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Performance Evaluation of IEEE 802.19.1 Coexistence System

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Abstract—**In this paper we analyze mechanisms of coexistence between different cognitive radio systems operating as secondary users in white space frequency bands. In particular, our focus is coexistence mechanisms that can be provided by IEEE 802.19.1 coexistence system. IEEE 802.19.1 standard is at the early stage of its development. At this stage it is very important to consider different design directions and focus areas. This paper presents results of performance evaluation of the IEEE 802.19.1 coexistence system based on simulation. We believe that simulation results shown in this paper and analysis of these results are very important for the future of both IEEE 802.19.1 standard and products based on this standard.**

Keywords-white space, IEEE 802.19.1, coexistence

I. INTRODUCTION

In radio communications, spectrum is very limited resource. FCC measurements have indicated that 90% of the time, many licensed frequency bands remain unused [1]. This provides opportunity to radio systems to detect and use temporally unused spectrum, thus improving spectrum utilization. To enable such opportunity, two requirements shall be satisfied: 1) radio systems shall have capability to detect and use the temporally unused parts of the spectrum; 2) radio regulations shall be in place to allow radio systems to operate in the temporally unused parts of licensed frequency bands.

The first requirement can be satisfied by the current state of radio communication technology, in particular by using cognitive radio systems. The second requirement is currently satisfied in some countries. The “Second Report and Order in the Matter of Unlicensed Operation in the TV Broadcast Bands” was published by FCC in November 2008 [2]. This document regulating the USA market allows secondary operation in TV white space for portable devices. Currently, other countries, for example, UK, Canada, Singapore, and some European countries, are considering similar actions.

Frequency bands in which radio regulations allow cognitive radio systems to operate in temporally unused parts of these frequency bands are typically called “white space frequency bands.” Here, the term “white space” refers to the temporally unused parts of the frequency bands. Radio systems to which these frequency bands are assigned are called “primary radio systems” or “primary users.” Cognitive radio systems which operate in white spaces of these frequency bands are called “secondary radio systems” or “secondary users.” Using USA radio regulations [2] as an example, TV broadcast systems are primary users, while cognitive radio systems are secondary users. In this example, white space frequency bands are limited to some channels in TV frequency bands.

In addition to regular functionality (delivery of user traffic) of radio systems operating in licensed bands, cognitive radio systems operating in white space frequency bands shall have two additional functions: 1) primary user protection; 2) coexistence with other secondary users.

The first function is typically mandatory as required by radio regulations. The reason is that the cognitive radio system is operating as a secondary user. This means that it is allowed to operate only in temporally unused parts (white space) of white space frequency bands.

The second function, that is, coexistence with other cognitive radio systems is not required by radio regulations. The reason to have this function is as follows. White spaces are not exclusively assigned to one particular cognitive radio system. Any cognitive radio system that satisfies radio regulations for primary user protection can use white spaces. Consequently, more than one cognitive radio system can select the same white space for its operation. In such case, several cognitive radio systems operating in the same white space may create interference to each other which may lead to performance degradation or even to inability to continue operation. The mechanisms that allow cognitive radio systems to avoid such situation are called “coexistence mechanisms.”

The coexistence mechanisms can be categorized into two groups: 1) mechanisms of coexistence between similar cognitive radio systems; 2) mechanisms of coexistence between different cognitive radio systems.

The first group of coexistence mechanisms is mechanisms of coexistence between similar cognitive radio systems also called “self-coexistence mechanisms.” By similar cognitive radio systems we mean cognitive radio systems operated according to the same radio communication standard. Examples of radio communication standard defining radio systems capable of operating in white space frequency bands are IEEE 802.22 [3], IEEE 802.11af [4], and ECMA 392 [5]. Typically, self-coexistence mechanisms are incorporated into a radio communication standard and thus can be used by cognitive radio systems operating according to this standard.

Self-coexistence mechanisms provide various mechanisms to solve the coexistence problems for cognitive radio systems operating according to the same radio communication standard. However, such mechanisms cannot be used to solve the coexistence problem for different cognitive radio systems operating according to the different radio communication standard.

With understanding the need to provide coexistence solutions for different cognitive radio systems operating in

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white space frequency bands, IEEE 802 committee started project 802.19.1 to develop standard for “TV White Space Coexistence Methods” in December 2009. This standard will specify radio technology independent methods for coexistence among dissimilar or independently operated TV Band Device networks and dissimilar TV Band Devices [6].

In other words, this standard will define services and mechanisms to enable coexistence of different cognitive radio systems operating in USA TV white space frequency bands. Examples of such services are discovery of neighboring white space radio systems, selecting operating channels for white space radio systems, providing some level of fair use of available channels.

IEEE 802.19.1 standard is at the early stage of its development. At this stage it is very important to consider different design directions and focus areas. This paper presents results of performance evaluation of the IEEE 802.19.1 coexistence system based on simulation. We believe that simulation results shown in this paper and analysis of these results are very important for the future of both IEEE 802.19.1 standard and products based on this standard.

The rest of the paper is organized as follows. Section II gives brief overview of the current status of the IEEE 802.19.1 coexistence system. Section III describes simulation used for performance evaluation in this paper. Section IV presents and discusses simulation results. Section V concludes the paper.

II. IEEE 802.19.1 OVERVIEW

According to standardization procedure of IEEE 802, 802.19 Task Group 1 is responsible to prepare the draft standard before it is approved by IEEE Standards Association Standards Board. Task Group 1 decided to create a system design document with the intention of creating a common understanding of the system architecture of IEEE 802.19.1 coexistence system and of the general design goals [7]. The system design document describes IEEE 802.19.1 system architecture, system requirements, terminology and possible outline of the standard.

In the IEEE 802.19.1 system architecture shown in Figure 1, three logical entities are defined according to their functional roles [7]: Coexistence Manager, Coexistence Enabler, and Coexistence Discovery and Information Server.

The Coexistence Manager is responsible for making coexistence decisions and providing corresponding commands. Another responsibility of the Coexistence Manager is discovery of and communication with other Coexistence Managers.

The Coexistence Enabler provides interface between white space radio system and IEEE 802.19.1 coexistence system. It obtains information from white space radio system and forwards commands received from the Coexistence Manager to white space radio system.

The Coexistence Discovery and Information Server supports discovery of the Coexistence Managers by each other and stores coexistence related information. Coexistence Managers register themselves and their white space radio systems in the Coexistence Discovery and Information Server. Based on this information, the Coexistence Discovery and Information Server can inform each white space radio system about its neighboring white space radio systems. Also, the Coexistence Discovery and Information Server can be used to share other information related to coexistence within the IEEE 802.19.1 system and among white space radio systems.

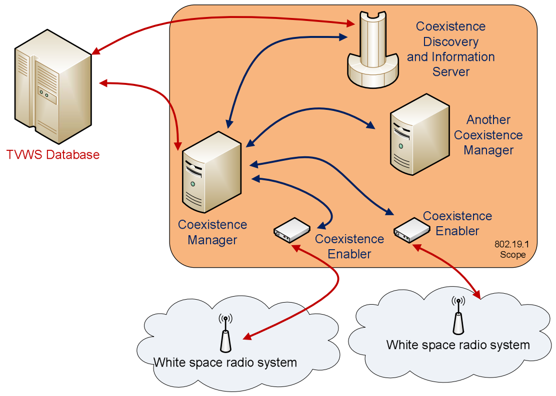


Figure 1. IEEE 802.19.1 system architecture.

External entities shown in Figure 1 are: white space radio systems and TV white space database. The key function of the TV white space database is primary user protection. Before starting operation, each white space radio system must access the TV white space database to obtain list of available channels.

The IEEE 802.19.1 coexistence system can provide many services to white space radio systems. The services analyzed in this paper are:

- Discovery service
- White space management service.

The discovery service allows white space radio system to discover neighboring white space radio systems with which it needs to coexist. In response to request from the white space radio system, the IEEE 802.19.1 coexistence system will provide information on neighboring white space radio systems and on white space channels used by each of these neighboring systems.

The white space management service helps white space radio system to select operating channel among available channels indicated by TV white space database. Also, this service can provide transmission schedule in the selected operating channel if there is a need to share one channel by several white space radio systems to provide fair spectrum access opportunities to different white space radio systems.

III. SIMULATION DESCRIPTION

We have performed performance evaluation of the IEEE 802.19.1 coexistence system to understand advantages that it can provide to white space radio systems and to identify the key directions of the IEEE 802.19.1 coexistence system design.

A. Simulation Parameters

We have selected geographic area of 100x100 km. Within this area we randomly distribute the given number of white space radio systems. In this paper we show results for the number of white space radio systems from 10 to 200.

For each of these systems, we randomly select radius of its coverage area from the given range of values. By changing the range of values, we selected three types of operational environment, characterized by different average number of neighboring white space radio systems:

- Good operational environment (coverage area radius is randomly selected from the range between 1 km and 10 km)
- Medium operational environment (coverage area radius is randomly selected from the range between 5 km and 25 km)
- Bad operational environment (coverage area radius is randomly selected from the range between 10 km and 50 km).

We assume that within the selected geographical area the given number of TV channels is available for white space communication. In this paper we show results for one, three, and five available channels. We also assume that each white space radio system needs one channel for its operation.

Finally, in our simulation we do three types of averaging of the simulation results. We average the results over different randomly selected positions of white space radio systems, over different randomly selected coverage area radius, and over different randomly selected order of white space radio systems which select their operating channels. To get each simulation result, we do averaging over 100 realizations of above mentioned random variables.

B. Simulation of Discovery Service

We call two white space radio systems neighboring if their coverage areas overlap. We assume that neighboring systems cannot use the same channel for operation, they must use different channels. If they have selected the same channel, we assume that both of them cannot operate due to mutual interference.

We consider two simulation scenarios:

- Coexistence simulation scenario
- Non-coexistence simulation scenario.

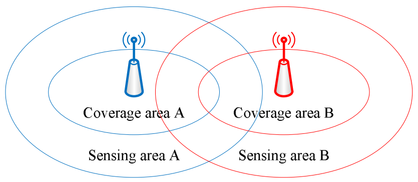
In coexistence simulation scenario, all white space radio systems can use the discovery service of the IEEE 802.19.1 system. In particular, each white space radio system reports its coverage area and operating channel to IEEE 802.19.1 system. Using coverage areas information, IEEE 802.19.1 system calculates list of neighbors for each white space radio system and provides this list of neighbors and their operating channels to white space radio systems.

When coexisting white space radio system is selecting channel for its operation, it selects one of the available channels that is not used by any of its neighboring white space radio systems. If no such channel is available, such white space radio system is not operating.

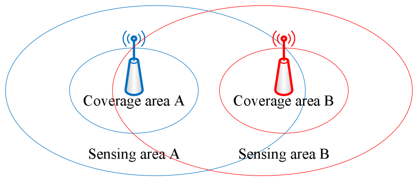
In non-coexistence simulation scenario, all white space radio systems do not use the discovery service of the IEEE 802.19.1 system. Correspondingly, they need to determine their neighbors and occupied channels by themselves using sensing.

We model this by using sensing area concept. We define parameter called "ratio of sensing area radius to coverage area radius." We call white space radio system A as detected neighbor of white space radio system B if white space radio system A is located within sensing area of white space radio system B. In such case, two types of bad situation can occur, as illustrated in Figure 2:

- Misdetection situation
- False alarm situation.



Misdetection situation



False alarm situation

Figure 2. Misdetection and false alarm situations.

Misdetection situation means that coverage areas of white space radio systems A and B overlap, but white space radio system A is out of sensing area of white space radio system B. In this case, if eventually white space radio system A selects operating channel which is the same with operating channel of white space radio system B, they will create interference to each other. In our simulation we assume that in this case both systems cannot operate due to mutual interference.

False alarm situation means that coverage areas of white space radio systems A and B do not overlap, but white space radio system A is inside sensing area of white space radio system B. In this case, white space radio system B can use the same channel that is used by white space radio system A, but it will not use it because it is detected as occupied by white space radio system A.

C. Operational Environment

We have introduced three types of operational environment: good, medium, and bad. Here, we would like to give some numerical values describing these three types of operational environment.

Figure 3 shows average number of neighboring white space radio systems for one white space radio system as a function of total number of white space radio systems in the area.

When total number of white space radio systems increases from 10 to 200, the average number of neighbors changes from 0 to 7 for good operational environment, from 1 to 43 for medium operational environment, and from 5 to 120 for bad operational environment.

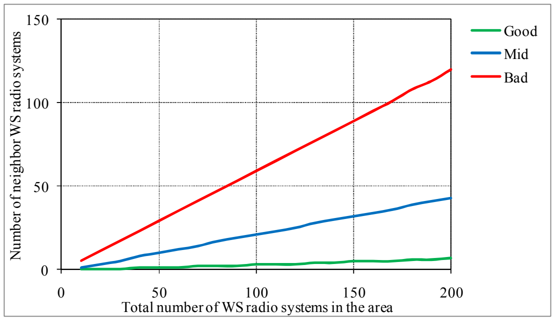


Figure 3. Illustration of operational environment.

D. *Selection of Sensing Area*

When we compare coexistence and non-coexistence scenarios, the results are very much dependent on the ratio between sensing area radius and coverage area radius. For fair comparison, we need to select this ratio such that misdetection situations and false alarm situations are minimized as much as possible. To do so, we compare average number of actual neighbors with average number of detected neighbors using simulation.

As could be expected, when sensing area radius is two times larger than coverage area radius, the average number of detected neighbors is very close to the average number of actual neighbors. When the sensing area is the same with the coverage area, the average number of detected neighbors is considerably smaller than the average number of actual neighbors. This will lead to many misdetection situations. When the sensing area radius is four times larger than the coverage area radius, the average number of detected neighbors is considerably larger than the average number of actual neighbors. This will lead to many false alarm situations.

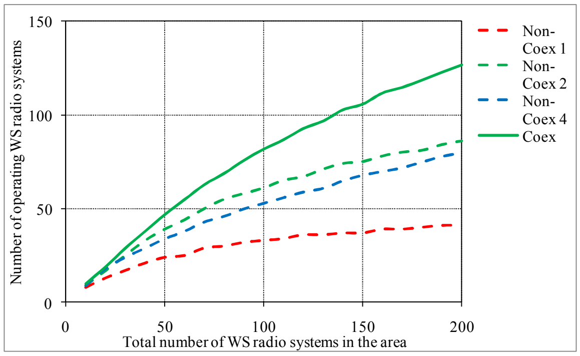


Figure 4. Checking selection of sensing area.

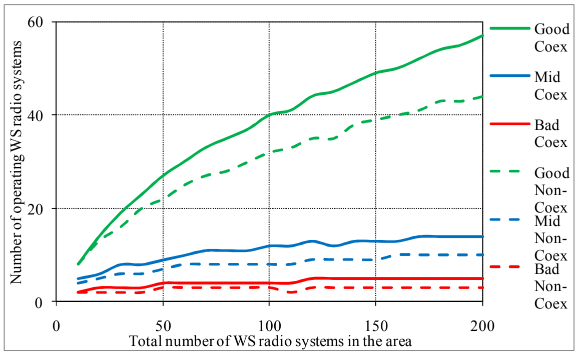
As a result, on average the best choice is to make sensing area radius two times larger than coverage area radius. To check this result we simulated coexistence and non-coexistence scenario for the number of available channels equal to three, for good operational environment, for the ratio between sensing area radius and coverage area radius equal to one, two, and four. Figure 4 shows average number of operating white space radio systems as a function of total number of white space radio systems in the area for this simulation. Results shown in Figure 4 prove our selection of sensing area size. So, for the rest of the simulation we will set sensing area radius two times larger than coverage area radius for fair comparison of coexistence and non-coexistence scenarios.

IV. SIMULATION RESULTS

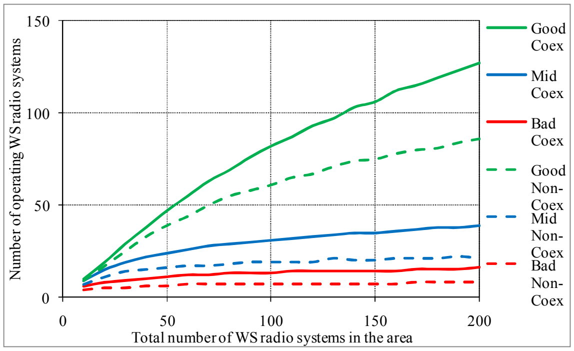
A. *Performance Evaluation of Discovery Service*

To analyze the performance of the discovery service of the IEEE 802.19.1 coexistence system, we have compared coexistence simulation scenario (discovery service is used) and non-coexistence simulation scenario (discovery service is not used).

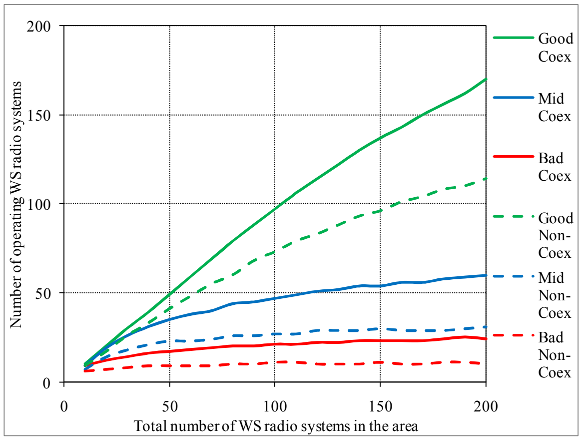
Figure 5 shows average number of operating white space radio systems as a function of total number of white space radio systems in the area for coexistence and non-coexistence scenarios for different number of available channels and for different operational environment types.



(a) One available channel



(b) Three available channels



(c) Five available channels

Figure 5. Comparison of coexistence (using discovery service) and non-coexistence (not using discovery service) scenarios.

From Figure 5 we see that with quite small increase in the number of available channels from one to three and to five, the average number of operating white space radio systems increase considerably. For example, for good operational environment for the total number of the white space radio systems in the area equal to 200, the average number of operating white space radio systems increases from 57 to 127 and then to 170 for coexistence scenario.

Table 1 shows the average gain in the number of operating white space radio systems for coexistence scenario compared to non-coexistence scenario. The averaging is done over the total number of white space radio systems in the area. In other words, each pair of curves in Figure 4 is represented by one value in Table 1. The following observations can be done from the results presented in Table 1.

Table 1. Gain from using discovery service of IEEE 802.19.1.

	Good operational environment	**Medium operational environment**	**Bad operational environment**
One available channel	1.22	1.37	1.53
Three available channels	1.32	1.62	1.85
Five available channels	1.32	1.72	2.04

First, when operational environment goes from good to medium and then to bad, considerable increase in gain of coexistence scenario compared to non-coexistence scenario can be observed due to the following reason. Even for optimized sensing area size, only the average number of detected neighbors is approximately equal to the average number of actual neighbors. For each particular white space radio systems there is difference in the list of detected neighbors compared to the list of actual neighbors. When operational environment goes from good to medium and then to bad, the average number of actual neighbors increases. Correspondingly, the number of detection mistakes also increases.

Then, when number of available channels increases, considerable increase in gain of coexistence scenario compared to non-coexistence scenario can be observed especially for medium and bad types of operational environment. The reason is that with perfect knowledge of actual neighbors in coexistence scenario the increased number of available resources can be better utilized.

Finally, it is worth to mention that even for optimized sensing area size the gain of coexistence scenario compared to non-coexistence scenario is quite large, ranging from 20% to 100% for simulation parameters considered. This shows the importance of the discovery service of the IEEE 802.19.1 coexistence system.

B. *Performance Evaluation of White Space Management Service*

As has been shown above, the discovery service of the IEEE 802.19.1 coexistence system is very important. We analyze the white space management service under assumption that the discovery service is used.

First, we analyze the case when the white space management service is not used.

Figure 6 shows scattering plot of percentage of operating white space radio systems out of total number of white space radio systems in the area as a function of average number of neighbors for one, three, and five available channels. Each scattering plot in Figure 6 combines all three types of operational environment.

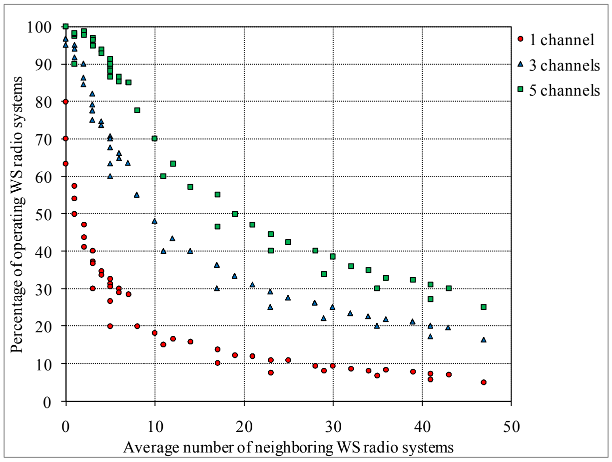


Figure 6. Percentage of operating white space radio systems.

The most interesting observation from the results shown in Figure 6 is that even for the average number of neighbors much larger than the number of available channels, the percentage of operating white space radio systems is quite large.

This observation is summarized in Table 2. For example, for 5 neighbors and five available channels, 90% of white space radio systems can operate. For 20 neighbors and five available channels half of white space radio systems can operate. Even for one available channel, if the average number of neighbors equal to 5, 30% of white space radio systems can operate. This means that even if the white space management service of the IEEE 802.19.1 system is not used, the average number of operating networks is quite large even for small number of available channels.

Table 2. Percentage of operating white space radio systems.

	One available channel	**Three available channels**	**Five available channels**
5 neighbors	30%	70%	90%
10 neighbors	20%	50%	70%
20 neighbors	10%	30%	50%

Secondly, we show some indication of how much gain can be obtained from using the white space management service. For this purpose we compare autonomous channel selection algorithm and optimal channel selection algorithm, which checks all possible combinations of channel assignments and select the one corresponding to the maximum number of operating white space radio systems. Such optimal algorithm corresponds to the best possible performance of the white space management service of the IEEE 802.19.1 coexistence system.

Figure 7 shows average number of operating white space radio systems as a function of total number of white space radio systems in the area for coexistence scenario for autonomous and optimal channel selection algorithms. Due to high computational complexity of optimal algorithm, we have selected one available channel.

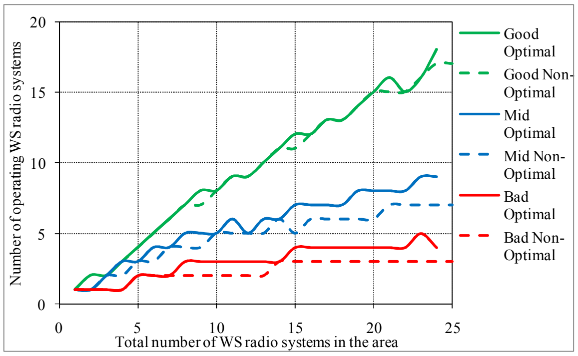


Figure 7. Comparison with optimal algorithm.

As can be seen from Figure 7, the gain of the optimal algorithm is very small compared to the autonomous algorithm. So, at least for one available channel, we do not expect big advantage from using the white space service of the IEEE 802.19.1 coexistence system.

So far we have used the average number of operating white space radio systems as a comparison criterion. In practice, some level of fairness between the white space radio systems should be definitely provided. In such case instead of having operating and non-operating white space radio systems, all white space radio systems will operate, for example, by occupying one channel for only some portion of time. We see enabling fairness as the main role of the white space management service of the IEEE 802.19.1 coexistence system.

One of the appropriate methods to enable some level of fairness is to provide time-frequency scheduling by the white space management service of the IEEE 802.19.1 coexistence system. This means that instead of operating and not operating white space radio systems considered in this paper, in practice we will have white space radio systems sharing one or several channels according to schedule provided by IEEE 802.19.1 coexistence system.

For such practical scenario, the simulation results presented in this paper directly apply by interpreting the number of operating networks as capacity. For example, if the total number of white space radio systems in the area is 100 and the number of operating white space radio systems is 50, than in case of fair sharing each white space radio system will have half of the capacity it can get from one channel. For example, Table 1 can be directly used to see gain in the capacity of one white space radio system. Table 2 can be used to see expected capacity of one white space radio system compared to its capacity when fully occupying one channel.

V. CONCLUSIONS

In this paper we have analyzed coexistence mechanisms that can be provided by IEEE 802.19.1 coexistence system. IEEE 802.19.1 coexistence system can provide many services to white space radio systems. In this paper we have considered two services: discovery service and white space management service.

The discovery service provided by the IEEE 802.19.1 coexistence system is the most important one. This service allows each IEEE 802.19.1 compliant white space radio system to know its neighbors and their operating channels. Even for optimized sensing area (sensing is used by non IEEE 802.19.1 compliant white space radio systems to detect occupied channels), the gain in the number of operating networks obtained from using the discovery service is very high. In the simulation results presented here this gain ranges from 20% to 100%. For not optimized sensing area size the gain is much more.

The white space management service provided by the IEEE 802.19.1 coexistence system is not expected to provide any considerable gain in the number of operating networks. The reason is that the autonomous channel selection algorithm provides quite good results in case white space radio systems are using the discovery service of the IEEE 802.19.1 coexistence system. Even for large average number of neighbors like 5, 10, and 20, and for small number of available channels like 1, 3, and 5, the percentage of operating networks is quite high.

The provided comparison with the optimal algorithm (which corresponds to the best possible performance of the white space management service) does not give indication that we can get any noticeable gain in the number of operating networks by using the white space management service provided by the IEEE 802.19.1 coexistence system.

However, the white space management service is necessary to enable some level of fairness between the white space radio systems. This can be done by providing time-frequency scheduling, that is, white space radio systems will share one or several channels according to the schedule provided by the IEEE 802.19.1 coexistence system.

The IEEE 802.19.1 standard is at the early stage of its development. At this stage it is very important to consider different design directions and focus areas. We believe that simulation results shown in this paper and analysis of these results are very important for the future of both the IEEE 802.19.1 standard and products based on this standard.

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