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A Reliability Aware Protocol for Cooperative Communication in Cognitive Radio Networks

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Abstract: One of the challenging tasks in cognitive radio (CR) networks is to agree on a common control channel to exchange control information. This paper presents a novel medium access control (MAC) protocol for CR network which efficiently and intelligently establishes a common control channel between CR nodes. The proposed protocol is the first CR MAC protocol which is hybrid in nature and lies between global common control channel (GCCC) and non-GCCC family of MAC protocols. The dynamic nature of the protocol makes the CR nodes converge on a newly found control channel quicker whenever the interference from a licensed user is sensed. The analytical results show that the dynamic, hybrid and adaptive nature of proposed protocol yields higher throughputs when compared with other CR MAC protocols.

Keywords: Cognitive radio, common control channel, co-operative communication, medium access control (MAC) protocols, DTMC.

1 Introduction

The radio spectrum is a precious natural resource with a limited frequency bands between 30 kHz to 300 GHz. Different studies (such as [1]) have revealed the fact that most of the time the licensed users of the spectrum, referred to as primary users (PUs), are not transmitting and the spectrum experiences severe under utilization and forms spectrum holes or white spaces (WSs). This unoccupied spectrum or white spaces are opportunistically accessed by the unlicensed users (also referred to as secondary users, SUs, or CR users), and this technique is called cognitive radio (CR) technology. The proposed CR technology has proven to be the smartest and most intelligent technology in wireless networking to resolve the spectrum scarcity issue and to increase spectrum efficiency[2−4]. SUs can use the unused portion of spectrum without imposing any type of interference to the PUs. In this paper, an ad-hoc CR network scenario is considered and a dynamic, decentralized and hybrid MAC protocol is developed.

One of the challenging issues in CR networks is to ensure deployment of an MAC protocol which will incorporate any changes at physical layer to eliminate collisions while sending frames to the destinations. This will help in avoiding the frame retransmissions which will ultimately save mobile energy and the overall network throughput will be increased. It is believed that the most important aspect of cognitive radio network is the exchange of free channel list (FCL) because communication between two cognitive nodes cannot take place unless and until cognitive nodes have agreed upon white spaces which are common between the communicating partners. This agreement could only be accomplished through FCL transaction on a control channel. Therefore the primary operation that a CR node must perform prior to any communication is scanning and searching its environment to create a list of all white spaces (FCL) available. After all the CR nodes have created their individual FCLs, they contend for exchange of control information on some common medium. This exchange of FCL could take place in two ways: centralized if there is a central entity that is responsible for governing the cognitive functionality (e.g., IEEE 802.22[5]) or decentralized where it is mandatory to have a common control channel which will be used by all cognitive nodes to setup the initial communication dialogue. After two CR nodes agree upon common white spaces, they conclude the transmission and then rescan the environment if spectrum changes have occurred.

The rest of the paper is organized as follows. Section 2 reviews some of the related work. Section 3 presents the framework of the proposed protocol followed by mathematical modeling in Section 4. Section 5 discusses results and performance evaluation before the paper is concluded in Section 6.

2 Review of previous work

A number of MAC protocols for CR networks have been developed since the inception of CR technology. Different characteristics (such as access mechanism, physical layer characteristics, single/multi channel, data transmission on single/multiple or backup channel, and the number of transceivers) are considered while designing the CR MAC protocol[6].

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2.1 Selection criteria for a control channel

CR MAC protocols dialogue control information on a well known and well defined control channel. Based on the selection criteria of the control channel, CR MAC protocols could be broadly classified into the following three categories:

1) Global common control channel (GCCC): MAC protocols: This category makes use of GCCC in either industrial scientific and medical band (ISM), e.g., 2.4 GHz, or any other unlicensed band. The MAC protocol using statistical channel allocation for wireless ad-hoc networks[7] is a decentralized GCCC-based CR MAC protocol that can speed up transmission by using more than one channel for data transmission and can wait for some time for a channel with higher bandwidth to become available. A hardware-constrained cognitive MAC (HC-MAC) for efficient spectrum management[8] uses an unlicensed band as the control channel and addresses the hardware issues (sensing constraints and transmission constraints) to make CR more practical. A new MAC protocol with control channel auto-discovery for self-deployed cognitive radio networks (DUB-MAC) is presented in [9], which uses a different unlicensed spectrum band other than ISM and employs one frequency band as the control channel and another frequency band to transmit data. The protocols in [7–9] emphasize on data transmission but ignore the pre-transmission overheads such as the time required in dialogue to exchange initial configuration and the time required to converge on the common control channel.

2) Non-GCCC CR MAC protocols: Protocols in this category either use one of the white spaces as the control channel or use a different band other than ISM to exchange control information before they can actually start communication. Synchronized MAC protocol for multi-hop cognitive radio networks (SYNC-MAC)[10] selects one of the channels which is common between itself and neighbours to exchange control information while other channels are selected to send data. In opportunistic-cognitive MAC (OC-MAC)[11], initially all nodes make use of a non-global common control channel, perform three-way handshakes to select a data channel from the FCL, and confirm the data transmission through an acknowledgement. CR nodes in OC-MAC predict the length of spectrum hole, but this prediction is strongly criticized because the CR network is an opportunistic network and it is very hard to find the exact duration during which the PU is not utilizing the spectrum so that the length of available spectrum hole could be calculated[12]. The cognitive MAC protocol for multi-channel wireless networks (C-MAC)[13] selects the so-called R channel within the free channels and uses this channel as a control channel and manages the communication on R channel. In [10–12], the selection criterion for the control channel has not been clearly defined, and most importantly, the clarification about which node will set the control channel and how the rest of nodes will be synchronized is missing.

3) Assumed CCC MAC protocols: The protocols in this category do not delve into a control channel setup mechanism and simply assume that a control channel has already been established prior to any data transmission. Cognitive radio-enabled multi-channel MAC (CREAM-MAC)[14] is a decentralized CR MAC protocol that applies a four-way handshake with cooperating nodes on the control channel under the assumption that the control channel remains always available and is reliable. Emphasis has been given on data transmission with complete ignorance of the overheads of determining and agreeing upon the control channel. It is strongly believed that finding a common channel to dialogue on the exchanged control information is the primary task of cognitive nodes, and that subsequent operations could not take place if the existence of the control channel has not been well addressed. So the assumption of available control channel is not a well-built justification. Tripathi and Shah[15] propose an MAC protocol for single channel which assumes a licensed channel be available all the time. The protocol divides the time in K mini-slots of a fixed length which are used as a backoff unit. We believe that the authors have restricted the opportunity to access the spectrum to a single channel while there might be many channels. Each of which can be used to speed up transmission. Cacciapuoti et al.[12] designed a channel-availability estimation strategy which assumes the CU activity into fixed-sized slots of duration T. Better date rates are achieved by the said scheme, however, higher PU updating rates are resulting in higher energy consumption for mobile CR nodes.

To summarize, GCCC based protocols[6−8,14] suffer from the drawbacks such as saturation of the GCCC (since it is widely available for anyone, imposing high computational cost from backing off) and security vulnerabilities. While the synchronization mechanism on control channel is missing in non-GCCC MAC protocols[10−12], the assumption of existence of a control channel is too strong for subsequent data transmission which is heavily dependent on the control channel. Also, CR nodes must release the occupied spectrum to avoid interference with PUs. Most of the mbox protocols[6−11] assume that SUs will vacate the spectrum whenever a PU activity is detected. However, this assumption needs to be carefully justified because if SUs are busy in transmitting, they cannot detect PUs activity and interruptive signals are not generated by PUs. Emphasis should be given to the clear methodology about the selection of the control channel rather on how data transmission amongst two CR nodes will take place (because CR nodes can only switch to actual data transmission if safe and secure FCL transactions have taken place).

3 A reliability aware QoS provisioning algorithm for cooperative communication in cognitive radio systems

The drawbacks of using GCCC, as discussed in the previous section, and the unclear methodology about the selection of a non-GCCC control channel in some of the published protocols motivated us to design a hybrid CR MAC protocol lying between GCCC and non-GCCC, named DDH-MAC (dynamic decentralized hybrid MAC) protocol for cognitive radio networks. DDH-MAC not only overcomes drawbacks of GCCC but also benefits from the 24 × 7 free of cost availability of GCCC. In this paper, we extend our research[16] with extensive mathematical modeling. Performance evaluation for parameters such as throughput, and comparison with existing CR MAC protocols are exclusively added in this work. Simulation experiment to determine PU interference probability is also a contribution to this work.

Prior to initialization, DDH-MAC makes a few assumptions, i.e., each CR node is equipped with two transceivers (G-transceiver to scan a global control channel and D-transceiver to transmit data), and a sensor to detect the PU activity on the licensed channel, and the spectrum has been sensed and an FCL has been generated by the physical layer. Cognitive nodes implementing the DDH-MAC scan the GCCC for a beacon frame (BF). If the nodes do not find any BF, then one of the CR nodes is responsible for launching the BF in the GCCC which lets other CR nodes in the vicinity know about one of the white spaces (WS) to be used as the primary control channel (PCCH) and another as the backup control channel (BCCH). BCCH only serves as a backup channel and will only be used if PCCH is re-claimed. If the node finds the BF, it reads the information about PCCH and BCCH updates its FCL and starts using PCCH for exchange of control information otherwise, it assumes itself as the starting node and launches the BF in GCCC. The protocol takes into account four case scenarios in the cognitive radio environment and tunes its parameters efficiently and intelligently according to the current situation of the network, which makes the protocol adaptive, secure and energy efficient. We have defined these case scenarios in the following section and will represent all the states with a $2n$ binary function where $n=2$. All the possible states of DDH-MAC are 00, 01, 10 and 11, as specified below:

Network initialization and launch of BF 00

Reading BF and contending for exchange of FCL 01

Concluding transmission on agreed WS and scanning PCCH 10

Concluding transmission on agreed WS and scanning BCCH 11

During the initial scanning, if the BF is successfully received by a CR node in GCCC, it reads the information to learn about the chosen PCCH and BCCH. Before communicating CR nodes start exchanging the FCL, they always verify a PU re-claim on PCCH. After the successful exchange of FCL, the CR nodes eventually switch to agreed empty spaces which will be used by the actual data transmission. It is likely that there is a re-claim by PUs on both PCCH and BCCH, and in this case the nodes go to the initial state (00) where they rescan the GCCC for any new BF. The operation of proposed protocol, with the help of the state diagram, has been presented in Fig. 1.

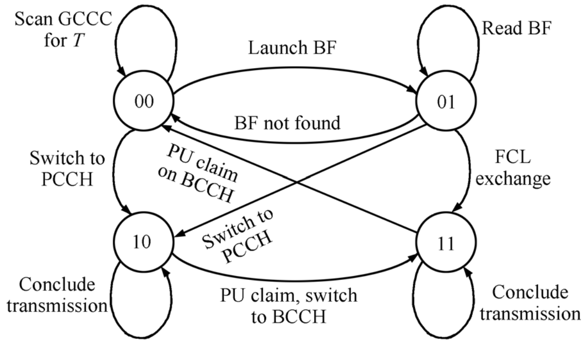

Fig. 1 State diagram of the proposed protocol

Like other CR MAC protocols, DDH-MAC also exchanges control information on the control channel. Four types of control messages are exchanged amongst CR nodes deploying DDH-MAC protocol, i.e., beacon frame (BF), DDH-MAC control frame (DMCF), free channel list (FCL) and ACK frame. Further information about these frames has been provided in Table 1. As previously discussed, the operation of the DDH-MAC is started by scanning the GCCC first. If any SU does not find any BF in the GCCC, it assumes that it is the first node in the network and will launch a BF in the GCCC at regular intervals. Other SUs joining afterwards will simply read the BF and converge to the newly established PCCH. The rest of the control information exchanged will be carried out by all CR nodes in the PCCH.

The protocol is dynamic because whenever there is a PU claim, nodes switch to a newly found and agreed-upon control channel. Moreover the CR nodes are always certain that they have access to at least one control channel. To observe the performance of the protocol, a mathematical analysis has been done, which is provided in the following section.

Table 1 Types of control frames exchanged in the DDH-MAC

Frame name	Type	Size	Fields
BF	Management frame	14 Bytes	Header, destination node, MAC, PCCH id, BCCH id, FCS
DMCF	Control frame	20 Bytes	Header, sending node MAC, destination node MAC, DMC information, FCE
FCL	Control frame	20 Bytes	Header, destination node MAC, FCL, FCS
ACK	ACK frame	14 Bytes	Header, sending node MAC, destination node MAC, ACK, FCS

4 Mathematical modeling for the DDH-MAC

A very important key performance indicator of MAC protocols that has been computed mostly in the relevant studies is throughput, which is briefly defined as data transmitted per unit time. Throughput, in CR MAC protocols, is heavily affected by multiple factors. Consider the example of calculating the throughput between two CR nodes which have agreed on a common WS to transmit after exchanging their FCL on a common channel. Throughput in this case could only be calculated if all the factors that can affect the communication process have been considered. One of these factors could be the probability that node will win contention to exchange the FCL on a control channel. The other factors could be how many WSs are common between intended communication partners, the number of secondary users that are also contending for the control channel and the time required to setup the initial configuration dialogue. The overall performance of the DDH-MAC protocol is also affected by many similar factors (Table 2). Also, some of the factors are co-related with each other. For example pre-transmission time is comprised of number of frames that are exchanged as control information, which ultimately contributes towards delay. The probability that a SU will launch BF in GCCC heavily depends upon the congestion which causes an increased size of contention window (CW). The mathematical analysis of DDH-MAC is further discussed below.

4.1 CCC access and *SU* transmission probabilities

Since the cognitive radio is an opportunistic network, the probability to seize the opportunity to transmit heavily affects the performance. There are two types of probabilities that influence the performance of the DDH-MAC.

a) *SU* probability (denoted as P_{BF}) to launch BF in GCCC.

b) *SU* probability (denoted as P_{PU}) to transmit in white spaces.

Also referred to as *PU* re-claim probability.

To calculate P_{PU}, we compute the channel utilization of *PU*, under two states, i.e., when transmitting it is *PU* On, or else it is *PU* Off. In fact, *PU* off is the state which is opportunistically used by a *SU* to utilize. The Markov chain model for the channel idle-busy periods has been used to find the probability of SU_s using spectrum opportunistically. Let P_α represent the probability that a *PU* will change its state from on to off. Then the probability that the *PU* will remain in on state can be expressed by $1 - P_\alpha$. The probability that a *SU* will utilize and keep utilizing the white space is given in Fig. 2 below:

Let $Ch = \{Ch_1, Ch_2, \cdots, Ch_n\}$ be the set of white spaces and $SU = \{SU_1, SU_2, \cdots, SU_n\}$ be the set of secondary users, then the channel utilization of the *PU*, denoted as δ, could be derived as

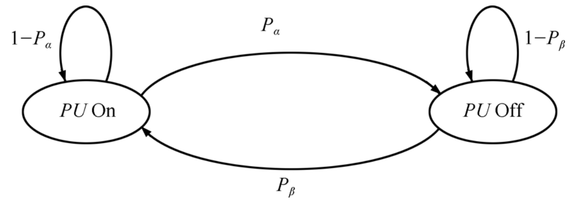

Fig. 2 Markov chain model for spectrum opportunity for SU_s

$$\delta = \frac{\sum_{i=1}^{n} Ch_i}{1 - P_\alpha} \tag{1}$$

where $1 \le i \le n$. Then the total probability that *SU* will have white spaces to utilize can be calculated as

$$P_{WS} = 1 - \frac{(1 - P_\alpha)}{(1 - P_\alpha) + (1 - P_\beta)}. \tag{2}$$

In DDH-MAC, a classical contention based wireless environment is considered, where all nodes use the same medium to transmit. So there is a contest between all the CR nodes to win the medium. The higher the number of users, the higher will be the probability of collision in the network. With DDH-MAC, a node has to contend for GCCC to launch the BF. Since GCCC is in the ISM band, its free availability to any type of user makes it more saturated. It is uncertain whether or not the CR nodes will collide with each other and launch BF in GCCC. We calculate *SU* collision probability (P_{CF}) which has been derived in [17] as shown below:

$$P_{CF} = \left(1 - \frac{1}{CW}\right)^{n-1} \tag{3}$$

where CW is the size of contention window and $CW = \{16, 32, \cdots, 512\}$ and n represents the number of users contending for the control channel in the cognitive radio environment. If (3) represents the probability that SUs have fewer chances to gain the GCCC to launch the BF, then the probability that the nodes will successfully launch the BF in GCCC would be represented as

$$P_{BF} = 1 - \left(\left(1 - \frac{1}{CW}\right)^{n-1}\right). \tag{4}$$

4.2 A single-*SU* and single-*PU* discrete time Markov chain (DTMC) model

In this section, a discrete time Markov chain model (DTMC)[18−20] has been used. The reason to select DTMC model is that DDH-MAC undergoes transitions from one state to another on a state space. The probability of being in a state (say 01) in DDH-MAC depends on the current state. This means that the future behaviour of the protocol (current state and next state) depends only on the current state of the model (see Fig. 1). The DTMC is used to determine the coalition of *SU* and *PU* (Figs. 3 and 4). Let *idle*, *SU*, *PU*, *PSU* be the four states of the DDH-MAC DTMC model where idle represents the state that no user is accessing the spectrum, *SU* represents that a secondary user is accessing, PU represents that a primary user is accessing and PSU represents that both primary and secondary users are accessing the spectrum respectively. Let P_{SU} represent the probability that only the SU will be using the spectrum, then $1 - P_{SU}$ will be the probability that the PU will remain in on state. P_{PU} is the probability that the PU will become on after an off state, then $1 - P_{PU}$ will be the probability that the PU will remain in off state.

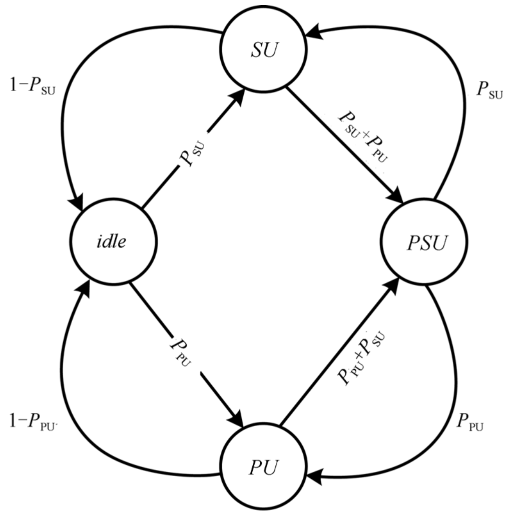

Fig. 3 A pair of SU and PU under the DTMC model

The balancing equations with equal rate of flow are given as below:

$$\pi_{idle}P_{SU} + \pi_{PSU}(1 - P_{PU}) = \pi_i((1 - P_{SU}) + P_{PU}) \Rightarrow$$
$$\pi_{SU} = \frac{\pi_{idle}P_{SU} + \pi_{PSU}\,(1 - P_{PU})}{(P_{PU} + (1 - P_{SU}))} \tag{5a}$$
$$\pi_{idle}P_{PU} + \pi_{PSU}(1 - P_{SU}) = \pi_{PU}(1 - P_{PU}) + P_{SU} \Rightarrow$$
$$\pi_{PU} = \frac{\pi_{idle}P_{PU} + \pi_{PSU}(1 - P_{SU})}{(P_{SU} + (1 - P_{PU}))} \tag{5b}$$
$$\pi_{SU}(1 - P_{SU}) + \pi_{PU}(1 - P_{PU}) = \pi_{idle}(P_{SU} + P_{PU}) \Rightarrow$$
$$\pi_{idle} = \frac{\pi_{SU}(1 - P_{SU}) + \pi_{PU}(1 - P_{PU})}{(P_{SU} + P_{PU})} \tag{5c}$$
$$\pi_{SU}P_{PU} + \pi_{PU}P_{SU} = \pi_{PSU}((1 - P_{SU}) + (1 - P_{PU})) \Rightarrow$$
$$\pi_{PSU} = \frac{\pi_{SU}P_{PU} + \pi_{PU}P_{SU}}{((1 - P_{SU}) + (1 - P_{PU}))} \tag{5d}$$
$$\pi_{idle} + \pi_{SU} + \pi_{PU} + \pi_{PSU} = 1 \tag{5e}$$

where π represents existence in any of the 4 possible states $\{idle,\ SU,\ PU,\ P_{SU}\}$. Supposing that $P_{SU} = P_{PU} = P$ and $(1 - P_{SU}) = (1 - P_{PU}) = (1 - P)$, then solving (5a)−(5e), we get the following state probabilities:

$$\pi_{idle} = \frac{1 - P}{P}\left(\frac{1}{2 + \frac{P}{(1-p)} + \frac{(1-P)}{P}}\right) \tag{6a}$$

$$\pi_{SU} = \pi_{PU} = \pi = \frac{1}{2 + \frac{P}{(1-P)} + \frac{(1-P)}{P}} \tag{6b}$$

$$\pi_{PSU} = \frac{P}{(1 - P)}\left(\frac{1}{2 + \frac{P}{(1-P)} + \frac{(1-P)}{P}}\right). \tag{6c}$$

An important performance metric using DTMC models for access networks is the blocking probability (P_{BLK}). When using one SU in coalition with one PU, the third secondary user is blocked, because the coalition is only possible at maximum between two users, i.e., between SU and PU in Fig. 3. Formally, for a newly arriving secondary user, P_{BLK} in one pair of SU and PU DTMC is given by

$$P_{BLK}\,(1\ \ SU\ \ \text{and}\ \ 1\ \ PU) = \pi_{SU}, PU. \tag{7}$$

4.3 The DTMC model for multiple SUs transmitting in coalition with multiple PUs

The discrete time Markov chain model for multiple SUs transmitting in coalition with PUs can be drawn similarly as in the case of single SU and PU DTMC. That is, for $NSUs$ and $MPUs$, we have $SU_1 = SU_2 = SU_3 = \cdots SU_K = \cdots SU_{N-1} = SU_N = SU^{s-1}$ and $PU_1 = PU_2 = PU_3 = \cdots PU_K = \cdots PU_{M-1} = PU_M = PU^{s-1}$, respectively.

One SU is required to form a coalition with a PU and after that several requesting SUs can join the coalition. The requesting SU can interact with multiple SUs (in its neighbourhood) and can form multiple coalitions, simultaneously.

Additionally, let $m = \{1, 2, 3, \cdots, N\}$ represents the size of a coalition. For example when $m = 2$, then any secondary user 1 can form a coalition of size 2 with any other secondary user K in the form as $(1, K)$. Similarly, when $m = 3$, then 1 can form a coalition of size 3 with any two other secondary users K and o in the form as $(1, K, o)$. This pattern continues till m=N. The number of states (S_N) in multiple SUs, which transmit in coalition with PUs DTMC at each value of m, follows the pattern given below:

$$S_N = 1 + C_N^1 + C_N^2 + \cdots + C_N^{m-1} + C_N^m \Rightarrow S_N = 1 + \sum_{m=1}^{N} C_N^m = 2^N \tag{8}$$

where

$$C_N^m = \frac{N!}{((N - m)!^{\times} m!)}.$$

For example, when $N = 4$, by (8), we have

$$S_4 = 1 + C_4^1 + C_4^2 + C_4^3 + C_4^4 = 16$$

Equations (5) and (6) can be combined to obtain the blocking probabilities for N users[17].

$$P_{BLK}(\text{Multiple SUs and multiple } PU_s) = \pi(SU_1,\ PU_1,\ SU_2,\ PU_2,\ \cdots,\ SU_N,\ PU_N) \tag{9}$$

where $\pi = \{\pi_{idle},\ \pi_{SU},\ \pi_{PU},\ \pi_{PSU}\}$.

5 Performance evaluation and discussion

For convenience of presentation, Table 2 lists all the important parameters and their relationship with throughput of DDH-MAC. Let SU be the number of secondary users and WS be the number of available white spaces in a CR environment.

P_{SU} denotes the probability that SU will utilize the white spectrum when it is not used by the PU and P_{BF} is the probability that the initiating node will launch the BF in GCCC. A constant payload (PL) of 2000 Bytes has been used. Clearly P_{BF} depends on the level of saturation on GCCC as derived in (3). Since the aggregated throughput denoted by T is proportional to multiple factors as mentioned in Table 2, T is derived as

$$T\alpha\frac{TR_xC_{CH}PLP_{BF}}{SUP_{PU}Pre-T_x} \tag{10}$$

$$T\alpha\frac{TR_xC_{CH}PL(\breve{R})P_{BF}}{SUP_{PU}Pre-T_x} \tag{11}$$

where $\breve{R}$ is the data rate of the licensed channel and is used as constant. $Pre-T_x$ time has been computed in [17] and is given below:

$$Pre-T_x=\{\frac{DMCF+FCL+Ack+2\times SIFS+DIFS}{\breve{R}}\} \tag{12}$$

where DMCF stands for DDH-MAC control frame; FCL is free channel list; and Ack is acknowledgement with frame sizes as 20 Bytes, 20 Bytes and 14 Bytes respectively exchanged as control information frames.

5.1 Aggregated throughput

We first investigate the aggregate throughput for the saturated network case, where apart from the PU interference probability (δ), there is a contention amongst SUs to launch the BF in GCCC. Using (11) we plot the aggregate throughput (T) against the BF launching probability (P_{BF}) in Fig. 5. It is observed that the aggregated throughput changes with different numbers of contending secondary users. This is expected because the higher is the probability of launching the BF by the SU, the higher is the aggregate throughput. The aggregate throughput of the DDH-MAC protocol depends on the pre-transmission time which could be different for different case scenarios and the time to launch the BF over the control channel which is ultimately determined by the IEEE 802.11 DCF parameters such as $CW_{\min}$ and $\breve{R}$.

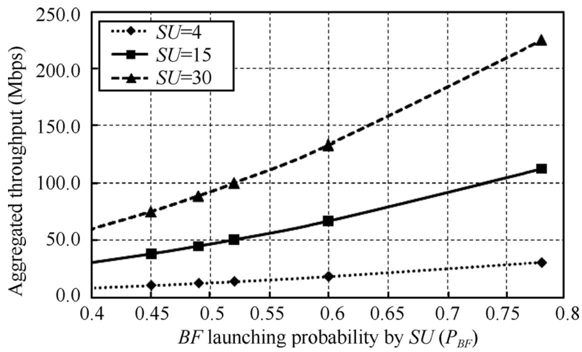

Fig. 5 The aggregate throughput against the probability (P_{BF}) that BF will be launched with the average number of white spaces (WS) for each SU. $Pre\text{-}Tx$ is 128 μs. The number of C_{CH} and the number of transceivers (T_x) are 2.

Table 2 Factors influencing the throughput

Parameter	Notation & proportionality	Relationship with throughput
Number of transceivers	$\alpha\, TR_x$	More no. of transceivers, more rapid sensing and searching, more rapid data transmission
Number of control channels	$\alpha\, C_{CH}$	More no. of control channels, more frequent exchange and update of FCL
Number of WS	α WS	More no. of WS, more data transmissions
Number of SUs	$\alpha\ \frac{1}{SU}$	More no. of SUs contending for SCCH and white space, less chance to seize the opportunity to transmit
Pre-transmission time	$\alpha\,\frac{1}{Pre-T_x}$	Less $Pre\text{-}T_x$ time, faster network convergence, less wait before actual transmission starts
BF launch probability	$\alpha\, P_{BS}$	Higher the probability of successful launch of BF, quicker network initialization
PU interference probability	$\alpha\ \frac{1}{P_{PU}}$	Higher PU interference, fewer chances that CR nodes will seize the opportunity to transmit
Payload	$\alpha\, PL$	Higher PL will yield higher throughput

$$M=\left[\begin{array}{l|cccc} \text{States} & idle & SU & PU & PSU \\ \hline idle & 1-((1-P_{SU})+(1-P_{PU})) & P_{SU} & P_{PU} & 1 \\ SU & 1-P_{SU} & -(P_{SU}+(1-P_{PU})) & ((1-P_{SU})+P_{SU}) & P_{SU}+P_{PU} \\ PU & 1-P_{SU} & ((1-P_{PU})+P_{SU}) & -(P_{PU}+(1-P_{SU})) & P_{PU}+P_{SU} \\ PSU & 0 & P_{SU} & P_{PU} & -(P_{SU}+P_{PU})+(P_{PU}+P_{SU})) \end{array}\right]$$

Fig. 4. One SU in coalition with one PU under the DTMC model

After setting the optimal values for the BF launching probability, an average number of WS with each SU, and $Pre\text{-}T_x$, we have used (11) to determine the aggregate throughput of DDH-MAC protocol against the PU interference probability. The numerical values obtained from (11) have been plotted in Fig. 6. It is observed that the aggregate throughput reaches the highest when there is no or minimal PU interference. Nodes will only have to wait to read/launch the BF in the control channel, and with two frames exchanged as a control information, nodes will immediately start utilizing white spaces opportunistically. The aggregate throughput decreases and reaches to zero as the PU interference probability increases.

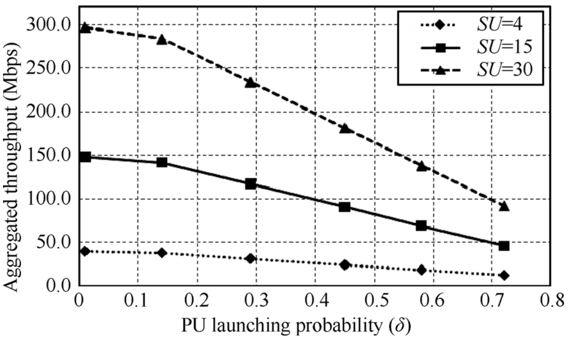

Fig. 6 The aggregated throughput against the PU interference probability (δ) with the average number of white spaces (WS) for each SU. $Pre-T_x$ is 128 μs. The number of C_{CH} and the number of transceivers (T_x) are both 2.

5.2 Performance comparison

We compare the performance of the DDH-MAC protocol with two CR MAC protocols reported in the literature, CREAM-MAC and OC-MAC. The reason for selecting these protocols is that both the protocols use the same physical layer parameters, i.e., direct-sequence spread spectrum which the DDH-MAC is using. Also, CREAM-MAC and OC-MAC have been highly cited and are famous in research community. For comparison, we have considered the same set of DSSS physical layer parameters for all three protocols.

The aggregate throughput for 30 SUs is plotted in Fig. 7 for DDH-MAC, CREAM-MAC and OC-MAC protocols, against the average value of the probability that SUs will utilize the spectrum, the average number of white spaces (WS) available to each SU, and $Pre\text{-}T_x$ set to 128 μs. The obvious reason for better throughput of DDH-MAC is the number of control channels being used which significantly reduce the overhead of network convergence, ultimately improving the pre-transmission time spent on the exchange of control information whenever there is a PU activity.

5.3 Simulation results

We verify the consistency of our analytical model and add a simulation experiment. We have developed a simulation experiment to investigate the system performance of our proposed DDH-MAC protocol. For our simulation experiment, we have used OPNET modeler[21] which is a discrete event simulator and provides a comprehensive development environment for the specification, simulation and performance analysis of communication networks. We investigate the aggregated throughput against the PU interference probability. Let the number of T_x with each SU be 2, and the channel utilization $\breve{R}$ be equal to 11 Mbps. The experiment is run for two different numbers of SUs, i.e., when SUs are equal to 15 and 30 respectively.

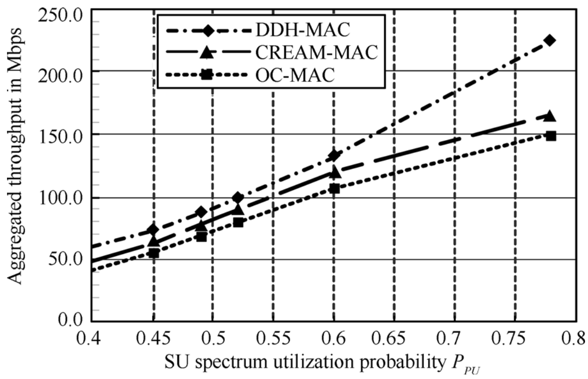

Fig. 7 The aggregate throughput for $SU = 30$, against the probability (P_{BF}) that BF will be launched with the average number of white spaces (WS) with each SU. $Pre\text{-}T_x$ is 128 μs; the number of C_{CCH} and number of T_x are 2.

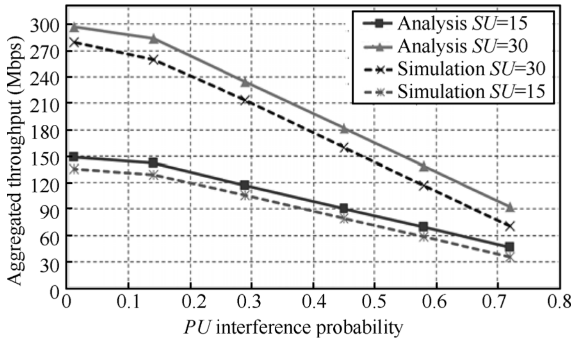

Fig. 8 Aggregated throughput from a mathematical experiment and a simulation experiment for two different numbers of SUs against the PU interference probability (δ), under the assumption that the number of transceivers is 2, that the channel data rate has been set to 11 Mbps, and that the number of available data channels is 15.

The highest aggregated throughput of approximately 300 Mbps is achieved when there is no PU interference and thus SUs can fully utilize all the available data channels. The aggregated throughput for the two numbers of SUs degrades linearly as the PU is more likely to claim the licensed data channels. This is expected because, given that there are sufficient licensed channels available, the aggregated throughput only depends on δ. The same applies to the simulation experiment where we know the number of contending SUs in advance and thus we select the optimal value of $CW_{\min}$ which results in the highest throughput.

For different numbers of SUs, $CW_{\min}$ could be adjusted accordingly. This will help achieve the optimal performance.

It can be observed that there is a slight difference between the values of simulation results and analytical modelling. This is expected as OPNET modeler takes several other entities into account during the simulation which cannot be captured in an analytical model, e. g., radio channel conditions, backoff window, and the values of DIFS and SIFS. Apart from these values, OPNET modeler also generates random seed values for different simulations. However, we have not considered any value like seed in our analytical model. We believe, this could be another reason for the gap between simulation results and analytic results.

6 Conclusions

Different MAC protocols have been designed, but unrealistic assumptions or unclear methodologies have been used to address very critical part of CR networks exchanging the FCL on a common channel. This paper proposes a novel CR MAC protocol which to the best of our knowledge, is the first CR MAC protocol lying hybrid between GCCC and non-GCCC families of protocols. DDH-MAC partially uses GCCC for BF transmission and intelligently selects one of the channels as control channel and another as backup channel. The *PU* claim, which is not unusual in the CR network, is efficiently dealt with by performing a channel-switching activity, and this way CR nodes always remain in the state of being able to access at least one control channel. More control channels lead to the exchange of fewer frames for agreeing upon transmission rules whenever a licensed channel is occupied. Having access to at least one control channel in any circumstances to dialogue control information makes our protocol more time efficient and performs better when compared with other CR MAC protocols, especially when a *PU* activity is sensed. When this happens, nodes do not renegotiate for communication rules and instead switch to backup channels. The results obtained from the mathematical modeling reveal that the proposed protocol performs better in terms of aggregated throughput. Currently, the protocol is under extensive simulation, and in future security features such as the encryption of BF and the inclusion of time stamp in data frames will be incorporated to make the protocol resilient against security vulnerabilities and flaws. Based on *PU* interference and historical transmission over data channel, a criterion to find best channel would be integrated to optimize the performance of the DDH-MAC protocol.

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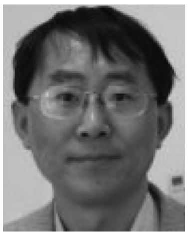

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