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A Cognitive CSMA-based Multichannel MAC Protocol for Cognitive Radio Networks

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***Abstract*—Multichannel media access control (MAC) protocols have been widely considered for future mobile ad hoc networks and various wireless data networks. However, ALOHA-based protocols have been extensively studied in current researches for their simplicities both in design and analysis. To cope with co-existing multiple systems under the cognitive radio (CR) paradigm, we introduce the cognition capability and CSMA into multichannel MAC protocol, along with learning functionality of CR and a multichannel stabilization mechanism. Via facilitating spectrum sensing, cognition and adaptation for probability of transmission attempt optimize the proposed cognitive CSMA-based multichannel MAC protocol. Simulation results validate our analysis of steady-state approximation and suggest a pertinent throughput improvement over existing multichannel MAC protocols.**

I. INTRODUCTION

Multichannel MAC protocols have been widely considered to utilize multiple orthogonal channels for throughput improvement by allowing parallel transmissions. In mobile ad hoc networks, two major engineering challenges of multichannel MAC are collision avoidance/resolution and channel access negotiation. Collision avoidance/resolution [1] is inherited from conventional MAC. Devices must avoid simultaneous transmission and resolve further possible transmission failure after collision happens. On the other hand, channel access negotiation which considers distributed channel selection of communication pairs is the new challenging issue which recently attracts most efforts [2]–[6]. Before transmission, the transmitter and the receiver must find a way to locate each other and negotiate the channel for communication. By utilizing a common hopping group [2] or splitting time into control and data phases (i.e. split-phase protocol) [4], single transmission can be ignited in one slot/frame. As discussed in [5], with multiple orthogonal channels, a promising feature of multichannel MAC protocol is the capability to igniting parallel transmissions to improve the system throughput. A reserved dedicated control channel [3] or random hopping [6] are possible solutions. However, current researches are flawed in the requirement of a dedicated control channel and the lack of joint consideration in collision avoidance/resolution and channel access negotiation.

A more challenging scenario lies in co-existing multiple wireless networks, such as dynamic channel access in cognitive radio network (CRN) [7]. In CRN, CRs are categorized as secondary users who sense for the spectrum/channel opportunity and access the channel with a lower priority in comparison to primary system (PS) users. Since CR and PS belong to different systems, for these devices to coexist with each other while sharing the common media, a feasible multichannel MAC protocol for CRN is required to resolve not only intra-system (within CRN) but also inter-system (CR-PSs) media contention.

In this paper, a cognitive CSMA-based multichannel MAC protocol is proposed to meet these challenges. By evolving McMAC [6] from the ALOHA-based protocol, intra-system media contention is alleviated by CSMA mechanism. With the capability of CR to perform spectrum sensing and avoid channel access, the proposed multichannel MAC protocol is capable of coexisting with PSs. Moreover, a seeded random channel selection mechanism is proposed for CRs to ignite parallel transmissions over multichannel and hence improves the system throughput.

To further optimize the throughput performance under all network conditions, we develop a multichannel stabilization mechanism. Under the CR paradigm - a multichannel environment with diverse channel capacities and different PSs' behavior, the stabilization mechanism differs from conventional single channel mechanism [8], [9]. Intra-system (within CRN) information: the load distribution over multiple channels and inter-system (CR-PSs) information: behavior of PSs is required for throughput optimization.

In this paper, we realize the foresight in [10] that CR "senses" the environmental information to "adapt" for better MAC performance. We develop two *cognitive* functions including 1) *sensing* function that extracts and cognises inter-system and intra-system information and 2) *adaptation* function that utilizes the cognizant information to adapt the multichannel MAC to achieve a significant throughput improvement. These two *cognitive* functions fulfill the original expectations of CR in [7] that devices may learn (i.e., sense and adapt) from the environment. To our best knowledge,

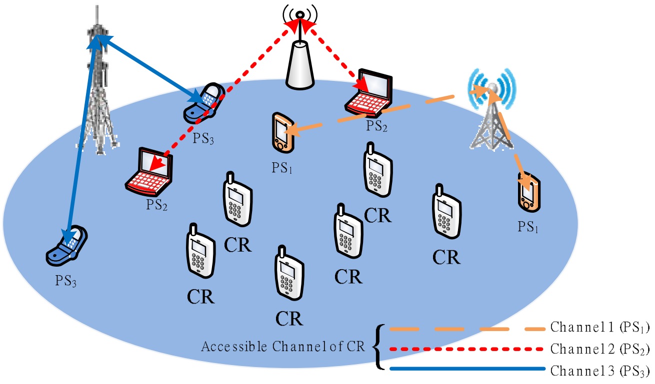

Fig. 1. MAC under CRN paradigm

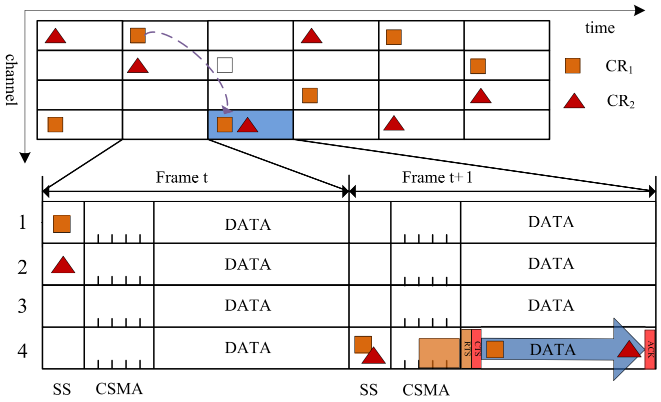

Fig. 2. Cognitive CSMA-based McMAC protocol for CRN

it is the first CSMA-based multichannel MAC protocol with cognitive capability.

The contribution of this paper lies in the integration of cognitive capability of CR in multichannel MAC protocol design, including sensing, contention alleviation and throughput optimization. Section II describes the system model and the proposed protocol. In Section III, we model, analyze and provide a steady-state throughput approximation. CSMA stabilization and performance optimization is developed in Section IV. Simulation results are discussed in section V. Conclusion and future work are presented in section VI.

II. COGNITIVE CSMA-BASED MULTICHANNEL MAC PROTOCOL FOR CRN

A. System Model

We consider a 1-hop fully-distributed synchronous ad-hoc network similar to [5]. As shown in Fig. 1, we further extend and generalize the multichannel scenario under the CR paradigm. The generalized multichannel scenario is characterized by: $\{M, N, \mathbf{q}, \mathbf{C}\}$. M is defined as the number of multichannel while N indicates the number of CRs in the CRN. Each channel is supposed to be independently utilized by some PS. We model the channel as a discrete two-state (on/off) Markov chain. CR may access the channel if there is no PS appearance and vice versa. The availability of a channel can thus be represented as a Bernoulli random variable with parameter q_k, where k is the channel index. We define $\mathbf{q} \triangleq \{q_k | k = 1, 2 \ldots M\}$ as the set of probabilities of PSs' appearance over channel $1 \ldots k$. If PS appears, CR must not access the channel in prevention of interference with PS. Without losing generality, channels are supposed to have different capacities. The last term $\mathbf{C} \triangleq \{C_k | k = 1, 2 \ldots M\}$ is defined as the capacities over channel $1, 2, \ldots M$.

Suppose that each CR is equipped with only one radio and there is no reserved control channel for CRN. Therefore, at a given time, CR can only transmit/receive on one determined channel. Moreover, without a reserved control channel, the decision of the transceiving channel is made in a distributed manner. That is, CR transmitter must predict and locate its CR receiver and negotiate with it before transmission. If more than one CR communication pair simultaneously transmit over the same channel, their packets collide and transmissions fail. The aim of design of multichannel MAC for CRN is to (i) efficiently utilize the multiple channels by initiating parallel transmissions, and (ii) alleviating contention within CRN. In addition, since PSs are with higher priorities, (iii) the requirement that CR transmissions are interference-free to PSs must be satisfied. In the following subsection, we design and proposed a feasible cognitive CSMA-based multichannel MAC protocol for CRN.

B. Protocol Description

The proposed cognitive CSMA-based multichannel MAC protocol for CRN is shown in Fig. 2. Time is divided into synchronized operating frames (We use the term ''frame" in comparison of slots in slotted-CSMA). Since spectrum/channel opportunity frequently varies under the CR paradigm, in the proposed protocol, transmissions are initiated and terminated within one frame in avoidance of further interference with PSs. At the beginning of every operating frame, CR firstly switches to its determined channel. Then the operating frame is further divided into three phases: the *spectrum sensing (SS) phase*, the *CSMA contention phase*, and the *data transmission phase*.

The alleviation of contention within CRN in the proposed protocol can be considered as two steps. The first step is to separate the load of CRN over multiple channels while the second step is the CSMA mechanism to resolve co-channel contention. The separation of CRs over multiple channels load is analogous to the intuition of initiating parallel transmissions. To achieve so without a reserved control channel, every CR hops over channels with a unique hopping sequence generated from a random number generator (RNG) according to its MAC address (s_i) and time (t). CR$_i$ selects channel $k = (RNG(s_i, t) \bmod M)$ at the beginning of the frame. The expected number of CRs over a channel is therefore N/M. With the same RNG, the locating channel k of CR$_i$ can be predicted with its unique MAC address s_i and time t. If there is no queued packet, CR$_i$ follows its original hopping sequence $(RNG(s_i, t) \bmod M)$. If CR is queued with packet for CR$_j$, with probability p (probability of transmission attempt), it deviates from its original hopping sequence and selects the channel where its receiver currently located ($(RNG(s_j,t) \bmod M)$) and attempts transmission.

Spectrum sensing phase is designed to alleviate the collisions between CRN and PSs. Every CR senses its currently locating channel at the beginning of the frame. CRs on the same channel shall remain silent during the operating frame if PS appears. The distinguished SS from CSMA is because of the fact that PSs have higher priorities than CRs, in addition, PSs may share different radio access technologies from CRN. Therefore, feasible spectrum sensing mechanism as in [11] for detecting the appearance of specific primary system must be properly performed.

The slotted CSMA contention phase is proposed to further alleviate intra-system contention/collision. In data transmission phase, the proposed protocol utilizes RTS/CTS/DATA/ACK four-way handshake as in IEEE 802.11 CSMA/CA.

CR shares the capability of cognition and is reconfigurable for better performance. In MAC, we facilitate the learning functionalities of CR as sensing and adaptation which aims at optimization of throughout under diverse multichannel scenarios. The *cognitive* functions in our protocol includes *sensing* (performed in every frame) and *adaptation* (periodical). The $sensing$ function is to acquire information from the environment including inter-system (PSs-CRN) information and intra-system (within CRN) information. The spectrum sensing result updates probabilities of PSs' appearance $\mathbf{q}$ which are provided as inter-system information. For intra-system information, every sent packet is embedded with the transmitter's MAC address (for RNG) with a validating time which updates CRN size N in every reception. The inter-system information and the intra-system information is provided for multichannel CSMA stabilization in *adaptation* function which periodically set the optimal probability of transmission attempt p^*. The details of *adaptation* function are presented in Section IV.

C. Protocol Operations

Based on the features described above, the detailed operations of the proposed cognitive CSMA-based multichannel MAC protocol are stated as below:

1) (Channel Selection) At the beginning of a frame, the channel k is selected if $RNG(s,t) \bmod M = 0$. Periodically set optimal p with the cognizant information. (*adaptation* function)
   a) If CR (s_T) is queued with packet(s) for a specific receiver (s_R), with probability p, set $s = s_R$.
   b) Else, $s = s_T$.
2) (Spectrum Sensing Phase) Perform spectrum sensing to detect the appearance of specific PS on its currently locating channel (k) and update the probabilities of PS appearance $\mathbf{q}$. (*sensing* function)
   a) If PS appears, update q_k and skip step (3) and (4).
   b) Else, update q_k and proceeds.
3) (CSMA-contention Phase) CR transmitter pick a backoff value between [0, N_{cw}], where N_{cw} is the contention window size. CR transmitter decrements its backoff value by one during each idle slot. In this phase, all CR(s) keeps listening.
   a) If the channel becomes busy before the backoff value reach 0, gives up transmission.
   b) Else, sets access indicator ($S = 1$).
4) (Data transmission Phase) Four-way handshake, the transmission terminates before end of frame.
   a) If($S = 1$), sends RTS. Transmit data after receiving CTS, terminates after ACK or before end of frame.
   b) If RTS is received, check and reply CTS, waiting for transmission. Transmits ACK if the data correctly received.
   c) Otherwise, remains silent until the end of frame.

CR maintains a valid MAC address table for communication. Throughout the proposed protocol, every sent packet is embedded with the transmitter's MAC address. While receiving the packet, CR sets the valid time t_v of that MAC address to the maximum valid time $t_{v_{max}}$. CRs decreases t_v by one for each passing frame and eliminates the MAC address with $t_v \leq 0$ and updates N (*sensing* function). A transmission may fail if CR gives up transmission at channel selection phase, or the selected channel is occupied by PS, or CR fails the CSMA. When transmission fails at frame t, CR re-computes its receiver's locating channel and switch to the channel with probability p at frame $t+1$.

D. Implementation Issues

There are some implementation issues of the proposed cognitive CSMA-based multichannel MAC protocol. The first one is the network initialization which is simple in realistic design. With the uniform channel selection feature from RNG, a new CR may turn on and listen to one channel for a long enough time (e.g. 10 seconds) to acquire the latest MAC address information to determine the CRN size (N) and all other CRs' seeds to compute their hopping sequences. Then the new CR starts hopping and attempts transmission to inform other CRs its existence.

Another important issue is the update of cognizant information from the $sensing$ function. Different spectrum sensing mechanisms can be utilized to optimize the probability of detection of specific PS(s) [11]. In addition, probabilities of PS appearance ($\mathbf{q}$) can be updated using Bayes formula [12] with the collection of spectrum sensing results from CR's physical layer. Other learning mechanism as in [13] can be implemented to speedup the learning rate of sensing. On the other hand, feasible adaptation timing design is also discussed in [14]. With different implementation criteria, different sensing mechanisms along with adaptation timing can be further fine-tuned for practical use.

III. PERFORMANCE ANALYSIS

In this section, we analyze the throughput performance of the proposed cognitive multichannel MAC protocol. For simplicity, we assume that all CRs are under the same multichannel environment and are synchronized. Every CR is at saturated load (i.e. CR is always queued with packet). Suppose that every CR has perfect spectrum sensing capability, that is, if a PS appears during a operating frame, it is distributedly detectable by CRs at the spectrum sensing phase. Since every CR uniformly hops over channels, the transmitters and the receivers they choose are uniformly distributed over multichannel. Therefore, we can change from exactly analyze channel dynamics to analyze the averaged and symmetric behaviors of CRs using indicator functions.

We apply a steady-state approximation approach introduced in [12] to analyze the protocol performance. Define X_i as the indicator of transmission attempt of CR$_i$; K, A, B as the random variables denoting the selected channel, simultaneous transmitters (including CR$_i$), and other co-channel ($K = k$) transmitters in the same operating frame, respectively. We use S as the (winning) channel access indicator of CSMA phase; F as the indicator of successful receiver discovery. For CR$_i$ to successfully transmit its packet, the following conditions must hold:

1) CR$_i$ decides to transmit. ($X_i = 1$.)
2) The selected channel ($K = k$) must be free from PS appearance.
3) CR$_i$ wins CSMA contention ($S = 1$) with other $A = a$ out of $B = b$ co-channel transmitter,
4) CR$_i$ successfully discovers its receiver ($F = 1$): The receiver must not attempt to transmit or attempt but fail CSMA contention on the same channel ($K = k$).

From above, let $P_{succ}^{(i)}$ denotes the probability of successful transmission for CR$_i$. The probability of successful transmission $P_{succ}^{(i)}$ is thus conditioned on $\{F,\ S,\ B,\ A,\ K,\ X_i\ \}$:

$$\begin{aligned} P_{succ}^{(i)} &= \sum\nolimits_{a,b,k} P[F=1,S=1,B=b,A=a,K=k,X_i=1] \\ &= \sum\nolimits_{a,b,k} P[F=1|S=1,B=b,A=a,K=k,X_i=1] \\ &\quad \cdot P[S=1|B=b,A=a,K=k,X_i=1] \\ &\quad \cdot P[B=b|A=a,K=k,X_i=1] \\ &\quad \cdot P[A=a|K=k,X_i=1] \\ &\quad \cdot P[K=k|X_i=1] \\ &\quad \cdot P[X_i=1] \end{aligned} \tag{1}$$

At saturated load, CR$_i$ is always queued with packet. Therefore, the probability that CR$_i$ attempts to transmit to some receiver is p. It is clear that,

$$P[X_i = 1] = p. \tag{2}$$

With the random channel selection feature, the selected receiver of CR$_i$ is uniformly distributed over M channels. Hence, the probability that CR$_i$ selects channel k is

$$P[K = k|X_i = 1] = \frac{1}{M}. \tag{3}$$

All CRs independently make decision for transmission attempt. The probability that there are exactly a simultaneous transmission attempts (including CR$_i$) in the same operating frame becomes

$$P[A = a|K = k, X_i = 1] = \binom{N-1}{a-1} p^{a-1}(1-p)^{N-a}. \tag{4}$$

Given CR$_i$ is at channel k attempting transmission. The probability that there are exactly b co-channel transmission attempts out of $a-1$ (excluded CR$_i$) simultaneous transmission attempts in the same operating frame is

$$P[B = b|A = a, K = k, X_i = 1] = \binom{a-1}{b} (\frac{1}{M})^b (1-\frac{1}{M})^{a-b-1}. \tag{5}$$

For CR$_i$ to ''win" the channel in CSMA contention phase, the channel it selected must be free from primary system occupation and the backoff time it pick should be the smallest one of other b device. Thee contention window size is denoted by N_{cw} and we can derive:

$$\begin{aligned} &P[S = 1|B = b, A = a, K = k, X_i = 1] = \\ &\qquad (1-q_k) \sum_{n=0}^{N_{cw}-1} (\frac{1}{N_{cw}})(1-\frac{n+1}{N_{cw}})^b. \end{aligned} \tag{6}$$

CR$_i$ completes its transmission if it can find its receiver after sending RTS in the data transmission phase. To successfully replying CTS, its receiver either not attempting transmission (remaining on the predicted channel) or attempting on the same channel but failing the CSMA contention. Then, the probability of successful transmission can be obtained as:

$$P[F = 1|S = 1, B = b, A = a, K = k, X_i = 1] = \frac{N-a+b}{N-1}. \tag{7}$$

Define the multichannel frame utilization (U) as the portion of utilized channels per frame, substituting (2-7) into (1). Then the multichannel frame utilization is:

$$\begin{aligned} U &= \sum_i P_{succ}^{(i)} \\ &= N \sum_{a,b,k} P[F=1,S=1,B=b,A=a,K=k,X=1]. \end{aligned} \tag{8}$$

The second equality holds since all CRs follows a symmetric behavior and we can remove the subscript i. It should be noted that the multichannel frame utilization is comparable to the normalized throughput in convention single channel MAC which is defined as average packet successfully transmitted frame/slot (per channel).

Define the multichannel frame operation efficiencies $\boldsymbol{\eta} = \{\eta_k | k = 1, 2 \ldots M\}$, $0 \le \eta_k \le 1$ as the ability for CR to utilize channel capacities over channel $1, 2, \ldots M$ during one frame. That is, the practical throughput over channel k in one operating frame is $\eta_k \cdot C_k$. And The expected aggregated throughput R is:

$$R = N \sum_{a,b,k} \eta_k C_k P[F=1,S=1,B=b,A=a,K=k,X_i=1]. \tag{9}$$

From above, we establish the steady-state approximation of the aggregated throughput performance. The expected aggregated throughput R is related to $\{M, N, \mathbf{q}, \mathbf{C}, \boldsymbol{\eta}\}$. The first three terms is related to the generalized multichannel model while the last term is related to the efficiency of the protocol design. In the proposed protocol, CRs may ignite parallel transmission and alleviate the inter/intra-system contention. However, with a fixed probability of attempts p, the protocol cannot fully utilize the available multichannel when there is fewer CRs. On the other hand, when the number of CR N is larger, suffered from the unstable phenomenon of CSMA, the aggregated throughput R converges and then drop. The protocol optimization is discussed in the following section.

IV. STABILIZATION AND PROTOCOL OPTIMIZATION

CSMA-based protocol suffers from its unstable nature, a stabilization mechanism is required and will significantly contribute to performance improvement. When there are too many CRs, every CR shall decrease its potential channel access in prevention of collision with other CRs, while CR shall increase the probability of channel access when there are much resource left.

From section II and III, N and $\mathbf{q}$ can be acquired from the *sensing* function in the long run; M, N_{cw}, $\mathbf{C}$ and $\boldsymbol{\eta}$ are predetermined during CR design. Therefore, the throughput optimization in the proposed multichannel MAC protocol can be done by finding the optimal probability of transmission attempt p^* that maximizes the aggregated throughput. Rewrite (9),

$$R = \sum_{a=1}^{N} G(a) p^a (1-p)^{(N-a)} \tag{10}$$

Where:

$$G(a) = \sum_{b=0}^{a} \sum_{k=1}^{M} \sum_{n=1}^{N_{cw}-1} \eta_k C_k (1-q_k)\left(\frac{1}{N_{cw}}\right)\left(\frac{N_{cw}-n+1}{N_{cw}}\right)^b \cdot \binom{N-1}{a-1}\binom{a-1}{b}\left(\frac{1}{M}\right)^{b+1}\left(\frac{M-1}{M}\right)^{a-b-1} \tag{11}$$

It should be noted that $G(a)$ is a non-decreasing function of a. In comparison to conventional single channel stabilization [9], information over diverse multichannel for both inter-system (CR-PSs) and intra-system (within CRN) is required. Information retrieval can be done with the *sensing* function described at Section II. From (11), The optimization problem can thus be formulated as follows:

Maximize

$$R = \sum_{a=1}^{N} G(a) p^a (1-p)^{(N-a)} \tag{12}$$

Subject to

$$0 \leq p \leq 1$$

Since the optimization parameter $p \in [0, 1]$, (12) can be easily transformed and solved by interior-point method [15] to find the optimal probability of transmission attempt p^*. Another instinct method is to construct a look-up table. This table can be pre-determined and embedded in the design of CR. By periodically adapting (*adaptation* function) the probability of transmission attempt p to $p*$, the expected throughput of CRs is then optimized. The proposed multichannel protocol is therefore optimized by *cognitive* functionalities - *sensing* function (inter- and intra-system information retrieval) and *adaptation* function (adapt to fit the environment.) It should be noted that the stabilization and optimization depends on the cognizant information. The speed and accuracy of information retrieval will affect the performance. More sophisticated information extracting/exchanging mechanisms will be our future works.

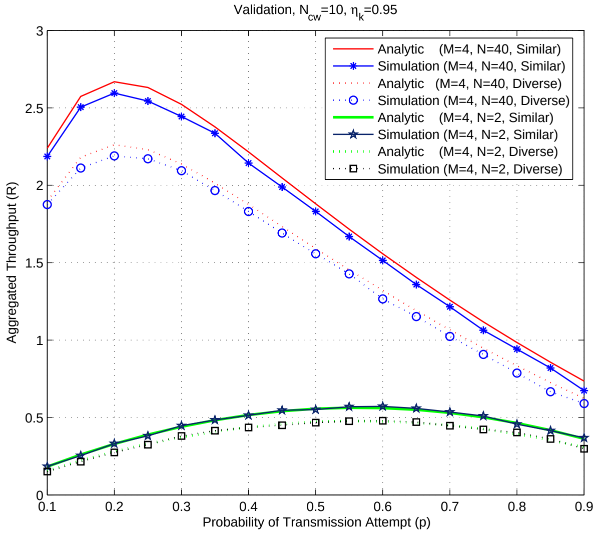

Fig. 3. Validation: the normalized throughput

V. SIMULATION RESULTS

In this section, first we validate our analysis of the proposed cognitive CSMA-based multichannel MAC protocol by comparing the analytic and simulation results under two (light and heavy) modes. The light mode is with $M = 4$ and $N = 2$, CRs are sparsely distributed over multichannel. And the heavy mode is with $M = 4$ and $N = 40$, channel are crowded and CRs compete for the relatively limited resource. Moreover, various multichannel scenarios are simulated. The first one is the ''similar'' multichannel scenario where every channel is with unity capacity and a same probability of PS appearance $q_k = 0.01$; the other one is the ''diverse'' multichannel scenario where channels are with diverse capacities $C_k = [0.8, 0.9, 1.1, 1.2]$ and the probabilities of PS appearance $q_k = [0.01, 0.05, 0.1, 0.5]$, respectively. In order to provide an intuitive sense of the multichannel MAC performance, all analysis and simulation results are with $N_{CW} = 10$, and the multichannel frame operation efficiency $\eta_k = 0.95$.

The simulation and analytic results under different modes (heavy/light) and scenarios (diverse/similar) are depicted in

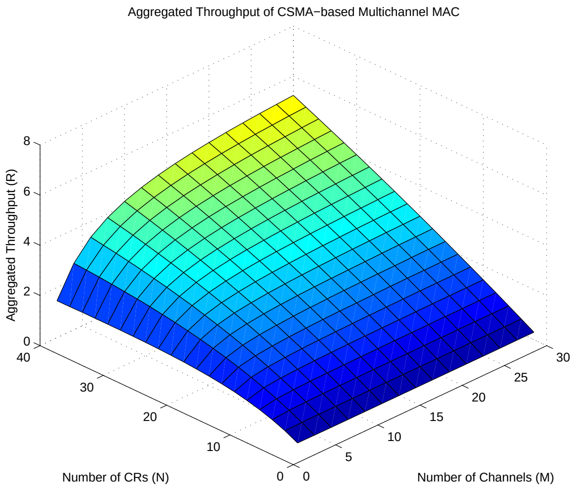

Fig. 4. Aggregated multichannel throughput with $p = 0.3$

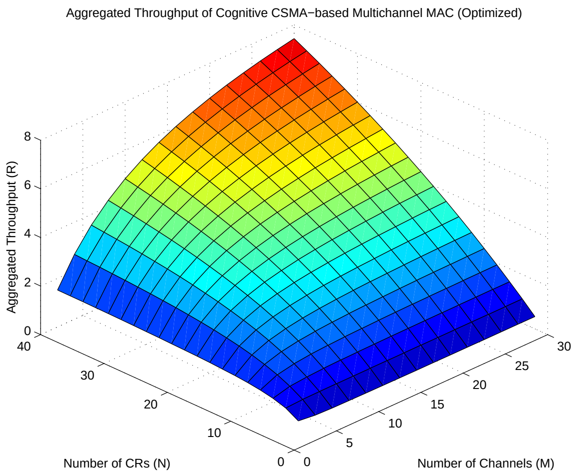

Fig. 5. Aggregated multichannel throughput with $p = p*$

Fig. 3. Comparing the simulation and analytic results, our steady-state analysis is validated in all modes and multichannel scenarios. It is noteworthy that when channels are crowded, as in the heavy mode with $M = 4$ and $N = 40$, CRs shall decrease probability of transmission attempt p in avoidance of contention and collision.When there are relatively abundant resource, as in the light mode with $M = 4$ and $N = 2$, CR shall increase p. Note that in the light mode, there are not enough CRs to fully utilize the multichannel. The varying results over p also suggest a vital throughput improvement from *adaptation* function under different modes and scenarios. With feasible spectrum sensing mechanisms, CRs detect and avoid all PSs' transmission, resulting in zero interference to PSs. Comparing the difference of the diverse and the similar scenarios, the higher probabilities of PSs appearance decrease the throughput performance of CR. As predicted, the impact of appearance of PSs is more harmful in the heavy mode.

Fig. 4 shows the aggregated multichannel throughput R via number of CRs N and number of channels M. Here we turn off the *cognitive* functions to see the performance of original CSMA-based protocol performance with constant $p = 0.3$. The results are comparable to the original work of Aloha-based McMAC [6] with improvement in co-existence multiple system support of PSs and collision alleviation by CSMA. When the number of channel is increased, the throughput is first increased and then converged. It is because that p and N are fixed, CRs can not initiate more parallel transmissions even if there is still resource available. On the other hand, for a fix number of channels, increasing the size of CRN linearly increases the throughput since there are more CRs try to transmit, which is a feasible property of multichannel MAC for CRN.

Fig. 5 illustrates the aggregated multichannel throughput with *cognitive* functions that maximizes throughput with $p*$. In addition to spectrum sensing and CSMA, with the help of cognizant information from PSs and CRN, our protocol empowers CRN to adapt to the optimal probability of transmission attempt p^*. Without losing intuition, here we simulates a stable CRN without entering/leaveing CRs, and the environmental information is correctly and distributively acquired by CRs in the long run. The cognitive CSMA-based multichannel MAC protocol outperforms the original protocol since it can increase p to initiate more transmissions while there is more resource for the CRN and decrease p to avoid collisions while the resource is rare. Therefore, the throughput performance can be improved in comparison with the non-cognitive protocol shown in Fig. 4. By comparing Fig. 5 (the proposed cognitive MAC) and Fig. 4. (as a evolved version of [6] which outperforms [2]–[5]) , the proposed cognitive CSMA-based multichannel MAC protocol provides a pertinent throughput improvement. The average improvement is 27.4% under our simulation setting.

VI. CONCLUSION

The cognitive capability of secondary users can make multichannel MAC more intelligent. In this paper, we introduce and integrate *cognition* into multichannel MAC for CRN. The proposed cognitive CSMA-based multichannel MAC protocol utilizes CRs' *sensing* and *adaptation* functionalities to extract both inter- and intra-system information and optimize the throughput performance. For both PSs' and CRs' operators, the proposed protocol is feasible to the generalized multichannel MAC scenario such as CRN since it offers detection and avoidance for PSs, and provides diverse multichannel support and adaptation that optimizing the throughput performance. Simulation results further validate our analysis of the proposed protocol and suggests a significant performance improvement. Advanced research in cognitive MAC for CRN is obviously crucial in the future. Our cognitive CSMA-based multichannel MAC protocol is an exciting first step.

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