PAPER *Special Section on Dynamic Spectrum Access*

A Simple MAC Protocol for Cognitive Wireless Networks

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SUMMARY A simple distributed Medium Access Control (MAC) protocol for cognitive wireless networks is proposed. It is assumed that the network is slotted, the spectrum is divided into a number of channels, and the primary network statistical aggregate traffic model on each channel is given by independent Bernoulli random variables. The objective of the cognitive MAC is to maximize the exploitation of the channels idle time slots. The cognitive users can achieve this aim by appropriate hopping between the channels at each decision stage. The proposed protocol is based on the rule of least failures that is deployed by each user independently. Using this rule, at each decision stage, a channel with the least number of recorded collisions with the primary and other cognitive users is selected for exploitation. The performance of the proposed protocol for multiple cognitive users is investigated analytically and verified by simulation. It is shown that as the number of users increases the user decision under this protocol comes close to the optimum decision to maximize its own utilization. In addition, to improve opportunity utilization in the case of a large number of cognitive users, an extension to the proposed MAC protocol is presented and evaluated by simulation.

key words: *medium access control (MAC), opportunistic spectrum access, spectrum utilization*

1. Introduction

There exists an increased research effort in wireless communications and networking for the optimal or efficient use of scarce and costly network resources in recent years. By deploying new physical transmission techniques as well as revised and cross layer protocols, considerable improvement in network resource management and specially in the network spectrum utilization is achieved.

On the other hand, measurements of the FCC show that much of the costly spectrum is idle or unutilized at any given time and location [1]. Therefore, it seems that a revised approach to spectrum management and utilization is also required, i.e., the current licensed spectrum allocation and utilization is inefficient. The cognitive radio concept, proposed by Mitola [2], in its general meaning, shapes the structure of the networks where the nodes are empowered to sense the environment and opportunistically exploit the licensed networks spectrum white spaces. Hence, the cognitive or secondary user should infer the spectrum status and adapts its transmission time and parameters accordingly. Then, his decision is based on the history of spectrum sensing and previous transmission results.

This idea results in some unique and new challenges in the architecture design as well as all layers of the protocol stack. In these networks, the basic assumption is the ability to sense the spectrum perceptively and correctly for utilization. Therefore, the main characteristic of these networks is the tight coupling between the physical (PHY) layer operation and other layers.

In this paper, we focus on the cognitive MAC layer assuming simple model of spectrum sensing and transmission at the PHY layer. The objective of the cognitive MAC is to maximize the exploitation of the channels idle time slots by the cognitive users.

The cognitive MAC involves with two problems of exploration and exploitation [3], [4]. The former deals with perceptively selecting channels to be sensed at the beginning of each sensing slot by cognitive user. The exploration outcomes are used to infer the stochastic traffic model information of the primary network on each channel which is subsequently used for better decisions in exploitation. That is the aim of exploration is not to utilize an opportunity instantly. In the exploitation, the cognitive user aims to select the best channel, i.e., channel which is more likely to be idle, and instantaneous utilization at each decision step. Spending more time for channels exploration leads to making better decisions at upcoming slots in the cost of missing the instantaneous utilization opportunities. As a consequence, there exists a tradeoff between the time that is assigned for channels exploration and the channel exploitation at the MAC layer.

In [3] using dynamic programming, a recursive structure for the optimal medium access control of a cognitive user is derived. Also, to avoid the computational complexity, an asymptotic optimal strategy with low complexity is developed. In [4] the opportunistic spectrum access problem is analyzed in the framework of partially observable Markov decision process. A decentralized cognitive MAC is suggested to optimize the performance of the cognitive users while limiting the interference for the primary users.

The channel selection problem for spectrum agile user is formulated as a multiarmed bandit problem in [5]. The optimal policy for channel selection is then derived by computing the Gittins indices. Since the computation of these indices is complex in general, approximate values are computed by truncating the state space to find an appropriate finite state Markov chain. For the primary network traffic modeling, a simple model is adopted which is also vali-

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dated by experimental measurements of an IEEE 802.11b network. The developed algorithm is based on the number of failures and successes on each channel to estimate the channels Bernoulli traffic parameter and to select the best channel at each decision step. In addition, exploring the channels continuously, this algorithm can track the channels traffic variations and consequently select the best channel over time as in [5]. We note that the primary network traffic on the channels could change over time and the cognitive MAC is responsible to track these variations. The achievable gain by spectrum agility is also discussed in [6] in terms of two performance criteria, i.e., spectrum utilization and spectrum access blocking. Furthermore, a framework consists of three building blocks namely “spectrum opportunity discovery, spectrum opportunity management, and spectrum usage coordination” is proposed and evaluated via simulations.

In this paper, applying the results of Kelly on the theory of multiarmed bandit problem in [7], we develop and analyze a simple MAC protocol for the cognitive users. The proposed scheme requires uncomplicated computations and stores a simple state vector. In the case of a single cognitive user, it could track the best channel as in [5] without computing the Gittins indices. In the case of multiple cognitive users, the protocol can be deployed by each user independently. It is shown that as the number of users increases, their distributed decisions follow the optimal trend to maximize each user utilization while the fairness is also guaranteed. In addition, an extension to this protocol is presented and evaluated by simulations that achieves better utilization in the case of large number of cognitive users.

The rest of this paper is organized as follows. The system model and problem statement are presented in Sect. 2. In Sect. 3, the algorithm based on the rule of least failures is presented and its optimality for the case of a single cognitive user is discussed and evaluated by simulation. The multiple user cognitive MAC protocol, its performance study and simulation are presented in Sect. 4. In Sect. 5, an extension to the protocol is proposed that leads to better utilization when the number of cognitive users is large. Section 6 concludes the paper.

2. System Model and Problem Statement

We assume that the spectrum assigned to the primary network consists of N non-overlapping channels, $\mathcal{N} = \{1, 2, \ldots, N\}$. It is also assumed that the system is time slotted. The channels usage in different time slots depends on the primary users aggregate traffic in practice. We use a statistical model to describe this traffic. Since the objective of the cognitive MAC is the exploitation of the remaining white spaces, the adopted statistical model is a key parameter in the system model that affects the cognitive MAC analysis and evaluation. It is assumed that channel j is busy or black in each time slot with probability of q_j. Therefore, the number of white spaces or idle time slots between any two black spaces has a geometric distribution with mean $(1 - q_j)/q_j$. This model is used in [3], [5], where in [5] its consistency with the experimental measurements for the traffic of networks using IEEE 802.11b standard is verified.

The cognitive network consists of M users. It is assumed that each user could sense one channel in a time slot and its possible transmission is synchronized with the primary network. At the beginning of each decision slot, the cognitive user decides on selecting a channel to sense. The selected channel could be idle or busy. If the channel is idle, the cognitive user transmits a packet and furthermore updates his history for this channel state. The state of other channels does not change in this case. Therefore, the state of channel j reflects the number of encountered failed and successful transmissions on it and can be used for the estimation of its traffic parameter, i.e., q_j. Hence, the sequence of selected channels determines the rewarded gain from the spectrum which depends on the decision strategy of the user.

The objective is to maximize the exploitation of the spectrum white spaces by applying an optimal policy. This policy uses the past observations which are summarized in the current state. Let the attained reward in each time slot is denoted by $R(t)$, where $R(t) = 1$ is for successful transmission upon selecting an idle channel and $R(t) = 0$ is for busy one. The objective is to maximize

$$\mathbf{E}\left[\sum_{t=0}^{\infty} \beta^t R(t)\right] \tag{1}$$

over all possible channel selection policies where $\beta \in (0, 1)$ is a discount factor. This problem is referred to multiarmed bandit problem and the best decision at each stage could be found by computing the Gittins indices [8]. Assume an uncertain system which returns different rewards for each possible excitation according to a probability distribution. Multiarmed bandit problem is a model for an agent that aims to attain new knowledge of this system and simultaneously optimize its decision based on the current knowledge. The agent should make a tradeoff between exploring the system by new excitations to attain more knowledge about these probability distributions and instantaneous exploitation based on current knowledge. The optimal decision should yield the maximum reward over all possible ending time.

The Gittins indices are an ordered set and can be computed according to the current state of the channels. The main problem is that computing the Gittins indices are complex in general. Hence, other algorithms have been proposed to find optimal or suboptimal solutions with less complexity by adding new assumptions to the problem [7], [8]. In this paper, according to the structure of the defined problem, we deploy one of these algorithms for the case of single cognitive user and then extend the results to multiple cognitive users.

Algorithm 1 The MAC Protocol Based on the Least Failure Rule

Initialization: Set $S_j^0 = F_j^0 = 0$ for $j \in \mathcal{N}$
for $t = 1, 2, \ldots$ **do**
  $v = least\_failure(\mathbf{S}^{t-1}, \mathbf{F}^{t-1})$
  sense channel v
  if busy **then**
    $F_v^t = F_v^{t-1} + 1$
  else
    $S_v^t = S_v^{t-1} + 1$
    exploit channel v
  end if
end for

3. Single Cognitive User Case

3.1 The Least Failure Rule

In [7], Kelly shows that as the discount factor approaches one, the simple least failure rule tends to be the optimal policy. This rule states that at each stage the cognitive user should select the channel which has incurred the least number of failures and in the case that this rule returns more than one solution, the channel with the largest number of successes should be selected. Therefore, it is just required that the user maintains the number of incurred successes and failures on each channel and decides based on the above simple rule.

We first discuss about the reasonability of the assumption $\beta \to 1$ for the cognitive MAC problem. In multiarmed bandit problem, β is used as a discount factor indicating the preference of the nearer time horizon rewards against the farther ones. The rationale behind this is the exploitation of the opportunities over all possible terminating time. The assumption of $\beta \to 1$ neglects this preference. This assumption is reasonable if we assume that the spectrum opportunities are not vanished, the cognitive users always have data to transmit, and they could tolerate transmission delay.

3.2 Single Cognitive User MAC Algorithm

Let S_j^t, F_j^t be the number of incurred successful and failed accesses to channel j till the time slot t. The state of all channels are shown by the vectors $\mathbf{S^t} = (S_1^t, \ldots, S_N^t), \mathbf{F^t} = (F_1^t, \ldots, F_N^t)$. Algorithm 1 is used by the cognitive user for spectrum exploitation.

In this algorithm, the $least\_failure$ function returns the best channel according to the rule of least failures. It should be noted that after exploiting channel j, S_j is incremented while F_j and the state of other channel do not change. Therefore, this channel would be the best channel in forthcoming time slots for exploitation till a failure is incurred on it.

3.3 The Achievable Utilization

The cognitive user utilization of the channels white spaces is the percentage of successful access to the total number of access. The following result is stated in [7], where we represent its proof by a simple reasoning for completeness.

Lemma 1: Using the least failure rule the maximum achievable utilization by the cognitive user after a long period is given by:

$$U_{opt} = \lim_{T\to\infty} \mathbf{E}\left[\frac{1}{T}\sum_{t=1}^{T} R(t) \mid q_1, q_2, \ldots, q_N\right]$$
$$= \left(\sum_{j=1}^{N}\frac{1}{q_j}\right)^{-1}\sum_{j=1}^{N}\frac{1-q_j}{q_j} \quad (2)$$
$$\leq \max(1-q_1, 1-q_2, \ldots, 1-q_N) \quad (3)$$

Proof: Let at time t, j be the best channel under this rule. The average achieved utilization on this channel is $\frac{1-q_j}{q_j}$ while the cognitive user encounters a failure on it. Hence, it tries this channel $\frac{1-q_j}{q_j} + 1 = \frac{1}{q_j}$ times. It then switches to the new best channel according to the least failure rule. Therefore, all channels are scanned to encounter a failure on them and then we return to exploit channel j again after $\sum_{j=1}^{N}\frac{1}{q_j}$ time slots. Scanning the channels in round robin manner, the maximum average achievable utilization is given by (2). To find (3) we note that the utilization is a weighted average of $1 - q_j$ and hence is less than their maximum value. □

We should note that the cognitive user does not have prior knowledge about the channels traffic parameters. Therefore, it is not surprising that that the maximum average utilization is less than $1 - q_{min}$, i.e., when the cognitive user locks on the best channel. We could think that the difference between these two values, i.e., $(1-q_{min}) - U_{opt}$ as the cost of learning and tracking the channels traffic status if their parameters are not known or is varying in time. If the primary network traffic on channels is not varying in time or its variation is slow, the cognitive user could estimate the channels traffic parameters and lock on the best channel. Specifically, after enough observation, q_j could be estimated according to [5]:

$$q_j = \frac{F_j}{S_j + F_j + 1} \quad (4)$$

The following property is also constructive.

Lemma 2: Applying the least failure rule, the average probability of selecting channel j is given by:

$$p_j = \frac{1/q_j}{\sum_{j=1}^{N} 1/q_j} \quad (5)$$

Proof: The algorithm based on least failure rule exploits the channels white spaces in a round robin fashion such that after any long period of time, i.e., T, the number of failures on each channel is almost equal. Therefore, after T slots we should have:

$$(Tp_j)q_j = F_0 \quad \forall j \in \mathcal{N}$$

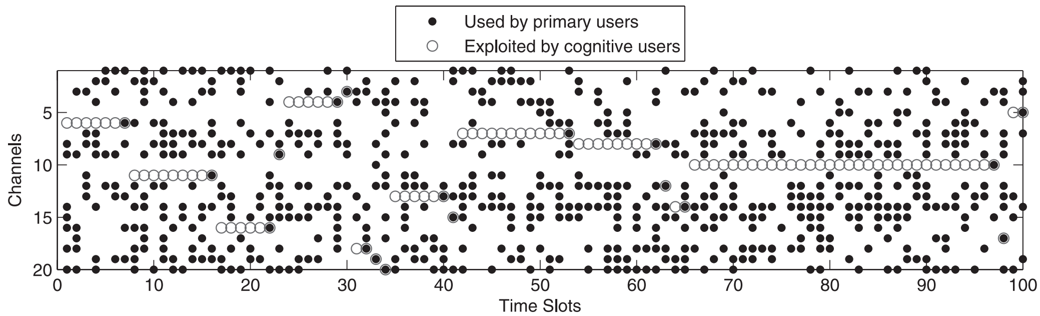

Fig. 1 The exploited time slots by the cognitive user in 100 consecutive time slots using least failure rule.

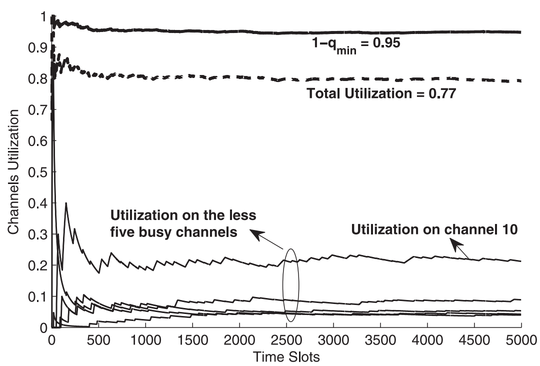

Fig. 2 Channels utilization over time and maximum achievable utilization.

where F_0 is a constant. This leads to $p_j = \frac{1/q_j}{T/F_0}$. Since $\sum_j p_j = 1$, we find (5). Also, $F_0 = \frac{T}{\sum_j 1/q_j} = \frac{T}{T_0}$ shows that in average at each round, i.e., T_0 slots, we have one failure on each channel. □

3.4 Numerical Evaluation

The primary network spectrum is assumed to consist of $N = 20$ non overlapping channels. The parameters of random variables describing the primary traffic on each channel, are selected randomly in the range [0.1 0.5] for 19 channels while for one arbitrarily selected channel, i.e., channel 10, we set $q_{10} = 0.05$. Therefore, this channel is the least busy channel. The algorithm operation on this channel is tracked in the following simulation. In simulation, the primary network traffic on each channel, busy and idle time slots, is determined by generating random uniform numbers in the range [0 1] and comparing with its Bernoulli parameter. The cognitive user stores the number of perceived successes and failures on each channels for his decisions. Also, the percentage of perceived idle slots to the total simulation time is considered as the cognitive user utilization. The utilization of white spaces by cognitive user, using Algorithm 1, in 100 consecutive time slots is depicted in Fig. 1. As this figure shows, the cognitive user switches from one channel to another one when it encounters a failure on the current channel.

In Fig. 2, the achieved utilization of the five less busy channels specifically channel number 10 as well as the total achieved utilization over time is depicted. The steady achieved utilization is $U_{opt} = 0.77$ which is consistent with (2). The achieved utilization by simulation on channel 10 is also consistent with the expected one and is equal to $p_{10}(1 - q_{10}) = 0.20$ where p_{10} is computed using (5). Also, compared with the steady available white space on the best channel, $1 - q_{min} = 0.95$, the cost of learning is 0.18.

4. Multiple Cognitive Users Case

If the cognitive network consists of M users, then a fraction of opportunities is wasted due to the simultaneous secondaries transmissions on the channels. The secondary user encounters this type of collision when he senses a channel idle at the beginning of a time slot but at the end of that slot he does not receive ACK from his receiver. Therefore, he could discriminate these types of collisions from the collisions with the primary users.

In the multiple user scenario the objective of the cognitive MAC is to maximize the sum of cognitive users exploitations as well as providing the fairness among them. To this end, their transmissions on channels should be scheduled such that each user could exploit the opportunities while perceiving minimum interference from others.

In Alg. 1, a collision with a primary user triggers the channel hopping. Intuitively, if we increase the hopping between the channels according to the secondaries collisions, then the probability of simultaneous exploitation by two cognitive users is decreased. On the other hand, we should keep the fraction of times that each user exploiting channel j as in Alg. 1 to ensure the near maximum utilization of available white spaces. By appropriate hopping between the channels one hopes to achieve the total utilization MU_{opt} when U_{opt} is given by (2), i.e., when each user exploits the opportunities without interfering for others. Since the less busy channels are more visited by the cognitive users, we expect to have more secondary collisions on these channel. Therefor, the main problem is on designing the hopping sequence according to the incurred primary and secondary collisions on each channel. Also, we note that the users decisions should be make in a distributed fashion. We start with the case of two cognitive users and then extend to the general case.

4.1 Two Cognitive Users

Assume that $M = 2, N \gg M$. We first discuss that taking into account the secondaries collisions as failure in Alg. 1, i.e., these collisions are also trigger channel hopping, a near optimal and fair solution could be achieved. In other words, the fraction of times that each user exploits channel j dose not changed much compared with a single user scenario while the fraction of secondaries collisions is limited. Let $F^t_j = F^t_{1j} + F^t_{2j}$, where F^t_{1j}, F^t_{2j} are the number of incurred failures on channel j by each user due to collisions with primary and the other secondary users respectively.

Also, assume that the channel selection process by each user in the consecutive time slots is independent, i.e., at the beginning of a time slot each cognitive user selects channel j with probability $\hat{p}_j, \quad j = 1, \ldots, N$. We note that according to Alg. 1, the selected channel by each user at the beginning of a time slot depends on his previous deploying channel because he does not hop to a new channel until a failure is incurred. However, the probability of finding a channel idle in some consecutive time slots is not large. Also, this assumption is a pessimistic assumption in our analysis and as we will see in following the results based on is consistent with simulation. Using this assumption after an enough long time slots, T, we have:

$$F_{1j} = T\hat{p}_j q_j \tag{6}$$
$$F_{2j} = T\hat{p}_j^2 \tag{7}$$

Where (7) is probability of selecting channel j by both users simultaneously. According to the rule of least failure, the incurred total number of failures on each channel should be the same named $\hat{F}_0$. Therefor, applying Alg. 1, we should have:

$$\hat{p}_j^2 + q_j\hat{p}_j - \hat{F}_0/T = 0, \quad j = 1, 2, \ldots, N \tag{8}$$

The acceptable solution for $\hat{p}_j$ is: $\hat{p}_j = \frac{q_j(\sqrt{1+4\hat{F}_0/Tq_j^2}-1)}{2}$. Let $c = 4\hat{F}_0/T$. Hence, $c/4$ is the ratio of incurred failed to the total number of time slots on each channel. To compare the results with one cognitive user scenario, noting that $\sqrt{1 + c/q_j{}^2} \leq 1 + 0.5\, c/q_j{}^2$, we use the approximation:

$$\sqrt{1 + c/q_j{}^2} \simeq 1 + 0.5\left(c/q_j{}^2\right)\zeta(c, q_j),\ \zeta(c, q_j) < 1 \tag{9}$$

where $\zeta(c, q_j) < 1$ is used as a correction factor that come close to one if $c/q_j{}^2 \ll 1$. Using (9), we have $\hat{p}_j = \frac{1/q_j}{T/\hat{F}_0}\zeta(c, q_j)$. Applying $\sum_j \hat{p}_j = 1$, we found:

$$\hat{F}_0 = \frac{T}{\sum_j (1/q_j)\zeta(c, q_j)} \tag{10}$$
$$\hat{p}_j = \frac{(1/q_j)\zeta(c, q_j)}{\sum_j (1/q_j)\zeta(c, q_j)} \tag{11}$$

Comparing with a single cognitive user case in the previous section we conclude that:
1) If c is sufficiently small, e.g., when the number of channels is sufficiently large compared to the number of users, such that $\zeta(c, q_j) \simeq \zeta(c)\ q_j \in (0, 1)$, according to (11) the channels access probabilities does not change much, i.e., $\hat{p}_j \simeq p_j$, while the perceived number of failures increased to $\hat{F}_0 = \frac{F_0}{\zeta(c)}$.
2) In average, each cognitive user utilization on each channel and hence their total utilization are equal. Therefore, the fairness is guaranteed. For numerical evaluation, Alg. 1 is used by $M = 2$ cognitive users independently considering secondaries collisions as failure. The channel hopping of the users and exploited time slots are depicted in Fig. 3. The steady achieved utilization is $U_1 = U_2 = 0.74$.

4.2 *M* Cognitive Users

Assuming M cognitive users, the average perceived failures due to the secondaries collision on channel j from the perspective of one cognitive user is given by:

$$F_{2j} = T\hat{p}_j[1 - (1 - \hat{p}_j)^{M-1}] \tag{12}$$

That is if at least one user from the remaining $M-1$ ones exploits channel j simultaneously. Again, adding with the failures due to collisions with primary users and equating a constant number of failure, we should solve an equation of degree M to find $\hat{p}_j$. To find how the algorithm performs when the number of users increased, we can use the approximation $(1 - \hat{p}_j)^{M-1} \simeq 1 - (M - 1)\hat{p}_j$ and hence $F_2^j \simeq T(M - 1)\hat{p}_j{}^2$ to obtain:

$$(M - 1)\hat{p}_j^2 + q_j\hat{p}_j - \frac{\hat{F}_0}{T} = 0 \tag{13}$$

This leads to the solution $\hat{p}_j = \frac{q_j(\sqrt{1+4(M-1)\hat{F}_0/Tq_j^2}-1)}{2(M-1)}$. Compared with the case of $M = 2$ users, $c = 4(M - 1)\hat{F}_0/T$ is increased and hence $\zeta(c, q_j)$ is decreased for each channel. Also, using the pessimistic assumption of independent channel selection in consecutive time slots, an under estimate of each user utilization is given by:

$$\hat{U} = \sum_j \hat{p}_j(1 - q_j) - (M - 1)\sum_j \hat{p}_j^2 \tag{14}$$

Compared with (2), the utilization degradation has two reasons. The first one roots in the changes in the channel access probabilities, i.e, because of $\zeta(c, q_j)$. Specifically, according to (9), if $q_j < q_k$ then $\zeta(c, q_j) < \zeta(c, q_k)$. Since the sum of all channels access probabilities is one in this case too, we found that by using (11) the channel access probability to the less busy channels is decreased while it is increased for more busy channels compared to the ones in (5). Intuitively, adding a failure to the number of failures on a less busy channel is more destructive compared to a more busy channel. The second one is due to the simultaneous access to the channels.

The former is the main reason of utility degradation

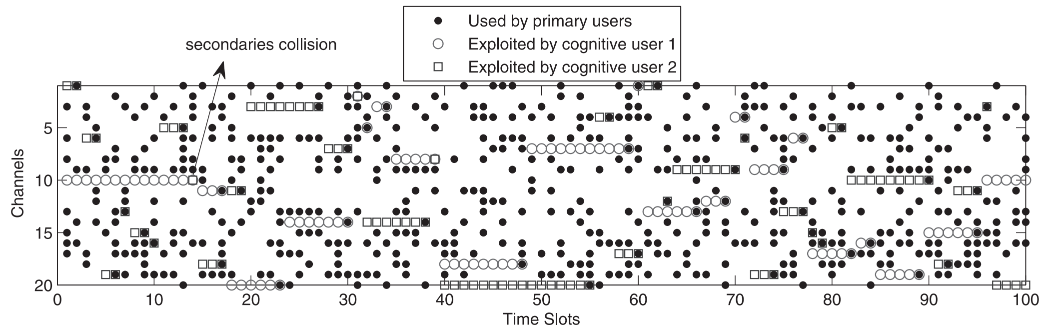

Fig. 3 The exploited time slots by $M = 2$ cognitive users in 100 consecutive time slots using Alg. 1 independently.

when $M \ll N$ because considering the secondary collision as failure for channel hopping, strongly decreases the probability of selecting the same channel in the near future time slots. However, as the number of users increased, the latter would be more important in utility degradation. Specifically, as the number of users increased, the access probability to channel j converges to $1/N$ regardless of q_j. This fact can be shown according to (9) and (11). From (9), we have:

$$\frac{\zeta(c, q_j)}{q_j} = \frac{2[\sqrt{{q_j}^2 + c} - q_j]}{c} \tag{15}$$

Which shows that as c increase, i.e., because of increases in M, the value of $\zeta(c, q_j)/q_j$ would be approximately independent of q_j. Now according to (11) we found that for a large number of users $\hat{p}_j \simeq \frac{1}{N},\ j = 1, 2, \ldots, N$.

Therefore, without any coordination between the users in exploiting the channel, i.e., just hopping upon any primary and secondary collision a fair solution is achieved. This behavior is also near the optimal one that any user should be take to maximize its own utilization from the white spaces. To see this consider the problem:

$$\max\ \hat{U} = \sum_j \hat{p}_j(1 - q_j) - \sum_j (M - 1)\hat{p}_j^2 \tag{16}$$

$$s.t.\ \sum_j \hat{p}_j = 1 \tag{17}$$

$$0 \leq \hat{p}_j \leq 1 \tag{18}$$

That is each user adjust the channels access probability, $p_j, j = 1, 2, \ldots, N$, to maximize its own utilization. The Lagrangian function of this concave optimization problem is given by:

$$\mathcal{L}(\hat{p}_1, \ldots, \hat{p}_N, \lambda) = \sum_j \left[\hat{p}_j(1 - q_j) - (M - 1)\hat{p}_j^2\right] + \lambda\left[\sum_j \hat{p}_j - 1\right] \tag{19}$$

where λ is the Lagrange multiplier for constraint (17). Applying the KKT conditions [9], it is easy to show that the optimal access probability to channel j, $\hat{p}_j^*$, is given by:

$$\hat{p}_j^* = \frac{1}{N} + \frac{(1 - q_j) - \frac{1}{N}\sum_j(1 - q_j)}{2(M - 1)}\quad j = 1, \ldots, N \tag{20}$$

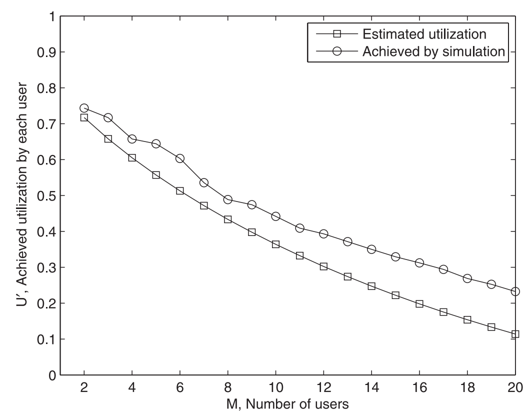

Fig. 4 Utilization of each cognitive user.

This shows that given M, the access probability to the less busy channels should be greater. Also, as the number of users increased the optimal channel access probability tends to $1/N$. This is consistent with the users decisions deploying Alg. 1. We should note that the users adjust their access probabilities to channels in a distributed fashion while they don't have any prior knowledge about the traffic parameter of the channels and the number of users.

For numerical evaluation, Alg. 1 is applied to the network setting of Sect. 3.4 for different number of users, M. The achieved users utilization by simulation and using the estimated one in (14) are shown in Fig. 4. The difference between the estimated utilization and simulated one is due to the deployed pessimistic assumption of independent channel selection by each cognitive user at the beginning of each time slot as it is explained in Sect. 4.1. In fact using this assumption the probability of secondaries collision is increased and its effect on decreasing the utilization is over estimated. However, the same trend is seen between the simulated and estimated utilization when the number of cognitive users is increased. In Fig. 5 a typical user access probability to the best channel, i.e. channel number 10, is depicted. This figure shows that for small number of cognitive users this channel is more visited while for large number of users the access probability to this channel is decreased to $1/N = 1/20 = 0.05$. That is as the number of cognitive users increased, random channel selection is the best decision to

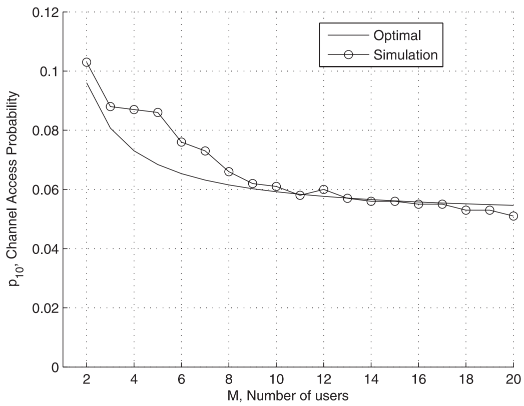

Fig. 5 Average access probability to channel number 10 for different number of cognitive users.

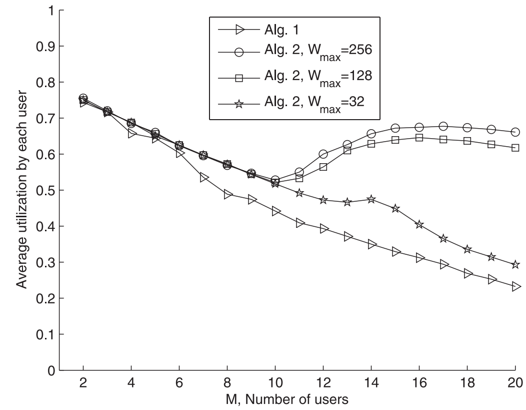

Fig. 6 Average achieved utilization by using Alg. 2 for different number of cognitive users.

reduce the secondary collision. The difference between the optimal access probability and simulated one to limit the secondary collisions is due to the independence assumption which is used in estimating the cognitive user utilization.

5. Extension to the Multiple Users Cognitive MAC

From Fig. 4, we found that as the number of cognitive users increases most of the spectrum opportunities are wasted due to their competition. In this case, an appropriate decision by each user is to exploit a fixed channel in consecutive time slots to reduce the probability of collision with other users. To find the winner of each channel, the competing users transmissions on that channel are deferred randomly according to the perceived number of secondaries collisions on it. That is, the number of failure and hence their transmissions delays on that channel, are increased in an exponential backoff manner. The winner of that channel is one who has the minimum backoff and is encouraged to exploit that channel in forthcoming time slots. The encouragement is done by decrementing its perceived secondaries collision on that channel upon a successful transmission on it. Therefore, the winner of channel j would encounter a small backoff on channel j and large backoff on other channels. The result is that as the number of users increased each user tends to exploit a fixed channel. Algorithm 2 shows this strategy for decision making.

In this algorithm, function $ceil(x)$ returns the smallest integer not less than x, *rand* returns a random number in the range $(0, 1)$, and W_{max} is a constant for the maximum allowable backoff for each channel. In the case of small number of users, Alg. 2 behaves like Alg. 1 because the probability of secondary collision on channel j and hence F_{2j} is low. Also, it is obvious that by limiting the maximum backoff on each channel, W_{max}, this algorithm come close to Alg. 1.

We should note that the users utilization in Alg. 1 are almost equal. However, their achieved utilization when using Alg. 2 depend on the selected channel for exploiting. In other words, Alg. 1 leads to equal and fair utilization even in short scale periods. To investigate the fairness degradation

Algorithm 2 Multiple Cognitive Users MAC Protocol

```
Each cognitive user follows these steps independently
Initialization: Set W_max and S_j^0 = F_j^0 = F_2j^0 = 0 for j ∈ N
for t = 1, 2, ... do
    ν = least_failure(S^{t-1}, F^{t-1})
    sense channel ν
    if busy then
        F_ν^t = F_ν^{t-1} + 1
    else
        S_ν^t = S_ν^{t-1} + 1
        exploit channel ν
        if exploitation is successful then
            F_2ν^t = max{0, F_2ν^{t-1} - 1}
        else
            F_2ν^t = F_2ν^{t-1} + 1
            W = 2^{F_2ν^t} - 1
            B = min{W_max, ceil(W * rand)}
            F_ν^t = F_ν^{t-1} + B
        end if
    end if
end for
```

in Alg. 2 we can use the Jain's fairness index as a measure given by [10]:

$$f = \frac{\left(\sum_{j=1}^{M} U_j\right)^2}{M \sum_{j=1}^{M} U_j^2} \tag{21}$$

where U_j, $j = 1, 2, \ldots, M$ is the achieved utilization by user j.

For numerical evaluation, Alg. 2 is deployed by M cognitive users independently for the network setting of Sect. 3.4 and different values of W_{max}. The average achieved utilization are depicted in Fig. 6. This figure shows that by limiting the number of secondaries collisions on the channels by deferring their exploitation on channels randomly the achievable utilization is increased. This is more highlighted when the number of cognitive users is large, i.e. $M > 8$, when the secondaries collisions are the main reason of utility degradation. Also, using larger values for maximum backoff window better protection against competing simultaneous access can be provided. It is also interesting to note that Alg. 2 outperforms Alg. 1 even for moderate number of users. On the other hand, the fairness index is more decreased using larger value for backoff window. For example, using $W_{max} = 256$ the fairness index decreases from $f = 1$ to $f = 0.95$ for $M = 16, 17, 18, 19, 20$ users. This index for smaller values of W_{max} would be closer to one because the algorithm is more like to Alg. 1, e.g., for $W_{max} = 32$ this index is about $f = 0.999$. Therefore, we could make tradeoff between increasing the sum of the achieved utilization and the users fairness.

6. Conclusion

A simple MAC protocol for cognitive wireless networks is presented. The objective is to opportunistically exploit the spectrum white spaces by multiple cognitive users. Each user maintains the history of the number of success and failures on each channel. Failure at a time slot on a channel is happened if it was occupied by a primary or exploited by another cognitive user simultaneously. The protocol is based on the rule of least failures. That is at each decision stage, the cognitive user hop to the channel which has incurred the least number of failures. The properties of the protocol for multiple cognitive users is investigated and its performance is shown analytically and verified by simulations. It is shown that the users utilizations are almost equal and depend on the traffic statistics of the primary network and the number of competing users. Using the independent channel access assumption, an estimate of the achievable utilization by each user is derived. It is shown that for a large number of cognitive users, their distributed decisions using the proposed algorithm come close to best decision to maximize each user's utilization rate.

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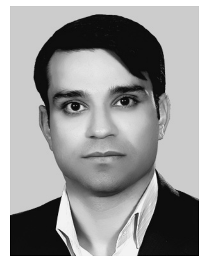

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