A Cognitive MAC Protocol for Ad Hoc Networks

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Abstract – The cognitive radio is a secondary wireless communication system that can overlap the frequency band assigned to the primary system by recognizing the frequency status. Having maximum throughput of Secondary Users, Primary Users also need their own QoS factor guaranteed. We introduce the metric to protect primary users' performance, named "collision probability" that gives insight around the SUs.' Having satisfied this factor, we express a new access scheme using different sensing, back-off, and transmission mechanisms that prevents wasteful actions in the MAC layer. Also an algorithm proposed in order to maximize the transmission rate. Combination of these two plans is proposed in some paragraphs. Simulation results for each part are provided as independent sections and at last benefits of the overall scheme are reviewed.

Index Terms—*Cognitive Radio, QoS, Multi-Bans Systems, Rate Prediction*

INTRODUCTION

Mobile ad hoc networks are flexible and dynamic systems that can operate without the aid of a fixed communication infrastructure. The topology of an ad hoc network is expected to change over time and it depends on the location of the nodes and the resources available. Node locations determine the establishment of links between nodes whenever the distance and other external factors, such as the presence of obstacles and interference, do not prevent nodes from communicating. In addition to acting as end systems, nodes in ad hoc networks also act as transit nodes for other communications. Their participation in the process of searching for paths (routing) and forwarding of packets depends on the availability of internal resources. These resources are typically scarce because of the mobile nature of the nodes. One vital component is the stored energy in batteries of mobile nodes, which is limited because of weight and size restrictions. Furthermore, advances in battery technology lag behind advances in computing and storage technologies [7]. Ad hoc networks inflict extra energy consumption at nodes, as they need to receive, process, and transmit packets to assist others communications. As a result, as nodes consume their resources, they may quickly become unreliable and contribute to create an error-prone system. Ad hoc networks are therefore characterized by unpredictable topologies that require a highly dynamic routing algorithm to cope both with unreliability and mobility of nodes, while attempting to provide good quality routes.

In contrast to the apparent spectrum scarcity is the pervasive existence of spectrum opportunity. Extensive measurements indicate that, at any given time and location, a large portion of licensed spectrum lies unused [4]. Even when a channel is actively used, the bursty arrivals of many applications result in abundant spectrum opportunities at the slot level. These observations form the key rationale for opportunistic spectrum access (OSA) envisioned by the DARPA XG program [11]. The idea is to exploit instantaneous spectrum availability by opening licensed spectrum to secondary users (for example, sensor networks). This would allow secondary users to identify available spectrum resources and communicate in a manner that limits the level of interference perceived by the primary users. Even for the unlicensed spectrum, OSA may be of considerable value in improving spectrum efficiency by supporting both subscribers and opportunistic users. While conceptually simple, OSA presents challenges not present in the conventional wired or wireless networks. We will focus in this paper on two fundamental issues in ad hoc OSA networks where there is no central coordinator or dedicated communication/control channel.

The first issue deals with sensing and access strategies that integrate opportunity identification and exploitation. We do not assume that each secondary user has full knowledge of the availability of all channels; such knowledge implies continuous full-spectrum sensing synchronous among secondary users. While simplifying the design of OSA networks, continuous full-spectrum sensing is energy inefficient and hardware demanding, especially for low-cost battery-powered wireless nodes with bursty traffic. We assume instead that each secondary user can choose to sense a subset of the possible channels (only when it has data to transmit) and must decide whether transmission is possible based on the sensing outcome. When only part of the spectrum can be sensed at a particular time, sensing and access need to be considered jointly. This joint design also allows the handling of spectrum sensing errors at both physical and MAC layers so that interference to primary users is limited below a prescribed level.

As a solution to this problem, we refer to [9] that defines and proves the capacity limit to the general MAC access. Some schemes are proposed in order to decrease the calculations of opportunistic access of the channel. Generalizing the idea to the ad hoc networks with imperfect sensing is performed here.

RELATED WORKS

Along to spectrum sharing, researchers have considered the design of a common control channel to exchange spectrum access and sensing information and facilitate collaborative sensing and spectrum reservation/sharing, e.g., in [12], [13], [14]. Centralized and decentralized spectrum auction and brokerage have been proposed for efficient spectrum sharing, e.g., in [15], [16], [17]. Co-existence of cognitive users in unlicensed band has also been studied [18], [19], [20]. Researchers have also considered sensing-based decentralized cognitive medium access schemes [21], [22], [23]. In [15], the authors model the states of primary bands as two state Markovian process and maximize the transmission rate of secondary users in certain time slots. In [8], the authors design a CSMA/CA-based cognitive radio MAC protocol that uses channel statistics to determine the optimal access range and the number of channels to access. In [9], the authors develop a slotted transmission scheme of secondary user via periodic channel sensing based on Constraint Markov Decision Processes. In comparison, our model is more general. We do not assume exponential busy period of primary users (required in Markovian models), neither synchronization between multiple users or feedback from receivers. Our work introduces explicit guarantee on the performance of primary users and we provide closed form analysis on the capacity limit of secondary users under the primary constraints. Statistical history of the channel is considered as a factor to the future decisions.

In [9], a cross-layer approach to OSA that integrates the spectrum sensing with spectrum access is proposed.
Opportunity identification in the presence of fading and noise uncertainty has been studied in [3], [5] and [8]. Spatial opportunity allocation among secondary users can be found in [9]–[12] and references therein.

CHANNEL ACCESS

In this part, as an introduction, we investigate the schemes and metrics defined in [1]. We assume the arrival process of a PU is Poisson while the service time distribution can be arbitrary. This assumption holds in many situations. M/G/n queue is a good equivalent for this model when n is the number of channels.

Two protection metrics are "Collision Probability" and "Overlapping Time". Collision probabilities are defined as:

$$P_1^c = \lim_{T\to\infty} \frac{\text{No. of collisions in [0,T]}}{\text{No. of busy periods of PU in [0,T]}}$$

$$P_2^c = \lim_{T\to\infty} \frac{\text{No. of collisions in [0,T]}}{\text{No. of packets transmitted for SU in [0,T]}}$$

That P_1^c and P_2^c are collision probabilities of PU and SU respectively. When the average packet length of SUs, is a very small portion of PU's another metric is defined as:

$$P_1^r = \lim_{T\to\infty} \frac{\text{Length of overlapping time}}{\text{T}}$$

It can be proved that P_1^r is the same as P_1^c [8]. To protect the transmission of PUs, the system sets the following constraints:

$$P_1^c \le \eta \quad \text{or}$$

$$P_1^r \le r_0$$

The media access schemes (or protocol) we consider in this paper are illustrated in Fig. 1 and described as below:

- VX Scheme (Virtual-Xmit-if-Busy): The SU senses the channel. If the channel is idle, the SU transmits a packet of length L2. Then, the SU starts a vacation of length V2. If the channel is busy, the SU starts a so-called virtual transmission stage and then enters into the vacation stage afterward. Here, virtual transmission means that the SU does not actually transmit the packet but waits for a time interval which is equal to the packet length. After vacation, the SU senses the channel again.

- KS Scheme (Keep-Sensing-if-Busy): After a vacation, the SU senses the channel. If the channel is idle, the SU transmits a packet and then starts vacation. If the SU senses the channel busy, it keeps sensing until the channel is idle. Then, the SU transmits a packet and starts a random vacation of length V2.In the VX scheme, the transmission activity (including virtual transmission) of the SU is independent of the PU's occupancy of the channel, thus its analysis is simplified. In this paper, we obtain closed form analysis on the collision probability, the overlapping time, the capacity of the SU. The closed-form solutions provide insights on the system performance and facilitate the implementation of the MAC protocol. On the other hand, the analysis is more difficult in the KS scheme, since the transmission of the SU is some what dependent on the activities of the PU. Interesting enough, simulation results show that the throughput performance of the KS scheme is indistinguishable from that of the VX scheme under the same collision probability constraint.

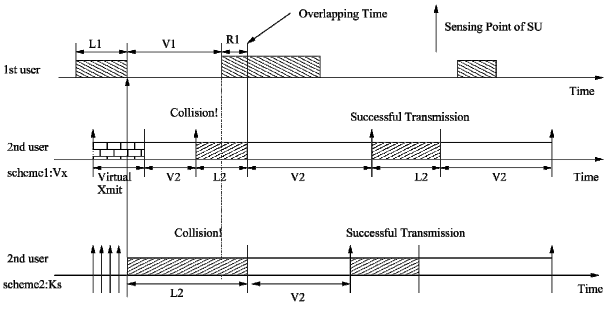

Fig.1: Random Access Schemes of A Cognitive Radio User.

Let V_1 and V2 be random variables denoting the idle periods of primary and secondary bands and L1 and L2 be busy periods of primary and secondary bands respectively. Let υ_i = E[V_i] and l_i = E[L_i].

$$\alpha = \frac{v1}{v1 + l1}$$

Note that α is the probability (or the percentage of time) that a primary band is idle.

The maximum throughput of the SU, according to [8] is calculated as:

$$C_2^{\max} = \eta\alpha \frac{\int_0^\infty \frac{\tau}{\upsilon_1} e^{-\frac{\tau}{\upsilon_1}} f_{L2}(\tau) d\tau}{\int_0^\infty (1 - e^{-\frac{\tau}{\upsilon_1}}) f_{L2}(\tau) d\tau}$$

It is obvious that our objective is to find the optimum $l_2, f_{L2}(\tau)$ and υ_2 to Maximize the SU's capacity under the collision probability constraint $P_1^c \leq \eta$.

In the following, we consider two special cases, i.e., exponentially distributed L2 and fixed L2.

1) Exponentially distributed L2: When the packet length of the SU, L2, is exponentially distributed, in order tosatisfy the collision probability, for a given l2, the optimal v2 should be chosen such that

$$\upsilon_2 = \max\left\{0, \frac{\upsilon_1 l_2}{\eta(\upsilon_1 + l_2)} - l_2\right\}$$

Therefore, for given l2 and η, $C_2^{\max}$ is given as:

$$C_2^{\max} = \eta\alpha \frac{\upsilon_1}{\upsilon_1 + l_2}$$

We can observe that the smaller l_2, the larger the C_2. This is intuitive. With smaller l_2, the collision probability is smaller, and the amount of transmission wasted is smaller when a collision happens. Therefore, more packets can be transmitted successfully with the collision constraint satisfied. We note that $C_2^{\max}$ →ηα when l_2 →0.

2) Fixed Packet Length of SU: If the SU uses fixed packet length, i.e., $L_2 = l_2$, we have

$$\upsilon_2 = \max\left\{0, \frac{\upsilon_1(1 - e^{l_2/\upsilon_1})}{\eta} - l_2\right\}$$

$$C_2^{\max} = \eta\alpha \frac{l_2 e^{-l_2/\upsilon_1}}{\upsilon_1(1 - e^{-l_2/\upsilon_1}) + l_2}$$

Proposition 2. For VX, Under the constraint P c 1 ≤ η and E[L2] = l2, the SU achieves the maximum throughput when it transmits fixed length packets, i.e., L2 = l2. The proof of the Proposition is also available in [1].

RANDOM ACCESS SCHEME FOR MULTI BAND COMPETITIVE SYSTEM

Now consider the system with multiple primary channels and multiple SUs. Denote the number of channels N, and the number of SUs M. Let only one PU own each channel. Each SU can only transmit in one channel at a time. Multiple SUs compete for available spectrum in N channels. We consider the VX scheme only in this section. All SUs adopt the same access parameters, and thus they can be viewed as homogeneous. They do not com transmissions by both the PU and other SU's in a channel. Assuming instantaneous sensing, as in Section IV, collision in channels can only happen between the returning incumbent PU and a transmitting SU. Two sensing strategies are considered:

- Random-Sensing: After a random vacation time V_2, each SU randomly selects a channel, and then detects whether the channel is busy. If it is, then SU enters the Virtual Transmission stage. If the channel is idle, the SU transmits its packet before taking a vacation.
- All-Channel-Sensing: After a vacation, each SU senses all channels. If there is no idle channel, the SU enters the Virtual Transmission stage. Otherwise, the SU randomly selects an idle channel for packet transmission.

With the Random-Sensing strategy, the SU only needs to monitor one band at each instant. By comparison, the All-Channel-Sensing strategy requires that each SU monitor all channels. Thus, the former is much easier to implement than the latter.

We present Monte-Carlo simulations on the performance of the two strategies. We set l_1 = 0.5, v_1 = 1, and l_2 = 0.1. Due to limited paper length, we only present results for exponentially distributed L_2 here. The aggregated SU throughput is defined as the sum throughput of all SUs in one particular channel. Similarly, the aggregated collision probability is the collision probability observed by the PU. For comparison, we introduce a One-Band-One-Secondary system (OBOS), where the SU has the same average packet length l_2 and the collision constraint of the PU is equal to the aggregated collision probability in the multi-band competitive system. Fig.2 illustrates the aggregated throughput of M SUs and the collision probability of the PU when N = 1. We can see that, for fixed l_2 and under the same collision probability, the aggregated throughput of M SUs is the same as the throughput of the SU in an OBOS system. In other words, given the same collision probability constraint, the system with multiple SUs has no throughput loss/gain. This is reasonable, because there is no collision between SUs under perfect sensing. Since SUs are homogeneous, each SU achieves an equal fraction (1/M) of the total throughput. We can also observe that collision probability caused by one individual SU with M>1 is less than the collision probability with M=1. This is due to the lower probability of the channel being idle from the perspective of one SU. Additionally, as perfect sensing is assumed, an SU can detect there is no collision between SUs under perfect sensing. Since SUs are homogeneous, each SU achieves an equal fraction (1/M) of the total throughput. We can also observe that collision probability caused by one individual SU with M>1 is less than the collision probability with M=1. This is due to the lower probability of the channel being idle from the perspective of one SU. Additionally, each SU contributes proportionally to the collision probability of the PU, demonstrated by the almost linear increase of P_1^c with respect to M.

Next, we test a more general case where there are M SUs and N primary bands with M = 3N. Note that the primaries' activities are i.i.d., and all SUs behave in the same way, the performance is the same for all channels. Therefore, we only show the results for one of N channels here. The aggregated throughput of SUs and collision probability in each channel for Random-Sensing and All-Channel-Sensing strategies are shown in Fig.3. The results show that, the aggregated throughput of SUs for both sensing strategies matches very well with the throughput in the OBOS system under the condition that they have the same collision probability for each channel. If we adjust the values of l_2 and v_2, such that the aggregated collision probabilities caused by Random-Sensing and All-Channel-Sensing strategies are the same, then they will have the same throughput. This indicates that, All-Channel-Sensing strategy does not improve the total spectral efficiency, despite the added complexity. This is mainly due to the memoryless characteristics of the idle time, rather than the limitation that each SU can access one channel each time. We also observe that, without dividing the available bands explicitly among multiple SUs, the autonomous random access performs the same as the coordinated method of organizing SUs into separate groups, each assigned a group of spectral bands. This is the main idea used in the paper to propose a MAC layer protocol in order to increase the throughput of SUs.

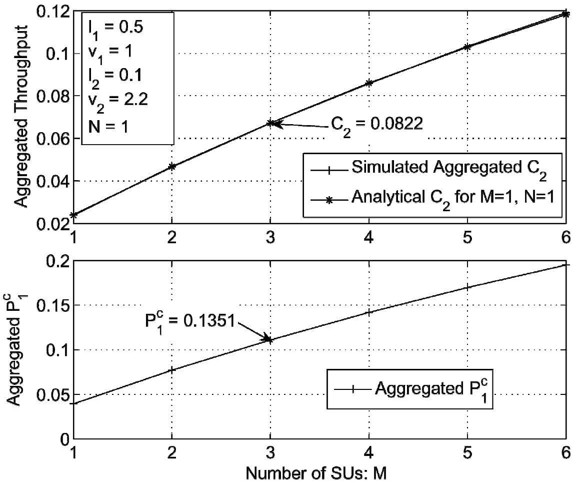

Fig. 2: Aggregated Throughput of SUs in VX scheme.

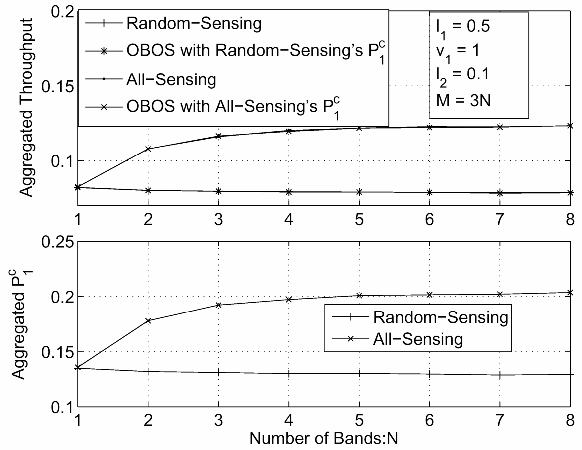

Fig. 3. Aggregated Throughput of SUs with Multiple Primary Bands.

As a summary for multi-band multi-user systems, we have:

- For the same collision probability constraint, the system with multiple SUs has no loss/gain in terms of total throughput. Under the same collision probability constraint, sensing all the frequency bands does not improve the total throughput of SUs.
- Dividing SUs into groups to access partitioned bands has the same throughput as the strategy of allowing each SU to randomly access all bands.

STATISTICAL CHANNEL ALLOCATION

According to the points of spectrum access mentioned above, here we propose another aspect of cognitive radio as channel aggregation. We will solve the problem of "Which Channels to Use" by means of past swaths of the PUs. Studying the history of primary users' manner in the past is useful in predicting the future positions. We have a look at Statistical Channel Allocation MAC (SCA-MAC) as a glimpse. To allocate channels such that the interference to the primary service is bounded below an acceptable level, we should evaluate the successful rate of any transmission before it takes place. Channel aggregation and the packet length affect the transmission successful rate. For cognitive radio, the total number of available channels and the number of potential combinations can be very large. Thus, we need to set some parameters and rules to lower the complexity.

1) Optimum Operating Range:

Although it is straightforward to calculate the successful rate of a single channel, the complexity to evaluate all available combinations could be significant for a wide range of operating spectrum. To reduce such a complexity, we introduce a parameter r, called the operating range to specify the proper spectrum range that a node would search for transmission opportunities. It is a parameter related to the level of availability of spectrum holes. A CR device can dynamically change its operating range. If the spectrum is crowded and finding a roomy enough spectrum hole is difficult, the CR device may increase its operating range, and vice versa. To decrease the level of overlapped operating ranges among neighboring nodes, we can use some algorithm based on device's MAC address to spread the central channels of devices over the whole spectrum. Such a technique achieves spectrum load balancing nicely, and largely prohibits neighboring nodes from selecting the best but the same opportunity, which causes unwanted collision or renegotiation.

2) Maximum Channel Aggregation:

By transmitting over multiple channels simultaneously, we can decrease the transmission time and increase the successful rate. According to Shannon's channel capacity formula, channel capacity W is proportional to bandwidth B, W=B.Log2(1+SNR) Thus, we can get m fold shrinkage on transmission time with m channels aggregated together.

3) Closest Possible Opening:

An idle channel is normally the first choice. However, a higher successful rate may require a CR device to wait for some channels to become idle. Intuitively, if several similar opportunities coexist, we prefer the opportunity that demands the shortest waiting time. As a result, we should judge each opportunity by its successful rate α based on collected channel statistics, and employ a successful rate threshold, α_T , to bound the interference to the primary service to be under 1- α_T . This bound guarantees that the interference is within the tolerance and will result in no noticeable impact on the QoS of primary users.

SUCCESSFUL RATE PREDICTION

In this section, we evaluate the successful rate of a channel for the prediction purpose. It consists of two subproblems: the probability of successful channel allocation within the operating range and the probability that the spectrum hole on allocated idle channels can accommodate the specific incipient packet. They deal with the following two problems, respectively: 1) the probability of collision with another CR devices in an available channel, and 2) the probability of interference to the primary service by studying the packet length and the spectrum hole duration. In the following analysis, we use r to denote the dynamic operating range, n the number of neighboring nodes, and m the number of data channels in channel aggregation for the transmission opportunity under evaluation. Furthermore, τ denotes the utilization of the primary service, $\overline{\tau}_C$ denotes the average utilization of neighboring nodes, and $\overline{m}$ denotes the average channel aggregation of neighboring nodes.

Channel availability, α_C

Parameter α_C represents the probability of successful channel allocation within the operating range of the receiver. The expected number of idle channels is (1- τ)r while the expected number of channels occupied by CR devices is $\alpha_C .n.\overline{m}$. Then, their ratio is the probability of collision with neighboring CR nodes. With the consideration of channel aggregation, we obtain:

$$\alpha_C = (1 - \frac{\overline{\tau}_C .n.\overline{m}}{(1\text{-}\tau)r})^m$$

Spectrum Hole sufficiency α_L

Parameter α_L represents the probability of a specific packet of length L can fit the spectrum hole of duration T on channel i with statistics C_i in terms of transmission time. For example, channel C_1 has been idled for time t_0, the probability that it will remain idle for another L period can be written as:

$$p(C_1 : T \geq t_0 + L \mid T \geq t_0) = \frac{p(C_1 : T \geq t_0 + L)}{p(C_1 : T \geq t_0)}$$

Then, by considering channel aggregation of channel i to channel i + m - 1, we can get

$$\alpha_L = \prod_{j=i}^{i+m-1} p(C_j : T \geq t_{0,j} + \frac{L}{m} \mid T \geq t_{0,j})$$

By combining equations above, the successful rate for a packet of length L to be transmitted on channels i to i+m¡1 can be written as:

$$\alpha([i, i+m-1], L) = \alpha_C . \alpha_L$$

For all idle channels and their combinations with maximum channel aggregation m_t within operating rage r, we can calculate their successful rates and then select the highest one as the prediction to the successful rate:

$$\upsilon_2 = \max\left\{0, \frac{\upsilon_1 l_2}{\eta(\upsilon_1 + l_2)} - l_2\right\}$$

The complexity of exhaustive search is $\frac{r(r+1)}{2}$. However, by excluding channels that are currently occupied, the complexity is reduced to $\frac{(1-\tau r)(2-\tau r)}{2}$. This is an upper bound since available channels may be separated. We see from above equations that the successful rate highly depends on operating range r, channel aggregation m and packet length L, which can be controlled by a CR device. Besides, the successful rate also depends on the number of neighboring nodes n and channel statistics C_i. The predicted and simulated successful rates α are plotted as a function of operating range r and channel aggregation m in Figs. ****, respectively, where all channels are assumed to be equally likely with the same statistical parameters.

SIMULATION RESULTS

Our simulation environment consists of one primary service network and one cognitive radio network which runs SCAMAC in proximity. The channel is equally divided into 100 subchannels. Instead of a specific system, we implemented a general primary service which has following properties. Each primary service device transmits its packets over the channel without channel sensing. The packet arrival rate of primary users is exponentially distributed, and so is the packet length. Moreover, we assumed the number of primary users is sufficiently large. As a result, the overall access pattern is expected to be in normal distribution due to the central limit theorem and each subchannel would have similar statistics in terms of average idle/busy time. We also represented the user experience of primary user in term of packet error rate (PER). Although the fixed payload length is adopted in simulation, the actual transmission time varies due to the possibility of channel aggregation. We set the successful rate threshold α_T to 0.9, which means it transmits only when the predicted successful rate is higher than the threshold. Otherwise, the CR device renegotiates for a better opportunity. This limits the expected interference to the primary service to be 1-α_T = 0.1. The utilization of primary service is chosen to be τ = 0.5.

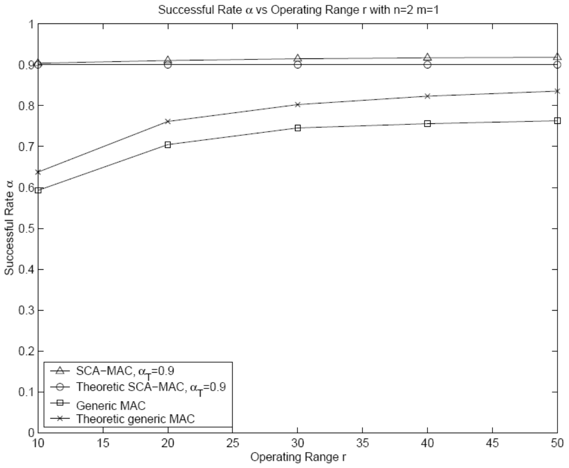

Fig. 4. Analytical and simulated results of successful rate α as a function of operating range r at τ = 0.5.

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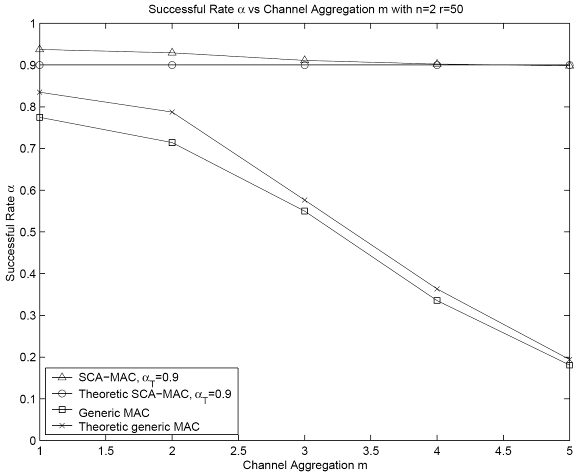

Fig. 5. Analytical and simulated results of successful rate α as a function of channel aggregation m at $\tau = 0.5$.

Although there may be unused gaps in the spectrum between different primary services in reality, all subchannels are assumed to be occupied to test the extreme case in simulation. Since the collision between primary users is not our concern, we assume no collision among primary services. All CR devices adopt SCA-MAC and every device is a neighbor node to one another. It is assumed that there is always a packet to transmit for each CR device. Concurrent transmission of a CR device with primary service is possible as long as they are on different subchannels. Otherwise, collision and interference would take place. For performance benchmarking, we have implemented a simple cognitive MAC, which has no channel prediction and no guarantee on interference. It simply selects an idle channel (or channels) to transmit randomly. We show analytical and simulation results of the successful rate and the throughput with respect to operating range r in Fig. 4 and with respect to channel aggregation m in Fig. 5. All simulation data plotted in Figs. 4 and 5 are the averaged results of at least 20 runs. A larger operating range gives the CR device higher flexibility on opportunity selection and a higher probability on finding qualified ones. Thus α increases as r increases for the simple MAC as shown in Fig. 4. The proposed SCA-MAC outperforms the simple MAC in all operating ranges. The performance gap becomes more obvious when the operating range is smaller.

We see from Fig. 5 that α decreases as m increases for the simple MAC. This can be explained as follows. In the simulation, we implemented a general primary user access pattern in which each subchannel has resembled statistics in terms of average idle/busy time. However, their idle periods do not begin and end at the same time. Thus, even higher channel aggregation could shorten the transmission time by several fold, the benefit of channel aggregation does not offset the potential retransmission overhead incurred by the unsynchronized channel access. In contrast, our SCA-MAC protocol always maintains the success rate at the desired level and the throughput at a level higher than that of generic MAC due to the prediction of spectrum opportunities. If a primary service has a high level of synchronized channel access, a higher improvement could be achieved.

CONCLUSIONS

- A cognitive MAC using Statistical Channel allocation, called SCA-MAC, was proposed in this work. An analytical model was developed to explain its performance. To fully exploit the spectrum-time-space opportunity, we introduced couple controllable parameters, the operating range and the channel aggregation. Computer simulation was conducted to demonstrate the superior performance of SCA-MAC over that of a simple cognitive MAC.
- VX and KS schemes have indistinguishable throughput for the SU under the same collision probability constraint. Therefore, insistent sensing in KS scheme does not help. The main reason is that the idle period of channel, V1, is exponentially distributed and the SU has to guarantee the collision probability.
- For VX scheme, an upper-bound of the throughput of the SU is $C \leq \eta\alpha$. We conjecture that this upper-bound is valid for any access schemes that exploit the idle time of a memoryless channel without coordination from the PU under the collision probability constraint.
- For a large range of packet length l_2, fixed length packet achieves the best capacity over other packet length distributions.

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