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MAS-based auction for channel selection in mobile cognitive radio networks

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Abstract

Cognitive radio network is a concept of wireless communication for mobile devices that offers the possibility to exploit the unused spectrum resources opportunistically. These networks bring out the need for new solutions that mitigate the spectrum management issue. However, existing works do not focus on devices mobility whereas serious problems arise when users are mobile specifically about their provided quality of services. In this work, we study spectrum sharing and spectrum handoff for mobile secondary users (SUs) and we propose a novel approach that can be executed by a mobile SU when traveling through wireless networks. The proposed solution is inspired from multi-agent system auctions and integrates a learning module which accelerates SUs' spectrum bands allocation. One of the main contributions of this paper is the realistic implementation of the learning based auction and the interesting results obtained through a network discrete event simulator. Results prove that our proposal enhances spectrum utilization and guarantees users satisfaction.

***Keywords*:** *Auction, Spectrum Access, Mobility, Cognitive radio, resources management, learning*

1. Introduction

In the last decade, cognitive radio [1, 2] technology has received a tremendous attention thanks to its opportunistic spectrum access abilities and its reconfiguration capabilities. A cognitive radio network is a set of wireless devices that tries to access the spectrum resources opportunistically. These devices are known as secondary or unlicensed users (SUs). Licensed devices, known as primary users (PUs), will share license spectrum with SUs.

Spectrum management task is an important challenge in a CR network as it includes the four main functionalities of a cognitive radio (CR) device: (1) spectrum sensing to detect spectrum holes; (2) spectrum decision to select the most appropriate frequency band; (3) spectrum sharing; (4) and finally spectrum handoff to switch channel whether it is necessary.

Node's mobility magnifies the spectrum management problem since user's handover can badly affect the provided quality of service (QoS). Consequently, the need of complementary researches in CR spectrum handoff is extremely important.

This work aims to provide a seamless spectrum handoff while ensuring efficient spectrum allocation for mobile CR users.
The major contributions of this paper are as follows.

1) We propose a multi-agent system based auction algorithm for both spectrum sharing and handoff decisions.
2) We derive a realistic implementation that can be easily deployed on PUs and SUs.
3) We enhance the system performances using a straightforward learning module.

Broadly, existing works use analytical approaches and game theory solutions which produce theoretical results. However, the need for more easily deployable, distributed, and scalable solutions is highly relevant. For this reason, we rely on multi-agent system (MAS).

The remainder of the paper is organized as follows. Section II describes recent works on auction based spectrum management in CR networks. Section III details our proposed approach. We present the context and the MAS-based auction we propose for handoff and spectrum access. We depict both PU's and SU's behaviors with the optional learning. Section IV gives the extensive simulation results and section V concludes the paper.

2. Related word

Extensive literature is available on the study of dynamic spectrum management [3, 4] in cognitive radio networks using various mechanisms. Among the different mechanisms proposed to address spectrum allocation, an effective technique has been the use of auctions [5]. There is substantial agreement among economists that auctions are the best way to assign scarce resources [6].

Furthermore, spectrum trading via auctions allows a more dynamic, competitive and efficient communications market than is possible under the traditional systems implemented so far, mainly because spectrum users and wireless service providers have better knowledge than regulators about their spectrum requirements and valuations. For further details, we can refer to the survey of auction mechanisms designed for dynamic spectrum allocation in [7] and the tutorial paper in [8], which discuss the use of auctions for dynamic spectrum allocation in CR networks. Details on other schemes that have been proposed to address the problem of dynamic spectrum management are available in the surveys [9] and [10].
Among the limitations of existing work using auction theory for spectrum allocation, we quote the extensive use of analytical approaches and game theory solutions which

produce theoretical results while we need for more deployable solutions.

For example, in [11] the auction occurs between one PU and multiple SUs sharing the same spectrum in a CR network. Each SU makes a bid for the amount of spectrum it requires and the PU assigns the spectrum band to the SU that do not damage its quality of service (QoS). The objective of this study was to find the Nash Equilibrium (NE) state. In [12], authors formulate the problem as a non cooperative auction game and study the structure of the resulting NE by solving a non-continuous two dimensional optimization problem. Each SU updates its strategy based on local information to converge to the NE. This study can theoretically serve as a decision and control routines for the SUs to exploit the underutilized spectrum resource.

A further limitation in existing auction based spectrum management researches consists in focusing simply on a MAC layer solution ignoring the rest of layers.

In [13], for instance, a Q-learning based bidding algorithm for spectrum auction is proposed, which enables SUs to bid for available frequency bands automatically. This study presents a bidding algorithm for SUs in each time slot. Authors study buffering and channels occupation and they are not interested in the pricing issue for spectrum bands allocation.

Authors in [14] propose a cognitive MAC protocol for CR networks on the basis of the combinatorial auction principle. Moreover, both of the two designs proposed in [15] and [16] are based on analytical analysis to solve channel access at the level of low layers.

In this paper, we implement the First Price Sealed Bid auction at the application level with a real billing system to provide an easily deployable and scalable solution. Furthermore, we have introduced an effective solution for channel selection and spectrum access by considering users' mobility. We have integrated a learning module to enhance system performances.

3. Novel auction based protocol

In this section, we briefly describe the scenario we use and we present our proposed approach for spectrum access and handoff in mobile CR networks.

We propose a solution for spectrum management at the application layer where we integrate the selection and learning modules. We are referred to the IEEE 802.11 standard for the physical and MAC layers and we consider the IP protocol at the network layer. Fig. 1 shows our model's architecture from a stack layers point of view. .

We keep our protocol general so that it can be applied in any current or future system equipped with CR technology as IEEE 802.11af or IEEE 802.22 standards, which have advocated using white spaces left by the termination of analog TV to provide wireless broadband internet access. A device intended to use these available channels is called a "white-spaces device" (WSD). In our model, SUs have the abilities to be WSDs. The spectrum is located in the VHF/UHF bands (470-806 MHz) and has the characteristics that make it highly desirable for wireless communications.

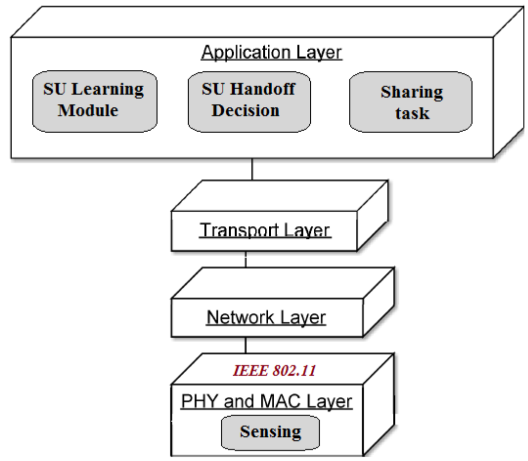

Fig.1. Model's Architecture

For this work, we consider ad-hoc network with a set of primary and secondary users. SUs are mobile nodes and PUs are fixed ones. Each node is operating in a frequency band and each PU can have unused frequencies (sub-bands). With cognitive radio technology, nodes become able to switch from one frequency to another. When an SU is moving from one zone to another one, available resources may change and the CR node will be able to use another available spectrum band.

The challenge in the previous scenario consists in allowing SUs to select the target channel promptly and to move from one zone to another one seamlessly without causing service interruption.

Spectrum handoff and allocation processes will be modelled through an auction between PUs and SUs existing in the same zone. Each PU having free bands starts an auction and is considered to be the auctioneer. On the other side, SUs are the bidders and try to submit their offer until a potential win. Besides, the proposed auction is improved with a learning module to enhance the system efficiency and users' band attribution.

The price for spectrum band access is determined by CR users (i.e., bidders). The multiunit sealed-bid auction as the first price sealed-bid auction (FPSB) is very suitable to execute in a determinable time with an acceptable signaling effort in comparison to the sequential auction such as the English one. In addition, the FPSB allow assigning spectrum holes to CR users faster than the traditional English auction as the FPSB is a single round auction however the English one is a multiple round auction [17]. For these reasons, we use the FPSB in our proposed solution.

Accordingly, all bidders (SUs) simultaneously submit their sealed bids. The highest bidder wins and the corresponding SU pays its submitted bid. Fig.2 illustrates the considered FPSB auction between PU and SUs agents.

First, each PU initiates an auction when some of its licensed bands is released. It forwards a START_AUCTION message to neighbouring CR users. An SU needs to access spectrum in two cases: (1) When coming close to a new zone where the radio resources change; (2) When its attributed spectrum use duration expires.

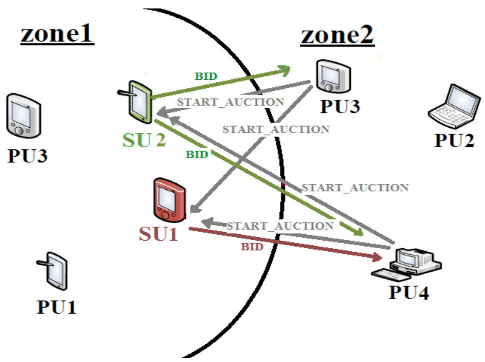

Fig.2. Auction modeling

The START_AUCTION message sent by the PU contains its licensed frequencies (*Freq(PU)*) as well as the amount of free spectrum sub-bands that can be allocated ($S_{free}(PU)$). Whenever this amount of available sub-bands covers an SU's needs in terms of spectrum resources ($S_{Needed}(SU)$), this SU participates in the initiated auction and sends a BID message containing its offer in terms of unit price per second (*PPS*). The other SUs who need more spectrum sub-bands do not participate and wait for another auction.

The PU auctioneer selects among received bids the one that presents the highest price per second and sends WINNER message to the corresponding SU (SU_w:*SU winner)* in order to start sharing bands. The PU assigns its proposed use duration (*D(PU)*) for a price (P_{paid}). Each PU has its own fixed *D(PU)*. Use duration can be different for each PU. P_{paid} is calculated as a function of the price per second proposed by the SU winner (*PPS*(SU_W)). The PU waits for a positive acknowledgment (*ACK(OK)*) from the SU_W to start sharing.

The SU shares bands with the PU that answers the first. If it receives another WINNER message later from other PUs while it is already sharing a PU's bands, the SU withdraws and sends a negative acknowledgment (*ACK(NO)*) to precise that it has already won an auction. In this case, the negatively notified PU restarts the auction process to choose another available winner.

In case of positive ACK, the PU shares the required sub-bands with the SU winner and restarts another auction if it still disposes of free sub-bands. Note that the PU's own spectrum bands utilization varies over time.

In the following, we present in details the sequence diagram, the PU's behavior and SU's algorithm. We depict the proposed algorithms dealing with their different steps.

3.1 Sequence Diagram

Fig. 3 describes the sequence diagram between a PU (the auctioneer) and an SU (a bidder). The PU forwards a **START_AUCTION** message and waits for SUs bids. This call for auction contains the licensed frequencies and the amount of free sub-bands of the PU. Interested SU responds with a **BID** message containing its PPS_{bid}. The PU sends **WINNER** message with the proposed duration (*D(PU)*) to the SU offering the highest PPS. If the selected SU has not won another auction (no sharing band), it responds with positive ACK and a sharing band starts. Otherwise, it sends a negative ACK. In this case, the PU has to restart another auction.

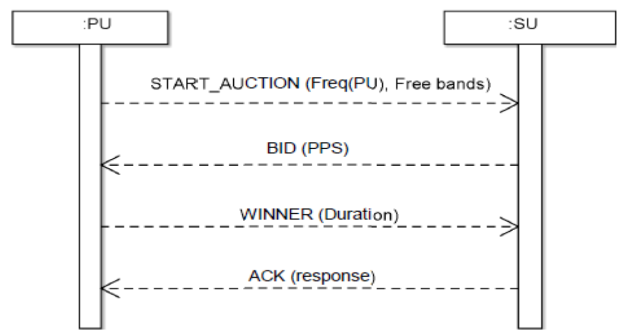

Fig.3. Sequence diagram

3.2 PU behavior algorithm

The PU behavior is described in the algorithm A.

Whenever a PU starts an auction, it waits for a given time to receive SUs' bids. This waiting time is noted Γ.

Each PU has a Price Per Second Reserve $PPS_{reserve}$. The PU cannot accept an offer (*PPS*) lower than its $PPS_{reserve}$. This later is given by equation (1).

$$PPS_{reserve}(PU_i) = \frac{PR_i(PU_i)}{DR_i(PU_i)} \quad (1)$$

$$\text{Where } \begin{cases} PR_i(PU_i) \in [PR_{min}(PU), PR_{max}(PU)] \\ DR_i(PU_i) \in [DR_{min}(PU), DR_{max}(PU)] \end{cases}$$

$PR_{min}(PU)$ and $PR_{max}(PU)$ represents the minimum and the maximum prices that can propose a PU for its bands allocation. They are fixed values and are the same for all PUs.

Algorithm A: PU behavior

```
BEGIN
Sharing == false //The PU is sharing its bands
FreeBands=true //The PU has free bands
Repeat
  If (FreeBands==true)
  Then // The PU forwards START_AUCTION message
     FWD (START_AUCTION_MSG)
    //The PU waits for a given time (Γ) to receive bids
     While (Γ not expires)
        If (receive bid)
        Then
           Insert the bid in Bids_Vec
        End If
     End While
     If ( Γ expires)
     Then //The PU selects the SU winner
        For i = 1 … Nb // Nb number of bids; Nb =Bids_Vec.Size()
           If ( PPS_i < PPS_reserve ) // PPS_i :the bid number i
           Then
              Elimination of PPS_i bid
           End If
        End For
        SU_Winner ← SU that proposes the highest PPS
        P_paid ← D(PU) * PPS(SU_W)* S_Needed(SU_W)
        //The PU send WINNER message with the attributed duration
        SEND (WINNER_MSG) to SU_W
     End If
     If (SU's ACK == OK)
     Then
        Sharing ← true // sharing band
      //Test if SU's band needed (S_Needed) is less than PU's free band (S_free)
        If (S_Needed(SU)< S_free(PU))
        Then
           FreeBands ← true
        Else
           FreeBands ← false
        End If
     Else //SU is sharing another band
        Sharing ←false
     End If
  End If
Until (Sharing == true and FreeBands == false)
END
```

$DR_{min}(PU)$ and $DR_{max}(PU)$ represents the minimum and the maximum use durations that can attributes a PU for bands allocation. Likely, these values are fixed and the same for all PUs.

From received bids in Γ time, the PU eliminates the bids where the *PPS* is lower than its $PPS_{reserve}$. Then, it chooses the SU that proposes the highest *PPS*. The PU sends a WINNER message to this selected SU (SU_W) for a spectrum sharing with the price P_{paid} given by the following equation (2) and for the use duration *D(PU)* initially proposed by the PU.

$$P_{paid} = D(PU) * PPS(SU_W) * S_{Needed}(SU_w) \tag{2}$$

Where $PPS(SU_W)$ is the unit Price Per Second of the SU that wins the auction and $S_{Needed}(SU_W)$ is the amount of spectrum bands needed by SU_W .

If the PU receives the same offer more than once from two or more different SUs (i.e. same *PPS*), the PU chooses one of them randomly. The following sub-section details the SU's algorithm.

3.3 SU behavior algorithm

Algorithm B: SU behavior

```
BEGIN
HO_Var = true //The SU is switching network
InShare = true /The SU is sharing PU's bands
ηA(PU_i) = 0 // Number of received Auction from the same PU_i

// If the SU is changing zone, it has to search for another free band
If (HO_Var == true)
Then
   InShare ←false
End If
If ( (InShare == false) and reception of START_AUCTION
(Freq(PU_i), S_free(PUi)))
Then  // The SU verifies if the auction call propose sufficient free bands
   If ( S_free(PU_i) ≥ S_Needed(SU))
   Then // Learning Module
      // ηA is the number of auction calls received from the same PU_i
      ηA(PU_i) ← ηA(PU_i) + 1
      If ( ηA(PU_i) > 1)
      Then
         PPS_bid ← PPS_initial(SU) + ηA(PU_i) * ψ
         If ( PPS_bid >PPS_max)
         Then
            PPS_bid ← PPS_max
         End If
      Else
         PPS_bid ← PPS_initial(SU)
      End If
      SEND_BID (PPS_bid)
   End If
End If
If (received WINNER_MSG(duration(PU)))
Then
   If (InShare ==false) // The SU reply by a positive acknowledgment
      SEND(ACK(OK))
      ηA(PU_i) ← 0
      P_paid ← duration(PU) * PPS(SU)* S_Needed(SU)
      Freq(SU) ← Freq (PU) //Spectrum handoff
      InSahre ← true
   Else //The SU reply by a negative acknowledgment
      SEND(ACK(NO))
End If
If ( duration expires)
Then
   InShare ← false
End If
END
```

Once an SU comes close to a new zone, it waits for incoming auction calls. When it receives a START AUCTION message, the SU verifies if the PU initiating this auction offers sufficient sub-bands as it demands. The SU participates only to auctions where the PU's available bands ($S_{free}(PU)$) cover its requirements ($S_{Needed}(SU)$). The SU takes part in all auctions that satisfy its needs until it is selected as winner of an auction. In each involvement, the SU proposes a bid in terms of *PPS*.

Each SU_i has a price $P_i(SU_i)$ to provide for spectrum allocation, it has also a favorite duration $D_i(SU_i)$. Hence, it has an initial price per second noted $PPS_{initial}(SU_i)$, given by equation (3).

$$PPS_{initial}(SU_i) = \frac{P_i(SU_i)}{D_i(SU_i)} \quad (3)$$

Where $\begin{cases} \mathrm{P_i(SU_i)} \in [\mathrm{P_{min}(SU), P_{max}(SU)}] \\ \mathrm{D_i(SU_i)} \in [\mathrm{D_{min}(SU), D_{max}(SU)}] \end{cases}$

$P_{min}(SU)$ and $P_{max}(SU)$ represents the minimum and the maximum prices that can bid an SU for bands allocation. $D_{min}(SU)$ and $D_{max}(SU)$ are the minimum and the maximum use durations that can demand an SU for bands allocation. All SUs have the same prices and use durations' bounds.

Firstly, we have implemented our proposed auction based spectrum management protocol considering that each SU sends its PPS_{intial} (as a bid). This case is referred as without learning:

$$PPS_{bid}(SU_i) = PPS_{initial}(SU_i)$$

Then, we have integrated a learning module in the SU's behavior to increase each SU chance to win auctions and access the spectrum more quickly. The following sub-section describes our used learning module, which is for this study, straightforward.

Learning process

We define $PPS_{max}(SU)$ as the maximum price per second that can propose an SU for spectrum allocation. The PPS_{max} is given by equation (4):

$$PPS_{max}(SU) = \frac{P_{max}(SU)}{D_{min}(SU)} \quad (4)$$

$P_{max}(SU)$ and $D_{min}(SU)$ are previously defined as follows

$$\begin{cases} \mathrm{P_{max}(SU) = Max(P_i(SU_i))}\ \forall\, \mathrm{i} \\ \mathrm{D_{min}(SU) = Min(D_i(SU_i))}\ \forall\, \mathrm{i} \end{cases}$$

The key idea behind our Learning module is to increase the SU's bid (PPS_{bid}) whenever the SU receives an auction re-call from the same PU provided that the new PPS_{bid} does not exceed PPS_{max}.This increase will be modelled by the learning parameter noted $\boldsymbol{\psi}$.

The PPS_{bid} will depend on the number of auction calls received from the same PU_i. This number is noted $\eta_A(PU_i)$. $PPS_{bid}(SU)$ is calculated by equation (5).

$$\begin{cases} PPS_{bid}(SU) = PPS_{initial}(SU) + \eta_A(\mathrm{PU_i}) * \psi \\ PPS_{bid}(SU) \le PPS_{max} \end{cases} \quad (5)$$

The SU resets its PPS_{bid} to its $PPS_{initial}$ after each successful band sharing.

We assume that the SU is changing its environmental parameter (HO_Var←true in the algorithm B) automatically when it comes close to a new zone. The SU anticipates changing zone when its average Received Signal Strength (RSS) becomes lower than the RSS limit, which ensures a good QoS. The SU behavior is detailed in the algorithm B.

To evaluate the performances of our proposed protocol, extensive tests are conducted. In the following section we analyse the simulation results.

4. Result

We perform our tests under OMNETPP simulator [18], which is a discrete event simulation network tool.

We consider the specific case where SUs move from an initial zone to a second one. We randomly deploy PUs over these two zones and SUs arrive following a Poisson distribution with parameter λ set to 5. We suppose that SUs are continuously requiring spectrum access. Spectrum is divided in equal bands of 4 MHz bandwidth. Each band is sub-divided into 4 equal sub-bands of 1 MHz. We assume that a PU can own 0 to 4 free sub-bands. The number of simulation runs is set to 10 and the results are averaged to plot graphs. In all our simulations, a 95% confidence interval is computed for each average value represented in the curves. These intervals are plotted as error bars. The rest of the simulation parameters are given in table1.

TABLE 1
SIMULATION PARAMETERS

Parameters	Values
SU distribution (λ)	5
PU number (nb_{PUs})	100
SU number (nb_{SUs})	{100, 110, 120, 130,140,150,160}
Bid Waiting Time (Γ)	0.6 s
Learning parameter (ψ)	{0.1, 0.2, 0.3, 0.4, 0.5}
$P_i(SU) \in [P_{min}(SU), P_{max}(SU)]$	[30, 50] (unit price)
$D_i(SU_i) \in [D_{min}(SU), D_{max}(SU)]$	[45, 120] (unit time)
$PR_i(PU_i) \in [PR_{min}(PU), PR_{max}(PU)]$	[35, 55] (unit price)
$DR_i(PU_i) \in [DR_{min}(PU), DR_{max}(PU)]$	[60, 240] (unit time)
Size of spectrum band	4 MHz
Size of spectrum sub-band	1 MHz
SU speed	10mps
SU Mobility type	Linear
Simulation time	600 s
Simulation runs number	10

First, we have evaluated the implementation of our auction based approach without learning. We present the spectrum utilization and the handoff delay, then we study the impact of the $PPS_{reserve}(PU)$ on the handoff blocking rate, on users' utility and on Handoff delay.

Next, we evaluate the impact of learning contribution on the performance of the spectrum management protocol. For that, we have compared obtained results when we integrate the learning module with the case *without learning*. Besides, we study the impact of the learning parameter (ψ) on the system performances.

4.1 Auction implementation results

In this subsection, we present results of the basic auction protocol (without learning). We introduce first the spectrum utilization over time. Then, we expose Handoff delay, the average blocking rate and users' utility as a function of SUs number.

Spectrum utilization

The spectrum utilization rate is equal to the amount of spectrum bands utilized by all PUs and all SUs present in the same zone divided by the total amount of existing bands. Fig.4 shows the average rate of spectrum use within 600s for a total of 130 SUs and 100 PUs.

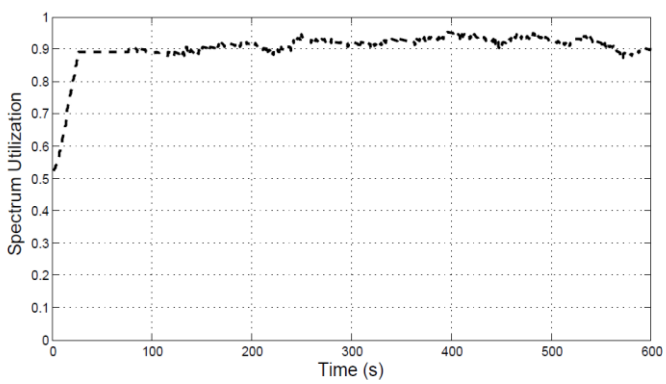

Fig.4. Spectrum utilization rate over time

We observe from Fig.4 that the spectrum utilization rate can achieve up to 94% of the whole available spectrum and then reaches a steady state in a transient time until the end of the simulation. This proves clearly that our protocol improves significantly the spectrum use.

In the next sections, we will study the impact of the number of SUs on the handoff delay and the blocking rate.

Handoff Delay

The Handoff delay (D_{HO}) in these analyses is calculated as the average waiting time between two successive spectrum accesses. The Handoff delay is given by equation (6).

$$D_{HO} = \frac{1}{nb_{SUs}} * \sum_{nb_{SUs}} [\frac{1}{N_{all}} * \sum_{i=1}^{N_{all}} (T_A(B_{i+1}) - (T_E(B_i)] \quad (6)$$

Where $T_A(B(_{i+1}))$ is the time allocation of a band (i+1) and $T_E(B_i)$ is the end time of the ith band used by SU. N_{all} is the total number of spectrum allocations for SUs and nb_{SUs} is the number of SUs present in the system.

The bar chart in Fig. 5 presents the handoff delay as a function of SUs number compared to the average spectrum use duration that can an SU obtain. Fig.5 shows also the rate of SUs that have successfully access the spectrum.

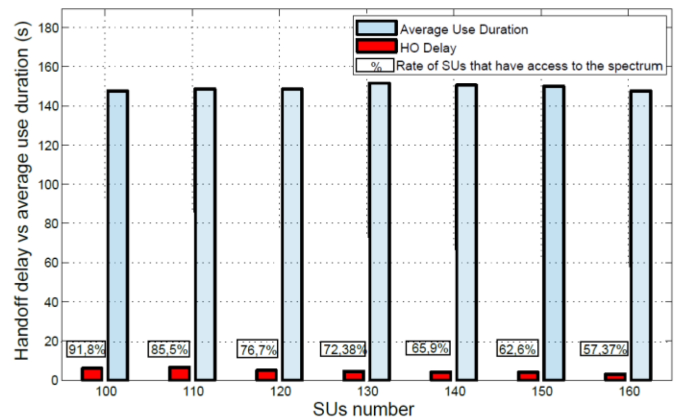

Fig.5. Handoff delay versus the average use duration

The most interesting result is that the handoff delay is extremely low compared to the average spectrum use duration. This result proves that the proposed auction based approach ensures low interruption time and guarantees service continuity.

Besides, we observe that the handoff delay decreases slightly when the number of SUs increases. This is explained by the fact that the percentage of SUs successfully accessing the spectrum decreases. For example, with 100 SUs there are an average of 91.8 SUs that have successfully access the spectrum resources. Consequently, the handoff delay presented is relative to 91.8% SUs.

Blocking rate

To evaluate the smooth functioning of the proposed system, we measure the percentage of SUs that have failed to use the spectrum, i.e. SUs that lost all tripped auctions. This percentage is noted blocking rate and is plotted in Fig. 6 as a function of SUs number.

Furthermore, we study the impact of PU's $PPS_{reserve}$ on the blocking rate and then on users' utility. We consider three cases of $PPS_{reserve}$: a random case and two boundaries values of $PPS_{reserve}$, respectively (Min($PPS_{reserve}$)) and Max($PPS_{reserve}$). Note that Min($PPS_{reserve}$) and Max($PPS_{reserve}$) are as follows:

$$Min(PPS_{reserve}(PU)) = \frac{PR_{min}(PU)}{DR_{max}(PU)}$$
$$Max(PPS_{reserve}(PU)) = \frac{PR_{max}(PU)}{DR_{min}(PU)}$$

Fig. 6 shows that the blocking rate increases considerably when the $PPS_{reserve}$ is equal to Max($PPS_{reserve}$). This result is expected since the $PPS_{reserve}$ in this case is generally higher than the average PPS proposed by the SUs. Consequently, PUs will eliminate most received bids and few SUs access successfully to the spectrum. However, we clearly observe that the blocking rate is notably lower when the $PPS_{reserve}$ is the minimum. It is important to note that when the $PPS_{reserve}$ is random value, i.e. the general case, we obtain low blocking rate near to the minimum case. This proves that our approach ensures a significant exploitation of the spectrum resources and can satisfy the needs of most SUs.

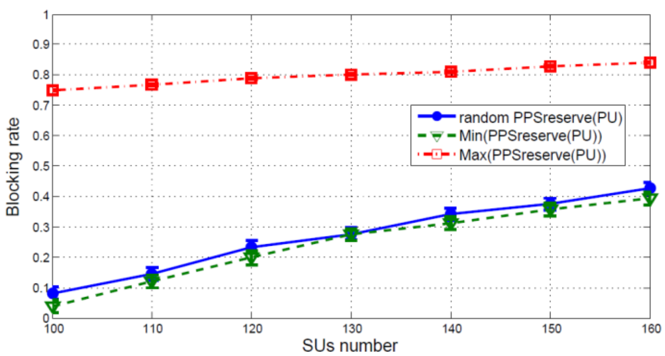

Fig.6. Blocking rate

The blocking rate increases when the number of SUs rises, which is expected since the available resources are unchanged and first coming SUs will be the first served. Thus, the probability to receive a call for auction that presents sufficient free bands becomes too low when the number of SUs increases.

Users Utility

User's utility is a very important metric to evaluate the satisfaction of the network's users. Therefore, we have measured CR users' utility as well as PUs' utility. We have also studied the impact of the $PPS_{reserve}$ on both measures.

SUs' utility

In this scenario, the SUs' utility can be defined as the SUs' benefit from PUs offers. In other words, an SU wants to have more spectrum use duration with a minimum price. The utility of the i[th] SU noted $U(SU_i)$ is given by equation (7).

$$U(SU_i) = \frac{1}{N_{all}} \sum_{N_{all}} \left(\frac{PR_{min}(PU)}{P_{Unit\,paid}} * \frac{D_{attributed}}{DR_{max}(PU)} \right) \qquad (7)$$

Where N_{all} is the total number of successful spectrum allocation of the SU_i in the simulation. $P_{Unit\,paid}$ is the unit price paid (for a sub-band allocation) and $D_{attributed}$ is the attributed duration for the spectrum access. Recall that $PR_{min}(PU)$ and $DR_{max}(PU)$ represents the minimum price and the maximum use duration for PU's allocated spectrum bands, respectively.

The SU's utility can be presented otherwise, as a function of the SU's proposed PPS. $U(SU_i)$ can be given by the following:

$$U(SU_i) = \frac{1}{N_{all}} \sum_{N_{all}} \left(\frac{Min(PPS_{reserve}(PU))}{PPS_{bid}(SU_i)} \right) \qquad (8)$$

Fig.7 shows the average SUs' utility in the previous three cases of $PPS_{reserve}$. We observe that our proposed auction protocol ensures a good SUs' utility when we consider flexible PUs (random $PPS_{reserve}$) very nearly to the case of non-strict PUs (Min ($PPS_{reserve}$)) and is largely better than obtained SU's utility with strict PUs (Max ($PPS_{reserve}$)).

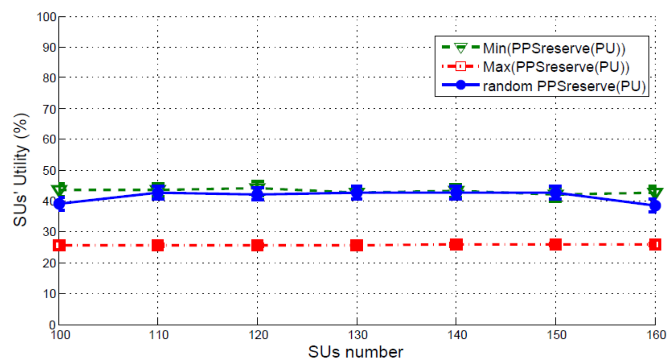

Fig.7. Impact of $PPS_{reserve}$ and SUs number on the SUs' utility

In the next subsection, we present the impact of the PU's flexibility (i.e. boundaries of $PPS_{reserve}$) in its average utility.

PUs' utility

We define the PUs' utility as the PUs' profit from SUs' bids. The utility of the i[th] PU noted $U(PU_i)$ is given by the equation (9).

$$U(PU_i) = \frac{P_{Unit\,paid}}{P_{max}(SU)} * \frac{D_{min}(SU)}{D_{attributed}} \qquad (9)$$

Where $P_{max}(SU)$ and $D_{min}(SU)$ represents the maximum price and the minimum favorite use duration that can propose an SU for spectrum allocation respectively.

PU's utility can be presented otherwise, as a function of the SU winner's proposed bid (PPS_{bid}) and inversely proportional to the SUs' PPS_{max} as given by equation (10).

$$U(PU_i) = \frac{PPS_{bid}(SU_W)}{PPS_{max}(SU)} \qquad (10)$$

Fig. 8 draws the PUs' utility as a function of SUs number. It shows that PUs' utility is more important when the PU is very strict (Max ($PPS_{reserve}$)), which is obvious since the PU accept only bids offering very high PPS. Our proposal with random $PPS_{reserve}$ ensures important PUs' satisfaction that reaches 70%.

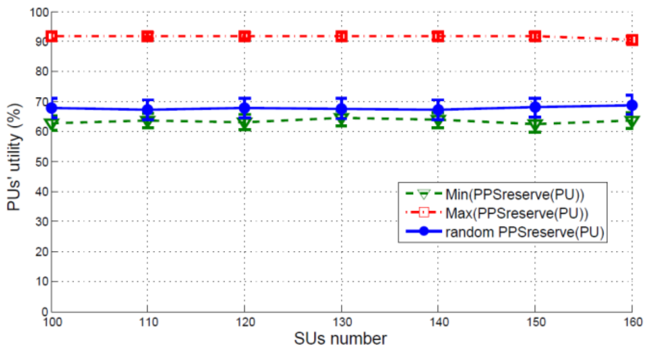

Fig.8. Impact of $PPS_{reserve}$ and SUs number on the PUs' utility

Since we showed above, the implemented auction protocol provides high spectrum utilization, low blocking rate and ensures users' satisfaction. $PPS_{reserve}$ study proves that the proposed bids (SUs' PPS) should not be far from the $PPS_{reserve}$ to have efficient system. This condition is generally satisfied since bidders in auction market know approximately the price range of the proposed product.

Hence, it is widely interesting to involve the learning process into CR devices. Whenever its bid is rejected, the SU tries to increase it so as to reach the $PPS_{reserve}$.

The remainder of conducted simulations is devoted to study the impact of the integrated learning module in our proposed spectrum management based auction protocol.

4.2 Learning based auction for spectrum management results

In this section, we compare the two alternatives of the proposed auction based protocol, one with learning module and the second without learning. We study the impact of the SUs number as well as the learning parameter ψ on some important metrics such as handoff delay and users satisfaction.

Average number of attempts before spectrum access

One of the major objectives when introducing the learning process is to accelerate SUs' spectrum access. Thus, we measure the average number of SUs' attempts (failed bids) before spectrum access (i.e. before auction win).

First, we assume the learning parameter ψ is equal to 0.1 in equation (5) and study the average number of attempts before spectrum access as a function of SUs number. Results are shown in Fig. 9.

Fig. 9 clears that the learning module decreases extremely the average number of SUs' attempts before spectrum access. This number is reduced from more than 120 to 25 attempts.

This important result proves that our proposal of using learning based auction for spectrum management enhances largely the bidding efficiency and the access opportunity.

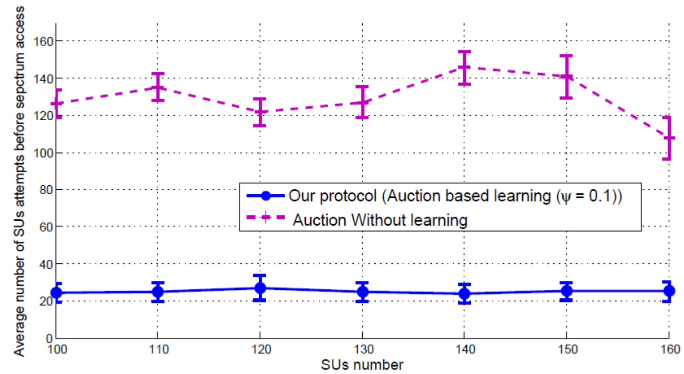

Fig. 9 Average number of SUs' attempts before spectrum access as a function of SUs number

The learning process is modeled through the learning parameter ψ. Consequently, we study the impact of ψ on the average number of attempts before spectrum access as shown in Fig.10. We fix the SUs number to 120 and we vary the ψ parameter between 0.1 and 0.5.

Fig.10 proves that increasing the learning parameter allows to further reduce the average number of attempts before spectrum access. This is explained by the fact that the SUs' bids reach the PUs' $PPS_{reserve}$ more quickly.

Besides, we present in Fig.10 the auction based protocol when considering that all SUs send the same bids, equal to PPS_{max}. When the learning parameter increases, the average number of attempts obtained with our protocol is approaching obtained results when SU's PPS_{bid} is equal to PPS_{max}.

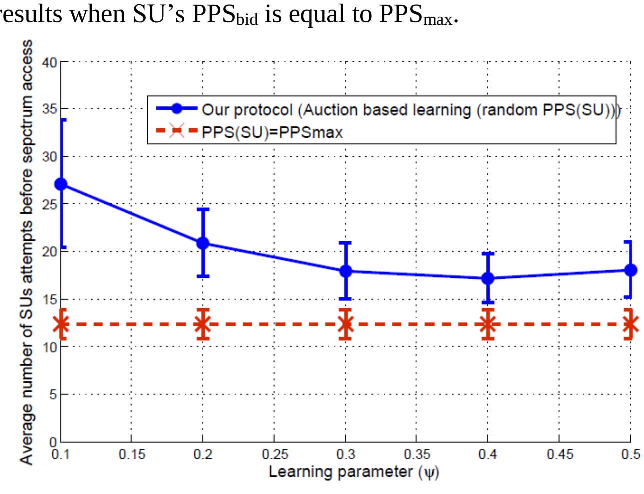

Fig. 10 ψ impact on the average number of SUs' attempts before spectrum access

In the next subsections, we study the impact of the learning process on blocking rate, handoff delay and users' utility.

Average blocking rate

Another objective of the learning module is to make more SUs able to access the spectrum. To confirm this property, we have measured the blocking rate that reflects the percentage of SUs that have failed to access the spectrum. Fig. 11 presents the comparison results between the learning based approach and without learning alternative.

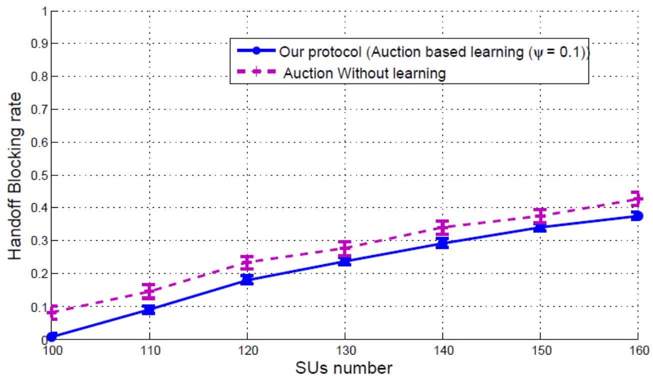

Fig. 11 Impact of learning module on the blocking rate

Fig.11 shows that the learning module decreases the blocking rate, which proves that the learning based auction proposal improves the number of SUs accessing the spectrum resources. As previously explained (section IV.A.3) the blocking rate increases when the SUs' number rises. This is due to the scarcity of free spectrum bands when having a large number of SUs.

Users' Utility

Learning module can impact on users' utility as the SUs will send higher bids and PUs will receive more interesting offers. Thus, a priori, the PU will be the beneficial from the learning process in terms of reward. Effectively, as confirmed by results in Fig. 12, PUs' utility is enhanced inversely to the SUs' utility.

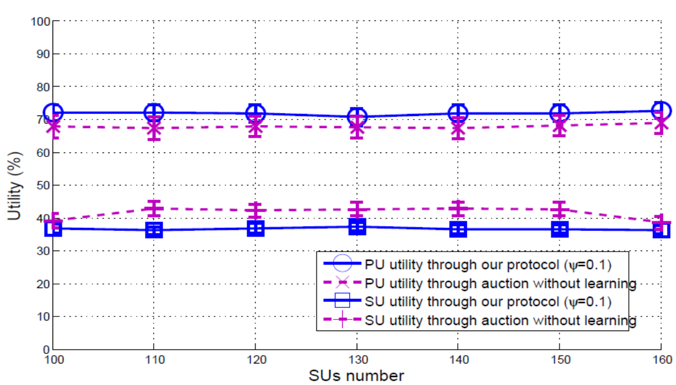

Fig. 12 Impact of learning module on users' utility

To reveal the learning parameter influence on users' utility, we varied ψ while fixing the SUs number to 120. Fig.13 presents the comparison between the obtained results with random $PPS_{reserve}$ and the case where all bids are maximized (PPS_{bids}=PPS_{max}).

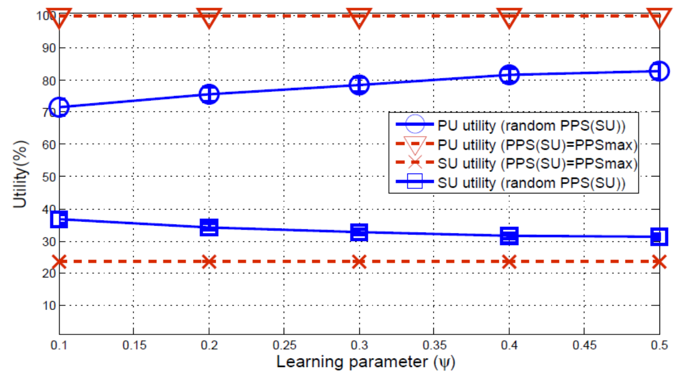

Fig. 13 Impact of ψ parameter on users' utility

Fig.13 shows that the PUs' utility increases when ψ rises. Contrary to SUs' utility that decreases when ψ increases and tends towards the lowest utility that can be obtained in the case of sending the PPS_{max}.

Handoff Delay

Another important metric that must be studied when considering learning module is the handoff delay. We present in Fig.14 the corresponding results. We observe through Fig.14 that the handoff delay increases slightly with the learning process. This is obvious and expected because the number of SUs successfully access the spectrum increases. This involves more spectrum bands occupancy and more time for channels release. Consequently, SUs will need additional time to perform handoff and to access the spectrum.

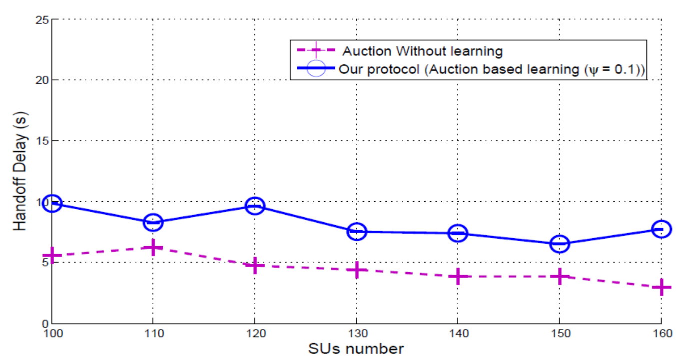

Fig. 14 Impact of learning module on the handoff delay

To summarize, the implemented learning based auction protocol for spectrum access and channel selection ensures an important spectrum exploitation and low handoff delay compared to the average use duration. Our proposal guarantees likewise good utility for both primary and secondary users.

5. Conclusions

In this paper, we designed a novel multi-agent based auction system for spectrum allocation and channel selection. We have improved our approach through a straightforward learning module. Besides, our proposal integrate a real billing and pricing system that can be easily deployed in actual and future wireless networks.

Simulation results prove that our proposal provides high spectrum utilization, low blocking rate and ensures users' satisfaction. Furthermore, we showed that the learning module improves mobile cognitive radio users' behavior in terms of bidding efficiency and access opportunity. In addition, it enhances the primary users' utility and reduces the overall blocking rate.

As future work, we intend to study different learning strategies for cognitive radio users and we will propose an additional learning process on the primary users' side.

Acknowledgments

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