Medium Access Control for Multi-Channel Parallel Transmission in Cognitive Radio Networks

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***Abstract*— A multi-channel parallel transmission protocol is proposed for the medium access control in cognitive radio networks (CRNs). This protocol contains two key elements: multi-channel assignment and multi-channel contention. For an incoming flow-based connection request, the minimum number of parallel channels are assigned to satisfy the rate and interference mask constraints. For the contention of the assigned channels, our protocol provides an extension of the single-channel RTS-CTS-DATA-ACK handshaking of the IEEE 802.11 scheme. The proposed MAC coherently integrates optimization results into a practical implementation. Through numerical examples, we verify that our protocol provides lower connection blocking probability and higher system throughput for CRNs than its single-channel counterpart.**

I. INTRODUCTION

Over the past few years, we have witnessed rapid proliferation of wireless networks in various environments (home, office, public hotspot, and so on). This trend will ultimately lead to *ubiquitous networking*, where not only computers but ordinary electronic devices will be connected in a wireless way. The large population of connected devices imposes a great demand on spectrum resource, which is now crowded with most frequency segments being statically and exclusively allocated to specific types of wireless devices. On the other hand, a recent report from the FCC Spectrum Policy Task Force indicated that at any given time and place, less than 10 percent of the allocated spectrum is being utilized [1]. To solve this dilemma and improve spectrum utilization, *cognitive radios* (CRs), have been proposed to implement *opportunistic* and *dynamic* spectrum access [2].

In this paper, we assume the availability of cognitive radio technologies at the physical layer, and focus our attention on designing a medium access control (MAC) protocol for multiple one-hop point-to-point communications in a cognitive radio network (CRN). Particularly, we focus on extending the contention-based carrier sensing multiple access with collision avoidance (CSMA/CA) scheme defined in the IEEE 802.11 standard due to its maturity and wide deployment in practical networks.

A basic requirement for CRNs is that the communication between CRs should not lead to unacceptable interference to legacy primary radios (PRs) that share the same channel. The spectrum-sharing nature of CRNs imposes tremendous challenges for MAC design. Firstly, multi-channel parallel transmissions over a link are necessary for CRs; to support a prescribed data rate under a given interference mask, a CR needs to use multiple parallel channels to reduce its interference level by spreading power over multiple bands. The multi-channel assignment and contention differ from the conventional single-channel assignment and contention used in current protocols. Secondly, when multi-channel parallel transmissions are adopted, we need to decide the rate and power allocation across these parallel channels in such a way that certain objectives (such as total interference, rate, or power) are optimized. Considering a dedicated control channel for CRNs and N shared data channels between primary radio networks (PRNs) and CRNs, this paper describes and evaluates a novel RTS-CTS-DATA-ACK based 802.11-like MAC protocol, which is designed to support multi-channel parallel transmissions in CRNs. We investigate the minimum-power/rate allocation across parallel channels under constraints on rate and CR-to-PR interference. Numerical examples are used to verify the performance of the proposed protocol in terms of connection blocking probability and system throughput.

The rest of the paper is organized as follows. The system model and problem statement are given in Section II. Interference-optimal power/rate allocation over parallel channels is presented in Section III. Our contention-based protocol is described in Section IV. Numerical results are presented in Section V and conclusions are given in Section VI.

II. MODEL DESCRIPTION AND PROBLEM STATEMENT

A. System Model

We consider a hybrid system consisting of N types of legacy PRNs and one CRN. The $N+1$ networks overlap with each other geographically. PRs in the same PRN operate over the same frequency band, but the different PRNs are allocated different (non-overlapping) bands. Although in reality a PRN may occupy more than one band, such a network can be equivalently treated as multiple (virtual) PRNs working over different bands. For the ith PRN, we denote its carrier frequency and bandwidth by f_i and W_i, respectively.

The motivation for using CRN is to enhance the spectrum utilization by allowing CRs to share the same spectrum, $W_1 \cup \ldots \cup W_N$, with the PRNs. Here we consider flow-based traffic for individual CRs. When a CR initiates a flow of rate R_0, it chooses m channels, $1 \leq m \leq N$. Accordingly, the data flow is converted into m parallel sub-flows, which are transmitted simultaneously over the m selected channels with appropriately assigned powers and rates. Without loss of generality, let the selected set of channels be $(1, 2, \ldots, m)$ and let the transmission power of CR k at channel i be denoted as $P_k^{(i)}$, $i = 1, \ldots, m$. To ensure a feasible channel sharing, we have the following four constraints:

1) *Maximum number of parallel channels*: A CR can simultaneously use up to M channels from channels 1 to N. Due to the limitation of cost, typically $m \leq M \ll N$.
2) *CR-to-PR interference spectrum mask*: The average transmission power of CR k for channel i must be constrained by $\mathrm{E}\left\{P_k^{(i)}\right\} \leq P_{mask}^{(i)}$. The vector $\vec{P}_{mask} = (P_{mask}^{(1)}, \ldots, P_{mask}^{(N)})$ is referred to as the *CR-to-PR interference spectrum mask*. This mask is needed to ensure that transmissions from a CR will not cause unacceptable interference to the co-channel PRs. The determination of $\vec{P}_{mask}$ is certainly an important issue worth investigation, but is out of the scope of this paper. Here, we simply assume that $\vec{P}_{mask}$ is given.
3) *Sum-transmission-power constraint*: The total average transmission power over the m selected channels should be limited by a maximum value $P_{\max}$, i.e., $\mathrm{E}\left\{\sum_{i=1}^{m} P_k^{(i)}\right\} \leq P_{\max}$. This constraint is imposed, for example, by the CR's battery.
4) *Aggregate flow-rate constraint*: Let the data rate provided by channel i be R_i (i.e., the rate of the ith subflow). The rate allocation must satisfy $\sum_{i=1}^{m} R_i = R_0$. Here we only consider the case when $R_1, \ldots, R_m$ are constants. This corresponds to the scenario where the channel selection and rate allocation are decided at the beginning of the flow, e.g., at the hand-shaking phase, and are maintained throughout the duration of the flow.

To facilitate channel sharing, we assume that the kth CR node periodically senses channels and estimates the instantaneous interference to the CR at individual channels as a vector $\mathbf{I}_k = (I_k^{(1)}, \ldots, I_k^{(N)})$. This interference vector is used to drive the channel selection, rate allocation, and power control algorithms, as described later. In addition, to coordinate channel access between CRs, we assume that an out-of-band spectrum segment, W_{N+1}, can be assigned to the CRN as a dedicated control channel. A CR is capable of either transmitting or receiving control packets on this channel at any time. It is worth noting that in a pure cognitive radio environment, a common in-band dedicated control channel may not exist due to the spectrum heterogeneity caused by the coexistence of heterogeneous PRNs. The allocation of an out-of-band control channel greatly simplifies the coordination among CRs, but may somehow counter the motivation of improving the spectrum utilization through channel sharing. However, because of the short length of control packets, the bandwidth of the control channel is typically negligible compared with that of the data channels, i.e., $W_{N+1} \ll \sum_{i=1}^{N} W_i$. Thus, we argue that the allocation of a dedicated control channel does not significantly influence the overall spectrum utilization of the system.

B. Problem Statement

Without loss of generality, we focus on an arbitrary source-destination CR pair whose flow-rate demand is R_0. The medium access process consists of two key elements: channel assignment and channel contention. Channel assignment is executed at the destination node, while channel contention is conducted in an coordinated way between the source and destination CRs.

1) Channel Assignment: The task of channel assignment is to optimally decide the channel selection and the associated power/rate allocation for the selected channels subject to the interference mask and transmission power constraints. As mentioned earlier, a flow from a source CR is converted into m parallel sub-flows, which are transmitted simultaneously over the m selected channels according to the assigned rates and powers. To ensure an efficient utilization of each channel, the optimal channel assignment should allocate each flow the minimum number of channels that satisfy both the rate requirement and interference constraints. We present the optimal channel assignment algorithm in Section III.

2) Channel Contention: The actual occupying of the assigned channels is accomplished by the channel contention functionality. In our protocol, the channel contention mechanism is designed to ensure non-overlapping local channel occupancy between CRs, i.e., a channel which is occupied by a CR cannot be allocated to other CRs in its one-hop communication range. This mechanism excludes CR-to-CR interference although it still suffers from the co-channel PR-to-CR interference, thus largely simplifying the CR-to-PR interference control process. The inclusion of CR-to-CR interference by allowing multiple CRs to share overlapping channels locally is a more general scenario for CRNs. However, it demands distributed iterative power adjustment of individual CRs, leading to potential convergence issues that can be extremely difficult to address. Related work on such a problem has been discussed in the context of interference channels, which is a well-known open problem [6]. In this paper, we focus on the simplified case mentioned above. The detailed contention protocol is presented in Section IV.

III. OPTIMAL CHANNEL ASSIGNMENT

For an incoming CR access request, we divide the channel assignment into two routines that are executed iteratively. First, for a given channel assignment, we compute the optimal power/rate allocation that leads to the minimum CR transmission power under the interference mask. Second, we change the channel combination and repeat the first procedure. This algorithm explores different channel combinations to seek the optimal one that has the minimum number of channels and requires the minimum transmission power while satisfying the CR-to-PR interference mask. Once the optimal channel combination is determined, the associated power/rate allocation is also determined by routine one.

A. Optimal Power/Rate Allocation for a Given Channel Combination

We consider a one-hop source-destination CR pair (A, B) that requires a flow rate of R_0. For an arbitrary channel combination, label these channels by $1, \ldots, m$. Assuming

AWGN and treating interference as noise, the maximum error-free rate of the ith channel is given by the Shannon capacity formula [7]:

$$R_i = W_i \ln\left(1 + \frac{P_A^{(i)} g_{AB}^{(i)}}{I_B^{(i)}}\right), \quad i = 1, \ldots, m \tag{1}$$

where $P_A^{(i)}$ is the transmission power of CR A on channel i, $g_{AB}^{(i)}$ is the distance-dependent signal-power attenuation over channel i, $I_B^{(i)}$ is the instantaneous interference-plus-AWGN power at CR B on channel i (a random variable in our model), and R_i is the rate measured in nats/second. To provide a constant rate of R_i on channel i, the transmission power must satisfy

$$P_A^{(i)} = \frac{I_B^{(i)}}{g_{AB}^{(i)}}\left(e^{r_i} - 1\right) \tag{2}$$

where $r_i \overset{\text{def}}{=} R_i / W_i$. Accordingly, the expected transmit power is given by

$$\bar{P}_A^{(i)} = \left(e^{r_i} - 1\right)\frac{\bar{I}_B^{(i)}}{g_{AB}^{(i)}} \tag{3}$$

where $\bar{I}_B^{(i)} = \int_0^\infty I_B^{(i)} f(I_B^{(i)}) dI_B^{(i)}$ with $f(I_B^{(i)})$ being the p.d.f. of the random variable $I_B^{(i)}$. The optimal power/rate control problem can be formulated as optimizing the rate allocation across channels 1 to m such that the total average transmit power is minimized. Mathematically, this optimization is expressed as

$$\begin{array}{ll} \text{minimize}_{\{r_1,\ldots,r_m\}} & \sum_{i=1}^{m}(e^{r_i} - 1)\frac{\bar{I}_B^{(i)}}{g_{AB}^{(i)}} \\ \text{such that} & \sum_{i=1}^{m} r_i W_i = R_0 \\ & 0 \le r_i \le \ln\left(1 + \frac{P_{mask}^{(i)} g_{AB}^{(i)}}{\bar{I}_B^{(i)}}\right) \quad i = 1, \ldots, m. \end{array} \tag{4}$$

The upper bound on r_i is due to the CR-to-PR interference mask, which is given as $(e^{r_i} - 1)\frac{\bar{I}_B^{(i)}}{g_{AB}^{(i)}} \le P_{mask}^{(i)}$.

An observation of (4) indicates that it is a strictly convex optimization problem with upper and lower bounds on individual variables. The optimal solution $(r_1^o, r_2^o, \ldots, r_m^o)$ to (4) can be derived by first removing the upper bounds and then sequentially determining the variables that exceed their upper bounds. Specifically, this sequential algorithm is described as follows:

1) We first solve the optimization problem where the upper bound on r_i is not imposed, i.e.,

$$\begin{array}{ll} \text{minimize}_{\{r_1,\ldots,r_m\}} & \sum_{i=1}^{m}(e^{r_i} - 1)\frac{\bar{I}_B^{(i)}}{g_{AB}^{(i)}} \\ \text{such that} & \sum_{i=1}^{m} r_i W_i = R_0 \\ & r_i \ge 0, \quad i = 1, \ldots, m. \end{array} \tag{5}$$

Obviously, (5) is a convex problem and its Lagrangian is given by

$$L(\vec{r}, \kappa, \vec{\epsilon}) = \sum_{i=1}^{m}(e^{r_i} - 1)\frac{\bar{I}_B^{(i)}}{g_{AB}^{(i)}} + \kappa(R_0 - \sum_{i=1}^{m} r_i W_i) - \sum_{i=1}^{m} \epsilon_i r_i, \tag{6}$$

where κ and $\vec{\epsilon} = (\epsilon_1, \ldots, \epsilon_m)$ are the Lagrange multipliers, κ is an arbitrary real number, and ϵ_i's are non-negative real numbers. Without loss of generality, we rank the channels such that $\frac{g_{AB}^{(1)} W_1}{\bar{I}_B^{(1)}} \ge \frac{g_{AB}^{(2)} W_2}{\bar{I}_B^{(2)}} \ge \ldots \ge \frac{g_{AB}^{(m)} W_m}{\bar{I}_B^{(m)}}$. The optimal solution to (5) can be obtained in closed form:

$$r_i^{o'} = \max\left\{\ln \frac{\kappa g_{AB}^{(i)} W_i}{\bar{I}_B^{(i)}}, 0\right\} \tag{7}$$

and

$$\kappa = \exp\left(\frac{R_0}{\sum_{i=1}^{K_1} W_i}\right) \prod_{i=1}^{K_1}\left(\frac{\bar{I}_B^{(i)}}{g_{AB}^{(i)} W_i}\right)^{\frac{W_i}{\sum_{i=1}^{K_1} W_i}} \tag{8}$$

where K_1, $1 \le K_1 \le m$, is determined in a way such that $f(K_1) > 1$ and $f(K_1 + 1) \le 1$, with the function $f(n)$ defined as:

$$f(n) = \frac{g_{AB}^{(n)} W_n}{\bar{I}_B^{(n)}} \exp\left(\frac{R_0}{\sum_{i=1}^{n} W_i}\right) \prod_{i=1}^{n}\left(\frac{\bar{I}_B^{(i)}}{g_{AB}^{(i)} W_i}\right)^{\frac{W_i}{\sum_{i=1}^{n} W_i}} \tag{9}$$

for $1 \le n \le m$. The uniqueness of such a K_1 can be proved in a similar way as in [4]. Denote the channel set in the design space by $\mathbf{V}$, which initially includes $\{1, \ldots, m\}$.

2) Due to the monotonically-increasing property of the objective function over r_i's [5], if any of the $r_i^{o'}$ in (7) violates the upper bound on r_i in (4), then the corresponding bounded optimal solution r_i^o must be the upper bound itself, i.e., $r_i^o = \ln\left(1 + \frac{P_{mask}^{(i)} g_{AB}^{(i)}}{\bar{I}_B^{(i)}}\right)$. Denote the set of channels whose unbounded optimal solutions exceed their upper bounds by $\mathbf{U}$, and we set $\mathbf{V} = \mathbf{V} - \mathbf{U}$.

3) With the knowledge of r_i^o for $i \in \mathbf{U}$, the objective function in (4) is modified to the following form

$$\text{minimize}_{\{r_i | i \in \mathbf{V}\}} \sum_{i \in \mathbf{V}} (e^{r_i} - 1)\frac{\bar{I}_B^{(i)}}{g_{AB}^{(i)}}. \tag{10}$$

Accordingly, we set $R_0 = R_0 - \sum_{i \in \mathbf{U}} r_i^o W_i$, and the rate constraint in (4) is updated as

$$\sum_{i \in \mathbf{V}} r_i W_i = R_0 - \sum_{j \in \mathbf{U}} r_j W_j. \tag{11}$$

The modified optimization problem, which consists of the objective function (10), the rate constraint (11), and $r_i \ge 0$, $i \in \mathbf{V}$, is a degenerated version of (4). The un-bounded optimal solution to this new optimization problem has the same form as in (7) and (8).

4) Steps (2) and (3) are repeated until all un-bounded solutions $r_i^{o'}$ of the degenerated problem are within their bounds.

The minimized sum transmission power of CR A can be derived by substituting the optimal rate allocation $(r_1^o, \ldots, r_m^o)$ into the objective function of (4). This value is compared against the transmission power upper bound $P_{\max}$ to decide whether the given channel combination is feasible. Different channel combinations will be tested using the above algorithm and the optimal channel assignment is found among those feasible combinations, as described in the subsequent section. In addition, to maintain the assigned rates for individual channels through the flow duration, CR A conducts closed-loop power control based on the feedback of the receiver-side instantaneous interference level. The optimal power control policy in channel i is derived by substituting r_i^o into (2), which leads to the desired average power $\bar{P}_A^{(i)}$.

B. Optimal Channel Assignment

The optimal channel selection is a feasible channel combination that contains the minimum number of channels among all feasible combinations involving with no more than M channels. In case that more than one feasible combinations contain the same minimum number of channels, the one requiring the minimum sum transmission power will be selected. The search process can be efficiently implemented by sequentially exploring the channel combinations, starting from those containing only one channel, with the goal of finding the minimum-size optimal combination. If there is no feasible channel combination in current round, the algorithm proceeds to those combinations containing two channels, and so on. The search continues until an optimal combination is found, or all combinations containing no more than M channels have been tested. Therefore, in the worst case, a total number of $\sum_{i=1}^{M} C_N^i$ channel combinations need to be tested by the algorithm, where $C_x^y = \frac{x!}{y!(x-y)!}$ for integers x, y, $y \le x$.

IV. PROTOCOL DESCRIPTION

Based on the optimal channel assignment algorithm presented in Section III, we now describe the proposed MAC protocol for CRNs. This protocol is an extension of the single-channel RTS-CTS-DATA-ACK handshaking scheme used in the 802.11 standard. For brevity, we only focus on the parallel-channel transmission aspect in our description. To facilitate multi-channel contention, each CR needs to maintain a local free-channel table (FCT). This table contains the set of channels that are un-occupied by other CRs within the node's one-hop communication range. Initially, the FCT contains all N data channels and is continuously updated according to the channel access dynamics. The proposed protocol is specified as follows.

1) Whenever a CR is idle, i.e., neither transmitting nor receiving data, it listens to the control channel and updates its FCT as described in STEP 3. When a CR intends to establish a flow-based connection, it transmits a request-to-send (RTS) packet to the destination CR over the control channel using the largest transmission power and the physical carrier sensing scheme. Specifically:
    a) All channels in the FCT of the source CR are indicated in this RTS packet. The duration of the flow (DOF), which is given by dividing the flow length (in the units of bits) by the desired flow rate, is also given in the RTS packet. This information provides other CRs with an estimate of the ending time of the underlying flow.
    b) If the FCT at the source CR is empty, the source CR defers its RTS transmission, backs off, and retransmits the RTS packet at the end of backoff. During the backoff period, the source CR continues to listen to the control channel and keeps updating its FCT as described later in STEP 3.
    c) Other nodes receiving the RTS on the control channel defer their control-packet transmission until the appearance of the ECTS packet (described later in STEP 3) or the timeout of a predefined period. The timeout value should be set reasonably larger than the typical interval between the RTS and the ECTS to avoid interrupting normal hand-shaking.
2) Upon successful reception of the RTS packet but before transmitting the clear-to-send (CTS) packet, the destination CR conducts the logic *"and"* operation between its FCT and the source CR's FCT. Those channels that appear in both FCTs are tagged as *available channels* for the data communication. Based on this set of available channels, the following actions are taken:
    a) The channel assignment algorithm described in Section III is executed to test various combinations of the available channels.
    b) If a particular combination of m channels is selected, the identities of these channels and the associated power/rate allocation information are indicated in the CTS packet. In addition, the destination CR also copies the DOF information from the RTS packet to the CTS packet. If the set of available channels is empty or if no feasible channel combination is found by the channel assignment algorithm, an "empty" flag will be indicated in the CTS.
3) When the source CR receives the CTS packet, it transmits an Echo-CTS (ECTS) packet over the control channel, including in this packet the channel assignment and DOF information provided in the CTS. After that, the source and destination CRs begin the parallel data-flow communication on the assigned channels using the assigned powers and rates. All other CRs that overhear the CTS and ECTS packets will remove the assigned channels from their local FCTs for a DOF amount of time. When the DOF-equivalent time expires, these channels will be appended back into their local FCTs. If an "empty" flag is indicated in the CTS and ECTS, the source CR enters backoff and retries afterwards.
4) During the flow transmission, both the source and the destination CRs keep listening to the control channel for CTS and ECTS packets from other CRs, and updating their FCTs accordingly as described in STEP 3. In addition, to maintain the assigned rates for individual sub-flows through the flow duration, the source CR conducts closed-loop power control based on the feedback of the receiver-side instantaneous interference level. The rule for this power control has been given by (2).

V. PERFORMANCE EVALUATION

To evaluate the effectiveness of the proposed MAC protocol, we conducted numerical experiments using MATLAB and also simulated a hybrid system that consists of 2 PRNs and 1 CRN. Nodes in these networks are uniformly distributed over a 100-meter-radius circular area. The first PRN operates in the 900 MHz band, occupying five non-overlapping 1-MHz channels that are labelled as channels 1 to 5 in the simulation. The numbers of PRs in each channel are 100, 200, 300, 400, and 500, respectively. The second PRN operates in the 2.4 GHz band, also occupying five non-overlapping 1-MHz channels that are labelled as channels 6 to 10 in the simulation. The numbers of PRs in each channel of PRN 2 are 100, 200, 300, 400, and 500, respectively. The signal strength is attenuated by d^4 with d the propagation distance [7]. We divide the time into slots, each of length 10 ms. At any given slot, each PR in the first and the second PRNs attempts to transmit with a probability of 0.1 and 0.4, respectively. The transmission power of each PR is 1 W when it is on.

We simulated 10 pairs of one-hop source-destination CRs. To simplify our simulation, we assume that the distance between each pair is equal, and we take the path loss to be -30 dB. We assume that all CRs are within the transmission range of each other, so that any control packet sent from a CR can be heard by all other CRs. The instantaneous interference sensed by a CR in a certain channel is the sum of the interference from all active co-channel PRs. The flow generation at each source CR follows a Poisson process with parameter λ flows/second. Each flow has an exponentially distributed duration with mean $1/\mu$ second. The flow from the ith source CR requires a constant data rate of $0.5 \times i$ MegNats/second. We assume that a CR can use up to two data channels simultaneously. We set the CR-to-PR interference spectrum mask to $P_{mask}^{(1)} = \ldots = P_{mask}^{(10)} = 20$ mW, and the transmission-power upper bound to $P_{\max} = 20$ mW.

We compare the performance of the multi-channel parallel transmission MAC protocol with the multi-channel RBCS MAC protocol proposed in [3]. In contrast to our proposed multi-channel parallel transmission strategy, the multi-channel RBCS protocol only selects the best available channel for data transmission (i.e., a node uses only one channel at a time). Although it is not originally designed for a CRN, we adapt it to the CRN application by modifying the channel selection condition: if the average transmission power associated with the best available channel satisfies the CR-to-PR interference mask, then it will be selected; otherwise no channel will be assigned and the incoming access request will back off. The performance criteria to compare include the connection blocking rate (plotted in Figure 2) and the system throughput (plotted in Figure 3). The connection blocking rate is defined as the ratio between the number of requests that end in backoff to the total number of connection requests. The system throughput is defined as the average volume of CR traffic transmitted by the system in one second. The simulation results verify that significant reduction in the connection blocking probability and considerable increase in throughput are achieved by the proposed MAC protocol.

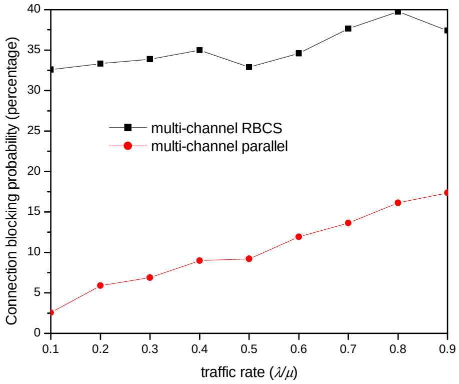

Fig. 1. Connection blocking rate vs. traffic load.

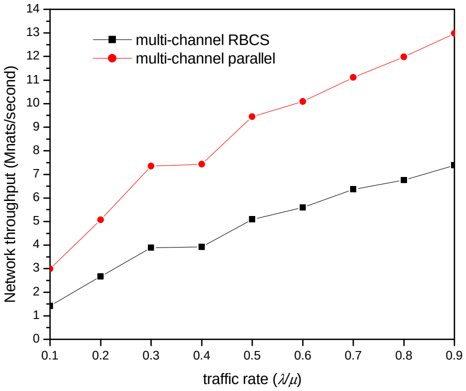

Fig. 2. System throughput vs. traffic load.

VI. CONCLUSIONS

A multi-channel parallel transmission protocol was proposed for medium access control in cognitive radio networks. This protocol contains two key elements: multi-channel assignment and multi-channel contention. The proposed MAC coherently integrates the optimization results in multi-channel assignment into a practical implementation of the multi-channel contention. Compared with a reference protocol, the proposed one provides better spectrum utilization in terms of smaller connection blocking probability and larger system throughput.

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