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BIOlogically-inspired Spectrum Sharing in Cognitive Radio Networks

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Abstract— **Cognitive radio is the promising radio technology, which aims to detect and utilize the temporally unused spectrum bands by sensing its radio environment in order to enhance spectrum utilization. However, these objectives bring significant challenges and required functionalities such as spectrum sensing, sharing, management and mobility for the realization of Cognitive Radio Networks (CRN). In particular, efficient spectrum sharing problem in cognitive radio communication is one of the most important problem which must be addressed in order to enhance the overall spectrum utilization in dynamic spectrum access environments. In this paper, we introduce a new BIOlogically-inspired Spectrum Sharing (BIOSS) algorithm which is based on the adaptive task allocation model in insect colonies. Without need for any coordination among the unlicensed users, BIOSS enables each unlicensed user to distributively determine the appropriate channel(s) over which it can communicate. Performance evaluations clearly reveal that BIOSS achieves efficient dynamic spectrum sharing with high spectrum utilization and without any coordination among the users and hence yielding no spectrum handoff latency overhead due to coordination.**

I. INTRODUCTION

The spectrum access of the wireless networks is generally regulated by governments via a fixed spectrum assignment policy. Thus far, the policies have satisfactorily met the spectrum needs of the wireless networks. However, in the recent years, the dramatic increase in the spectrum access of the pervasive wireless technologies has caused scarcity in the available spectrum bands. Therefore, the limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the entire existing wireless spectrum opportunistically [1]. This new networking paradigm is referred to as NeXt Generation (xG) Networks as well as Dynamic Spectrum Access (DSA) and Cognitive Radio Networks (CRN) [1].

Cognitive radio has the ability to capture or sense the information from its radio environment. Based on interaction with the environment, cognitive radio enables the users to communicate over the most appropriate spectrum bands which may be licensed or unlicensed. Since the most of the spectrum is already assigned to the licensed users (primary user) by the governmental policies, cognitive radio mainly strives for the communication over the licensed spectrum band. In the licensed spectrum bands, cognitive radio exploits the temporally unused spectrum which is defined as the spectrum hole or white space [2]. If cognitive radio encounters the licensed user at the licensed spectrum band, it moves to another spectrum hole or stays in the same band without interfering with the licensed user by adapting its communication parameters such as transmission power or modulation scheme. As for the unlicensed spectrum bands in which the licensed users cannot exist, all users have the same priority to access the existing unlicensed spectrum bands. The cognitive radio technology enables the users to opportunistically access the available licensed or unlicensed spectrum bands through four main functionalities required: (i) spectrum sensing, (ii) spectrum managing, (iii) spectrum mobility and (iv) spectrum sharing [1]. Among these, *spectrum sharing* is one of the most important function in cognitive radio, which allows cognitive radio to fairly share the available spectrum bands among the coexisting cognitive radios.

There exist some research efforts on the problem of spectrum sharing in cognitive radio. In some of these studies, the conventional approaches based on the centralized control [3], [4] are introduced. However, due to the heterogeneous and dynamic nature of cognitive radio, centralized approaches are not practical. Instead, in some studies, the distributed approaches which do not need any central controller are suggested [5], [6]. In [5], a distributed coordination which does not need any central controller is proposed. In [6], Asynchronous Distributed Pricing (ADP) scheme is proposed, based on the signal exchange via coordination between users to compensate the ascendant interference level. Due to their distributed approaches, these studies provide better adaptation capability to cognitive radio in the dynamically changing heterogeneous environment. However, the coordination among cognitive radios results in significant amount of coordination delay. Since cognitive radio should experience minimum delay to provide seamless communication capability during the spectrum handoff, the distributed spectrum sharing must provide minimum delay. In [7], decentralized cognitive medium access control protocols are proposed which enable secondary users to share the available spectrum according to their partial observations. However, the protocols do not consider the fairness of the spectrum sharing. In [8], a device-centric spectrum management scheme with low communication costs is proposed. According to this scheme, users observe their

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local interference patterns and select the appropriate spectrum and communication parameters. This scheme enables cognitive radio to non-cooperatively and fairly share the available spectrum. However, it does not consider the spectrum sharing for the multiple spectrum sharing case. In this paper, we introduce BIOlogically-inspired Spectrum Sharing (BIOSS) algorithm which is based on the adaptive task allocation model of an insect colony. Without need for any coordination among the unlicensed users, BIOSS enables each cognitive radio in the same environment to distributively share the available licensed or unlicensed spectrum bands over which it can effectively communicate. Furthermore, BIOSS enables cognitive radios to distributively decide the multiple spectrum bands over which it can simultaneously communicate without any coordination among cognitive radios.

The rest of the paper is organized as follows. In Section II, we discuss some relation between biological task allocation and spectrum sharing in cognitive radio. In Section III, we introduce the BIOSS protocol algorithm and its detailed operation principles. Performance evaluation results and discussions are provided in Section IV, which is followed by Section V with concluding remarks.

II. INSECT COLONY AND SPECTRUM SHARING IN COGNITIVE RADIO NETWORKS

As a result of its ability to interact with its environment, cognitive radio enables the users to communicate over the most appropriate spectrum bands which may be licensed or unlicensed. Furthermore, cognitive radio can use multiple spectrum bands simultaneously. Moreover, the selected spectrum bands are not necessary to be contiguous [1]. This provides less performance degradation during spectrum handoff to cognitive radio [1]. This is mainly because, when cognitive radio vacates a spectrum band (spectrum handoff) due to any reason such as appearing licensed user, cognitive radio communication is not interrupted since cognitive radio continues the communication over the rest of spectrum bands. Although the multi-spectrum transmission promises for cognitive radio applications, a spectrum sharing model which can effectively share the all available spectrum bands is a challenging issue.

Similar to cognitive radio, in insect colonies, individuals sense the environment to detect the tasks and then, the detected tasks are performed simultaneously by individuals which are better equipped for the task. Here, we adopt this natural mechanism to introduce an effective spectrum sharing model for CRN.

A. Task Allocation Model of Insect Colony

In the ant colonies, each ant has relatively little intelligence, while the collaborative behavior of the colony provides a great deal of global intelligence which is capable of optimizing certain tasks. In social insect colonies, different activities are often performed simultaneously by individuals which are better equipped for the task. This phenomenon is called division of labor [9].

Here, for task allocation problem in insect colony, every individual has a *response threshold* for every task [9]. Response threshold refers to the likelihood of reacting to a task-associated stimuli. Task-associated stimuli s, is defined as the intensity of an activator associated with a particular task and it can be a number of encounters such as a chemical concentration, or any cue sensed by individuals. For example, if the task is larval feeding, the task-associated-stimuli s, may be larval demand expressed through the emission of the pheromone, i.e., a chemical substance deposited by real life ants [9]. Individuals perform the task when the level of the task-associated stimuli s, exceeds their threshold. Therefore, a response threshold θ determines the tendency of an individual to respond to the stimuli s, and perform the associated task.

Thus, based on the above definitions, the probability of performing task as a function of stimuli intensity s, and response threshold θ, is given by

$$T_\theta(s) = \frac{s^n}{s^n + \theta^n}, \tag{1}$$

where $n > 1$ determines the steepness of the threshold. As observed in (1), for $s << \theta$, the probability of performing the task is close to zero and for $s >> \theta$, this probability is close to 1. Therefore, performing the task is likely for $s >> \theta$ and unlikely for $s << \theta$.

In the following, we apply the task allocation model of insect colony to establish an effective dynamic spectrum sharing model for CRN.

B. Biological Task Allocation Based Spectrum Sharing Model for Cognitive Radio Networks

Spectrum sharing in cognitive radio has great similarities with task allocation in insect colony. For example, cognitive radio senses the environment for the available spectrum bands and then, simultaneously transmits its packets to available spectrum bands. Similarly, in an insect colony, individuals sense the environment through the pheromone for available tasks and, then available tasks are accomplished by individuals better equipped for the tasks. In biological model, each task is shared to individuals better equipped for this task through the task performing probability given in (1). Similarly, in CRN, the available spectrum bands should be fairly shared to cognitive radios by the effective spectrum sharing model. According to this analogy, we adopt the task performing probability given in (1) to introduce the *channel selection probability* which enables cognitive radios to effectively share the best available spectrum bands. To this end, we map the task allocation model given in Section II-A to spectrum sharing in CRN as follows:

- We consider an insect in a colony as a cognitive radio.
- We consider a task as an available channel.
- We consider the task associated stimuli (s) as the estimated permissible power [10] to channel j (P_j), where j denotes channel j.
- We consider the response threshold of an insect (θ) as the required transmission power (p_{ij}) for cognitive radio

i to channel j. Cognitive radio i determines p_{ij} as the power which can meet the user requirements[1].

To summarize this mapping between CRN and insect colony, it is also outlined in Table I.

TABLE I
MAPPING BETWEEN CRN AND INSECT COLONY

Insect Colony	**Cognitive Radio Networks**
Insect	Cognitive radio
Task	Available channel
Task associated stimuli (s)	Permissible power to channel (P_j)
Response threshold (θ)	Required transmission power p_{ij})

According to the mapping discussed above and following (1), we introduce the channel selection probability T^{csp} as

$$T_{ij}^{csp} = \frac{P_j^n}{P_j^n + \alpha p_{ij}^n + \beta L_{ij}^n}, \tag{2}$$

where $n > 1$ determines the steepness of the channel selection probability T_{ij}^{csp} and α and β are the positive constants for respective influences of L_{ij} and p_{ij}.

L_{ij} is a learning factor which enables cognitive radio i to learn or forget the channel j. If channel j provides the QoS requirement of cognitive radio i, channel j is learned by cognitive radio i and L_{ij} is updated as $L_{ij} - \xi_0$. If channel j cannot provide the QoS requirement of cognitive radio i, channel j is forgotten by cognitive radio i and L_{ij} is updated as $L_{ij} + \xi_1$. ξ_0 and ξ_1 are the learning and forgetting coefficients, respectively.

For sharing the available spectrum bands, each cognitive radio computes the channel selection probability for every available channel ($T_{ij}^{csp}, \forall j$). Then, the channel selection probabilities ($T_{ij}^{csp}, \forall i, j$) are used by the cognitive radios to effectively capture the available spectrum band in the following way:

- When the estimated permissible power to channel j (P_j) is immensely larger than the required transmission power of cognitive radio i ($P_j >> p_{ij}$), T^{csp} is close to one and it is most probable that cognitive radio i transmits to channel j.
- When the estimated permissible power to channel j (P_j) is much less than the required transmission power of cognitive radio i ($P_j << p_{ij}$), T^{csp} is close to zero and it is almost impossible that cognitive radio i transmits to channel j.
- For a constant p_{ij}, as the permissible power to channel j (P_j) increases, the probability that cognitive radio i transmits to channel j increases.
- For a constant P_j, as the required transmission power of cognitive radio i (p_{ij}) increases, the probability that cognitive radio i transmits to channel j decreases.
- If channel j has the small P_j, it is highly likely that channel j is allocated by the cognitive radios having the small required transmission power (p_{ij}). This provides that the channels having less permissible power are allocated by cognitive radios having less user demand.
- If channel j has the large P_j, channel j may be allocated by the cognitive radios having the small or big required transmission power (p_{ij}). This provides that the channels having more permissible power are allocated by cognitive radios having less or more user demand.
- If the spectrum handoff is triggered by the appearance of licensed user or any location change, (2) becomes zero for channel j due to $P_j = 0$ for all cognitive radios ($\forall i$) until channel j is again available. Furthermore, in this case, for channel j, all learning coefficients ($L_{ij}, \forall i$) are set to initial values.

(2) is computed by each cognitive radio when there is any change in the time-varying environment or user requirements. Thus, (2) enables cognitive radio to easily adapt to the instantaneous changes in the environment or user requirement, such as small holding time, user mobility, appearing the licensed user and hence to distributively share the available spectrum bands without any central controller and any coordination.

III. BIO-INSPIRED SPECTRUM SHARING PROTOCOL (BIOSS)

According to the model given in Section II-B, the detailed operation of BIOSS protocol algorithm is outlined here. In order to distributively conduct spectrum sharing by following the steps below, each cognitive radio i:

- determines the available spectrum bands by means of the appropriate spectrum sensing algorithms.
- estimates the permissible powers (P_j) to the all available channels ($P_j, \forall j$).
- sets the learning factor for every available channel ($L_{ij}, \forall j$) as the same initial values and sets the learning coefficients ξ_0, ξ_1 to appropriate values (e.g., $\xi_0 = \xi_1 = 10$ assumed for simulation experiments in Section IV to have equal learn and forget rates).
- computes the channel selection probability T^{csp} for all available channels ($T_{ij}^{csp}, \forall j$)
- selects the channel having maximum T_{ij}^{csp} to transmit its packets. Similarly, to use the multiple spectrum bands, cognitive radio selects the channels having larger T_{ij}^{csp}. If the number of channels is not adequate to meet the QoS requirements, cognitive radio increases the number of channels to transmit its packets.
  - If the selected channel meets the QoS requirements, cognitive radio using this channel *learns* this channel by updating learning factor ($L_{ij} = L_{ij} - \xi_0$).
  - If the selected channel can not meet the QoS requirements, cognitive radio using this channel *forgets* this channel by updating learning factor ($L_{ij} = L_{ij} + \xi_1$).
- When the spectrum handoff is triggered by the licensed user appearance or any location change, the permissible

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[1] The required transmission power (p_{ij}) can be determined according to the user requirements, acceptable interference level, acceptable path loss and channel link error by the effective spectrum management model.

power to vacated channel is set to zero $(P_j = 0)$ and all learning factors for this channel $(L_{ij}, \forall i)$ is set to initial values.
- Apart from the spectrum handoff, when any change occurs at the environment, all channel selection probabilities $(T_{ij}^{csp}, \forall i, j)$ is distributively computed by all cognitive radios.

Thus, BIOSS enables cognitive radios to distributively share the available spectrum bands without any coordination. This provides the better adaptation capability to instantaneous changes in the dynamically changing radio environment. It also provides cognitive radio the seamless communication capability. Furthermore, the learning capabilities of BIOSS enables cognitive radio to learn the slowly changing radio environment.

According to BIOSS, while the interference increase, the permissible power to channel decrease. Therefore, the channel having small permissible power due to the interference can be preferred by the cognitive radio which needs the small power. This enables the cognitive radios to control the interference in the channels such that the channel having more interference can be preferred by the cognitive radio which needs the less transmission power.

BIOSS has the spectrum efficiency such that according to the biologically inspired channel selection probability, while the cognitive radio which needs the more transmission power for its Qos demands prefers the channel which permits the more transmission power, the cognitive radio which needs the less transmission power prefers the channel which permits the less transmission power.

Consequently, BIOSS allows cognitive radio to effectively share the available spectrum bands and provides the seamless communication capability.

IV. PERFORMANCE EVALUATIONS

In this section, we present the simulation results on the performance of BIOSS protocol. In order to evaluate the performance, we develop a simulation environment using MATLAB. Firstly, we give some assumptions for the simulation environment and then, we present the results on the performance of BIOSS. Our first results are related to the case that each cognitive radio uses only single channel among the available channels. The second set of results are for the case that each cognitive radio uses multiple channel simultaneously.

A. Simulation Environment

We assume that the randomly deployed licensed and unlicensed users with cognitive radio coexist in the environment. The number of users changes from 5 to 50 while the number of channel changes from 5 to 25. Each unlicensed user can access all available channel while the licensed users can access any channel to transmit with a fixed probability. We also assume that licensed users give only the instantaneous interrupt to the channels.

B. Spectrum Sharing with Single Channel Selection

In this section, we give the performance evaluations of BIOSS when each cognitive radio selects and communicates over one channel. We give simulation parameter in Table II.

TABLE II
SIMULATION PARAMETERS

Number of channels	$5 - 25$
Number of cognitive radios	$5 - 50$
Initial permissible power interval (P_j)	$0 - 400mW$
Transmission power interval (p_{ij})	$10 - 40mW$
Initial learning factors interval (L_{ij})	$10 - 40$
Learning coefficient (ξ_0)	10
Forgetting coefficient (ξ_1)	10
α	10
β	5

Firstly, we conduct the simulation to observe that how the used power at the channels changes according to time. In Fig. 1, it is observed that $0 < t < 25$ $seconds$, the used power at the channels oscillates because of the available channels are being captured by cognitive radios. However, after $t = 25s$, since each cognitive radio learns its appropriate channel, the channel shows stationary behavior although the channels are interrupted by licensed user. BIOSS enables the cognitive radio to eventually learn the appropriate spectrum band. This provides the convergence to appropriate spectrum band. However, since the system is dynamically interrupted by the licensed user, it is not possible to completely converge the proposed algorithm. In Fig. 2, similar to Fig. 1 we show that the used power at the channels without the interruption of the licensed user. As observed, after $t = 25s$, each cognitive radio finds and learns its appropriate channel, that is, the channel allocation process converges.

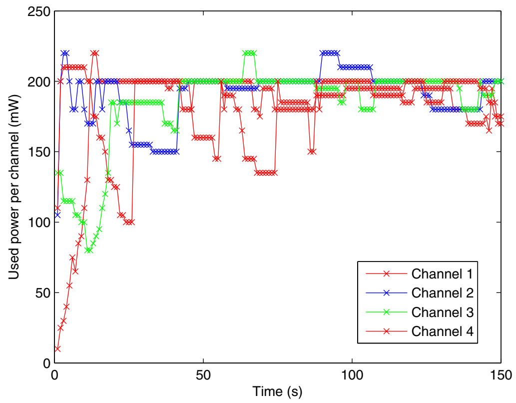

Fig. 1. The changes in the used power at the four channels according to the time in the single selection case with the licensed user interruption.

The overall spectrum utilization as a function of the number of channels is shown in Fig. 3. The number of channels is set to be in between 5 and 25. Here, the number of cognitive radios is

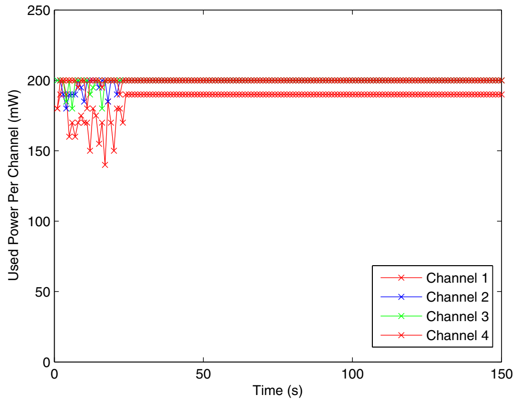

Fig. 2. The changes in the used power at four channels according to the time in the single selection case without the licensed user interruption.

fixed at 10. As shown in Fig. 3, the overall spectrum utilization is slightly above 50% regardless of the number of channels used. Therefore, the utilization is not affected by the number of channels. For this, the main reason is that BIOSS enables cognitive radios to learn their best spectrum which keeps utilization per user even the number of channel increases. We note that the main aim of the spectrum utilization part in the performance analysis is to show that BIOSS provides the great spectrum utilization while providing the seamless communication to cognitive radio.

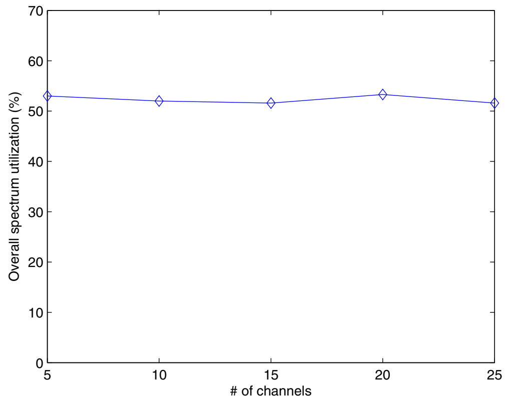

Fig. 3. The channel utilization according to the different number of channels in single channel selection.

C. Spectrum Sharing with Multiple Channel Selection

In this section, we give the performance evaluations of BIOSS when each cognitive radio selects and communicates over multiple channel. According to the same simulation parameters given in Table II, we assume that each cognitive radio selects three channels to communicate and transmits the same amount of power to the selected channels. Again, we conduct the simulation to observe that how the used power at the channels changes according to time. In Fig. 4, it is shown that in $0 < t < 15\ seconds$, the used powers at the channels oscillates because of a lot of spectrum handoff which result from sharing of available spectrum bands. However, after $t = 15s$, since each cognitive radio allocates the available channels, the used power at the channels shows nearly static behavior although the channels are interrupted by the licensed users.

In the multiple channel selection, the licensed user interrupts slightly affect the channel usages of unlicensed users with respect to the spectrum sharing with single channel selection. Moreover, while in single spectrum case channel allocation process converges after $t = 25s$, in multiple case, channel allocation process converges faster (e.g., after $t = 15s$). This is mainly because that in the multiple spectrum selection, the power load of all unlicensed users is shared to the available channels.

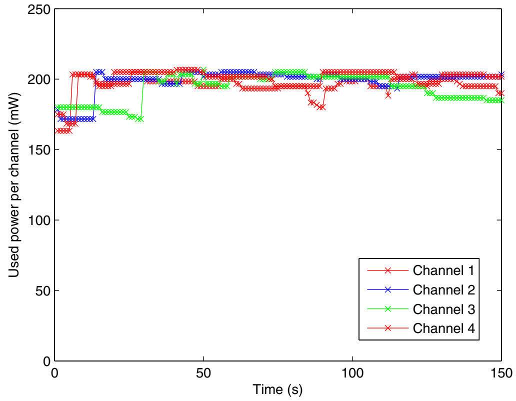

Fig. 4. The changes in the used power at the four channels according to the time in the multiple selection case.

The overall spectrum utilization as a function of the number of users is shown in Fig. 5 for both single spectrum and multi-spectrum cases. As observed in Fig. 5, while the number of unlicensed users increases from 0 to 30, the channel utilization increases for both cases from 0 to 95 percent. However, there is a slightly higher increase in the utilization of multi-spectrum case, which is mainly due to the fact that it intrinsically enables better utilization of the overall spectrum. Note also that as the number of users further increases, the improvement achieved by the multi-spectrum case over single-spectrum is also amplified due to the same reason.

On the other hand, in Fig. 6, we observe the expected handoff delay due to coordination with different number of unlicensed users in a single channel selection case. Here, recall that BIOSS does not require any coordination among unlicensed users. Therefore, the objective of this experiment is to show that how much BIOSS saves in terms of potential spectrum handoff delay compared to the existing spectrum sharing techniques which achieve distributed spectrum sharing with a cost of coordination incurred handoff delay. Here, we assume that every spectrum handoff attempt incurs 1 unit of additional coordination related latency. Therefore, as observed

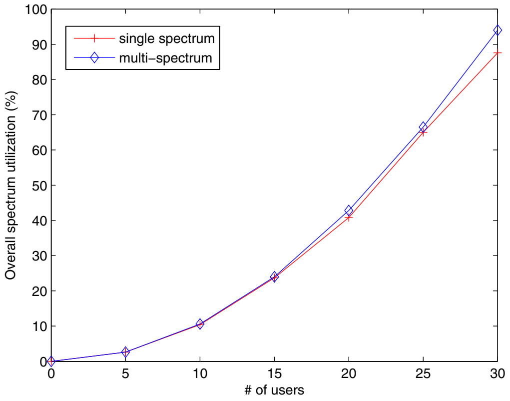

Fig. 5. The channel utilization according to the different number of unlicensed users in the single and multiple channel selection.

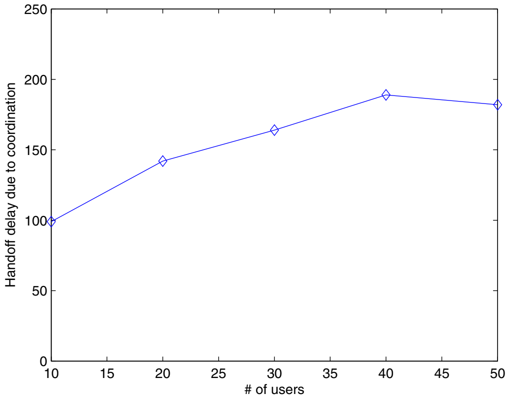

Fig. 6. Expected spectrum handoff delay due to coordination for varying number of unlicensed users in single channel selection.

from Fig. 6, as the number of users increases, the latency overhead of coordination based methods increases as well. Consequently, BIOSS outperforms the existing methods in terms of seamless spectrum mobility support by avoiding additional spectrum handoff delay.

V. Conclusion

Efficient spectrum sharing is an important and challenging problem in cognitive radio networks which must be addressed in order to enhance the overall spectrum utilization. In this paper, we introduced a new BIOlogically-inspired Spectrum Sharing (BIOSS) algorithm which is based on the adaptive task allocation model in insect colonies. BIOSS does not need any coordination among the unlicensed users and achieves distributively determination of the appropriate channel(s). Simulation experiments show that BIOSS realizes efficient dynamic spectrum sharing with high spectrum utilization and without any coordination among the users and hence yielding no spectrum handoff latency overhead due to coordination.

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