A Cognitive MAC Protocol Using Statistical Channel Allocation for Wireless Ad-hoc Networks

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***Abstract*— The MAC protocol of a cognitive radio (CR) device is supposed to enable the device to dynamically access unused or under-utilized spectrum without (or with minimal) interference to primary users. To fulfill such a goal, we propose a cognitive MAC protocol using statistical channel allocation and call it SCA-MAC in this work. SCA-MAC is a CSMA/CA-based protocol, which exploits statistics of spectral usage for decision making on channel access. For each transmission, the sender negotiates with the receiver on transmission parameters through the control channel. A model is developed for CR devices to evaluate the successful rate of the transmission. A CR device should pass the threshold of the successful transmission rate via negotiation before it can begin a valid transmission on data channels. The operating range and channel aggregation are two control parameters introduced to maintain the MAC performance. To validate our ideas, we conducted theoretical analysis and simulations to show that SCA-MAC does improve the throughput performance and guarantees the interference to incumbents to be bounded by a predetermined acceptable rate. The proposed MAC protocol does not need a centralized controller, as the negotiation between the sender and the receiver is performed using the CSMA/CA-based algorithm.**

I. Introduction

There is a significant amount of unused space (or white space) in the licensed radio spectrum due to non-uniform spectral demand in time, frequency and space and static spectrum allocation policies widely used today. Studies sponsored by FCC in [1] show that over 70% of the allocated spectrum is not in use at any time even in a crowded area where the spectral usage is intensive. On the other hand, the remaining portion of the unlicensed spectrum (*e.g.* the ISM band) is being exhausted by emerging wireless services and applications, leading to the so-called *spectral scarcity* problem. One solution to this problem is to allow unlicensed spectrum users to use the white space and keep the interference to licensed users below an acceptable level. This is called the *dynamic spectrum access* (DSA) scheme, which can be realized by cognitive radio (CR) techniques [2]–[5].

A CR device monitors a swath of spectrum including those occupied by licensed services and attempts to identify the "white" space (or the spectrum hole), which is referred to as the idle period between consecutive accesses of licensed users, and exploits it for communication at that specific geographical location. A CR device obeys the following two principles. First, it has to confine its harm within a stipulated upper bound to preserve the quality of services (QoS) of licensed users to a certain degree when borrowing the licensed spectrum. Second, it has to coexist with other spectrum agile radios or with existing open spectrum systems whether they have the coexistence mechanism or not [6]. In this work, we use *interference* to refer to overlapped transmission incidents between cognitive radio and the primary service, and use *collision* for overlapped transmission incidents among CR devices. Even though quite a few CR research efforts have been reported in the past, there is still a lot of work to be done before reaching the goal of full cognitive and adaptive software defined radio, which is also called Mitola radio [7].

To address the interoperability issue and achieve higher efficiency of spectrum utilization, we propose a CSMA/CA-based cognitive MAC protocol using statistical channel allocation (SCA) for wireless ad hoc networks. It is therefore called SCA-MAC. The proposed protocol allows CR devices to do real-time opportunistic access to any continuous part of the spectrum, licensed or not. The CR device gains intelligence by sensing the environment and collecting the statistics of spectrum usage. Based on the statistics, the probability of successful transmission can be increased and the probability of interference to licensed users can be reduced. As a result, SCA-MAC can use the spectrum hole effectively to improve spectrum efficiency with little deterioration on the performance of coexisting licensed users. Computer simulation will be provided to demonstrate the superior performance of SCA-MAC.

The rest of this paper is organized as follows. Related previous work is reviewed in Sec. II. The proposed SCA-MAC protocol and its features are described in Sec. III. The prediction of the successful rate of the proposed protocol is conducted in Sec. IV while the corresponding throughput is analyzed in Sec. V. Then, theoretical analysis is validated by simulation results in Sec. VI. Finally, concluding remarks are given in Sec. VII.

II. Review of Previous Work

One of the most challenging tasks in developing DSA networks is the design of cognitive medium access control (MAC) protocols. This is especially true in developing decentralized cognitive MACs. There have been several decentralized cognitive MACs proposed in the literature. An optimal DC-MAC and a suboptimal greedy DC-MAC along with an analytical framework were studied in [8]. The framework includes three components: 1) a channel occupancy model that captures the dynamics of channel availability; 2) a performance metric that guides the design of MAC strategies, and 3) a method that makes decision on selecting a channel to sense and access. The optimal DC-MAC was optimized based on the partially observable Markov decision process (POMDP), and the suboptimal solution of lower complexity was derived based on a greedy algorithm. The decision on channel selection in [8] was made upon the slotted time basis. However, there is no guarantee that the channel is slotted in reality since synchronization among all CR devices is an extremely difficult and challenging job in ad-hoc networks. To exploit the unused space, it is essential to estimate the length of the spectrum hole. This is why the statistical analysis of spectrum utilization is needed.

A tri-band protocol, called the dynamic open spectrum sharing (DOSS) MAC, that employs the control band, the data band and the busy-tone band was proposed in [9]. This protocol allows CR devices to negotiate in the control band, and then send data through any continuous fraction of the data band. The hidden/exposed node problem can be eliminated by raising the busy-tone signal in the busy-tone band. DOSS MAC provides a scalable real-time efficient spectrum allocation solution. However, multiple radio transceivers are needed for the tri-band design. There is also concern on interoperability with existing open band 802-family wireless devices.

A cognitive MAC protocol based on opportunistic spectrum access (OSA) [3] was proposed in [10]. A testbed was set up to characterize the relationship between secondary users' loading and interference on primary users. However, important issues such as the impact of secondary user's spectrum utilization upon primary user's carrier sensing, the MAC protocol overhead, secondary on secondary user interference were not addressed.

III. Proposed SCA-MAC Protocol

There are several desired features for an efficient cognitive MAC protocol. First, it should be able to predict future spectrum usage based on statistics of local spectrum utilization up to the current time instance. To implement this feature, a CR device should monitor the spectrum usage continually to maintain an accurate view of spectrum utilization. Second, it can bundle several continuous idle channels from a wide spectrum hole to speed up data transmission. Third, it should be a distributed algorithm so as to be employed in ad-hoc networks.

The proposed SCA-MAC protocol is designed to possess the above three properties. It is a CSMA/CA-based protocol so that it is a distributed algorithm by nature. It is also designed to allow channel aggregation. To control the influence on the QoS of primary users, SCA-MAC can evaluate its impact in real time, which means it can predict the successful rate based on the incipient packet length and collected statistics to make decision among alternative choices.

A. Overview of SCA-MAC Protocol

The proposed SCA-MAC protocol consists of three major operations: (1) environment sensing and learning, (2) CRTS/CCTS exchange over the control channel, (3) DATA transmission and ACK over data channels. These operations are detailed below, and an example is shown in Fig. 1.

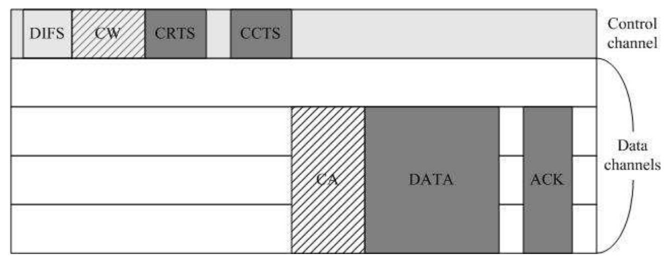


Fig. 1. An illustrative example of the SCA-MAC protocol.

1) Environment Sensing and Learning: One way to learn about the environment is achieved by extensive spectrum sensing. For cognitive radio, it is not just ordinary spectrum sensing, but sensing with broadband capability and narrowband resolution. For example, a CR device should sense a swath of spectrum in one shot and discover the detail utilization information of spectral partitions. Such advanced spectrum sensing technology is crucial to the success of CR devices. It is feasible via a DSP technique called the cyclostationary feature detection [11]. An alternative way to acquire such high resolution broadband utilization information is through successive partial sensing, *i.e.* one fraction of the spectrum after another randomly or sequentially. Naturally, the latter takes longer time to finish spectrum sensing and the information may not be up-to-date.

Sensing is performed continuously and periodically. The sensing period is predefined but adjustable. Upon activating the protocol, a run length of the idle/busy period is maintained for each channel. When the idle duration is ended by a transmission incurred by the primary user, the run length is recorded in a circular buffer, *e.g.* a circular buffer of size 1000 records the run length of the last 1000 idle periods. These spectrum holes are opportunities that CR devices can use. These records provide the statistics of each channel and help the device make decision on intelligent channel allocation with bounded interference.

2) CRTS/CCTS Exchange over Control Channel: Generally speaking, a CR protocol attempts to align transmission in spectrum holes inside the accessible spectrum. When the channel access is opportunistic, we have to determine which channel a sender should use to communicate with the receiver in the first place, which demands a mechanism to initiate the transmission. Here, we introduce a control channel that provides a common channel for initiation hand-shaking. The access to this single control channel is implemented by the CSMA/CA mechanism so that our protocol is still a decentralized one. A careful design can resolve the control channel saturation problem [12].

When a CR device wants to initiate a transmission, it follows the standard CSMA/CA protocol to access the control channel to negotiate with the receiver. To be more specific, the sender listens to the control channel and waits until it becomes idle. Then, it waits for the channel to remain idle for another DIFS duration before it begins the countdown of the contention window (CW). If the channel is still idle after the contention window period, it transmits a Control-channel-Request-To-Send (CRTS) packet. Upon receiving CRTS, the receiver screens the potential transmission opportunities based on its own statistics and the current channel status, and then replies with a Control-channel-Clear-To-Send packet (CCTS) which contains the information of the best opportunity. If there is a collision on CRTS or CCTS, the sender would repeat the negotiation process but double the contention window size. The channel allocation mechanism will be described in the next section. In short, the control packets carry the information of channel aggregation and packet length, whose expected successful rate meets the interference threshold. Renegotiation is needed if no choice satisfies the interference threshold.

A parameter carried by CCTS has to be specified. It is the collision avoidance (CA) window for the coming transmission on the data channel. This backoff window is designed to reduce the probability of collision resulted by two transmission pairs that happen to select the same or overlapped data channels for transmission. Even though the basic idea is borrowed from CW in CSMA/CA, it is adopted by our protocol here because of its desired property. We assume that the number of neighboring nodes of the receiver is n, which can be obtained from CCTS. Then, the sender assigns CA according to

$$N = |CA| = \begin{cases} 2 & , n = 0, \\ 2^n & , 1 \leq n < 5, \\ 32 & , n \geq 5. \end{cases} \quad (1)$$

because the probability of collision at the receiver highly depends on n. This CA window is only related to n at the receiver side, and will not change with respect to the count of retransmission.

3) DATA/ACK Transmission over Data Channels: Once CRTS/CCTS have been successfully exchanged, the sender and the receiver will tune their transceivers to the agreed data channels. The sender begins the countdown of a counter randomly selected from the range of the CA window received via CCTS. If the channel is still idle upon the end of countdown, the sender begins the DATA transmission. If data are successfully received, an ACK will be sent by the receiver after SIFS. If some other node acquires the channel before the end of countdown, the sender has to go back to the control channel to renegotiate. The transmission is considered done after ACK is successfully received. If the transmission failed (*e.g.*, no ACK received), the sender has to go back to the control channel for negotiation again.

B. Statistical Channel Allocation

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 re-negotiation.

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, *i.e.*, $W = Blog_2(1 + SNR)$. 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 $1 - \alpha_T$. This bound guarantees that the interference is within the tolerance and will result in no noticeable impact on the QoS of primary users.

IV. 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 $(1-\tau)r$ while the expected number of channels occupied by CR devices is $\overline{\tau_c} \cdot n \cdot \overline{m}$. Then, their ratio is the probability of collision with neighboring CR nodes. With the consideration of channel aggregation, we obtain

$$\alpha_c = (1 - \frac{\overline{\tau_c} \cdot n \cdot \overline{m}}{(1-\tau)r})^m. \quad (2)$$

- 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

$$p(C_1 : T \geq t_0 + L | T \geq t_0) = \frac{p(C_1 : T \geq t_0 + L)}{p(C_1 : T \geq t_0)}. \quad (3)$$

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

$$\alpha_L = \prod_{j=i}^{i+m-1} p(C_j : T \geq t_{0,j} + \frac{L}{m} | T \geq t_{0,j}). \quad (4)$$

By combining Eqs. (2) and (4), the successful rate for a packet of length L to be transmitted on channels i to $i+m-1$ can be written as

$$\alpha([i, i+m-1], L) = \alpha_c \cdot \alpha_L. \quad (5)$$

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:

$$\alpha(r, m_t) = \max_{\forall m \in [1, m_t], \forall i \epsilon [0, r-m]} \{\alpha([i, i+m-1], L)\}. \quad (6)$$

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 Eqs. (2)-(6) that the successful rate highly depends on operating rage 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. 2(a) and 3(a), respectively, where all channels are assumed to be equally likely with the same statistical parameters.

V. Throughput Analysis

To analyze the throughput, we first analyze the collision and the interference phenomena of the SCA-MAC protocol. Since the control channel occupies the spectrum without any primary service, there is no interference. All CRTS/CCTS failures are caused by collision among neighboring nodes and it will incur renegotiation over the control channel. The average negotiation time, $\overline{T_c}$, in the control channel can be calculated as

$$\overline{T_c} = DIFS + \overline{CW} \times T_{slot} + T_{CRTS} + SIFS + T_{CCTS}. \quad (7)$$

We use p_c to denote the collision probability on the control channel. Then, $E[R_c] = \frac{p_c}{1-p_c}$ is the expected number of renegotiation due to such a collision. Renegotiation is also needed if no agreement is reached after the exchange of CRTS and CCTS. This is denoted by R_c'.

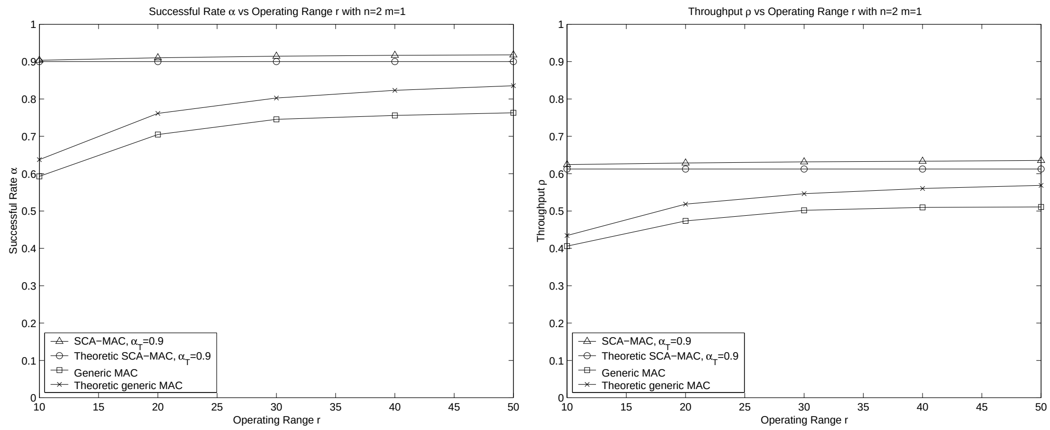
The cases with the data channel are more complicated. Despite prediction, there is still a probability that a transmission is corrupted by an early primary service access, which causes mutual interference, or by some neighboring CR device that chose the same CA counter. Either case will trigger a renegotiation and a retransmission. The average time for a successful transmission, $\overline{T_s}$, on the data channel is

$$\overline{T_s} = \overline{CA} \times T_{slot} + \overline{T}_d + SIFS + T_{ACK}. \quad (8)$$

The time required for a retransmission over the data channel is the same as that for a successful transmission, *i.e.* $T_r = T_s$. Unlike the CW on the control channel, CA does not change with the retransmission count. It only reflects the local spectrum usage. With the predicted successful rate α, the expected number of retransmission is equal to $E[R_d] = \frac{1-\alpha}{\alpha}$.

In addition to the above cases, there is another scenario. That is, when some CR device is in the middle of CA, another device acquires the idle channel first. Then, the current CR device will dismiss the countdown and renegotiate for another opportunity. Thus, a collision and the retransmission process can be avoided due to the use of the collision avoidance mechanism. We use p' to denote the data channel collision avoidance possibility and $E[l]$ the expected number of waiting time slots before finding that a channel is occupied. Then, the expected number of renegotiation caused by collision avoidance is

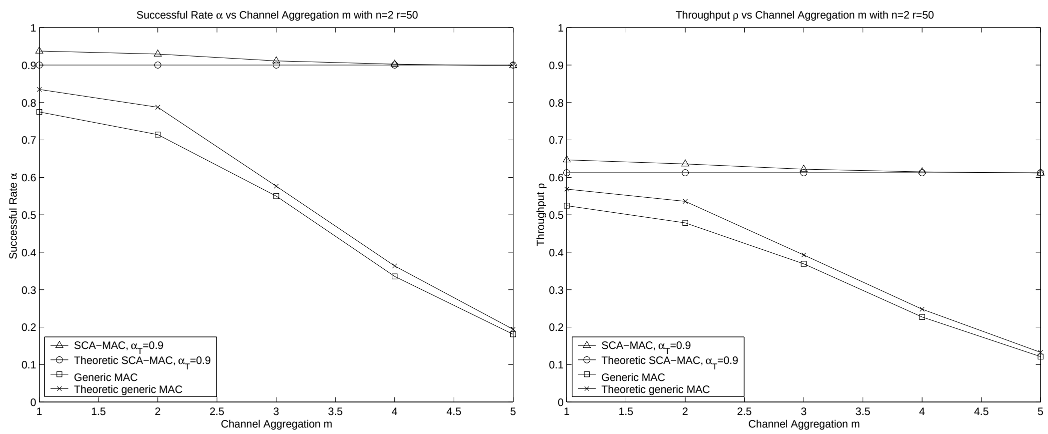
$$E[R_{ca}] = \frac{p'}{1-p'},$$



(a) Successful Rate α vs. Operating Range r with $(n, m) = (2, 1)$

(b) Throughput ρ vs. Operating Range r with $(n, m) = (2, 1)$

Fig. 2. Analytical and simulated results of successful rate α and throughput ρ as a function of operating range r at $\tau = 0.5$.



(a) Successful Rate α vs. Channel Aggregation m with $(n, r) = (2, 50)$

(b) Throughput ρ vs. Channel Aggregation m with $(n, r) = (2, 50)$

Fig. 3. Analytical and simulated results of successful rate α and throughput ρ as a function of channel aggregation m at $\tau = 0.5$.

where $p'(k) = \frac{k}{N}$, $k = 0, 1, 2, \cdots, N-1$, and $p' = E[p'] = \frac{(N-1)}{2N}$, and

$$E[l] = \frac{1}{N} \sum_{k=0}^{N-1} l(k) = \frac{n(N-1)(N-2)}{6N},$$

where $l(k) = \frac{n}{N} \sum_{i=0}^{k-1} i = \frac{nk(k-1)}{2N}$. Then, the expected transmission time on control channel $T_{control}$ and data channel T_{data} for a packet are equal to

$$\begin{aligned} E[T_{control}] &= (1 + E[R_c] + E[R'_c] + E[R_{ca}] + E[R_d])\overline{T_c}, \\ E[T_{data}] &= E[R_{ca}]E[l]T_{slot} + (1 + E[R_d])\overline{T_s}, \end{aligned}$$

respectively. With all parameters available, we can determine the throughput of the data channel as

$$\rho = \frac{\overline{T_d}}{E[R_{ca}]E[l]T_{slot} + (1 + E[R_d])\overline{T_s}}. \tag{9}$$

The predicted and simulated throughput values ρ are plotted as a function of operating range r and channel aggregation m in Figs. 2(b) and 3(b), respectively.

VI. Simulation Results

Our simulation environment consists of one primary service network and one cognitive radio network which runs SCA-MAC 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 $1 - \alpha_T = 0.1$. The utilization of primary service is chosen to be $\tau = 0.5$. Other system parameters are shown in Table I.

Parameter	Assigned Value
PHY header	192 bits
MAC header	224 bits
Slot_time	20 μs
DIFS	50 μs
SIFS	10 μs
CRTS	160 bits
CCTS	112 bits
CW_{min}	32
CW_{max}	1024
CA	Eq. 1
Payload	11000 bits
ACK	112 bits
α_T	0.9
subchannel #	100
τ	0.5

TABLE I
PARAMETERS OF CONTROL AND DATA CHANNELS.

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 theoretical and simulation results of the successful rate and the throughput with respect to operating range r in Fig. 2 and with respect to channel aggregation m in Fig. 3. All simulation data plotted in Figs. 2 and 3 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 and ρ increase as r increases for the simple MAC as shown in Fig. 2. 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. 3 that α and ρ decrease 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.

VII. CONCLUSION

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.

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