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Opportunistic Cognitive MAC (OCMAC) Protocol for Cognitive Radio Network

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***Abstract*— Cognitive radio is being intensively researched as the enabling technology for license-exempt access to the so-called White Spaces (WS), large portions of spectrum in the UHF/VHF bands which become available on a geographical basis. We are proposing an opportunistic MAC protocol for the cognitive radio network which is based on IEEE 802.11b protocol. Opportunistic MAC protocol consists of three phases namely, initialization phase, spectrum sensing phase and data transmission phase. Each phase is discussed and simulation results using MATLAB are shown so that spectrum utilization can be increased.**

***Keywords*- ad hoc network, channel availability, channel capacity, cognitive radio network (CRN), white spaces (WS) sensing, cognitive transmission.**

I. INTRODUCTION

Spectrum is becoming congested with the rapid growth of communication applications. Studies have shown that the large portion of the assigned spectrum is used sporadically and geographical variations in the utilization of assigned spectrum ranges from 15% to 85% with a high variance in time. With the underutilization of valuable spectrum resource and greatly increased demand of spectrum for wireless communication services, more efficient spectrum management schemes are needed. There is a need of solution so that the spectrum can be fully utilized. J Motila [1] proposed a solution by allowing unlicensed users to utilize licensed bands assuming that it would not cause any interference. The unlicensed users, also called secondary users (SUs), need to continuously monitor the activities of the licensed users, also called primary users (PUs), to find the spectrum holes or white space [2], which is defined as the spectrum bands that can be used by the SUs without interfering with the PUs. The Federal Communications Commission (FCC) proposed the unlicensed operation in the white space in December 2004 and enforced its temporary regulation [3] in November 2008. The second memorandum opinion and order which is the official regulation was issued in September 2010 and third memorandum and order [4] was issued in April 2012.

The idle spectrum resources available for CRN to use are time varying due to PUs arrival and departure on different channel. Thus transmission parameter should be changed according to the changing channel opportunities. One open issue in open channel CRN is how to make the best use of those time varying channel opportunities.

The remainder of this paper is organized as follows. Section II describes the opportunistic cognitive MAC (OCMAC) protocol in detail. In section III, IV and V we discuss initialization phase, spectrum sensing phase and data transmission phase respectively, that are used to implement OCMAC protocol, in section VI we analyze channel capacity based on channel availability. Section VII we discuss the simulation results for spectrum sensing which represent ROC curves for error free environment and with Rayleigh fading channel. We also discuss results for the data transmission phase by comparing the success rate, transmission time and number of hop count for two different network sizes.

II. OPPORTUNISTIC COGNITIVE MAC PROTOCOL

Growing interest and penetration of wireless networking technologies is underlining new challenges in the design and optimization of communication protocols. There have existed many MAC protocols which act similar ways as parts of CR's behavior, such as frequency hopping of Bluetooth, channel allocation of cellular network, channel selection of IEEE 802.11b and multi-channel multi-radio transmission issues [5]. None of them could be applied directly to CR because they don't take other systems, that is, primary users into account while it is necessary for CR.

In wireless communication environment, the protocol should be able to deal with the following problems.

- The hidden terminal problem [two terminal are out of range (hidden from) each other by hill, a building, or some other physical obstacle opaque to ultra high frequency (UHF) signals but both within the range of central or base station];
- The near far effect (transmission from distant users are more attenuated than transmission from user close by);
- The effects of multipath fading and shadowing experienced in radio channels;

- The effect of co channels interference in wireless communication systems caused by use of the same frequency band in an adjacent band.

In this paper we are going to analyze a new MAC protocol, opportunistic cognitive MAC protocol. This protocol will implement three phases- initialization phase, sensing phase, data transmission phase, as shown in fig.1. In initialization phase of CR network, the available spectrum is equally divided into N non overlapping data channels. However the channels available to SUs are subject to PU behaviors which are not necessarily slotted or synchronized. Each SU is equipped with a single identical transceiver and each SU can only sense one channel in one constant and independent MAC period τ, i.e., a SU cannot transmit or receive data and perform sensing at the same time. The transceiver is able to turn to any desired combination of channels when transmitting. Assumption is made that SUs always have packets to transmit whenever there is a chance.

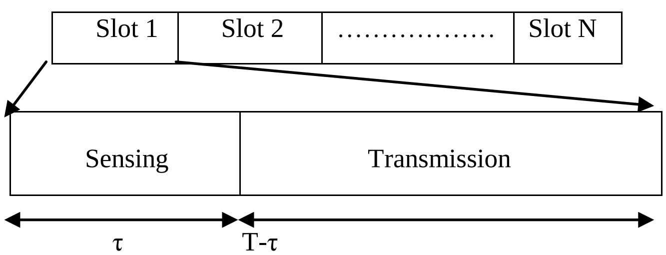

Figure 1- Frame structure for periodic spectrum sensing, where τ denotes the sensing period and T - τ denotes the data transmission or silent period.

This protocol is based on IEEE 802.11 standard, in which CR nodes send IEEE 802.11 DCF [6] (distributed coordination function) like messages and record the status of each data channel by receiving others' information. The sender sends its available channel set and possible transmission durations in RTS packet to the receiver. The possible transmission duration is predicted from the basis of utilization and probability theory. Utilization means the PU preference on this channel. Higher utilization refers to high possibility of collision with PU. Thus, a CR node trends to transmit on a low-utilized channel. Consequently, the receiver decides the best channel by maximizing the overlap of possible transmission duration. The specified channel and the maximum duration are sent back to the sender by clear to send CTS packet. The sender sends Confirm-RTS (CRTS) to inform its neighbors with the information of the coming connection and hence transmits data cumulatively within the free span. In the subsequent section we will study these phase of OCMAC in detail.

III. Initialization Phase

For CR users (also called secondary users in this paper), the channel availability depends on the primary users channel usage patterns. In order to transmit multimedia data in a CRN, secondary users should first find out the spectrum holes unoccupied by primary users. The spectrum pool concept could be used to describe the model of secondary users' total available spectrum holes [7]. After the available spectrum holes are detected, secondary users divide them into small channels, each of which has a bandwidth of (Hz). Then, secondary users select a set of available channels (denoted as) to form an RF link in a special way to ensure high performance and low interrupted ratio. For example, a good channel selection strategy can make sure that the arrival of a primary user will not cause the *complete* failure of the secondary user's radio link. In other words, the radio link can be established by multi-channel, which may not be reoccupied by primary users simultaneously.

Since the secondary users work on unlicensed channels, it should vacate the channel immediately when primary user appears. We consider each primary channel as an ON-OFF model [8]. An ON/OFF state represents the case whether or not a primary user is occupying a channel, and the channel state alternates between state ON (active) and state OFF (inactive). The secondary user can only utilize the OFF time slot to transmit their own packets. We assume that each primary channel changes its state independently. For simplicity, we assume the primary user's packet arrival rate follows Poisson process in this paper. Then, primary user inter-arrival time follows the exponential distribution.

IV. Sensing Phase

Spectrum sensing is the most important task for the establishment opportunistic MAC protocol. Algorithms for spectrum sensing seek to balance the conflicting goals of minimizing interference to the PU while maximizing the rate of the SU. Performance of a sensing algorithm is typically characterized in terms of the probability of missed detection P_m i.e., failing to sense the existence of the PU and thus causing interference, and the probability of false alarm P_f , i.e., falsely declaring that the PU is active and thus missing a spectrum opportunity [9].

Our objective is to maximize the probability of detection while satisfying a requirement on the probability of false alarm. In cognitive radio networks, a larger leads to less interference to primary radios and a smaller results in higher spectrum efficiency. This interpretation is based on the assumption that if a primary signal is detected (possibly a false alarm), cognitive radios are restrained to use the channel (such that spectrum is wasted in case of false alarms); if no primary signals are detected, cognitive radios use the channel (such that interference is generated in case of miss-detection). To achieve the above goal, we first derive bounds on the probability of detection for a given probability of false alarm [10].

A. k out of n rule

We assume that the decision device of the fusion center is implemented with the k-out-of-n rule [11](i.e., the fusion center decides the presence of primary activity if there are k or more cognitive relays that individually decide the presence of primary activity). When k = 1 and k =n, the k- out-of-n rule represents OR rule and AND rule respectively. If the sensing channels (the channels between the primary user and cognitive relays) are identical and independent, then every cognitive relay achieves identical false alarm probability pf and detection probability pd. If there are error free reporting channels (the channels between the cognitive relays and the fusion center), Pf and Pd at the fusion center can be written as

$$P_\chi = \sum_{i=k}^{n} \binom{n}{i} \left(P_\chi\right)^{i} \left(1 - P_\chi\right)^{n-i} \qquad (1)$$

Where the notation 'χ' means 'f' or 'd' for false alarm or detection, respectively.

In cooperative spectrum sensing, all CRs identify the availability of the licensed spectrum independently. Each CR makes a binary decision based on its local observation and then forwards one bit of the decision to the common receiver. Let Di belongs to {0, 1} denote the local spectrum sensing result of the ith CR. Specifically, {0} infers the absence of the PU in the observed band. In contrast, {1} infers the operating of the PU. At the common receiver, all 1-bit decisions are fused together according to the following logic rule:

$$Z = \sum_{i=1}^{k} D_i \begin{cases} \geq n, & H_1 \\ < n & H_0 \end{cases} \qquad (2)$$

Where H1 and H0 denote the inferences drawn by the common receiver that the PU signal is transmitted or not transmitted, respectively. We have considered two scenarios, in one the channel is assumed to be error free and in the other the reporting channel is erroneous. Additive white Gaussian noise (AWGN) is also added to the received signal. We have shown the results for the Rayleigh fading on the signal, with path loss exponent value 2 for free space.

V. TRANSMISSION PHASE

At the network level, a source node may need a number of relay nodes to route the data stream toward its destination node. Clearly, a route having only a single path may be overly restrictive and is not able to take advantage of load balancing. A set of paths (or multi-path) is more flexible to route the traffic from a source node to its destination.

Our work focuses on CR ad hoc networks, without assumptions of specific network topologies, and where each user has limited knowledge of the environment. Moreover, we believe that the consideration of the PU receivers, CR traffic classes and scalable routing approaches uniquely distinguish CRP from the other works in the literature. Our aim in this paper is to provide network layer support for multi-hop CR networks, thereby allowing the use of any underlying MAC protocol or physical layer spectrum sensing techniques. We are using cognitive ad-hoc on demand distance vector protocol [12]. The route-setup in the CRP protocol is composed of two stages. The spectrum selection stage- The source node broadcasts the RREQ over the control channel, and this packet is propagated to the destination. Each intermediate forwarder identifies the best possible spectrum band and the preferred channels within that band during spectrum selection. Next hop selection stage, where the candidate CR users rank themselves depending on the choice of the spectrum and the local network and physical environmental conditions [13]. These ranks determine which CR users take the initiative in the subsequent route formation.

When an intermediate CU receives the first RREQ through a channel free from PU activity, say channel i, it sets up a reverse path toward the sender CU through the same channel. As it is being forwarded, intermediate nodes add their own spectrum opportunities – SOPs, a list of currently available and unavailable channels – to the RREQ messages. If the receiving CU can supply a valid route for the desired destination, then it sends a unicast route reply (RREP) back to the sender through the same channel. Otherwise, it broadcasts a copy of the RREQ packet through the channel i. If an additional RREQ is received through the same channel, the CU checks if the RREQ is newer or it refers to a better reverse route than the one stored in the routing table. In both cases the node updates the reverse path and it sends a RREP or it broadcasts the RREQ, differently the node simply discards the packet. We note that, since the route discovery processes associated with each channel are independent each other, it can happen that routes on different channels can be composed by different intermediate nodes [14].

When an intermediate CU receives the first RREP through a free channel, say i, it sets up a forward route through the same channel toward the RREP sender and it forwards a copy of the RREP along the reverse path through channel i. If an additional RREP will be received through channel i, the CU will update the forward path only if the RREP is newer or it refers to a better forward route.

VI. Analysis of Channel Capacity Based on Channel Availability

SUs want to utilize channel availability in its best way. For simplicity we are taking single primary user in a channel. We are using an alternating ON-OFF renewal process to model our channel. We assume that all ON/OFF durations are independent. Let PToff (x) be the probability density function (p.d.f.) of the channels OFF (idle) duration and PTon(x) be the p.d.f. of the ON (busy) duration. Thus, channel availability A is the expected fraction of time when the channel stays in its OFF state:

$$A = \frac{E[T_{off}]}{E[T_{on}]+E[T_{off}]} \quad (3)$$

We will use renewal theory [15] to the channel's alternating renewal process, if the channel is sensed OFF, the remaining time x of this OFF state from the sensing point is related to the complementary cumulative distribution function (c.c.d.f.) of the channels OFF state and has a p.d.f. form

$$P_{T_{off'}}(x) = \frac{\int_{\infty}^{\infty} P_{T_{off}}(t)dt}{E[T_{off}]}\ ; x\geq 0. \quad (4)$$

Where Toff is the random variable representing the residual life of the channel's OFF state. Similarly, when the channel is sensed ON, we have

$$P_{T_{on'}}(x) = \frac{\int_{\infty}^{\infty} P_{T_{on}}(t)dt}{E[T_{on}]}; x\geq 0. \quad (5)$$

Where Ton_ is the random variable representing the residual life of the channel's ON state.

Let Tavg be the average sum of time spent in by the OCMAC in spectrum sensing phase and Tp be the whole MAC period. For a successful data transmission the SU reserves the channel successfully for (Tp−Tavg) as long as the channel remains idle at least for the whole MAC period Tp.

We can calculate the channel utility for a successful data transmission using

$$U= \frac{T_P - T_{avg}}{T_P} \int_{T_P}^{\infty} P_{T_{off'}}(x)dx \quad (6)$$

Using channel availability and channel utility, the average channel capacity can be calculated as

$$C= AU = \frac{A(T_P - T_{avg})}{T_P} \int_{T_P}^{\infty} P_{T_{off'}}(x)dx \quad (7)$$

VII. Simulation

All simulation work is done using MATLAB software. For the initialization phase bandwidth is taken in terms of time. This time slot is divided into equal time 20 minislots. We have considered that there are 3 secondary users in the network with the probability of successful transmission of message to each channel to be 0.8. If the channel have received the message (i.e. greater than the probability), then put its trigger value 1 else 0. A one indicates that the channel can be used by the SU and 0 indicates that it is occupied by the PU.

For spectrum sensing phase Fig 2 and 3 show the ROC curves for k out of n rule in decision fusion strategy for error free and erroneous reporting channel respectively. Two fusion rule AND and OR are considered. The average SNR in each link is 15 dB. In Fig. 2, we plot the maximum probability of detection against the probability of false alarm and in figure 3 we plot the minimum probability of miss detection against the probability of false alarm. These curves indirectly measure the interference level to the primary radios. Curves show that OR rule always outperforms AND rule and has better detection capability. Fig.3 considers a multihop cognitive relay network and its detection capability over Rayleigh fading. The average SNR in each hop is 15 dB. A path loss exponent is assumed to be 2 for free space propagation.

For transmission phase we consider the random topology, a network of size 100*100(m) forming an ad hoc network and number of node 10 and 20 in the network. We have calculated the success rate, total transmission time and number of hop count for the network size 10 and 20 respectively. Success rate for the data transmission from source to destination node is better for the network size 20 but it is having greater response time and number of hop count also increases as well.

For a single-channel network, we compare the analytical and simulation channel utility U of OCMAC under different channel availability A. the channel has the normal distribution of the on- off state with mean value 0 and standard deviation 1. In figure 7 we take the case of MAC period T_P= 5ms. In table I we compare the simulation results of figure 7 with the analytical results. The comparison shows that the simulation results matches with the analytical results with very few difference.

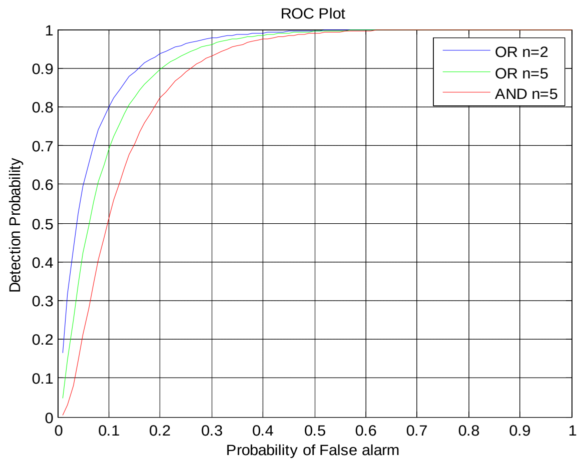

Fig 2. - ROC curve for AND and Or rule for error free reporting channel.

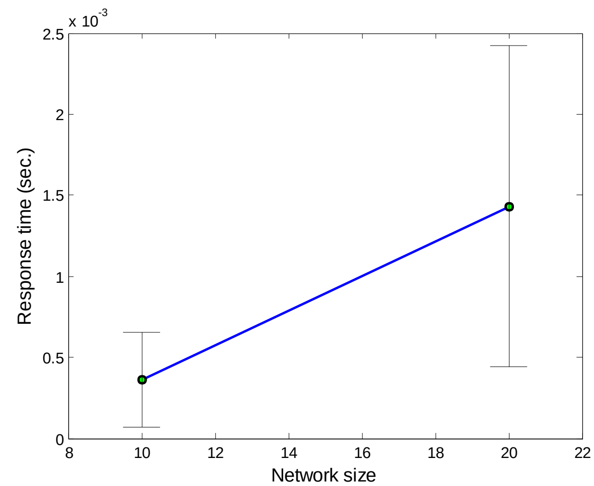

Fig 5. Response time (sec) Vs. Network size

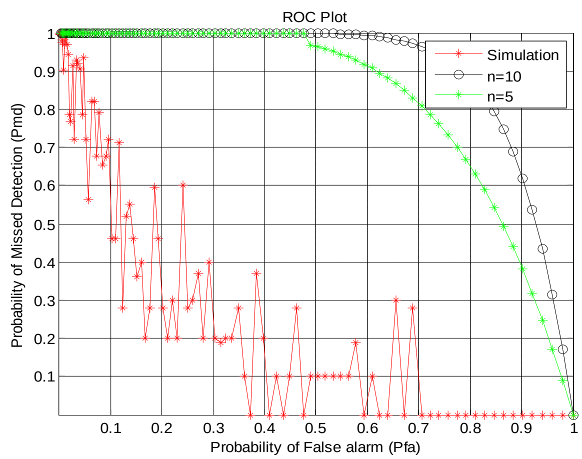

Fig 3. ROC curve for AND rule with the direct link over Rayleigh fading channel.

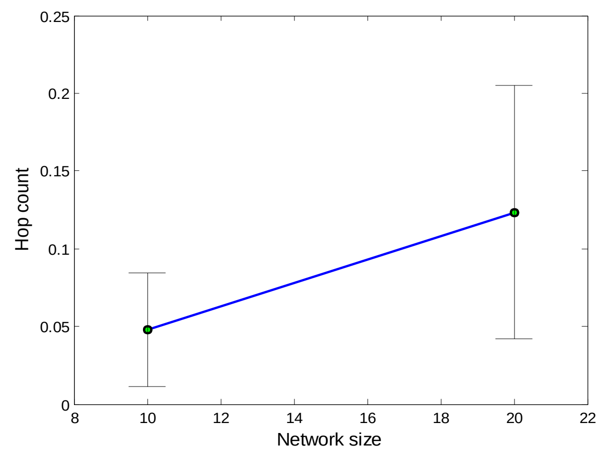

Fig 6. Hop count Vs. Network size

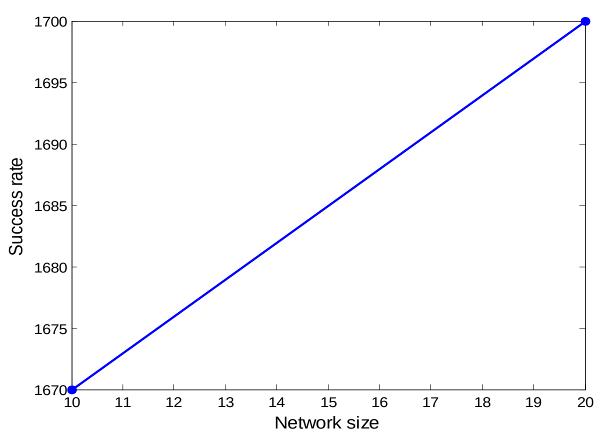

Fig 4. Success rate Vs. Network size

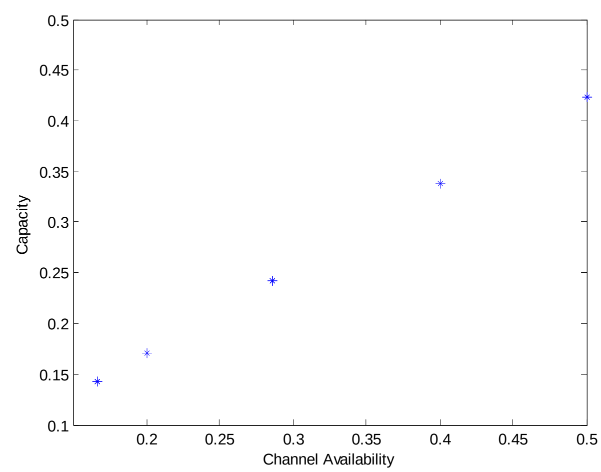

Fig 7. Capacity Vs. Channel Availability

TABLE 1

Simulation and analytical results of channel capacity for different channel availability for MAC period, T_P =5 ms

Channel Availability(A)	Capacity C (Simulation)	Capacity C (Analysis)
0.04	0.14	0.03
0.2	0.17	0.18
0.29	0.25	0.27
0.39	0.34	0.36
0.5	0.43	0.40

VIII. Conclusion

In this paper we discuss OCMAC protocol which is basically composed of three phases, initialization phase, spectrum sensing phase and data transmission phase. Simulation results are shown for these phases. K-out of n AND and OR rule is used for spectrum sensing in error free environment and in Rayleigh faded channel. Simulation results are also discussed for data transmission phase with different network sizes. Finally we have compared the channel capacity of simulation results with the analytical results. In this paper we have not consider the effect of return of primary user in the network.

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