Spectral Utilization and Coexistence Strategies in Cognitive Radio Devices

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Abstract

One of the main limitations in next-generation wireless systems is bandwidth scarcity. Nowadays, most of the spectrum is allocated to specific applications by the Federal Communications Commission (FCC); however, statistics shows the spectral utilization is low in most of the reserved ranges. So, trying to use the idle bandwidth and let the secondary users to communicate when the channel is free sounds reasonable. In the past decade, Cognitive Radio devices have been considered to increase the efficiency in these circumstances. Nevertheless, there are lots of issues like, fairness and coexistence strategies that needs special consideration before we can realize such a system. In this report, we will take a look at recent papers and their approach regarding these issues. More interestingly, there are some new ideas that are proposed and developed, afterward.

I. Introduction

Performance of the typical radios is highly restricted by physical layer and medium access control protocols. While, these concrete protocols guaranty the reliable communication between radios and simplify the software and hardware implementation, the statistics shows that they are really poor from bandwidth efficiency point of view. In other words, there exists a lot of less crowded frequency ranges, but the conventional protocols prevents users from crowded bands access them.

In the last decades, cognitive radios have proven to be helpful in increasing the spectral efficiency. Recently, spectral-agile radio has attracted attention of engineers, since it can remarkably improve the mentioned index. As a part of this paper, we will have a report on the works done in [1] regarding this concept.

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Nevertheless, realizing agile systems requires a huge improvement in software and hardware of typical radios. Specifically, we need radios sense the channel precisely and consider the appropriate action with as less amount of latency as possible. Hopefully, recent achievements in Software Defined Radios (SDR) and new technologies have opened exceptional opportunities in this field. Moreover, new regulations of FCC is opening new view points in this field. These topics are considered in [2], but they are out of the scope of this work.

On the other hand, considering the fact that there would be a lot of cognitive radios in near future, one can expect the crazy race between them for accessing the idle bandwidth. So, considering the coexistence strategies sounds an interesting topic. Specifically, we want to increase fairness in these systems. As the second portion of this paper, the effort of the authors in [3] in dealing with this problem is discussed.

In fact, the authors in [3] have tackled the problem by modeling the channel access with a Markov chain with adaptive traffic load distribution. However, this means that in order to realize the solution we need to reshape the traffic of the radio. To make that happen, you either need to have an infinite memory or drop some packets. However, dropping packets may results in inefficiency.

Thus, it seems to be an interesting topic to devise new method which are independent from the channel model and more importantly, keep fairness without complicated and somehow impossible traffic reshaping. In the last section, I will introduce new algorithms, which regardless of the channel model will keep the fairness and does not need complicated computations for channel access permissions.

The following material is organized as follows: The next section deals with the work in [1] regarding spectrum utilization. Section III, reconsider the coexistence strategies and approaches, in [3]. The new ideas are developed and proposed in Section IV. Finally, the conclusion ad future studies are presented in the last section.

II. Spectrum Utilization and Spectral-Agile Devices

In this section, the work in [1] is considered. Specifically, spectral-agile network are proposed and it will be shown that spectrum utilization can be improved drastically, for a network with these devices. Let's start with describing the model, first.

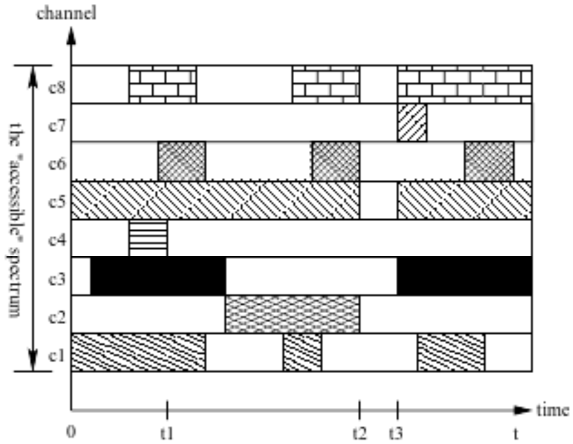

Fig. 1. Spectrum opportunity for spectral-agile devices (courtesy [4]).

A. System Model and Defenition

It is assumed that we have two different types of devices. The first one is called primary, and as you can guess has the highest priority and exclusive access to the specific spectrum. On the other hand, the second type is called secondary, which can only access the channel if it is left idle. Here, we assume that secondary networks are spectrum agile. In fact, they have four main characteristics: (1) Policy Enforcement Entity (PEE), (2) Measurement Management Entity (MME), (3) Resource Management Entity (RME), and (4) Group Coordination Entity (GCE) [1]. Put in simple words, they can listen to the channel and find the idle slots promptly and start using them with negligible latency.

Moreover, It is assumed that the spectrum is divided into sub-channels. Although each radio could use the whole spectrum, we will assume that each secondary system has access to only one channel during each communication. However, it is worth mentioning that SDR could realize network in which the radios could take the advantages of idle period of every channel during single communication. For example, one could use the idea of multi-carrier modulation (e.g OFDM) for this purpose. Figure 1 makes the concept more clear.

In order to have a numerical basis, it is assumed that we have N channel available. Moreover, the usage pattern of primary users , in each channel, is assumed to follow i.i.d. ON/OFF exponentially-distributed random processes with means equal to T_{on} and T_{off} , respectively. During the ON period the channel is occupied by a primary user so it cannot be accessed by secondary ones. On the other hand OFF-period represents that the channel is idle, so there is a spectral opportunity for secondary users. In addition, suppose that M spectral agile communication groups contend for the N sub-channels. Group, is a number of devices, when accessing the channel, share the opportunity according to the MAC layer protocol.

In order to have a numerical basis for comparison we define the Spectrum Utilization to be the percentage of time that a spectral-agile group has access to some channel. If two different groups try to use same idle channel, then the spectrum utilization is evenly divided between them. Based on this metric, the throughput can be found for each specific MAC design. So, our analysis is independent from MAC protocol used in the network.

To appreciate the gain achieved from spectral agile networks, note that the spectral utilization for a non-agile network is simply

$$U_{nonagile} = \frac{T_{off}}{T_{off} + T_{on}} \tag{1}$$

Now let's consider the agile networks and compute this metric for them. Actually, it is a pretty hard problem, in general. Thus we will consider a simple scenario, first. The general case will be discussed after that.

B. Simple Case: Only One Group ($M = 1$)

Assume that there is only one secondary user group. As illustrated in Figure 2, this group is blocked if and only if all the channels are occupied by the primary users. Moreover, it is clear that the block period stars when one of the primary users begins accessing the channel, and ends when one of them transits from ON state to OFF. It can be simply seen that:

$$t_{block} = min(T^{(i)}_{remain}) \quad for \quad i = 1, 2, \ldots, N \tag{2}$$

where t_{block} is the length of blocked period and $T^{(i)}_{remain}$ is the remaining ON-period in the i^{th} channel. Note that the ON-periods are iid with exponential distribution. So, we have

$$P(t_{block} = t) = \frac{N.e^{-\frac{T_{on}}{N}t}}{T_{on}} \tag{3}$$

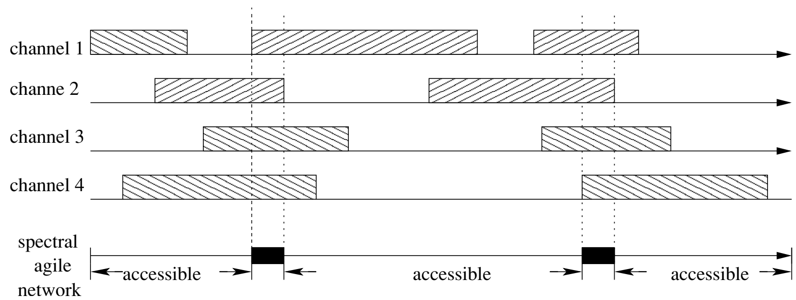

Fig. 2. Special case, $N = 4$ and $M = 1$ (courtesy [1]).

In fact this relation shows that the average blocking time is reduced to $\frac{T_{on}}{N}$ (compare this number with T_{on} for non-agile devices). Considering this and the fact that the block interval starts when $N-1$ channels are already occupied and the idle one switches from the OFF to ON state, one can deduce that

$$U_{agile} = \quad 1 - \frac{N(p^{N-1}.T_{on}/N)}{T_{on}+T_{off}} = \quad 1 - (\frac{T_{on}}{T_{on}+T_{off}})^N \tag{4}$$

where $p = \frac{T_{on}}{T_{on}+T_{off}}$. It is worth mentioning that p does not change even if the channel distributions are changed.

Interestingly, from (4) you can see we could conclude the same results with another rather simple argument. Specifically, U is the compliment of the probability of having all channels occupide (p^N). This argument sugest that we can generalize this calculation for the case where different channels have different distributions. Let $T_{on}^{(i)}$ and $T_{off}^{(i)}$ be the mean ON and OFF intervals in the i^{th} chnnel, respectively. defining $\tau_i = \frac{T_{on}^{(i)}}{T_{on}^{(i)}+T_{off}^{(i)}}$, then in general for non identical distribution we have

$$U_{agile} = 1 - \prod_{i=1}^{N} \tau_i \tag{5}$$

This value should be compared with the one for non-agil case, in (1).

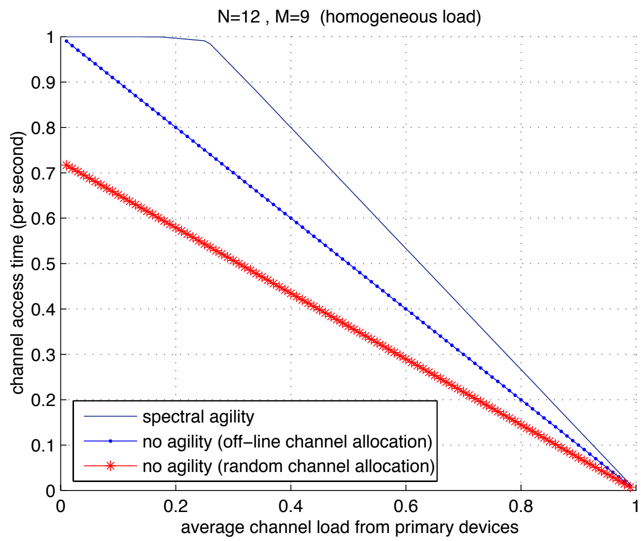

Fig. 3. Special case, $N = 12$ and $M = 9$ (courtesy [1]).

C. General Case: Multiple Group ($M > 1$)

Firstly we want to find the number of idle channel. In other words, the fraction of primary users that are OFF, so secondary users have the opportunity to communicate. Following the same argument as in (5), we see that the channel access time is a function of τ_i and the fraction of time when there k channels available can be calculated as

$$r_k = \sum_{c=1}^{\frac{N!}{k!(N-k)!}} \left[\prod_{i \in S_c^k} (1 - \tau_i) \prod_{j \in \{1,2,\ldots,N\} - S_c^k} \tau_j \right] \tag{6}$$

where S_c^k is a set of k from N channels. Now, if $(M \leq k)$, then each group has one specific channel. Otherwise, they should share k available channels cooperatively. All in all the spectrum utilization could be found as

$$U_{agile} = \sum_{k=0}^{N} \frac{min(M,k) r_k}{M} \tag{7}$$

For comparison, now that $M > 1$, (1) is no longer valid. For non-agile case, we consider two different scenarios: (1) each non-agile group randomly selects its own channel independently of others, and (2) all non-agile groups choose different channels, if possible, possibly via an

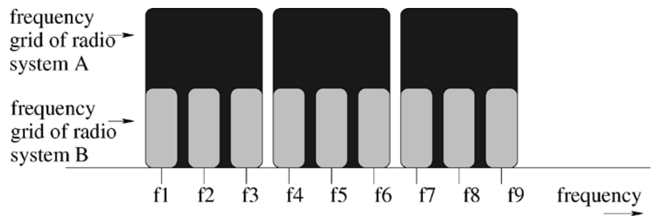

Fig. 4. Frequency channels used by two different types of radio systems (A, B). Each radio system represents a group of communication radio devices. (courtesy [3]).

off-line channel allocation policy [1]. All these cases and are compared in Figure 3. You can see the great improvement for the case of low traffic primary users. Moreover, note that when the channel load from primary users approaches 1, there is no opportunity left for the secondary users and the comparison is not useful.

III. Coexistence Strategies

This section is based on the results in [3]. As it can be decipher from the topic of this part, we are going to discuss about how radios can access the spectrum so that the fairness is kept. In fact, the mentioned spectrum could be any free bandwidth; whether the idle time of the primary users or open spectrum bands allocated by FCC.

If all the systems were the same, there could not be any fairness problem due to random access and inherent fairness of it. However, the point is that, there are different types of devices with various characteristics. For example, they may have different traffic distributions or required bandwidth ranges. Figure 4 depicts this concept, where we have two type of device and one of them has required bandwidth three times of the other. Each type represent a group of devices, as stated in previous section. It is obvious, if radio type B access the channel in a greedy manner, then it has more opportunities because of the better flexibility in contending for the channel.

While it is desirable to increase the efficiency of the channel usage, we should make sure that different types of radios share the allocated opportunity in a fair manner. As expected, this phenomenon introduce a trade of between fairness and efficiency, as will be discussed later.

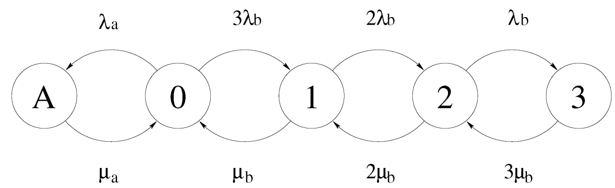

Fig. 5. Continuous time Markov chain with five states to model the accessed channel (courtesy [3]).

A. Traffic and Channel Access Models

Consider the model depicted in Figure 4. Since different segments are independent, for the rest of this section we will assume one third of this model. General case would a simple extension it.

The traffif in each radio system is modeled with two random processes; one for arrival traffic and the other for access duration. The arrival traffic is modeled as a Poisson random process with rate λ_i, so the interval time is exponentially distributed with mean $1/\lambda_i$. Moreover, the access duration time is also exponentially distributed with mean$1/\mu_i$, so the departure of the radio is a Poisson random process with rate μ_i.

Now let's talk about spectrum access. In fact, it is modeled as the continuous time Markov chain, as depicted in Figure 5. In other words, the two-type radio system in Figure 4 is modeled as 5 state Markov chain according to the whether type A is occupying the channel or a number of type B radios are accessing the channel, or channel is totally free.

In order to simplify the process we define infinitesimal generator matrix, $\mathbf{A}$, as follows

$$\mathbf{A} = \begin{bmatrix} -\mu_a & \mu_a & 0 & 0 & 0 \\ \lambda_a & -\lambda_a - 3\lambda_b & 3\lambda_b & 0 & 0 \\ 0 & \mu_b & -\mu_b - 2\lambda_b & 2\lambda_b & 0 \\ 0 & 0 & 2\mu_b & -2\mu_b - \lambda_b & \lambda_b \\ 0 & 0 & 0 & 3\mu_b & -3\mu_b \end{bmatrix} \tag{8}$$

Then we have

$$\mathbf{\Pi A} = 0 \tag{9}$$

where $\mathbf{\Pi} = [\Pi_A, \Pi_0, \Pi_1, \Pi_2, \Pi_3]$ is the steady-state probability vector. From, the model we conclude that

$$\mathbf{\Pi} = [1, P_0, P_1, P_2, P_3]P_A \tag{10}$$

where

$$\begin{aligned} P_A &= \left[\frac{\mu_a}{\lambda_a} + 1 + \frac{3\lambda_b\mu_a}{\lambda_a\mu_b} + \frac{3\lambda_b^2\mu_a}{\lambda_a\mu_b^2} + \frac{3\lambda_b^3\mu_a}{\lambda_a\mu_b^3}\right]^{-1} \\ P_0 &= \frac{\mu_a}{\lambda_a}, P_1 = \frac{3\lambda_b\mu_a}{\lambda_a\mu_b}, P_2 = \frac{3\lambda_b^2\mu_a}{\lambda_a\mu_b^2}, P_3 = \frac{3\lambda_b^3\mu_a}{\lambda_a\mu_b^3} \end{aligned} \tag{11}$$

Now, let's define the metric for fairness. If N_{type} shows the number of the same type i radios, then

$$airtime_{typei} = \frac{1}{N_{type}} \sum_{i=1}^{N_{type}} \frac{allocationtime_i}{referencetime} \tag{12}$$

Considering this definition and applying the mentioned Markov model it is obvious that

$$\begin{aligned} airtime_{type=A} &= \Pi_A \\ airtime_{type=B} &= \frac{1}{3}\Pi_1 + \frac{2}{3}\Pi_2 + \Pi_3 \end{aligned} \tag{13}$$

Now we are in the position to tackle the problem. It will be considered in the next subsection.

B. Proposed Random Access Scheme

From (13), we can see that when radio system A and B are given the same high traffic load, $airtime_B \gg airtime_A$. So, how we can achieve the fairness. The idea is that we should not let radio type B contend for the channel in a greedy manner. So, assume that each radio system will only contend for the spectrum with probability p_i. This way, the previous Markov model should be updated with a new traffic load of $p_i\lambda_i$, instead of λ_i. Then, for perfect fairness

$$airtime(p_a, p_b)_A = airtime(p_a, p_b)_B \tag{14}$$

And, from (13) we conclude

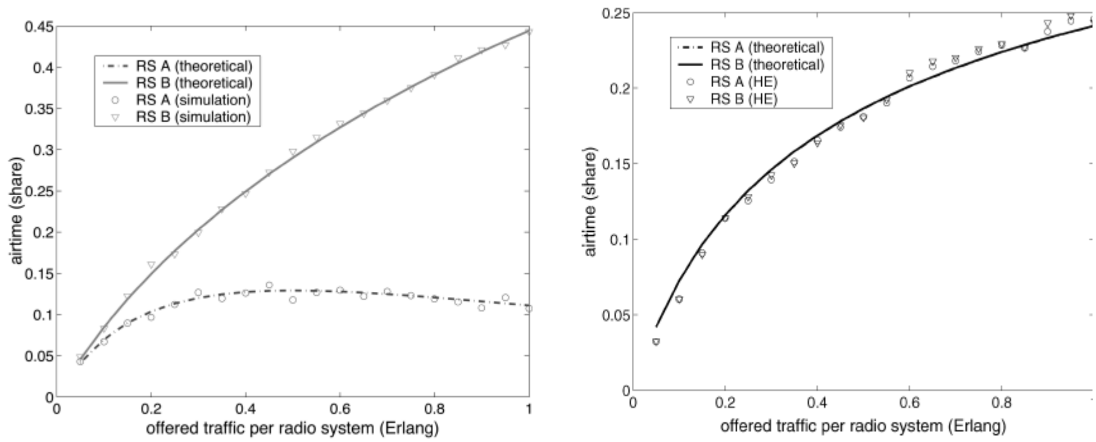

Fig. 6. Simulated and the Markov modeled spectrum access airtime before (right) and after (left) applying proposed random access scheme (courtesy [3]).

$$p_a(p_b) = \frac{1}{3}p_bP_1 + \frac{2}{3}p_b^2P_2 + p_b^3P_3 \tag{15}$$

which results in

$$airtime_A(p_b) = \frac{\frac{1}{3}p_bP_1 + \frac{2}{3}p_b^2P_2 + p_b^3P_3}{P_0 + \frac{1}{3}p_bP_1 + \frac{2}{3}p_b^2P_2 + p_b^3P_3 + p_bP_1 + p_b^2P_2 + p_b^3P_3} \tag{16}$$

Here, it comes the trade of we mentioned earlier. Now we want to keep fairness and maximize the efficiency, which is ”airtime” here. In order to find optimum p_b, note that $\frac{dairtime_A}{dp_b} > 0$. So, the optimum p_b is the largest possible one and depending on $lambds$ and μ could take different values. Figure 6 compares the the airtime metric for two types, before and after applying the proposed random access approach. As you can see, this approach results in exact fairness. However, as you can see, the cost is the slightly lesser aggregate airtime (the trade off).

In [3], there are more general type of Markov model for different cases, as well as a simpler approach for computing the contending probabilities named Homo Egualis (HE) society. Moreover, the airtime normalized by the traffic of each type is introduced and considered as a better metric for fairness. More interestingly, the spectral agility concept is used in the MAC layer design to ”pack” the same type of radios so that they can field the gaps. However, We won’t consider these ideas anymore, since they are not in the scope of this work.

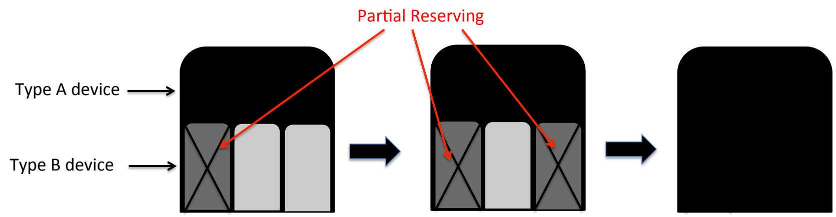

Fig. 7. Partial Reserving concept. Radio type A, senses that B has a better airtime, so starts reserving an integral part step by step as soon as the sub channels are free.

IV. New Proposed Techniques for Coexistence Problem

There are a couple of deficiencies with the approach used in [3]. First and for a most, this method is based on the assumption that the traffic load for devices has a fixed well defined distribution, which is not the case in real world. Secondly, the technique for keeping the fairness suggests that the radios should be allowed to contend for the channel with a specific probability. In fact, this means that when they have a traffic to send they are not always permitted to access the channel. so, they should have an infinite queuing memory for keeping the track of postponed traffics. Last but not least, the approach for finding the optimum contending probabilities is complicated and it needs the information about the traffic distribution of each device which is not available necessarily.

Considering all these facts, we propose a new access control technique which is not only independent of the traffic distribution of the radios, but also works under every model and most importantly, it can be implemented easily with out complicated computations.

The main idea is that we give the devices with wider required bandwidth (say type A in Figure 4) a special authority such that whenever their airtime is less than the lower order types (say type B in Figure 4) they can start partially reserving the channel. By "partial reserving" we mean that it reserves the free spots by sending a busy carrier step by step until it has a packed set of channels for communication. Figure 7 illustrate this approach.

This way, whenever there is an imbalance in the airtime metrics, it is revised. However, the cost is efficiency, because the partially reserved slots cannot provide service until there is a whole pack of them. Nevertheless, this technique is independent of the traffic models and mitigates the greediness of the lower level devices practically without complicated and sometime impossible (due to lack information) approaches.

V. Conclusions and Future Studies

In this work, we considered the efficiency and fairness in cognitive radios. Specifically, the trade off between them had been bolded. Spectral-agile networks have been introduced as a solution to improve both of these metrics in comparison with naive networks.

Moreover, we investigated the previously proposed coexistence techniques. Despite the elegant mathematical structure, these approaches are totally dependent on the channel model and fail when they are not satisfied. So, we proposed a new approach in dealing with the greediness of the devices which is adaptive and independent of the traffic models.

Combining the spectral agility and partial reserving technique to improve the performance seems to be an interesting idea for future studies.

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