A new Opportunistic MAC Layer Protocol for Cognitive IEEE 802.11-based Wireless Networks

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***Abstract*—In this paper, we propose a cognitive radio based Medium Access Control (MAC) protocol for packet scheduling in wireless networks. Cognitive MAC protocols allow a class of users, called secondary users, to identify the unused frequency spectrum and to communicate without interfering with the primary users. In our proposed MAC protocol, each secondary user is equipped with two transceivers. One of the transceivers is used for control messages while the other periodically senses and dynamically utilizes the unused data channel. The secondary users report the status of channels on control channel and negotiate on the selected data channel itself for onward data transmission. Each channel is used by different set of secondary users. Contrary to existing protocols, data transmission takes place in the time slot in which spectrum opportunity is found. We develop a new analytical model, while taking into account the backoff mechanism. Our simulation results show that throughput increases with the increase in the number of channels.**

I. Introduction

The current spectrum allocation policy is usually allocating a fixed frequency band to each wireless service. The wireless services are growing very rapidly, a fact that has imposed increasing stress on the fixed and limited radio spectrum. Allocation of fixed frequency spectrum to each wireless service is an easy and natural approach for the elimination of interference between different wireless services. But this static spectrum allocation leads to a low utilization of the licensed radio spectrum ranging from 15% to 85% due to temporal and geographical variations as mentioned by Akyildiz et al in [2]. This means that the main reason behind the spectrum scarcity is in its inefficient utilization, rather than in its unavailability. The limited spectrum availability and inefficient spectrum utilization require new communication paradigm to opportunistically exploit the existing wireless spectrum [10]. In order to efficiently utilize the licensed spectrum, the Federal Communication Commission (FCC) has suggested a new concept of dynamic spectrum allocation. Recently, the Opportunistic Spectrum Access (OSA) problem has been the focus of important research activities [7][9]. The underlying idea is to allow the unlicensed users ($i.e.$, secondary users) to access the available spectrum when the licensed users ($i.e.$, primary users) are not active. The concept of OSA networks or Cognitive Radio (CR) networks is still in its initial phase. The word cognitive can be defined in simple words as implying that secondary users are attributed with special properties, like intelligence and knowledge. The former can be acquired through learning while the latter can be achieved through the intelligence. Cognitive radios [7][8][9] have become an enabling technology to solve the problems of spectrum scarcity for wireless applications by exploiting the advantage of open spectrum policy. Due to the heterogeneous nature of the spectrum, CR networks require greater coordination among its users unlike the traditional wireless networks ($e.g.$, IEEE 802.11). Secondary users of OSA networks require fresh design of MAC protocols. Indeed, MAC protocols have to operate based on the results of the spectrum sensing due to the fact of spectrum heterogeneity. MAC protocols, such as Carrier Sense Multiple Access (CSMA) used in traditional networks were designed for homogeneous spectrum and the same can not be applied directly to OSA networks. As it is not possible to find a common channel for coordination among all the users if the spectrum allocation is varying both geographically and temporally, the legacy MAC protocols should be applied in a different manner. Varying channel availability poses many non-trivial problems to the MAC layer. One of the major problems pertains to the way a secondary user should decide when and which channel to use for transmitting/receiving packets respecting the rights of the licensed users. we propose a novel MAC protocol for cognitive IEEE 802.11-based wireless networks. In this paper, we propose a novel approach for CR based MAC protocols. Each SU first senses one of N data channels and sends beacon on the control channel if a channel is sensed to be idle. Then, all SUs, which sense the Channel i idle, negotiate for it immediately after i^{th} mini-slot on data channel itself. Successful SUs start data transmission immediately after negotiation process during the ongoing time-slot instead of waiting for the upcoming slot as in [1]. This feature is important as it is not sure whether the channel will still continue to be idle during the next time-slot or not. Thus, our approach ensures secure data communication without causing interference to primary users. To avoid control channel saturation problem, negotiate among SUs is carried out on data channels instead of the control channel. The overall concept of our proposed protocol is totally different from the one of IEEE 802.11h. Indeed, IEEE 802.11h assumes all users to be identical and operates only in 5GHz frequency band: this is why only a single transceiver/device is needed. Contrary to Spectrum sharing in cognitive radio, unlicensed users (i.e., secondary users) intend to access the available spectrum when the licensed users (i.e., primary users) are not active. The considered constraints are very different. In the second case, at the beginning of a slot, a secondary user senses the available channels to find an idle one, uses it, and releases it at the end of the slot so it can be immediately used by a newly arriving primary user. The rest of this paper is organized as follows. Section II details some interesting related work. Section III presents the model and our proposed protocol. A analytical model is derived to analyze our proposed protocol in section IV. Section V gives an evaluation of the protocol based. We conclude the paper in Section VI.

II. Related Work

Several MAC protocols for CR networks have been developed recently. In the Partially Observable Markov Decision Process (POMDP) based DC-MAC [3] scheme, a node has only partial system information because it uses only one transceiver that is able to observe only one channel at a particular time. There can be two channel states that depend on the presence of primary users. These states are busy state ($i.e., 0$) and idle state ($i.e., 1$). The node models the channel opportunity a POMDP process that is based on the observations of the channel status. The possibility of channel occupancy by primary users can be represented by a Markov model that consists of ($M = 2^N$) states in a system of N identical channels. This scheme can exploit the unused frequency spectrum well but its implementation is more complicated and hardware-constrained. The reason is that in this scheme, each Secondary User (SU) needs multiple sensors to detect the channel activity. In HC-MAC [4], sensing policy gives an optimal stopping criterion for sensing operation based on the hardware constraints for the data transmission. Control messages containing sensing results are exchanged on the common control channel between the sender and the receiver. An expected reward for sensing more channels is calculated by the pair independently, bounded by their hardware constraints. Sensing continues till the maximization of the expected reward. The HC-MAC consists of three phases, namely contention, sensing and data transmission. The nodes exchange control messages (RTS/CTS) on the common control channel during the three phases. "A k-stage look ahead stopping" rule was proposed. In [4], the throughput is maximized but the spectrum utilization is inefficient. Sensing results are impacted by only the two hop away neighboring nodes which leads to further exposed node problem as compared to IEEE 802.11 network. This MAC protocol involves control messages overheads in all the three phases, which increase with the number of sensed channels. Hang et al in [1] proposed a cognitive radio based multi-channel MAC protocol for wireless ad hoc networks. In their proposed protocol, two spectrum sensing policies were described to identify the maximum number of available channels. Each secondary user is equipped with two transceivers. One (control transceiver) operates on a dedicated control channels while the other Software Defined Radio (SDR) transceiver is used as a cognitive radio that periodically senses and dynamically utilizes the identified unused channels. They proposed two types of sensing policies to help MAC protocols to detect the unused channels. The secondary users first sense the channel by using SDR transceivers and report, by using the control transceivers in the corresponding mini slots during the reporting phase, if the channel is found idle. Then, they contend during the negotiation phase of time slot (t) for getting permission for data transmission. The winner of the negotiation phase uses all available channels in the next time slot for data transmission. However, it is likely that primary users attempt joining the network via the chosen channel in the upcoming slot time $(t+1)$. This may lead to interference to primary users which is against the spirit of usage of licensed channels. Moreover, all the channels that are sensed idle are supposed to be utilized by only one pair for transmission. In addition to that, all users contend on the control channel during the negotiation phase, the issue of control channel saturation then arises. In [6], a MAC protocol for multi-channel wireless networks using a single radio transceiver is proposed. All the available channels have the superframe structure and one of the channels is configured as a Rendezvous Channel (RC). Nodes can multicast or broadcast the beacons that contain the identities of the nodes using RC.

III. Model and Protocol Description

A. Model

As in [1], our protocol consists of N channels licensed to primary users for data communication and one control channel common to M secondary users whereby they can exchange their sensing results and transmit to the base station in a BS-STA fashion. Each SU is equipped with two transceivers. One transceiver, devoted for operations related to control messages, is called control transceiver. SUs use the control transceivers to obtain information about unused licensed channels and to negotiate with others via contention-based function (DCF) protocol and CSMA on the corresponding channel. The second transceiver consists of a SDR module that can tune to any licensed channel to sense, transmit and receive signals/packets and is called Software Defined Radio-transceiver. Primary Users (PUs) communicate on data channels based on a synchronous slot structure. At the same time, a number of SUs synchronized with primary users can access the licensed spectrum in an opportunistic way without causing interference to licensed users. The state of the channel is the same at the transmitter and the receiver. The state of each channel is represented as ON/OFF. The ON state represents the presence of PUs while the OFF state refers to when the channel is idle. So the channel can be either busy or idle. During the next time slot, it can either remain in its current state or transit from one state to other. Let λ_i be the probability that the state of channel i changes from ON to OFF and μ_i be the probability of changing from OFF to ON state. The state of the i^{th} channel is denoted by $I_i(t)$ in a time-slot indexed by t with $\{t = 1, 2, ..., T, (T+1), (T+2), ...,\}$. It corresponds to a binary random variable with 0 and 1 representing the idle and the active states, respectively. So the network state in the time-slot t can be represented as $[I_1(t), I_2(t), ..., I_N(t)]$. Then the i^{th} channel utilization denoted by z_i, with respect to the primary users, can be written as in [1]:

$$z_i = \lim_{t \longrightarrow \infty} \frac{\sum_{t=1}^{T} I_i(t)}{T} = \frac{\mu_i}{\lambda_i + \mu_i} \tag{1}$$

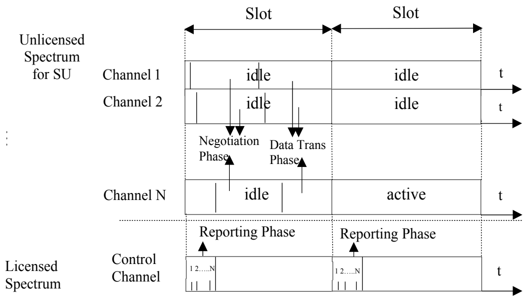

Fig. 1. The mechanism of the proposed MAC protocol

During each time-slot, z is supposed to be the same for all channels $i.e.$, $z = z_1 = z_i$.

B. Proposed protocol

In our proposed protocol, the control channel consists of periodic time slots having the same length as those of data channels. Moreover, the slots of data channels as well as the control channel are synchronized. Each time-slot consists of three phases: reporting phase, negotiation phase and data transmission phase. The reporting phase is carried out on the control channel while the two others are performed on the data channels between the concerned secondary users. In the reporting phase, the control channel is divided into N mini-slots, $i.e.$, equal to the number of channels. Each SU can use its SDR-transceiver to sense one of the N channels randomly. All secondary users that sense the i^{th} channel idle, send the beacons on the i^{th} mini-slot. Only those SUs who sensed i^{th} channel to be idle and their intended receivers tune their transceivers to Channel i after i^{th} mini-slot and they compete for that data channel by using CSMA/CA. The other SUs compete for the other channels which were sensed idle previously. The negotiation for a data channel among the secondary users who sensed that channel idle takes place on data channel. Successful SUs use the remaining portion of the ongoing time-slot for data transmission. In this way, secure data transmission is ensured as the data transmission starts immediately after negotiation phase, so the likelihood of primary users arriving within the remaining time period of that time-slot is null. Further, simultaneous transmissions can take place between many pairs of secondary users and hence a maximum utilization of the spectrum holes can be achieved. Fig. 1 shows the mechanism of our proposed protocol. During the negotiation phase, SUs use the control transceivers to negotiate data channels by exchanging RTS/CTS packets over the corresponding data channel they found idle. All users have the same collision probability. The SU, with successful contention for the data channel, starts data transmission immediately after the end of the negotiation phase. The process is the same for all channels. SUs can accordingly exploit the maximum number of channels opportunistically and several pairs of SUs can start data transmission in parallel.
Algorithm 1 gives the description of the proposed MAC protocol for spectrum sharing between secondary users.

Algorithm 1 Opportunistic MAC protocol: code for every secondary user.

- Initialization:
$ready_i$:= 0 /* indicate that data channel (i) is ready for transmission
$ChNP := \phi$ /* Data Channel where the Negotiation phase will be carried out
- Reporting Phase:
For Control Transceiver:
1: Listens on the control channel
2: WHEN receiving a beacon at i^{th} mini-slot
$ChNP := \phi$ /* update channel for negotiation
3: WHEN being informed by SDR that i^{th} channel is idle.
$ChNP := i$ /* update channel for negotiation tune its transceiver to i^{th} data channel.
For SDR:
4: sense Channel i
5: IF Channel i is idle THEN
inform the Control Transceiver that channel i is idle
- Negotiation Phase: On i^{th} data channel
For Control Transceiver:
6: WHEN receiving RTS
update the channel to sense
send CTS to source node
7: WHEN receiving CTS
update the channel to sense
8: IF destination address is myself THEN /* successful negotiation.
set $ready_i := 1$ at the end of the phase
9: IF the outgoing buffer is not empty THEN
contend to send RTS to the destination node
- Data Transmission Phase: On i^{th} data channel
For SDR
14: IF $ready_i = 1$ THEN
$ready_i := 0$
transmit the data packet over Channel i

IV. Analysis of the Throughput

We consider a saturated networks where the transmission buffer of each SU is always non-empty. Therefore, all secondary users who sensed Channel i idle contend to send RTS packets during the negotiation phase using CSMA. Let T_{s_i} and T_{c_i} denote the average time of the channel being busy because of successful transmissions and the average time of the Channel i sensed busy by each station during a collision, respectively. Considering the RTS/CTS mechanism, we have

$$\begin{cases} T_{s_i} = T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + \\ T_{data_i}(1 - z_i) + T_{SIFS} + T_{ACK} + T_{SIFS}, \\ T_{c_i} = T_{RTS} + T_{DIFS}, \end{cases} \quad (2)$$

In Equation 2, T_{RTS} and T_{CTS} respectively denote the time to send RTS and CTS packets. Whereas T_{SIFS} and T_{DIFS} are the short and Distributed inter-frame space time intervals, respectively. ACK denotes that the packet has been successfully received by the receiver. T_{data_i} represents the time available for data transmission on i^{th} channel during the ongoing time-slot. Let T and T_{ms} denote the total time duration of the slot and the time of each mini-slot. Then

$$T_{data_i} = T - (iT_{ms} + T_{NP}) \quad (3)$$

T_{ms} is equal to the duration of one mini-slot. The negotiation time (T_{NP}) can be calculated as

$$T_{NP} = (\sum_{j=0}^{m} q^j(b_j + T_{DIFS} + T_{RTS} + T_A)) + T_{CTS} + T_A \quad (4)$$

In Equation 4, A denotes SIFS while b_j represents the backoff stage. The value of b_j is equal to $(2^j * W_{min} * 9)$. q_i denotes the constant and independent probability with which each packet collides at each transmission attempt, and regardless the number of retransmissions. m is the maximum back-off stage. Let τ denotes the probability that a station transmits in a randomly chosen time-slot; as each transmission occurs when the backoff counter is zero regardless of the backoff stage, the attempt rate, as defined in [5], for the i^{th} channel is

$$\tau_i = \frac{2(1-q_i)}{(1-2q_i)(W+1) + q_i W(1-(2q_i)^m)} \quad (5)$$

Where $W = CW_{min}$ and $CW_{max} = 2^m W$. The notation $(Wi = 2^i W)$ is adopted where $i\epsilon(0, m)$. τ depends on the conditional collision probability q. To find q, it is enough to note that q is the probability that, in a time slot, at least one of the $(u_i - 1)$ remaining stations transmit. Each transmission sees the system in the same state. So

$$q_i = 1 - (1-\tau_i)^{u_i - 1} \quad (6)$$

In Equation 6, u_i denotes the number of users who sensed the i^{th} channel idle. Finally, we obtain

$$\tau(q)_i = \frac{2}{1 + W + q_i W \sum_{i=0}^{m}(2q_i)^i} \quad (7)$$

A. Saturation Throughput

In this section, we compute the saturation throughput of the secondary users, all with non-empty queue and always contending for data channels during the negotiation phase. Let S denote the achievable throughput on Channel i, it is given by

$$S_i = \frac{P_{s_i} P_{tr_i} T_{data_i}(1-z_i)}{(1-P_{tr_i})T_{idle_i} + P_{tr_i} P_{s_i} T_{s_i} + P_{tr_i}(1-P_{s_i})T_{c_i}} \quad (8)$$

In Equation 8, T_{data_i} is the time available for data transmission on Channel i after a successful negotiation. (1-z_i) denotes the probability of Channel i being idle as z_i is the probability that Channel i is used by a primary user. P_s is the probability that a successful transmission occurs on the channel and is conditioned on the fact that at least one station transmits. P_{tr} is the probability that there is at least one transmission and all the contending stations transmit with probability τ and these are represented by the following equations. T_{idle_i} is the duration of an empty slot time and is equal to iT_{ms}.

$$\begin{cases} P_{tr_i} = 1 - (1-\tau_i)^{u_i}, \\ P_{s_i} = \frac{u_i \tau_i (1-\tau_i)^{u_i - 1}}{P_{tr_i}} = \frac{u_i \tau_i (1-\tau_i)^{u_i - 1}}{1-(1-\tau_i)^{u_i}}, \end{cases} \quad (9)$$

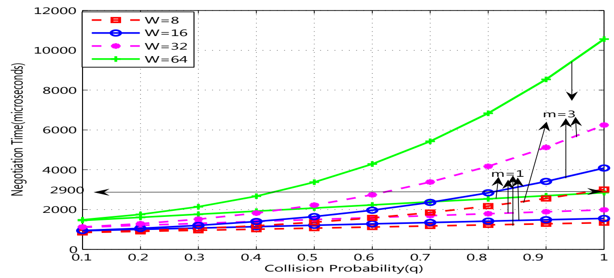

Fig. 2. Negotiation time against different collision probabilities when m=1,3 and W=8,16,32 and 64.

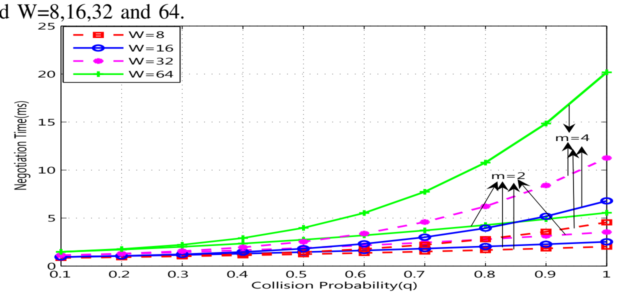

Fig. 3. Negotiation time against different collision probabilities when m=2,4 and W=8,16,32 and 64.

The aggregate throughput is then given or formulated as:

$$S_{all} = \sum_{i=0}^{N} \frac{P_{s_i} P_{tr_i} T_{data_i}(1-z_i)}{(1-P_{tr_i})T_{idle_i} + P_{tr_i} Ps_i T_{s_i} + P_{tr_i}(1-P_{s_i})T_{c_i}} \quad (10)$$

V. Numerical Results

Our proposed protocol considers cognitive IEEE 802.11-based wireless networks. Backoff mechanism RTS/CTS was considered. The values shown in Table I were used in the simulations. The probability of i^{th} channel being busy is taken as 0.3 and the value of N (number of channels) is considered in all simulations. First, the results for the negotiation time against various values of the contention window (W), backoff stage (m) and collision probabilities (q) are obtained in order to ensure that the negotiation phase is completed before the ongoing time-slot and users have some time for data transmission $i.e.$, T_{data}. Figs. 2 and 3 show the time spent during the negotiation part against the collision probabilities for various values of W and m. Our simulation results show that the negotiation time increases as we increase the values of m and W. To minimize interference with primary users, we set slot duration to 3 ms. If a slot is sensed idle, then primary user's chances of returning to the channel will be after the lapse of this time. Figs. 2 and 3 show that as we increase the value of m for some W, the negotiation time increases. Also, as the q increases, the negotiation time also increases. For ensuring successful negotiation before the end of slot time, we assumed only values with which the negotiation completes before the slot time and we are left with some time for data transmission. In Fig. 4, saturation throughput against different number of channels N is shown. The throughput increases with increase in the number of channels as data transmission takes place in parallel on all

TABLE I
PARAMETERS USED TO OBTAIN NUMERICAL RESULTS.

N	10
T	2997 μs
Tms	9 μs
ACK	240 bits
RTS	352 bits
CTS	304 bits
Channel Bit Rate	1 Mbit/s
SIFS	15 μs
DIFS	34 μs
W	8,16,32,64
m	0 to 5
z_i	0.3

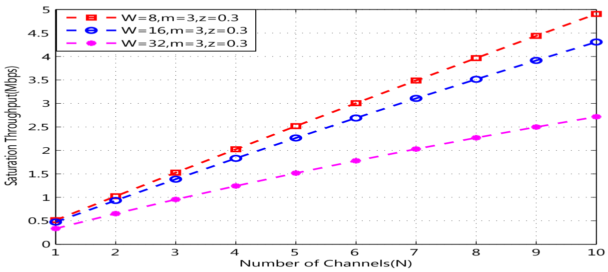

Fig. 4. The saturation throughput achieved against different number of channels from 1 to 10 when z=0.3, m=3, W=8,16,32.

idle channels by different SUs. Moreover, if we increase the initial contention window size, throughput decreases for a constant value of number of channels, backoff stage, collision probability and PUs' channel utilization probability. Saturation throughput against different collision probabilities is shown in Figs. 5 and 6. In Fig. 5, different results are obtained for $m = 1$ and $z = 0.3$ while changing the values of W to 8, 16, 32 and 64. These values ensure a successful transmission within the current time slot. Throughput decreases along with increasing collision probability. Moreover, if we increase the initial contention window size, throughput also decreases.

In Fig. 6, the value of W is unchanged and m is changed from 0 to 2. Saturation throughput is drawn against the collision probability values. Numerical results prove that for successful data transmissions, maximum value of m can be 2 with contention window size 8 and 16 for all values of collision probability from 0.1 to 1. This ensures the successful transmission of data packets within the ongoing time-slot. The optimal value of m is 1 for all values of W as shown in Fig. 5.

VI. CONCLUSION

We proposed a MAC protocol for cognitive radio-based wireless networks, which allows secondary users to identify and utilize the unused frequency spectrum while respecting the priority of primary users. An analytical model is developed, while taking into consideration the backoff mechanism, to evaluate the performance of the proposed MAC protocol. Hence, we showed that we increased the throughput. Principally, it is not secure that secondary users sense the channel in the current time-slot and then communicate in the next time-slot. In this paper, we have contributed to resolve the above problem by reducing the duration of the reporting phase and begin the negotiation in the selected data channel itself. In order to benefit from the negotiation phase already done, we are currently extending our protocol to make reservation of the selected channel for more than one slot.

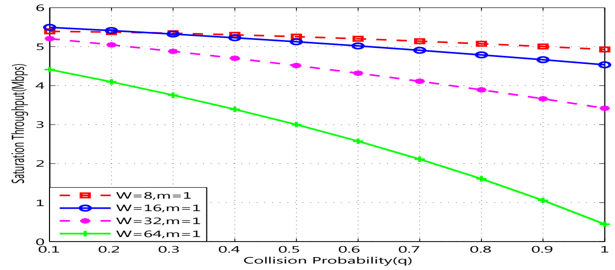

Fig. 5. The saturation throughput achieved against different collision probabilities when n=10, z=0.3, m=1, W=8,16,32,64.

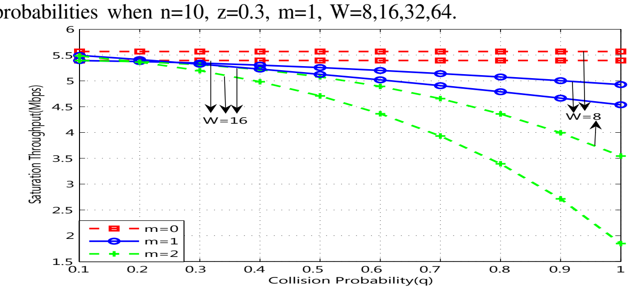

Fig. 6. The saturation throughput achieved against different collision probabilities when n=10, z=0.3, W=8,16, m=0 to 2.

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