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CROSS LAYER BASED THROUGHPUT OPTIMIZATION IN COGNITIVE RADIO NETWORKS WITH EFFECTIVE CHANNEL SENSING SCHEMES

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Abstract
Cognitive Radio technology is a novel and effective approach to improve utilization of the precious radio spectrum. Spectrum sensing is one of the essential mechanisms for cognitive radio (CR) and various sensing techniques are used by the secondary users to scan the licensed spectrum band of the primary radio (PR) users to determine the spectrum holes. These can be intelligently used by the secondary users also referred to as CR users, for their own transmission without causing interference to the PR users. In this paper, a MAC protocol with two spectrum sensing schemes, namely Fusion based Arbitrary sensing scheme and Intelligence based sensing scheme are analyzed including the effects of interference. Rayleigh channel model for PR-PR interference and CR-PR interference is considered. An expression for the aggregate throughput of the cognitive radio network is derived for the two channel sensing schemes. The effects of interference on throughput are studied both by analysis and by simulation. It is found that interference affects the sensing efficiency which in turn affects the throughput of the cognitive radio users. Rate Adaptation techniques are further employed to enhance the cognitive radio network throughput.

Keywords:
Cognitive Radio, Interference, Spectrum Sensing, Rate Adaptation

1. INTRODUCTION

The demand for new wireless services and applications as well as the number of users demanding these services is steadily increasing. This growth is ultimately constrained by the available frequency spectrum. According to current frequency allocation policies, fixed frequency band is being allocated to different wireless services to eliminate interference between them. The prime radio frequency spectrum (less than 3 GHz) is already exclusively assigned, and the deployment of new wireless services is restricted to either the overpopulated license free ISM bands or bands located above 3 GHz. However a number of studies have shown that about 90% of the prime radio spectrum is significantly underutilized. In many bands, spectrum access is a more significant problem than the physical scarcity of spectrum, due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access [1]-[4]. To achieve a better utilization of the licensed radio spectrum the FCC has recently suggested a new concept/policy for dynamically allocating the spectrum, referred to as Cognitive Radio (CR), which is a form of software-defined radio technology. In a CR scenario, various spectrum sensing techniques are used by the secondary users to scan the licensed spectrum band of the primary radio (PR) users to determine the spectrum holes. These are then intelligently used by the CR users, for their own transmission without causing interference to the PR users. Cognitive radio is viewed as a novel approach for improving the utilization of electromagnetic spectrum [5]-[7].

The dynamically changing spectral usage scenario necessitates the design of a suitable MAC protocol for the CR network. A number of CR MAC protocols have been proposed in the recent past. In [8], Chia-Chun Hsu et al propose a cognitive MAC protocol SCA-MAC, based on CSMA/CA. Decision making for channel access is based on the spectrum usage statistics. For each transmission, the sender negotiates with the receiver on transmission parameters through CRTS/CCTS exchange over the control channel. However collisions necessitate frequent renegotiations. DOSS-MAC proposed by L. Ma et al in [9] allows nodes to adaptively select an arbitrary spectrum for the incipient communication subject to spectrum availability. High spectrum utilization is achieved without relying on any infrastructure and the hidden terminal /exposed terminal problems are avoided by including the tri band (Busy tone band, Control Channel & Data band) approach. However the devise cost is increased due to the need for multiple transceivers. The SYN-MAC proposed in [10] by Yogesh R Kondareddy et al, is applicable for heterogeneous environments where channels have different bandwidths and frequencies of operation. The use of a Common Control Channel (CCC) is avoided in the protocol and a solution to issues like CCC saturation problem, Denial of Service attacks (DoS) and multi-channel hidden problem is provided. Better connectivity and higher throughput is obtained but requires all the nodes in the network to be synchronized. Long Le and Ekram Hossain proposed OSA-MAC in [11], where time is divided into beacon intervals and all the secondary users are synchronized. Each beacon interval consists of a channel selection phase, a sensing phase and a data transmission phase. Four-way handshake mechanism as in IEEE802.11 CSMA/CA protocol is used for data transmission. Uniform Channel Selection/Spectrum Opportunity-Based Channel Selection is employed. The system throughput increases with the number of secondary flows until reaching a maximum value and then slightly decreases. Hang Su et al, in [12] propose a cross-layer based MAC protocol, where two transceivers are used, one operates over a dedicated control channel and the other can be tuned to any one of the licensed channels on being found idle. Random sensing policy and negotiation-based sensing policy are proposed for spectrum scanning. Throughput and packet transmission delay are analyzed for CR networks using probability concepts and queuing theory. In paper [4], co-operative channel sensing using cognitive relays is discussed, where each relay makes a one bit decision about the channel and forwards to a common receiver which fuses all the decisions based on AND / OR / Majority logic. Protection of decision information using space time codes is also investigated.

The key contribution of our paper lies in analysing the effect of interferences on the primary communication link, and its subsequent impact on the secondary user's throughput in a CR scenario. Further, an attempt is made to adaptively increase the throughput of the secondary users and hence that of the CR network by employing rate adaptation techniques on the secondary users' data transmission with a novel cross-layer based MAC protocol.

In any wireless channel, interferences are unavoidable and these reduce the signal to interference and noise ratio (SINR) of the link. This in turn will have an impact on the effective spectrum sensing by the secondary users leading to misdetection. Misdetection is the case when a busy channel is identified to be an idle one by the CR network, due to the adverse effect of interference on the primary link. In the case of misdetection, the secondary users transmit their information via a particular band assuming that the primary user is not utilizing it. But in reality, the primary user will be using the band albeit with a low SINR. In this situation the primary user and the secondary user both cause interferences to one another. To combat such effects, interference analysis and its mitigation is very essential. Herein, the interferences to a given primary user's receiver are modelled and their impact is analysed.

The system model considered for the study is shown in Fig.1. The primary user's transmitter and receivers are considered to be in a fixed position. The secondary nodes are assumed to be distributed randomly within the area. The interference range shown in the Fig.1 is the area around a given secondary node within which it can cause harmful interference to the primary nodes. This can happen under misdetection of spectrum availability by the secondary node. The detection range is that area around a given secondary node within which it can detect the presence of any active primary user. For every secondary user, its detection range is maintained comparatively larger than its interference range so as to minimize the interferences from a secondary node to any other primary receiver. This is achieved by controlling the secondary users transmit power level to be always lesser than that of the primary transmitter. Hence it can interfere only over a smaller range while being able to detect the presence of primary users over a wide range. Thus, the secondary user in spite of using an idle portion of the licensed frequency band ensures that, it in no way poses interference threat to the primary user.

The interference range and the detection range are uniquely defined for each secondary user in the primary-secondary co-operative network. The interference range, D, as depicted in Fig.1 is defined by the following condition,

$$I_t = \frac{P_P L(R)}{P_S L(D) + P_b} \tag{1}$$

where I_t is the minimum SINR needed at the primary receiver, $P_P L(R)$ and $P_S L(D)$ are powers received from the primary transmitter and the interfering secondary transmitter respectively, inclusive of the path loss and P_b is the background noise power.

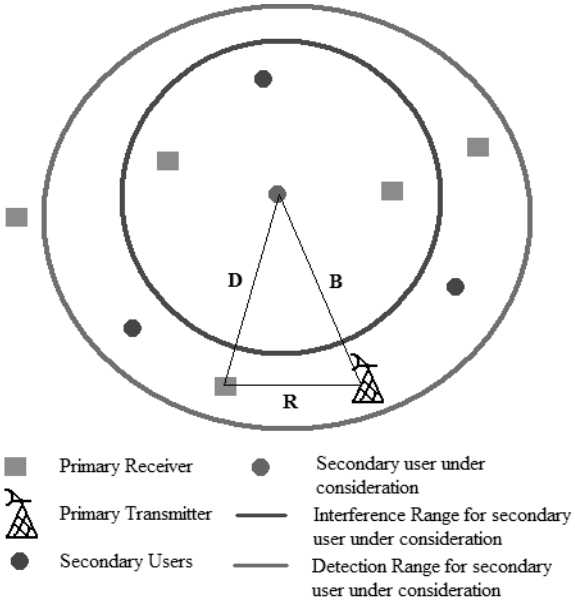


Fig.1. System model

The detection (sensing) threshold, which is the minimum SNR at which the primary signal may still be accurately detected by the cognitive radio, is expressed as

$$\Re = \frac{P_P L(B)}{N} \tag{2}$$

where $P_P L$ (B) is the primary transmitter power received by secondary receiver inclusive of path loss and N is channel noise power. In Fig.1 these are shown for one secondary node. Similarly these parameters can be defined for every other secondary node in the network [13]. This helps the secondary user to estimate it's interference effect on the primary receiver, and hence adjust its transmission strategy (access policy and/or transmit power) accordingly. In wireless networks, transmission power defines the network topology and determines the network capacity [14]. The transmission power of secondary user not only determines its communication range but also affects its usage of idle spectrum. A secondary user can use a higher power to reach it's intended receiver, only when the primary user band it is using is inactive within its interference region. Optimal power control in cognitive radio systems thus requires careful analysis of the impact of secondary user transmission power on the primary user's receiver.

The rest of the paper is organized as follows. The spectrum sensing schemes employed in the MAC protocol to efficiently detect the white spaces in the spectral bands are discussed in Section 2. Section 3 presents an analytical study of the indirect effects of interferences on the secondary user's throughput. The algorithm proposed for rate adaptation is also explained. Section 4 deals with the simulation results, related discussions and inferences drawn from them. Section 5 presents the conclusion and the future work. Throughout the paper the terms secondary users and cognitive users are used interchangeably. The parameters with suffix *CR* refer to those of secondary users and the parameters with suffix *PR* refer to those of primary users.

2. SPECTRUM SENSING AND THE MAC PROTOCOL

The key requirement envisaged as one of the basic features of any cognitive radio is that, it must be able to accurately sense the spectrum holes. A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, is not being utilized by that user. It is therefore required that the secondary users appropriately decide when and which channel they should tune to in order to communicate among themselves without affecting the communication among the primary users. For this the secondary users must either continuously or periodically scan the radio spectrum to identify the spectrum holes. Thus, the secondary nodes equipped with cognitive radio must be capable of being aware of the environment by using the methodology of understanding-by-building to learn from the environment and adapt to the statistical variations accordingly to achieve the two primary objectives such as highly reliable communication whenever and wherever needed and efficient radio spectrum utilization [4].

2.1 SPECTRUM SENSING SCHEMES

In this paper, two channel sensing schemes namely the *Fusion-based Arbitrary channel Sensing Scheme* (FASS) and the *Enhanced Intelligence-based channel Sensing Scheme* (EISS) are developed by combining the Random sensing policy and Negotiation based sensing policy proposed in [12] and the *Majority Fusion* technique proposed in [4], incorporating a novel rate adaptation algorithm.

In cognitive radios, channel sensing and data transmission cannot be carried out simultaneously and hence each secondary user is required to be equipped with two transceivers. These are called the control transceiver and the data transceiver respectively. To communicate among themselves the secondary users have a small chunk of frequency spectrum allocated to them. This frequency band is called control channel. This control channel is time slotted with equal period and is divided into two parts namely the *reporting phase/slot* and the *contending phase*. The reporting slot is further divided into smaller mini-slots corresponding to the number of licensed channels in the network

In the FASS, the secondary users sense the channels independently and according to Arbitrary Sensing Scheme (ASS) there is a chance that a single channel gets sensed by more than one secondary user, as in case of RSP. The secondary users transmit their one bit decisions in the corresponding mini-slots for the licensed channels, regarding the primary channels' status over the control channel, mutually among themselves. Then based on majority rule [4], the decision fusion is done at the control transceivers of the secondary users, which work in synchronism among themselves. Since the primary channels are arbitrarily chosen for sensing there are possibilities that some channels are sensed by more than one cognitive user while some channels may not be sensed at all. Also due to inefficiencies in spectrum sensing there can be ambiguities in the sensing outcome. This simply means that a channel may be sensed to be busy by one secondary user while it might be sensed to be idle by another secondary user, though the channel is actually busy. Since energy detection based techniques are employed for spectrum sensing such cases of misdetection are possible due to multi-path fading and shadowing effects on the primary signal, reducing their strength below the sensing threshold. By exchanging their sensing information the secondary users will be able to accurately detect the presence of primary users even under fading and shadowing environments. Further, by making decisions based on majority fusion, the number of unused channels perceived by the secondary user will increase and thus improve the overall network performance in terms of spectrum utility.

The enhanced intelligence-based channel sensing scheme (EISS) is similar to that of the Negotiation based sensing policy of [12] which is considered here as simple ISS, except for the enhancement realized by the rate adaptation techniques. In this policy the secondary users have an idea of the channels that have already been sensed by other secondary users and select a new channel that has not yet been sensed. This is possible because the secondary users overhear the RTS/CTS packets of the secondary user transmissions on the control channel which contain information about the channels which have already been sensed. Herein, the number of licensed channels which are sensed by the secondary users in the (t+1)th time slot is considered to be always larger than or equal to that in the tth time slot for any t=0,1,2…. So, if the number of secondary users is larger than or equal to the number of licensed channels, all the licensed channels can be eventually sensed by using this policy. It is intelligent because each secondary user senses a new channel in each time slot.

The primary channel is modeled to be a Markovian chain that alters between two states at any given time slot. When the primary users are occupying a channel it is said to be busy (ON state/1), else it is said to be idle (OFF state/0) [15]. Hence, a primary user's channel usage may be viewed as a Markovian random process. The probability that a channel goes from ON state to OFF state is 'α' and the probability that it goes from OFF state to On state is given by 'β'. The probability that the channel remains in the ON state is '1-α' and the probability that the channel remains in the OFF state is '1-β'. Thus, the primary users' channel utilization factor, γ, is given as

$$\gamma = \frac{\beta}{\alpha + \beta} \tag{3}$$

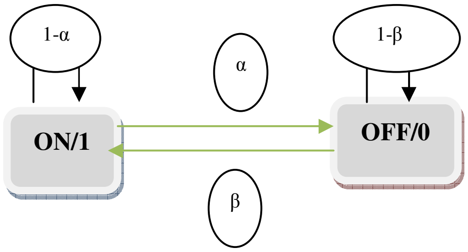


Fig.2. Primary user's channel usage model

From the probability transition matrix of this Markovian chain, the relationship between the number of secondary users and the probability that they can sense a given number of primary channels can be found out and it is seen that the probability that all the channels are sensed by the secondary users depends on the number of secondary users here. The more the number of secondary users, the more likely a larger number of channels is sensed. When the number of secondary users is large enough, they can sense all of the idle licensed channels even using a simple arbitrary channel sensing scheme [16].

In FASS, it is ensured that the channels are correctly sensed where as in EISS it is ensured that all the channels are sensed. The channel sensing schemes may be selected as per the application requirements.

2.2. CROSS-LAYER BASED RATE ADAPTIVE MAC PROTOCOL WITH INTERFERENCE CONSTRAINTS

Cross-layer design has been in focus over the past decade more so in the field of cognitive radios as it is found to improve the performance of wireless networks. The inter-layer coupling among/between the layers of the protocol stack can be exploited for optimization of QoS parameters such as the data rate, throughput, delay constraints, overall fairness etc. In this work, the spectrum sensing in the physical layer is integrated with packet scheduling at the MAC layer as proposed in [12]. However the dynamic channel allocation and rate adaptation for secondary user transmission is additionally subject to interference constraints which have not been considered in [12].

The primary users are assumed to be synchronized among themselves and the secondary users are also synchronized among themselves. The secondary users also work in synchronism with the primary receivers. This synchronism is realized by having the control channel and the licensed channels equally time slotted. In the reporting phase of the time slot the secondary users perform the process of channel sensing according to the sensing scheme and reporting the same while in the contending phase they are allocated the unused frequency band based on the interference range constraints of a secondary node on a primary receiver.

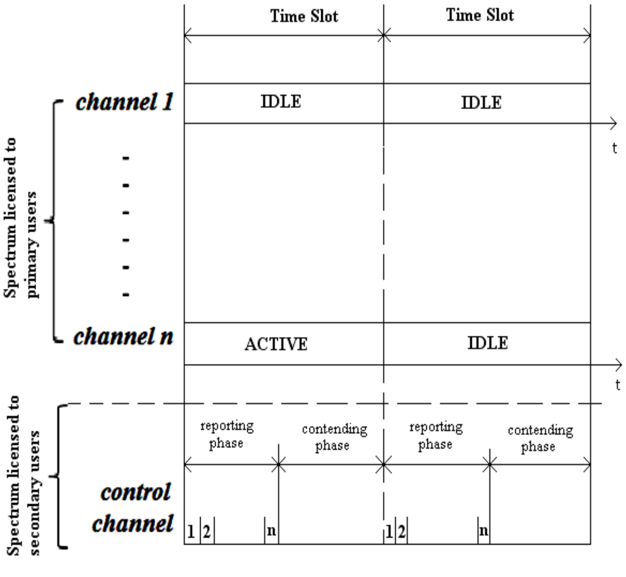


Fig.3. Time-slotted MAC Protocol

Referring to Fig.3, during the reporting slot the data transceiver senses the channel and makes a decision on the channel according to the channel sensing scheme. If it finds, say the j^{th} channel to be idle, it informs the control transceiver that the j^{th} channel is idle by transmitting a beacon in the k^{th} mini-slot if k=j. As the control transceiver keeps on listening to the control channel, when it receives a beacon at the k^{th} mini-slot, since k=j it updates the number and the list of the unused channels. Thus in the reporting phase, the secondary users sense the licensed channels and report the channel state by sending beacons in the corresponding mini-slots. As the control channel has a very narrow bandwidth the cognitive users send only single bit information regarding the status of the channel sensed by them.

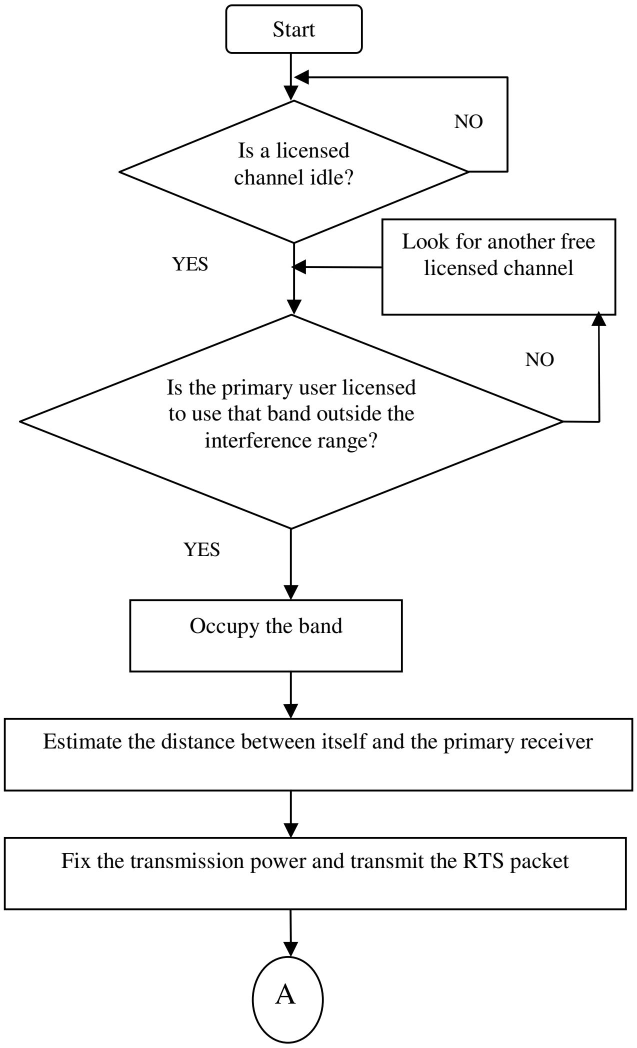
To understand the working of the contending phase, consider two secondary nodes, A_{CR} and B_{CR}. Assume that A_{CR} wants to transmit data to B_{CR}. A_{CR} initiates transmission following a contention-based algorithm such as the p-persistent CSMA protocol to access the control channel to negotiate with B_{CR}. A_{CR} continuously listens to the control channel and waits until it becomes idle. Then it transmits the RTS packet with a probability ‘p’ [17]. Upon receiving this RTS packet (which contains information about the channel sensed by A_{CR}), the control transceiver of B_{CR} will update the channel it should sense in the upcoming time slot, according to the channel sensing scheme and sends CTS packet to the source node A_{CR}. When A_{CR} receives this CTS packet (which also contains the information about the channel sensed by A_{CR}) it also updates the channel that it will sense according to the channel sensing scheme. If this RTS/CTS packet exchange is successful, it is concluded that the contention is succeeded, that is, the A_{CR} has acquired the channel for communicating with B_{CR}.

The control transceiver of A_{CR} sets a flag s=1. The data transceiver of A_{CR} transmits the data packets to B_{CR} via the channel allocated to them temporarily based on the interference constraints and resets the ‘s’ flag for the next consecutive time slot. The secondary users transmit data packets in the time slot following the one in which they successfully exchange RTS/CTS packets with their destination secondary users. Thus, in the contending slot, the cognitive users use their control transceivers to negotiate or discuss among themselves about the data channels by exchanging RTS/CTS packets over the control channel and perform the actual data transmission among them. Thus, an idle licensed channel is an opportunity to a pair of secondary users if they can communicate successfully without violating the interference constraint.

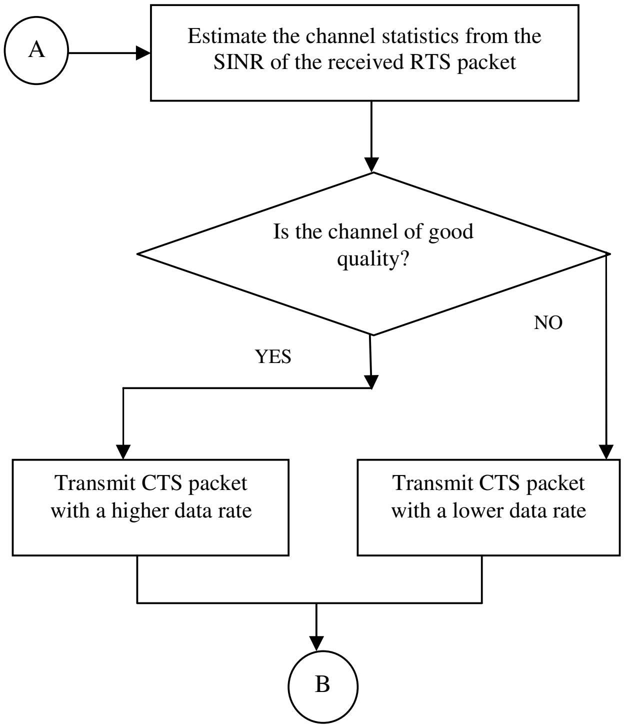
Regarding the bandwidth allocated to secondary users for transmission over an idle primary channel, if it is uniform the throughput obtained is much lower than that estimated from equations derived under ideal conditions. This is overcome in this work by proposing interference based rate adaptation algorithm for the secondary users, executed at the control transceivers of the secondary users after the reporting phase, when they have acquired knowledge about the idle channels. On finding a channel to be idle, the secondary user must estimate the distance between itself and the relevant primary user to confirm if the primary user licensed to use that band falls outside its interference range. If so, the secondary user can use the channel for data transmission (as it does not cause any harmful interference to the primary receiver), else it should refrain from using the channel. Also depending on this distance, the transmit power of the secondary user is fixed. To start with it sends the RTS packet to its intended secondary receiver node with arbitrary rate in its rate field. On receiving the RTS packet at specific signal strength, the secondary receiver node will have an idea about the nature of the channel, inclusive of the interference constraint. Depending on its estimation of the channel characteristics, it will decide the data rate possible for further communication between them and will in turn acknowledge the reception of RTS packet by sending a CTS packet to the source secondary node. The CTS packet will contain information about transmission (modulation) rate that will ensure successful transmission between them for the current channel status. When the transmitter receives the CTS packet, it will use that rate for further data transmissions.

Fig.4 shows the flowchart for the rate adaptation algorithm used in the MAC protocol. The basic idea here is to reduce the probability of misdetection and/or its impact. Thus, this is a kind of indirect interference mitigation technique.

Initially, at the secondary transmitting node,



At the secondary receiver upon receiving the RTS packet,



At the secondary transmitter upon receiving this CTS packet,

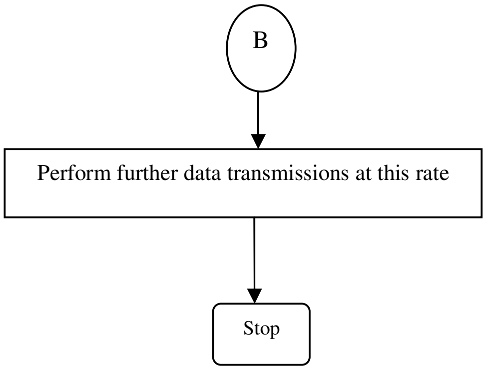


Fig.4. Flowchart for Rate Adaptive MAC protocol

Since cognitive radio is defined on a software platform, it can adaptively change its transmission parameters such as the frequency, transmit power, modulation technique, data rate etc,. Here the rate adaptation scheme is used to maximize the throughput utilizing the available resources such as the power and bandwidth, efficiently. When the idle primary channel is found to be more prone to interference and fading effects thus resulting in a low SINR a very low rate data will be transmitted through that channel. But when the channel is found to be excellent (causing negligible interference to primary), information is sent at a higher data rate. This technique is found to enhance the throughput of the cognitive network when compared to the throughput obtained under uniform data rates.

3. NETWORK THROUGHPUT ANALYSIS

The cognitive radio network throughput is defined here in terms of the number of unused primary channels as perceived by the cognitive users and the bandwidth (data rate) allocated to each of these licensed bands, rather than in terms of the number of packets. Also, the throughput equations are defined based on the channel sensing schemes. This emphasizes the importance of a proper spectrum sensing scheme.

3.1 THROUGHPUT EQUATIONS

The throughput of the cognitive network based on the simple arbitrary sensing scheme, η_{ASS} , is given by

$$\eta_{ASS} = \frac{RU_{ASS}T_{CP}}{T_S} \tag{4}$$

where R is the data rate of each cognitive user and U is the number of unused channels as perceived by the secondary users. The data transmission among the secondary users starts immediately after the sensing slot and continues for the entire contention slot in every time slot. T_{CP} and T_S are the time durations of the contending phase and the whole time slot respectively.

Similarly, for the case of ISS the throughput is obtained as

$$\eta_{ISS} = \frac{RU_{ISS}T_{CP}}{T_S} \tag{5}$$

The above equations obtained from [12] assume there is accurate channel sensing, since ideal (no interference) conditions are assumed, which may be practically infeasible.

3.2 INTERFERENCE MODELING

Interference plays an important role in characterizing the system performance in any communication network especially in the case of networks that operate in a wireless environment. In the case of cognitive radio wireless networks, this interference affects both the primary as well as the secondary users' networks either directly or indirectly. Hence statistical modeling of the interference and its analysis would help to a greater extent in mitigating these effects to improve the overall performance of a cognitive system.

To any given primary user, another primary user and cognitive user can be interferences [18]. These interference powers are statistically characterized. The stochastic models for PR-to-PR and the CR-to-PR interference under a Rayleigh fading channel model are constructed and the variance or the total interference power at the primary receiving node is obtained for a path loss exponent corresponding to a relatively lossy environment [19]. The characteristic function of this random process, that is, aggregate interference at the PR receiving node, is obtained, from which its variance or power is estimated. They are estimated for a terrain of n=4, as follows. The primary user to primary user interference is given as

$$\sigma_{P_{\text{PR-PR}}}(i) = [\pi\gamma_i\rho_i/3]\left[2P_o^{(i)}d_o^{(i)}\exp(-\pi\gamma_i\rho_i(b_i)^2)\right]^2(b_i/d_o^{(i)})^{-6} \tag{6}$$

The cognitive user to primary user interference is given as

$$\sigma_{P_{\text{CR-PR}}}(i) = [\pi\gamma_i\rho_i/3]\left[2P_o^{(i)}d_o^{(i)}\exp(-\pi\gamma_i\rho_i(b_i)^2)\right]^2 \tag{7}$$

The parameters in these equations are defined as follows

γ_i – ith primary users' channel utilization given by

$$\gamma_i = \frac{\beta_i}{\alpha_i + \beta_i} \tag{8}$$

ρ_i – mean number of primary users per unit area

$P_o^{(i)}$ – path loss of the i^{th} channel

$d_o^{(i)}$ – reference distance between a given transmitter and receiver

Here, '*i*' refers to the channel other than that used by the primary user under consideration. The total interference that accumulates at this primary receiver is thus given by

$$\sigma_{total} = \sigma_{P_{PR-PR}(i)} + \sigma_{P_{CR-PR}(i)} \tag{9}$$

The signal power of the primary user is given by

$$S = \delta\, |\, h(t)\, |^2\ P_P \tag{10}$$

where h(t) is the channel impulse response, δ is the average channel power gain, P_p is the normalized transmit power of the primary user. The radio propagation between any two primary nodes is assumed to be affected by slow flat fading channels. The signal to interference ratio is now derived as

$$\Psi = \frac{S}{\sigma_{total}} \tag{11}$$

The secondary users can detect the presence of primary users when the SIR of the primary link is greater than a given sensing threshold, $\Re$. The probability of erroneous sensing is

$$P(\text{error in sensing}) = P_e = P(\Psi < \Re) = 1 - \exp(\Re/\delta) \tag{12}$$

which gives the probability that a primary link's SIR is less than the sensing threshold that results in erroneous sensing [20]. Now the throughput equations would be modified as follows. For the case of ASS,

$$\eta_{ASS\_INT} = (1 - P_e)\eta_{ASS} \tag{13}$$

Following a similar kind of analysis for ISS,

$$\eta_{ISS\_INT} = (1 - P_e)\eta_{ISS} \tag{14}$$

These are the actual throughputs that can be achieved considering the impact of misdetection due to interferences.

After the majority fusion technique incorporated along with rate adaptation, the throughput equations become

$$\eta_{FASS\_Rate} = \frac{R_{Adapted} U_{FASS} T_{CP}}{T_S} \qquad (15)$$

for the case of Fusion based ASS and for ISS with rate adaptation(EISS),

$$\eta_{EISS\_Rate} = \frac{R_{Adapted} U_{ISS} T_{CP}}{T_S} \qquad (16)$$

The rate $R_{Adapted}$ is obtained according to the algorithm discussed in section 2.2.

4. RESULTS AND DISCUSSION

A cognitive radio network scenario similar to that in Fig.1 was simulated using MATLAB 7.0. In the simulation 10 primary users are considered. The primary users are assumed to be stationary. The number of secondary users is taken upto 20. The secondary nodes are randomly distributed and form an Ad hoc network with distributed control. The terrain is considered to be having a path loss exponent value of 4. The wireless channel with Rayleigh fading and log normal shadowing effect is taken. A saturation network is considered where all the secondary users are assumed to be ready with data to transmit. For the throughput analysis the time duration of the slot is considered as 1.89 ms and the time duration of the contending phase is half of the time slot. The primary users' channel utilization factor is taken to be 0.2. The data rate of each channel is uniformly taken as 1 Mbps. Fig.5a shows the throughput obtained from theoretical analysis and Fig.5b shows the throughput obtained from the simulation of simple ASS. Here throughput is defined as the total data rate perceived by the network, that is, the aggregate throughput of the network. From these curves it is clear that with misdetection, the cognitive users get a false notion that they are achieving a greater throughput than what is actually realized.

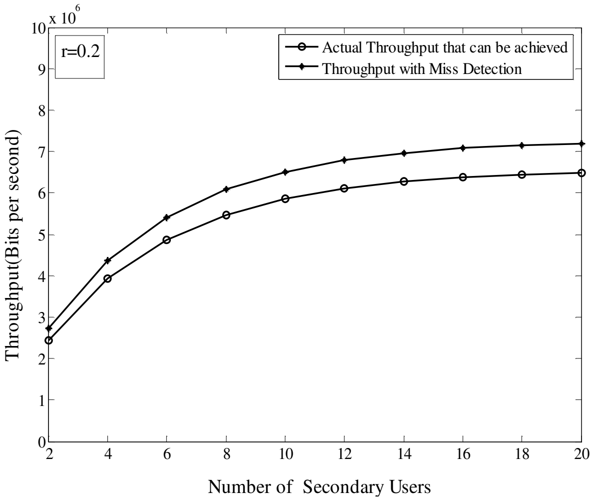


Fig.5a. Comparison of throughput performance of simple Arbitrary Sensing Scheme (ASS) for CR Network with and without interference constraint using analysis

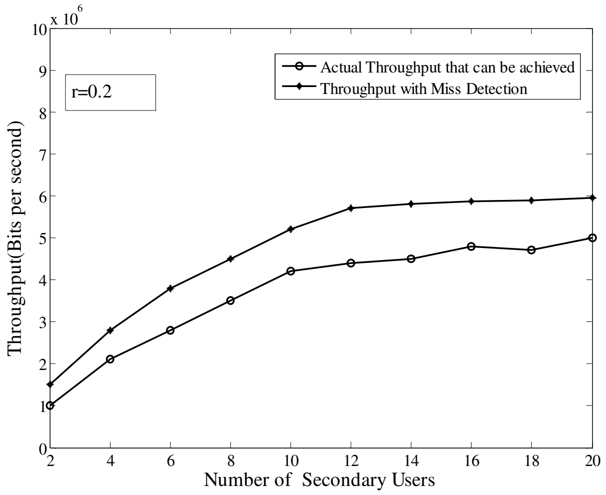


Fig.5b.Comparison of throughput performance of simple Arbitrary Sensing Scheme (ASS) for CR Network with and without interference constraint using simulation

The throughput obtained using analysis and simulation for the Intelligence based sensing policy with the same parameters is shown in Fig.6a and Fig.6b, respectively. Here again a similar observation is made as for the case of ASS. This proves that throughput estimation without considering interference constraints gives a false notion of performance. Comparing the throughputs of the two spectrum sensing schemes, the throughput is improved in ISS compared to simple ASS since ISS makes sure that a primary channel is sensed by only one secondary user and also that the number of channels sensed by the secondary users is higher.

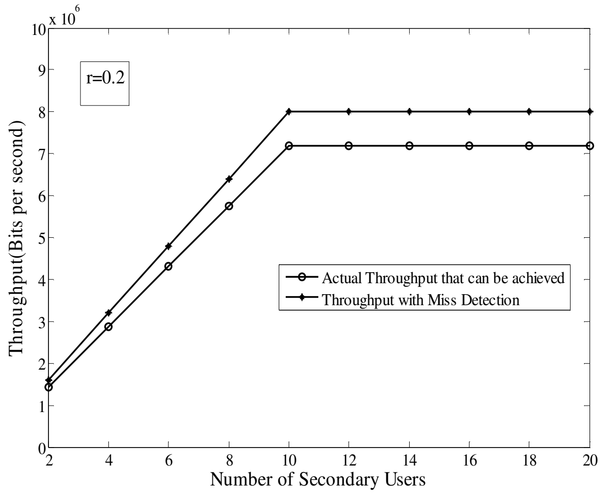


Fig.6a. Comparison of the throughput performance of Intelligent Sensing Scheme (ISS) for CR network with and without interference constraint using analysis

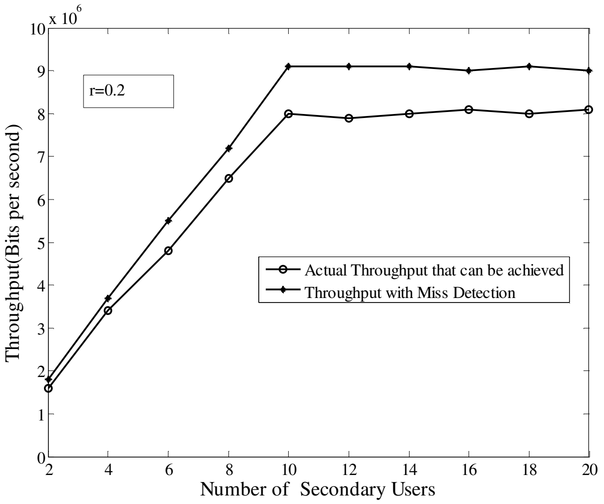


Fig.6b. Comparison of the throughput performance of Intelligent Sensing Scheme (ISS) for CR network with and without interference constraint using simulation

A Majority fusion based ASS is then simulated with five primary nodes and up to 20 secondary nodes with same parameters. The system model generated using MATLAB 7.0 for this scenario is shown in Fig.7.

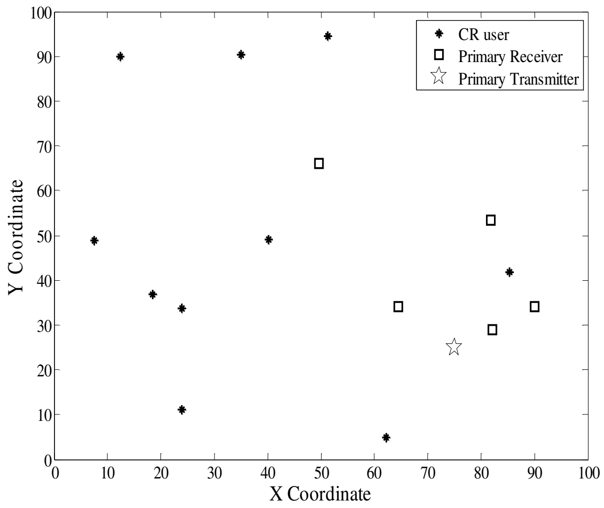


Fig.7. Simulation Scenario of Cognitive Radio Users with Primary Users

With the use of fusion technique which exploits the cooperation among secondary users about sensed results, the probability of misdetection is reduced. Also the MAC protocol integrates the rate adaptation on each perceived channel thereby significantly improving the aggregate network throughput. The data rates used for rate adaptation are 1Mbps, 2Mbps, 5.5Mbps and 11Mbps. A link which is estimated to have low SNR uses low rates for transmission while that with high SNR uses relatively higher rates for transmission. These results are shown in Fig.8 for different values of utilization factors and compared with simple ASS under fixed rate. It is observed that as the number of secondary users increase the throughput also increases since the possibility of more channels being sensed increases. It is also observed that when the primary users channel utilization factor is reduced from 0.6 to 0.2 the throughput achieved by the cognitive network increases.

Fig.9 gives the corresponding results for Enhanced intelligence based sensing scheme with rate adaptation. In the simple ASS (~ RSP) and the simple ISS (~ NSP) of [12], the data transmission is performed at a fixed rate whereas in the FASS and EISS proposed and simulated here, data is transmitted at dynamically adapted rates according to the rate adaptation algorithm. This, as well as the majority fusion of sensing information accounts for the increase in the throughput of the secondary users' network.

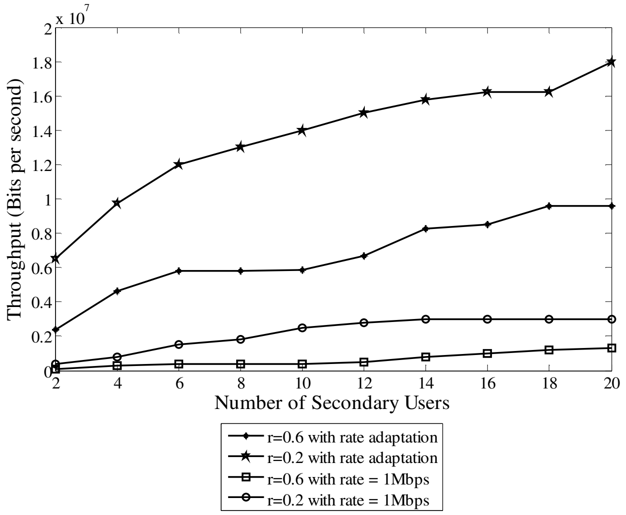


Fig.8. Comparison between Fusion based Arbitrary Sensing Scheme (FASS) with Rate adaptation and simple ASS for different utilization factors

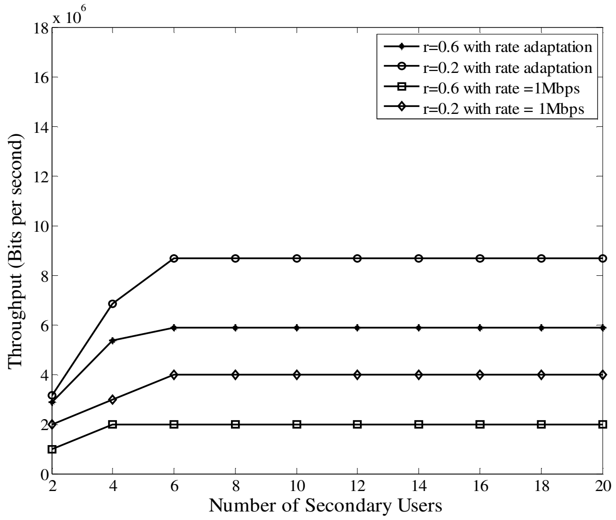


Fig.9. Comparison between Enhanced Intelligence - based Sensing Scheme (EISS) and simple ISS for different utilization factors

5. CONCLUSION AND FUTURE WORK

In this paper, a novel interference based rate adaptive MAC protocol is proposed for cognitive radio networks with Fusion-based Arbitrary Channel Sensing Scheme (FASS) and Enhanced Intelligent Channel Sensing Scheme (EISS) and the throughputs are analyzed. Sensing a channel effectively in the presence of interference is observed to significantly affect the throughput of the Cognitive Radio Network. A system model is generated and the novel rate adaptation algorithm including interference constraints is implemented and found to significantly improve the throughput of the cognitive network. To further understand the effectiveness of this approach, the performance of the two channel sensing schemes and hence the rate adaptive MAC protocol are to be analyzed in terms of the delay constraints and modifications are to be carried out in the proposed MAC protocol. An appropriate optimization also needs to be carried out between the throughput and the delay according to the Quality of Service (QoS) required by the cognitive radio application.

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