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# Towards Sensing Performance and Energy Efficiency Trade-off of Spectrum Sensing in Cognitive Radio Networks

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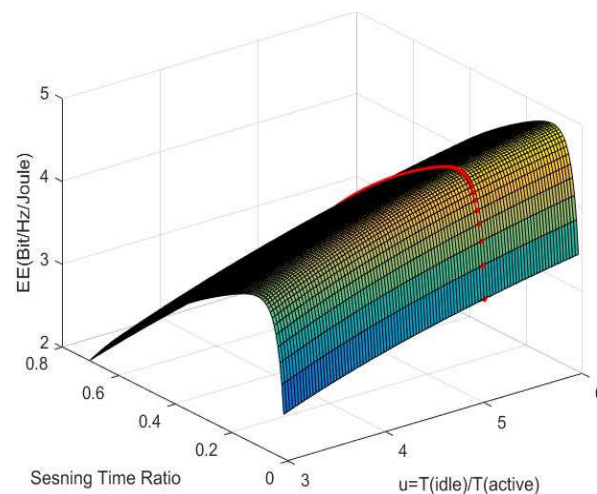
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Thèse  
de doctorat  
de l'UTT

**Tian YANG**

# Towards Sensing Performance and Energy Efficiency Trade-off of Spectrum Sensing in Cognitive Radio Networks



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# THESE

*pour l'obtention du grade de*

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**Spécialité : SYSTEMES SOCIOTECHNIQUES**

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**Tian YANG**

*le 14 janvier 2019*

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**Towards Sensing Performance and Energy Efficiency Trade-off of  
Spectrum Sensing in Cognitive Radio Networks**

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# Résumé

Les différentes priorités sont définies afin de distinguer l'usage du spectre dans les réseaux cognitifs: Les utilisateurs principaux(UP) accèdent à la bande en priorité ; les utilisateurs secondaires(US) ne possèdent l'accès que pendant l'absence d'UP.

Premièrement, les activités d'UP sont optimisées pour améliorer l'efficacité énergétique(EE). Une présence dominante d'UP peut baisser l'opportunité d'US pendant sa transmission; une absence dominante d'UP peut influencer le signal reçu du côté US, puis augmenter le risque de fausse alerte. Par conséquent, le problème du compromis des activités d'UP est considéré sous une forme d'EE conjointe pour l'UP et les US. Grâce à la méthode de dichotomie, la présence d'UP est optimisée avec le temps de détection dans un frame d'US pour pouvoir atteindre l'EE maximale.

Deuxièmement, une fonction d'utilité est formulée sous forme de "le débit moins la consommation d'énergie" pour décider s'il est rentable de transférer l'énergie au débit. Ainsi, l'accès opportuniste d'US peut être contrôlé dynamiquement par le jeu d'évolution de manière coopérative. Un schéma de réactivation est proposé pour résoudre la baisse du débit et de la performance de détection avec le temps insuffisant de détection, en activant les US d'une manière plus fréquente dans cette situation.

Les simulations indiquent que notre méthode peut gérer mieux les ressources dans les réseaux cognitifs, la coordination entre l'EE et la performance est améliorée. Selon l'observation de l'équilibre d'évolution, le comportement d'accès d'US est coordonné et évolué dynamiquement.

**Mots clés** — Radio cognitive; Théorie des jeux; Économies d'énergie; Qualité de Service; Allocation de ressources (radiotéléphonie)

# ABSTRACT

Different priorities of users' access are defined in cognitive radio networks (CRNs) in order to differentiate the spectrum usage: primary user (PU) preferentially occupies the band, whereas secondary users (SUs) can only have access to the band if PU is absent.

Firstly, PU activities are optimized to improve the energy efficiency (EE). Too much presence of PU could leave less opportunities for SU to access and transmit data; too much absence of PU could influence the received signal to noise ratio of SUs and therefore increase the false alarm probabilities. Hence, in this thesis, the tradeoff problem of PU's activities is considered in the coordinated PU-SUs formulation of EE. Using bi-section search method, PU's active ratio is optimized with sensing time ratio of a SUs' frame to always achieve the maximal EE of the whole network.

Secondly, a mixed utility function is formulated as "throughput-energy cost" to determine whether it is worthy of transferring energy into additional throughput, in order to dynamically control SUs' access attempts using an evolutionary game in cooperative sensing model. A re-activation scheme is especially presented to conquer the great fallings of throughput and sensing performance at low sensing time and to make SUs more active on the transmissions.

Simulation results show that our methods can better manage the resources in CRNs, EE and sensing performance are improved between PU and SUs. The observation of evolutionary equilibrium also shows that a balance can be achieved by adapting SUs' access behaviors in a cooperative way.

**Keywords** — Cognitive radio networks; Game theory; Energy conservation; Service-level agreements; Resource allocation

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# Glossary

<b>CRNs</b>	Cognitive Radio Networks
<b>(C)SS</b>	(Cooperative) Spectrum Sensing
<b>PU</b>	Primary User
<b>SU</b>	Secondary User
<b>FC</b>	Fusion Center
<b>SNR</b>	Signal-to-noise Ratio
<b>EE</b>	Energy Efficiency
<b>CoMAC</b>	computation over multiple-access chann
<b>QoS</b>	Quality of Servive
<b>DSA</b>	Dynamic Spectrum Access
<b>AWGN</b>	Additive White Gaussian Noise
<b>ESS</b>	Evolutionary Stable Strategy
<b>WFAS</b>	Water-filling Factor Aided Search
<b>OFDM</b>	orthogonal frequency-division multiplexing
<b>CSMA</b>	Carrier Sense Multiple Access
<b>MAC</b>	Medium Access Control
<b>QPSK</b>	Quadrature phase-shift keying
<b>Q(•)</b>	Standard Gaussian's complementary distribution function

# Chapter 1. General Introduction

## 1.1. Background of research

The industry of wireless communications has always been working on a high spectrum efficiency and low energy-cost network infrastructure with proper amount of service access distributed to unlicensed spectrum band. At the end of 20<sup>th</sup> century, the concept of cognitive radio was firstly proposed to solve the issue of limited spectrum resources and to improve the capacity of data transmission. In [1], S. Haykin gave an early definition of cognitive radio in a broad sense and considered it as *an intelligent self-learning system that automates operational parameters and adapts them to the best environment in terms of channel selections, power adaptations and resource allocations, etc., in order to always maintain the service quality and to provide reliable transmission.*

In this context, the cognitive radio (CR) networks are considered as spectrum-efficient and highly adaptive networks, which can automatically detect the availability of spectrum band, and select and occupy the unused channels in order to behavior opportunistic spectrum access, especially without interfering existing users on the band.

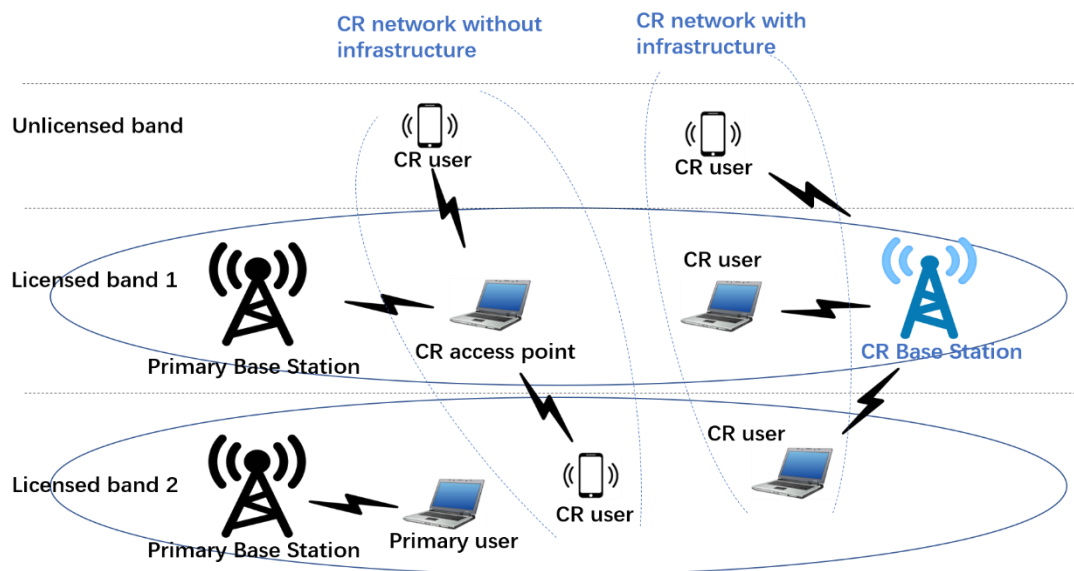


Figure 1.1. Infrastructure of cognitive radio networks

In Fig. 1.1, the general model of CR networks is presented with three spectrum bands divided for spectrum sharing. CR users (i.e. also called as secondary users in this thesis) can be connected either directly to a CR base station or to a primary user (PU)

who works as an access point. These users can work at any bands other than the one that PU is actually using, but they should respect the priority and avoid interfering PU. In addition to the use of conventional radio resources, employing CR resources (i.e., correspond to unlicensed band) is preferred to improve the total system performance. The functionalities of CR networks can be divided into two basic characteristics [1]:

- (1) **Cognitive abilities:** this characteristic indicates the capability of cognitive users to capture the information of spectrum usages.
- (2) **Reconfigurabilities:** this characteristic allows to automatically adapt the system parameters to the most suitable conditions according to the detected information.

These two characteristics represent how cognitive users detect and determine the presence of primary user, and how they react to it. To further study the architecture of cognitive radio, we present basic CR functions as follows:

- (1) **Spectrum sensing:** this function gives decisions of sensing results by periodically detecting the presence of PUs. Since it collects signal samples directly from radio environment and monitors PU's states, spectrum sensing (SS) technique is considered as one of the most critical functions in CR networks.
- (2) **Spectrum management:** it allows to find the best available channel and perform dynamic accesses once PU is detected as in absence state. The transmission mode should be adapted to the best condition of spectral resources, which refers to channel selection and interference management so as to improve the accuracy of decisions.
- (3) **Spectrum sharing:** it enables coordinating the CR users and performing information exchange among these users so that the availability of channel can be utilized in an optimized way by avoiding causing collisions of users on the spectrum band.
- (4) **Spectrum mobility:** this function explores new available access opportunities and transfers CR services into the vacant channels, without breaking down the quality of service. This CR function is especially suitable for the case of PU reactivation where PU requests to reoccupy the channel and the service should be transferred to others.

Among these functions, spectrum sensing is the most critical technique because it determines PU's state, and the result of sensing result is considered as the resource of decision-making in CR networks. Moreover, the accuracy of sensing process has a great impact on the quality of data communication, on the coordination between primary and secondary users, and on the rate of collision avoidance. Thus, the spectrum sensing technique is of great concern in this thesis.

Spectrum sensing techniques should provide CR users with timely and accurate reports of access opportunities and inform them to quit the band as soon as PU is detected present. The error rate of spectrum sensing is basically "0-1" and "1-0" mistakes (caused by latency, additive noise, etc.) either of these mistakes could cause important loss on transmission performances [2]-[6].

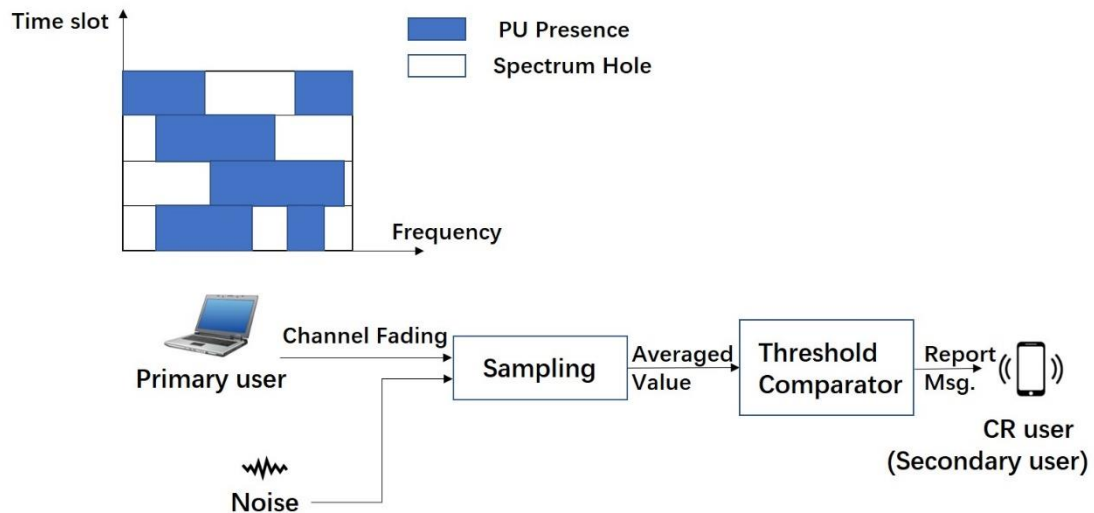


Figure. 1.2. The process of spectrum sensing techniques

As presented in Fig. 1.2, PU's presence is a random process due to the probability distribution and it evolves over time. With proper sampling frequency, the received signal of PU's presence is quantized and compared to a pre-set threshold to make sensing decision. This process ensures SUs to be aware of PU's states changes at any time and to report the measurements of states to the whole system, so that an opportunistic access can be notified and well-prepared.

However, the locations of SUs are in such a great mobility that the received signal at SUs is depended on different conditions of Rayleigh channel fading, shadowing, etc.

Thus, the diversity of SUs' received SNRs is caused by the uncertainty of SU's positioning and the selection of transmission channels.

To improve the accuracy of spectrum sensing, the cooperative spectrum sensing (CSS) technique is proposed in this thesis. Instead of individual SUs in conventional SS model, CSS groups some SUs as a cluster, and makes decisions from the common information of their results. For example, SUs, having obstructions (e.g. tall buildings, etc.) on their transmission paths, tend to only receive weakened signals, therefore PU is likely to be detected as idle, which brings potential risks of collisions. Thus, the CR network should request the SUs with less obstructions to be selected as the head of cooperative sensing process. In this way, CSS technique can avoid the uncertainty of the SUs detecting PU in a worse channel condition, and can thus increase the opportunity of correct detections.

In addition, the information of different SUs is collected based on the comparison of utility functions. These utility functions are defined according to several criteria, namely SNR, EE, sensing performance, etc. SUs who hold better sensing conditions are more likely to be selected as sensing performers (i.e., the "contributors") before reporting and fusing the final results.

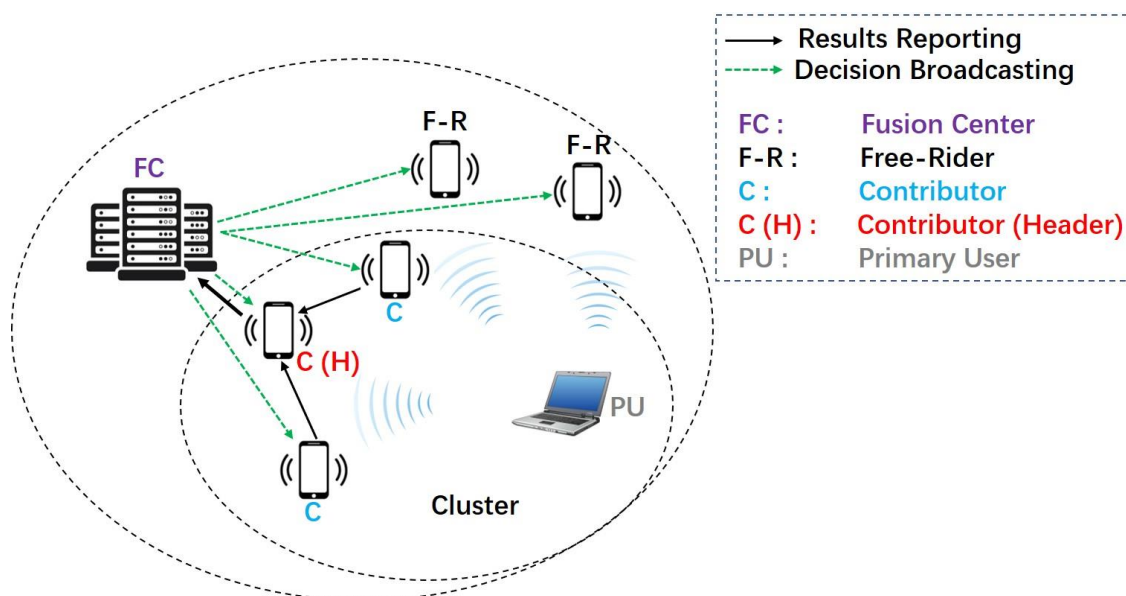


Figure. 1.3. Infrastructure of cooperative spectrum sensing (CSS):

An example of clustered-based CSS

As shown in Fig. 1.3, SUs in CSS model are divided into either the contributor who performs sensing or the free-rider who does not participate but only enjoys overhearing the final decision. For cluster-based CSS, a cluster head is selected to collect information within a cluster of SUs and to forward the sensing results to a decision center, which is called fusion center (FC). The head must possess high reliability and sensing accuracy. Then, each contributor makes individual sensing decisions according to their received signal strength, until a final decision is generalized at FC. Afterwards, the decision of FC is declared to all SUs including free-riders with a radio broadcasting message, after which all SUs start to perform consistent and regular transmissions on the spectrum band.

## **1.2. Problematic: Coordinative design between primary and secondary users**

Although spectrum sensing technique can remarkably improve the spectrum efficiency in an ideal case, the sensing performance is of great concern in a more practical view. The sensing errors can cause either spectrum waste that lowers spectrum efficiency, or collisions between PU and SUs which degrade the transmission qualities of both sides. Thus, the sensing performances depend on two major aspects:

(1) **At the source** – PU should be present and emit positive signals to guarantee the minimum received SNR. If PU presents seldomly, then the additive noise and channel fading could cause a serious deterioration on received signals. Thus, SUs might not be able to collect enough information for making a correct decision. In this regard, a minimum presence of PU should especially be guaranteed.

(2) **At the receiver** – SU turns received sensing results into access actions. During each SU frame, the sensing process accounts for a portion of time and the rest of a frame is fully contributed to the transmission. The sensing performance is highly related to the sensing time ratio and is rather important to consider while making the access decisions. For example, in cooperative sensing model, SUs that suffer from channel deteriorations should be excluded from the decision cluster in advance. Therefore, as the performance metrics can be estimated at the receiver's side, SUs should manage their access actions according to the reliability of their sensing performance.

For these reasons, to optimize the transmission targets (e.g. throughput, EE, etc.) which are basically depended on the sensing performance, the activities of both PU's and SUs' parts should be coordinated. Since the optimization of CR networks is a conjoint process subjected to QoS, SNR, power, etc. from these two parts, it requires PU and SUs to follow certain requirements while being designed as an integrated system. SUs' actions are relied closely on PU's behaviours, thus an intelligent access control scheme should be deployed so as to utilize the spectrum holes (i.e., available spectrum intervals of PU) properly without disturbing to PU's presence.

For PU's activities, it is of great concern that PU adapts its probability of presence to approach to the optimum of sensing and transmission targets. PUs must contribute to the transmission and energy efficiency while guaranteeing the sensing performance constraints being satisfied. Other impacts, like the reawake probability, should also be considered on PU, in order to avoid the abnormal transmissions and even the collisions caused by PU's irregular activities.

For SUs' reactions, the first problem is how to design the structure of SU's frame. A satisfaction of sensing performance should be achieved by spending more time on the sensing process, whereas sufficient duration should also be remained for data transmission in a frame. In addition, SUs' sensing results should be only accepted when the estimated sensing performance meet the requirements, otherwise SUs might tend to take an opposite decision other than the inaccurate sensing result. This is especially the case when high error rates are observed in CR network, where SUs cannot detect PU's states correctly and the use of spectrum band is wasteful. However, it still remains a question that how SUs get cooperated with each other in cooperative sensing and how to take the adaptive strategies to maintain the accuracy of spectrum sensing, especially to avoid the risks of miss detection and false alarm.

### **1.3. Objectives and main contributions**

The objective of this thesis is to propose solutions for maximizing the energy efficiency (EE) in CRNs, where EE is denoted by the transmission rate per unit energy consumption. EE optimization is an averaged target in a frame duration and is

composed of the calculations for SUs of different conditions. Thus, to achieve an optimized solution of EE, several situations are analyzed in parallel concerning analysis of channel conditions and error rates. The main contributions of our thesis are indicated as follows:

- (1) We analyzed the lower bound of PU presence probability to provision the adequate sensing performance, by solving a quadratic equation on minimal conditions of SNR received at SUs.
- (2) We formulated the EE as a constrained 3-dimension optimization problem, then we adopted the bi-section search algorithm to find optimized solutions at lowest PU presence.
- (3) We proposed an opportunistic access scheme for SUs of CSS, in order to perform more access at high false-alarm probability. Then, SUs' sensing time ratio is gradually approached to an equilibrium based on evolutionary game method.

#### **1.4. Thesis structure**

The outline of this thesis is arranged as follows:

- (1) In the first chapter, the architecture of cognitive radio network (CRN) is introduced. The structure, principal functionalities and characteristics of spectrum sensing (SS) technique are demonstrated. Then, the importance of PU-SUs coordination challenge is expounded from both PU's and SUs' sides, after which the objectives of research are notably presented in this section. At the end of chapter, the objectives, research scopes and main contributions of this thesis are introduced.
- (2) In the second chapter, the core existing methods and their advantages are introduced, such as dynamic spectrum access schemes and cooperative sensing techniques. Several methods and related algorithms of spectrum sensing methods are classified and compared in details.
- (3) The impact of PU's activities is analyzed in the third chapter. The minimum presence of PU is formulated according to the minimum requirement of SUs'



sensing performance, based on which a constrained EE-optimization problem is proposed and the optimum is obtained by applying bi-section search methods.

- (4) In the fourth chapter, we study dynamic sensing decisions and access actions for secondary users (SUs) from the perspective of evolutionary game, in order to maintain SUs' sensing performances while cutting down the sensing time expenses and the power consumptions. This chapter notably considers the energy-sensing transformations from SUs' view.
- (5) In the fifth chapter, we present initial parameters, simulation environment and results of our proposed methods in third and fourth chapter of thesis. We analyze the improvement of our methods in different conditions, and we give comprehensive explications to the simulation results of our techniques.
- (6) In the sixth chapter, this thesis is concluded with our key research domains. The purposes and significances of our simulation results are pointed out, and we also present prospects of our future work.

## **1.5. Conclusion**

In this chapter, we mainly presented the spectrum sensing (SS) technique in cognitive radio networks (CRNs). We also introduced our research interests, objectives, and main contributions in this thesis. In next chapter, we introduce recent techniques and methods of related works in CRNs.

# Chapter2. Related Techniques and Comparisons

## 2.1. Introduction

A large number of technique schemes were proposed on accurate and efficient spectrum sensing in CR networks. These contributions can be roughly divided into three categories:

- 1) Sensing techniques and scheduling schemes that improved the spectrum or energy efficiency of CRNs. Different SE and EE targets are formulated to enhance the system performance.
- 2) PU activities towards the reawake probability, detection constraints, collisions, interferences, QoS provisioning, etc. These aspects can act as the conditions of an optimization formulation. On the other side of sensing, the main focus is on SU's frame structure including optimized sensing time ratio, sensing threshold and fusion rules.
- 3) SU's access actions and transmission. For example, when and how should a SU access to the channel and which channel to access in order to achieve the optimal transmission. This topic is especially discussed in CSS (cooperative spectrum sensing).

In this chapter, various related spectrum sensing schemes are explicated with some examples. Dynamic Spectrum Access (DSA) is referred as a policy which provides the capability to share the wireless channel to the unlicensed users (i.e. Secondary Users) along with licensed users (Primary Users) in an opportunistic manner [7]. The objective of DSA is to design the strategies which always provide low-waste high-efficiency secondary user access: DSA strategies are aimed to optimize the channel usage among SUs, to enforce the cooperation of SUs, and to avoid causing conflicts with primary users at the same time. Several typical works on the basis of DSA (dynamic spectrum access) concept have been presented in this chapter. These works provided a large sum

of techniques and frameworks of CRNs, and they especially proposed solutions towards the core task of CR, that is, the efficient spectrum usage. Moreover, we analyzed different methodologies against different scenarios of EE optimizations. The main focuses of EE formulations are compared in detail, especially under different constraints (e.g. interference, collision, PU protection, etc.). Afterwards, our comments and propositions have also been added towards the drawbacks of these works. Finally, the performances of related algorithms of these methods are evaluated and compared.

## **2.2. Sensing techniques and scenarios of related works**

Many recent literatures focused on novel innovations and techniques of spectrum sensing. In this section, firstly we introduce the principles of some typical related works and their scenarios; after then, more literatures will be classified and will be presented in categories.

In [8], the authors aim to optimize the dynamic spectrum access while guaranteeing sufficient PU protection. The paper proposes a new sensing scheme in which the sensing process is divided into two individual processes. A second sensing is performed to confirm the presence of PU in addition to the first sensing result, and to improve the sensing accuracy of the system. However, the additional expenditure of the second sensing is rather important to consider and the difficulty of synchronicity issue should also be noticed.

In [9], A. Azarfar *et al.* propose a mixed scheduling scheme of cooperative spectrum sensing (CSS) to enhance the system throughput performance. For the sequential sensing technique, SUs take turns to sense the related channel, but the transmission time is determined by the access order. For this reason, the transmission duration appears to be random. For the parallel sensing technique, SUs can sense the channels simultaneously. However, the channels are not supposed to be accessed if no SUs contribute to the sensing, since the status of channels is unknown. In this regard, the authors employ a hybrid design of dynamic spectrum access (DSA) schemes to optimize the opportunistic access chance and the average transmission duration, under detection constraints. Then, the performances of heuristic methods in three DSA

techniques (i.e., parallel, sequential and hybrid) are analyzed and compared, the authors present the suitable occasions of these techniques and the sensing time was determined adaptively. As an advanced version of [9], in [10] A. Azarfar *et al.* point out that the user assignment to channels should be considered in order to optimize the transmission performances. The paper analyzes the spectrum opportunities of each channel (i.e., channel vacancy) after the SUs take turns to sense scheduled by a DSA strategy. The paper also proposes heuristic algorithms to solve the tradeoff problem between cooperative sensing time occupation and remaining transmission duration, especially under certain user assignment and sensing schedule strategies. In addition, the received SNRs are also considered and are associated to SUs while assigning channels to SUs, then SUs are scheduled to always pick the best SNR in a heterogeneous multi-channel CR network. However, the proposed methods are only suitable to small-scale CR networks. Even though the authors have considered the comparisons of computational complexity and memory storage, the CR networks with large number of channels and SUs could take rather long computational time to solve the optimization problem. Other work such like [11] proposes admission control DSA schemes based on states predictions in a discrete-time Markov chain model. The paper analyzes the cases of states transitions in order to launch channel handoff actions at suitable occasions, and SU's QoS is especially guaranteed by measuring the forced termination probability and minimizing this probability.

[12] focuses on the channel assignment and scheduling problem in a heterogeneous model. The authors investigate the optimization problem of PU-SU channel mapping. They notably consider the overall energy cost on switching, sensing, and reporting phases. Afterwards, by scheduling PU's available channels and controlling SU's channel search duration, they analyze the channel assignment matrix to optimize energy and spectrum efficiency targets under detection requirements. This work, however, combines too many targets on PU channels' scheduling problem (i.e., channel access, channel switch, channel search, etc.). Indeed, the PU's channel accesses has its randomness and it is due to probability distributions, therefore it is rather difficult to control the channel search duration in practice, not to mention to predict the latest

arrival of SU. More attention should be paid to channels' states changes instead of only considering a static binary hypothesis for PU channels.

These aforementioned techniques mainly study the DSA strategies of users' channel access and assignment in multi-channel conditions, especially to make the most of spectrum opportunities and to optimize the efficiency of spectrum utilization. Nevertheless, since PU's presence is uncertain and unpredictable in practical channels, SUs could only obtain information from their detected results. In this regard, apart from the proposed scheduling methods, the distribution of PU's activities and corresponding performance metrics (e.g. SNR, error probabilities, etc.) should also be analyzed in detail.

A recent contribution [13] proposes a reconfiguration scheme of SNR predictions according to the dynamical channel gain. Then, the sampling size is notably adapted according to the feedback of channel state estimations. Authors of the paper also formulate sensing-throughput tradeoff and proposed schematic algorithm to optimize the sensing duration. Unlike other papers who only focus on scheduling the channel assignment, the advantage of [13] is that they consider PU's activities as a two-states Markov chain, and they especially study the interactive behavior between PU and SUs, which contributes to a better sensing quality.

Other papers concentrate on the integration of new spectrum sensing techniques into EE maximization problem: The authors of [14] study CoMAC-based spectrum sensing scheme and propose to solve the EE maximization problem by jointly optimizing the sensing time and symbol sequence length. The sensing threshold is especially analyzed so as to define the boundary conditions of sensing performances. In [15], the authors adopt the continuous sensing by considering the total spectrum band of the sensing and the transmission period as a fixed number and allocated proper bandwidths and power for each of two periods.

### **2.3. Related works of PU-oriented EE optimization**

In this section, we introduce the related papers about the problematics of energy efficiency, especially the contributions of the adaptations on primary user's side (e.g.

transmission power, PU presence, and performance achievement, etc.). In which follows, some tables are presented to indicate the focusing points of existing works, others are given to compare the performances and the complexities of related algorithms.

### 2.3.1. Definitions of energy efficiency (EE) optimization

Table 2.1. Definitions of EE and Related Contributions in Literature

Reference	Main focuses on the formulation of EE optimization
[1]	It considers PU's reoccupation and SUs' interferences on PU when designing EE with the sensing and transmission durations.
[4]	It studies the influences of network scale and fusion rule in EE maximization to find suitable and efficient CSS scenario for SUs
[8]	It formulates EE as averaged throughput per energy during a frame time, where the analysis of a frame of SU is divided into several cases of access actions determined by first and second sensing results.
[16]	It proposes to solve the joint optimization of EE by adapting both sensing/transmission durations and transmission power
[17]	It selects a suboptimal transmission power of SU, which is a unimodal to averaged EE. Then, for the second optimization of averaged EE, sensing time and detection threshold are jointly optimized.
[18]	It formulates the target function as a linear one with both unimodal properties of SE and EE being considered. The solution of SE/EE tradeoff was obtained by optimizing both sensing time and threshold.
[19]	It focuses on EE formulation under transmit/interference power and collision constraints. Then, the paper is aimed to maximizing the throughput under minimum EE requirements. It proposes power control schemes and adapts frame duration to achieve this purpose.

Several works contribute to the formulation of EE problem. The authors of [4] and [20] propose to distribute proper sensing time to achieve the peak of EE function, where the latter applies the original form of EE defined as throughput per unit energy consumption. Then, they take into account the number of sensing performers, they adapt suitable fusion rules and related energy detector thresholds to further improve the performances. [1] and [2] investigate the sensing-EE tradeoff problem. The sensing and transmission durations are adapted to the optimum while guaranteeing PU's detection at the same time. These papers aim to reduce the risks of collision and to prevent from SUs' greedy accesses. Similarly, the authors of [21] formulate a novel utility function

by removing the miss detection loss and power consumption parts from throughput gain, then they optimize the utility in the proposed cooperative sensing framework. [22] formulates the energy saving and the transmission time maximization as a bi-objective optimization and applies outer linearization methods to find optimal solutions. However, the paper only focuses on the scheduling problem on SU-channel pairs, whereas PU's presence activities have not been particularly considered.

### 2.3.2. Primary user activities and influences on EE

Some papers mainly discuss the influence of the transmission power on EE optimization with primary users. The authors of [3] prove that EE is a concave function to the transmission power that an optimized power could be always found by iterative bi-section search. [17], [23] apply golden section methods to select an optimized transmission power, and to fix a proper sensing duration, respectively. The authors consider the EE together with optimized fusion rules. In addition, the authors of [1] and [24] consider the PU activities. Particularly, they study the reawake probability of PU during the transmission period. As PU's presence is subject to random process, the states' change of PU could increase the potential collision risks caused by miss detection, and eventually the system throughput could be decreased. Therefore, the reawake problem should be particularly noticed in practice. Other works as [25], [26] studied how to control PU's rate loss and its interferences imposed on SU's transmission, based on which power allocation schemes are designed to achieve higher transmission rate, while guaranteeing the sensing constraints being achieved.

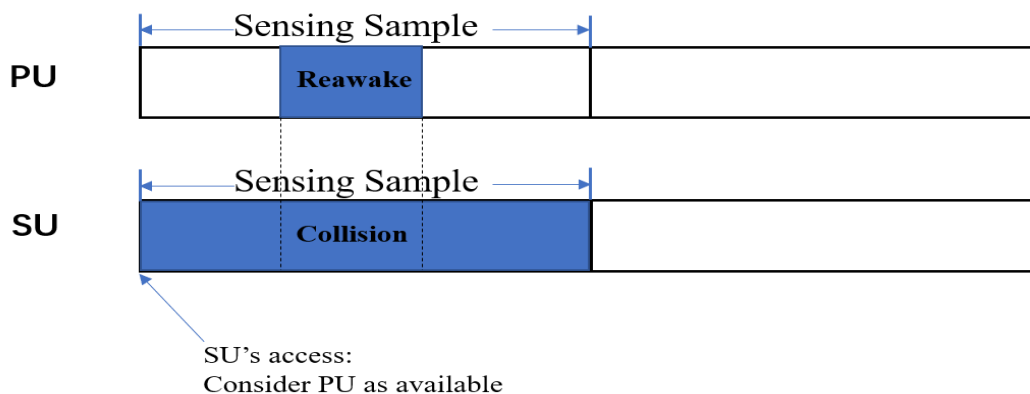


Figure 2.1. PU's reawake probability considered in [1] and [3]

### 2.3.3. Performance metrics, PU protection and SNR targets

Furthermore, PU's protection and SNR provisioning are also widely discussed in related papers. Hereby, PU's protection stands for the performance targets such like detection probability, therefore this is different from PU's aforementioned activities. In this section, PU's activities are normally considered as a constant, and we particularly analyze the impact of PU's detection constraints to the system performance (e.g., throughput). In Table 2.2., the principal aspects considered in two main categories (i.e., PU's activities and to PU's protections) are concluded together, to present and to classify the existing works and methods towards PU's design.

Table 2.2. Related researches on the side of primary users

<b>PU's activities</b>	Reawake	[1], [3], [24], [27]
	Transmission power	[3], [17], [23], [28]
	PU Interference	[25], [26], [28]
<b>PU's protections</b>	Detection Constraint	[29], [30], [31]
	Collision Avoidance	[27], [32], [33]
	Traffic Load	[34], [35], [36]
	QoS Provisioning	[20], [37], [38]

[3], [6], [29]-[31] mainly apply a lower bound of detection probability to guarantee the accuracy of detection, and consider other targets (e.g. EE, throughput, PU's spectrum utilization, etc.) under performance constraints. [20] presents the opportunistic access techniques to realize PU protection while maintaining SU's QoS at the same time. The authors of [32] have evaluated the reward of each action and selected an optimized operation mode for each operating or backup channels, in order to avoid the disturbance of PU-existence channel to the data transmission. [33] proposes a MAC-level protocol where SUs employ CSMA to determine the back-off time and to



avoid collisions by monitoring the channel. Then, FSS (fast spectrum sensing) technique is particularly applied after the channel contention phase to confirm the detection of PU before the transmission. This scheme can improve the protection of PU at the cost of high expenditure of additional headers. [35] regulates the queue length in order to control PU traffic load and thus satisfy the QoS provisioning of PU. [39] utilize spectrum sharing technique to compensate parts of SUs' power to PU and assist its transmission. Other papers (e.g., [14], [40], [41]) study the dynamic optimization of energy detector threshold to guarantee proper decisions of PU's signal and to reduce the total sensing error rate. Among them, a recent paper [41] has investigated the distribution of error probabilities related to PU's dynamic presence under certain sampling frequency, and then it formulates the problem as a two-state Markov chain with PU states changes.

#### **2.3.4. Algorithm analysis and complexity comparison**

In the context, a large number of papers have proposed diverse searching method to locate the optimum from different views of EE optimization. In this section, we mainly introduce golden section search [17], [23], bi-section search [1], [3], linear search methods [42], and heuristic method [22], [43], [44], [45]. The occasions and conditions of using these related methods are analyzed and the examples of application scenarios are given to each method. Then, with the introduction of the similar scenarios on EE optimizations, the performances of calculations are compared among these scenarios, and the algorithms' complexities are studied for each method.

Firstly, we introduce the water-filling algorithms which are suitable for resource management problems, especially in multi-subcarrier scenario. Water-filling is a set of methods who contribute to calculate the restored power level for each channel, and to allocate power resources accordingly based on the calculations of Lagrange patterns. For example, authors of [25], [46] both consider the optimized power allocation scenarios in multiple subcarriers OFDM-based CR system. [46] applies water-filling form into bi-section search based on interference power constraints and rate

requirement. The authors first propose an original form of bi-section search to optimize power allocation of subcarriers using two searching loops. Then, by proving that Lagrange multiplier is a decreasing function of total transmission power  $P$  (i.e., lemma.5 of [46]), the original WFAS algorithm is simplified by removing the outer search of  $P$ . The simplification saves significant complexity of  $\log_2(P_T/\epsilon)$ , where  $P_T$  is the total maximum transmission power and  $\epsilon$  represents the accuracy of convergence. Similarly, [25] utilizes water filling based bi-section search to dynamically find the optimum of hybrid PU protections under rate loss constraints, and especially compares this method to conventional formulation with interference power constraints to highlight the advantage. However, the complexity is not improved for the proposed algorithm, the paper only discusses the breakthroughs on performance comparison.

In addition, other algorithms such as linear search and heuristic search also propose complementary strategies of EE optimized resource allocation problem in multi-channel system. Followed by a discretion step of transmit power and sensing duration, [42] develops a linear search method to find feasible solutions of EE function, subject to the sensing duration constraints. As the search list indicates, the complexity of linear search method equals to the product of length of both two axis (i.e., power and sensing time). Since linear search is based on traversing the entire search list, it is considered still more complex than binary search or hash tables which refer to sequential and fast research. To further shorten the computational time, authors of [42] also propose iterative-based algorithm to alternatively optimize the two targets. However, the solution of iterative based algorithm might be only a local optimum, and thus cannot be guaranteed as global optimum. The principal advantage of this work is supposed to be the reduction of computational time comparing to conventional exhaustive search.

Considering the channel assignment and channel switching problems, heuristic methods are proposed by several contributions to properly schedule on the diversity of CR users, in order to achieve the general maximization of EE. For instance, [22] focuses on the greedy channel assignment to SUs and especially proposes to save the sensing and reporting energy without breaking the sensing tasks. More specifically, the SUs

with optimized SNR values are selected to make a match with a specific channel, and the remaining sensing time is updated for the next round. The loop continues until the minimum number of SUs contributing to cooperative sensing tasks is reached. However, the complexities of two proposed algorithms are still as high as  $O(MN \log N)$ , depending on the number of channels  $M$  and the number of SUs which is denoted by  $N$ . As a comparison, with a uniform and direct formulation on EE, [43] tentatively fulfills the transmission requests of SUs in their buffers upon frequency assignments, and the complexity is denoted as  $O(FN)$ , with  $F$  being the number of CR channels. As an extensive work of [43], authors of [45] apply heuristic algorithms to solve frequency-SU pairs matching problem in polynomial-time, and they propose more options of target functions such as throughput optimization under EE restrictions, or energy minimization subject to minimum throughput requirement, which are both considered as LP (linear integer programming) problem as a replacement to the original non-LP formulation of EE. The heuristic scheduling algorithm EEHS of [45] holds the same complexity as the one presented in [43].

Secondly, for a simplified channel scenario in CRNs which contains only PU and SUs (i.e., without differentiating the resource allocations on each channel), the bisection and golden section searches are widely used. The objective of these searching methods is to locate the optimum under certain targets (e.g., transmission, energy efficiency, spectrum usage, interference, etc.) and within a relatively short computational time.

The first step to execute these unique-axis searching methods is to confirm the precondition of optimization, that is, to prove the target function is a concave one; or in the opposite cases, to convert the target problem into a concave function. Then, the searching range is obtained based on the analyzed restrictions on the other sub-targets. As presented in Fig. 2.2., the golden section method proposes to utilize the ratio of golden section to realize dynamic, proportional and fast search recursion. The recursive algorithm is designed based on the comparison of two golden section bounds calculated by the golden ratio distribution. The bound corresponding to smaller value on the target function will be defined as new bound of next loop (e.g., lower or upper bound). Then,

the research is repeated until a convergence is found (i.e., the distance between upper and lower bound is controlled below a certain constant).

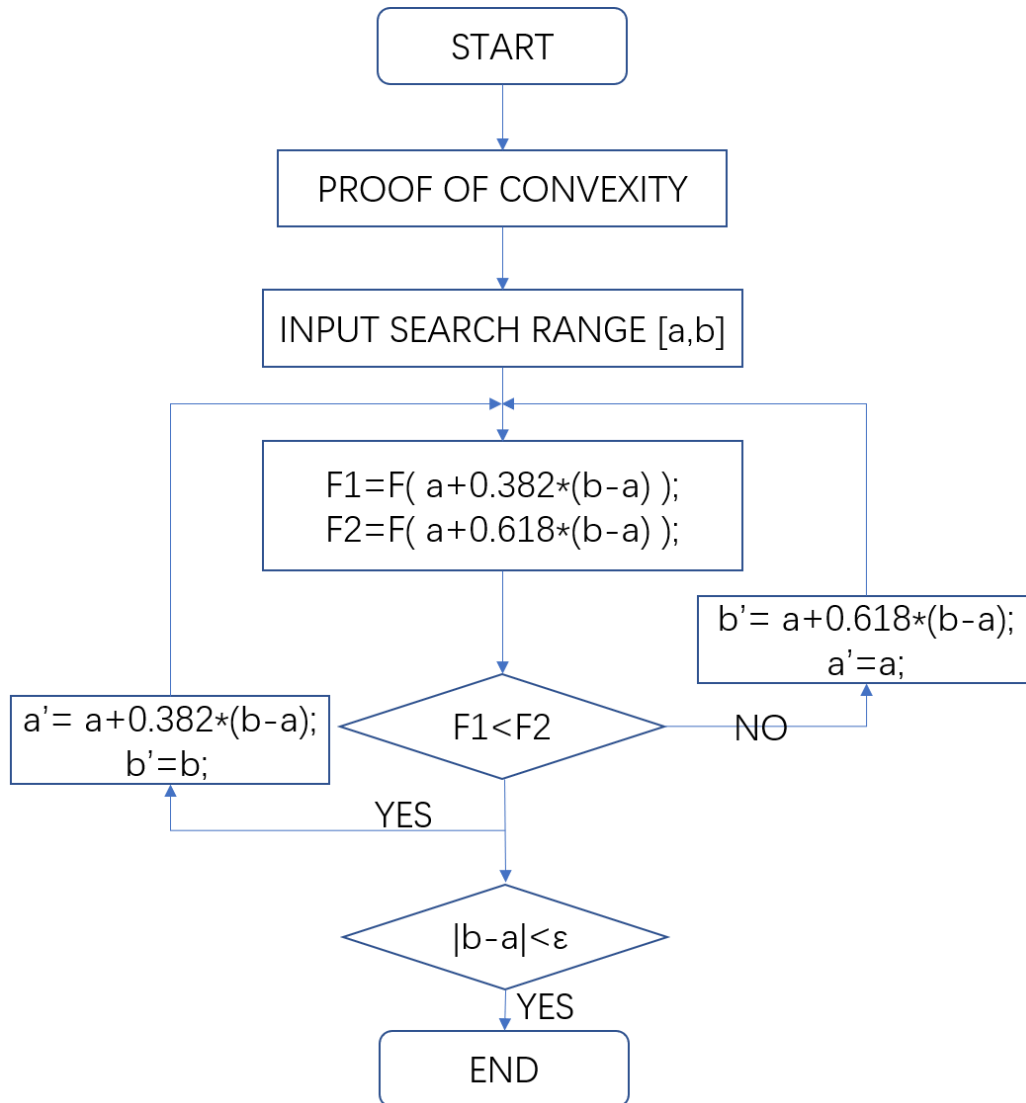


Figure 2.2. Flowchart of golden section search algorithms

Different from golden section search, the bi-section search presented in Fig. 2.3. focuses on the tendency of target function instead of values' comparison. The range of search becomes narrowed with the relocation of a subset of the convex interval. For a convex function, " $F'(X1)*F'(X0) < 0$ " represents that the starting and finishing bound of the searching range hold different tendency (e.g., increasing at the beginning and decreasing at the end). Thus, an optimum point can still be found in this searching range. Otherwise, " $F'(X1)*F'(X0) > 0$ " indicates increasing or decreasing on the same direction, where the optimum can never be found between two endpoints. Therefore, this searching range should be deducted from the one of next iteration. In the end, after

several iterations, the two endpoints are considered narrow enough to obtain a final optimum of target function.

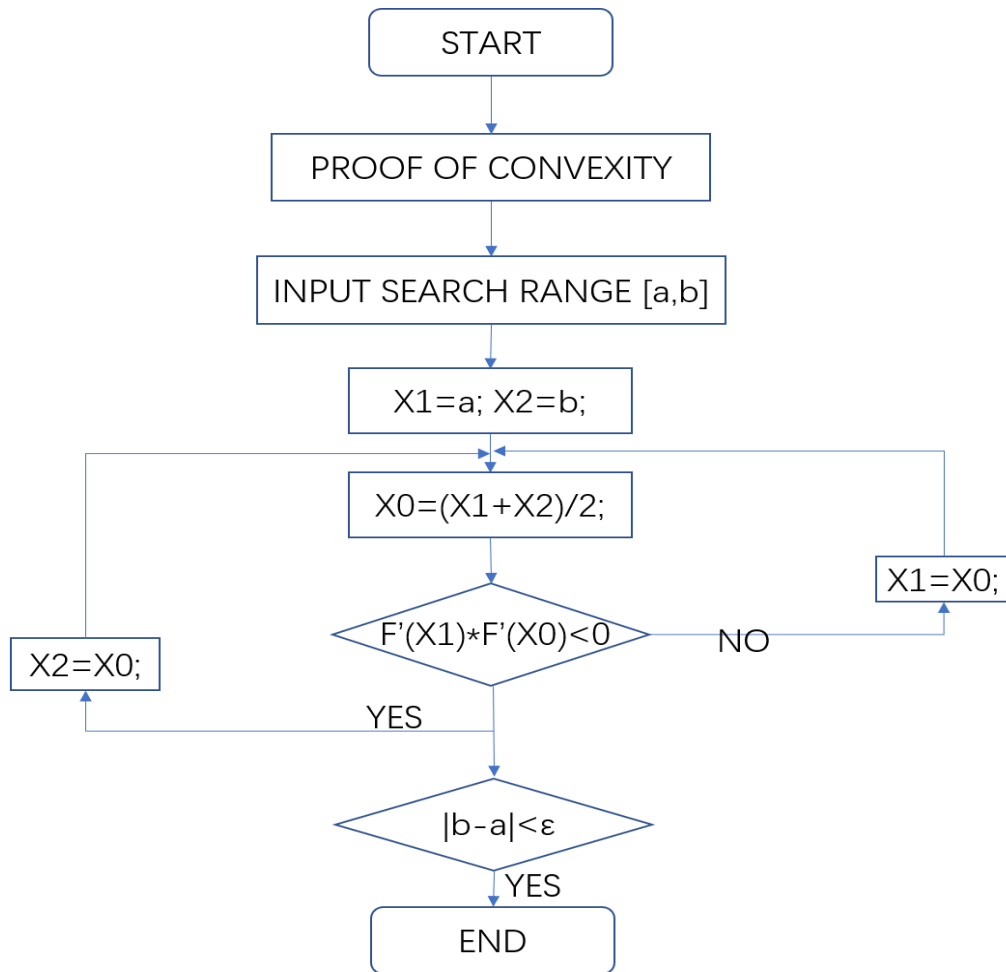


Figure 2.3. Flow process chart of bi-section search algorithms

The bi-section and golden section methods are both based on iterative replacement of searching range, so the principles of these algorithms are similar. The complexities of algorithms are depended on the margin of searching range and related requirement of searching accuracy. These searching methods are especially useful while the initial function is well-known or at least the convexity is derivable. Besides, the target function should also hold the continuity so that a global optimum can be guaranteed to be existent.

To better compare the efficiency of algorithms proposed in each category, we present the complexities and generalize them in Table. 2.3. It can be observed from this figure that the complexities of searching methods are mostly depended on the variables

and applied method. The references of both nested iteration methods and double-variables optimizations are introduced and compared in the following figure.

Table 2.3. Comparison of algorithm complexities in related works

Methods	References	Complexities	Remarks
Heuristic	[22]	$O(MN \log N)$	$M$ : number of channels, $N$ : number of secondary users
	[43], [45]	$O(FN)$	$F$ : number of CR channels $N$ : number of secondary users
Bi-section search	[28]	$O\left(\log_2 \frac{P_{th}}{\epsilon_p} \log_2 \frac{u_{max}}{\epsilon_u}\right)$	$P_{th}$ : power threshold $u_{max}$ : maximum rate
	[3]	$O\left(\log_2 X \log_2 \frac{\theta_{max} - \theta_{min}}{\epsilon_\theta}\right)$	$[\theta_{min}, \theta_{max}]$ : range of sensing ratio.
Linear Search	[42]	$O\left(X \log_2 \frac{\phi_{max} - \phi_{min}}{\epsilon_p}\right)$ $+ O\left(Y \log_2 \frac{\theta_{max} - \theta_{min}}{\epsilon_\theta}\right)$	$[\phi_{min}, \phi_{max}]$ : range of SU's power $\epsilon_\theta, \epsilon_p$ : unities of search
Exhaustive Search	[47], [48]	$O(XY)$	$X, Y$ : resolution of search

#### 2.4. Secondary user adaptation by evolutionary game in CSS

Efficient spectrum utilization has become a great challenge to wireless networks as the diversity and service requirements of wireless services are both growing rapidly. Cooperative spectrum sensing technique (CSS) allows allocating available spectrum resources of a primary user (PU) to a group of secondary users (SUs) (under certain rules) during its “spectrum hole” in order to increase the spectrum efficiency of the network [49]. SUs have to conduct periodical sensing in order to monitor PU's current

state, then a fusion center (FC) collects SUs' sensing results and makes access decisions for them accordingly.

#### 2.4.1 Related works on cooperative spectrum sensing techniques

Existing contributions mainly focus on the expected throughput under a given fusion rule, or the sensing and accessing time distribution depended on the scheduling scheme. These contributions incent SUs to become contributors by setting reward functions, either to attract high-SNR SUs by allocating different sensing priorities [50], or to allocate more accessing possibilities to the channels in better condition [49][51]. Other contributions consider throughput with miss detection probability in order to avoid collision between PUs and SUs and to guarantee the sensing performance. Fairness is guaranteed in [52] by allocating high priority to SUs which contributes to CSS, and by detecting selfish and malicious SUs which deviate from the equilibrium of general utility function. The authors in [53] investigate the total error rate in different channels and observe the optimized number of SUs for reaching an adequate sensing performance.

The authors in [49] propose a novel game to distribute SUs to choose from parallel sensing or cooperative sequential sensing, and to calculate the payoff accordingly. However, this method is not feasible in practice because the evolutionary game only allows determining the probability of contribution for SUs, and it is difficult to be used on making flexible choices for SUs between two existing techniques. In [54], the authors analyze the SUs' evolutionary stable strategy (ESS) in synchronous /asynchronous scenario where PU shares the same clock with SU (or not). Wang et al. [55] propose to optimize the throughput by dynamically selecting SU' status between “**contributor**” and “**free-rider**” based on the analysis of transmission gain. The authors of [50], [54], [55] focus on the optimization of energy and throughput, but they haven't considered impact of different detection performance.

As a conclusion, the energy has been presented as the total energy consumption in most cases, which is related to the number of contributors. Most papers target other

objectives (i.e. throughput, detection performance, channel selection, etc.) to control the number of contributors, then they compute average energy based on this number. However, spectrum waste of CSS should be considered with SU's actual sensing effort (i.e. the sensing time ratio). Therefore, the energy should always be compensated for the spectrum waste to guarantee the performance.

#### **2.4.2. Game theory methods and applications in spectrum sensing**

Several game theory approaches have been proposed to solve the resource allocation problem in cooperative spectrum sensing. Common game approaches include: evolutionary game [50]-[57], auction game [59]-[61], coalition game [49],[62]-[70], bargaining game [71][72][73], Stackelberg Game [74][75], snowdrift Game [76], non-cooperative Game [77], etc.

As an important game model of cooperative sensing, the evolutionary game proposes to observe the rules or the histories of precedent game results, and to adapt them gradually into replicator dynamics until an equilibrium is found. The evolutionary game is a learning model game where informations are continuously collected and analyzed with the observation of game process.

Auction-based contributions propose Vickrey-Clarke-Groves (VCG) auctions to allocate the resource evenly between multiple SUs, by making them bidding for the true values, instead of taking the risk of their selfish or collusive behaviors. Auction-based methods usually allow the SU head to group its members as a coalition, in order to select a winner of auction according to the average utility function, and to stay truthful while virtually paying for the bids. The bidding system should let the header SU compare the gain and select new cooperating members from this competition. Furthermore, as mentioned in [60], the access of bidders should follow a back-off control scheme to avoid causing collisions, and more importantly, higher bids can be received first. Other work such as [59] has proved that there exists a core of coalition in designed auction game, that is, any subset of the coalition is also rational. The utility function should reflect well the desire of a SU for achieving information collection from



PU and for acting a cooperative role. After grouping the coalition and proving it as a core, each SU should bit truthfully and should find a most suitable vacant channel to connect with, in order to obtain an associated optimal solution.

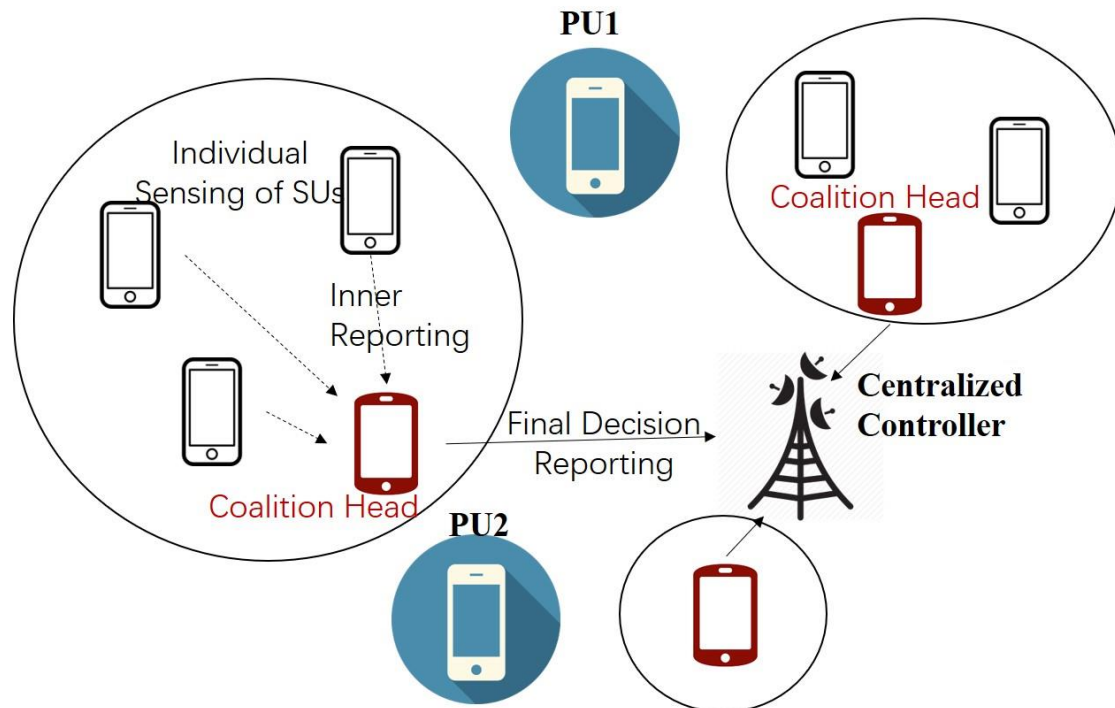


Figure 2.4. Coalition game model of cooperative spectrum sensing (CSS)

The coalitional games (i.e. an example is presented as in Figure 2.4) are more suitable to a distributed and dynamic environment. A coalition can select its members through merge-and-split strategies. These strategies allow SUs to act in a collaborative way and to improve their common utility as a coalition. The primary objectives of applying non-transferable utility coalition games can be concluded as follows:

- 1) The first objective is to increase the detection performance and to decrease the false alarm probabilities. In other words, to solve the trade-off between the increasing interference of PU-SUs and satisfying the service quality targets (e.g. efficient utilization of the spectrum) which are denoted by false alarm probabilities. The latter is considered as cost constraints of coalition formation in some papers such like [66] whereas the detection targets are usually set as the utility function.
- 2) The second objective is to avoid the deterioration of SNR and the channel fading when reporting SUs' sensing results to the coalition head. With conventional centralized solutions, each SU takes risks of reporting wrong information to the head,

which could be rather dangerous while accessing themselves to the spectrum. By adopting distributed algorithms, coalitional games take into account the characteristics of reporting channels (e.g. Rayleigh channel fading) from any SU to the head. In this way, the system performance of cooperative sensing can be improved greatly and evenly. Moreover, the mobility and flexibility of the network can also be enhanced.

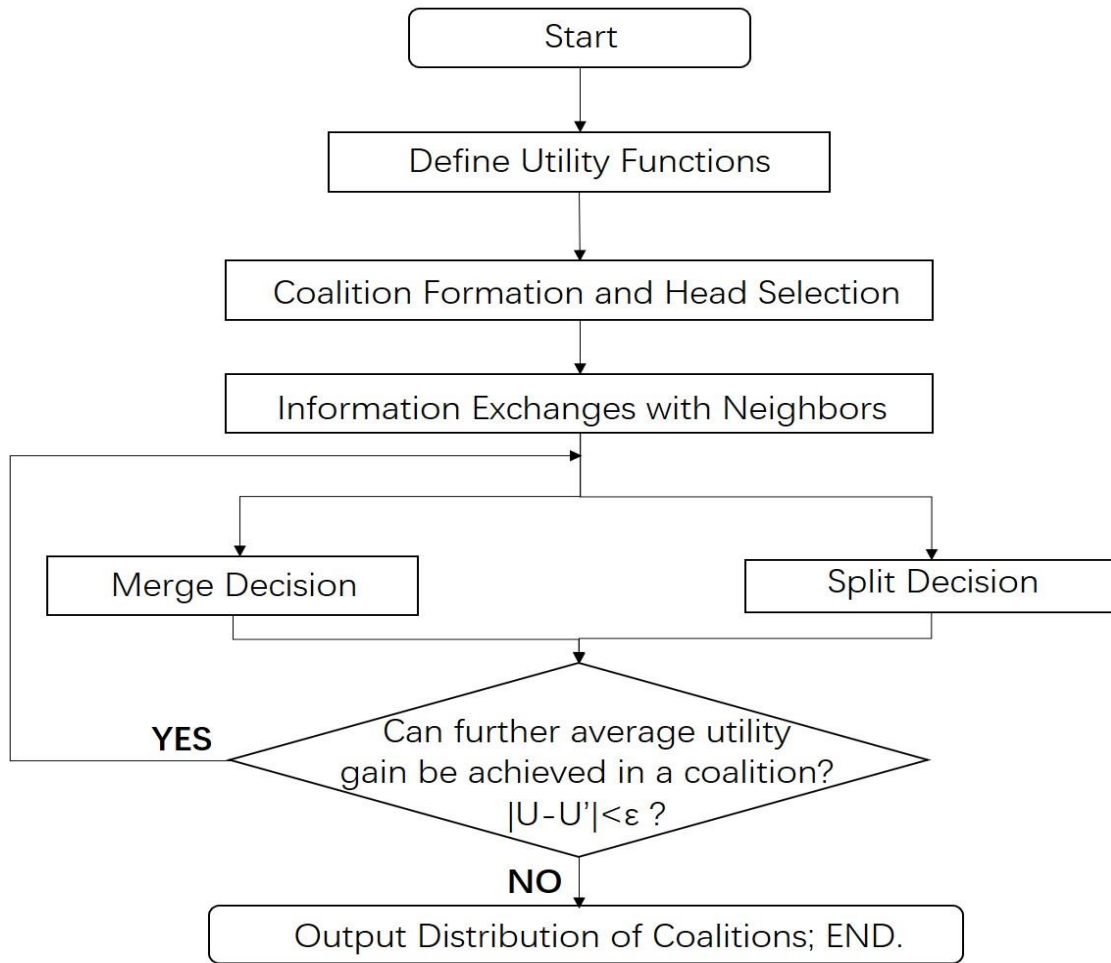


Figure. 2.5. General steps of coalition games in CSS

Compared to centralized solutions, distributed coalitional game algorithms tend to allow SUs to autonomously select a merge strategy or a split strategy to follow. Each SU evaluates independently the collaborative gains of accurately collecting and contributing information to the head against its own selfish behavior, which is SU's individual cost of false alarm constraints satisfaction by forming a coalition. As Fig 2.5, the figure presents how each SU evolves its utility value while taking new merge/split decisions at the time.

Before choosing a strategy, SU compares its individual utility to the utility of a coalition. Then, the result is reported to the centralized controller to either integrate or to dismiss this SU. By repeating this iteration, a self-organized minimal winning coalitions (MWCs) can be formed to make balance between self-interest and coalitional interest. These MWCs can be taken as the final decision of the game, known as the feasible and stable solution after iterative comparisons and competitions among SUs. The comparisons are based on an exploration process of SUs, which allow them to detect relay neighbors inside a distance range. The information of investigations on neighbors is transmit through a control channel. However, this process is totally self-organized and is not related to the centralized controller. The latter only receives information reported from the coalition heads and controls the access actions of an already-formed SUs' coalition.

## **2.5. Conclusion**

In this chapter, current sensing techniques are introduced in the scenarios that are aimed at improving the sensing accuracy and reducing the spectrum wastes. The chapter is especially divided into two sub-sections where several related contributions are presented towards PU's and SUs' activities, respectively.

For PU-related methods, the objective is to maintain the sensing performance while protecting PU and avoiding to cause any collisions among PU-SUs. Several resource allocation methods are presented, notably the water-filling, and the bisection/golden section search methods. The computational complexity of algorithms is compared among various methods, where bi-section/ golden search is proved to take shorter execution time than other methods. From SUs' side, various related works focus on the concepts of cooperative spectrum sensing and they propose game theory schemes to obtain a feasible solution. Basically, game theory methods send SUs to take different strategies and to behavior as a cooperative or a selfish way. Each SU learns informations from external environment and evolves over the time. At last, an equilibrium (or a core) can be found for the game, where a static and stable solution can be achieved. Under

definitions of a particular utility function, the principles of evolutionary and coalitional game are elaborated, and examples are presented to show how SUs adapt their utilities with the game and act different roles in a self-organized way.

In the next chapter, we start to present the state of art of our work in PU-adapted spectrum sensing, and we attempt to apply bi-section search method to solve this problem. A tradeoff problem is notably proposed between the energy efficiency of sensing and the performance maintenance in Chapter 3.

# Chapter3. PU-Oriented Design of Energy Efficiency in Cognitive Radio Networks

## 3.1. Introduction

In this chapter, a new solution is proposed towards PU's activities. Different from traditional optimization solutions which only adapt the power of SUs based on a fixed frequency of PU's presence, our method is proposed based on the following major assumptions:

(1) PU is designable and its activities are subject to a random access with a probability.

PU should be as flexible as SUs since they are both users who rent service from a common band and submit to the resource allocation of CR network. However, since PU holds a higher priority, the design of PU should have advantages on channel occupations than SUs.

(2) PU and SUs should work in an interactive way to avoid collisions and to obtain optimal service quality. For example, SUs should concede to access if PU has a major presence, and they should benefit from using the spectrum holes if PU is not busy. PU stands for a premise for SUs' coordination, it determines how to make compromise between SUs' opportunistic accesses and high sensing performances.

In what follows, we analyze the system model of PU-SUs spectrum sensing by investigating multiple situations. Next, extensive formulations of EE are presented, with boundary conditions being defined accordingly. Then, we give detailed proofs to testify the feasibility of achieving an optimized solution in the given range, based on which we introduce our algorithm. Finally, we conclude this chapter.

## 3.2. Main challenges and problematics

In the last chapter, a detailed related works towards energy optimizations issues in CR networks is introduced. However, to the best of our knowledge, only few contributions have investigated PU activities with EE maximization in CRNs. Besides, the reawake probability of PU traffic is not the only aspect of PU activities that should

be considered in performance metrics and throughput of CRNs. More importantly, the distribution of PU's idle/active states contributes to very different sensing results.

Fig. 3.1 presents an example of sensing process under different conditions of PU's presence probabilities. When there is a sparse presence as PU1, the spectrum band is more available, which makes the transmission of SUs easier to access. Otherwise, when PU presents frequently as PU2, the received SNR at SU's side becomes more evident to be detected. Therefore, the false alarm probability (i.e. the letter "F" in Fig.3.1) can be better controlled than sparse presence case under the same target detection probability condition. Although the access of transmission is limited, the spectrum sensing is more efficient, thus the EE is also improved. These two situations should be considered in parallel, and PU activities should be adapted to an optimum where sensing and accessing are both guaranteed.

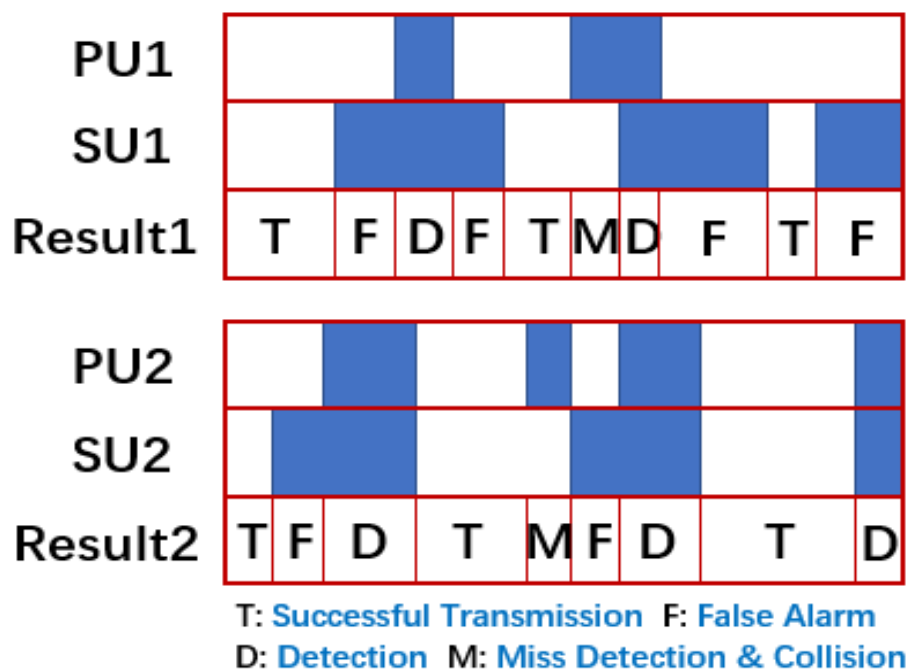


Figure 3.1. Example: Impacts of different PU activities on sensing results

In this context, PU's activity is designed towards an interactive behavior of SU's access. On the one hand, given a fixed probability of PU's presence, SUs are able to optimize EE by finding their most suitable sensing ratio. On the other hand, PU's activity has critical impacts on EE. In the following sections, the overall EE of both PU and SUs is studied, and the relation between EE and PU's presence is especially

analyzed. We prove that a maximized EE is subject to a sparse presence of PU, similar to PU1 case in Fig 3.1, where the assumption of free access is admitted as principal impact other than the advantage of false alarm probabilities of PU2.

Nevertheless, the design of PU is subject to certain constraints in order to always obtain sufficient sensing performance. According to these key challenges, a PU-related EE optimization model is proposed. In the next sections, our main contributions towards these problems are concluded as follows:

- (1) We analyzed the lower limit of PU presence probability to provision the adequate sensing performance, by solving a quadratic equation at the minimum condition of SNR received at SUs.
- (2) We formulated the EE as a constrained 3-dimension optimization problem, then we adopted the bi-section search algorithm to find optimized solutions at lowest PU presence.

### 3.3. System model

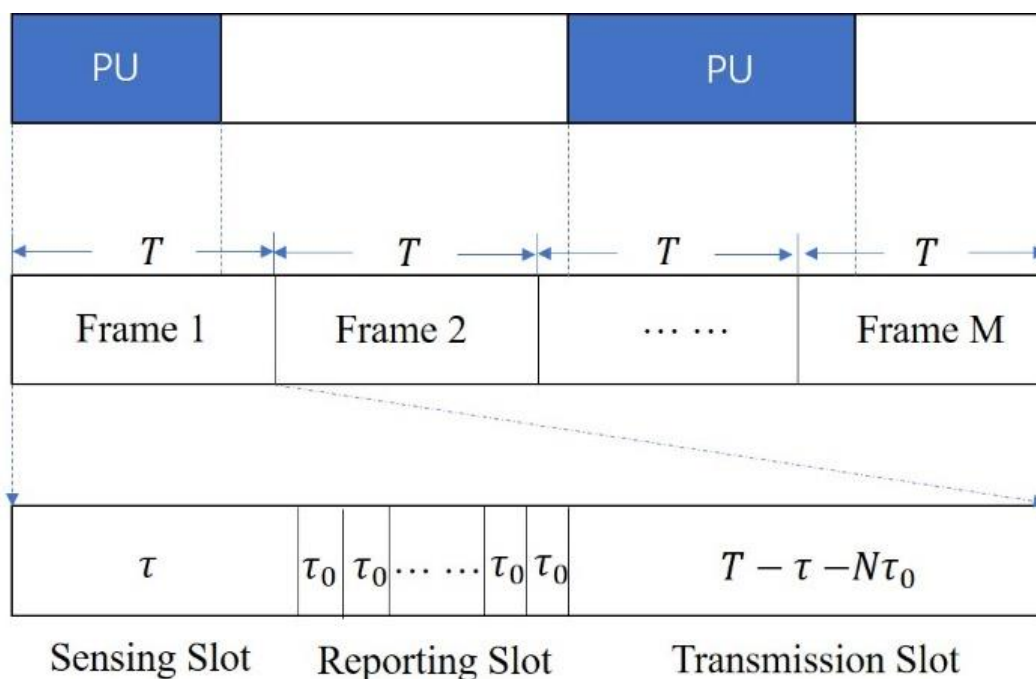


Figure 3.2. Frame Architecture in CRNs

We consider a CRN with one PU and  $N$  SUs. SUs are assumed to be homogeneous users which have similar distance to PU and similar averaged SNR received at SU's side during the PU's presence period; the latter is denoted by  $\gamma$ . The

signals of PU and SUs are both considered as white gaussian ones, and the interference of PU is ignorable (i.e. comparing to white gaussian noise) to SU during its data transmission, unless PU is exceptionally switched on in a miss-detection case. Besides, in order to provide sufficient sensing performance, the received SNR  $\gamma$  is particularly defined to guarantee the detection of PU's presence and to prevent SUs from collisions caused by miss detection. Apart from  $\gamma$  which is transmitted by PU and received at SU's side, it should also be noticed that the data rate is calculated based on SU's SNR during data transmission, which is relevant to the transmitted power of SU.

During the sensing process, SUs take turns to perform sensing by listening to PU's signal. Let us denote by  $H_0$  that PU is available, and  $H_1$  means that PU is present, where "available" indicates that SUs are accessible whereas "present" means PU is in charge of the band and the band is too busy to be reutilized by SUs. The relative probabilities of PU staying at  $H_0$  and  $H_1$  states are denoted as  $p_0$ ,  $p_1$ , respectively. SU can only access to the channel for its own transmission while PU is detected in  $H_0$  state. Each SU takes an individual decision by comparing the received signal power to an energy detector threshold  $\xi$ . The received signal is composed of detected signal of PU after channel fading, and AWGN (additive white Gaussian noise) signal  $u(i)$  with zero means and variance  $\sigma^2$ , which is written as (3-1):

$$y(i) = \begin{cases} u(i) & , H_0 \\ x(i)h(i) + u(i) & , H_1 \end{cases} \quad (3-1)$$

where  $i = 1, 2, \dots, \lceil \tau f_s \rceil$  denotes the number of sensing samples;  $h(i)$  is the channel gain. The main error risks in CRN are expressed in two aspects: 1) false alarm describes that SU receives 1 and falls into sleep while the channel is actually available (state 0), which leads to spectrum waste; 2) miss detection indicates that SU receives 0 and starts transmission while channel is occupied by PU; this case increases the probability of collision between PU and SUs. Given the sensing time ratio  $\tau$  and sampling rate  $f_s = 1/T$ , the individual false alarm and miss detection probabilities are computed in (3-2)~(3-3):

$$p_f = Q\left(\left(\frac{\xi}{\sigma_0^2} - 1\right)\sqrt{\tau f_s}\right) \quad (3-2)$$



$$p_d = Q\left(\frac{\xi}{\sigma_0^2} - \gamma - 1\right) \sqrt{\frac{\tau f_s}{2\gamma+1}} \quad (3-3)$$

$Q(x)$  is complementary distributed Gaussian standard function defined by  $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt$ . The individual sensing results are generalized by FC (i.e. fusion center) which stores the fusion rules and makes a conclusive decision for all SUs. In this context, the  $k$ -out-of- $N$  rule is applied: FC requires at least  $k$  positive decisions are received from  $N$  SUs to make a final decision that PU is present. Then, the probabilities of general false alarm and miss detection are computed as (3-4) and(3-5):

$$\mathbb{P}_f = \mathbb{P}\{n \geq k | H_0\} = \sum_k^n \binom{n}{k} p_f^k (1 - p_f)^{n-k} \quad (3-4)$$

$$\mathbb{P}_d = \mathbb{P}\{n \geq k | H_1\} = \sum_k^n \binom{n}{k} p_d^k (1 - p_d)^{n-k} \quad (3-5)$$

### 3.3.1. Energy efficiency analysis

To study the energy efficiency of CRN, the cooperative sensing model is divided into four cases where  $\mathbb{P}_f$  and  $\mathbb{P}_d$  are jointly considered:

**Case (1):** PU is occupied while SU detects it correctly. SUs transfer the spectrum band to PU as they possess lower priority. SUs only spend power on sensing and reporting phases denoted by  $E_{S1} = NE_{ss}\tau + NE_{st}\tau_0$  ( $\tau$  and  $\tau_0$  as defined in fig.3.2.), with the transmission power of SU on reporting and transmission slots are the same denoted by  $E_{st}$ , and the sensing power is denoted as  $E_{ss}$ . They make contribution to sensing but receive 0 throughput in this case.

**Case (2):** PU is occupied while SU detects it to be available (i.e. miss detection). SUs make efforts to both sensing and transmission, but they still suffer serious collisions with PU during the transmission as they share the same band, then total energy cost is calculated as (3-6):

$$E_{S0} = NE_{ss}\tau + (T - \tau)E_{st} \quad (3-6)$$

The data rate of SU is denoted as  $C_{10}$ , then we assume in case (2) that the probability of this case is  $(1 - \mathbb{P}_d)p_1$ . The expected throughput of SU under miss detection is defined as (3-7):

$$T_{10} = (T - \tau - N\tau_0)(1 - \mathbb{P}_d)p_1C_{10} \quad (3-7)$$

**Case (3):** Under the circumstance of false alarm, SUs receive “occupied” state and cease the transmission. However, spectrum waste is caused in this case, as the spectrum band is actually available. The energy cost equals  $E_{S1}$ . In return, SUs earn zero throughput as they refuse to transmit data. At the receiving part, SU has similar action as in case (1); the case (3) is considered as an irregular case since it only brings spectrum waste. In this regard,  $\mathbb{P}_f$  should be minimized to improve the throughput.

**Case (4):** A successful transmission is the scenario where SUs transmit data while PU is truly available. The energy cost in this case is  $E_{S0}$ . SU’s data rate is denoted as  $C_{00}$ . The interference introduced by the presence of PU is evident in case (2), while SUs enjoy successful transmissions where no in-band interference happens. Similar to (3-6), the throughput is calculated as (3-8):

$$T_{00} = (T - \tau - N\tau_0)(1 - \mathbb{P}_f)p_0C_{00} \quad (3-8)$$

### 3.3.2. Energy detector

The test statistics defines the average energy detected in  $[\tau f_s]$  samples received at each SU during its sensing period, which is defined as in (3-9):

$$\psi(y) = \frac{1}{[\tau f_s]} \sum_{i=1}^{[\tau f_s]} |y(i)|^2 \quad (3-9)$$

Then, the test statistics of each SU is compared individually to a detection threshold  $\xi$ . The probability of detection is defined as the integration of probability density functions (P.D.F.s)  $p_1(x)$  on the range  $[\xi, \infty)$ , which is shown in (3-10):

$$p_d(\xi) = Pr(\psi(y) \geq \xi | H_1) = \int_{\xi}^{\infty} p_1(x) dx \quad (3-10)$$

As shown in (3-4)~(3-5), FC collects all test statistics and makes the global decisions with a selected fusion rule (e.g.  $k$ -out-of- $N$ , OR, AND, majority, etc.), then FC broadcasts the results to the whole CRN. The probability of detection  $\mathbb{P}_d$  should be determined according to the lower bound of detection  $\mathbb{P}_{d0}$ , which is  $\mathbb{P}_d \geq \mathbb{P}_{d0}$ , to avoid the potential in-band collisions caused by miss detection. According to (3-2)~(3-3),  $Q(\cdot)$  is a monotone decreasing function of  $\xi$ . It implies that the decrease on the

detection threshold can improve the chance for a PU's presence to be detected. However, this action doesn't only increase  $\mathbb{P}_d$ , but also increase  $\mathbb{P}_f$  because  $\mathbb{P}_f$  and  $\mathbb{P}_d$  are changing in the same direction with  $\xi$ . Thus, the throughput also tends to decrease. For instance, from (3-2), it is indicated that  $\xi \geq \sigma_0^2$  should always exist in order to control  $\mathbb{P}_f$  below 0.5; from (3-3) we can deduce that  $\xi$  should be beneath a threshold to satisfy the detection requirement. In this regard, it is difficult for  $\xi$  to thoroughly optimize the energy efficiency while meeting the detection requirement at the same time.

### 3.4. Problem formulation

#### 3.4.1. Minimum required transmission power of PU

Assuming that the instantaneous transmission power of PU is determined as  $E_{pt}$ , and the gain of fading channel is given as  $G$  between primary and secondary users. The system bandwidth is  $W$ . The data rate of SU in cases (3-2) and (3-4) are defined as follows based on Shannon's equation:

$$C_{00} = W \log_2 \left( 1 + \frac{GE_{st}}{\sigma_0^2} \right) \quad (3-11)$$

$$C_{10} = W \log_2 \left( 1 + \frac{GE_{st}}{GE_{pt} + \sigma_0^2} \right) \quad (3-12)$$

From (3-11)~(3-12), we observe that  $\frac{GE_{st}}{GE_{pt} + \sigma_0^2} = \frac{GE_{st}}{(1+\gamma)\sigma_0^2} < \frac{GE_{st}}{\sigma_0^2}$ . Intuitively, the data rate of successful transmission is larger than the miss detection because of the unavoidable interference caused by PU's transmission, i.e.  $C_{10} < C_{00}$ . The corresponding system throughput of these miss detection and transmission are defined as  $T_{10}$  and  $T_{00}$ , respectively. According to (3-7)~(3-8), the overall system throughput  $\mathbb{T}$  can be expressed as a function related to  $E_{pt}$  and  $E_{st}$ , which is calculated as (3-13):

$$\mathbb{T} = T_{10} + T_{00} = \left( 1 - \frac{\tau + N\tau_0}{T} \right) \left[ (1 - \mathbb{P}_d)p_1 C_{10} + (1 - \mathbb{P}_f)p_0 C_{00} \right] \quad (3-13)$$

It is noticed that in order to guarantee the detection accuracy,  $\mathbb{P}_d \gg \mathbb{P}_f$  should always exist; besides,  $p_1 \ll p_0$  (i.e. PU is not dominant in the spectrum band) is a basic hypothesis of spectrum sensing to reallocate the spectrum resource; otherwise the

presence of SU interferes with dominant PU, so it is not worthwhile to sense the band. Hence, it can be found in (3-13) that  $T_{10} \ll T_{00}$  always exists.

Furthermore, as  $\mathbb{P}_d \geq \mathbb{P}_{d0}$  and  $\mathbb{P}_f \leq 0.5$  are considered as the conditions of detection performance,  $\gamma$  should be large enough to guarantee the difference of  $P_d$  and  $P_f$  if a fixed threshold is applied for  $\xi$ . According to (3-4)~(3-5), the  $k$ -out-of- $N$  rule can be understood as an extensive logic of OR rule, that is,  $k$  positive samples should be collected to support the decision. Thus, the probability of general decision is referred logically to the individual probabilities. To achieve the detection performance,  $P_d$  and  $P_f$  have to meet the following requirement:

$$P_d \geq P_{d0}(k, \mathbb{P}_{d0}) > P_{f0}(k, \mathbb{P}_{f0}) \geq P_f \quad (3-14)$$

where the expected SNR of PU's signal received at SU  $\gamma^*$  is given as (3-15) based on (3-2)~(3-3), with a couple of threshold  $\{P_{d0}, P_{f0}\}$ :

$$Q^{-1}(\mathbb{P}_{f0}) = \sqrt{2\gamma^* + 1}Q^{-1}(\mathbb{P}_{d0}) + \sqrt{\tau f_s} \gamma^* \quad (3-15)$$

For simplicity, we denote the following values with  $Q^{-1}$  function:  $F_0 = Q^{-1}[P_{f0}(k, \mathbb{P}_{f0})]$ ,  $D_0 = Q^{-1}[P_{d0}(k, \mathbb{P}_{d0})]$ .  $\gamma^*$  is subject to a quadratic equation as (3-16):

$$\tau f_s \cdot \gamma^{*2} - 2\{\sqrt{\tau f_s} F_0 + D_0^2\} \gamma^* + F_0^2 - D_0^2 = 0 \quad (3-16)$$

As  $P_{d0}(k, \mathbb{P}_{d0}) > P_{f0}(k, \mathbb{P}_{f0})$ ,  $\mathbb{C} = F_0^2 - D_0^2 > 0$ , delta of quadratic equation (3-16) is calculated as follows:

$$\Delta = \mathbb{B}^2 - 4\mathbb{A}\mathbb{C} = 4\{D_0^4 + 2\sqrt{\tau f_s} F_0 D_0^2 + \tau f_s D_0^2\} > 0 \quad (3-17)$$

These conditions indicate that (3-16) has two positive roots for  $\gamma^*$  denoted as  $\gamma_1^*, \gamma_2^*$ . To follow the conditions of (3-14), (3-16) has to be transformed into a positive inequation where the solution can be found inside the range  $(0, \gamma_1^*]$  and  $[\gamma_2^*, \infty)$ . Obviously, the received SNR should follow the latter range to guarantee the sensing performance. Besides, it should be noticed that  $\gamma^*$  is an averaged conception during a sampling period. SUs might experience different detection results of PU states in the sampling period as PU applies random access, but the receiver of SUs reports only one specific answer to FC which is depended on the averaged detection value in such a

sampling. For this reason, in order to achieve averaged SNR requirement, the instantaneous transmission power and the presence of PU should be mutually adapted. Thus, the lower bound of PU's power provision is subject to (3-18):

$$E_{pt}^*(k, \tau) = \frac{\sigma_0^2 \gamma_2^*}{G} = \frac{\sqrt{\tau f_s F_0 + D_0^2} - D_0 \sqrt{D_0^2 + 2\sqrt{\tau f_s F_0 + \tau f_s}}}{\tau f_s G} \sigma_0^2 \leq p_0^{ON}(\tau) E_{pt} \quad (3-18)$$

where  $p_0^{ON}(\tau)$  denotes the actual active probability of PU during the sensing period and  $E_{pt}$  is the instantaneous power. According to [24],  $p_0^{ON}(\tau)$  can be calculated as (3-19):

$$p_0^{ON}(\tau) = p_1 e^{-\frac{\tau}{\alpha_1}} \quad (3-19)$$

where  $p_1$  is the active probability represented by:

$$p_1 = \frac{\alpha_1}{\alpha_0 + \alpha_1} \leq \varepsilon \quad (3-20)$$

In (3-20),  $\varepsilon$  is defined as the threshold of active probability according to the basic hypothesis of spectrum sensing: PU's presence is not dominant in the band, and there exists some opportunities to reuse the band. Then, the first lower-bound condition of  $\alpha_0$  is implied as (3-21):

$$\alpha_0 \geq \alpha_0^{(1)} = \alpha_1 \left( \frac{1}{\varepsilon} - 1 \right) \quad (3-21)$$

Substituting (3-19)~(3-20) into (3-18), the upper bound of  $\alpha_0$  is indicated as (3-22):

$$\alpha_0 \leq \alpha_0^* = \alpha_1 \left( \frac{E_{pt}}{E_{pt}^*(k, \tau)} e^{-\frac{\tau}{\alpha_1}} - 1 \right) \quad (3-22)$$

(3-22) defines the maximal idle duration ratio, as a protection of PU's presence. As  $\alpha_1$  is basically a small ratio (e.g.  $\alpha_1$  equals only 0.352 seconds [3]), the boundary is a monotonously increasing function to  $\tau$  under certain fusion rule. For the concern of satisfying SU's sensing performance, the maximal idle ratio, that PU can tolerate, is obtained at the worst sensing case of SU, where  $\tau$  reaches its minimum  $\tau_{min}$ . If PU presents more frequently than the threshold in a better sensing case of SUs, the sensing performance (e.g. detection and false alarm) can be further improved. However, for PU's design, idle period always concedes to the presence by meeting the maximum requirement of SNR at the minimum sensing ratio.

In addition, although decreasing PU's power brings less interference and improve the data rate  $C_{10}$ , this has very limited influence on the system throughput. In contrary, the average transmission power should be increased to a threshold  $E_{pt}^*$  to reduce the false alarm probabilities and therefore to improve the throughput. Thus, the active time of PU should surpass a minimum value defined in (3-18) to guarantee the sensing performance.

### 3.4.2. Adaptation of PU's active durations

For primary user who uses multiple channels in parallel, the access to each channel is assumed to be individual and identical. Due to the random behavior of PU based on its *P.D.F.s*, the probability of PU's presence is unfixed in a frame and the active/idle states are subject to an exponential distribution with average duration denoted as  $\alpha_0$ ,  $\alpha_1$  respectively. Thus, the probabilities of PU switching between OFF and ON states  $P_{ON \rightarrow OFF}^{Trans}$ ,  $P_{OFF \rightarrow ON}^{Trans}$  are computed as integrations of related *P.D.F.s* during the transmission period, as (3-23)~(3-24), respectively:

$$P_{ON \rightarrow OFF}^{Trans} = \int_0^{T-\tau-N\tau_0} \alpha_1^{-1} e^{-t/\alpha_1} dt = 1 - e^{-(T-\tau-N\tau_0)/\alpha_1} \quad (3-23)$$

$$P_{OFF \rightarrow ON}^{Trans} = \int_0^{T-\tau-N\tau_0} \alpha_0^{-1} e^{-t/\alpha_0} dt = 1 - e^{-(T-\tau-N\tau_0)/\alpha_0} \quad (3-24)$$

The second lower-bound condition of  $\alpha_0$  is denoted as  $\alpha_0^{(2)}$  in (3-25) to set the constraint of the state switch during a transmission period:

$$\alpha_0 \geq \alpha_0^{(2)} = -\frac{T-\tau_{min}-N\tau_0}{\ln(1-\beta)} \geq -\frac{T-\tau-N\tau_0}{\ln(1-\beta)} \quad (3-25)$$

where  $\beta$  denotes the maximum reactivation probability of PU that SUs can tolerate. The principal influence of states' switch is the reawake of PU, which could interfere with SUs and descends their data rate from  $C_{00}$  to a much lower level  $C_{10}$ . Therefore, PU's reawake also decreases the average data rate. This reawake is unpredictable and could happen at any time of the transmission period. Besides, in miss detection case, even the probability exists for PU to transit from ON to OFF, which makes the band becomes available again, the probability of miss detection is already very small and the transmission can hardly recover to the normal data rate  $C_{00}$  if a collision happens just before the state switch. Thus, this PU's action brings no real gain on the system

throughput. Since it is indicated that the collision between PU and SU is rather important to consider, hereafter,  $C_{10}$  is assumed as an ignorable factor comparing to  $C_{00}$ . Taking into account the state switches on PU, the total throughput is formulated as (3-26):

$$\mathbb{T}_{total} = (T - \tau - N\tau_0)(1 - \mathbb{P}_f)p_0C_{00}e^{-(T-\tau-N\tau_0)/\alpha_0} \quad (3-26)$$

The global energy consumption with PU's state switch is composed of two aspects: From SUs' view, the energy consumption only depends on the state reported from FC after the sensing period. As the samples are collected at the beginning of each sub-frame, PU's state change has no impacts on the reporting message, which is already sent to SUs before the transmission. Thus, the total energy consumption in an entire frame  $T$  is calculated in (3-27):

$$\begin{aligned} \mathbb{E}_{total}^{SU} &= [(1 - \mathbb{P}_f)p_0 + (1 - \mathbb{P}_d)p_1]E_{S0} + [\mathbb{P}_fp_0 + \mathbb{P}_dp_1]E_{S1} \\ &= NE_{SS}\tau + NE_{St}\tau_0 + (T - \tau - N\tau_0)E_{St}[(1 - \mathbb{P}_f)p_0 + (1 - \mathbb{P}_d)p_1] \end{aligned} \quad (3-27)$$

In addition, energy consumption is determined by PU's fluctuated activation time. The average duration of PU being active state in an entire frame's time  $T$  is estimated in (3-28):

$$t_0^{ON}(T) = p_1Te^{-\frac{T}{\alpha_1}} \quad (3-28)$$

The circuit power is assumed to be small enough comparing to the power spent on operations of sensing and data transmission. Hence, the overall energy consumption in a frame's time for CRN (both PU and  $N$  SUs) is computed as (3-29):

$$\begin{aligned} \mathbb{E}_{total} &= \mathbb{E}_{total}^{SU} + \mathbb{E}_{total}^{PU} = NE_{SS}\tau + NE_{St}\tau_0 + p_1TE_{pt}e^{-\frac{T}{\alpha_1}} \\ &\quad + (T - \tau - N\tau_0)E_{St}[(1 - \mathbb{P}_f)p_0 + (1 - \mathbb{P}_d)p_1] \end{aligned} \quad (3-29)$$

Eventually, the global energy efficiency target  $\mathbb{F}$  and related conditions in the optimization problem is formulated in (3-30):

$$\begin{aligned}
& \mathbf{max}_{\tau, \alpha_0} \quad \mathbb{F} = \frac{\mathbb{T}_{total}}{\mathbb{E}_{total}} \\
\text{Subject to } \mathbb{C}_1: & \quad P_d \geq P_{d0}, P_f \leq P_{f0} \\
& \mathbb{C}_2: \quad \max\{\alpha_0^{(1)}, \alpha_0^{(2)}\} \leq \alpha_0 \leq \alpha_0^* \\
& \mathbb{C}_3: \quad \tau_{min} \leq \tau \leq T - N\tau_0.
\end{aligned} \tag{3-30}$$

Under the hypothesis that PU is designable on the durations of idle/active states, the objective is to allocate the suitable probabilities to PU's states at particular sensing time, where the energy efficiency of the whole CRN is maximized. To find a feasible solution for this optimization problem, the first step is to study the relation with PU's idle/active duration ratio (i.e. defined as  $\mu = \alpha_0/\alpha_1$ ). For simplicity, the following sub-functions of the sensing time  $\tau$  are defined in Table 3.1.

Table 3.1. Useful sub-functions of EE with  $\tau$  as a variable

$I_A(\tau)$	$(T - \tau - N\tau_0)(1 - \mathbb{P}_f) C_{00}$
$I_B(\tau)$	$T - \tau - N\tau_0$
$I_C(\tau)$	$(T - \tau - N\tau_0) (1 - \mathbb{P}_f) E_{st}$
$I_D(\tau)$	$NE_{ss}\tau + NE_{st}\tau_0$
$I_E(\tau)$	$(T - \tau - N\tau_0) (1 - \mathbb{P}_d) E_{st}$

The target function of EE can be then rewritten in (3-31) as a function of  $\{\tau, \mu\}$ , based on which *Theorem 1* is given.

$$\mathbb{F}(\tau, \mu) = \frac{\mu I_A(\tau) e^{-\frac{I_B(\tau)}{\mu\alpha_1}}}{\mu [I_C(\tau) + I_D(\tau)] + I_D(\tau) + I_E(\tau) + TE_{pt} e^{-\frac{T}{\alpha_1}}} \tag{3-31}$$

*Theorem 1.* Let us consider  $\mathbb{F}$  as a monotone increasing function to the idle/active duration ratio  $\mu$ . The optimized value of EE is obtained at the upper bound  $\mu^*$  determined by PU's minimum power constraint as in (3-22).

*Proof 1:* For a non-dominant presence of PU (i.e.  $\varepsilon < 50\%$ ),  $\mu$  is a positive factor subjected to  $\mathbb{C}_2$  of (3-30), where  $\alpha_0^{(1)}$  and  $\alpha_0^{(2)}$  are both positive values in (3-21) and (3-25). Hence,  $\frac{\partial \mathbb{F}}{\partial \mu} > 0$  always exists for positive  $\mu$ . Detailed proofs are given in Appendix (I).

According to this theorem, it is inferred that the presence probability should be



kept low in order to achieve maximum EE. However, the presence of PU is no less than minimum power provision threshold to meet the SNR requirements of sensing phase. It should also be noticed that this threshold is determined by both sensing time and related fusion strategies. In our second theorem, EE is formulated as a function of  $\tau$  to study the influence of sensing time.

*Theorem 2.*  $\mathbb{F}$  is a concave function to  $\tau$ . An optimized sensing time  $\tau^*$  can always be obtained to maximize EE, given a probability of PU's active durations.

*Proof 2:* Details are presented in Appendix (II).

According to Theorem 2, to further calculate the optimized sensing time of SUs' frame under PU's power provision, bi-section search is applied. Bi-section search is a fast and efficient method which allows estimating the optimum within limited iterations. Based on the proposed theorems, bi-section method is applied for EE maximization to find a feasible location of the optimum with a couple of variables  $\{\mu^*, \tau\}$ . In **Algorithm 1**, under *k-out-of-N* serial fusion rules, the recursive algorithm is repeated until the difference of two boundaries is smaller than the range of tolerable error.

**Algorithm 1.** Bi-section Search Algorithm for EE

1. Initialize  $N, err_0, \varepsilon, \beta, \mathbb{P}_{d0}, \mathbb{P}_{f0}, \tau_{min}, \tau_0, \gamma, \alpha_0^{(1)}, \alpha_0^{(2)}, \alpha_1$ ;
2. For  $K = 1:N$
3. Calculate  $\mu^*(\tau_{min}, K)$ ;
4. If  $\mu^*(\tau_{min}, K) \geq \max\{\alpha_0^{(1)}, \alpha_0^{(2)}\}/\alpha_1$ ;
5.  $f_{min} = \frac{\tau_{min}}{T}, f_{max} = \frac{T-N\tau_0}{T}$ ;
6. While  $f_{max} - f_{min} > err_0$
7. Calculate  $f_0 = (f_{min} + f_{max})/2$ ;
8. If  $EE'(f_{min}) \cdot EE'(f_0) < 0$ ;
9.  $f_{max} = f_0$ ;
10. Else
11.  $f_{min} = f_0$ ;
12. End
13. End
14. Output  $EE^*, f^*$ ;
15. End

### 3.5. Conclusion

As a conclusion of this chapter, the concept of PU's interactive design is presented to adapt SUs' sensing time according to PU's activities, and to achieve the maximum gain against both the low energy efficiency on sensing and the massive collision risks, where the latter causes sensing performance fallings. In our research, the boundary of EE optimization problem is defined by minimum SNR requirement, based on which the solution is approached to the optimum with bi-section search methods being applied.

In the next chapter, the focus point is to adapt SUs' behaviors between EE and QoS in a cooperative game model of cooperative spectrum sensing (CSS). A scheme of gain exchanging between these two main objectives is introduced, and evolutionary game is proposed as a gradual and iterative adaptation of utility function until an equilibrium is found.

# Chapter 4. SUs' Energy-Activated CSS Scheme Through Evolutionary Game

## 4.1. Introduction

In Chapter 3, the optimization problem is investigated towards PUs' activities, which is consistent to the first essence of CR networks: cognitive capabilities. However, in the scenario of cooperative spectrum sensing, the system model is quite different because SUs tend to behavior independently under a common rule, in order to finally adapt themselves to a stable ratio of cooperate/deny actions, which reveals the second essence of CR networks, that is, the reconfigurability.

In which follows, the CCS (i.e., cooperative spectrum sensing) model is described and the utility function is defined according to an energy-to-throughput transferable gain. The replicator dynamics are utilized to dynamically adapt the ratio of the two strategies in this evolutionary game until an equilibrium is found.

## 4.2. System model

We consider a Cognitive Radio (CR) network in which some of  $N$  SUs periodically perform the CSS process and detect PU's state (as shown in Fig. 4.1). PU holds a licensed spectrum band and rotates between an active and an idle state (i.e. the "spectrum hole"). We assume that the CSS process is time-slotted and is synchronous with PU. Once PU turns to an active state, it occupies all the channels for its own transmission; SUs can only have access to the spectrum when PU is detected idle. FC learns PU's current state by detecting SUs' sensing results and then broadcast the final fusion decision to each SU.

We denote PU's two states as  $H_0$  and  $H_1$ , representing PU is idle or occupied, respectively.  $SU_i$ 's received signal from PU can be expressed as (4-1):

$$y(t) = \begin{cases} x(t) * h(t) + n_0, & H_1 \\ n_0, & H_0 \end{cases} \quad (4-1)$$

where  $x(t)$  is PU's transmitted signal at time slot  $t$  with zero means and variance  $\sigma^2$ ,  $h(t)$  is the channel gain,  $n_0$  is circularly symmetric complex Gaussian noise (CSCG) with zero mean and variance  $\sigma_0^2$ . The average received signal strength of  $M$  sensing samples is compared with a threshold value  $\lambda^{th}$  to judge and then to report sensing results of PU.

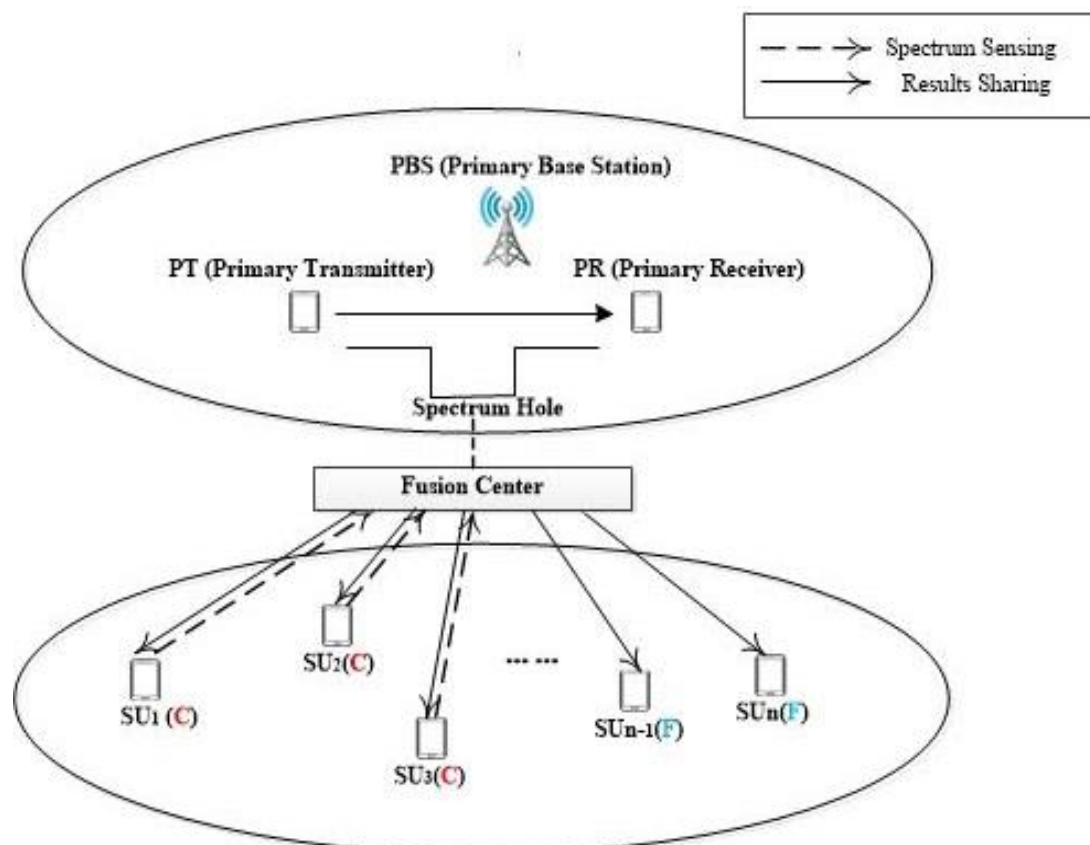


Figure 4.1. Spectrum Sensing Model in CR network

Let  $S_i (i = 0,1)$  denotes the sensing results of SU. As Fig. 4.2 (# showed on Page 50.),  $S_0|H_0$  symbolizes a correct transmission access of SU, and the probability of successful detection ( $S_1|H_1$ ) and false alarm ( $S_1|H_0$ ) are denoted as  $P_d$  and  $P_f$ , respectively. According to [53], for a complex-valued phase shift-keying (PSK) signal, the false alarm probability of a SU sample can be calculated as  $P_f$ :

$$P_f = Q\left(\left(\frac{\lambda^{th}}{\sigma_0^2} - 1\right)\sqrt{M}\right) \quad (4-2)$$

where  $Q(\bullet)$  represents a standard Gaussian's complementary distribution function.

Giving SNR  $\beta = \frac{|h|^2\sigma^2}{\sigma_0^2}$ ,  $P_d$  is calculated as:

$$P_d = Q\left(\frac{\lambda^{th}}{\sigma_0^2} - \beta - 1\right) \sqrt{\frac{M}{2\beta+1}} \quad (4-3)$$

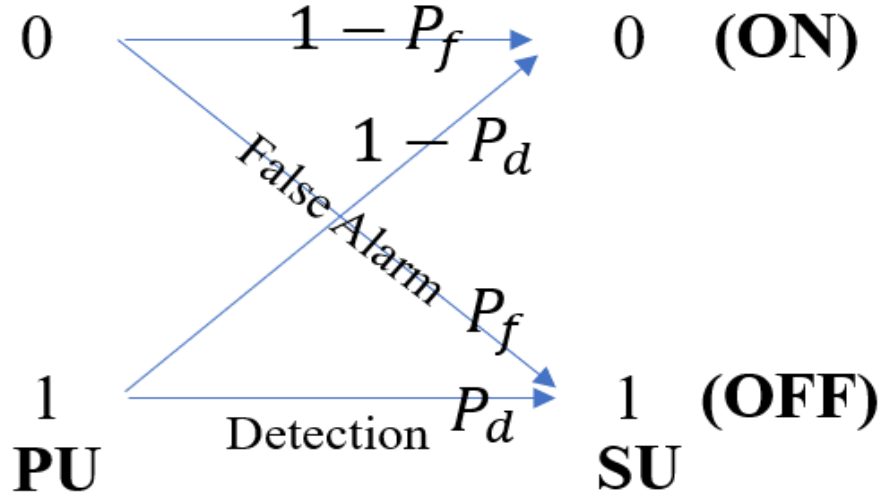


Figure 4.2. Conventional PU-SUs state mappings

A target detection probability is set as  $\widetilde{P}_d$  for SUs. The individual false alarm probability  $P_f$  can be rewritten as (4-4) by substituting (4-3) into (4-2):

$$P_f = Q\left(\sqrt{(2\beta+1)} \cdot \left(Q^{-1}(\widetilde{P}_d)\right) + \beta\sqrt{M}\right) \quad (4-4)$$

Each SU chooses whether to conduct CSS (i.e., contributor) or not to participate and only overhear other SUs' sensing results (i.e. free rider). We denote the probability of being a contributor as  $p_c$ ; the expectation of total contributors' number is  $E(n_c) = Np_c$ .

Fusion rules are introduced to consider the sensing results and related performance on sensing accuracy. Fusion rules generalize sensing results after detecting the number of contributors which report PU to be occupied. For example, 'AND' rule judges PU to be occupied only if all the contributors report PU occupied; 'OR' rule judges PU to be occupied if any contributors report PU occupied; 'MAJORITY' rule lets all the contributors "vote": PU is judged occupied if more than half of them report it occupied. We denote  $n_c$  as number of SUs contributors. More generally, we consider the system detection and false alarm probability under 'K-OUT-OF-N' rule as:

$$P_F(n_c) = \sum_k^{n_c} \binom{n_c}{k} P_f^k (1 - P_f)^{n_c - k} \quad (4-5)$$

$$P_D(n_c) = \sum_k^{n_c} \binom{n_c}{k} P_d^k (1 - P_d)^{n_c - k} \quad (4-6)$$

Obviously, ‘OR’, ‘AND’, and ‘MAJORITY’ rules can be all considered as special examples of ‘K-OUT-OF-N’ where  $k=1$ ,  $k = n_c$ ,  $k = \left\lceil \frac{n_c}{2} \right\rceil$ , respectively. In the context, we apply a common ‘MAJORITY’ rule ( $k = \left\lceil \frac{n_c}{2} \right\rceil$ ), where  $P_F(n_c)$  is considered as the major half of a Bernoulli process with individual probability at  $P_f$ .  $P_F(n_c)$  fluctuates with parity of  $n_c$ , but unlike ‘K-OUT-OF-N’ rule, the fluctuation can be controlled in a limited range. Hereafter, we denote  $P_F$  as an average of  $P_F(n_c)$ .

We observe from (4-5) ~ (4-6), given the number of contributors  $n_c$ ,  $P_F$  and  $P_D$  are calculated from those who report “occupied” under a same fusion rule. However, these collected samples should be considered differently under  $H_0$  and  $H_1$  states. On the one hand, the system false alarm probability  $P_F$  determines whether PU’s spectrum resources can be exploited efficiently by SUs, and whether throughput can be satisfied for SUs during  $H_0$  states. On the other hand, the system miss detection probability  $1 - P_D$  should be controlled inside a proper range in order to make SUs concede correctly and to avoid causing collisions with PU during PU’s  $H_1$  state. These two error probabilities (i.e., false alarm and miss detection) are the main causes of inconsistency between PU and SUs.

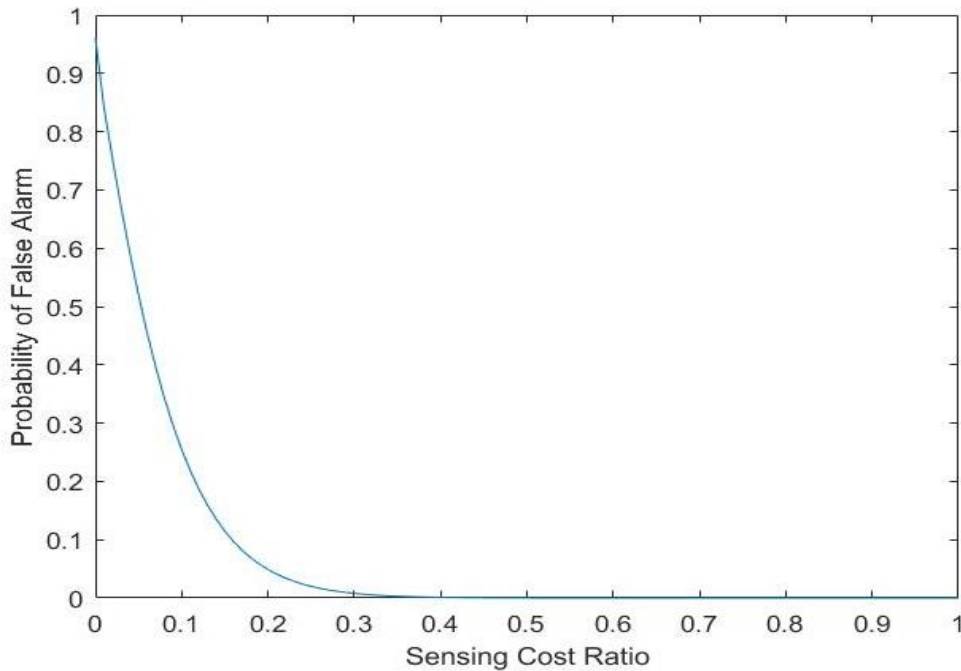


Figure 4.3 False Alarm Probability vs. Sensing Cost (N=6, SNR= -12dB)

For instance, Fig. 4.3 considers 6 secondary users and  $P_F$  is calculated at FC under -12dB signal-noise-ratio according to Eq. (4-4) ~ (4-5).  $P_F$  can be observed as a rapid decreasing function with the sensing cost ratio. The false alarm probability becomes ignorable for a sensing time larger than 30% of the frame. This is because small sensing “investments” tends to cause insufficient number of samples, which results in inaccuracy of the fusion decision. The sensing performance increases rapidly until reaching a threshold (0.3), from which point no more time cost need to be spent on sensing and SU should always follow its sensing result.

### 4.3. Problem Formulation

In this section, we formulate the payoff function of evolutionary game, and allocate a number of contributors to achieve an optimized gain. In general, SUs tend to behave selfish and act as free riders to maximize their own benefits, to save sensing cost and to achieve more time on data transmission. However, as FC only detects the states of the contributors, adding more contributors can reduce the system error rate and guarantee the detection accuracy of FC.

#### 4.3.1. Transmission Rate

Let  $p_{H_i}, R_{H_i} (i = 0,1)$  denote respectively the probability and the average transmission rate during  $H_0$  and  $H_1$  state of PU. The general transmission rate  $E(R)$  can be expressed as the sum of expectations during PU’s states. The transmission rate performs much lower in state  $H_1$  comparing to state  $H_0$  since the spectrum band shared between PU and SUs can cause a very serious interference. Therefore, the total expected transmission rate  $E(R)$  can be estimated as the throughput in a period of  $H_0$  and computed as in (4-7):

$$E(R) = p_{H_0}R_{H_0} + (1 - p_{H_0})R_{H_1} \approx p_{H_0}R_{H_0} \quad (4-7)$$

We assume that the time spent on results broadcast sharing is very limited compared to sensing and transmission. The transmission time is the rest after sensing process. The sensing time ratio is computed as  $a(n_c) = \frac{t_s}{n_c T}$ , where  $t_s$  is the sensing

time shared on  $n_c$  contributors and  $T$  is the length of frame, depending on the number of contributors. The contributors' expected transmission rate is calculated as (4-8):

$$\mathbf{E}(R_c) = p_{H_0} C_{H_0} (1 - a(n_c))(1 - \mathbf{P}_F) \quad (4-8)$$

where  $C_{H_0}$  is the data rate of SU during state  $H_0$  calculated by Shannon-Hartley Equation. Evidently, for each individual contributor, with an increasing number of contributors, the transmission time ratio and the sensing performance are both growing; thus, the transmission rate of contributors increases. However, their rate cannot exceed a free-rider because of the time spent on sensing. As the free riders receive directly the sensing results from FC without any contributions, their expected transmission rate is given as in (4-9):

$$\mathbf{E}(R_t) = p_{H_0} C_{H_0} (1 - \mathbf{P}_F) \quad (4-9)$$

Note that in the conventional model (Fig. 4.2), the transmission rate estimated by (4-8) ~ (4-9) represents a 0-to-0 (i.e., the state available-to-available) mapping excluding false alarm, which means that SUs only transmit data if they receive an "idle" state from FC, while there is truly an available spectrum hole on PU. SUs' decisions are based entirely on the information received from FC, whether they are efficient enough or not. Therefore, the conventional policy may cause enormous potential waste when the false alarm is large.

Since there may exist many missed frequency holes on PU that can be potentially reutilized by SUs, even if FC always reports "occupied" state to SUs, the ON/OFF decisions should be taken adaptively. SUs should be opportunistically turned on to transmit data at large false alarm probability; otherwise, SU desires to trust the sensing result, in order to save energy and to avoid PU being interrupted by its own transmission. Hence, we propose a periodically activated transmission mode to reuse the frequency holes. Let  $\rho$  denotes the probability of SU still turned on while receive "occupied" state, then (4-8) ~ (4-9) are rewritten as:

$$\mathbf{E}(R_c) = p_{H_0} C_{H_0} (1 - a(n_c))(1 - \mathbf{P}_F \cdot (1 - \rho)) \quad (4-10)$$

$$\mathbf{E}(R_t) = p_{H_0} C_{H_0} (1 - \mathbf{P}_F \cdot (1 - \rho)) \quad (4-11)$$



### 4.3.2. Energy Consumption Analysis

From a SU's view, the sensing power as a contributor ( $e_s$ ) and the power consumed on data transmission ( $e_t$ ) have to respect  $e_s < e_t$  for all SUs. In the sensing process, SU spent a relatively low power on sensing, depending on the cooperative sensing duration. In the transmission part, SU only observes the received information from FC and accesses to the channel with the probability  $\rho$  if it receives an "occupied" state. Once the access succeeds, SU spends  $e_t$  on data transmission; otherwise, SU should be turned off to save energy.

Giving the probability of receiving an occupied state as  $P_{occ}$ , we define SU's idle probability as  $P_{idle} = 1 - P_{occ} = 1 - (p_{H_0} \mathbf{P}_F + p_{H_1} \mathbf{P}_D)$ . SUs tend to transmit data based on  $P_{idle}$ . SUs may also suffer from an external influence of miss detection (0/1), but this part can be ignored as  $p_{H_0}$  and  $(1 - \mathbf{P}_D)$  are both very small. We denote the battery consumption per unit power consumption as  $\sigma$ , the average energy cost during time slot T can be described respectively for contributors and free-riders as:

$$E_c = \sigma[e_s a(n_c) + e_t (1 - a(n_c))(P_{idle} + P_{occ} \cdot \rho)] \quad (4-11)$$

$$E_f = \sigma e_t (P_{idle} + P_{occ} \cdot \rho) \quad (4-12)$$

Then, we analyze the activation part on this mapping: as PU is supposed to be available in most time periods (i.e.  $p_{H_0} \gg p_{H_1}$ ), even though a large  $\mathbf{P}_D$  is set as a target, the false alarm acts as more dominant factor at a low sensing cost, where  $\mathbf{P}_F$  is not too small (Fig. 4.3). Hence, with a low sensing time,  $\rho$  should be increased to turn on SU more often, in order to compensate for the loss on transmission rate. At a high sensing cost, the detection of PU is accurate enough, so SUs should be switched off to save energy and to avoid potential collision with PU. Thus,  $\rho$  turns to a very small value. To express this trade-off problem, the activation parameter  $\rho$  is given as a monotonic increasing function to  $\mathbf{P}_F$  :

$$\rho(\mathbf{P}_F) = \rho_0 [1 - \cos\left(\frac{\pi}{2} * \mathbf{P}_F\right)] \quad (4-13)$$

### 4.3.3. Definition of Payoff Function

The payoff of our sensing game is expressed in two aspects, the transmission rate and the energy saving. By applying the adapted energy control scheme, SU can choose to either enjoy earning higher bit rates, or to save energy and achieve some energy compensations, which depends on the value of threshold  $\mathbf{P}_F$ . Let us define  $\lambda$  as the factor to decide the influence of energy. In our proposed scheme, according to (4-8) ~ (4-11), we compute  $U_0$  as:

$$U_0^c = p_{H_0} C_{H_0} (1 - \mathbf{P}_F (1 - \rho(\mathbf{P}_F))) (1 - a(n_c)) - \lambda E_c \quad (4-14)$$

$$U_0^f = p_{H_0} C_{H_0} (1 - \mathbf{P}_F (1 - \rho(\mathbf{P}_F))) - \lambda E_f \quad (4-15)$$

The construction of this game allows allocating proper sensing time to SUs in order to find a balance between transmission and energy consumption. The objective is to find the equilibrium of the bit rate-energy game to jointly optimize these two tasks by applying the game model. In the next section, the equilibrium will be studied to realize the optimization of payoff under our proposed scheme.

## 4.4. Evolutionary Game Formation

### 4.4.1. Introduction of Game Approach

Evolutionary game provides an approach to take strategies for players and to dynamically evolve the probabilities of their strategies according to the payoff function. Each player collects information of other players' current strategies and takes a move accordingly. In this way, the game will gradually converge to an equilibrium, which is considered as a final convergence of evolution where no further gain can be achieved for any players by playing this game.

In our model, two strategies are defined for each player. Replicator dynamics stores the learning knowledge of the game; it adaptively and continuously affects the cooperation probability of each SU until an equilibrium is found. The probability for a single SU to select a strategy  $S \in \{\text{ON}, \text{OFF}\}$  at period  $t$  is denoted as  $p_S(t)$ . Thus,

replicator dynamics can be defined as the rate of probability change, and calculated as follows:

$$\dot{p}_S(t) = \frac{dp_S(t)}{dt} = \varepsilon p_S(t)(U_S(t) - \overline{U}(t)) \quad (4-16)$$

where  $\varepsilon$  represents the learning rate of the game. The absolute value of these dynamics will be decreased with the game; eventually it reaches 0 at the equilibrium.

The probability that a strategy S taken from {ON, OFF} at time  $(t + 1)$  can be estimated as a difference equation as follows:

$$p_S(t + 1) = p_S(t) + \dot{p}_S(t) = p_S(t) + \varepsilon p_S(t)(U_S(t) - \overline{U}(t)) \quad (4-17)$$

$U_S(t)$  denotes the weighted value of payoff function for all users taking specified strategy S at  $t$ ,  $\overline{U}(t)$  is the weighted value where the payoffs of mixed strategies are considered. Each strategy taken at a time slot is subject to a uniform distribution based on the probability of strategy; thus, the following equations should be respected at any time:

$$\sum_{S \in \{C, F\}} \dot{p}_S(t) = 0 \quad (4-18)$$

$$\sum_{S \in \{C, F\}} p_S(t) = 1 \quad (4-19)$$

As the game begins, each player plays a strategy with a pre-determined probability and receives a correlated payoff based on the total number of contributors at these moments. Then, it calculates the advantage (i.e. the payoff gain) by continuously playing this pure strategy over an averaged payoff value of mixed strategies. The game counts the gain on each strategy and evolves the probability for the future.

In this way, the dominated strategy will be taken more frequently in the future and the inferior strategy will be gradually eliminated. However, according to the definition of our payoff function, one player tends to be active if no one plays a contributor's role but may stay "lazy" if someone contributes. The payoff value is only related to the number of contributors and the two strategies take turns to win depending on the own evolution process of the game. The equilibrium can be achieved after a long-term competition between these two behaviors of payoff function. This competition ensures that the probability of strategy selection converges to the same equilibrium at the end, no matter at which probability it starts with.

#### 4.4.2. Analysis of The Equilibrium

Let us consider a homogeneous system where each SU (1,2,...N) has same information for a random user  $SU_k$  (denoted by strategy  $S_k$ ); the expectation of its payoff is given as:

$$\bar{U} = \sum_{S_k \in \{C,F\}} p(S_k) \bar{U}(S_1 \dots S_{k-1} S_{k+1} \dots S_N | S_k) \quad (4-20)$$

Depending on the current strategy, the general form of averaged payoff  $\bar{U}(S_1 \dots S_{k-1} S_{k+1} \dots S_N | S_k)$  is computed in (4-21) based on the distribution of probabilities for any SU other than  $k$ :

$$\bar{U}(S_1 \dots S_{k-1} S_{k+1} \dots S_N | S_k) = \sum_{i=I_k}^{N-1+I_k} C_{N-1}^{i-I_k} p^{i-I_k} (1-p)^{N-i-1+I_k} \cdot U(i) \quad (4-21)$$

where  $U(i)$  is subject to the definition of payoff in (4-14)~(4-15),  $I_k$  is an indicator of cooperation where  $I_k = 1$  if  $SU_k$  chooses “ON” and 0 otherwise. From (4-21), we compute the average payoff for each state as:

$$\bar{U}_C = \sum_{i=0}^{N-1} C_{N-1}^i p^i (1-p)^{N-i-1} \cdot U_0^C(i+1) \quad (4-22)$$

$$\bar{U}_F = \sum_{i=0}^{N-1} C_{N-1}^i p^i (1-p)^{N-i-1} \cdot U_0^F(i) \quad (4-23)$$

At the equilibrium  $t^*$ ,  $\dot{p}_S(t^*)$  equals to 0 where no more gains can be achieved by playing the game. No matter which strategy a SU acts as, it will not deviate from the equilibrium, and the proportion of both strategies remains static. The probability of cooperation is considered to be the same for any SU at  $t^*$ , i.e.  $p(S_k = ON) = p$ . (4-20) can be written as:

$$\bar{U} = p \cdot \bar{U}_{ON} + (1-p) \cdot \bar{U}_{OFF} \quad (4-24)$$

Substituting (4-22) into (4-16), the final form at equilibrium can be expressed as:

$$\dot{p} = \varepsilon p(1-p)(\bar{U}_{ON} - \bar{U}_{OFF}) = 0 \quad (4-25)$$

From (4-25), four combinations of pure strategy equilibrium can be achieved at (0,1), (1,0), (1,1), (1,0). Setting  $\mu = \lambda\sigma$  and applying the steps in appendix, the mixed equilibrium  $p^*$  can be solved according to equation (4-26):

$$\tau(M + \mu e_s)(1-p)^N + N M p(1-p)^{N-1} - \tau(M + \mu e_s) = 0 \quad (4-26)$$

where  $M$  is simplified for free riders' payoff  $U_0^F$  (as in appendix). In addition, the payoff can be adjusted by applying different activation ratio with our activation function  $\rho(P_F)$  defined in (4-13), in which more energy is spent on SUs to achieve better gains.

(4-26) reflects the relation between the equilibrium of cooperative probability and the sensing cost ratio spent in a frame. With SUs gradually learn information from the game, after enough iterations, the game converges to such an equilibrium depending on the sensing cost, the energy consumption and the activation ratio.

#### **4.4. Conclusion**

In this chapter, the evolutionary game model is applied to solve energy-efficient cooperative sensing problem. In the conventional model, SUs always respect the sensing results acquired from a reporting channel, no matter how accurate the spectrum sensing is. Nevertheless, the main cause of transmission rate falling is the lack of sensing performance accuracy, the sensing time ratio has to be improved to prevent the increase of false alarm probability.

To overcome the issue of performance degradation, in our scheme a proportion of SUs are allowed to independently and opportunistically turn on data transmission while the false alarm risk is reported to be too high. This functionality is controlled by defining a utility function, which is the core step of evolutionary game approach. The evolutionary game leads SUs to appropriately act with cooperate/deny strategies, and make recursive decisions until a stable solution is finally achieved.

In the next chapter, the simulation environments and parameters are introduced. Then, the major simulation results are given based on our two proposed solutions in chapter 3 and chapter 4, respectively. The comparisons are also showed in order to demonstrate the advantages of our algorithms.

# Chapter 5. Simulation Results

## 5.1. Introduction

This chapter is divided into two subsections where the simulation results are presented for our proposed PU- and SUs- objected spectrum sensing schemes, respectively. Our major simulations are implemented on Matlab, with parameters and variables defined in the lists at the beginning of the following sections. Next, the typical variables are investigated in order to present the gains of inventing our methods. At last, comparisons are implemented and analyzed to show the advantages of the proposed algorithms.

## 5.2. Simulation Results of PU-objected EE Optimization

In the preceding chapters, we introduced bi-section search methods aimed to solve PU-objected optimization problem in CR networks. The initial parameters of this simulation are presented in Table 5.1. For the part of fusion rule,  $k$  is tested from 1 to  $N$ . SNR at the transmit end of SUs is considered as 20 dB, based on which  $C_{00}$  is calculated as 6.65bps/Hz.

TABLE 5.1.  
Units & Values for Cognitive Properties

Symbol	Parameter	Value
$E_{ss}$	SU sensing power	0.2 Watt
$E_{st}$	SU transmission power	1 Watt
$E_{pu}$	PU transmission power	1.5 Watt
$\alpha_1$	Mean value of PU's presence	0.372 [3]
T	Duration of a frame	100 ms
$\tau_{min}$	Minimum sensing time	1.5 ms
$\tau_0$	Reporting time	5 ms
$f_s$	Sampling frequency	1MHz
$\gamma$	Signal noise ratio	-18 ~ -13dB
$err_0$	Qualified error rate	1‰
$\mathbb{P}_{d0}$	Target detection probability	0.8:0.02:0.98
$\mathbb{P}_{f0}$	Maximum false alarm probability	0.05:0.05:0.5
G	Channel gain (PU to SU)	-10 dB
N	Number of SUs	6

In Fig. 5.1, we take an example of  $N=4$ , with different  $k$  applied on the fusion rule. The individual probabilities of detection and false alarm depend on the values of  $k$ . In this figure,  $\mathbb{P}_{d0}=0.9$  and  $\mathbb{P}_{f0} = 0.1$  are defined as the threshold of the detection/ the false alarm probabilities, since the fusion rule is more difficult to attain for a larger  $k$ , the threshold of SU's individual probability is also increased. For example, the AND rule ( $k=N=4$ ) requires detection probability to arrive at 0.974, while the OR rule ( $k=1$ ) only requires 0.438. This implies that the minimum SNR in (4-18) which follows the requirement of sensing performance is also a function of  $k$ . More details of impact of fusion rules are shown in Fig. 5.5.

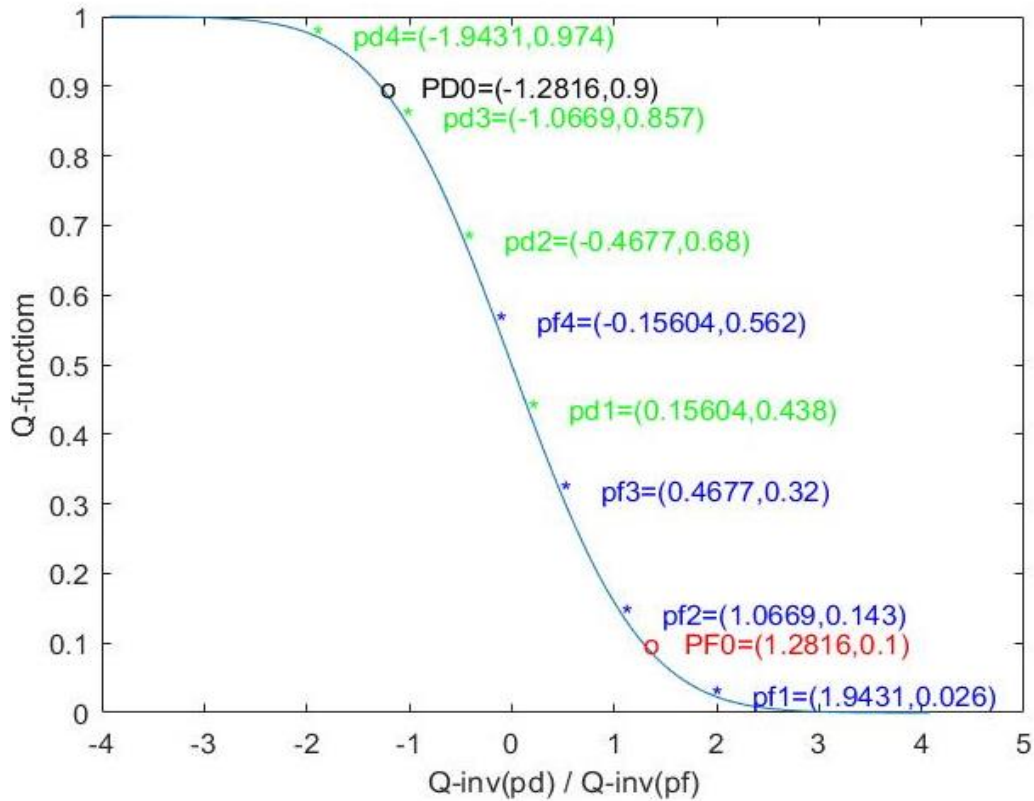


Figure 5.1. Detection performance with different  $k$

Fig. 5.2 and fig. 5.3 indicate the impact of idle/active ratio on the optimization. Fig. 5.2 draws the contour lines of different  $\mu^*$  threshold, which is the reflect of target sensing performance. It is observed that at the same  $\mu^*$  value, if the target detection probability  $\mathbb{P}_{d0}$  increases, then the target false alarm probability  $\mathbb{P}_{f0}$  can be relaxed (i.e. increased). In this figure, when  $\mu^*$  is up to 7.7884 where low presence of PU occurs,  $\mathbb{P}_{d0}$  performs no better than 0.812 whereas  $\mathbb{P}_{f0}$  exceeds 0.454. In return,

higher  $\mu^*$  also contributes to larger EE. Fig.5.3 shows an example of the 3-dimension curve of EE. We observe that EE increases with  $\mu$  until the threshold  $\mu^* = 5.044$  (the red line in Fig. 5.3) is reached at  $\mathbb{P}_{d0} = 0.9$ ,  $\mathbb{P}_{f0} = 0.5$ ,  $k = 3$ . For a specified  $\mu^*$ , one unique peak of EE can be found by implementing the bi-section search on the sensing ratio axis.

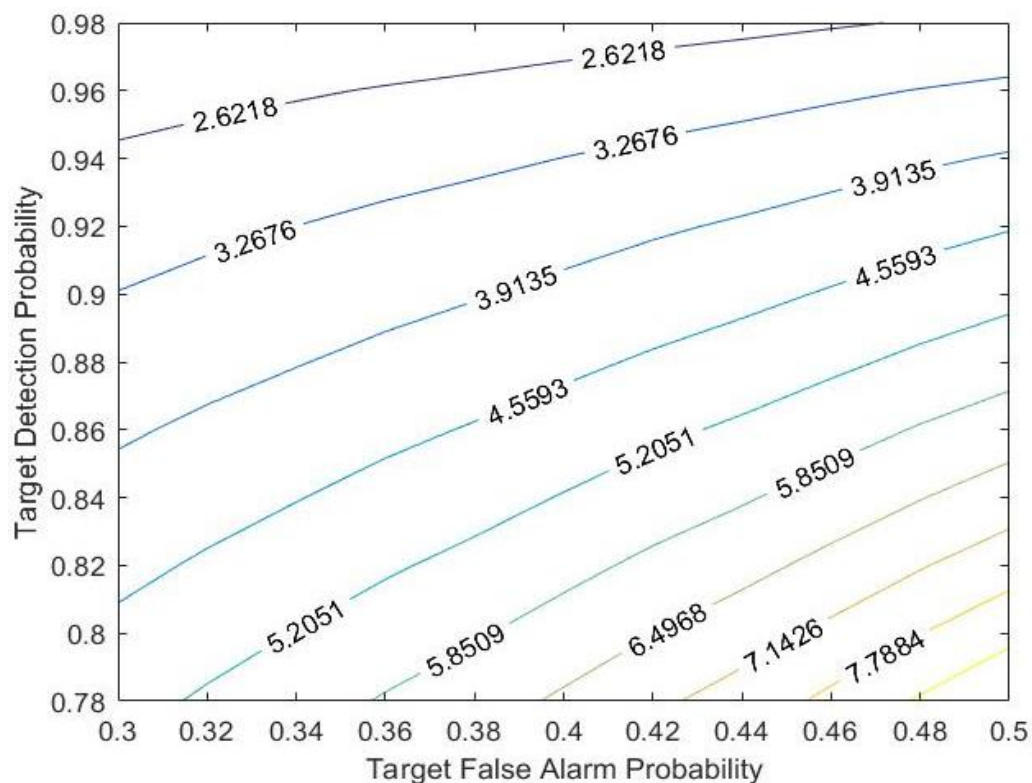


Figure 5.2. Contour lines of maximal idle/active ratio with performances constraints

The complexity of our algorithm is calculated as  $\Omega\{N \log_2(\frac{\tau_{max}-\tau_{min}}{err_0 \cdot T})\}$ . Given the probability of PU's presence, it takes less than 10 iterations to achieve the optimized EE at  $err_0 = 1\%$ . For instance, it takes an execution time of 0.3248 seconds to reach the optimum using iterative bi-section search, this execution time is estimated by Matlab tool function.

Fig. 5.4 and Fig. 5.5 present the optimized EE under different fusion rules and network environments. For  $N=6$  SUs, the best case of EE is approached to 4.8 when  $k=3$  at the cost of only 4% sensing ratio in a SU's frame. The EE of  $k$  around  $(N/2)$  performs better than other values of  $k$ -out-of- $N$ , especially when comparing to OR



( $k=1$ ), AND ( $k=N=6$ ) rules. As the “majority” rule is considered as a common and stable fusion rule, it is applied to our simulations in order to obtain the optimum.

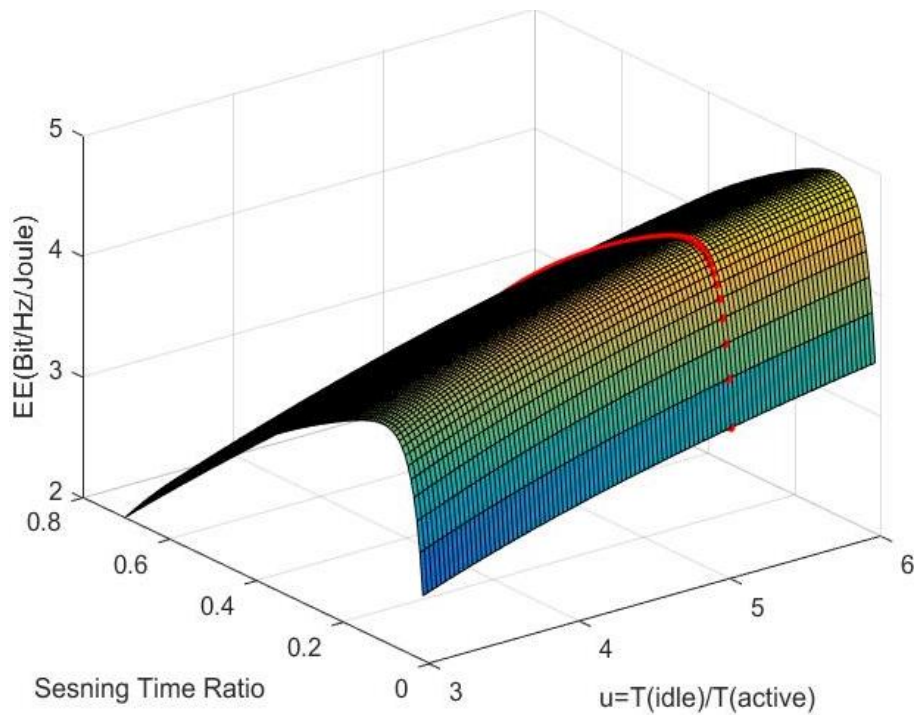


Figure 5.3. Example of 3-dimension EE optimization with PU’s idle/active ratio & sensing ratio ( $k = 3, N = 6$ )

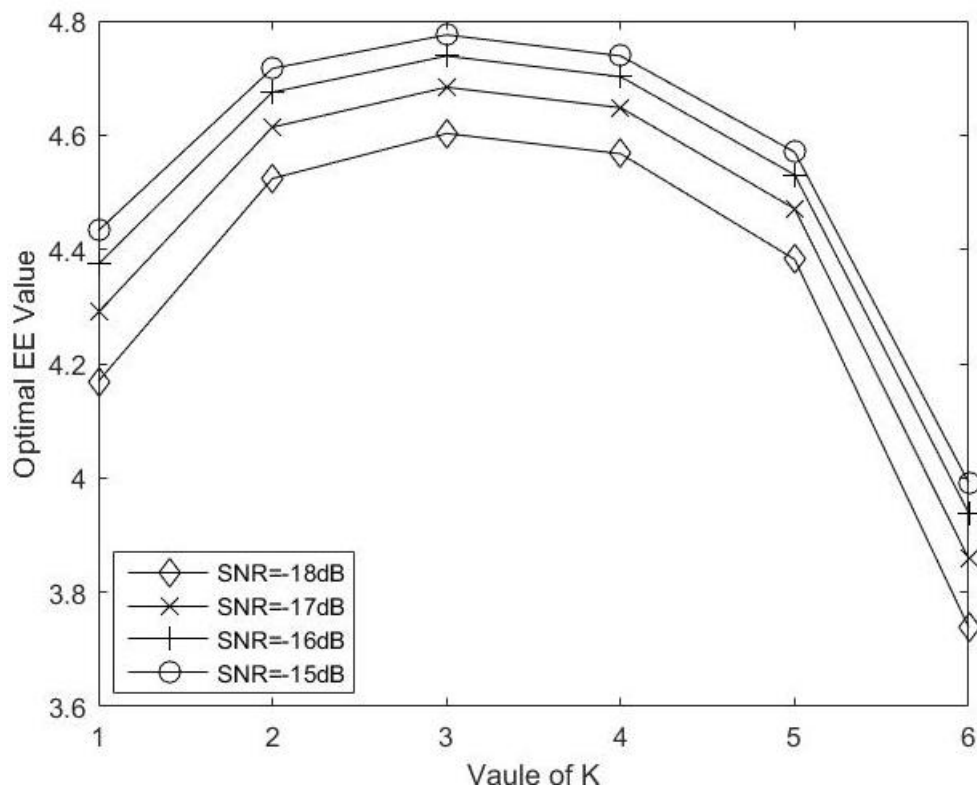


Figure 5.4. Optimal EE under different fusion rules

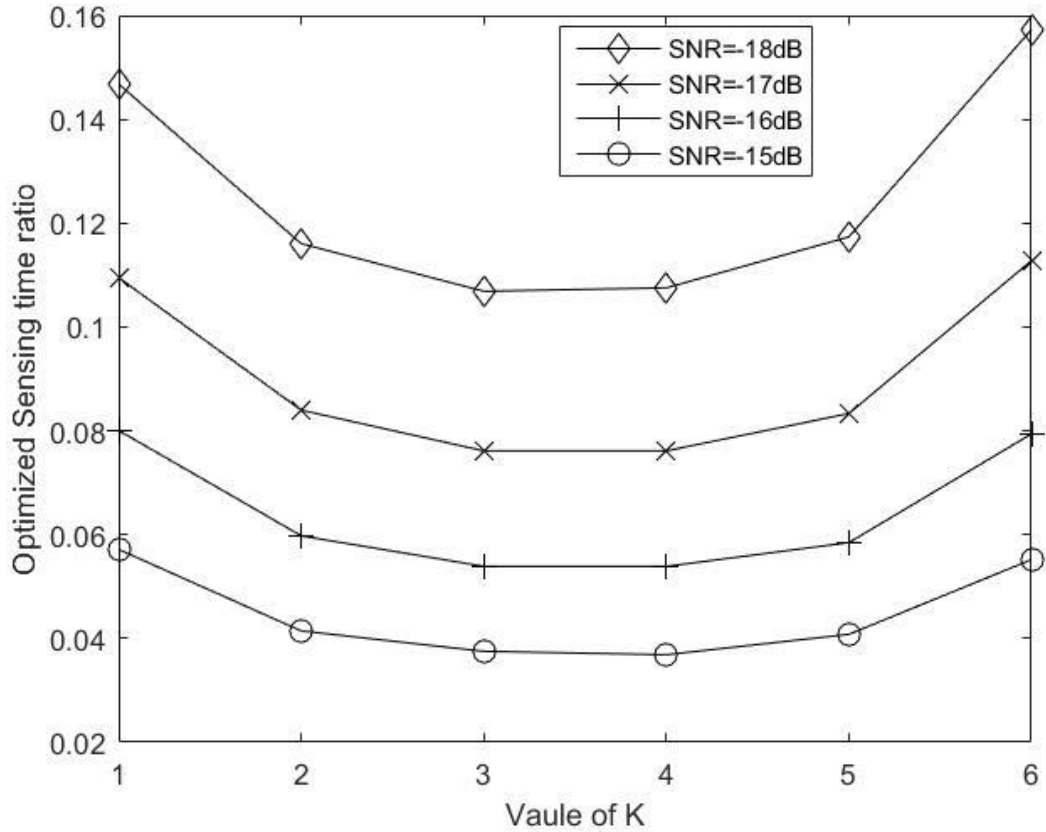


Figure 5.5. Optimized sensing ratio under different fusion rules

Fig.5.6 ~ Fig. 5.8 present a set of figures of the maximum EE and related optimized sensing ratio by bi-section search. By analyzing Fig. 5.6, we can infer that SUs need to contribute more time on sensing when larger  $\mathbb{P}_{d0}$  is required. In contrary, as an upper limit of  $\mathbb{P}_f$ ,  $\mathbb{P}_{f0}$  is utilized to estimate the minimum presence of PU, this has no impacts on optimized sensing ratio. Although  $\mathbb{P}_{f0}$  has an impact on  $\mu^*$ , and thus it influences the maximum EE, the optimized sensing ratio is only depended on  $\mathbb{P}_{d0}$  and irrelevant to  $\mathbb{P}_{f0}$ . However,  $\mathbb{P}_{d0}$  influences both the optimized sensing ratio and the optimum EE, as it contributes to both  $\mathbb{P}_f$  and  $\mu^*$ . For example, with  $\mathbb{P}_{d0}$  increasing from 0.9 to 0.95, the sensing time increases up to about 20% and the optimum EE value decreases by around 10%. This is because higher  $\mathbb{P}_{d0}$  calls for higher sensing effort of SUs in order to achieve the sensing performance target, but in return, EE is less because the opportunistic access of SUs is limited.

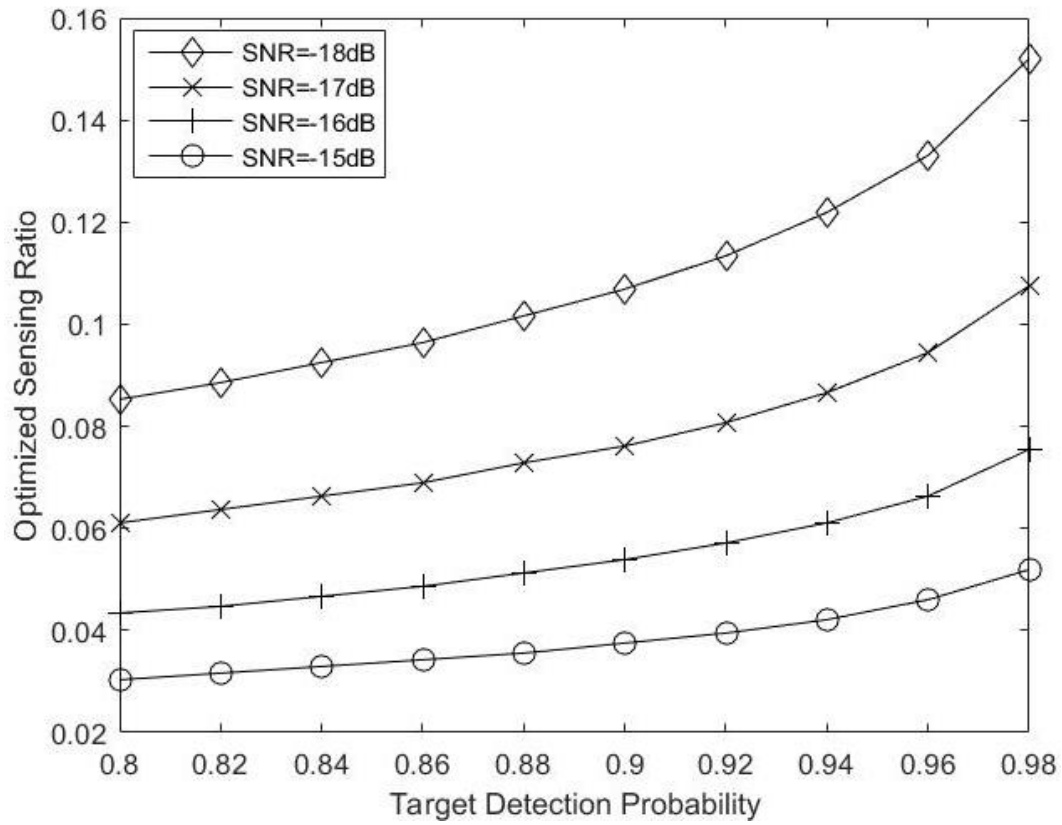


Figure 5.6. Optimized sensing ratio under target detection

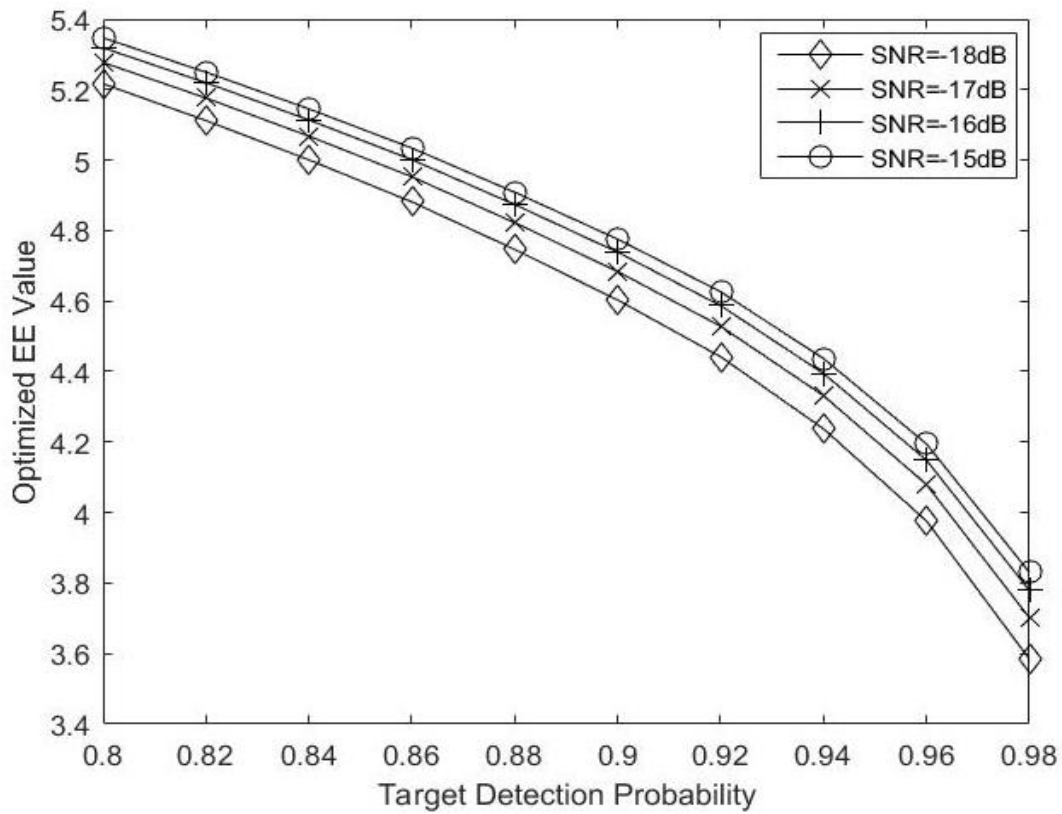


Figure 5.7. Optimal EE under target detection

Fig. 5.7 and Fig. 5.8 show that when the sensing performance requirements become stricter (i.e. higher  $\mathbb{P}_{a0}$  or lower  $\mathbb{P}_{f0}$ ), the minimum presence of PU increases and EE turns small, as argued in our first theorem. It should be pointed out that  $\mathbb{P}_{f0}$  cannot be too greedy although larger  $\mathbb{P}_{f0}$  contributes to higher EE. In practice,  $\mathbb{P}_{f0}$  should be designed based on the conditions of SNR and the minimum sensing ratio  $\tau_{min}$ . For example, at  $\tau_{min} = 3ms$ ,  $\mathbb{P}_{f0}$  should be no smaller than 0.1752 at SNR= -16dB, and 0.4290 at SNR= -18dB. The decrease in  $\mathbb{P}_{f0}$  to approach these values can improve the intensity of sensing performance metrics and also increase the throughput of data transmission during PU's "OFF" state.

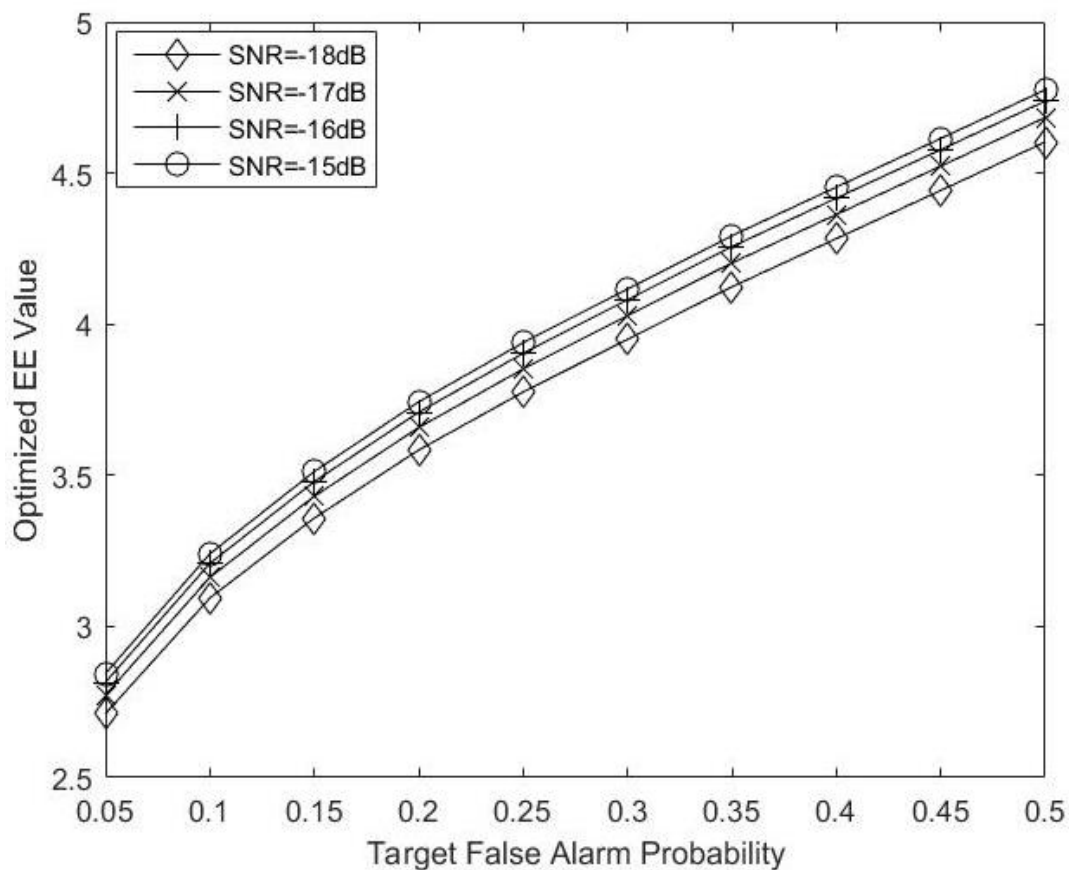


Figure 5.8. Optimal EE under target false alarm

Fig. 5.9 shows the impact of random PU activities compared to EE-oriented optimal PU activity in a practical view. Given the value of  $\mu^*$ , the optimal sleeping probability of PU  $p_0^*$  equals to 0.835, according to the output of Matlab. Other access activities of PU are tested under the same SNR requirement. When the presence of PU is sufficient to the performance metrics, the optimal EE increases slightly with SNR

requirement, and the portion of EE difference with optimal  $p_0^*$  almost stays the same for any received SNR.

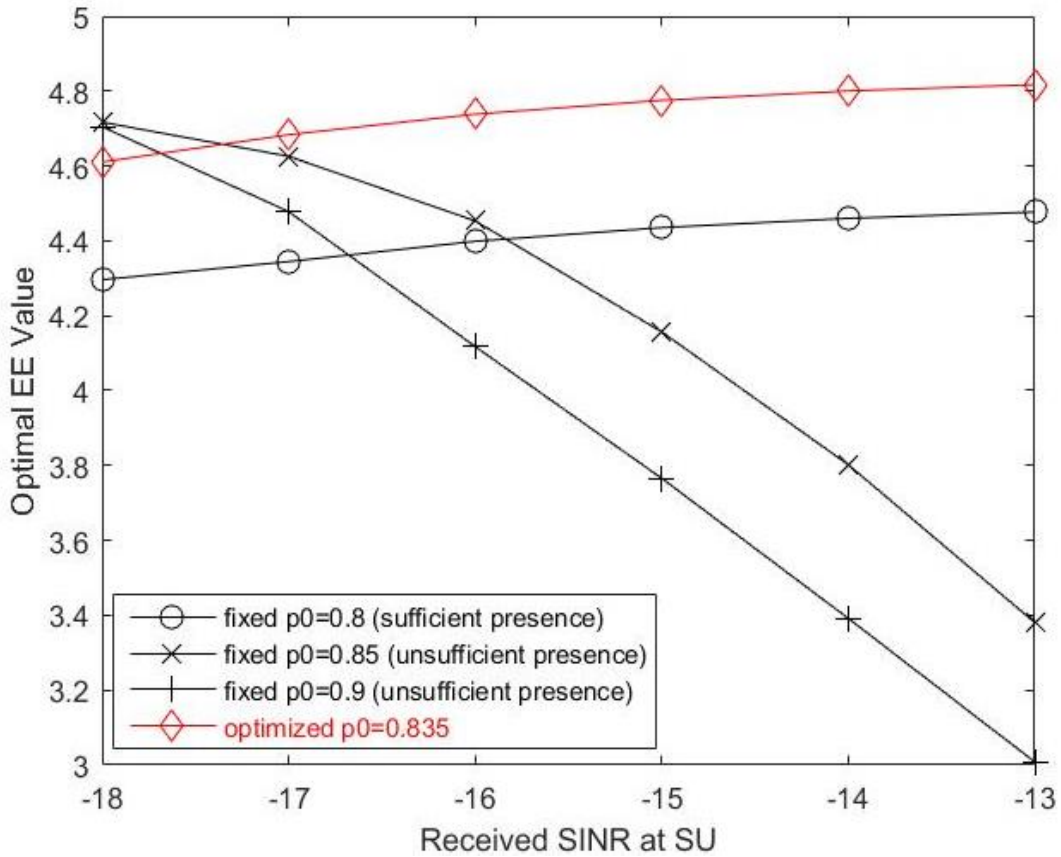


Figure 5.9. Comparison of EE with different PU activities

However, PU's redundant presence interferes with EE by occupying access opportunities of SUs; thus, the curve of  $p_0=0.8$  lies beneath the optimal  $p_0^*$ . In addition, it is observed that EE descends when the energy provisioning from PU is not sufficient (e.g.  $p_0=0.85, 0.9$ ). The more PU is absent, the less efficient it is on EE due to the increased false alarm risks, and the disadvantage becomes even more evident if better SNR condition is required. As a result, Fig.5.9 indicates that the optimally designed PU activity can earn higher EE of the whole CRN network and it resolves better the tradeoff problem between sensing performance and access opportunities of SUs.

### 5.3. Simulation Results of Energy-Activated Evolutionary Game in CSS

In this section, the parameters and simulations are presented for proposed game model. We consider the signal as QPSK-modulated. The sampling frequency is 1MHz. Other important parameters are presented in Table 5.2.

Table 5.2. Parameters of simulation

$e_s$	0.05 watt	$e_t$	0.2 watt
$p_{H_0}$	0.9	$C_{H_0}$	1Mbps
$P_{D\_Target}$	0.95	$\mu$	0.5
$\rho_0$	{0,0.1,0.2,0.3,0.4}	$SNR$	-14 dB

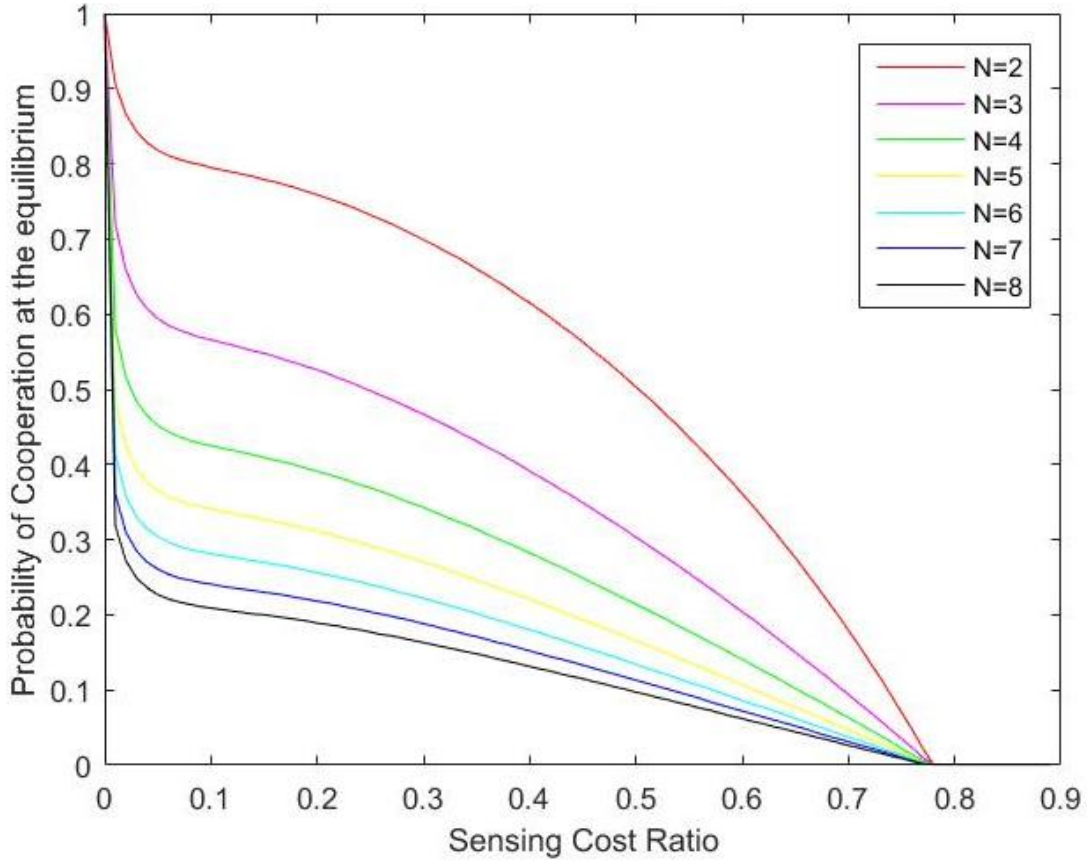


Figure 5.10. Equilibrium of game to sensing time ( $\rho_0 = 0.3$ )

SUs are considered as homogeneous ones and share similar channel conditions and SNR. As we consider different number of SUs in the system, from Fig. 5.10, it can be observed that SUs tend to contribute more to the sensing if there are only few ones in the system. In any condition, the probability will decrease to a same equilibrium and the sensing ratio at equilibrium is less than 1. This is because the sensing process is costly and no payoff can be gained if sensing accounts for most time in the frame, the transmission is compressed if higher sensing efforts are required. The condition to obtain a positive payoff is that the sensing process should be less costly and should

allocate enough time of a SU frame into the transmission. The maximum sensing ratio is achieved at around 78% where sensing and transmission cost are balanced and SUs still have few interests on cooperative sensing.

In Fig. 5.11 ~ Fig. 5.12, we consider different activation attitudes of SU's transmission  $\rho_0$ . As shown in Fig. 5.11, the higher  $\rho_0$  is, the more positive a SU tends to act on sensing. At low sensing cost, most of frame is spent on data transmission, but insufficient sensing causes high false alarm probability. Thus, it makes sense to sense at high false alarm probability and to exchange some energy to additional bit rate, in order to keep the balance between these two objectives. While the sensing cost increases, it is observed that the curves start overlapping, because most of SUs refuse to take the risk of colliding with PU, hence they stay on "OFF" state if they receive "occupied" state from FC.

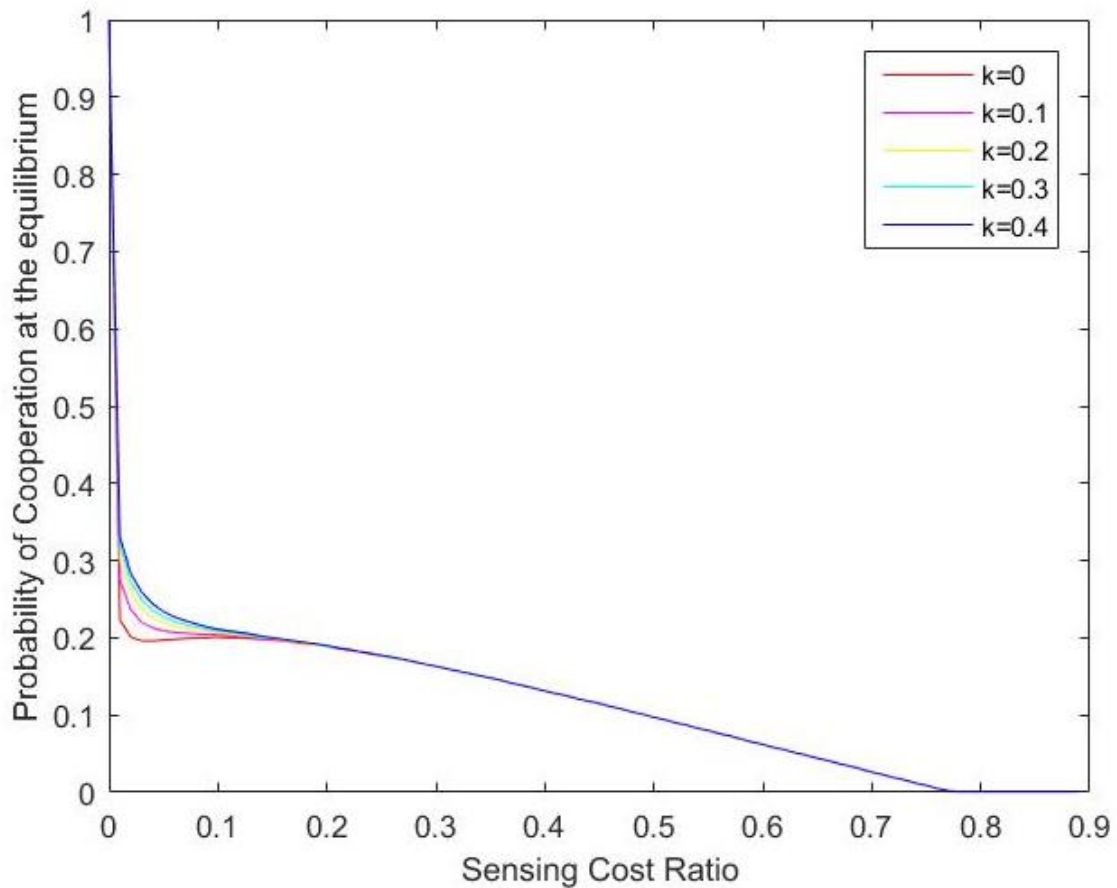


Figure 5.11. Cooperative probability with activation factor  $\rho_0$

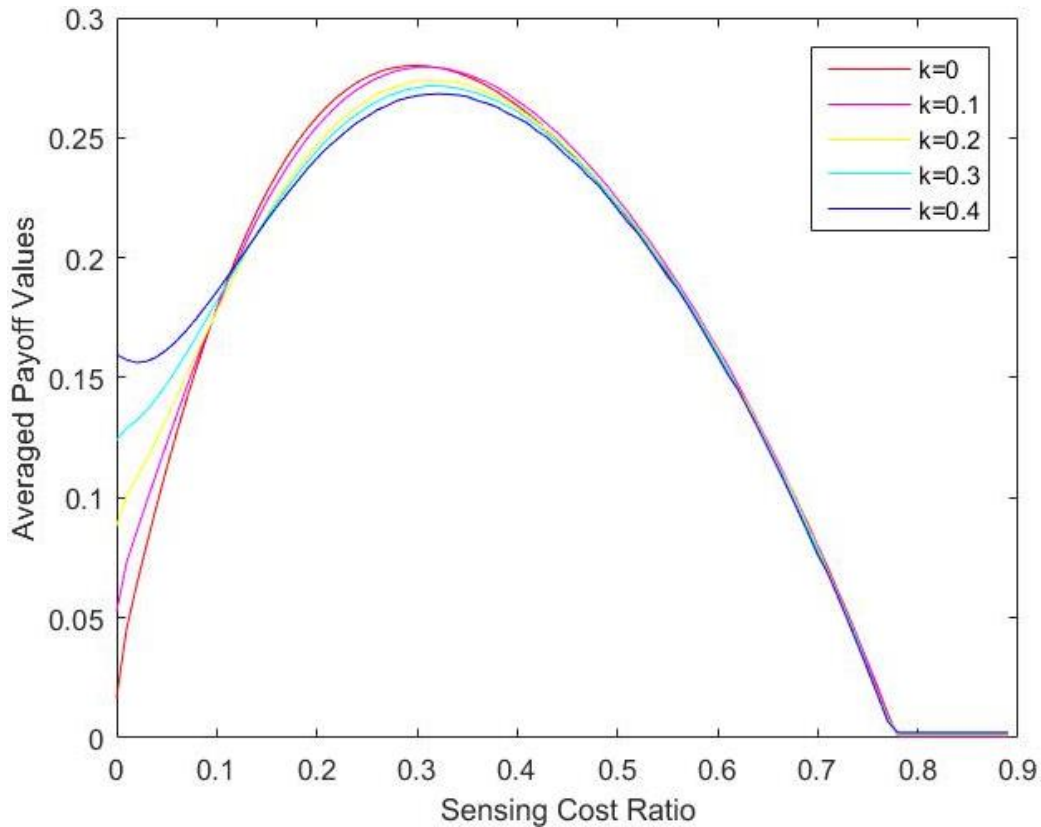


Figure 5.12. Average Payoff with activation factor  $\rho_0$

As a result, in Fig. 5.12, at  $\tau = 0.05$ , the payoff is around 0.17 for  $k=0.4$ , but it is only around 0.1 for  $k=0$ . Thus, under our proposed payoff function, the energy activation scheme can help achieve more payoff at low sensing cost. At the middle sensing cost (i.e., between 0.15 and 0.5), the payoff decreases because of the additional energy cost on activation. However, the decrease is slight and the payoff is still high enough at this range, and gradually the curves overlap at high cost (e.g. sensing cost  $>0.5$ ) where energy activation is entirely shut down.

#### 5.4. Conclusion

In this chapter, the simulation environments and results are presented for both our propositions. For PU-based EE optimization problem, an optimum is searched in a three-dimensions in order to study the influence of PU's activity to the general sensing efficiency. Different detection and false alarm probabilities are set as spectrum sensing targets, and the optimum is located by applying the proposed bi-section research method under diverse constraint boundaries.



For energy-activated SUs' CSS, the simulation presents well how an equilibrium can be found by a gradual adaptation of SUs' strategies. The result also proved that under certain conditions of utility definitions, the gain can always be expected while the sensing time is not adequate. Our method contributes to greatly improve the energy-performance gain, especially when the sensing effort is poor.

In the next chapter, the conclusion of thesis is drawn. Moreover, the key contributions of thesis are highlighted, and further research points and novel research directions are extended and presented with this thesis.

# Chapter6. General Conclusion and Outlook

## 6.1. Introduction

In this chapter, an overview of this thesis is presented. Firstly, the objectives of our works are restated. Secondly, the major propositions and contributions are highlighted for both of our works. Lastly, outlooks and prospects for our future work are also described at the end of chapter.

## 6.2. Conclusion of PU-oriented EE optimization

In our work, the design of PU activity [78] is jointly considered with SUs' sensing efforts to achieve the aggregate EE maximization. The status changes of PU during the transmission period influences the throughput received at SUs. In addition, more available absence of PU contributes to a higher EE. However, the increase of absence ratio should not be greedy and should be controlled below a threshold so that the sensing performance of SU can be guaranteed and PU can be protected. We prove that EE is a concave function of sensing time given a fixed probability of PU's presence. To optimize EE in the interactive scenario of PU-SUs, a bi-section search algorithm is proposed to dynamically locate the optimum. Simulation results show that the optimum of the optimization problem is subject to the requirement on sensing performance targets, and we prove by simulations that the optimized solution of our proposed scheme outperforms other percentage of PU's presence (i.e., either too much or too few).

## 6.3. Conclusion of energy-activated CSS game

Cooperative spectrum sensing can help the system to better allocate resources among a group of SUs, especially to achieve the throughput optimization. However, the throughput can be extremely low if there is high false alarm risk at fusion center. In an evolutionary game, throughput should be considered with energy consumption to jointly formulate the payoff function. We propose a control scheme at receiver's side to flexibly turn on the data transmission if the waste caused by false alarm is too much. By constructing and studying this game, the equilibriums are found at different sensing

costs. The simulation results show that the activation scheme can help achieve much higher payoff at low sensing cost, which maintains the stability of the whole system at any sensing cost conditions.

#### **6.4. Prospects and outlooks**

The conventional methods to solve EE optimization problem under performance constraints in CRNs mainly focus on the physical layer, such as proposing either an adaptation of detection threshold, or power allocation schemes (e.g. water filling, power optimizations, etc.). Our thesis also based on physical layer, and PU-SUs' interactive activities and behaviors are of great concern in our works. The purpose of our work is either to make the best decisions under the competitive gains' model, or to find the most profitable activities so that the primary and secondary users can act in a cooperative way.

In the future works, further methods should be developed onto the cross-layer optimization problems [79]. Apart from the conventional targets such as sensing performance accuracy, throughput and power allocations, the PU-SUs mapping system is always evolving with more and more researches being proposed in CRN. The environment of spectrum sharing between these two layers of users is considered a comprehensive target. For example, according to [80][81][82][83][84][85], novel schemes are focusing on the multiple-PUs-multiple-SUs spectrum sensing issue which is more complicated than one-PU case.

Thus, routing schemes become more important in order to better manage the coordination between PUs and SUs, and to improve the performance gain of the whole CR system. Based on cross-layer DSA (dynamic spectrum access) schemes presented in [83], more DSA algorithms should be studied, to further adapt the sensing and transmission interval and to improve EE. and to deal with more complex network scenarios (e.g. multi-hop MIMO [85]) and the constraints in multi-dimensions optimization problems.

Last but not least, the geometry parameter of routing session such as normalized distance between PU-SUs pairs should be considered, the interference is calculated

according to this distance and channel fading situations. Other targets such as mobility and fairness between users also deserves to be further studied.

As a conclusion, EE and sensing performances should be further reinforced in our future work. The cross-layer model will be applied while analyzing the likely routing strategies. Besides, the sensing interval and thresholds should be considered to maintain the high efficiency in an opportunistic spectrum access. Based on these key points, cross-layer methods combining routing, channel assignment and resource allocation schemes should be designed in our future studies.

# Appendix (I)

## Proof of Theorem 1. (Chapter 3)

In addition to the sub-functions defined in Table I, to further simplify the target function of EE, we define  $I_P(\tau) = I_C(\tau) + I_D(\tau)$ , and  $I_Q(\tau) = I_D(\tau) + I_E(\tau) + TE_{st}e^{-\frac{T}{\alpha_1}}$ .

$$\begin{aligned} \frac{\partial \mathbb{F}}{\partial \mu} &= \partial \left( \frac{\mu I_A(\tau) e^{-\frac{I_B(\tau)}{\mu \alpha_1}}}{\mu I_P(\tau) + I_Q(\tau) + TE_{pt}e^{-\frac{T}{\alpha_1}}} \right) / \partial \mu \\ &= e^{-\frac{I_B(\tau)}{\mu \alpha_1}} \left\{ \frac{\mu I_A(\tau) \cdot \left( \frac{I_B(\tau)}{\mu^2 \alpha_1} \right)}{\mu I_P(\tau) + I_Q(\tau)} + \frac{I_A(\tau) I_Q(\tau)}{[\mu I_P(\tau) + I_Q(\tau)]^2} \right\} \\ &= I_A(\tau) e^{-\frac{I_B(\tau)}{\mu \alpha_1}} \frac{[I_B(\tau)I_P(\tau) + I_Q(\tau)\alpha_1] \mu + I_B(\tau)I_Q(\tau)}{\mu \cdot [\mu I_P(\tau) + I_Q(\tau)]^2} \end{aligned} \quad (\text{I})$$

In (I), it is observed that each of the aforementioned sub-functions are positive and  $\mu > 0$ . Thus,  $\partial \mathbb{F} / \partial \mu > 0$ .

## Proof of Theorem 2. (Chapter 3)

For convenience, we name sub-terms of  $\tau$ :  $\mathbb{M}(\tau) = I_B(\tau)$ ;  $\mathbb{R}(\tau) = (1 - \mathbb{P}_f)$ ;  $\mathbb{Z}(\tau) = (\mu + 1)I_D(\tau) + TE_{pt}e^{-\frac{T}{\alpha_1}}$ .

Firstly, we calculate the derivation of throughput and energy consumption with ratio  $\mu$  respectively, as (II-1) and (II-2):

$$\frac{\partial \mathbb{T}}{\partial \tau} = \mu C_{00} e^{-\mathbb{M}(\tau)/\alpha_0} \left( \frac{\mathbb{M}(\tau)\mathbb{R}(\tau)}{\mu \alpha_1} - \mathbb{M}(\tau) \frac{d\mathbb{P}_f}{d\tau} - \mathbb{R}(\tau) \right) \quad (\text{II-1})$$

$$\frac{\partial \mathbb{E}}{\partial \tau} = (\mu + 1)NE_{ss} - E_{st} \left( \mu \mathbb{R}(\tau) + \mu \mathbb{M}(\tau) \frac{d\mathbb{P}_f}{d\tau} + 1 - \mathbb{P}_d \right) \quad (\text{II-2})$$

Secondly, we calculate the derivation function of EE as (III):

$$\begin{aligned} \partial \mathbb{F} / \partial \tau &= \partial (\mathbb{T} / \mathbb{E}) / \partial \tau = (\mathbb{E} \partial \mathbb{T} / \partial \tau - \mathbb{T} \partial \mathbb{E} / \partial \tau) / \mathbb{E}^2 \\ &= \frac{\mu C_{00} e^{-\mathbb{M}(\tau)/\alpha_0}}{\mathbb{E}(\tau)^2} \left\{ \frac{\mathbb{E}(\tau)\mathbb{M}(\tau)\mathbb{R}(\tau)}{\mu \alpha_1} - [\mathbb{Z}(\tau) + (\mu + 1)NE_{ss}\mathbb{M}(\tau)]\mathbb{R}(\tau) - \right. \\ &\quad \left. [\mathbb{Z}(\tau) + (1 - \mathbb{P}_d)E_{st}\mathbb{M}(\tau)]\mathbb{M}(\tau) \frac{d\mathbb{P}_f}{d\tau} \right\} \end{aligned} \quad (\text{III})$$

In (III), obviously  $\mathbb{M}(\tau)$  decreases with  $\tau$ , and  $\mathbb{R}(\tau)$  is a monotonously

increasing function with  $\tau$ . Then, we analyze the limit of derivation at two edges of sensing time as (IV)&(V):

$$\lim_{\tau \rightarrow 0} \mathbb{M}(\tau) = T - N\tau_0 \quad (\text{IV-1})$$

$$\lim_{\tau \rightarrow 0} \mathbb{R}(\tau) = 0 \quad (\text{IV-2})$$

$$\lim_{\tau \rightarrow T - N\tau_0} \mathbb{M}(\tau) = 0 \quad (\text{V-1})$$

$$\lim_{\tau \rightarrow T - N\tau_0} \mathbb{R}(\tau) = 1 - \mathbb{P}_f(T - N\tau_0) \quad (\text{V-2})$$

As the sensing time arrives at the maximum in (V-2), and ignoring the slight effect on false alarm probability caused by reporting time constraint, we consider  $\mathbb{P}_f(T - N\tau_0) \approx 1$ . Thus, (V-2) approaches to 0. Substituting (IV)&(V) into (III), we obtain:

$$\lim_{\tau \rightarrow 0} \frac{\partial \mathbb{F}}{\partial \tau} = - \frac{(T - N\tau_0)}{\mathbb{E}(0)} \cdot \frac{d\mathbb{P}_f}{d\tau} \quad (\text{VI-1})$$

$$\lim_{\tau \rightarrow T - N\tau_0} \frac{\partial \mathbb{F}}{\partial \tau} = - \mathbb{Z}(T - N\tau_0) \quad (\text{VI-2})$$

Obviously, as  $\frac{d\mathbb{P}_f}{d\tau} < 0$ , we have  $\lim_{\tau \rightarrow 0} \frac{\partial \mathbb{F}}{\partial \tau} > 0$ ,  $\lim_{\tau \rightarrow T - N\tau_0} \frac{\partial \mathbb{F}}{\partial \tau} < 0$ . From (III), we imply that EE has one unique local optimum on  $(\tau, T - N\tau_0)$ . With extensive derivations, we define this point as the global maximum  $\tau^*$  where  $\partial \mathbb{F} / \partial \tau$  is positive on the range  $[\tau_{min}, \tau^*)$  and negative on  $(\tau^*, T - N\tau_0]$ .

## Appendix (II)

### Proof of (4-26) in Chapter 4:

Set  $M = U_0^F = p_{H_0} C_{H_0} (1 - P_F (1 - \rho(P_F))) - \lambda E_f$  ;  $P = M + \mu e_s$ . Then  $U_0^C = (1 - a(i))M - \mu e_s$   $a(n_c) = M \cdot (1 - \frac{M + \mu e_s}{M} \cdot \frac{t_s}{i \cdot T})$ . The payoffs of SUs playing different roles are given as:

Table. Payoff form with number of contributors

$i$	0	1	...	N	...	N
$U_0^C$	X	$M - P\tau$	...	$M - P\tau/n$	...	$M - P\tau/N$
$U_0^F$	0	$M$	...	$M$	...	X

The difference of two strategies' payoffs is calculated as:

$$\begin{aligned}
 & \bar{U}_C - \bar{U}_F \\
 = & \sum_{i=0}^{N-1} C_{N-1}^i p^i (1-p)^{N-i-1} \cdot [U_0^C(i+1) - U_0^F(i)] \\
 = & \sum_{i=1}^{N-1} C_{N-1}^i p^i (1-p)^{N-i-1} [U_0^C(i+1) - U_0^F(i)] + (1-p)^{N-1} U_0^C(1) - 0 \\
 = & - \sum_{i=1}^{N-1} C_{N-1}^{i+1} p^{i+1} (1-p)^{N-i-1} \frac{t_s(M+\mu e_s)}{TNp} + (1-p)^{N-1} U_0^C(1) \\
 = & - \frac{t_s(M+\mu e_s)}{TNp} \sum_{i=2}^N C_N^i p^i (1-p)^{N-i-1} + (1-p)^{N-1} (M - \frac{t_s(M+\mu e_s)}{T}) \\
 = & - \frac{t_s(M+\mu e_s)}{TNp} [1 - (1-p)^N - Np(1-p)^{N-1}] + (1-p)^{N-1} (M - \frac{t_s(M+\mu e_s)}{T}) \\
 = & - \frac{t_s(M+\mu e_s)}{TNp} \left[ 1 - (1-p)^N - \frac{TNMp}{t_s(M+\mu e_s)} (1-p)^{N-1} \right] = 0
 \end{aligned}$$

By using L'Hôpital's rule, since  $p \rightarrow 0$ ,  $\bar{U}_{ON} - \bar{U}_{OFF} \rightarrow 0$ , the only solution is subject to the polynomial equation (4-26).

# Résumé de thèse en français

## 1. L'introduction de la radio cognitive (Chapitre 1)

La radio cognitive, aussi connue sous le nom de “radio intelligente”, est devenue une thématique intéressante dans le domaine des réseaux sans fil, grâce à sa haute efficacité lors de la réutilisation de la bande passante. S. Haykin a présenté une définition initiale de la radio cognitive dans son travail [1]: *La radio cognitive est un système intelligent et auto-apprentissage, qui peut ajuster les paramètres opérationnels et chercher un environnement le plus conforme à l'égard de la sélection des chaînes, l'adaptation de la puissance, et l'allocation des ressources, etc. Ainsi, la qualité des service peut être bien maintenue, et la fiabilité de la transmission peut également être garantie.*

Les réseaux de la radio cognitive sont capables de détecter automatiquement la disponibilité de la bande. Ils accèdent aux bandes inutilisées et les choisissent pour effectuer un accès opportuniste sur la bande, sans interférer les utilisateurs existants.

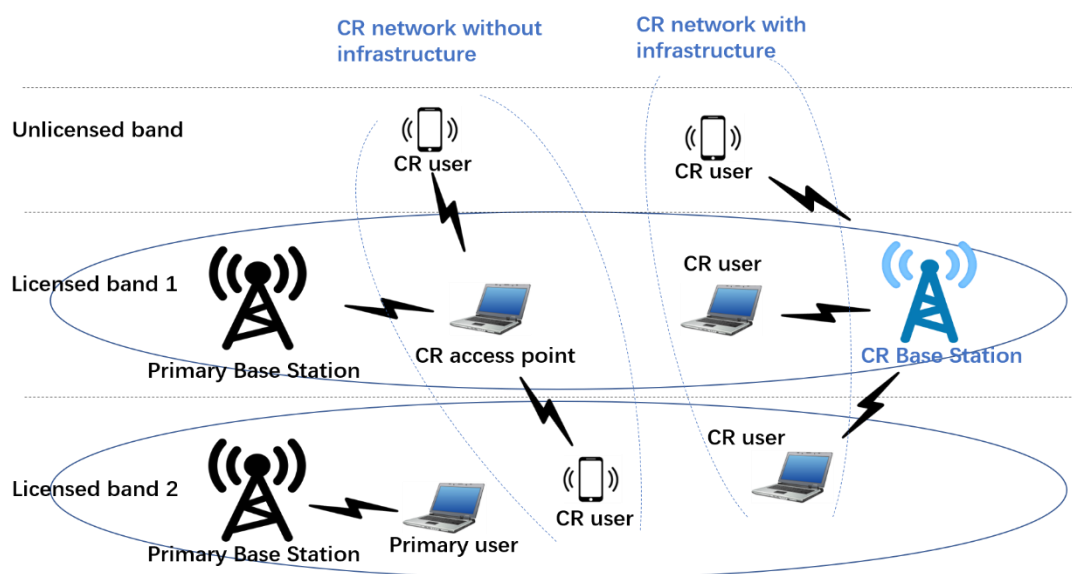


Figure 1. La structure des réseaux de la radio cognitive

Les fonctionnalités des réseaux de la radio cognitive se classifient en deux principales catégories:



- (1) **Les capacités cognitives** : Elles permettent de capturer des informations sur l'usage de la bande par les utilisateurs cognitives (c.-à-d., les utilisateurs secondaires).
- (2) **Les reconfigurabilités** : Ils permettent d'adapter automatiquement les paramètres du système à ses meilleures conditions en analysant les informations collectées.

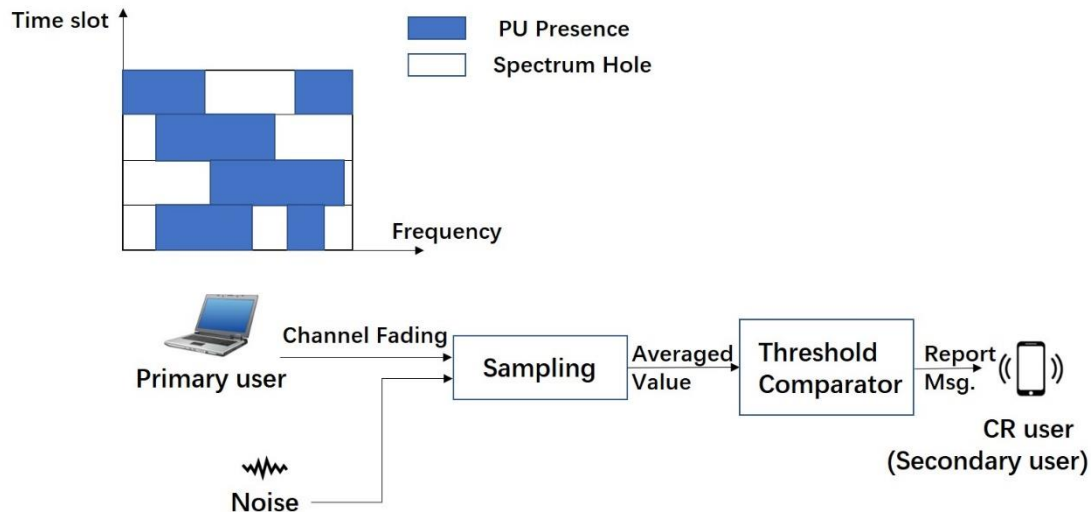


Figure 2. Le processus de l'écoute du spectre

Notre objectif de thèse est la construction d'un modèle où les utilisateurs principaux et secondaires peuvent se réunir pour améliorer conjointement l'efficacité énergétique et la performance de l'écoute du spectre. Pour atteindre ce but, cette thèse propose d'aborder les problématiques suivantes :

- (1) **Coté source** : Les utilisateurs principaux doivent se présenter fréquemment pendant un fragment de temps pour que les utilisateurs secondaires peuvent les détecter correctement. Une présence faible des utilisateurs principaux peut causer la détérioration du signal réceptionné, et la diminution de la performance d'écoute. Cependant, les utilisateurs secondaires préfèrent qu'il existe des "espaces" sur la bande pour qu'ils puissent y accéder sans apporter des interférences. Dans cette situation, comment est-il possible de désigner les activités des utilisateurs principaux pour construire une balance entre ces deux objectifs?
- (2) **Coté destinataire** : Les utilisateurs secondaires (Les USs) ne peuvent que rapporter les résultats qu'ils ont détectés et votés au contrôleur centralisé pour que ce dernier arrive à prendre une décision sur l'état des utilisateurs principaux. Les utilisateurs

secondaires sont auto-organisés, mais comment peuvent-ils s'adapter aux meilleures stratégies, et surtout éviter les erreurs de l'écoute du spectre?

Dans cette thèse, nous présenterons des nouvelles méthodes permettant d'optimiser l'efficacité énergétique (EE). Ce dernier critère est défini par le débit de transmission réceptionné par l'unité de consommation d'énergie. L'optimisation d'EE est considérée comme un but général et un moyen. Plusieurs situations sont étudiées en parallèle pour l'EE, avec l'analyse de la condition du canal et du taux d'erreurs. Nous présentons nos principales contributions comme suit:

- (1) Nous analysons la limite inférieure de la présence des utilisateurs principaux afin de garantir une performance suffisante de l'écoute du spectre, en résolvant une équation quadratique basée sur la limite minimum requise du signal par des utilisateurs secondaires.
- (2) Nous formulons l'efficacité énergétique en tant qu'un problème d'optimisation conditionnelle sur trois dimensions, puis nous appliquons l'algorithme de dichotomie pour trouver un optimum à la présence minimale requise des utilisateurs principaux.
- (3) Nous proposons une méthode de l'accès opportuniste pour des utilisateurs secondaires dans le contexte de l'écoute coopérative du spectre (l'ECS), afin de permettre plus d'accès à une probabilité élevée de la fausse alerte. Finalement, le taux du temps consommé sur l'écoute du spectre est adapté progressivement à l'équilibre basé sur le jeu d'évolution.

## **2. Les techniques connexes (Chapitre 2)**

### **A. Les techniques de l'accès dynamique du spectre**

Plusieurs articles ont étudié les nouvelles techniques de l'écoute du spectre. Dans [8], les auteurs ont proposé une nouvelle méthode de l'écoute du spectre où le processus de l'écoute est divisé en deux parties individuelles. Une deuxième écoute est effectuée pour confirmer la présence des utilisateurs principaux en plus du résultat de l'écoute du spectre, afin d'améliorer l'exactitude du système d'écoute. Pourtant, le temps

additionnel consommé sur la deuxième écoute est assez important à considérer et la difficulté de la synchronisation doit retenir l'attention.

Dans la référence [9], A. Azarfar *et al.* ont proposé un schéma d'ordonnement mélangé de l'écoute coopérative du spectre afin d'améliorer la performance des débits de la transmission. Pour la technique "l'écoute séquentielle du spectre", les USs s'alternent pour écouter la chaîne, mais le temps de la transmission est déterminé par l'ordre des accès, donc la durée de la transmission est aléatoire. Pour la technique de "l'écoute parallèle du spectre", les USs peuvent écouter le canal simultanément. Cependant, les canaux ne peuvent pas être accédés si personne ne contribue à l'écoute puisque l'état des chaînes est inconnu. De ce fait, les auteurs ont développé un schéma hybride pour l'accès dynamique du spectre (ADS), afin d'optimiser la chance de l'accès opportuniste et argumenter la durée moyenne de la transmission, sous les contraintes de la détection. Ensuite, les performances des trois méthodes heuristiques d'ADS proposées (c.-à-d. parallèle, séquentielle et hybride) sont analysées et comparées, les auteurs ont présenté les occasions où ces techniques sont appliquées. Ils ont expliqué comment le temps d'écoute peut être adapté. En tant qu'une extension de [9], A. Azarfar *et al.* [10] ont souligné que l'ordre des accès d'utilisateurs à la chaîne doit être considéré pour optimiser la performance de transmission. Cet article a surtout analysé l'opportunité d'accès de chaque chaîne sur le spectre (c.-à-d. la disponibilité de la chaîne) après que les utilisateurs secondaires s'alternent à l'écoute selon une stratégie d'ADS. Ils ont aussi proposé des algorithmes heuristiques afin de résoudre le problème du compromis entre l'occupation du temps consommé sur l'écoute coopérative et la durée restante pour la transmission (dans un fragment de temps), en utilisant certaines stratégies de l'affectation des utilisateurs et de l'ordonnement de l'écoute. En plus, le rapport "signal sur bruit" doit être considéré aussi à la réception de signal, et les utilisateurs secondaires doivent être associés et alloués aux canaux. Des stratégies d'ordonnement sont proposées pour pouvoir prendre le meilleur rapport signal sur bruit dans le cadre du réseau hétérogène multi-canaux. Ces méthodes proposées ont été appliquées dans les réseaux cognitifs à petite échelle. Même si les auteurs ont pris en

compte la comparaison de la complexité et de la mémoire de stockage, les performances réalisées sur les réseaux cognitifs avec de nombreux canaux et utilisateurs secondaires peuvent prendre de temps pour trouver une solution au problème d'optimisation. D'autres articles comme [11] ont proposé des schémas pour le contrôle d'admission d'utilisateurs, basé sur la prédiction d'états en utilisant un modèle des chaînes de Markov en temps discret. Cet article a analysé les cas de la transition d'états, afin d'effectuer un transfert intercanaux si nécessaire, la qualité de service d'utilisateurs secondaires est particulièrement garantie par l'estimation et la diminution de la probabilité des cessations forcées.

Les auteurs de [12] ont étudié l'optimisation du mapping des chaînes entre les utilisateurs principaux et secondaires. Ils ont notamment considéré l'énergie moyenne consommée sur le transfert interchaines, l'étape d'écoute et l'étape du rapport. Ils ont analysé l'ordonnement des utilisateurs principaux et l'adaptation de la durée de recherche. Pourtant, la présence des utilisateurs principaux est aléatoire selon la distribution des probabilités. Il est donc difficile de préciser la durée de recherche sur le canal et de prévoir le dernier arrivage des utilisateurs secondaires. De ce fait, le changement d'état des chaînes doit attirer plus d'attention au lieu de considérer uniquement les chaînes sous une hypothèse binaire.

Ces techniques susmentionnées ont étudié les schémas d'ADS et l'affectation des utilisateurs dans un réseau cognitif multi-chaîne, afin d'optimiser les opportunités de l'accès au spectre et l'efficacité de l'utilisation du spectre. Cependant, la présence des utilisateurs est aléatoire, et donc difficile à prévoir. Ainsi, à part les méthodes d'ordonnement proposées, la distribution des activités des utilisateurs principaux et leur performance d'écoute (p. ex., probabilité d'erreurs) doivent être analysées.

## **B. Influence de l'activité des utilisateurs principaux sur l'EE**

Plusieurs articles ont étudié l'influence de la puissance de transmission sur l'optimisation d'EE liée aux utilisateurs principaux. Les auteurs de [3] ont prouvé que l'EE est une fonction concave sur la puissance de transmission, donc la puissance

optimisée peut toujours être trouvée par la recherche dichotomique itérative. Les auteurs des [17],[18],[20],[23]-[26],[29]-[33],[35],[39]-[41] ont appliqué une méthode du nombre d'or pour fixer le temps d'écoute, puis rapprocher à un optimum par la recherche itérative. Ils ont notamment considéré l'EE sous une règle de fusion optimisée. Basé sur ces méthodes, [1] et [24] se sont particulièrement focalisé sur l'activité des utilisateurs principaux. Ils ont étudié la probabilité du réveil d'UP pendant la période de transmission. Puisque la présence d'UP est aléatoire pendant le processus d'écoute, le risque des collisions est potentiellement augmenté à cause de la détection erronée, ce dernier peut causer une décroissance des débits de transmission. Ainsi, nous devons notamment tenir compte du problème du réveil d'UP dans la pratique. Les autres travaux connexes comme [25],[26] ont étudié comment contrôler la décroissance d'UP et leur interférences imposées à la transmission d'UP sous certaines contraintes. Des schémas de l'allocation de puissance ont été désignés pour une meilleure performance des débits de transmission en respectant ces contraintes en même temps.

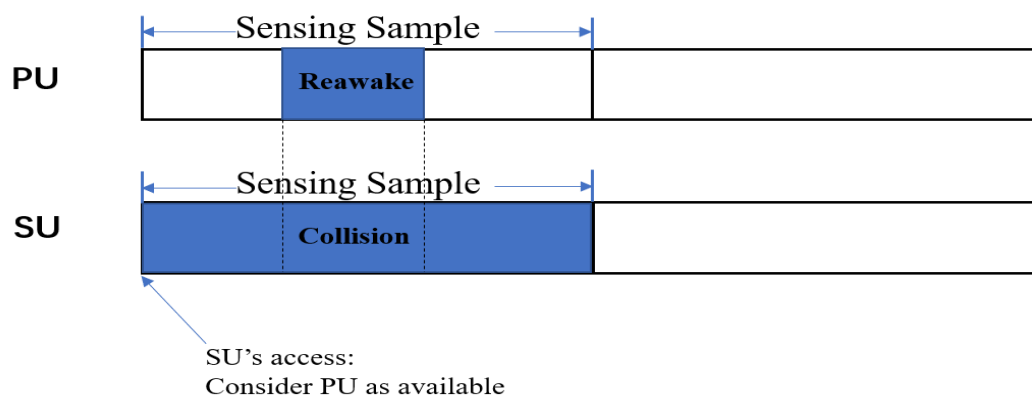


Figure 3. La probabilité du réveil d'UP considérée dans [1], [3]

### C. L'adaptation des utilisateurs secondaires par le jeu d'évolution dans l'écoute coopérative du spectre (l'ECS)

L'utilisation efficace du spectre est devenue un but important dans les réseaux sans fil puisque de plus en plus d'appareils demandent des services sans fil et exigent une meilleure qualité de service. L'écoute coopérative du spectre (l'ECS) permet d'allouer le spectre à un groupe (sous certaines règles) des USs pendant la disponibilité d'UP,

dans le but d'améliorer l'efficacité du spectre du réseau [49]. Les USs doivent effectuer une détection périodique afin de surveiller l'état actuel d'UP, puis un centre de fusion (CF) collecte les résultats de détection des USs et prend les décisions d'accès en conséquence. Les contributions existantes se concentrent principalement sur le débit de transmission prévu sous une certaine règle de fusion, ou sur la distribution du temps de détection et d'accès selon les schémas d'ordonnement.

Ces contributions ont incité les USs à devenir des contributeurs en définissant des fonctions de récompense, pour attirer des USs à un haut rapport de signal sur bruit en définissant plusieurs priorités de détection [50], ou pour distribuer des opportunités d'accès aux canaux en meilleures conditions [49] [51]. D'autres contributions ont considéré le débit avec la probabilité des erreurs de détection afin d'éviter la collision entre l'UP et les USs et de garantir une meilleure performance d'écoute. L'équité a été garantie dans [52] en distribuant les plus priorités les plus élevées aux USs qui contribuent le plus à l'écoute coopérative, et en détectant les USs "égoïstes" et malveillantes qui s'écartent de l'équilibre de la fonction d'utilité générale. Les auteurs de [53] ont étudié le taux d'erreurs dans les différents canaux et ont notamment analysé le nombre optimisé des USs pour atteindre une performance adéquate de l'écoute coopérative.

Les auteurs de [49] ont proposé un nouveau jeu pour distribuer les USs afin de choisir entre l'écoute parallèle ou l'écoute coopérative séquentielle, et de calculer le gain en conséquence. En revanche, cette méthode n'est pas réalisable en pratique car le jeu d'évolution permet seulement de déterminer la probabilité de contribution pour les USs, mais il est difficile de faire des choix flexibles pour les USs entre ces deux techniques existantes. Dans [54], les auteurs ont analysé une stratégie stable d'évolution (SSE) des USs dans un scénario synchrone /asynchrone, qui signifie que les UPs partagent la même horloge avec les USs (ou pas). Wang et al. [55] ont proposé d'optimiser le débit en sélectionnant dynamiquement le statut d'US entre "contributeur" et "bénéficiaire" en fonction de l'analyse du gain de transmission. Les auteurs des [50],[54],[55] se concentrent sur l'optimisation d'énergie et du débit de transmission, mais ils n'ont pas pris en compte l'influence des différentes performances de détection sur l'écoute.

En conclusion, dans la plupart des cas, l'énergie a été présentée sous forme de la consommation totale, qui est liée au nombre de contributeurs. De nombreux travaux de recherche ont visé des objectifs comme le débit, la performance de détection, et la sélection des canaux pour contrôler le nombre de contributeurs, puis ils ont calculé l'énergie moyenne en fonction de cette somme. Toutefois, la perte du spectre de l'ECS doit être étudiée avec l'effort actuel de l'écoute (c.-à-d, le taux du temps d'écoute) des USs. Par conséquent, l'énergie doit toujours être compensée à la perte du spectre pour garantir la performance.

### **3. L'adaptation aux UPs pour une optimisation de l'EE (Chapitre 3)**

#### **A. Principales contributions**

Dans ce chapitre, l'activité d'UP est désignée pour un comportement interactif de l'accès d'US. D'une part, ayant fixée la probabilité de la présence d'UP, les USs sont capables d'optimiser l'EE en cherchant leur taux du temps d'écoute le plus approprié. D'autre part, l'activité d'UP a une influence importante sur l'EE. Par la suite, l'EE moyenne entre UP et US est étudiée, la relation entre l'EE et la présence d'UP est analysée en particulier. Nous prouvons qu'une présence clairsemée d'UP contribue à l'optimisation d'EE. L'impact d'accès opportuniste est considéré comme l'impact principal, où l'impact de la diminution de "fausse alerte" sous une présence plus fréquente d'UP est considéré comme moins important.

Cependant, le design d'UP fait l'objet de certaines contraintes pour pouvoir toujours fournir la performance d'écoute prévue. Face à ces principaux défis, un modèle d'optimisation d'UP est proposé. Les principales contributions de notre travail dans ce chapitre sont indiquées comme suit:

- (1) Nous avons analysé la limite inférieure de la probabilité de présence d'UP pour pouvoir fournir une performance adéquate de l'écoute du spectre, en analysant la condition minimale du rapport signal sur le bruit (du côté US).

(2) Nous avons formulé l'EE comme un problème d'optimisation en trois dimensions, sous certaines contraintes de l'exactitude de détection, puis nous avons appliqué une méthode de dichotomie pour trouver l'optimum à la limite inférieure d'UP.

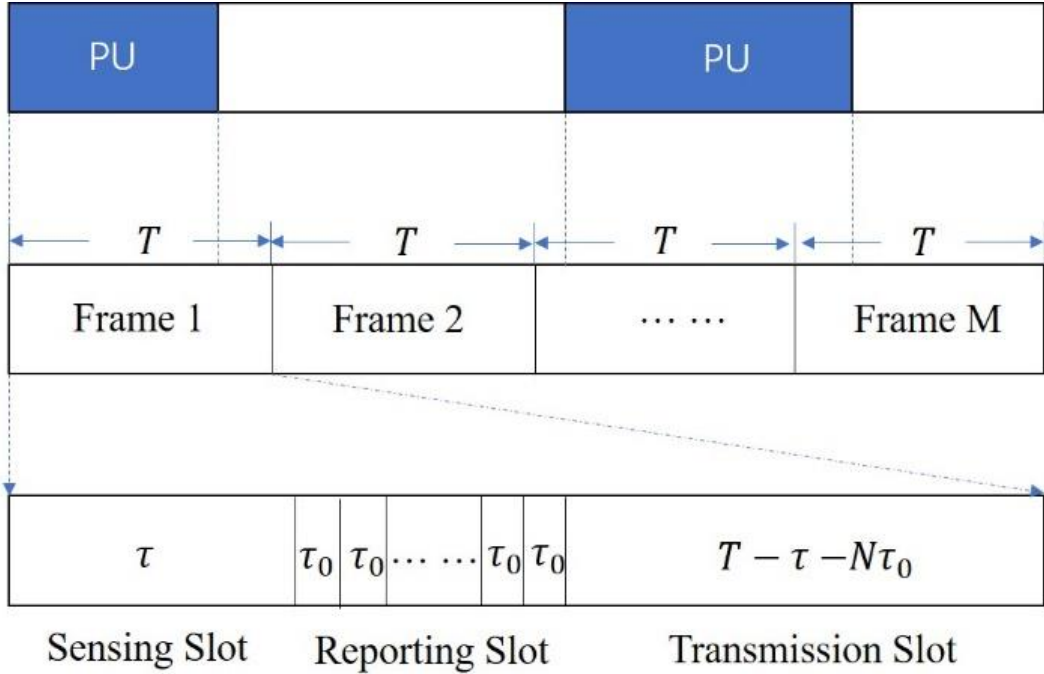


Figure 4. La structure d'un fragment dans les réseaux cognitifs

## B. La puissance de transmission prévue au minimum pour l'UP

Nous assumons que la puissance de transmission est définie comme  $E_{pt}$  et que le gain des chaînes d'évanouissement est  $G$ . La bande passante du système est  $W$ . Le débit des USs est défini par l'équation de Shannon-Hartley:

$$C_{00} = W \log_2 \left( 1 + \frac{GE_{st}}{\sigma_0^2} \right) \quad (3-1)$$

$$C_{10} = W \log_2 \left( 1 + \frac{GE_{st}}{GE_{pt} + \sigma_0^2} \right) \quad (3-2)$$

En se basant sur (3-1)~(3-2), nous remarquons que  $\frac{GE_{st}}{GE_{pt} + \sigma_0^2} = \frac{GE_{st}}{(1+\gamma)\sigma_0^2} < \frac{GE_{st}}{\sigma_0^2}$ .

Intuitivement, le débit d'une transmission réussite est plus grand que celui de la détection erronée (c.-à-d.,  $C_{10} < C_{00}$ ) à cause de l'interférence inévitable, cette dernière est causée par la transmission d'UP. Le débit total du système  $\mathbb{T}$  peut être exprimé par une fonction liée aux  $E_{pt}$  et  $E_{st}$ , le débit est donc calculé en fonction de (3-3):



$$\mathbb{T} = T_{10} + T_{00} = \left(1 - \frac{\tau + N\tau_0}{T}\right) [(1 - \mathbb{P}_d)p_1 C_{10} + (1 - \mathbb{P}_f)p_0 C_{00}] \quad (3-3)$$

Il faut noter que, afin de garantir l'exactitude d'écoute,  $\mathbb{P}_d \gg \mathbb{P}_f$  doit toujours être respecté. D'ailleurs,  $p_1 \ll p_0$  (c.-à-d., l'UP n'a pas une domination sur l'occupation du spectre) est une hypothèse basique de l'écoute du spectre lors de l'allocation des ressources du spectre; sinon la présence des USs interfère avec la présence d'UP, donc il ne sera pas rentable d'effectuer l'écoute du spectre. Ainsi, dans (3-3)  $T_{10} \ll T_{00}$  est toujours valide.

De plus, puisque  $\mathbb{P}_d \geq \mathbb{P}_{d0}$  et  $\mathbb{P}_f \leq 0.5$  sont considérées comme les conditions de la performance d'écoute, le rapport signal sur bruit  $\gamma$  doit être assez grand pour garantir la différence entre  $\mathbb{P}_d$  et  $\mathbb{P}_f$  si un seuil d'écoute fixe est appliqué. La règle “*k-out-of-N*” peut être considérée comme une logique extensive de la règle “*ou*”, qui signifie que  $k$  échantillons positifs doivent être collectés pour supporter la décision. Ainsi, la décision générale est associée logiquement aux probabilités individuelles. Pour atteindre la performance de la détection,  $P_d$  et  $P_f$  doivent satisfaire l'exigence comme suit:

$$P_d \geq P_{d0}(k, \mathbb{P}_{d0}) > P_{f0}(k, \mathbb{P}_{f0}) \geq P_f \quad (3-4)$$

où le rapport signal sur bruit prévu (le signal du UP reçu aux US  $\gamma^*$ ) est calculé comme (3-5) en se basant sur (3-2)~(3-3), avec un couple de seuils  $\{P_{d0}, P_{f0}\}$ :

$$Q^{-1}(\mathbb{P}_{f0}) = \sqrt{2\gamma^* + 1}Q^{-1}(\mathbb{P}_{d0}) + \sqrt{\tau f_s} \gamma^* \quad (3-5)$$

Pour simplifier, on définit ces valeurs avec la fonction  $Q^{-1}$  :  $F_0 = Q^{-1}[P_{f0}(k, \mathbb{P}_{f0})]$ ,  $D_0 = Q^{-1}[P_{d0}(k, \mathbb{P}_{d0})]$ .  $\gamma^*$  satisfait une équation quadratique comme écrite dans (3-6):

$$\tau f_s \cdot \gamma^{*2} - 2\{\sqrt{\tau f_s}F_0 + D_0^2\}\gamma^* + F_0^2 - D_0^2 = 0 \quad (3-6)$$

Étant donné  $P_{d0}(k, \mathbb{P}_{d0}) > P_{f0}(k, \mathbb{P}_{f0})$ ,  $\mathbb{C} = F_0^2 - D_0^2 > 0$ , le delta de l'équation quadratique (3-6) est calculé comme (3-7):

$$\Delta = \mathbb{B}^2 - 4\mathbb{A}\mathbb{C} = 4\{D_0^4 + 2\sqrt{\tau f_s}F_0D_0^2 + \tau f_s D_0^2\} > 0 \quad (3-7)$$

Ces conditions indiquent que (3-6) n'a que deux racines positives pour  $\gamma^*$ , dénotées par  $\gamma_1^*, \gamma_2^*$ . Pour satisfaire les conditions dans (3-4), (3-6) doit être transformé à une inéquation positive d'où une solution qui peut être trouvée dans le rayon  $(0, \gamma_1^*]$  ou  $[\gamma_2^*, \infty)$ . Évidemment, le rapport du signal sur le bruit reçu doit suivre le deuxième rayon, pour garantir la performance d'écoute. D'ailleurs, on remarque que  $\gamma^*$  est une valeur moyenne pendant la période d'échantillonnage, les USs peuvent recevoir les différents résultats de détection sur les états d'UP pendant une période d'échantillonnage, car l'accès d'UP est un processus aléatoire et dynamique, mais les USs ne rapportent qu'un résultat spécifique au centre de la fusion ; ce résultat dépend d'une valeur moyenne de la détection dans un tel échantillonnage. Pour cette raison, la puissance de transmission instantanée et la présence d'UP doivent s'adapter ensemble, afin d'atteindre l'exigence du rapport du signal sur le bruit. Ainsi, la limite inférieure de la puissance d'UP est présentée dans (3-8):

$$E_{pt}^*(k, \tau) = \frac{\sigma_0^2 \gamma_2^*}{G} = \frac{\sqrt{\tau f_s F_0 + D_0^2} - D_0 \sqrt{D_0^2 + 2\sqrt{\tau f_s F_0} + \tau f_s}}{\tau f_s G} \sigma_0^2 \leq p_0^{ON}(\tau) E_{pt} \quad (3-8)$$

où  $p_0^{ON}(\tau)$  indique la probabilité active d'UP pendant une période d'écoute,  $E_{pt}$  est la puissance de transmission instantanée. D'après [24],  $p_0^{ON}(\tau)$  est calculé comme dans (3-9):

$$p_0^{ON}(\tau) = p_1 e^{-\frac{\tau}{\alpha_1}} \quad (3-9)$$

où  $p_1$  est la probabilité active dénotée par (3-10):

$$p_1 = \frac{\alpha_1}{\alpha_0 + \alpha_1} \leq \varepsilon \quad (3-10)$$

Dans cette équation,  $\varepsilon$  est défini comme le seuil de la probabilité active, en se basant sur l'hypothèse principale de l'écoute du spectre: La présence d'UP est dominante sur le spectre, mais il existe des opportunités pour le réutiliser. Donc, la condition de notre première limite inférieure  $\alpha_0$  est présentée dans (3-11):

$$\alpha_0 \geq \alpha_0^{(1)} = \alpha_1 \left( \frac{1}{\varepsilon} - 1 \right) \quad (3-11)$$

En remplaçant (3-8) dans (3-9) et (3-10), la limite supérieure de  $\alpha_0$  est indiquée comme dans (3-12):

$$\alpha_0 \leq \alpha_0^* = \alpha_1 \left( \frac{E_{pt}}{E_{pt}^*(k,\tau)} e^{-\frac{\tau}{\alpha_1}} - 1 \right) \quad (3-12)$$

(3-12) définit le taux maximal de la durée inactive, en tant qu'une protection pour la présence d'UP. Puisque  $\alpha_1$  est une valeur assez petite ( $\alpha_1$  égale seulement 0.352 secondes [3]), cette limite est une fonction monotone croissante sur  $\tau$  sous certaine règle de fusion. Pour atteindre une performance d'écoute satisfaisante, le taux maximal d'inactivité qu'un UP peut tolérer se présente à la pire situation de l'écoute des USs, où  $\tau$  atteint sa valeur minimale  $\tau_{min}$ . Si l'UP se présente plus fréquemment que le seuil dans les situations positives des USs, la performance de l'écoute (ex. la détection de la fausse alerte) peut être renforcée. Toutefois, sur le design d'UP, la période inactive d'UP cède toujours à sa présence, en fournissant l'exigence maximal du rapport du signal sur le bruit (au taux minimal d'écoute  $\tau_{min}$ ).

En outre, même si la décroissance de la puissance d'UP apporte moins d'interférences et augmente le débit de transmission  $C_{00}$ , il y a moins d'influences sur le débit du système. Au contraire, la puissance moyenne de la transmission peut augmenter au seuil  $E_{pt}^*$ , pour baisser la probabilité de la fausse alerte et donc augmenter le débit. Ainsi, le temps actif d'UP doit surpasser une valeur minimale comme (3-8) pour garantir la performance.

### C. L'adaptation de la durée active d'UP

Pour les utilisateurs principaux qui utilisent plusieurs canaux en parallèle, l'accès à chaque canal est considéré comme individuel et identique. À cause du comportement aléatoire d'UP en fonction de sa densité de probabilité, la probabilité de la présence d'UP n'est pas fixée pendant un fragment de temps, et les états actifs/inactifs s'alternent en fonction de la distribution exponentielle, avec les durées moyennes notées respectivement comme  $\alpha_0$  et  $\alpha_1$ . Ainsi, les probabilités de transfert d'UP entre les deux états "ON/OFF" (c.-à-d., actif, inactif)  $P_{ON \rightarrow OFF}^{Trans}$   $P_{OFF \rightarrow ON}^{Trans}$  sont calculées comme l'intégration de la densité de probabilité corrélée pendant une période de transmission, comme le montrent (3-13)~(3-14):

$$P_{ON \rightarrow OFF}^{Trans} = \int_0^{T-\tau-N\tau_0} \alpha_1^{-1} e^{-t/\alpha_1} dt = 1 - e^{-(T-\tau-N\tau_0)/\alpha_1} \quad (3-13)$$

$$P_{OFF \rightarrow ON}^{Trans} = \int_0^{T-\tau-N\tau_0} \alpha_0^{-1} e^{-t/\alpha_0} dt = 1 - e^{-(T-\tau-N\tau_0)/\alpha_0} \quad (3-14)$$

La limite inférieure de  $\alpha_0$  sur la deuxième condition est présentée comme  $\alpha_0^{(2)}$  dans (3-15), afin de fixer une contrainte du transfert d'états pendant une période de transmission:

$$\alpha_0 \geq \alpha_0^{(2)} = -\frac{T-\tau_{min}-N\tau_0}{\ln(1-\beta)} \geq -\frac{T-\tau-N\tau_0}{\ln(1-\beta)} \quad (3-15)$$

où  $\beta$  signifie la probabilité maximale de la réactivation d'UP que les USs peuvent tolérer. La réactivation d'UP peut interférer les USs et baisser leur débit de transmission de  $C_{00}$  à un niveau beaucoup plus bas, qui est  $C_{10}$ . Ainsi, le débit moyen d'UP se diminue aussi. Cette réactivation est imprévisible, et elle peut apparaître à chaque moment pendant la période de transmission. D'ailleurs, dans le cas d'une détection erronée, même si la probabilité de transfert d'un état actif au état inactif existe toujours pour un UP, la bande peut devenir de nouveau disponible, puisque la probabilité de détection erronée est déjà assez faible. Il est alors difficile que la transmission revienne au débit normal  $C_{00}$  si jamais une collision se présente juste avant le transfert d'état. Ainsi, l'action d'UP n'apporte pas de gain sur le débit du système. Puisque la collision entre PU et SU est assez importante à prendre en compte,  $C_{10}$  est ci-après considéré comme un facteur à ignorer en comparaison avec  $C_{00}$ . En tenant compte des transferts d'états sur l'UP, le débit total est formulé comme (3-16):

$$\mathbb{T}_{total} = (T - \tau - N\tau_0)(1 - \mathbb{P}_f)p_0C_{00}e^{-(T-\tau-N\tau_0)/\alpha_0} \quad (3-16)$$

La consommation totale d'énergie est composée de deux aspects en prenant en compte le transfert d'états d'UP: Pour les USs, cette consommation ne dépend que des états rapportés du centre de fusion après la période d'écoute. Puisque les échantillons sont collectés au début de chaque sous-fragment, le transfert des états n'a aucune influence sur les messages du rapport, car ces messages sont déjà envoyés aux USs avant la transmission. La consommation totale d'énergie dans un fragment T est calculée comme dans (3-17):

$$\begin{aligned} \mathbb{E}_{total}^{SU} &= [(1 - \mathbb{P}_f)p_0 + (1 - \mathbb{P}_d)p_1]E_{S0} + [\mathbb{P}_f p_0 + \mathbb{P}_d p_1]E_{S1} \\ &= NE_{ss}\tau + NE_{st}\tau_0 + (T - \tau - N\tau_0)E_{st}[(1 - \mathbb{P}_f)p_0 + (1 - \mathbb{P}_d)p_1] \quad (3-17) \end{aligned}$$

En outre, la consommation d'énergie est déterminée par le temps d'activation fluctué d'UP. La durée moyenne dans un état actif par rapport au temps d'un fragment  $T$  est estimée comme dans (3-18):

$$t_0^{ON}(T) = p_1 T e^{-\frac{T}{\alpha_1}} \quad (3-18)$$

La puissance du système interne est considérée comme assez faible par rapport à la puissance consommée sur l'écoute ou sur la transmission. De ce fait, la consommation moyenne d'EE dans la durée d'un fragment de temps pour le réseau cognitif (l'UP et les N USs) est calculée dans (3-19):

$$\begin{aligned} \mathbb{E}_{total} = \mathbb{E}_{total}^{SU} + \mathbb{E}_{total}^{PU} = N E_{ss} \tau + N E_{st} \tau_0 + p_1 T E_{pt} e^{-\frac{T}{\alpha_1}} \\ + (T - \tau - N \tau_0) E_{st} [(1 - \mathbb{P}_f) p_0 + (1 - \mathbb{P}_d) p_1] \end{aligned} \quad (3-19)$$

Finalement, notre objectif de la consommation totale d'énergie  $\mathbb{F}$  et les conditions concernées dans le problème d'optimisation sont formulés comme (3-20):

$$\begin{aligned} \mathbf{max}_{\tau, \alpha_0} \quad \mathbb{F} &= \frac{\mathbb{T}_{total}}{\mathbb{E}_{total}} \\ \mathbf{Subject\ to} \quad \mathbb{C}_1: \quad &P_d \geq P_{d0}, \quad P_f \leq P_{f0} \\ \mathbb{C}_2: \quad &max\{\alpha_0^{(1)}, \alpha_0^{(2)}\} \leq \alpha_0 \leq \alpha_0^* \\ \mathbb{C}_3: \quad &\tau_{min} \leq \tau \leq T - N \tau_0. \end{aligned} \quad (3-20)$$

Dans l'hypothèse où l'UP soit adaptable sur la durée active et inactive, l'objectif est d'allouer les probabilités appropriées pour les états d'UP à un certain moment d'écoute, où l'efficacité énergétique du réseau cognitif est maximisée. Pour trouver une solution réalisable de l'optimisation, la premier étape est d'étudier la relation avec le rapport de la durée inactive contre la durée active d'UP ( $\mu = \alpha_0/\alpha_1$ ). Pour simplifier, nous définissons quelques fonctions corrélées au  $\tau$  dans le tableau 3.1 (page suivante).

Après la simplification de ces fonctions, l'objectif d'EE peut être réécrit comme (3-21), en tant qu'une fonction de  $\{\tau, \mu\}$ . En se basant sur cette équation (3-21), nous présentons notre premier théorème (*Le théorème 1*).

$$\mathbb{F}(\tau, \mu) = \frac{\mu I_A(\tau) e^{-\frac{I_B(\tau)}{\mu \alpha_1}}}{\mu [I_C(\tau) + I_D(\tau)] + I_D(\tau) + I_E(\tau) + T E_{pt} e^{-\frac{T}{\alpha_1}}} \quad (3-21)$$

Tableau 3.1. Quelques fonctions d'EE avec  $\tau$  en tant qu'un variable

$I_A(\tau)$	$(T - \tau - N\tau_0)(1 - \mathbb{P}_f) C_{00}$
$I_B(\tau)$	$T - \tau - N\tau_0$
$I_C(\tau)$	$(T - \tau - N\tau_0) (1 - \mathbb{P}_f) E_{st}$
$I_D(\tau)$	$NE_{ss}\tau + NE_{st}\tau_0$
$I_E(\tau)$	$(T - \tau - N\tau_0) (1 - \mathbb{P}_d) E_{st}$

*Théorème 1.*  $\mathbb{F}$  est une fonction monotone croissante du rapport de la durée inactive sur la durée active  $\mu$ . La valeur optimisée d'EE est obtenue sur la limite supérieure  $\mu^*$ , déterminée par les contraintes de la puissance minimale d'UP comme dans (3-12).

*Preuve 1:* Pour une présence insuffisante d'UP (c.-à-d.,  $\varepsilon < 50\%$ ),  $\mu$  est un facteur positif corrélé à  $\mathbb{C}_2$  de (3-20), d'où  $\alpha_0^{(1)}$  et  $\alpha_0^{(2)}$  sont tous les deux des valeurs positives dans (3-11) et (3-15). Ainsi,  $\frac{\partial \mathbb{F}}{\partial \mu} > 0$  toujours valable pour un  $\mu$  positif. La preuve détaillée est démontrée dans l'annexe (I).

En se basant sur ce théorème, on peut inférer que la probabilité de présence doit baisser au minimum pour obtenir l'EE optimisée. Cependant, la présence d'UP doit surpasser le seuil de l'alimentation minimale de la puissance pour atteindre l'exigence du rapport du signal sur le bruit dans la phase d'écoute. On remarque que ce seuil est déterminé par le temps d'écoute et aussi par la stratégie de la fusion. Par la suite, l'EE est formulée comme une fonction sur  $\tau$ , pour analyser l'influence du temps d'écoute.

*Théorème 2.*  $\mathbb{F}$  est une fonction concave sur  $\tau$ , le temps d'écoute optimisé  $\tau^*$  peut être toujours trouvé afin d'optimiser l'EE, étant donné la probabilité d'états positifs d'UP.

*Preuve 2:* Nous présentons nos détails dans l'annexe (II).

Dans le théorème 2, afin de calculer le temps d'écoute optimisé dans un fragment d'US sous des contraintes d'un subventionnement d'énergie de la part d'UP, nous appliquons la méthode de dichotomie. Cette méthode est rapide et efficace, elle permet d'estimer l'optimum dans un nombre limité d'itérations. En se basant sur le théorème proposé, la méthode de dichotomie est appliquée pour trouver un optimum réalisable pour la maximization d'EE avec un couple de variables  $\{\mu^*, \tau\}$ . Dans l'algorithme 1,

sous la règle  $k$ -out-of- $N$ , l'itération est répétée jusqu'à ce que la différence entre les deux limites devient plus petite que la distance de la tolérance d'erreurs.

Tableau 3.2. L'algorithme de dichotomie pour l'optimisation de trois dimensions

<b>Algorithme 1.</b> L'algorithme de dichotomie pour optimiser l'EE	
1.	Initialiser $N, err_0, \varepsilon, \beta, \mathbb{P}_{d0}, \mathbb{P}_{f0}, \tau_{min}, \tau_0, \gamma, \alpha_0^{(1)}, \alpha_0^{(2)}, \alpha_1$ ;
2.	Pour $K = 1:N$
3.	Calculer $\mu^*(\tau_{min}, K)$ ;
4.	Si $\mu^*(\tau_{min}, K) \geq \max\{\alpha_0^{(1)}, \alpha_0^{(2)}\}/\alpha_1$ ;
5.	$f_{min} = \frac{\tau_{min}}{T}, f_{max} = \frac{T-N\tau_0}{T}$ ;
6.	Tant que $f_{max} - f_{min} > err_0$
7.	Calculer $f_0 = (f_{min} + f_{max})/2$ ;
8.	Si $EE'(f_{min}) \cdot EE'(f_0) < 0$ ;
9.	$f_{max} = f_0$ ;
10.	Sinon
11.	$f_{min} = f_0$ ;
12.	La fin;
13.	La fin;
14.	Imprimer $EE^*, f^*$ ;
15.	La fin;
16.	La fin;

#### 4. Une méthode de l'activation d'énergie des USs en utilisant le jeu d'évolution (Chapitre 4)

Les utilisateurs secondaires (Les USs) emploient plusieurs stratégies dans un réseau d'écoute coopérative (l'EC). Étant donné le nombre de contributeurs  $n_c$ , la probabilité de fausse alerte  $P_F$  et la probabilité de détection  $P_D$  du système (c.-à-d. après l'intégration de tous les résultats rapportés par les USs) sont calculées selon le nombre de USs qui ont rapporté l'état "occupé" sous certaine règle de fusion. Toutefois, ces échantillons doivent être considérés séparément sous les états différents, soit l'état actif /inactif, appelés  $H_0$  et  $H_1$ . D'une part,  $P_F$  peut déterminer si les ressources d'UP peuvent être exploitées efficacement par les USs, ou si le débit peut être satisfait par les USs pendant les états  $H_0$ . D'autre part, la probabilité de la détection erronée

$1 - P_D$  doit être contrôlée dans un intervalle approprié afin de céder les USs correctement et d'éviter une collision potentielle avec l'UP pendant son état  $H_1$ . Ces deux probabilités d'erreurs (la fausse alerte et la détection erronée) sont les causes principales de l'incohérence entre l'UP et les USs.

### 4.3.1 Le débit de transmission

Nous considérons que  $p_{H_i}, R_{H_i} (i = 0,1)$  dénotent la probabilité et le débit moyen de la transmission pendant les états de  $H_0$  et  $H_1$  d'UP. Le débit total de transmission  $E(R)$  est l'espérance mathématique dans ces états. Le débit de transmission est meilleur dans l'état  $H_1$  par rapport à l'état  $H_0$ , parce que le spectre partagé entre l'UP et les USs peut causer des interférences sérieuses. Le débit total de la transmission prévu  $E(R)$  peut être estimé par le débit des états  $H_0$ . Le calcul est présenté dans (4-1):

$$E(R) = p_{H_0}R_{H_0} + (1 - p_{H_0})R_{H_1} \approx p_{H_0}R_{H_0} \quad (4-1)$$

Le taux d'écoute d'un seul fragment de temps est  $a(n_c) = \frac{t_s}{n_c T}$ , où  $t_s$  est le temps d'écoute partagé entre les  $n_c$  contributeurs et  $T$  est la longueur d'un fragment corrélée au nombre de contributeurs. Le débit prévu de contributeurs est calculé comme dans (4-2):

$$E(R_c) = p_{H_0}C_{H_0}(1 - a(n_c))(1 - P_F) \quad (4-2)$$

où  $C_{H_0}$  est le débit de transmission d'US pendant les états  $H_0$  (calculé en fonction de l'équation Shannon-Hartley). Pour chaque contributeur individuel, si une croissance de nombre de contributeurs se présente, le taux du temps de transmission et la performance d'écoute seront tous les deux améliorés; ainsi, le débit de transmission augmentera. Néanmoins, ce débit ne peut pas excéder celui des free riders (i.e. ceux qui contribuent pas à l'écoute) à cause du temps consommé sur l'écoute. Puisque les free riders reçoivent directement les résultats d'écoute envoyés par le centre de fusion sans contribuer à l'écoute, leur débit prévu est calculé comme (4-3):

$$E(R_t) = p_{H_0}C_{H_0}(1 - P_F) \quad (4-3)$$



Dans l'ancien modèle, les USs ne transmettent le débit qu'au cours de sa réception d'un état "inoccupé", qui est intégré et envoyé par le centre de fusion. La transmission, validée sous la condition de l'état "inoccupé", est rapportée correctement, c.-à-d., il y a une vraie disponibilité sur le spectre sans être interférée par la fausse alerte. Pour résumer, la décision d'US dépend entièrement des informations reçues d'un centre de fusion, quelle que soit l'exactitude de ces informations. Ainsi, l'ancien modèle peut causer une grosse perte potentielle importante si la fausse alerte se présente souvent.

Puisqu'il existe peut-être les disponibilités du spectre d'UP potentiellement réutilisables par les USs, même si le centre de fusion rapporte toujours un état "occupé" aux USs, la décision des USs doit être adaptée selon les circonstances comme suit: Les USs doivent s'allumer de façon opportuniste pour transmettre le débit au risque élevé de fausse alerte; sinon, les USs souhaitent faire confiance au résultat d'écoute, afin d'économiser l'énergie et d'éviter à interférer avec la transmission de l'UP. Ainsi, nous proposons un schéma de transmission en se basant sur des activations périodiques afin de réutiliser les disponibilités du spectre.  $\rho$  dénote la probabilité que les USs sont actives lors de la réception d'un résultat "occupé", puis (4-2) ~ (4-3) sont réécrites comme suit:

$$E(R_c) = p_{H_0} C_{H_0} (1 - a(n_c))(1 - P_F \cdot (1 - \rho)) \quad (4-4)$$

$$E(R_t) = p_{H_0} C_{H_0} (1 - P_F \cdot (1 - \rho)) \quad (4-5)$$

### 4.3.2 L'analyse de la consommation d'énergie

Du point de vue des USs, la puissance de l'écoute en tant que contributeur ( $e_s$ ) et l'énergie consommée sur la transmission ( $e_t$ ) doivent satisfaire la condition  $e_s < e_t$  pour chaque US. Pendant le processus d'écoute, l'US consomme une énergie plus faible sur l'écoute, qui dépend de la durée de l'écoute coopérative. Pendant la transmission, l'US n'observe que l'information réceptionnée d'un centre de fusion, il accèdera au canal avec une probabilité  $\rho$  s'il reçoit un résultat "occupé". Une fois que l'accès est validé, l'US consomme  $e_t$  sur la transmission; sinon, l'US sera désactivé pour économiser l'énergie.

Considérons que la probabilité de recevoir un état occupé est noté  $P_{occ}$ , nous définissons la probabilité inoccupée d'un US comme  $P_{idle} = 1 - P_{occ} = 1 - (p_{H_0}P_F + p_{H_1}P_D)$ . Les USs transmettent les données en se basant sur  $P_{idle}$ . Ils peuvent probablement souffrir d'une influence externe de la détection erronée (0/1), mais la partie de la détection erroné peut être ignorée car  $p_{H_0}$  et  $(1 - P_D)$  sont toutes les deux assez faibles. Nous notons la consommation de batterie par unité de consommation de puissance comme  $\sigma$ , le coût moyen d'énergie pendant un fragment de temps T est présenté en conséquence pour les contributeurs et les bénéficiaires comme suit:

$$E_c = \sigma[e_s a(n_c) + e_t (1 - a(n_c))(P_{idle} + P_{occ} \cdot \rho)] \quad (4-4)$$

$$E_f = \sigma e_t (P_{idle} + P_{occ} \cdot \rho) \quad (4-5)$$

Par la suite, nous analysons la partie d'activation sur cette cartographie: puisque l'UP est considéré disponible la plupart du temps (i.e.  $p_{H_0} \gg p_{H_1}$ ), même si un grand  $P_D$  est défini comme un but, la fausse alerte agit comme un facteur dominant au petit coût d'écoute, d'où  $P_F$  qui est considérée comme une valeur pas plutôt faible. Ainsi, avec le temps limité sur l'écoute,  $\rho$  doit être augmenté pour activer les USs plus souvent, afin de compenser la perte sur le débit de transmission. En raison d'un coût d'écoute élevé, la détection d'UP est assez précise, donc les USs doivent être désactivés pour économiser l'énergie et baisser la probabilité d'avoir une collision potentielle avec l'UP. Ainsi,  $\rho$  est désignée comme une valeur assez faible. Pour formuler ce problème du compromis, le paramètre d'activation  $\rho$  est défini comme une fonction monotone croissante sur la probabilité  $P_F$ :

$$\rho(P_F) = \rho_0 [1 - \cos\left(\frac{\pi}{2} * P_F\right)] \quad (4-6)$$

La fonction d'utilité est exprimée en deux sens, l'économie d'énergie et le débit de transmission. En appliquant notre schéma adapté sur le contrôle d'énergie, l'US peut choisir soit de profiter d'un débit plus élevé, soit d'économiser l'énergie et d'obtenir plus de compensation d'énergie; cette dernière dépend du seuil de la probabilité  $P_F$ .

Nous définissons  $\lambda$  comme le facteur qui décide de l'influence d'énergie, dans notre schéma proposé, et en se basant sur (4-1) ~ (4-4), nous calculons  $U_0$  comme:

$$U_0^C = p_{H_0} C_{H_0} (1 - \mathbf{P}_F(1 - \rho(\mathbf{P}_F)))(1 - \alpha(n_c)) - \lambda E_c \quad (4-7)$$

$$U_0^F = p_{H_0} C_{H_0} (1 - \mathbf{P}_F(1 - \rho(\mathbf{P}_F))) - \lambda E_f \quad (4-8)$$

La structure du jeu permet d'allouer le temps approprié d'écoute pour les USs, afin de trouver un compromis entre la transmission et la consommation d'énergie. L'objectif est de trouver l'équilibre du jeu débit-énergie pour optimiser ces deux paramètres en appliquant un modèle conjoint du jeu d'évolution. Finalement, en se basant sur la fonction d'utilité présentée dans (4-7) ~ (4-8), nous analysons l'équation du réplicateur, et nous approchons de l'équilibre statique en adaptant le temps d'écoute. Nous présenterons nos résultats détaillés dans le chapitre 5.

## 5. Simulations et analyses des résultats (Chapitre 5)

### 5.1. Simulation de l'adaptation d'UP pour une meilleure EE

Tableau 5.1. Les valeurs/unités pour les paramètres du réseau cognitif

Symbole	Paramètres	Valeurs
$E_{ss}$	Puissance d'écoute d'US	0.2 Watt
$E_{st}$	Puissance de transmission US	1 Watt
$E_{pu}$	Puissance de transmission UP	1.5 Watt
$\alpha_1$	Présence moyenne d'UP	0.372 [3]
T	Durée d'un fragment	100 ms
$\tau_{min}$	Temps minimal d'écoute	1.5 ms
$\tau_0$	Le temps du rapport	5 ms
$f_s$	Fréquence d'échantillonnage	1MHz
$\gamma$	Le rapport signal sur bruit	-18 ~ -13dB
$err_0$	Le taux d'erreurs prévu	1‰
$\mathbb{P}_{d0}$	Le seuil de probabilité de détection	0.8:0.02:0.98
$\mathbb{P}_j$	La probabilité maximal de fausse alerte	0.05:0.05:0.5
G	Gain des chaînes (d'UP aux US)	-10 dB
N	Nombre des US	6

Dans notre simulation, nous appliquons la méthode de dichotomie pour optimiser l'EE avec l'adaptation d'UP dans les réseaux cognitifs. Les paramètres de notre

simulation sont présentés dans le tableau. Le rapport signal sur bruit du côté USs est considéré à 20 dB, donc on obtient  $C_{00}$  d'une valeur de 6.65bps/Hz.

La Fig. 5 est composée de deux figures qui indiquent l'efficacité énergétique (l'EE) en fonction du taux désactivé/activé de l'UP. La première figure trace les lignes de contour des différents seuils  $\mu^*$ , qui sont liés aux performances d'écoute. Avec un même seuil pour  $\mu^*$ , lorsque la probabilité de la détection prévue  $\mathbb{P}_{d0}$  augmente, l'exigence de la probabilité de fausse alerte  $\mathbb{P}_{f0}$  peut être relâchée (c.-à-d. être augmentée). Dans cette figure, lorsque  $\mu^*$  s'élève à 7.7884 où l'UP se présente moins souvent,  $\mathbb{P}_{d0}$  ne dépasse pas 0.812, mais  $\mathbb{P}_{f0}$  excède 0.454. Ainsi, un seuil  $\mu^*$  plus élevé contribue à une EE plus élevée. La deuxième figure présente un exemple de la courbe d'EE en trois dimensions. Nous observons que l'EE augmente avec  $\mu$  jusqu'au seuil  $\mu^* = 5.044$  (la ligne rouge) obtenu sous conditions que  $\mathbb{P}_{d0} = 0.9$ ,  $\mathbb{P}_{f0} = 0.5$ ,  $k = 3$ . Pour un seuil spécifique  $\mu^*$ , un seul optimum d'EE peut être trouvé en appliquant la méthode de dichotomie sur l'axe du taux d'écoute.

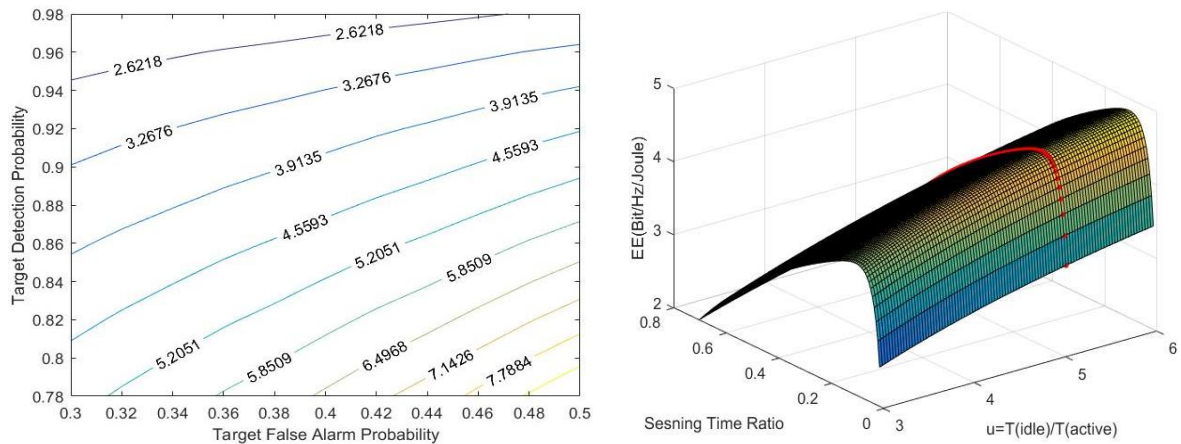


Figure 5. (1) les lignes de contour pour un taux maximal désactivé/activé sous les contraintes de performance (2) Un exemple de l'optimisation d'EE en fonction du taux désactivé/activé d'UP et du taux d'écoute ( $k = 3$ ,  $N = 6$ )

La complexité de notre algorithme est  $\Omega\{N \log_2(\frac{\tau_{max} - \tau_{min}}{err_0 \cdot T})\}$ . Étant donnée la probabilité de présence d'UP, notre algorithme ne prend que 10 itérations pour obtenir

l'EE optimisée avec  $err_0 = 1\%$ . Par exemple, le temps d'exécution est 0.3248 secondes pour notre méthode de dichotomie.

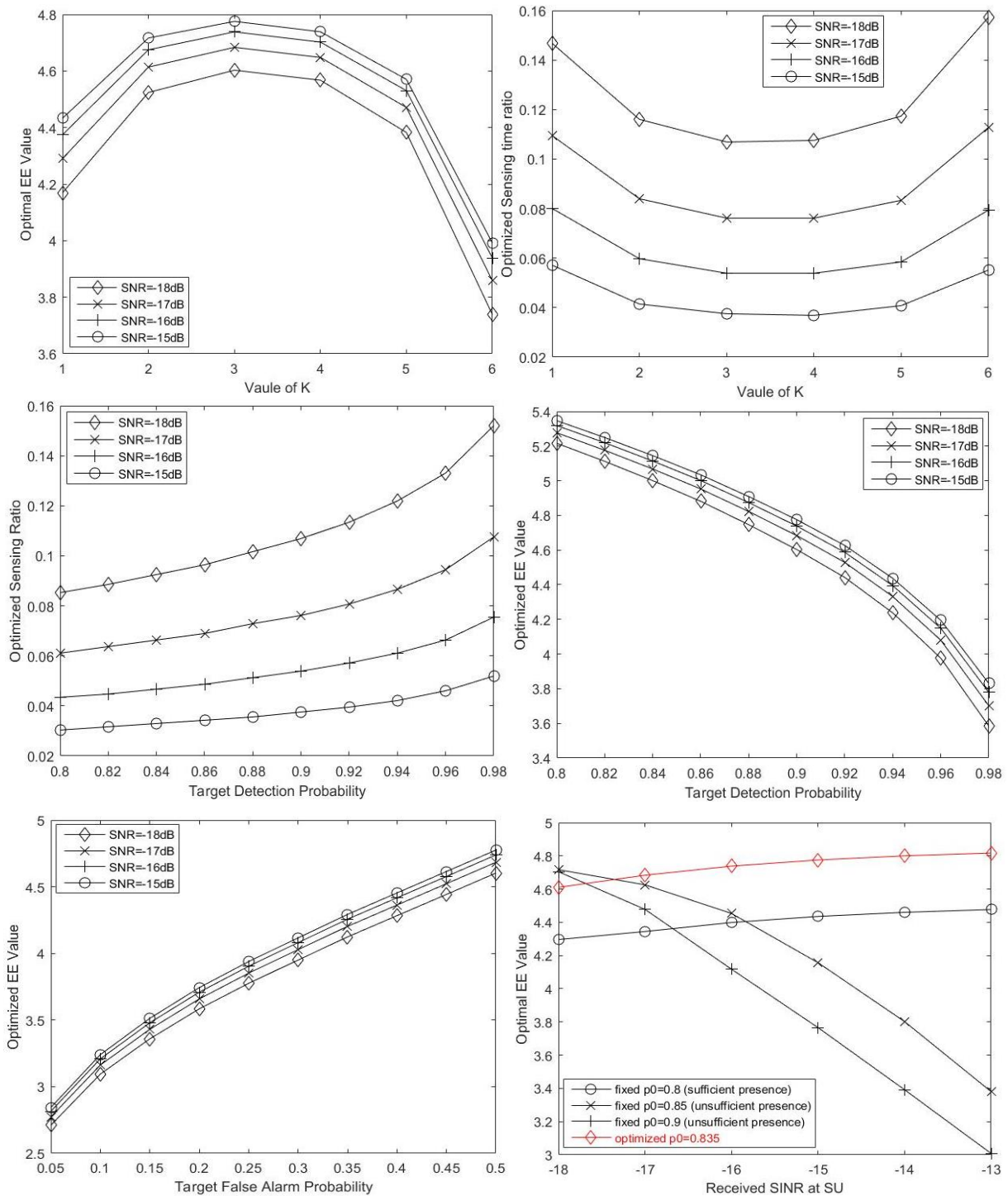


Figure 6. Un groupe de figures sur la comparaison du temps d'écoute et de l'EE  
 (1)-(2) : la règle de fusion (3)-(5) : la performance prévue (6) : la présence d'UP

La Fig. 6 présente une comparaison parmi un groupe de figures sur le temps d'écoute optimisé et l'EE optimale calculée par notre algorithme. Les figures présentent

en particulier l'impact de l'environnement du réseau et celle de la règle de fusion. Dans les deux premières figures, la meilleure EE est obtenue pour  $k=N/2$ . Pour cette raison, la règle de majorité est une règle préférée pour optimiser l'EE dans notre modèle.

Dans le troisième graphe de la Fig. 6, nous pouvons voir que les USs contribuent plus de temps sur l'écoute avec une  $\mathbb{P}_{d0}$  plus importante. Dans le cas contraire,  $\mathbb{P}_{f0}$  (la limite supérieure de  $\mathbb{P}_f$ ) est appliquée pour estimer la présence minimale d'UP, sachant que  $\mathbb{P}_f$  n'a aucun impact sur le temps d'écoute. Puisque  $\mathbb{P}_{f0}$  a un impact sur  $\mu^*$ , elle peut aussi influencer l'EE. Ainsi, la croissance de  $\mathbb{P}_{f0}$  contribue à élever l'EE (comme le montre la quatrième figure). D'ailleurs,  $\mathbb{P}_{d0}$  est critique non seulement pour le taux d'écoute, mais aussi pour l'EE optimisée, parce qu'elle influence  $\mathbb{P}_f$  et  $\mu^*$ . Dans la simulation, avec  $\mathbb{P}_{d0}$  augmentée de 0.9 à 0.95, la croissance du temps d'écoute est d'environ 20% alors que la décroissance de l'EE optimisée est de 10%. Une grande valeur de  $\mathbb{P}_{d0}$  demande plus d'efforts des USs pour atteindre la performance d'écoute, cependant l'EE est en baisse car les accès opportunistes sont limités par les USs. La quatrième et la cinquième figures indiquent que, si l'exigence de la performance d'écoute est devenue plus stricte (ex. une  $\mathbb{P}_{d0}$  croissante ou une  $\mathbb{P}_{f0}$  décroissante), la présence minimale d'UP augmente et l'EE baisse, ce qui correspond à la conclusion de notre premier théorème.

La dernière figure de la Fig. 6 compare la présence optimisée d'UP avec toutes les autres probabilités de présence, du point de vue pratique. En prenant en considération la variable  $\mu^*$ , la probabilité des disponibilités d'UP  $p_0^*$  est égale à 0.835. Les autres probabilités d'accès d'UP sont testées sous une même exigence du rapport signal sur bruit. Lorsque l'UP est suffisant pour atteindre la performance d'écoute demandée, l'EE augmente assez légèrement avec le taux signal sur bruit. Cependant, une présence d'UP plus fréquente a un mauvais impact sur l'EE car elle occupe les opportunités d'accès des USs, donc la courbe de  $p_0=0.8$  est en-dessous de l'optimum  $p_0^*$ . D'ailleurs, l'EE baisse si l'alimentation de l'énergie est insuffisante pour l'UP (ex.  $p_0=0.85, 0.9$ ). Si la présence d'UP devient plus faible, l'EE devient faible également à cause de la croissance de fausses alertes. En conséquence, cette figure indique qu'une activité

optimisée d'UP peut obtenir une bonne EE pour le réseau cognitif, et cette optimisation résout le problème du compromis entre la performance d'écoute et l'accès opportuniste des USs.

## 5.2. Simulations de l'activation d'énergie par le jeu d'évolution

Dans cette partie, les paramètres de notre simulation sont présentés dans le tableau 5.2. Nous considérons un signal modulé selon une modulation QPSK et une fréquence d'échantillonnage de 1MHz.

Tableau 5.2. Paramètres de la simulation du jeu

$e_s$	0.05 watt	$e_t$	0.2 watt
$p_{H_0}$	0.9	$C_{H_0}$	1Mbps
$P_{D\_Target}$	0.95	$\mu$	0.5
$\rho_0$	{0,0.1,0.2,0.3,0.4}	$SNR$	-14 dB

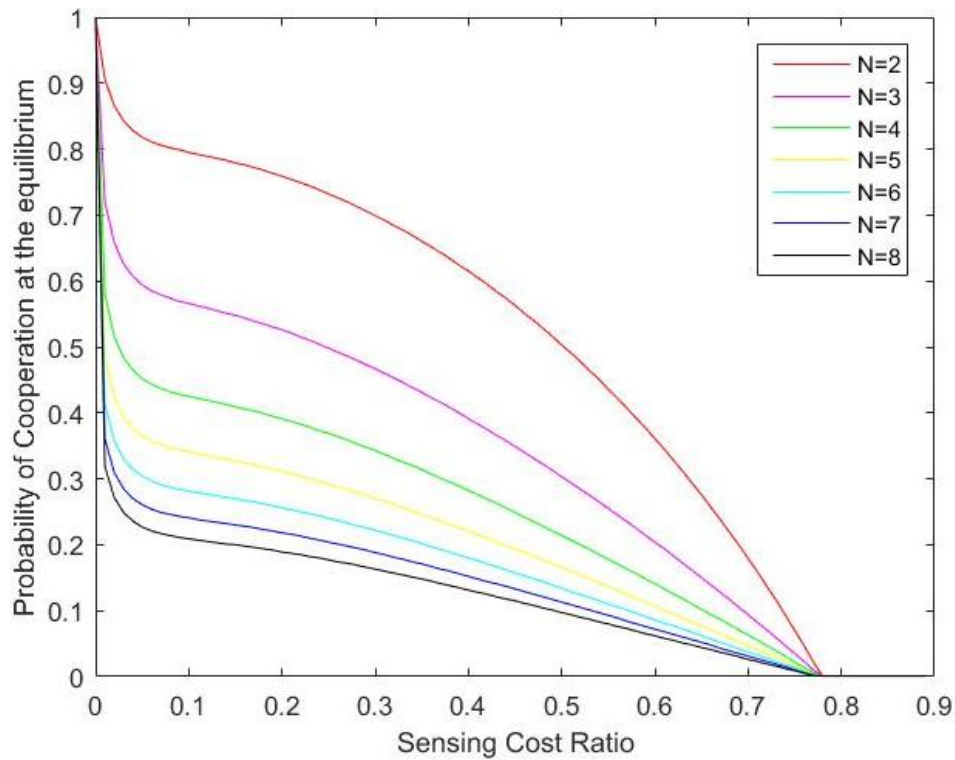


Figure 7. L'équilibre du jeu sur le temps d'écoute ( $\rho_0 = 0.3$ )

Nous considérons différents nombres de USs dans un réseau cognitif homogène. Dans la Fig. 7, les USs sont plus actifs pour participer à l'écoute si très peu de USs se trouvent dans le système. En toute circonstance, la probabilité est réduite à un même équilibre, car le processus d'écoute est coûteux et seulement un faible gain peut être garanti pour la transmission si l'écoute du spectre occupe la plupart du temps dans un fragment. Ainsi, le processus d'écoute doit être moins coûteux, et plus de temps doit être alloué sur la période de transmission. Le taux maximal d'écoute est obtenu à environ 78%, où le coût de l'écoute et de la transmission sont équilibrés; il reste encore l'intérêt pour les USs de participer à l'écoute coopérative.

Dans la Fig. 8, nous considérons différentes attitudes d'activation sur la transmission des USs, dénotées par  $\rho_0$ . Dans la première figure, les USs deviennent plus actifs sur l'écoute si  $\rho_0$  a une valeur élevée. Avec un taux d'écoute limité, la majorité du temps est consommée sur la transmission, mais l'écoute insuffisante a une forte probabilité d'engendrer une fausse alerte, donc il faut un transfert de l'énergie au débit additionnel. Lorsque le coût d'écoute augmente, les courbes commencent à se chevaucher, car un bon pourcentage des USs refuse à prendre le risque d'avoir une collision avec l'UP, donc ils restent à l'état "désactivé" s'ils reçoivent l'état "occupé" du centre de fusion.

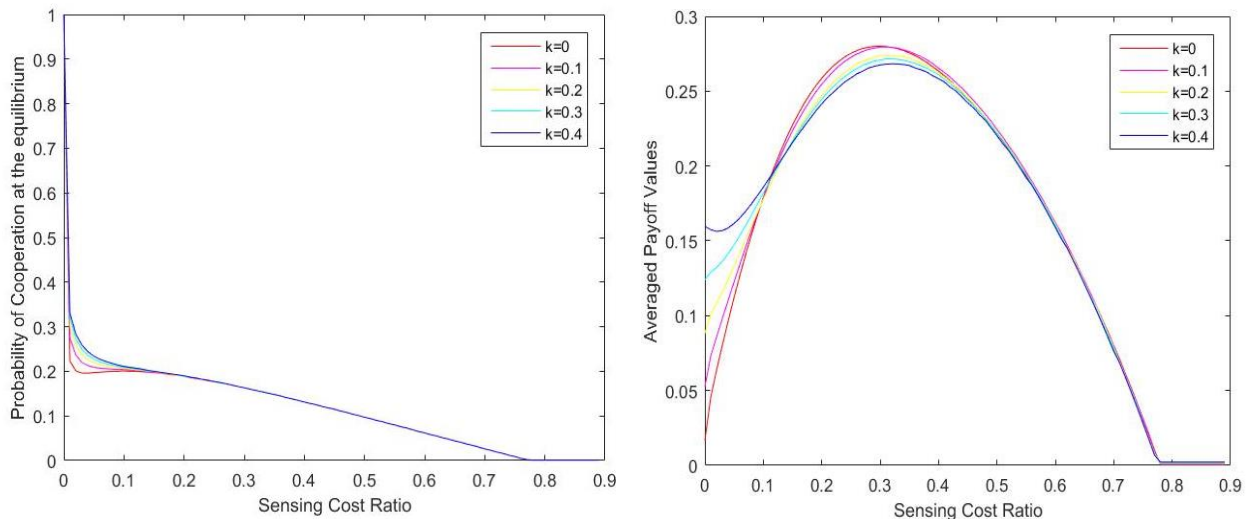


Figure 8. La probabilité coopérative, le gain moyen sous un facteur d'activation  $\rho_0$

En conséquence, dans la deuxième figure, lorsque  $\tau = 0.05$ , le gain est d'environ 0.17 pour  $k=0.4$ , mais le gain est seulement 0.1 pour  $k=0$ . Ainsi, sous la fonction



d'utilité proposée, le schéma de l'activation d'énergie peut contribuer à obtenir plus de gain avec un petit coût d'écoute. Avec un coût moyen (ex. entre 0.15 et 0.5), le gain descend à cause du coût additionnel de l'énergie consommée par l'activation d'US. Toutefois, cette décroissance est limitée, le gain est encore assez profitable dans cette plage, les courbes se chevauchent progressivement à un coût d'écoute élevé, d'où une activation d'énergie qui n'existe plus.

## 6. Conclusions (Chapitre 6)

Dans notre premier travail, le design des activités d'UP est considéré conjointement avec l'effort d'écoute des USs pour optimiser l'EE. Les transferts des états d'UP pendant la période de transmission influencent le débit reçu aux USs. D'ailleurs, plus d'absences d'UPs contribuent à une EE plus élevée. Toutefois, la croissance de taux d'absences ne doit pas être trop glouton et doit être contrôlée en-dessous d'un seuil pour que la performance d'écoute d'US peut être garantie et que l'UP peut être protégé. Nous prouvons que l'EE est une fonction concave du temps d'écoute pour une probabilité fixée de la présence d'UP. Afin d'optimiser l'EE dans un scénario interactif d'UP-USs, un algorithme de dichotomie est proposé pour localiser l'optimum d'une façon dynamique. D'après les simulations réalisées avec MATLAB, l'optimum du taux d'écoute est lié aux objectifs de la performance d'écoute. Nous prouvons aussi que la performance de notre solution optimisée surpasse les autres cas où l'UP se présente autrement.

L'écoute coopérative d'écoute contribue à allouer les ressources parmi un groupe de USs, et plus particulièrement à optimiser le débit de transmission. Le débit est extrêmement faible s'il existe un grand risque de fausse alerte au centre de fusion. Dans le jeu d'évolution, le débit doit être considéré avec la consommation d'énergie pour formuler ensemble la fonction d'utilité. Dans notre deuxième contribution, nous proposons un schéma du contrôle du côté de récepteur d'US, afin d'activer la transmission des débits à la demande si la perte causée par le risque de fausse alerte est considérée trop élevée. En analysant avec le jeu d'évolution, les équilibres sont trouvés aux différents prix d'écoute. La simulation indique que notre schéma d'activation

contribue à gagner plus de gain à un prix d'écoute optimisé. De ce fait, ce schéma peut maintenir la stabilité du système indépendamment du coût et de la condition d'écoute.

# Related Publications of Thesis

1. T. Yang, M. Esseghir, and L. Khoukhi, "An Evolutionary Game Approach Towards Energy-Activated Cooperative Spectrum Sensing", *IEEE 88th Vehicular Technology Conference (VTC-Fall)*, (ranked B by Core 2018), Chicago, USA, August, 2018.
2. T. Yang, M. Esseghir, and L. Khoukhi, "A survey of EE optimization methods for primary and secondary users in cognitive radio networks", *International Journal Network Protocols and Algorithms*, vol.10, no.3, Dec, 2018.
3. **{Under Revision}** T. Yang, L. Khoukhi, and M. Esseghir, "Primary User Power Design for Joint Optimization of Energy Efficiency in Cognitive Radio Networks", *AEU-International Journal of Electronics and Communications*, Oct, 2018.

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# Tian YANG

## Doctorat : Systèmes SocioTechniques

### Année 2019

#### Pour une analyse énergétiquement efficace sur la détection du spectre dans les réseaux de radio cognitive

Différentes priorités sont définies afin de distinguer l'usage du spectre dans les réseaux cognitifs : Les utilisateurs principaux (UP) accèdent à la bande en priorité ; les utilisateurs secondaires (US) ne possèdent l'accès que pendant l'absence d'UP.

Premièrement, les activités d'UP sont optimisées pour améliorer l'efficacité énergétique (EE). Une présence dominante d'UP peut baisser l'opportunité d'US pendant sa transmission ; une absence dominante d'UP peut influencer le signal reçu du côté US, puis augmenter le risque de fausse alerte. Par conséquent, le problème du compromis des activités d'UP est considéré sous une forme d'EE conjointe pour l'UP et les USs. Grâce à la méthode de dichotomie, la présence d'UP est optimisée avec le temps de détection dans un frame d'US pour pouvoir atteindre l'EE maximale.

Deuxièmement, une fonction d'utilité est formulée sous forme de "débit moins la consommation d'énergie" pour décider s'il est rentable de transférer l'énergie au débit. Ainsi, l'accès opportuniste d'US peut être contrôlé dynamiquement par un jeu d'évolution de manière coopérative. Un schéma de réactivation est proposé pour résoudre les problèmes de réduction de débit et de performance de détection, en activant les USs d'une manière plus fréquente.

Les simulations indiquent que les méthodes proposées peuvent gérer mieux les ressources dans les réseaux cognitifs. La coordination entre l'EE et la performance est également améliorée. Selon l'observation de l'équilibre d'évolution réalisé par simulations, le comportement d'accès d'US est coordonné et évolué dynamiquement.

Mots clés : radio cognitive – théorie des jeux – économies d'énergie – qualité de service – allocation de ressources (téléphonie).

#### Towards Sensing Performance and Energy Efficiency Trade-off of Spectrum Sensing in Cognitive Radio Networks

Different priorities of users' access are defined in cognitive radio networks (CRNs) in order to differentiate the spectrum usage: primary user (PU) preferentially occupies the band, whereas secondary users (SUs) can only have access to the band if PU is available.

Firstly, PU activities are optimized to improve the energy efficiency (EE). Too much presence of PU could leave less opportunities for SU to access and transmit data; too much absence of PU could influence the received signal to noise ratio of SUs and therefore increase the false alarm probabilities. Hence, in this thesis, the tradeoff problem of PU's activities is considered in the coordinated PU-SUs formulation of EE. Using bi-section search method, PU's active ratio is optimized with sensing time ratio of a SUs' frame to always achieve the maximal EE of the whole network.

Secondly, a mixed utility function is formulated as "throughput-energy cost" to determine whether it is worthy of transferring energy into additional throughput, in order to dynamically control SUs' access attempts using an evolutionary game in cooperative sensing model. A re-activation scheme is especially presented to conquer the great fallings of throughput and sensing performance at low sensing time and to make SUs more active on the transmissions.

Simulation results show that our methods can better manage the resources in CRNs, EE and sensing performance are improved between PU and SUs. The observation of evolutionary equilibrium also shows that a balance can be achieved by adapting SUs' access behaviors in a cooperative way.

Keywords: cognitive radio networks – game theory – energy conservation – service-level agreements – resource allocation.

Thèse réalisée en partenariat entre :

