Historian: A learning based Distributed Algorithm for Dynamic Spectrum Allocation

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Abstract—**In the current Spectrum allocation regime the Federal Communication Committee (FCC) is responsible for the allocation of frequencies to users. This ensures that owners will have an non interfering use of their frequency. However this approach leads to a significant underutilization of the spectrum [1], since most of the rightful owners use their frequency very sparse. Thus, for better utilization of the spectrum, has been proposed the use of the spectrum by non - rightful owners in a non-interfering way. In other words non-rightful owners of spectrum may use any frequency, as long as they don't interfere with its owner when the owner tries to access it. The functionalities of spectrum sensing and changing between frequencies can be provided by the state of the art technology of the *Cognitive Radios***

In this work we present Historian. Historian is a distributed algorithm for choosing frequencies in a network consisted of users other than the rightful owners. Historian is a learning based algorithm that tries to identify the presence of rightful owners, their characteristics and their traffic patterns in order to reuse spectrum more efficiently, by making more intelligent decisions. Historian based on observation and statistics can maximize the throughput of the network, by assigning frequencies that are less likely to be used by their owners.

We evaluated Historian via simulations and we show that can efficiently adapt to dynamic environments, where rightful owners of spectrum appear and disappear, while trying to maximize capacity. Moreover we show that Historian is continuously training, by observing the spectrum usage, and thus can take intelligent decisions, which results in the resilience and stability of the non - rightful owner network.

I. **Introduction**

Since the *Radio Act of 1912*, an independent Federal Communication Commission (FCC) was established and is responsible for issuing licenses for commercial use. These licenses determine the rightful owners of particular frequencies. Using these frequencies is prohibited by others and the outlaws could face legal consequences. The current fixed spectrum allocation scheme can lead to a significant amount of white space (frequencies that are not used, even though they have a rightful owner). Experiments [1] show that even in highly populated areas like near downtown Washington DC, where commercial and government spectrum is very intensive, the percentage of white space under the 3GHz band reaches 62% . The observation of the underutilization of spectrum in combination with the high demand in spectrum from a vast number of wireless commercial applications and services, yields the need of transforming the current fixed spectrum allocation mechanism into a more flexible and dynamic allocation mechanism.

The FCC and the federal government sense the pulse of the today's requirements for spectrum usage and therefore have taken initiatives to change the current policy for spectrum allocation [2] [3]. They introduce a more robust and flexible policy regulator, in which unlicensed users will be able to use licensed spectrum as long as they don't interfere with its rightful owner. Furthermore, in [2] they introduce regulators, in which the rightful owners will be able to sell dynamically their spectrum to users. This innovative initiative will result in a more utilized and profitable spectrum usage. In order the new era in spectrum allocation to become a reality, special hardware is needed that incorporates all the above functionalities.All these capabilities are enabled by the *Software Defined Radios (SDR)* or *Cognitive Radios (CR)*, which are able to sense and communicate in a wide range of frequencies. They can scan and find any unused frequency and thus they contribute in high spectrum reuse. In Section II, we will describe the capabilities and the differences of the Cognitive and Software Defined Radios.

Motivated by the new era to come, we created **Historian**. Historian is a distributed algorithm for the exploration of the white spectrum, by users[1] others than the primary licensed users[2]. The Secondary Users will form a multi-hop network by using the white space of the spectrum in an opportunistically manner, i.e. the SUs should coexist with the Primary Users in a non-interfering basis. The connectivity of the SUs network should be resilient in case a PU decides to transmit on his frequency, which is currently used by one or more pairs of the SU network. In order to achieve this, the SUs should continuously scan the whole range of spectrum in order to identify available frequencies and they should always be ready to cease transmission, change transmission frequency and give priority to the transmissions of the PUs. So, the SU network will be a dynamically formed network with ability to adjust and re-organize to the current conditions of spectrum usage. The intelligence of which frequency is most suitable for transmission at any current time will be provided by the Historian algorithm. Historian, based on historical information of the spectrum usage is able to identify traffic patterns of PUs and take intelligent decisions when necessary.

The rest of the paper is organized as follows: In Section II, we describe the current technologies and capabilities of Software Defined Radios and Cognitive Radios. In Section III we

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[1] From this point on these users will be referred as Secondary Users or SUs
[2] From this point on theses users will be referred as Primary Users or PUs

present the problem formulation, while in Section IV we introduce the network model that we will use. In Section V, VI we present Historian and the simulation results respectively. In Section VII we mention some related work and finally the paper concludes with Section VIII.

II. **Background**

In this Section we will describe the technologies that can be exploited, in order to take advantage the unused spectrum and utilize the spectrum usage.

Software Defined Radios*:* A Software Defined Radio (SDR) is a radio that all its operational parameters, such as frequency range, modulation type or maximum output power can be altered through software modifications, without any changes to hardware. In SDRs software defines all the waveform properties, cryptography and applications. Thus SDR can be easily upgraded and can provide newer and more advanced services. The significance of SDR is that it can be made to operate wherever spectrum is available, without the need of hardware replacement e.g in case the operational frequency changes. On the other hand SDR lack of intelligence and therefore they are not able to adjust to continuously changing conditions (i.e. to change their frequency in case of interference).

Cognitive Radios*:* The deficiency of SDR is filled up by the the Cognitive Radios (CR). The FCC suggests [3] that “A radio system whose parameters are based on information in the environment external to the radio system” is considered Cognitive Radio. [4] sums up all the desirable features of CR. In more detail, CR can *adapt* by changing their transmission parameters (e.g frequency, modulation, power) in order to meet their requirements, can *sense* the spectral environment over a wide range of bandwidth and can *detect* the use of spectrum. Moreover, CR are *intelligent* enough to *learn* based on previous and current conditions, to anticipate future actions and take the correct decision at the “right” time.

The CR, in contrast with the SDR, provide more flexibility for dynamic spectrum access. The sensing ability of spectrum and the intelligence to switch from a used frequency to an unused one, provide especially to the SUs the capability to use efficiently the white space and the flexibility to communicate without interfering with the PUs, when they choose to use their licensed frequencies. This can result in high utilization of spectrum usage, without causing communication problems to the rightful owners of spectrum.

III. **Problem Statement and Motivation**

We consider two types of users, which are deployed in a wide area. The primary users (PUs), who are the rightful owners of some portion of the spectrum and have strict access over it. The secondary users (SUs), who can use any available spectrum, as long as they don’t interfere with the transmissions of the PUs. The SUs, in order to have these functionalities should have sensing and detection abilities, which can be provided by exploiting the prosperous features of the cognitive radios. We consider that the PUs don’t care about the existence of the SUs and they don’t want to communicate with them. Likewise, SUs want to communicate only within their group and they want to create a network, in which all secondary users can talk with each other. In other words, the objective is the creation of a connected communication graph of SUs, that doesn’t interfere with the communication graph of the PUs. In this graph the nodes will be SUs and the links will represent the connectivity between two SUs using a particular frequency[3].

From this challenging formulation rise many questions. *How can we distributively allocate channels to the SUs, in order to form a connected graph? What happens if a transmission of a PU pair starts in a frequency that is currently used by an SU pair? How is the graph re-organized, in order to retain connectivity?* All the above questions are very challenging due to the dynamic conditions of the environment and we address them in our current work.

The answers to above questions can be of great benefit, because they address real deployment issues and can result in high utilization of the spectrum. The above formulation provides a pioneering way of thinking wireless networks, where networks can coexist in the same area and each network can reuse frequencies that the other network is not using in a non-interfering way. Moreover, each network can consist of links that have different frequencies, which can change dynamically based on current conditions of interference and QoS requirements.

IV. **Network Model**

In this Section we will describe the network model that will be used in order to explore the problem stated in Section III, as well as some necessary assumptions that will help us to study in depth the aforementioned problem.

Cognitive Radio Capabilities*:* As we stated in problem formulation, we consider two types of users, which correspond to two separate networks located in the same geographical area. The PUs are not cognitive radio aware and they don’t care about the transmissions of the SUs. The reason is that they are the rightful owners of the frequencies that they transmit and therefore they consider that they have the strict spectrum access on these frequencies. We assume that the transmissions of PUs don’t interfere with each other. This assumption is reasonable since the allocation of the licensed frequencies is performed by the FCC in a non overlapping way. SUs, on the other hand, we assume that they have cognitive radio capability. In other words, our network will consist of primary users and cognitive capable secondary users (i.e we don’t consider the case in which all or some of the SUs don’t have CR capabilities).

Channel Properties*:* Cognitive Radios are able to operate in a wide range of frequencies, covering from tens of MHz to several GHz. Frequencies that their difference is in order of tens of MHz, tend to have different physical properties, i.e. with the same transmission power low frequencies have larger range than the high frequencies. This fact complicates the analysis of such a system, because it introduces a new dimension to the problem. A simple example is that for different frequencies, an SU can cause interference to different PUs. In order to simplify our analysis, we consider that the SUs can choose within κ frequencies, which all have the same physical characteristics.

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[3] The terms frequency and channel represent a certain band of spectrum. From this point and on these terms will be used interchangeably

Moreover, all users use a certain transmission power and they don't adjust it dynamically according to the network conditions. All the above ensures that the communication graph that captures the connectivity and interference information between all user (PUs and SUs) doesn't change with time. In other words, the only attribute that the SU network can adjust, in order to operate in non-interfering basis with the PU network is the selection of channels.

Control Channel: The SUs, will use a control channel, in order to exchange control and sensing information. The Control Channel will be globally unique and will be known by all SUs. This channel can be in an unlicensed frequency, in order to avoid interfere with the primary users. The traffic that will be transfered through this channel will not be heavy, but the significance of the control channel is great since it will provide the bootstrap for a new secondary user to connect to the network. Through this channel, the secondary users can exchange control information (i.e. which frequency to choose, etc) and sensing information. The exchange of sensing information is very helpful in order to avoid *Hidden Terminal Effects* and to improve higher levels of detection of the primary users [5].

Sensing Properties: In our model we adopt an assumption made in [6], where PUs can tolerate interference no more than time Δt_x time units. We should note that this time is dependent on the primary system and may be different for different PU, but in order to simplify our model we will consider that all PUs have the same value of Δt_x. After this time, the SUs that interfere with the PU should cease transmission in the current channel and switch to another available channel. This means that all SUs should sense continually the spectrum for the presence of primary users or at least every Δt_x. This dictates a slotted timing in our model with slot time equals Δt_x, in which at the beginning of each slot every SU will know if the channel that is currently using is available for the next slot and which are the alternative channels, in case the secondary user needs to switch. We should point out that the slotted model doesn't need any central coordination (only pairs of SUs need to be synchronized and can be done through the control channel), neither require the transmissions of the PUs to start in the beginning of a slot. The transmission of the PUs can start at any point of the slot, since they can tolerate interference for time equals to Δt_x.

For our slotted model we use an very interesting formulation made in [7], where each slot contains a frame as shown in Figure 1. Each frame is divided into two phases, the Link Maintenance and the Data Transmission phase. In the Link Maintenance phase the SUs scan the spectrum and try to find an available channel to operate for the current slot, while in the Data Transmission phase the actual data transmission takes place in the channel which was selected. In detail, the Link Maintenance consists of three parts.

1) **Sense**: The whole spectrum is scanned, in order to detect any PU activity.
2) **Control**: The sensing information that is acquired has to be exchanged between the communicating nodes, in order to acquire a consistent view of the channel that can be used for future communication. This information, along with some information about the neighborhood of the communicating nodes, is exchanged using the control channel. The information about the neighborhood of the communication nodes is similarly very helpful, because it can provide to the SUs an insight of the SU network and can result in a more efficient channel allocation.
3) **Acquire**: In this part, the channel that is going to be used for the data transmission is acquired and the communicating SUs initialize their communication.We have to note that this part is executed only when the SUs have changed the channel that are communicating since the previous slot. In different case, the data transmission can start immediately.

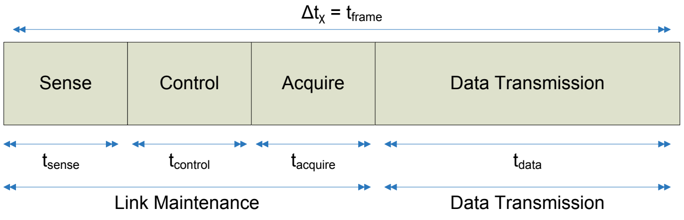

Fig. 1. Time Frame Structure

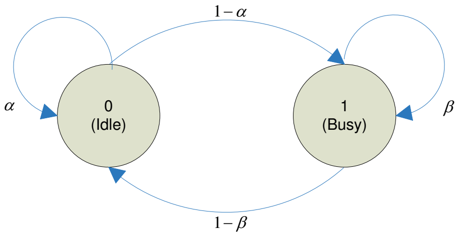

Fig. 2. PUs Traffic Pattern

Traffic Patterns: The traffic pattern of the PUs will follow a two state Markovian Model. As illustrated in Figure 2, 0 represents the Idle state, in which the PU has nothing to transmit and consequently its channel is available to be used by the SUs, while state 1 represents the occupancy of the channel by the PU. In this case, the channel cannot be used. The state transition probabilities $\{\alpha, \beta\}$, can be used to represent different kind of PU's behaviors. In other word, high probability β and low probability α represents intense traffic pattern, while the opposite case corresponds to sparse traffic pattern. Although in our slotted model the transmissions of the PUs are not required to start in the beginning of each slot as we mentioned above, we will make this assumption in order to simplify our analysis.

On the other hand the SUs will follow a different traffic pattern. They will always have data to send to all their neighbors. In this way we can explore the behavior of our proposed algorithm in the most extreme network conditions, since the SUs will have to utilize the channel allocation in order to achieve high network efficiency and connectivity.

Routing: The objective of the secondary users is to construct a connected multi-hop network, in which all users will be able to communicate with everybody else. In order these communications to be feasible, a routing algorithm must be deployed. In the bibliography there are many distributed routing algorithms, that can be deployed [8] [9] [10]. The routing scheme is not the main focus of our intended work. Therefore, we will consider that a simple routing scheme is deployed and every user knows where the destination user is.

V. HISTORIAN ALGORITHM

In this section we will present Historian. Historian is a distributed algorithm that is responsible for the assignment of channels to pairs of communicating Secondary Users. These decisions are based on criteria that are derived from observation of the spectral environment. First, we will introduce the History module, which is the heart our algorithm and then we will present the Historian Algorithm.

History Module: Every node will be responsible for observing the usage of the spectrum and keeping statistics. These statistics will be stored in the History module. This module will classify all available frequencies, that an SU can operate in, into two categories, the **Safe** and the **Risky**. The Safe category will contain all the frequencies that in the past have never been used by any PU, while the Risky category contains all the frequencies that have been used by a PU at least once in the past. This intuitively means that the probability of a PU to operate in the future in a frequency contained in the Risky Category is higher, since the PUs are rightful owners of certain channels and they don't switch randomly among available channels. In that way the History module is trained and can identify all the channels that belong to PUs and can potentially operate in its vicinity. Thus an SU can consult its History module, when it needs to choose a channel to operate in and will try to use first all the channels that are in the Safe category since the probability to interfere with a PU is smaller.

The History module is a learning entity within each SU. In the initialization of the user, the History module will have all its frequencies classified as Safe, since it doesn't have any statistics concerning the usage of the spectrum in its vicinity. In every round the SUs sense all the channels and if a PU appears using a frequency that is currently in the Safe category, then this frequency is moved from the Safe to the Risky category. If the frequency that the PU occupies is already in the Risky category, then we have for each frequency an associated weight that we call *risk factor* and we increase it in each round, that this frequency is used by the PU. The Risk factor is calculated by the equation 1:

$$Risk(i)_{n+1} = \frac{\gamma * Risk(i)_{n-1} + \delta * Risk(i)_n}{\gamma + \delta} \tag{1}$$

From Equation 1, we can clearly see that the Risk Factor is the weighted average of the past and present observations. Weight δ represents the robustness of the Risk factor to new observations. Small value of δ corresponds to less sensitivity of Risk factor to new observations, while large values result the Risk factor to take new observations more into consideration. Likewise, weight γ represents how fast past observations attenuate. In that way we can rank the frequencies inside the Risky category according to their usage frequency. The highest ranked frequency corresponds to the frequency with the smallest value of Risk factor and consequently to the least used frequency. Thus, from this ranking we can derive a rough estimation of the traffic patterns of the PUs and consequently we can prefer frequencies that belong to PUs with less intensive traffic.

Algorithm 1: History Evaluation

```
Input : A Set of Frequencies $S$
        History Modules of Secondary Users $A$, $B$
        Percentage P
Output: Set of Communicating Frequencies $S_f$ between
        $A$, $B$
1  begin
2      if $S_1 = (S \cap A.Safe \cap B.Safe) \neq \oslash$ then
3          return $P_{S_1}\ rand(S_1)$
4      else if $S_2 = (S \cap A.Safe \cap B.Risky) \neq \oslash$ then
5          return $P_{S_2}\ MaxRank(B.S_2)$
6      else if $S_3 = (S \cap A.Risky \cap B.Safe) \neq \oslash$ then
7          return $P_{S_3}\ MaxRank(A.S_3)$
8      else
9          return $P_S$
           $\max(MaxRank(A.S), MaxRank(B.S))$
10     end
11 end
```

History Evaluation: In algorithm 1, we present the selection process of a set of channels, based on the statistics provided by the History module, given a set of the common available channels S of SUs A, B. Percentage P corresponds to the number of channels that this selection process will return, given a set of channels of size k. Our algorithm selects among a set of channels S, the best channels for SUs A and B to operate in. From algorithm 1, we can clearly see that gives always higher priority to the frequencies that are least used by PUs. E.g. in Line 5, the selection process will return the percentage P of channels from set S_2 that have the highest rank in SU B and consequently have less probability to interfere with a PU.

Historian Algorithm: In Algorithm 2, we present the contribution of this work, the **Historian** Algorithm. Historian Algorithm is executed by every pair of nodes (A, B) in the network, in order to select, based on the current spectrum conditions and past observations, the best frequency to operate in. Every SU will maintain three list:

- The *used list*: Contains the frequencies used by the SU's neighbors
- The *available list*: Contains all the frequencies that the SU can use in the current slot and don't belong to the used list
- The *forbidden list*: Contains the frequencies that the SU cannot use, because they are used by their primary owners

Initially our algorithm finds the common set of frequencies that the pair of users (A, B) can use, in order to initiate a transmission. Afterwards, based on the History Evaluation (Algorithm 1) of this set it selects the most suitable frequency for this communication. The selected frequency is the first frequency in the returned set of frequencies from the History Evaluation Algorithm, which corresponds to the frequency, which has the minimum probability to interfere with a PU. From Algorithm 2, we can clearly see, that our algorithm gives always higher priority to the frequencies contained in the available list, compared to the frequencies in the used list. In this way we prefer to use frequencies that are not used by any interfering SU and thus we can achieve higher efficiency, since interfering SUs don't share

Algorithm 2: Historian Algorithm

```
Input  : Secondary Users $A$, $B$
Output : Set of Communicating Frequencies $S_f$ between $A$, $B$
begin
    if $S_1 = (A.available \cap B.available) \neq \oslash$ then
        return $HistoryEvaluation(S_1)$
    else if $S_2 = (A.available \cap B.used) \neq \oslash$ then
        return $HistoryEvaluation(S_2)$
    else if $S_3 = (A.used \cap B.available) \neq \oslash$ then
        return $HistoryEvaluation(S_3)$
    else if $S_4 = (A.used \cap B.used) \neq \oslash$ then
        return $HistoryEvaluation(S_4)$
    else
        return $ControlFrequency$
    end
end
```

the capacity of their links. Moreover, in the selection process, if a pair of SUs cannot find a common set of frequencies to communicate, then they are forced to operate in the control frequency, which as we stated in IV is an unlicensed frequency and is not used by any PU. In the Control Frequency SUs don't exchange traffic, but only control information. Therefore, in order to exchange traffic they have to wait until there is an available frequency to operate in. We should point out that the forbidden list doesn't appear in the selection process, because the Secondary Users are restricted from using these frequencies.

SU Operation: In Figure 3, we depict the flow diagram of the operation of a Secondary User. The highest priority of a Secondary user is to avoid interference with a PU. Thus in the flow diagram, the first condition check guarantees the operation of the licensed users in an non-interfering way. The second condition check is responsible to increase the efficiency of the SU network. If the current assignment doesn't interfere with any neighboring SUs it will be kept for the current slot, else the **Channel Estimation** process will be responsible to assign a different channel only if this will improve the throughput of the communicating pairs.

In the Channel Estimation process, we record in each round the observed throughput for the current channel. In this way we build a capacity estimator for the channels that an SU has operated in. The Channel Estimation process, will select among the channels, which are returned by the Historian Algorithm, the channel that is observed to have the highest achievable throughput. Thus, we try to maximize the performance of the SU network. We should point out that in the initialization of the estimator all the channels will have as estimated throughput the maximum theoretical achievable throughput. In this way all channel have equal probability to be selected. The estimator in case of ties will select randomly a channel. The flow diagram of the operation of the Channel Estimator is depicted in Figure 4.

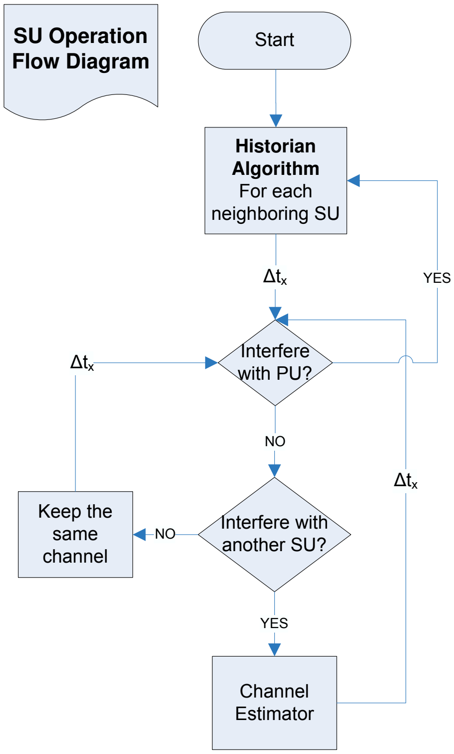

Fig. 3. SU Operation Flow Diagram

VI. SIMULATION RESULTS

In this section we evaluate our algorithm. We have built our own simulator and we explore the capabilities of our algorithm for different network conditions. Our network consists of 50 SUs and 30 PUs randomly placed in a $300x300$ area, while the communication range of each user is $50m$. Thus, two SUs can communicate and an SU can interfere with a PU, if their distance is less than $50m$. Every PU in the beginning of the simulation chooses its rightful channels randomly, over a set of channels. The total time of our simulation is 100 slots, while the capacity of each link is 11Mbps.

In order to evaluate the effectiveness of Historian we will use as a metric the average total capacity in the network and the unpredictability of the PUs, which is the number of times that an SU pair failed to predict the occupancy of the channel and thus was forced to change their communication channel due to PU presence. The first metric will reveal how effective Historian is in adjusting to current conditions and maximizing the average throughput of the network, while the second metric will explore the efficiency of the learning capability of our algorithm. We should point out that the topology has great effect on the observed total average throughput, due to the random positioning of the users. However, the intelligence and the adaptability of our algorithm due to the dynamic conditions can be seen clearly. Moreover, we compare our approach with the random approach, in which an SU chooses a channel randomly from the channels that are currently not used by any PU, without taking into consideration any previous knowledge.

For all our experiments we will use the same random topology, in order to see clearly how Historian adapts to the dynam-

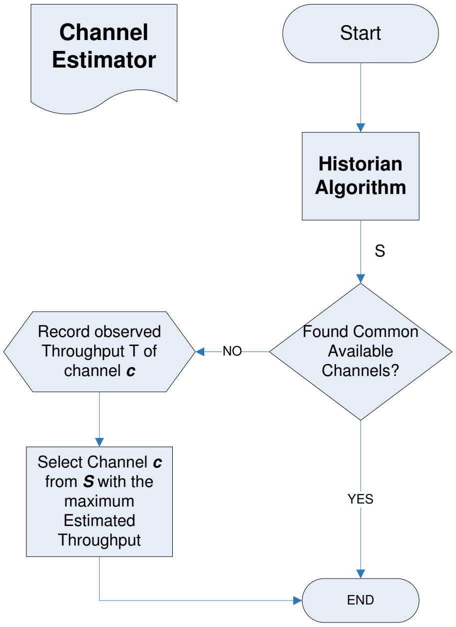

Fig. 4. Channel Estimator's Flow Diagram

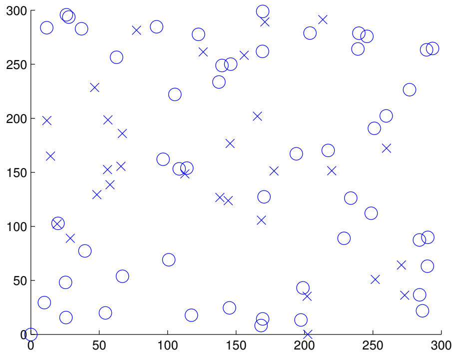

Fig. 5. Network Topology

ics of the network. The topology is depicted in Figure 5. The circles represent the SU network, while the PUs are represented by a cross.

A. No PU presence

Initially we try to find what is maximum achievable capacity for the SU network for this topology. The maximum capacity can be attained in the absence of any PU activity. Thus, in the first scenario we consider that all PUs have $(\alpha, \beta) = (1, 0)$, which corresponds to the continuously idle state. The average total throughput versus the number of channels that can be used, is depicted in Figure 6. From the figure we can clearly see, that with small number of channels many SUs pairs share the same channel and consequently the average observed throughput is low. However, as the number of channels increases the average total throughput converges to a maximum value, which corresponds to the network maximum throughput.

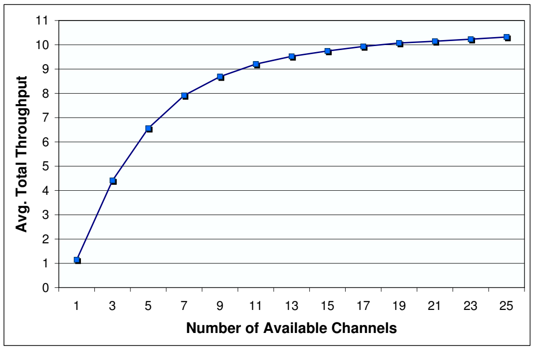

Fig. 6. Avg Total Throughput vs. Available number of channels

B. High PU presence

In Figure 7, 8, 9 we present the average total throughput per slot, in an environment where the PUs have very high traffic with $(\alpha, \beta) = (0, 1)$, for different number of available channels. In this scenario all the PUs access continuously their channel and thus they cannot be used by any SU. In this extreme environment the SU network can use only the remaining available channels. In the scenario presented in Figure 7, the SU network can use only 5 channels out of which some of them are taken by their rightful owners. Therefore since PUs continuously use their channel, SUs are forced to share a very small number of frequencies and consequently the average total throughput is the minimum possible. However, in Figure 8, 9 we can see that the average total throughput increases with the use of more channels, due to the existence of more channels that can be used by an SU.

Moreover, in these Figures we can see that Historian algorithm compared with the random approach can achieve better average total throughput. The advantage of our algorithm lies in the intelligence, which tries to maximize the observed throughput in the SU network. The difference in performance between these two algorithm is observable, but not dramatic. The reason is that in both algorithms the SU chooses a channel to operate in, from a set of channels that currently are not used by any PU. Since PUs continuously access their channel, the set of channels that a SU can choose from is constant and thus both approaches achieve similar results. However, the increased performance of the Historian algorithm shows the adaptability of the algorithm, which tries to re-assign channels in order to maximise the observed throughput of the SU network.

C. Medium PU presence

In this scenario, the PUs have medium traffic with $(\alpha, \beta) = (0.5, 0.5)$, which corresponds to 50% probability to transmit or remain idle. In this dynamic scenario, our algorithm compared with the random algorithm has greater performance, as we can see in Figure 10. The constrained number of channels (5) and the dynamicism of the PUs, can be used more efficiently by Historian and thus has better performance than the random algorithm. However, as the number of channels increases the difference in performace between the two algorithms is reduced, since the increased number of channel results in the existence of more channels that are available and won't be used by any

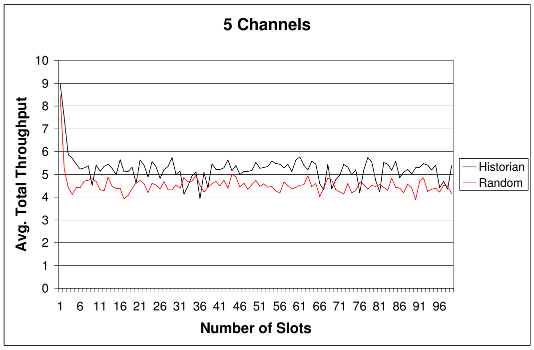

Fig. 7. High PU presence - Avg Total Throughput vs. Number of Slots

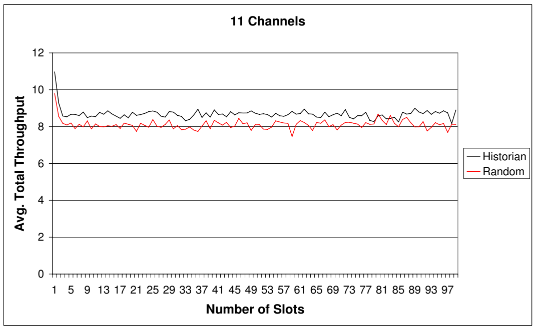

Fig. 8. High PU presence - Avg Total Throughput vs. Number of Slots

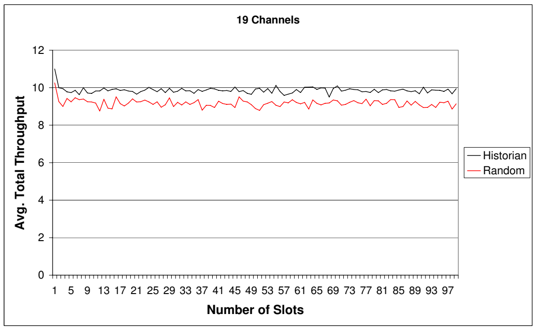

Fig. 9. High PU presence - Avg Total Throughput vs. Number of Slots

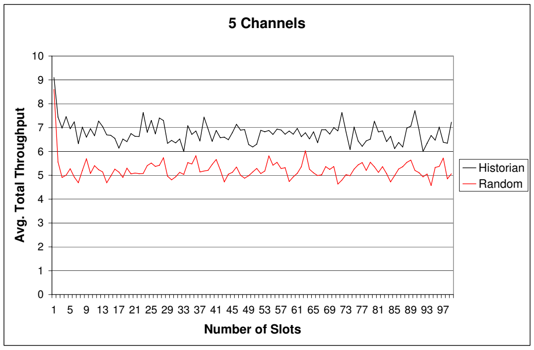

Fig. 10. Medium PU presence - Avg Total Throughput vs. Number of Slots

PU. Thus, the random algorithm chooses a channel that won't be used by a PU with higher probability. This behavior is illustrated in Figure 11. Similar results are observed for larger number of channels.

Apart from the maximization of the average total throughput of the SU network, Historian algorithm tries to capture the true characteristics of the Primary Users. In detail, Historian tries to learn the use of each channel by its owner. This information helps Historian, to make more intelligent decisions. In Figure 12 we present the Unpredictability metric of the two algorithms. In Figure 12 we can see that Historian uses effectively all the information that has acquired and thus makes more efficient decisions in contrast with the Random algorithm. The spike in the Unpredictability, during the first slot of the simulation is caused by the lack of previous knowledge of the spectrum usage. However, after it acquires some statistics it behaves more efficient. We should point out that some spikes of the Unpredictability of the Historian algorithm are due to the small number of channels, which forces our algorithm to use a frequency which has high probability to be used. However, as we can see in Figure 13, as the number of available channels increases our algorithm outperforms the Random Algorithm. The learning ability of Historian is very important since it tries to minimize the probability that a communication between a SU pair will be interrupted by the appearance of a PU. Thus contributes in making the SU network more resilient and stable.

VII. Related Work

Research community has showed an intensive interest in the field of Dynamic Spectrum Access in the last years. This statement is strengthen by the creation of the *IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks* or *DySPAN* for briefness, which was held in Baltimore, Maryland on 8 - 11November, 2005.

Dynamic Spectrum Access is a new research field and hasn't been thoroughly explored. Thus researchers try to approach the problem from different perspectives. In [11] [12] the authors use a MAC based approach, in order to guarantee that the rightful owner of the channel will have strict access over it. In the first paper the author reviews different spectrum management models and proposes several approaches for spectrum management. However, algorithms that will provide these functionalities as well as simulations, which prove their effectiveness, are not provided. In the latter paper the authors consider a slotted timing similar with our model, but with the difference that their slotted timing is fixed, synchronised and broadcasted by the primary users. An unrealistic assumption, since the primary users don't care about the SUs.

In [13] the pairs of users can select one channel from a set of available channels along with the transmission power. Then they exchange interference information with each other in order to adjust transmission power. In [14] they propose a game theoretic framework, in order to analyse the behavior of cognitive radios for distributed adaptive channel allocation. In their model they consider only pairs of nodes, which are uniformly distributed in space. An additional aspect of the channel allocation problem is introduced in [15], where they consider the presence of white space not only varying frequency and time, but also varying the geographic location. The authors contribute to better understanding the properties of spectrum agility. In [6],

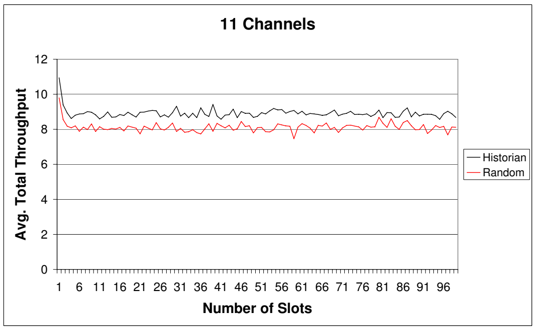

Fig. 11. Medium PU presence - Avg Total Throughput vs. Number of Slots

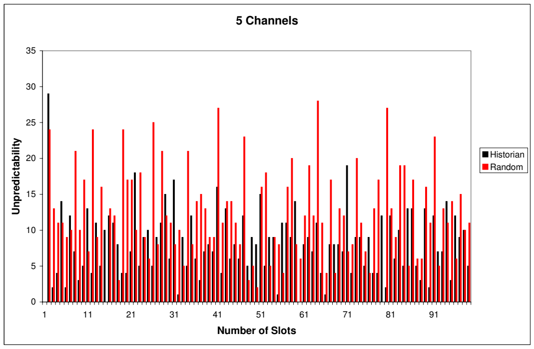

Fig. 12. Unpredictability vs. Number of Slots

the authors exploit the Spectrum Pooling resource sharing strategy, by dividing the available spectrum into N Sub-channels. Each time a pair of SUs wants to communicate, uses a pattern of sub-channels. In that way the communication is more resilient to the presence of PUs, since the appearance of a PU would affect only few sub-channels.

In contrast with the decentralized approaches, in [16] is proposed a centralized approach for coordination and management of spectrum access. In this model a server is responsible for managing and allocating channels, in order to avoid congestion, minimize interference and adjust the clients wireless medium access to meet the administrators needs.

VIII. CONCLUSIONS

In our work we presented Historian. Historian is a learning based distributed algorithm in assigning dynamically spectrum. We have shown by simulations that our algorithm is robust and based on observation of the spectrum usage can extract information about the presence of PUs in its vicinity, as well as their traffic pattern. This acquired information is used by Historian in order to intelligently assign a channel between a communicating pair of SUs, in such a way that minimizes the probability of this channel to be used by its rightful owner.

As a future work, we intend to explore other approaches in categorizing channels, as well as study the effect of different formulas that rank the channels within the Risky category of the History Module. Moreover, we plan to add mobility on the network and study the performance of our algorithm, as well as what changes should be considered to the algorithm in order to capture the characteristics of the user's mobility.

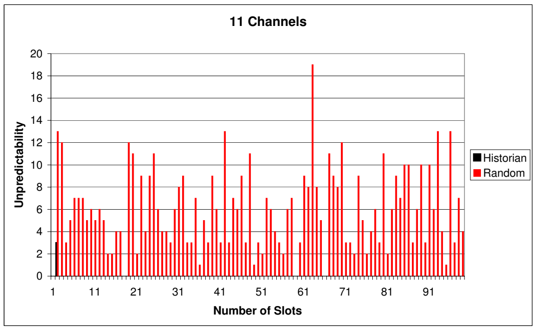

Fig. 13. Unpredictability vs. Number of Slots

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