		積體電路電路布局權			0		
		著作權			0		
		品種權			0		
		其他			0		
	技術移轉	件數			0	件	
		收入			0	千元	
國外	學術性論文	期刊論文			1	篇	Chien-Min Wu* and Chih-Pin Lo, “Geometry Distance Estimated MAC Protocol for TV White Space,” IEEE Systems Journal, DOI 10.1109/JSYST.2017.2701802, 25 May, 2017.
		研討會論文			1		Chien-Min Wu*, Chih-Pin Lo and Yi-Sheng Huang ， “Neighbor-aware Distance Estimated MAC Protocol for Multichannel Cognitive Radio Ad Hoc Networks,” Banff, Canada, IEEE SMC 2017, Oct. 5-8, 2017.
		專書			0	本	
		專書論文			0	章	
		技術報告			0	篇	
		其他			0	篇	
	智慧財產權及成果	專利權	發明專利	申請中	0	件	

				已獲得	0		
			新型/設計專利		0		
		商標權			0		
		營業秘密			0		
		積體電路電路布局權			0		
		著作權			0		
		品種權			0		
		其他			0		
	技術移轉	件數			0	件	
		收入			0	千元	
參與計畫人力	本國籍	大專生			2	人次	楊有傑及謝承岳負責程式撰寫之完成。
		碩士生			0		
		博士生			0		
		博士後研究員			0		
		專任助理			0		
	非本國籍	大專生			0		
		碩士生			0		
		博士生			0		
		博士後研究員			0		
		專任助理			0		
其他成果 （無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。）							

科技部補助專題研究計畫成果自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現（簡要敘述成果是否具有政策應用參考價值及具影響公共利益之重大發現）或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標
□未達成目標（請說明，以100字為限）
　□實驗失敗
　□因故實驗中斷
　□其他原因
說明：

2. 研究成果在學術期刊發表或申請專利等情形（請於其他欄註明專利及技轉之證號、合約、申請及洽談等詳細資訊）

論文：□已發表　□未發表之文稿　■撰寫中　□無
專利：□已獲得　□申請中　■無
技轉：□已技轉　□洽談中　■無
其他：（以200字為限）

本計畫研究成果目前正撰寫中，近期即可全文，將先投稿至國際學術研討會，之後並將投稿至國際學術期刊。

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性，以500字為限）

學術成就: 本計劃經由實驗結果證實，所提方法確實能夠降低MAC 競爭的時間延遲及節省電池能量，且對系統輸出量有極大的改善。目前正撰寫論文中。

技術創新: 在本計畫中，提出在無線感知隨意網路中動態長度之競爭視窗大小及SU傳送端持續佔有多個資料時槽機制。此競爭視窗包含四個控制訊框，控制訊框時槽長度將由SU所感測到PU空閒的資料通道個數及SU競爭節點個數多寡所共同決定。

社會影響: 對於資訊科技產業而言，如將此技術應用於無線通訊網路技術，必能提升無線通訊網路的系統效能，進而提升無線通訊網路的經濟產值。

4. 主要發現

本研究具有政策應用參考價值：□否　■是，建議提供機關國家通訊傳播委員會,

（勾選「是」者，請列舉建議可提供施政參考之業務主管機關）

本研究具影響公共利益之重大發現：□否　■是

說明：（以150字為限）

為了讓下一世代的感知無線網路盡快落實，有效率的媒介存取協定將扮演重要關鍵技術，本計畫藉由考慮降低PU干擾及提升SU通道使用率，提出動態長度之競爭視窗大小及SU傳送端持續佔有多個資料時槽機制，達到提升系統輸出量及降低單位傳輸週期能量消耗的目的，因此如能落實此結果，相信所提無線傳輸技術必能對公共利益有。