Design of an Efficient MAC Protocol for Opportunistic Cognitive Radio Networks

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ABSTRACT

Cognitive radio technology has been developed in recent years to make efficient use of the wireless spectrum especially for opportunistic spectrum access. Cognitive radio technology enables the secondary (cognitive) users to use the unused licensed spectrum of the primary users. Medium Access Control (MAC) protocol plays a vital role in spectrum utilization, primary user's (PU) interference management and secondary user's coordination in cognitive radio (CR) networks. Here, we propose a new MAC protocol where control transceiver attached with sensor improves the accuracy of spectrum sensing result as well as protects the primary user from interference. In our proposed MAC protocol, each secondary user (SU) is equipped with two radios, solves the multichannel hidden terminal problem (MHTP). Our proposed MAC protocol considers collision avoidance among SU's and between SU's and PU's. We develop an analytical model validated by simulation. Our scheme improves the network throughput in presence of sensing error.

KEYWORDS

Cognitive Radio, Medium Access Control, Common Control Channel (CCC), Opportunistic Spectrum Access

1. INTRODUCTION

Cognitive Radios are promising technologies which allow unlicensed users to access the radio spectrum when it is not occupied by licensed users. The cognitive radio (CR) network refers to the wireless network using CR technology [1]. As the demand for spectrum for wireless applications rises, cognitive radio technology has been proposed in recent years to solve the spectrum scarcity problem by exploiting radio spectrum unused by licensed users. However an important consideration is the control and coordination of communication over wireless channel and prevention of performance degradation to the licensed users of the band used for CR transmission associated with CR MAC protocol. This motivates the research in CR MAC protocols by designing an efficient MAC protocol for successful deployment of any CR network. The main objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and reconfigurable ability. Multichannel hidden terminal problem, sensing error, selection of common control channel, sensing delay, interference with primary users and network coordination problem might cause the MAC protocol to suffer from serious performance degradation [1]. Many MAC protocols have been already proposed for CR networks but research

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has shown that no one can work efficiently in a dynamic environment. Selection of common control channel (CCC) is one of the major research challenges in CR MAC protocol. CCC is used to facilitate the continuous operation of the CR users without any disruption. In this paper we assume that this dedicated channel may be owned by the secondary service provider. So selection complexity of primary user channel as a CCC is avoided. In order to increase system performance it is desirable that SU should sense many licensed channel as possible within short period. We propose, sensor equipped with main transceiver to sense multiple channel at a time thus reduce channel sensing time. Low sensing delay offer better system throughput. In our MAC protocol efficient design of the contention phase can effectively address the MHTP. In addition our proposed MAC protocol which is less prone to collision with PU's also offers better coordination among SU's.

The rest of the paper is organized as follows. Section 2 focuses on related work. We then introduce the proposed MAC protocol in section 3. In section 4, we develop analytical models to derive important performance measures. Section 5 presents the performance evaluations. In section 6, we overview the distinguishing features of our proposed scheme. Finally we conclude the paper in section 7.

2. RELATED WORK

Researchers try to invent efficient policy to tackle some new challenges in dynamic cognitive radio network environment. Most of the challenges are related to medium access protocol design. Some of the existing MAC protocols have been proposed in the literature and proposals like OSA MAC [2], HC MAC [3], and C MAC [4] work with a single radio. SU equipped with a single transceiver can listen to only a single channel at any time therefore can miss control messages when its radio is busy with transmitting and receiving data. Single transceiver MACs are more vulnerable to MHTP problem. Multi radio MAC can efficiently handle this issue. However single radio MAC is much cheaper than multi radio MAC. The authors of [4] developed a single radio MAC called C MAC. The rendezvous channel (RC) is used as a control channel. The authors assume that RC may be different initially for the different group of node but will converge to a network wide constant over time. This may not be feasible in distributed setting. Three radios are assigned distinctly to the control, data and busy time band in DOSS MAC [5]. The main drawbacks of the DOSS protocol is the inefficient spectrum use by the in band design. However Cross layer and Channel hopping based approach require global synchronization between PU's and SU's which is not easy to implement. SYN MAC [6] is a slotted protocol that integrates the control channel access with the regular data channels. This also addresses the problems of CCC selection but provides disrupted control channel coverage whenever PU occupies the control slot. The HC MAC [3] protocol aims at moderate spectrum access by considering the hardware constraints. Contention based channel selection phase followed by sensing phase in OSA MAC [2].Channel selection is done before channel sensing end up with selecting unavailable channels. In addition to avoid collision with PU user, SU user should perform sensing efficiently besides contention resolution phase. Without channel sensing information CSMA based MAC [7] can cause severe interference to PU's. Our proposed MAC is different from these MAC. Our MAC protocol provides efficient system throughput with tolerable sensing error.

3. PROPOSED MEDIUM ACCESS CONTROL PROTOCOL

In this section, we introduce our MAC protocol that addresses efficiently dynamic spectrum access problems. In our proposed protocol each secondary user is equipped with two radios. One of the two radios is used for just listening to the control signals (control radio) and other for receiving and transmitting data (main radio). In our proposed MAC, SU's assume a common control channel dedicated to them. SU's can be able to sense any n licensed channel by using n sensor at one time. We assume that time frame is divided into periodic beacon intervals. Secondary users are synchronized by periodic beacon messages. First node send beacon to synchronize the network when there are no cognitive users to form a network or whenever a new secondary user entering a secondary network first listens to a beacon signals for at least one beacon interval on the CCC and synchronize itself with rest of the network. The beacon interval is further divided into sensing and reporting phase, contention phase and data transmission phase.

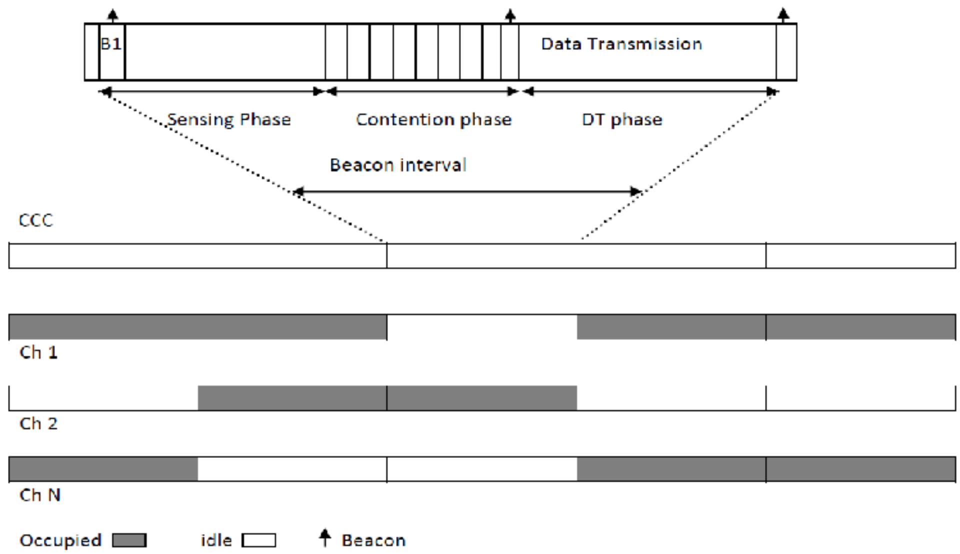

Fig 1. Timing diagram of our MAC framework

Each SU's maintain a list of available channel by the end of this phase. Each channel is assumed to be either occupied by a PU or idle. Duration of time slot should not exceed a threshold. Thus the constraint ensures that each channel access time of secondary users not more than the maximum tolerable interference period. Sensing phase provide up to data sensing information before going into data transmission phase. Since secondary users are not allowed to transmit in this phase, so sensing result free from transmission. Sensing capability affects system performance. We attempt to reduce each secondary users channel sensing time and also increase the number of sensed idle channels. We consider sharing of sensing results of a SU with the other SU's in sensing and sharing phase. Each SU maintains a list of available channel by the end of this phase. Secondary users can select and sense n licensed channels by using n sensors. So sensing delay is reduced. Overall mechanism is summarized below:

a. For control radio: Listen on the control channel upon receiving a beacon at k^{th} slot, update number of unused channel list. Upon informed by control radio j^{th} channel is idle and send a beacon at j^{th} time slot, then update unused channel list and the number of unused channel list.
b. For main radio: Senses channel j decided by sensing policy. If channel j is found idle, it inform the control radio that jth channel is idle.

3.1. Contention Phase

The contention mechanism over the control channel is based on a back off mechanism similar to IEEE 802.11 DCF [8]. When a SU wants to send packets to another secondary user, it participates in a channel negotiation and reservation mechanism. SU's reserve time for the following transmission operations within the neighbourhood through the control channel by exchanging RTS (Ready to send) –CTS (Clear to Send) control packets with the receiver. Suppose SU after successful in contention with its neighbour's gets access to the CCC. An unsuccessful node goes into a back off state waits for next turn. Sender 'SU' sends a RTS with the request information on the sensed available idle channels to a destination 'SU' at its selected contention slot waits for receiving CTS with the agreed idle channels from the destination SU. Receiver sends CTS after a Short inter frame space period (SIFS). If the source 'SU' receives the CTS correctly with selected common channel between them it is successful and the source 'SU' reserves the requested and agreed (by destination) idle channel sends a confirmation message to receiver. Otherwise it recognizes a collision with other SU's. If no common channel between sender and receiver then receiver ignore RTS. CCC will be idle after Distributed inter frame space period (DIFS) if a handshake message is lost. Neighbours of sender and receiver pair set network allocation vector (NAV) whenever a channel is reserved by a sender-receiver pair. Since all SU's control radio remained tuned to the CCC so a channel cannot be reserved by two or more secondary sender-receiver pairs. So the MHTP would not occur. Also secondary users just finished the data transmission can only participate in next transmission procedure after the selected waiting period. So SU's can prevent them for interfering the neighbours ongoing communications also receive any control packets during the waiting period allows the SU's to have enough time to observe the current available channels information. Based on the collected neighbour information and its own information each node updates the status of its primary channels list information as occupied or free. Users want to leave the network send RTL (Ready to Leave). They may leave either to save their power when they do not have packets to send or to join other networks. In order to decrease collision probability of the control packets each secondary user that has data to send attempts to send a RTS selects a back off counter within the contention window between [1, CW]. In the competing phase first winner has the key function of broadcasting beacon in this protocol. There should be a back up winner to do this if first winner fails to do it for any reason. If first winner fails second winner will replace it if not third. However simple channel sensing policy is not efficient enough when the number of secondary users is less than or close to the number of licensed channels. Negotiation based sensing policy let the secondary users to know which channels are sense by their neighbours and select the different ones to sense at the next time slot.

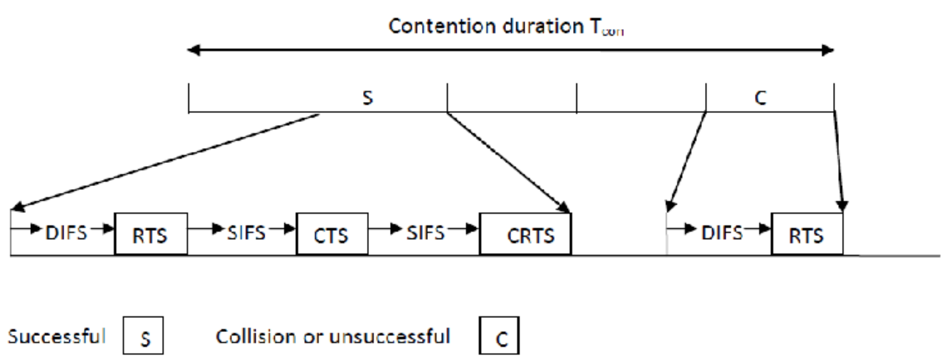

Fig 2. Contention interval in a cycle

3.2. Data Transmission Phase

If there are no channels which are sensed idle, the SU's are not active in the data transmission phase. Once negotiation is successful, data transmission takes place between sender and receiver using its reserved channel decided in contention phase. Data transmission occurs in parallel between multiple sender and receiver. Collision with PU can happen due to sensing error in sensing phase. In our proposed approach, this collision probability is very low. If such collision occurs we keep PU delay low as possible while the sender node affected by the collision will tune to CCC for next beacon interval. This data transmission phase is contention free. Our negotiation and data transmission mechanism is summarized below:

a. For control radio: Upon receiving RTS, send CTS to sender/source node with the identity of the selected channel. Upon receiving CTS, (check destination address with free channel) if negotiation is successful source node send confirmation RTS to receiver. Set NAV for the reserved channel (at the end of this phase).Neighbors of sender and receiver set their NAV for the reserved channel.
b. For main radio: Transmit the data packets over the reserved channels.

4. ANALYSIS OF PROPOSED MAC PROTOCOL

In order to obtain higher throughput for the secondary network, it is important to design and analyse efficient models related to our work. In our proposed MAC, we investigate critical MAC behaviour for distributed cognitive radio networks. Moreover we need to study the contention behaviour over the control channel where control packets are transmitted on the CCC using access mechanism IEEE 802.11 DCF [8]. During the contention phase, contending SUs will take part in contention trial which may consist of one or more empty slots, one or more unsuccessful message exchanges, and a successful message exchange [8][9] . Note that time is slotted when CCC is idle. A slot will be empty if no SU attempts to exchange message at the beginning of a slot. If only one SU attempts to send a message, then it will be the beginning of a successful message exchange period. Then by using Markov model as in [8],

$$Pt = \frac{2(1-Pcm)}{(1-2Pcm)(W+1)+PcmW(1-(2Pcm)^{m})} \tag{1}$$

Where $W = CWmin$ is minimum back off contention window size and m is the maximum back off stage. For constant back off window size W, Pt can be simplified as [8]. $Pt = \frac{2}{(W+1)}$ .Consider Nc = total number of data channels. Assume the average number of available data channel will be $(Nc \times P)$. Let p be the probability of availability associated with each data channel. Channel occupancy by primary users at different data channel is homogeneous. If $Tcon$ is the length of the contention phase the average length of contention phase thus can be approximated as $Tcon$ = $Tsi(Nc \times P)$. Now we are going to analyze saturation throughput .When the number of available channel is small, the contention phase may be empty after few initial channel reservations. If the number of channels is very high all channels may not be reserved in a contention phase. As saturation throughput is a top performance measure to evaluate cognitive radio MAC protocols. Now we consider $T_{DT,}$ $T_{BI,}$ and T_{SI} are durations of data transmission phase, beacon interval and sensing phase. It is easily seen that T_{DT} = (T_{BI} -T_{SI} -T_{con}). Total number of successful message exchanges per BI is $N_{succ.}$ Therefore the average number of channels that can be reserved during contention phase T_{con} is

$$N = \sum_{i=0}^{Nc} \min(i, Nsucc) \binom{Nc}{i} Pi(1-P)^{Nc-i} \tag{2}$$

The saturation throughput of the system averaged over several BIs normalized by per channel data rate can be calculated as

$$S = (NT_{DT}/ T_{BI}) \tag{3}$$

Table 1. Summary of major notations

Symbol	Description
Pt	Probability that a SU attempts to send a control message in a randomly chosen slot
Pcm	Constant and independent probability that control messages collide during contention phase
$Ptran$	Probability that at least one transmission in the considered slot
$Pcs = \frac{NsuPt(1-\mathrm{Pt})^{Nsu-1}}{Ptran}$	Conditional probability of success that one and only one SU transmits in a slot
$Tsi = \frac{(Pempty.\sigma + \mathrm{PsTs} + \mathrm{PcTc})}{Ps}$	Average length of one cycle of successful message exchange
$Pempty = (1 - Ptran)$	Probability that slot remain empty
$Ps = (Ptran.Pcs)$	Probability that transmission in a slot becomes successful
$Pc = Ptran(1 - Pcs)$	Probability that a transmission in a slot becomes unsuccessful
$Nsuc = \frac{Tcon.Ps}{Pempty.\sigma + \mathrm{PsTs} + \mathrm{PcTc}}$	Total number of successful message exchanges where $Tc =$ DIFS+t_{RTS} and $Ts = Tc$+2SIFS+t_{CTS}+t_{CRTS}

If $Nsucc \geq Nc$ average throughput $N = Nc$. Maximum throughput is reached if contention time just enough to reserve all channels. Throughput decreases with increases sensing time further increase in contention time will reduce data transmission time affect throughput. Our proposed method offer reduced sensing time. Now we discuss about sensing error. Many of the existing protocols (DOSS MAC, SYN MAC, and C MAC) seem to overlook the effect of sensing error in MAC design. Sensing error includes two events misdetection and false alarm. Since false alarm during sensing does not contribute to collision with a PU. Let us represent the average probability that an SU fails to detect PU's presence in a data channel by Pe .or average probability of miss detection of SU's nodes. Average collision probability of SU's with PU on a data channel can be given by $Pc = Pe^2(1 - \mathrm{p})$. It is apparent that the proposed MAC is expected to show highly scalable performance in minimizing interference to PU's. We assume that Pe is same for all SU's and data channels. For a specified upper bound on Pc proposed MAC can tolerate maximum Pe given by

$$Pe = \sqrt{Pc,limit/(1-p)} \quad (3)$$

Table 2. Parameters for proposed MAC protocols

Parameters	Description	Value
T_{BI}	Beacon interval length	100 ms
T_{SP}	Sensing phase length	10 ms
P_t	Probability that SU attempts to send a control message in a randomly chosen slot	0.02
W, m	W= Back off contention window, m= maximum back off stage	W=32, m=5
DIFS,SIFS	DCF inter frame space, Short inter frame space	128 µs,28 µs
N_{SU}	Number of secondary users	50
σ	Slots of length	50µs
RTS	The length of RTS packet	288 bits
CTS	The length of CTS packet	240 bits

5. PERFORMANCE ANALYSIS

The parameters used to evaluate the proposed MAC protocol are summarized in table 2.Fig. 3 shows that with an increase in contention phase throughput increases first and reaches a maximum then starts decreasing. Maximum achievable throughput increases with the increase in N_{ch} and P. More number of sensors equipped in a SU can lead to smaller sensing time and more available channels thus provide better throughput. Maximum throughput is reached when contention phase time T_{con} just enough to reserve all available channels. In fig. 4 the performance of proposed MAC is compared with two other MACs existing in the literature. Since HC MAC [3] allows only one user to transmit data even there are available data channels not being used by that user, its throughput degrades with increase in number of available channels compared to proposed MAC. In OSA MAC [2], multiple users may select a channel before channel sensing; as a result these users either go for contention during DTP if the selected channel is unoccupied by PUs or otherwise wait for next beacon interval. Furthermore it should be noted that our proposed MAC protocol is assumed to sense more channels without sensing delay thus total sensing period not become too long like [2], moreover improving the overall throughput. As shown in fig. 6, for a specified upper bound on acceptable maximum collision probability with PU (P_c) our proposed MAC can tolerate significantly higher sensing error at each SU compared to OSA MAC. OSA MAC uses IEEE 802.11 CSMA/CA mechanism to eliminate MHTP problem during data transmission hence use of IEEE 802.11 mechanism on data channels is not bandwidth efficient.

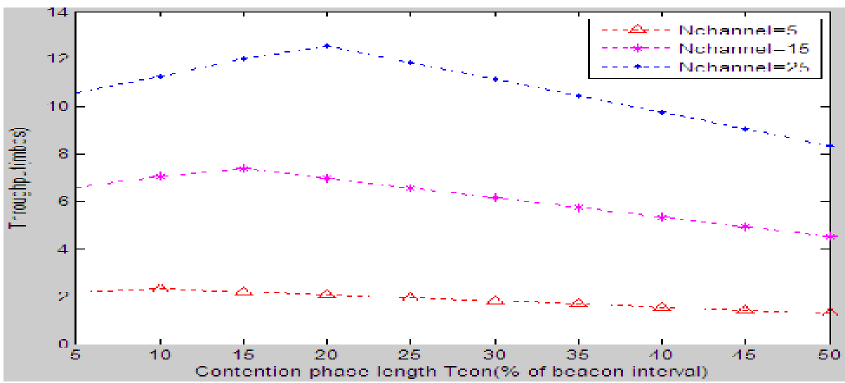

Fig.3. Throughput variation with contention phase length (T_{con}) and number of channels (p=0.6)

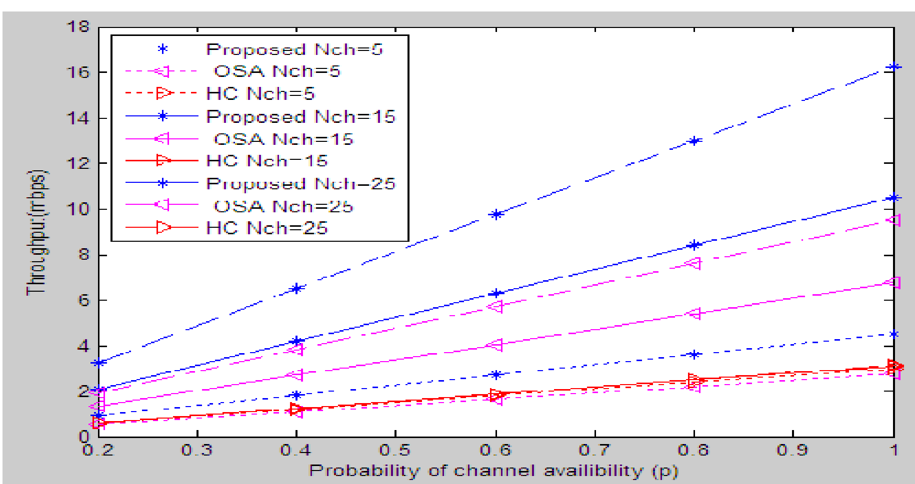

Fig.4. Variation of throughput with probability of channel availability (p)

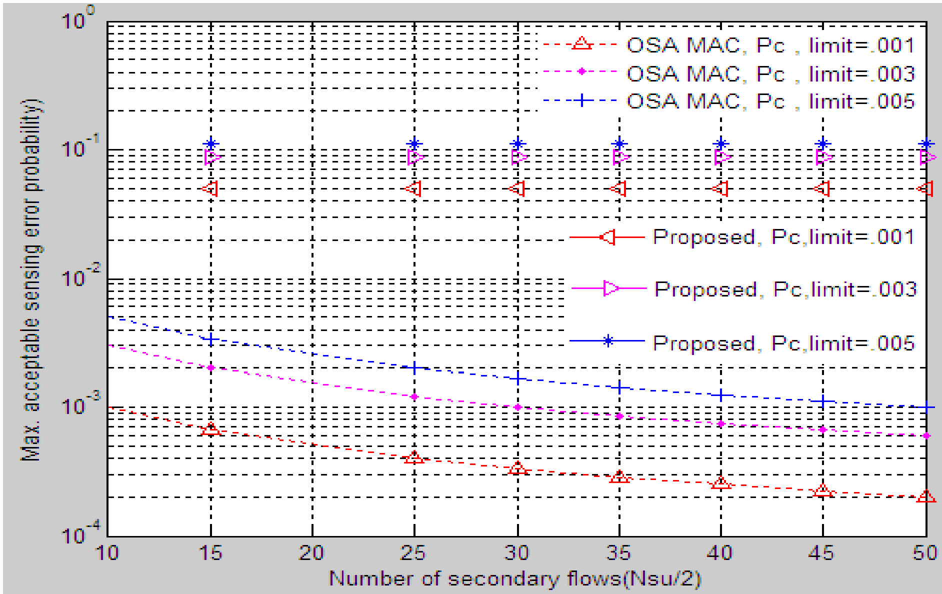

Fig.5. Acceptable maximum sensing error with secondary flows and upper bound on collision with PU's $P_{c,\,limit}$ (p=.6, N_{ch}=4)

In our proposed method both the sender and receiver have to make sensing error at the time to cause collision to PUs. Therefore proposed protocol keeps interference to PUs very low. In OSA MAC [2] the effect of sensing error grows with the size of secondary user's network.

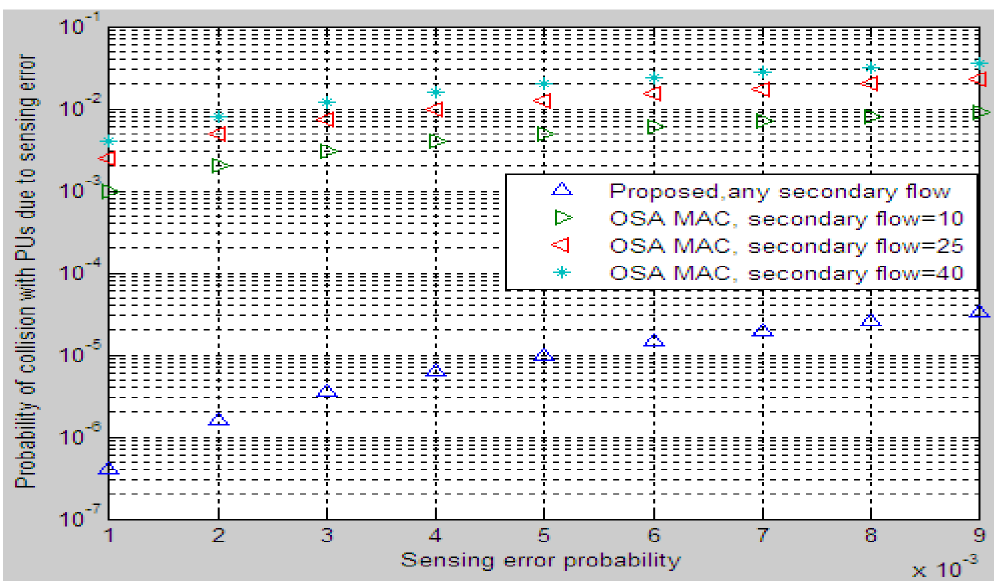

Fig.6. Variation of collision probability of SUs with PUs with sensing error probability and S_f

6. DISTINGUISHING FEATURES

Our proposed MAC protocol effectively addresses some important issues like multichannel hidden terminal problem (MHTP) problem, spectrum utilization, sensing error problem etc. Some of the existing MAC protocols (e.g. DOSS-MAC, C-MAC) seem to overlook the effect of sensing error problem which is vital for opportunistic environment in cognitive radio network. Although our proposed protocol effective address this issue. HC-MAC suffers from spectrum underutilization whereas our proposed method significantly improves spectrum utilization. Moreover our proposed MAC protocol provides moderate saturation throughput compared to others protocols such as OSA-MAC, HC-MAC.

Table 3. Relative comparison

MAC proposal	Throughput	Sensing error	Spectrum utilization
OSA MAC [2]	Not satisfactory	Not effectively address	Not more than our proposed protocol
HC MAC[3]	Not satisfactory	Overlook the effect	underutilization
SYN MAC[6]	Not satisfactory	Overlook the effect	Not satisfactory
DOSS MAC[5]	Not satisfactory	Overlook the effect	Not satisfactory
C MAC[4]	Not satisfactory	Overlook the effect	Not moderate
Our proposed MAC	Satisfactory	Efficiently address	Excellent spectrum utilization

7. CONCLUSION

Cognitive radio networks are envisaged to solve spectrum scarcity problem by making efficient and opportunistic use of frequencies reserved for the use of primary users of the band.In this article, we proposed a MAC protocol for opportunistic cognitive radio networks that can significantly boost spectrum utilization by exploiting radio spectrum unused by primary users. The numerical results reveal that our proposed MAC protocol shows excellent performance in providing higher throughput and keeping collision with PU lower in case of erroneous channel sensing than current MAC protocols. MHTP problem, sensing delay problem and selection of CCC problem are handled very efficiently in our proposed MAC. Our proposed MAC ensures no collision among SU’s during data transmission phase, which help to utilize the opportunistically available spectrum efficiently. Moreover common control channel is always known and available to SUs. Therefore network initialization, reconfiguration and coordination are easier and reliable in our proposed MAC. However, performance of our protocol can be further improved from partial channel sensing policy and is a future research work. It can be concluded that cognitive radio is without any doubt in the critical path to the wireless networks of the future. How-ever, a significant amount of work remains to be done.

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