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MAC Protocol for Secondary Link Maintenance Enhanced with Primary Behaviour Study

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Abstract: The critical aspect of the spectrum allocation in distributed cognitive radio networks is how efficiently the spectrum is managed and how the Secondary User's (SU) link is maintained once the Primary User (PU) arrives or when, the channel degrades due to interference. To address this problem, in this study a distributed cognitive MAC protocol is proposed to achieve compensation to the suspended secondary link and avoid collision with the primary, which obviously increases the network performance. The 802.11 based Backup Channel Reservation protocol (BCR-MAC) is proposed to reconstruct the second communication if forced termination occurred, the protocol operates over a separate common control channel and multiple data channels; hence it is able to deal with dynamics of resources availability effectively to facilities quicker and smoother channel switching to free sensed or reserved channel. A higher number of sensed channels lead to better chances for reservation procedure to be implemented. The protocol effectively improves the network throughput due to a higher successful transmission as demonstrated by analysis and simulation.

Key words: Cognitive radio, MAC protocol, channel reservation, SU, PU

INTRODUCTION

In a cognitive radio network consisting of primary users and cognitive users, the primary users may not fully exploit their spectrum; therefore the cognitive users temporary occupy the unused sub-band. However, evaluating the dynamic nature of the spectrum and collecting reliable and sufficient information is essential for opportunistic network. Sensing and scanning mechanism are working together to control the sequence of scanning and the portion of spectrum to be scanned. A cognitive radio regularly searches for a free channel during initial channel selection, when a SU scans the spectrum for free channel and when a SU evacuates the current channel and switches to another channel due to a primary user arrival or when the channel abruptly degrades with interference. Under dynamic channel conditions, every channel is susceptible to channel degradation or link termination during a PUs channel reclaim. For a channel to be sensed available, the user monitors the channel for a minimum period called detection time to estimate the occupancy nature and ensure the fitness of the channel for selection. Under such scenarios an active CR user may not have enough time to sense and search for free channels and access them during transmission. The latency in sensing and detecting the free-channels and using them for SU links may cause significant loss in QoS. Since, the available number of free-channels may vary considerably in this dynamic shared spectrum and every channel is susceptible to PU reclaim, it is difficult to separate a fixed number of channels as reserve channels. Although, plenty of research is being carried out on channel sensing and allocation mechanism to improve spectrum utilization, Solutions for spectrum mobility the ability of a distributed cognitive radio to scan the spectrum and adaptively switch channels to mitigate secondary user's link degradation is less explored. In this research, BCR-MAC protocol is proposed for decentralized multi-channel networks with continuous spectrum sensing and scanning capability. A novel idea of our protocol is to include the channel states table and reservation information for the backup reserved channel into the control messages of the current transmission instead of sending an extra control packet in separate period. Thus, the reservation information can be heard by all nodes within the transmission range of the sender with little extra overhead. This significantly improves the network performance especially, when sending large data packet size.

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In Chang *et al.* (2000) soft reservation is used, which attempts to assign the same channel that the sender node has used before; if the most recently used channel is idle, then the sender selects that channel; otherwise, it can choose the idle channel with minimum received signal strength. Soft reservation tends to reserve a channel for each node in order to minimize the chance of channel contention. The main drawback of this technique is that the channel is selected by considering signal powers at the sender only, which may result in the selection of a busy channel at the receiver. A mathematical model for cognitive channel reservation had been proposed by Xiaorong *et al.* (2007) it shows statistically that the channel reservation will significantly increases the network throughput due to the increase in the number of the successful transmission. The research doesn't mention any technique specification and/or implementation process. In Masahiro *et al.* (2008) although, not for cognitive radio, the researcher proposes a novel channel reservation for mesh network, this implemented simultaneously with the current communication to reduce the back off time and to utilize the gaps between the transmissions. The communicating nodes by exchanging reservation information announce their neighbours not to use that channel. The protocol enhances the multi hop network by reserving the channel in the next hop before the data forwarded to it. In Huei *et al.* (2004) a dynamic reservation for handoff calls in culler network is described; the proposed protocol adapts the recourse access priority via reservation and bandwidth adjustments in response to changes in signal strength and quality of calls in neighboring cell. DACRS satisfies the desired handoff blocking probability, reduce the blocking probability of new calls and maximizes the channel utilization in wireless networks. A novel CSMA/CA based reservation scheme is proposed to improve the multiple access throughputs of wireless ad-hoc networks by using switched beam antennas. Reservation message is been sent carrying the information about the intended direction of transmission on all unblocked beams, the number of the control/data packet collisions and the number of neighbors that back-off unnecessarily are going to be minimized. This is done by emphasizing the trade-off between packet collisions. In Ghurumuruhan and Li (2005) the studies demonstrate that the cooperation between cognitive user improve the primary detection time, specially if many nodes participate as a relay nodes to accomplish the communication to the same receiver, in our protocol simple approach is implemented, the two communicating nodes participate in primary's time detection procedure, where no relay nodes in between. In Panagiotis *et al.* (2008) the research proposes an effective sensing over the spectrum, a bidirectional and dual scanning mechanism is proposed to search over a broader and deeper spectrum space. Because conventional sequential scanning lacks the facility to find a free-channel in deeper spectrum region and may not be effective; scanning the multiple regions simultaneously in a dynamic spectrum sharing network, could provide diverse and sufficient spectrum information. The researcher considers the distributed cognitive radio system, in which both the transmitter and receiver mutually cooperate to scan different portions of spectrum and share the spectrum sensing information. The detection of the nearest available free channel in unidirectional scanning where the searching space is limited to one direction, may be missed, thus the bidirectional scanning method have been proposed so the radio scanner is able to scan the channel in both directions expanding through the spectrum space in both directions finding the nearest available channels. the reservation method in this research is discussed only if there is sensed free channels, in our proposed protocol, related to this reference we assume the availability of occupied channel but it is about to be released, that is to say it will be released before the primary regains, so the secondary link could be maintained.

IEEE 802.11 MAC protocol: Before we present our new protocol, in this study we first review some technique details of IEEE 802.11 MAC protocol. The IEEE 802.11 (info. Tech. 2003) has been widely deployed to provide wireless LAN access. Its MAC protocol is responsible for coordinating access to the shared radio channel. The IEEE 802.11 employs a CSMA-CA based approach along with virtual carrier sensing and channel reservation techniques. In CSMA-CA, the channel is always sensed before any transmission. If the channel is sensed busy, the transmitter waits for it to become idle and goes through a random back-off period before retrying. The random back-off period ensures fairness among transmitting hosts and also reduces the probability of collisions. In addition, transmitting and receiving hosts exchange Request-To-Send (RTS) and Clear-To-Send (CTS) control frames to reserve the channel before transmitting data packets. This effectively performs a virtual carrier sensing at the receiver. Successful exchange of these control frames also reserves the channel temporarily for the data transmission. Although, the IEEE 802.11 standard provides multiple channels, its MAC layer is designed for sharing a single channel. It performs well under low load conditions, but under heavy-load conditions, it causes bandwidth under-utilization due to collisions and back-offs. These problems motivate the spatial reuse of the wireless medium. Transmission power control with directional antennae and multiple channels are the most popular techniques for spatial reuse.

Next, we describe some specific operations of IEEE 802.11 DCF protocol. DCF defines two channel access modes: basic mode and RTS/CTS access mode. Both modes adopt the discrete-time back-off algorithm. Whenever a node has a packet to transmit, it generates a random back-off counter uniformly from [0; CW_i - 1], where CW represents the size of the contention window. As long as the carrier is sensed idle for a period of Distributed Inter Frame Space (DIFS), the node begins to decrement its back-off counter by one. After that, the back-off counter is reduced by one for each idle slot. If the carrier is busy, the back-off counter is frozen until the next idle DIFS is sensed. When the back-off counter is reduced to zero, the node begins the transmission. The minimum and maximum values of CW, CWmin and CWmax, are determined by the physical layer characteristics. For example, CWmin and CWmax are set to 16 and 1024, respectively for FHSS physical layer in IEEE 802.11b standard. After each successful transmission, CW is reset to its minimum value CWmin. After each unsuccessful transmission, the value of the back-off stage k will be increased by 1 and CW will be doubled until it reaches its maximum value CWmax, that is. Two short conversation frames, Request to Send (RTS) and Clear to Send (CTS), are sent prior to the transmission of the data frame. When the source node is ready to send a packet, it sends a RTS message instead of the data frame. The RTS message contains the expected duration information for the remaining transmission, which includes three Short Inter Frame Space (SIFS) intervals, one CTS message, one data frame and one ACK message. If no collision occurs, the destination node replies with a CTS message after a SIFS, which also contains the new expected duration information of the remaining transmission. Other nodes receiving the RTS and CTS messages update their Network Allocation Vector (NAV) based on the duration information in RTS and CTS messages. NAV is maintained by each node to indicate when the channel is available and is updated by RTS and CTS messages. All other nodes know when the current transmission will complete according to the updated NAV and avoid transmitting packets during this period. Since the length of the RTS/CTS message is usually much shorter than that of the data frame, even if the collision of several RTS messages occurs, it still can reduce the collision overhead compared to the collision of long data frames. It should be pointed out that although, the RTS/CTS mode has much merit compared to the basic mode; its performance is still very sensitive to the number of active nodes in the network. In recent years, many researchers have attempted to improve the performance of contention-based MAC protocols in WLANs.

Motivation: Since, the cognitive users are utilizing the licensed band, they must detect the presence of licensed users and vacate the band for the primary user when regains. Thus one of the main challenges that face this technology is how the cognitive users keep their communication active and how to compensate the loss of the data packet transmitted in that band. Thus the main requirement of cognitive radio architecture is to detect the presence of the primary (licensed) users as quickly as possible. The crucial aspect of the spectrum allocation in distributed cognitive radio network is how to manage the spectrum efficiently and how to maintain the SU link once the channel is affected by either the PU arrivals or when the channel is degrades due to interference. This might lead to SU communication degradation and loss of its data packets. For that reason, the cognitive users should continuously monitor the spectrum for PU detection. This motivates us to look for reserved backup channel to reconstruct and maintain SU link, previous research in this issues as in Panagiotis *et al*. (2008) selects some free channels to be dedicated as reserved channels, but this may degrade the system performance as the number of the sensed free channels to be used will be reduced. Consider this situation, where two cognitive radio users U1 and U2 communicating in a band and a primary user PU starts using the band soon after. Then, the two cognitive users need to vacate the band as soon as possible to make way for the primary user. In a contention-based algorithm, each node needs to overhear all traffic sent by nearby nodes within its transmission range. Control message, such as RTS, CTS and ACK messages specified in IEEE 802.11, are received by all neighbors within the transmission range of the sender and then discarded by non destination nodes. The overhearing feature of the contention based algorithms can be used to exchange information between nodes without introducing too much overhead. Hence, both RTS and CTS messages in IEEE 802.11 contain the remaining duration of the current transmission. Other active nodes update their NAVs based on the duration in RTS and CTS messages and they will not try to transmit packets until the current transmission is completed. Besides, the duration of the current transmission, if each node can inform other nodes more information about the backup or alternative channel in case the primary reclaim, communicating nodes as well as other nodes would try to avoid colliding with the primary. This protocol has been proposed to improve the cognitive radio network performance such as throughput, connectivity and reliability.

MATERIALS AND METHODS

Primary detection calculation: To assist channel scanning and sensing mechanism, study for primary behavior is suggested to estimate it is regain time. Two possible detection models are used to calculates the PU detection time first; by using analytical method according to the historical information of the primary appearance in specific channel, assuming that the behavior of the primary user is recorded as follows:

The primary P is arriving in random intervals t_0, t_1, t_2---t_n-tn+1

$$\Delta t_i = t_{i+1} - t_i$$

where, Δt_i is interval between the pervious and next occurrence, this is define as random variable X where, X = Δt_i and its probability function according to Poisson distribution is as follows:

$$P(x = r) = \frac{e^{-\lambda}\lambda^r}{r!}, r = 0, 1, ...,$$

Where:

r = The number of occurrence,
λ = Positive real number

If X follows the exponential distribution, then the probability density function is:

- And the mean is

$$f(x;\lambda) = \begin{Bmatrix} \lambda e - \lambda x, x \geq 0 \\ 0.........., x < 0 \end{Bmatrix}$$

- Taking the limit

$$E[X] = 1/\lambda.....$$
$$= 1/n\sum_{i=1}^{n} \Delta t_i$$

- Following this steps, we can find the value of λ

$$\lambda = \frac{n}{\sum_{i=1}^{n} \Delta t_i}$$

The probability of the primary appearance in time n+1 is given so the collision probability is evaluated with different values of λ.

The second PU's detection time calculation procedure is by using any signal detection techniques to measure it is signal appearance.

According to the studied done in the Daniel *et al*. (2009), which demonstrate that the primary behavior is improving the dynamic spectrum access, that study presented a large scale characterization of primary users in the cellular spectrum and discussing the implications on enabling cellular DSA.

Knowing the probability distribution of the arrival process of the primary communication (the call arrival as by Daniel *et al*. (2009)) and if assuming exponential arrival process.

$$Pi = 1 - e^{-\lambda T_S} \Leftrightarrow Ts = \frac{\ln(1 - Pi)}{\lambda}$$
$$Pi = P(X \leq Ts)$$

Where:

Ts = The sensing time
Pi = The probability that the SU interfere with the PU

Cumulative Distribution Function (CDF): The knowledge of the arrival process enables to adjust the time Ts after which, a channel needs to be sensed. And also assist the secondary link maintenance due to the research.

Proposed protocol and assumption: In this model, the primary users (PU) have higher priority to access the band and the secondary users (SU) opportunistically share it. The SUs sense the band to build a Channel States List (CSL) shown in Table 1, opportunistically use the unoccupied band and quit on sensing a PU's arrival. The sensing information is exchanged between the neighboring nodes.

Assumptions:

- A decentralized network with separate Common Control Channel (CCC) and multiple data channels. The CCC can be selected from the unlicensed band to assure its availability for long interval of time
- Channel scanning and sensing is carried out independently of the current communication and causing no interrupt for signal transmission or reception
- A primary user location, bandwidth and detection time in the current used channel, are known in prior (detection time is either statistically estimated due to the primary previous behavior or detected by using energy detection techniques)

The Sensed Channel List (SCL): Each node, say X, maintains a Sensed Channel List (SCL) that included the

Table 1: The Sensed Channel List table (SCL) in node X

Channel ID	The channel states	The release time
i	State i,X	RleaseT i,X
j	State j,X	RleaseT j,X
:	:	:
n	State n,X	RleaseT n,X

data channels sensed in a specific time and it is regularly updated. Each list entry CL[i] (i = 1, 2, ..., n) has two fields: Statei, X and RleaseTi X. Statei,X indicates whether, data channel i is available for node X or not at the current time. If channel i is used by X or by X's neighbor, then, Statei, x = {busy}. Otherwise, Statei,X = {idle}. RleaseTi,X indicates the exact time when channel i will be released by node X or by X's neighbors. If Statei, x = {idle}, then RleaseTi, x = 0.

The reservation method

First scenario: When, free reserved channel is available in both sides:

- A network is initialized when node A wants to transmit data to node B and node A has at least one idle data radio, A will send RequestM to B on the control channel. The RequestM frame carries node A's SCL and the duration time required to transmit the pending data
- After receiving the RequestM, node B compares A's SCL with its own SCL to check if there is free common data channel for subsequent communication, If there is no common data channel i.e. If data channel i (i = 1, 2, ..., n) satisfying Statei,A = Statei,B = {busy}, node B replies with a NgReplay frame to A on the control channel. The NgReplay frame indicates that node B has all the channels busy
- After receiving the NgReplay, node A stops sending frames to B, wait for a while, then it re-starts the backoff procedure and attempts to send an RequestM to B again
- Conversely, if there is at least one common data channel i (i = 1, 2... n) satisfying $State_{i,A}$ = Statei, B = {idle}, node B will reply with Replay to A on the control channel and will tune its data radios to the selected data channel i for the pending data transmission
- The Replay message includes the information of the selected data channel i and the duration information copied from RequestM. The Replay inhibits B's neighboring node from using the selected data channel i for the expected transmission duration time between A and B
- The sender seeks for another free channel available for both communicating nodes, If there is at least one data channel j (j = 1, 2, ..., n) satisfying Statej, A = Statej, B = {idle}, then channel j is chosen as backup channel for the subsequent transmission between A and B. that is to say; channel j is candidate as reserved channel to switch to; in case the current communication affected by the primary arrivals
- As the same time as node A sends the RES on the control channel, a data packet will be transmitted on the selected data channel i from node A to B
- The RES message includes the selected data channel information, the duration information compared with the primary arrival time and the candidate backup channel information. Similarly, the RES will inhibit A's neighboring nodes from using the selected data channel i and in the same time announce the reserved data channel j
- As the primary's reclaim time is known in prior, the usage of channel i should be terminated before the primary reclaim
- Both communicating nodes will tune to the reserved channel j to reconstruct the communication before collision occurs with primary transmission

The second scenario: When, the reserved channel is currently in use by the neighboring nodes (C and D).

Consider the network structure depicted in Fig. 1. Where the establishment of the communication is as described previously from 1 to -5. Then the following steps proceeded:

- The sender seeks for free channel available for both communicating nodes and there is no data channel j (j = 1, 2... n) satisfying Statej, A = Statej, B = {idle}, but there is common data channel occupied by neighboring nodes
- The sender starts to compare the release time of the occupied channel with the primary arrival time PrimeTj, thus, node A compares RleaseTj, A and RleaseTj, B and gets Idlej = max {RleaseTj, A, RleaseTj, B}. Idlej indicates the time when channel j becomes available for both nodes A and B
- Node A chooses data channel j for which, Idlej = min {Idlej, j = 1, 2... n} and satisfy the condition that idelj ≤ PrimeTj (j = 1, 2, … .n)
- Node A sends RES (Channelj, Start tj, NAV_j) to B on control channel and be ready to tune its data radio towards channel j to reconstruct the communication before the data collide with the primary transmission as shown in Fig. 2 and 3

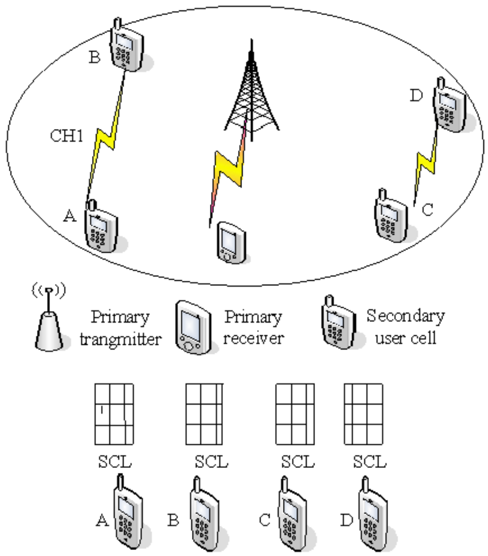

Fig. 1: The network structure

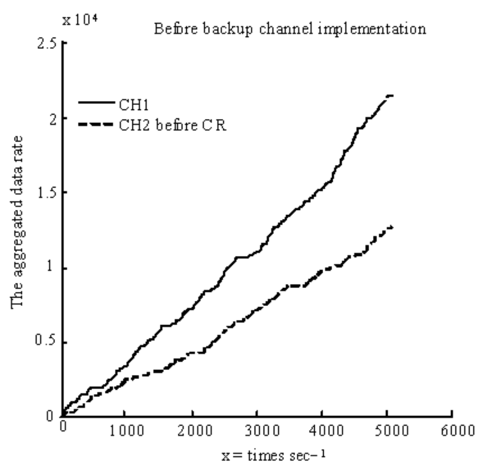

Fig. 2: The aggregated data rate before implementing channel reservation in both channel 1 and 2

$$\text{Start } tj = \text{Idle}j + T_{SIFS}, \text{ satisfy that, Start } tj \leq \text{PrimeT}j \quad (1)$$

$$NAV_j = (NAV_i - \text{Idle}j) + (T_{SIFS} + Tj_{DATA} + T_{SIFS} + T_{ACK}) \quad (2)$$

$Tj_{DATA} = T_{DATA} - T_{iDATA}$ (the duration of the rest of data = the total data size-the transmitted in channel i data size) (3)

- At the same time as node A sends data through the data channel i, it sends the RES message on the control channel and update RleaseTj, A = NAVj
- Upon receiving the RES, node A's neighboring nodes (e.g., node Y) update their RleaseTj,y as:

$$\text{RleaseT}j,y = \max(\text{RleaseT}j,y, NAV^*_j) \quad (4)$$

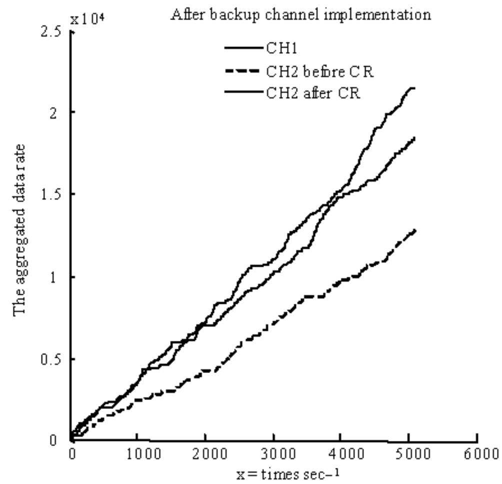

Fig. 3: The aggregated data rate after implementing the backup procedure compared with the pervious state in channel 2

Node B updates RleaseTj,B = NAV^*_j, where $NAV^*_j = NAV_J - T_{SIFS}$. (5)

Node B's neighboring nodes (e.g., node Z) update their RleaseTj,z as: RleaseTj,z = max(RleaseTj,z, NAV_j) (6)

Finally, node A will start sending data to B on the backup data channel j at the time Start Tj, i.e., as soon as the data channel j becomes idle to avoid collide with the primary's data packet.

RESULTS AND DISCUSSION

As mentioned before employing the reservation mechanism will significantly improve the network throughput as the rate of the successful communication increases and the data packet loss will reduce. As demonstrated with the simulation in Fig. 3. The aggregated data rate is increased compared before and after implementing the backup channel and as shown in the graph, the aggregated data rate in channel 2 is higher. The simulation parameters are as follows, (RequestM) = 20 µS, (Replay) = 20 µS, SIFS = 20 µS, DIFS = 50 µS, the data size is [300, 200, 150 and 100 M byte] and the data rate is 10, 5 Mbps, the number of times is 100, the length is 50. The collision percentage is reduced to 0.007. The protocol introduce no extra over head because the control message is used to carry the reservation information, the two scenario for selecting backup channel make it plausible to avoid inheriting the privilege of the primary user, mitigates collision with the primary, enhance the secondary user link maintenance and improves the network performance. Comparing with the case where, no reservation procedure, our protocol is significantly improves the aggregate data rate and avoids collide with the primary.

CONCLUSION

We propose an efficient cognitive multiple channel MAC protocol (BCR-MAC) with backup channel reservation mechanism to facilitate quick and smoother shift to a reserved channel before the secondary link degrades due to channel interference and/or primary user arrival. BCR-MAC protocol implemented in decentralized network with common control channel which could be available from unlicensed band and multiple data channel environment. The protocol significantly improves the network throughput; keeps the privilege to the licensee and utilizes the available free channel perfectly with less packet exchange overhead. Although, the primary detection time is a critical metric of this protocol the future research is to include the primary reclaim time accuracy using both statistical model and one of the accurate signal detection techniques to assure less error probability.

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