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# Spectrum Migration Approach Based on Pre-decision Aid and Interval Mamdani Fuzzy Inference in Cognitive Radio Networks

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**Abstract:** This study intends to improve the QoS of SUs and CRNs performance. A novel spectrum migration approach based on pre-decision aid and interval Mamdani fuzzy inference is presented. we first define spectrum migration factors as spectrum characteristic metrics for spectrum migration decision. In addition, we use pre-decision aid to reduce system complexity and improve spectrum migration efficiency. To shorten spectrum migration decision time and seek the optimal spectrum holes, interval Mamdani fuzzy inference is put forward. Finally, simulation results show the proposed approach can inhibit the upward trend of service retransmission probability and average migration times effectively, and improve the effective utilization of CRNs spectrum resource significantly.
**Keywords:** cognitive radio networks, spectrum migration, pre-decision aid, interval Mamdani fuzzy inference

## 1 Introduction

Opportunistic spectrum access (OSA) technology due to help SUs utilize the idle spectrum, effectively improve spectrum usage and system throughput for CRNs, and becomes a hotspot that academia concerned [1]- [5]. However, existing OSA technologies mainly focus on improving CRNs system throughput and spectrum resource utilization, the QoS requirement of SUs and the effective utilization of CRNs spectrum resource are little considered, that maybe cause system throughput and utilization of spectrum resource increase to a higher level, but the effective utilization of spectrum resource is still maintained at a lower level [6]- [7].

In order to improve the QoS of SUs and the CRNs performance, this paper introduces the concept of spectrum migration. Spectrum migration means SUs change their using spectrum dynamically for improving the success rate of SUs connections, it describes the whole process of SUs service transmission. The occurrence of spectrum migration includes two cases: (1) PU arrives at the spectrum that SU is using, (2) the quality of spectrum SUs using drops below the minimum value that can maintain normal data transmission [8]- [10]. Under normal circumstance, the probability of spectrum environment deterioration is lower, so we only consider SUs spectrum migration when PU arrives. Actually, frequency spectrum migration operations can decrease system performance and SUs QoS because of the operations is time-consuming. Therefore, the objective of this paper we pursue are the longest occupation time to single spectrum hole, the least spectrum migration times and the shortest spectrum migration decision time for SUs. In this paper, we define spectrum migration factors as spectrum characteristic metrics for spectrum migration decision, and use pre-decision aid to reduce system complexity and improved spectrum migration efficiency. At last, we propose interval Mamdani fuzzy inference (IMFI) method based on Mamdani fuzzy inference to shorten spectrum migration decision time and search for suitable spectrum holes.

# 2 Spectrum Migration Factors

## 2.1 Spectrum Occupation Probability

Spectrum occupation probability indicates the spectrum occupation degree for PUs and SUs. For a SU, when the spectrum is being occupied by PUs or other SUs, it can not migrate to the spectrum. Therefore, spectrum occupation includes spectrum occupation include PUs and SUs. From this point, spectrum occupation probability is the occupation probability of sub-spectrum divided, i.e., channel occupation probability. A higher spectrum occupation probability can lead to higher migration blocking probability for SUs. Until now, there is no accurate spectrum occupation model proposed, so we use statistical method to obtain spectrum occupation probability by calculating spectrum occupation data in the past time.

Considering the ON-OFF average time of spectrum $\eta$ are $t^{\alpha}$ and $t^{\beta}$ over a period of time $t\prime$ ( $t\prime = t^{\alpha} + t^{\beta}$ ) respectively, then spectrum occupation probability of spectrum $\eta$ can be calculated as $SOP = \frac{t^{\alpha}}{t^{\alpha}+t^{\beta}}$ . When spectrum $\eta$ undergoes $k$ times state changes, the spectrum occupation probability can be updated as

$$SOP = \frac{\sum\limits_{i=1}^{k} t^{\alpha,i}}{\sum\limits_{i=1}^{k} (t^{\alpha,i} + t^{\beta,i})} \tag{1}$$

Where $t^{\alpha,i}$ and $t^{\beta,i}$ indicate the ON-OFF time in the $i^{th}$ period on spectrum $\eta$ respectively.

## 2.2 Link Maintenance Probability

Link maintenance probability mainly reflects the link support degree for SUs data transmission. It indicates the capacity of continuous data transmission for SUs on a specific licensed spectrum. From Sect. 1 we know only PUs arrival can force SUs vacate the using spectrums and makes link maintenance fail. From this point, link maintenance probability is the same for licensed spectrum and its channels. When a PU arrives, there are three consequences for SUs: (1) SU needs to vacate its using spectrum and migrate to other spectrum to continue its data transmission. (2) SU vacates its using spectrum and waits for PU to leave, then SU continues its data transmission through the original spectrum. (3) SU vacates its using spectrum and link maintenance is failed.

Let $P_v$ denote the probability that an SU vacates its using spectrum, we have link maintenance probability as follows

$$LMR = P_v[(1 - r_b) + r_b P_r(\psi^t < \tau_t)] \tag{2}$$

Where $r_b$ denotes PU call blocking probability, and it is given by

$$r_b = (\rho^M / M!) \Big/ (\sum_{i=1}^{M} \rho^i / i!) \tag{3}$$

Where $\rho$ denotes the PU traffic intensity.

## 2.3 Spectrum Migration Degree

Spectrum migration degree reflects the pros and cons of the spectrum holes on each licensed spectrum for SUs directly. Before defuzzification operations, it is denoted as a specific level, and after defuzzification operations, it denotes as a specific value. We consider that the spectrum with higher spectrum migration degree, the more suitable for SUs spectrum migration.

Spectrum migration degree can be obtained by $SOP$ and $LMP$ using fuzzy inference, it is expressed as

$$SMD = Inf(SOP, LMP) \tag{4}$$

# 3 Spectrum Migration Approach Based on Pre-decision Aid and IMFI

## 3.1 Spectrum Migration Pre-decision Aid

In order to avoid all the SUs enter into fuzzy decision module and reduce CRNs complexity, we propose spectrum migration pre-decision aid method. It can be described as follows

1) When SU arrives at the spectrum for the first time, i.e., $A = A^f$ , where $A$ denotes the arrival of SU, and $A^f$ denotes the arrival of SU for the first time. When there are more than one spectrum hole, SU needs to enter into fuzzy decision. If there is only one spectrum hole, SU migrates to it directly, and if all spectrums are occupied, spectrum migration operations will be blocked. The process is shown as Figure 1 (a).

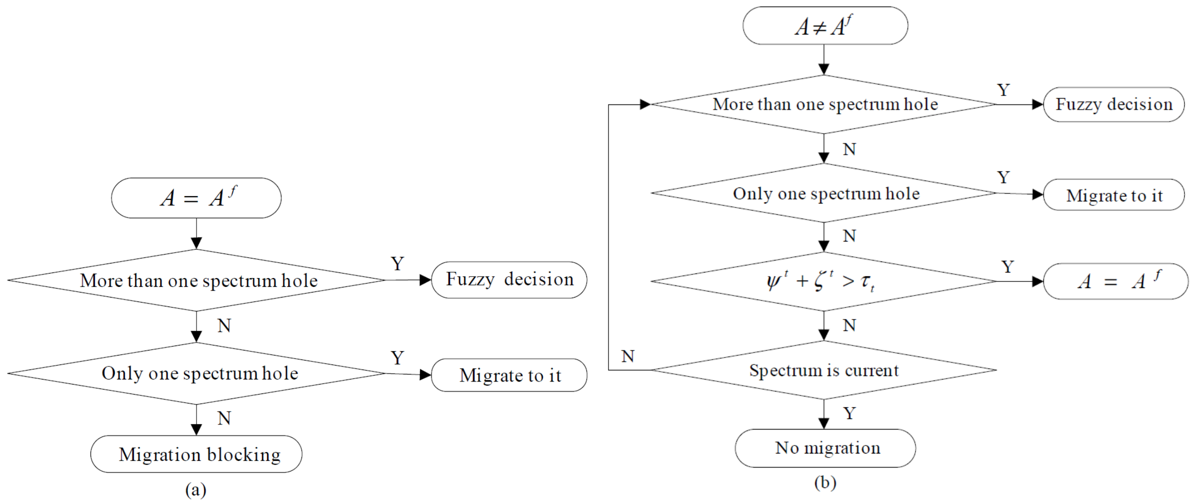


Figure 1: Process of Spectrum Migration Pre-decision Aid

2) When SU arrives and $A \neq A^f$ , if there are more than one spectrum hole, SU enters into fuzzy decision module. If there is only one spectrum hole, SU migrates to it directly. If there is no idle spectrum and the occupied duration is more than $\tau_t$ , i.e., $\psi^t + \zeta^t > \tau_t$ , SU connection will be interrupted, the data has been transmitted will be considered as ineffective. Then, $A$ will be reset to $A^f$ , and the retransmission operation will start for this SU. Otherwise, SU judges whether the idle spectrum is current spectrum, if it is indeed the current spectrum, then SU does not need to migration. Otherwise, SU selects spectrum migration manner according to the number of idle spectrums. This process is described as Figure 1 (b).

## 3.2 Spectrum Migration Method Based on IMFI

*A. Spectrum Migration Factors Fuzzification*

In fuzzification process, the more the number of fuzzy sets, the lower the probability of entering into the $2^{nd}$ decision, then, the spectrum migration decision time can be saved much. However, the number of fuzzy rules is polynomial growth with the growth of the number of fuzzy sets, when SUs enter into the $2^{nd}$ decision, excessive fuzzy rules will cause longer inference time, which may make SU on the effective use time of spectrum holes shorten, and the system throughput reduced. When $\psi^t + \zeta^t > \tau_t$ happens, it even leads to SU data retransmission. Simultaneously, rare fuzzy sets have fewer fuzzy rules, but they cause the probability of entering into the $2^{nd}$ decision increase, also extend the fuzzy inference time. In this subsection, we consider *SOP* and *LMP* as input fuzzy parameters, and *SMD* as output fuzzy parameter. Then, we establish the membership functions for *SOP*, *LMP* and *SMD* as Figure 2. In Figure 2, the universes of all the fuzzy variables are set to [0, 1]. For every licensed spectrum, *SOP* and *LMP* have five fuzzy sets, that denote as VL, L, M, H, VH, mean "Very Low", "Low", "Medium", "High" and "Very High" respectively. The fuzzification operations are same for *SOP* and *LMP*, they are shown as Figure 2 (a). Fuzzy variable *SMD* also has five fuzzy sets, and they denote as VS, S, M, B, VB, that mean "Very Small", "Small", "Medium", "Big" and "Very Big" respectively, they are shown as Figure 2 (b).

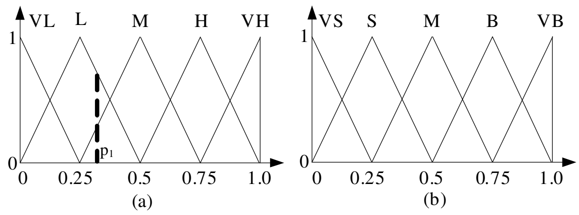


Figure 2: Membership Function of Fuzzy Variables

*B. IMFI Method*

In fuzzy decision phase, decision time has a big impact on spectrum migration performance. Traditional Mamdani fuzzy inference method calculates each fuzzy rule by max-min mode, makes it compute-intensive, and fuzzy inference time is long. For two-input single-output and 7-divisions fuzzy controller, the inference time accounts for 60% to 80% of the total fuzzy inference time, and the proportion will increase with the increase of the number of rules.

**Definition 1.** Let the universe of fuzzy variable $\pi$ is $U$ , its membership function is $F(x)$ . If there is an interval $X = [a, b] \subset U$ , and its membership function is $f(x)$ , $f(x) \in F(x)$ , i.e., $f(\pi) = F(\pi)$ . Then, we define interval $[a, b]$ as an inference interval for $\pi$ .

**Definition 2.** Inference interval $[a, b]$ is an effective inference interval if and only if $f(x) \neq 0$ for any $x \in [a, b]$ . Conversely, $[a, b]$ is defined to be ineffective inference interval.

**Definition 3.** Inference intervals $X_1, X_2, X_3, ..., X_h$ are defined to complete inference interval if and only if $X_1 \cup X_2 \cup X_3 \cup ... \cup X_h = U$ .

**Theorem 1.** *Fuzzy relationship on the universe is equal to fuzzy relationship on complete inference interval.*

*Proof:* Assuming $A_1, A_2, ..., A_n$ are complete inference intervals on universe $U$ . According to definition 3, we have $A_1 \cup A_2 \cup ... \cup A_n = U$ . Assuming the membership functions of $A_1, ..., A_n$ are $\mu_{A_1}(x), ..., \mu_{A_n}(x)$ respectively, and the membership function of $U$ is $\mu(x)$ , then, we have $\mu_{A_1}(x) \in \mu(x)$ , i.e., $\mu_{A_1}(a_1) = \mu(a_1)$ for any $a_1 \in A_1$ according to definition 1. Similarly, we have $\mu_{A_2}(a_2) = \mu(a_2)$ , . . . , $\mu_{A_n}(a_n) = \mu(a_n)$ for $a_2 \in A_2$, $a_n \in A_n$ on the intervals $A_2, ..., A_n$ . It completes the proof.

Table 1: Fuzzy Inference Rules

| LMP \ SOP | VL | L | M | H | VH |
|---|---|---|---|---|---|
| VL | M | S | S | VS | VS |
| L | M | M | S | S | VS |
| M | B | B | M | S | S |
| H | VB | B | B | M | S |
| VH | VB | VB | B | M | M |

Table 2: Table of Interval Mamdani Fuzzy Inference Decision

| LMP \ SOP | $I_1$ | $I_2$ | $I_3$ | $I_4$ |
|---|---|---|---|---|
| $I_1$ | (1,2/1,2) | (2,3/1,2) | (3,4/1,2) | (4,5/1,2) |
| $I_2$ | (1,2/2,3) | (2,3/2,3) | (3,4/2,3) | (4,5/2,3) |
| $I_3$ | (1,2/3,4) | (2,3/3,4) | (3,4/3,4) | (4,5/3,4) |
| $I_4$ | (1,2/4,5) | (2,3/4,5) | (3,4/4,5) | (4,5/4,5) |

From *Theorem* 1, we can simplify MFI to IMFI.

In order to apply IMFI method to spectrum migration, we formulate spectrum migration fuzzy rules as Table Table 1. Furthermore, according to Figure 2 (a), we make interval Mamdani fuzzy inference decision table as Table 2. For ease of comprehension, we provide detailed information on Table Table 1 and Table Table 2. In Table 3.2, we give an example to explain the expression of fuzzy rules. The three shaded tables with "M", "VL" and "S" stand for the fuzzy rule of "If *SOP* is M and *LMP* is VL, then *SMD* is S". For Table Table 2, $I_1$ , $I_2$ , $I_3$ , $I_4$ denote effective inference intervals for [0, 0.25], [0.25, 0.5], [0.5, 0.75], [0.75, 1.0] respectively, and 1, 2, 3, 4, 5 stand for VL, L, M, H, VH respectively. It can be seen that $I = I_1 \cup I_2 \cup I_3 \cup I_4 = [0, 1]$, so I is a complete inference interval for the universe. To explain the meaning of Table Table 2, we also use the shaded tables as an example. If the value of *SOP* located at the effective inference interval $I_3$ , and the value of *LMP* located at the effective inference interval $I_2$ , $I_3$ and $I_2$ denote the effective inference intervals [0.5, 0.75] and [0.25, 0.5], i.e., if $0.5 \leq Value_{SOP} \leq 0.75$, $0.25 \leq Value_{LMP} \leq 0.5$, then, we use fuzzy inference rules (3,4/2,3). The number on the left of backslash is fuzzy sets of *SOP*, and number on the right of backslash is fuzzy sets of *LMP*, they correspond to the following four fuzzy rules

If *SOP* is M and *LMP* is L, then *SMD* is S, If *SOP* is M and *LMP* is M, then *SMD* is M

If *SOP* is H and *LMP* is L, then *SMD* is S, If *SOP* is H and *LMP* is M, then *SMD* is S

If we do not use interval Mamdani fuzzy inference, there will be twenty five fuzzy rules used under the same case. Due to the limited space, we will not list the fuzzy rules. For the same inference results, interval Mamdani fuzzy inference can save more than three-quarters of the time compared with Mamdani fuzzy inference under our condition.

*C. Spectrum Migration Decision*

According to interval Mamdani fuzzy inference, we can get three kinds of inference results: 1) Some of the licensed spectrums have the same *SMD* levels, but there only one spectrum has the highest *SMD* level. 2) Some of the licensed spectrums have the same *SMD* levels, and there are more than one spectrum has the highest *SMD* level. 3) The *SMD* level for each spectrum is different. For 1) and 3), the system selects the spectrum with the highest *SMD* level to migration, we call it the $1^{st}$ migration decision. For the case of 2), the system should take defuzzification operations and selects the spectrum with the maximum *SMD* value to migration, we call it the $2^{nd}$ migration decision. Spectrum migration decision can be expressed as

$$Ch^* = \arg\max_{\forall Ch} \Theta_{SMD}(Ch) \tag{5}$$

## 4 Numerical and Simulation Results

We simulate and evaluate the performance of spectrum migration approach proposed in this paper. Meanwhile, we use the existing approaches that are RANDOM [6], MFI and GREEDY [7] to comparison. The following assumptions are adopted in the simulation. The CRN in which SUs coexist with PUs in a 5km × 5km area. The number of licensed spectrums in the area is 5, and each spectrum is divided to 5 channels. All the spectrums are independent identically distributed. We set the total bandwidth of licensed spectrum is 5 MHz. So, the bandwidth of each secondary channel is 0.2 MHz. This assumption is reasonable since that one voice channel is only 0.2 MHz in GSM cellular network. The signal to interference plus noise ratio (SINR) is set to 3dB. The average arrival rate of SUs is assumed to be 1.0, the retransmission waiting threshold is set to be 1.0s. Simulation data is recorded for 10000 times to avoid the contingency of the results.

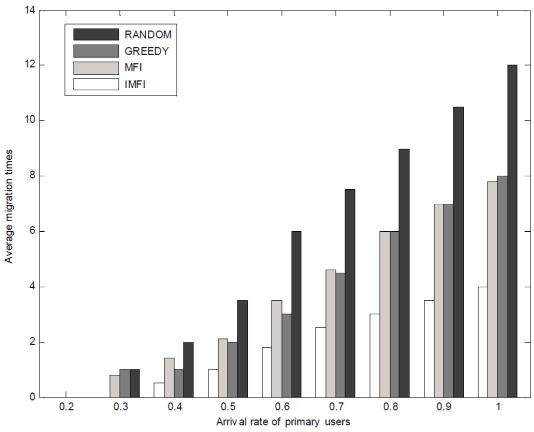


Figure 3: Average Migration Times

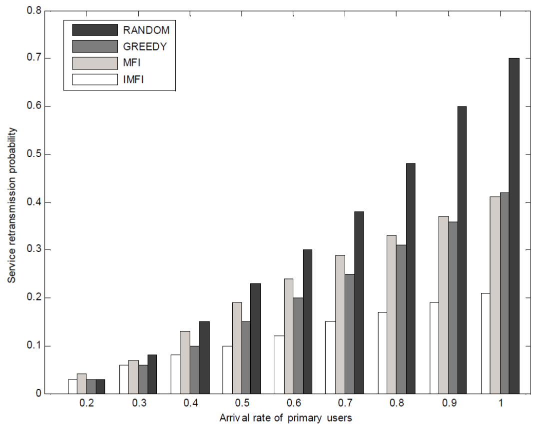


Figure 4: Service Retransmission Probability of SU at $\tau_t$ =1.0s

Figure 3 and Figure 4 show the average migration times of SU single service transmission and SU service retransmission probability at $\tau_t$ =1.0s respectively. It is obviously that IMFI algorithm has the least average migration times. Compared with RANDOM, the average migration times of IMFI reduce by about 65%, and also reduce nearly half compared with the MFI. Under the premise of service size fixed, average migration times are related to spectrum holes during time, migration waiting threshold and spectrum migration decision time. Compared with RANDOM and GREEDY, the advantage of IMFI reflects the accuracy and timeliness for the optimal spectrum selection. MFI has the same inference results with IMFI, so the advantage of IMFI reflects the timeliness of spectrum migration decision. When $\tau_t$ =1.0s, the tendency of service retransmission probability is close to average migration times for the four algorithms, that indicates there exists a positive relationship between SU service retransmission probability and average migration times. When $\lambda$ =1.0, service retransmission probability only reaches to 20% using IMFI, that is much lower than GREEDY and MFI, which confirms superior performance on the optimal spectrum selection and spectrum migration decision once again.

In Figure 5, we can see that the average throughput of CRNs all decrease with the increase of arrival rate of PUs. This is because the increase of $\lambda$ makes the spectrum holes duration shorten, and cause the use of spectrum holes tend to be difficult. Compared with RANDOM, the tendencies of GREEDY and MFI decrease obviously, the main reason is the two intelligent algorithms consume an inordinate amount of time for spectrum migration decision. Because of using spectrum migration pre-decision aid, and IMFI method, spectrum migration decision time with IMFI algorithm is shortened greatly. Compared with RANDOM, the average throughput of CRNs increases slightly.

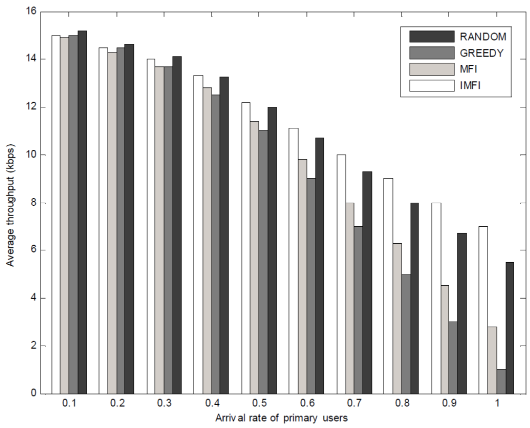


Figure 5: Average Throughput of CRNs

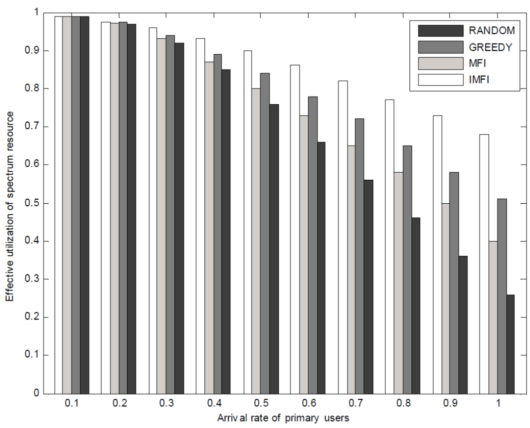


Figure 6: Effective Utilization of CRNs Spectrum Resource of SU

Figure 6 shows the effective utilization of CRNs spectrum resource. When $\lambda$ is small, the four algorithms are closer to this parameter and the effective utilization for each is higher. With the increase of $\lambda$ , service retransmission with RANDOM, GREEDY and MFI increases quickly, makes invalid data rapid upward, and cause the effective utilization of CRNs spectrum resource decline rapidly. IMFI can inhibit the service retransmission probability upward effectively, especially in the condition that the arrival rate of PUs is higher, the advantage is more obvious. When $\lambda$ =1.0, the effective utilization of CRNs spectrum resource using IMFI still reaches to 70%, that makes more efficient use of spectrum sources, and improve system performance effectively.

# 5 Conclusions

The objective of this paper is to improve the QoS of SUs and CRNs performance. In view of the problems that existing methods exist, we put forward a spectrum migration approach based on pre-decision aid and interval Mamdani fuzzy inference in CRNs. Through the establishment and analysis of the spectrum migration model, we define spectrum migration factors (*SOP*, *LMP* and *SMD*) as spectrum characteristic metrics for spectrum migration decision. Moreover, pre-decision is put forward to reduce system complexity and improve migration efficiency. For shorten spectrum migration decision time and seek the optimal spectrum holes, we propose an interval Mamdani fuzzy inference method based on Mamdani fuzzy inference, which can reduce inference time significantly. At last, simulation results show the effectiveness of our approach compared with other existing algorithms.

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## Bibliography

[1] Yuan, G. et al; Performance Analysis of Selective Opportunistic Spectrum Access with Traffic Prediction, *IEEE Trans. Vehicular Technology*, 59(4): 1949-1959, 2010.

[2] Chang, N.B.; Liu, M.(2009); Optimal Channel Probing and Transmission Scheduling for Opportunistic Spectrum Access, *IEEE/ACM Trans. Networking*, 17(6): 1805-1818.

[3] Pawelczak, P. et al; Quality of Service Assessment of Opportunistic Spectrum Access: A Medium Access Control Approach, *IEEE Wireless Communications*, 15(5): 20-29, 2008.

[4] Zhou, X. et al; Probabilistic Resource Allocation for Opportunistic Spectrum Access, *IEEE Trans. Wireless Communications*, 9(9): 2870-2879, 2010.

[5] Huang, S. et al; Optimal Transmission Strategies for Dynamic Spectrum Access in Cognitive Radio Networks, *IEEE Trans. Mobile Computing*, 8(12): 1636-1648, 2009.

[6] Huang, S.; Liu, X.; Ding, Z.; Opportunistic Spectrum Access in Cognitive Radio Networks, *Proc. of INFOCOM*: 1427-1435, 2008.

[7] Wang, L.C.; Wang, C.W.; Chang, C.J.; Modeling and Analysis for Spectrum Handoffs in Cognitive Radio Networks, *IEEE Trans. Mobile Computing*, 11(9): 1499-1513, 2012.

[8] An, C.; Ji, H.; Si, P.; Dynamic Spectrum Access with QoS Provisioning in Cognitive Radio Networks, *Proc. of GLOBECOM*: 1-5, 2010.

[9] Hamdaoui, B.; Adaptive Spectrum Assessment for Opportunistic Access in Cognitive Radio Networks, *IEEE Trans. Wireless Communications,* 8(2): 922-930, 2009.

[10] Stotas, S.; Nallanathan, A.; On the Throughput and Spectrum Sensing Enhancement of Opportunistic Spectrum Access Cognitive Radio Networks, *IEEE Trans. Wireless Communications*, 11(1): 97-107, 2012.