Dynamic Spectrum Sharing for Cognitive Radio Networks using Multiagent System

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***Abstract*— Dynamic spectrum sharing is a promising technique to optimize the spectrum utilization. It allows the cognitive radio (CR) nodes to access the available spectrum dynamically, without being restricted to static usage. In this paper, we propose multiagent system (MAS) based solutions to achieve licensed and unlicensed dynamic spectrum sharing. Firstly, we present a cooperative approach where the CR nodes embarked with agents are capable of performing spectrum sharing by exchanging a series of messages with the neighboring licensed devices. While analyzing the performance of this proposal under ad-hoc wireless conditions, we show that it achieves good performance in term of spectrum access, without incurring greater communication cost. Then, we focus on enabling unlicensed spectrum sharing between the CR users. Our proposed solutions can achieve good performance while maintaining fair spectrum distribution.**

***Index Terms*—Cognitive radios, dynamic spectrum sharing, multiagent systems, cooperation.**

I. Introduction

The traditional spectrum allocation methods are static where the spectrum is assigned to a dominant operator for longer durations. These methods are considered to be extremely favorable in order to avoid device-level collisions and interferences. However, the recent studies have shown that these static assignments can produce significant disjunctions creating empty “spectrum holes” or “white spaces”. In relation, the studies conducted by the Federal Communications Commission (FCC) prove that the empty holes can lead to scarcity problem where the spectrum utilization is as low as 5-10% in both the rural or urban areas [14]. Further, these studies have motivated the researchers towards cognitive radio (CR) [10] technology, which is considered to be an effective solution to alleviate the static spectrum assignment problem. It allows users to sense locally available spectrum portions and use them opportunistically, without interrupting the working of legacy primary (or licensed) users. CR devices can learn the spectrum fluctuations over time and adapt them accordingly to increase the efficiency of wireless communications. Nonetheless, the individual CR nodes seem to be very promising in their working, we argue that a single CR node seizing spectrum portions without coordinating them to its neighbors can lead to serious interferences, thus degrading the overall spectrum usage.

One effective solution to enable inter-device cooperation is Multiagent systems [15]. If a problem is particularly complex, interdependent and large, with the distributed nature of participating devices, then it can be efficiently solved by deploying a number of functionally specific autonomous components (agents) and making them cooperate via message exchanges. Moreover, similar to CR nodes, each agent maintains its local view and shares its knowledge (when needed) with other agents to solve the assigned tasks. These adherent features make them really suitable for dynamic spectrum allocations in CR networks.

Therefore, in this paper, we propose MAS based solutions for dynamic spectrum allocation in CR networks. Firstly, we focus on licensed spectrum distribution where the CR (or secondary) user agents cooperate with the neighboring primary user (PU) agents for spectrum access. The cooperation between these agents is performed using the message passing mechanism of *contract net protocol (CNP)* [16], which helps them to reach several spectrum sharing agreements. Further, secondary user (SU) agent selects the spectrum portion based on the amount of spectrum, time and price proposed by the PU agents. After using the acquired spectrum portion, SU should pay the agreed price to the relative PU. Secondly, we handle the case where all the users are unlicensed and present various proposals to achieve fair spectrum distribution among the unlicensed SU devices. Finally, we conduct simulations under ad-hoc situations to prove the efficient working of our proposals for both licensed and unlicensed spectrum sharing.

The remaining of this paper is organized as follows: The related work is discussed in Section II. Section III describes our cooperative licensed spectrum sharing framework. Simulation results and discussions for this approach are presented in section IV. Section V describes our proposals to achieve fair unlicensed spectrum distribution. Section VI concludes our work.

II. Related Work

Very few researchers have applied multiagent systems for dynamic spectrum allocation and sharing in the context of CR networks. A related approach is presented in [19], where MAS is used for information sharing and decision distribution amongst CR networks. Multiple wireless LANs (WLANs) are collocated in a geographical area with agents deployed at each of the access points (APs). All the AP agents form an interactive MAS, which is responsible for managing radio resources across collocated WLANs. Further, the works presented in [1][22] are based on the deployment of market-based competitive multiagent systems for spectrum sharing. The primary and secondary users are represented as the *provider* and *consumer* agents and they exchange bids for dynamic spectrum allocations. However, due to competition, the agents can sometimes send false bids, requiring complex schemes to be developed for managing and maintaining inter-agent trust mechanisms.

Broadly, game-theory is widely used for spectrum sharing, in variety of formats according to game models and author preferences and several interesting works exist [3][4]. In these approaches, each CR user has one goal i.e. to maximize its spectrum usage and the *Nash Equilibrium* is considered to be the optimal solution. Generally, in game-theoretical solutions, the players make the moves which maximize their own profits without taking into account the others. Therefore, in order to allow players to work interdependently, cooperative game models are proposed for efficient spectrum allocations [11][18]. In these solutions, the authors assume that the CR users' utilities, transmission powers and spectrum usage are common knowledge and their utility functions are chosen in order to maximize the global utility. Yet, still the cooperative approaches require a feedback from each player to be sent to the centralized player (or server) about its utility function, which increases their algorithmic complexity.

Our solutions are different from the above in a sense; firstly, they allow PUs to satisfy the SUs' spectrum demands by working cooperatively. Secondly, they provide the way in which the spectrum sharing between the SUs is performed fairly and efficiently.

III. A COOPERATIVE LICENSED SPECTRUM SHARING FRAMEWORK

In this section, we propose the deployment of a cooperative MAS for opportunistic and dynamic licensed spectrum sharing. We start our proposition by assuming an ad-hoc environment, with a number of primary and secondary user devices, where an agent is deployed over each of them for the purpose of cooperation and decision making. Whenever an SU needs spectrum, its agent starts communicating with the relative PU agents (having that empty spectrum portion), until a spectrum sharing agreement is made.

Fig. 1 depicts our proposed approach in its simplistic way. In this figure, an example of three primary and six secondary users is depicted, where the SUs have made spectrum sharing agreements with the neighboring PUs. Moreover, the primary and secondary users are not restricted to be involved in one spectrum sharing agreement at an instance of time; rather they can be the part of several agreements simultaneously. Likewise, Fig. 2 explains the internal architecture of an SU[1]. The spectrum sharing process starts by sensing the radio frequency signals via *Dynamic spectrum sensor (DSS)* module. It continues by characterizing the received signals using *spectrum characterizer (SC)* and getting the user request via *secondary user interface (SUI)*. The process moves further until the sending of *Call for Proposals (CfPs)* and receiving and analyzing of the received *proposals* using *AKM (agent's knowledge module)* and *ACM (Agent's cooperation module)*. This process ends, either by sending an accept or a reject message to the corresponding PUs. Obviously, the PU does not contain the CR and SUI modules, while the agent module is common in both the primary and secondary users. Finally, the PU follows the same working pattern by first analyzing the received *CfPs*, sending the *proposals* as responses and finally ending the process either by having an agreement or disagreement with the conforming SU. After finishing the spectrum sharing process with an SU, the corresponding PU can continue sending proposals to further available *CfPs*, for which the proposal sending deadline is not yet expired.

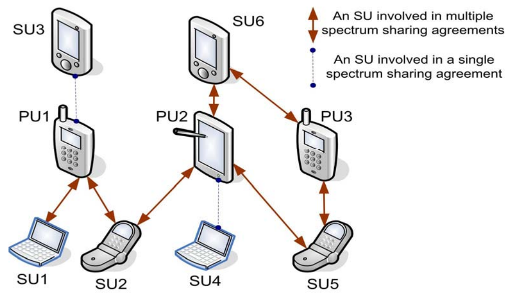


Fig. 1. Cooperative spectrum sharing in ad-hoc cognitive radio network

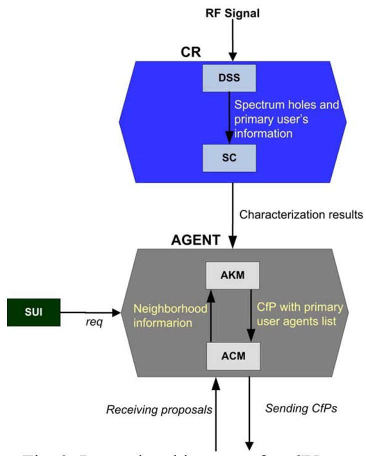


Fig. 2. Internal architecture of an SU

IV. EXPERIMENTAL RESULTS FOR LICENSED SPECTRUM SHARING

A. Simulation Setup

In this section, we present numerical results to evaluate the working of our proposed cooperative approach. The simulation is based on the following setup. Multiple primary and secondary user nodes are randomly placed according to Poisson distribution [9] in a noiseless and mobile ad-hoc network setting where their neighborhoods are continuously

[1] The detail explanation of the primary and secondary users' internal architectures, algorithms and behaviors can be found in [20][21].

changing. The SUs can cooperate with the neighboring PUs in order to make spectrum sharing agreements. Based on the studies presented in [5][23], we set the elapsed simulation time T_E to 90 minutes[2]. All the simulation experiments are conducted in Java Application Development Environment (JADE) [24], over a PC with 4GB memory and 2.4 GHZ dual processor.

The selection of parameters as shown in Table 1 is as follows. We set the bandwidth of each spectrum portion to *3.75MHz* as mentioned in [2]. The number of simulation runs (r_N) is set to 10 and the average results are taken to plot the graphs. According to [13], the fractional percentage of the time for which the spectrum is being used by the PUs (or holding time) in an urban environment follows the exponential distribution with mean μ_p and is measured as approximately 40 to 45%, thus we set the PUs' mean spectrum usage to 40%. The maximum number of primary and secondary users in a 90 minutes simulation run is 100 (in total), taking in account the capacity of running maximum number of agents on a single machine. Further, the Poisson distributions of primary and secondary users are denoted by rates λ_p and λ_s. For simplicity, we fix the value of λ_s to 5 and compare our parameters at various values of λ_p (i.e. λ_p = 3, 4, and 5). This variation factor helps us understanding the behaviors of SUs when they have to deal with different numbers of PUs. In addition, during a simulation run of 90 minutes, we also observe distinct values of our parameters over five different time intervals of 18 minutes each. This observation ensures that the parameters can be compared across various numbers of primary and secondary user agents, at several time instants. We denote the PU agent's utility (U_p) as the price paid by SU agents for spectrum utilization divided by the amount of spectrum it has shared for the respected time period as required by the SUs. The SU agent's utility (U_s) is represented as its spectrum usage for the required time divided by the corresponding price paid by the PUs. The total number of cooperation messages (*CfP*, *proposal*, *accept* and *reject*) generated in the system, determine the average communication cost (M_{cost}) for a successful spectrum sharing agreement. Finally, the number of non-allocated spectrum portions due to disagreements between primary and secondary user agents measures the overall spectrum loss α_{loss} (in percentage).

TABLE 1
SIMULATION PARAMETERIZATION

PARAMETERS	DEFAULT VALUE
Maximum number of PUs (N_{pmax})	50
Maximum number of SUs (N_{smax})	50
Size of a spectrum portion (B)	3.75 MHz
Primary user distribution (λ_p)	{3, 4, 5}
Secondary user distribution (λ_s)	5
PUs' mean spectrum usage	40%
Elapsed simulation time (T_E)	90 minutes
Number of simulation runs (r_N)	10

[2] We have also verified our simulation with different values of elapsed time and nevertheless the agents behaviors remain the same.

B. Results

In this section, we discuss our results obtained through simulations. We first plot the average communication cost (M_{cost}) associated with each successful agreement, in Fig. 3. By a successful agreement, we mean that an SU has completely utilized its required spectrum portion and in return it has paid the respected associated price. The figure clearly shows the differences in M_{cost} at λ_p = 3, 4 and 5. Initially, the value of M_{cost} starts from 4 reaching utmost to 8 in the end. This increasing trend in M_{cost} is directly relational to number of PUs (N_p) i.e. when the available PUs in an SU's neighborhood are less in numbers, the message exchange between the users is not high. Similarly, when N_p increases, the SUs can find more PUs in their neighborhood causing M_{cost} to augment. Nevertheless, the values of M_{cost} are not very high, showing the communication efficiency of our approach.

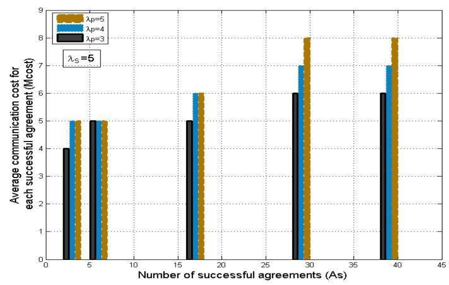


Fig. 3. Average communication cost associated with each successful agreement

Next, the histograms of PUs' spectrum usage at several values of λ_p are shown in Fig. 4. All three histograms depict the spectrum usage probability of PUs at different instances of time. This probability is high at early periods, but later, the spectrum is mostly unutilized and thus, the SUs can have more successful agreements during these times.

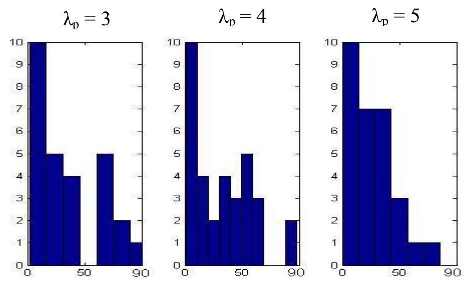


Fig. 4. Histogram of primary users' spectrum usage

Utility Graphs

In Fig. 5, we compare the average percentage utility of several numbers of SUs (N_s), at different time values. In particular, the achieved utilities are within 20 to 55% when λ_p=3, while they can reach to 70% (80% respectively) where λ_p=4 (λ_p=5 resp.). The graph is in conjunction with Fig. 4, where the available SUs can find more available PUs for spectrum sharing at time values greater than 50 minutes. Additionally, we can observe that the utility values can reach up to 80% (with λ_p =5) showing higher efficiency in terms of spectrum utilization. However, all the SUs are not entirely satisfied considering the environment is ad-hoc and the PUs are hesitant to share their spectrum portions for longer durations. On the other hand, in Fig. 6, the average utility of each PU (U_p) is almost 90% for all three values of λ_p, since the available PUs are always less (or equal) in number compared to *Ns* and there is relatively a higher chance that they can easily find SUs to share their unutilized spectrum.

Spectrum Loss

Another important aspect of our approach is the analysis of how its performance varies with time. A good stable solution is achieved when the performance of a network does not degrade drastically with the size of the system and the loss remains minimum. Here, we are trying to see whether the percentage of spectrum loss enhances with the higher number of agents. Thus, the spectrum loss (α_{loss}) is shown in Fig.7. At all three values of λ_p, the percentage of α_{loss} is higher at initial stages and it continues to decrease on a steady pace. This is because initially most of the PUs are occupied and the relative neighborhood of the SUs is constantly changing. From the figure, it is also clear that the value of α_{loss} can reach as high as 80%, but still there is not a rapid degradation in the overall system performance.

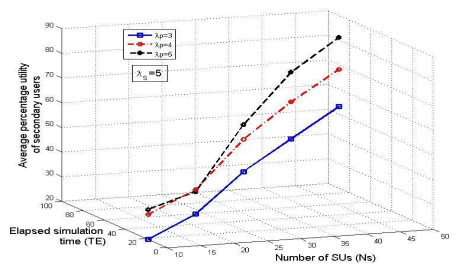


Fig. 5. Average percentage utility of SUs at different time values

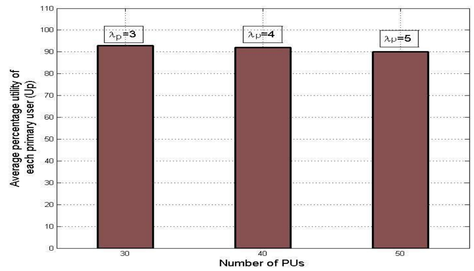


Fig. 6. Each PU's percentage utility

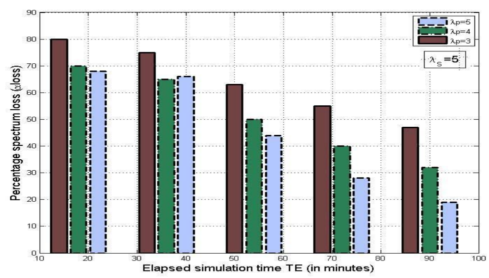


Fig. 7. Percentage spectrum loss

Explicit Agreements

Sometimes, it is also possible that a PU receives several *CfPs* and it may not be able to reply to any of these, because currently the status of its spectrum portion is set to busy. Our proposed approach addresses this issue in an efficient way and the PUs can explicitly send their *proposals* to SUs when they get unoccupied. In accordance, Fig. 8 delineates the percentage of explicitly awarded spectrum sharing agreements by the PUs to the neighboring SUs. It is apparent that on average 10 to 20% of the agreements are explicitly awarded by the PUs.

Comparison with Greedy Approach

Finally, we compare our cooperative approach to the greedy algorithm proposed in [7] and later compared to the approaches presented in [12][6]. We implement the greedy algorithm in our simulation setup where the primary and secondary users cooperate and the primary users' prime focus is to maximize their own utilities while showing greedy behaviors. By greedy it means that most of the PUs are self-interested and they are hesitant to share their available spectrum portions, until they get the highest offer that maximizes their individual utility. All the users are deployed following the same Poisson distribution processes with $\lambda_p = 5$ and $\lambda_s = 5$.

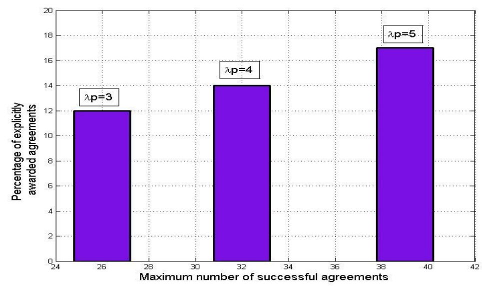
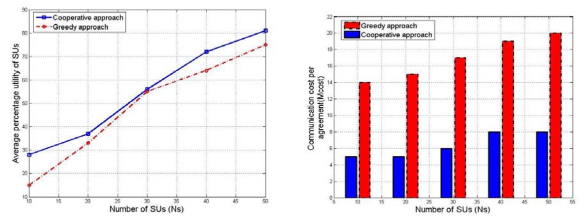


Fig. 8. Explicit agreements

Figs. 9(a) and 9(b) compare the average utility values achieved by the SUs and the communication cost associated with each successful agreement, respectively. We observe that the communication cost for greedy approach is very high considering the neighboring PU agents are naturally selfish. As a result, several messages are wasted and most of the time SUs receive unsatisfactory proposals. On the other side, our approach achieves good utilities while incurring lower complexity in terms of messages exchanged. This significant communication overhead reduction allows quick adaptation to ad-hoc network dynamics.

(a)



(b)

Fig. 9. Cooperative vs. greedy approach in terms of (a) achieved utilities and (b) communication cost

Briefly, in this section, we experimentally analyze the working and performance of our proposed algorithms allowing MAS cooperation for licensed spectrum allocation in CR networks. The proposed approach converges well such that it can find good utility based solutions using a small bilateral exchange of messages.

V. Unlicensed spectrum sharing

In this section, we handle the case of spectrum sharing where all the devices are unlicensed and have no priority over one another. Therefore, the available spectrum must be distributed fairly among the SUs (or agents). Similarly, the spectrum management processes, such as allocation functions and generated signaling traffic, must be performed in an efficient manner.

In the following, we propose some solutions to achieve fair spectrum distribution. At first, we present the key concepts of our solutions. Later, we explain our solutions for spectrum distribution, along with their comparison.

A. Key concepts

Universal Channel: [8] suggests a Common Spectrum Coordination Channel or a Universal Channel which is known by all the SUs. It supports new arrived SUs to select one of the available networks, and provides needed data to reconfigure them. Data is delivered only on demand for the following reasons [16]: (1) ongoing broadcast needs a wideband channel (2) data process would cause a relatively important delay and (3) delivering data is only useful for the connection process.

Cluster: A cluster of SUs is a set of independent terminals sharing the same radio conditions.

Cluster head: The cluster head (or coordinator) listens over the universal channel and replies to the newly arriving SU's request to join the cluster. It is also the first SU that comes into the coverage area.

Cluster channel: Like the universal channel, it is a specific frequency used only by the cluster members. All signaling and control messages are exchanged using the cluster channel. Consequently, interference is avoided between clusters while managing the spectrum.

Delegate: Each cluster member has a delegate agent which is in-charge of handling its requests. This latter can represent several SUs. While becoming cluster member, an SU selects a delegate based on one or more criteria such the pathloss or SNR. Delegate agents are useful to share spectrum management tasks between the SUs.

Allocation table: Each delegate agent has an allocation table. It contains the identifier and the allocated frequencies of the SU it represents.

Presence request: It is a control message used to keep up to date cluster topology. Every SU periodically exchanges presence request messages with its delegate.

B. Proposed solutions

As we aim to fairly distribute the unlicensed spectrum between the SUs, thus firstly, we propose a solution to maximize the cluster bit rate. Each SU has the maximum bit rate that can be afforded by the cluster. To do so, the total number of subcarriers must be divided by the total number of existing terminals. The straightforward way to achieve this is to centralize spectrum management process in the cluster head. In this case, the cluster head is the only agent in charge of spectrum distribution. When the number of SUs changes, a new redistribution of subcarriers is carried out under cluster head control. Rotating the cluster head among the SUs can realize spectrum management fairness. However, every arrival/departure of a cluster member generates an important amount of control messages in order to equally redistribute the spectrum.

As a second solution to distribute fairly the available spectrum, we propose a tradeoff between the number of agents and a constant bit rate. A constant, but not necessarily maximum, bit rate can be fixed by the cluster head while choosing a minimum and maximum number of cluster members. Number of subcarriers allocated to each SU is calculated based on the constant bit rate value. Initially, bit rate and the range of min-max number of SUs are fixed by default. When the number of SUs runs out of their fixed range, both the bit rate and range are redefined. For example, by default, the cluster head fixes the bit rate to 10 Mbps and the min-max number of agents to 1 - 10. In this case, the maximum bit rate per SU is 10 Mbps even there is one, two or ten SUs. When, 11^{th} SU joins the cluster, bit rates becomes 5 Mbps and min-max number of SUs 11 - 20. The minimum number is useful to revise upward the bit rate. With this solution, the control traffic for allocation/release is decreased especially when the number of SUs is within the fixed min-max range. However, spectrum exploitation is not as well optimized as in our first solution. Moreover, cluster head supports all the spectrum management tasks since it fixes bit rate and min-max range of cluster members.

As a third solution, we propose to share spectrum management tasks among delegates. In this case, the available spectrum is distributed between SUs and their delegate agents without any cluster head intervention. Every delegate shares its provided number of subcarriers with the SUs it represents, and similar is the case for all cluster members. Moreover, we have totally decentralized spectrum management process still; the number of subcarriers allocated to every SU depends strongly on the number of SUs associated with a delegate, which can lead to unfair spectrum distribution. To bring fairness, we can limit the number of SUs represented per delegate. To do so, we suggest optimizing this third solution while acting on the selection criteria of delegate. Previously, SUs choose delegate based on pathloss value. Now, we propose that an SU selects a delegate agent with the largest number of provided subcarriers. If two or more SUs have the same number of provided subcarriers, the pathloss criteria is used. Moreover, we propose that delegate gives half of its subcarriers to new arrived SU. Thus, no additional control traffic is generated to redistribute spectrum on associated SUs. To illustrate our optimized solution, we give the following example. Initially, the first arrived SU (A1) i.e. the cluster head, uses the entire available spectrum. Then, the secondly arrived SU (A2) selects the cluster head as delegate and shares with it the available spectrum. Each one has half of the available spectrum. When the third SU (A3) joins the cluster it selects a delegate based on pathloss as A1 and A2 have the same number of subcarriers. We assume that A3 selects the cluster head as delegate. A new SU A4 joins the cluster. A4 selects A2 as it has the largest number of subcarriers. A2 provides A4 with half of its spectrum without informing other SUs. In this example, spectrum is fairly distributed and decision is decentralized. However, we notice that perfect fairness is obtained for even number of SUs.

C. *Analysis and comparison*

We summarize in the following table the pros and cons of each solution.

Proposed solutions	1	2	3	Optimized 3
Bit rate	++			+
Traffic generated		+	+	++
Decentralization		+	++	++
Spectrum use	++		++	++
Fairness	++	++		+

As presented previously, solution 1 provides the maximum cluster bit rate, full and fair spectrum usage. However, it is a centralized solution that generates a large amount of control traffic especially at the cluster head level. Solution 2 ensures the same bit rate for cluster members, but does not provide maximum usage of spectrum. Solution 3 is completely distributed and generates less control traffic than solution 1 and 2. However, provided bit rate depends on the number of SUs associated to a delegate which can achieve unfairness between them. Optimized solution 3 brings fairness while selecting delegate based on the per agent provided spectrum. Perfect fairness is obtained with even number of SUs. Finally, optimized solution 3 achieves maximum spectrum usage and bit rate.

To prove our proposals' efficiency, we use the simulation environment presented in previous section and compared our solutions in Fig. 10, in terms of control traffic. It is clear that the optimized solution generates less control traffic compared to the others.

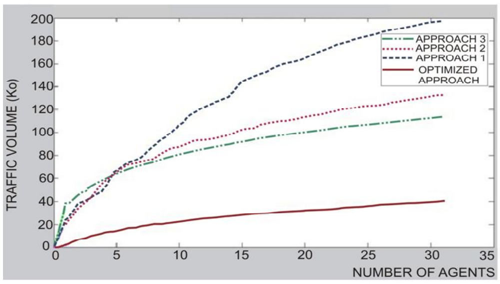


Fig. 10. Traffic volume as function of agents' number for proposed approaches to unlicensed spectrum sharing

VI. CONCLUSION

In this paper, we developed multiagent system based approaches for dynamic spectrum sharing. We proposed a cooperative framework for licensed spectrum sharing. Simulations results proved that our proposed framework works efficiently and it yields a significant contribution in dynamic spectrum access literature. Then, we presented different solutions to share unlicensed spectrum among secondary users. The proposed solutions can achieve good performance while allocating the available spectrum fairly.

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