Power Management and Bandwidth Allocation in a Cognitive Wireless Mesh Network

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***Abstract*— In this paper, we consider a cognitive wireless mesh network where mesh nodes on an unlicensed spectrum make opportunistic access to a licensed spectrum. Since the spectrum of interest is licensed to a Primary User (PU) or network, power management and bandwidth allocation at the mesh nodes should be carefully picked out such that the interference tolerated at the PU does not exceed a predefined threshold value. Our interest is to maximize the spectrum utilization of the cognitive radio network by serving the most possible mesh nodes while appropriately protecting the PU from harmful interference. The problem is formulated as a Non-Linear Integer Program (NLIP). However, due to the complexity of the problem, a lower complexity heuristic algorithm is proposed. Results provide how many and which cognitive mesh nodes have been served, their final transmitted power level, and the spectrum utilization.**

Keywords-cognitive radio; spectrum utilization; primary user; power management.

I. INTRODUCTION

Radio spectrum is one of the most scarce and valuable resource for wireless communications. It is commonly believed that there is a spectrum scarcity at spectrums that can be economically used for wireless communications. This can be seen when the FCC frequency chart [1] is inspected. Therefore, the increase in demand for wireless connectivity of unlicensed spectra has pushed researchers and agencies to be more aggressive in providing new ways to use spectra.

The concept of allowing opportunistic spectrum access can improve the overall spectrum utilization. However, transmission from cognitive radio networks can cause severe interference to the Primary Users (PUs) of the spectrum. Therefore, an algorithm which allows opportunistic spectrum access to a licensed spectrum in order to maximizing spectrum utilization at a cognitive network while not exceeding a predefined interference threshold at the PU is needed.

Previous work related to channel allocation using opportunistic spectrum access in cognitive mesh networks is reported in [2], [3], and [4]. In [2], the authors propose a greedy heuristic algorithm to maximize the total number of channels by opportunistically allocating unused licensed channels to cognitive base stations. Although a similar problem is considered in [3], the authors introduce a reward function that is proportional to the base stations' coverage areas and take into consideration interference in allocating channels. The main drawback of both works is that the interference model used is based on the overlap between two base stations. This could be problematic in real case scenarios since co-channel interference is not taken into consideration. Finally, in [4] the authors present a Cognitive Radio approach for usage of Virtual Unlicensed Spectrum (CORVUS). This approach is based on allocating spectrum in an opportunistic manner to create "virtual unlicensed bands." In other words, bands are shared with PUs on a non-interfering basis. The paper only provides the system requirements as well as the general architecture and basic physical and link layer functions of CORVUS. No problem formulation or results were presented to support the authors' claim. On the other hand, some work targeted channel allocation and power management, using the interference effect, at the same time [5], [6], and [7]. The authors in [5] proposed an objective function to maximize spectrum utilization while in [6], the authors proposed to minimize the total transmit power at base stations to support the rate requirements of all links. Although these approaches are realistic, they lack the opportunistic spectrum access and the protection of PU from harmful interferences. In [7], the authors formulated the problem of channel allocation and power control as a mixed-linear problem. They did take into account Signal-to-Noise Ratio (SNR) at the Customer Premises Equipment (CPE) level and the interference at the PU. However, user's bandwidth requirements were not taken into consideration which could impose a problem on the power control variable.

In this paper, we consider a cognitive radio network, which may be referred to as secondary users (SUs) mesh network, competing to access a particular licensed spectrum that is occupied by a PU. The spectrum of interest is divided into a set of *variable-bandwidth* non-overlapping channels. Each SU is to be served by one channel. The mesh network is governed by dedicated or shared channels. Since these channels are limited, the cognitive mesh nodes seek other available spectrums for use. Due to the presence of the PU at the licensed spectrum, some constraints need to be applied to the SU's opportunistic access method such that the aggregate interference level at the PU does not exceed a predefined threshold value. Therefore, a power management approach is employed to decrease the transmitted power levels at the SUs that will access the licensed spectrum in such a way that their data communication rate is not affected. In other words, the transmitted power at the SUs can not be dropped indefinitely. It has to be bounded by an upper and lower bounds such that the communications rate on the current traffic link is still supported.

The bandwidth (BW) or spectrum utilization is defined as the total BW provided to the accepted SUs on the licensed spectrum divided by the available PU spectrum BW.

The remaining of the paper is organized as follows: In section II, the problem definition and formulation is presented. In section III, a summary of the heuristic algorithm is provided. Numerical results and performance are discussed in section IV and section V, respectively. Finally, we conclude the paper in section VI and outline some future research objectives.

II. Problem Definition and Formulation

A. *Problem Definition*

We consider the following scenario. A cognitive wireless mesh network consisting of N SU nodes and P Primary User nodes are deployed in the same study area. In this paper, *only* one PU is considered. This scenario is depicted in Figure 1. The PU is defined by its bandwidth BW_{PU} and frequency f_P. The SUs are assumed continuously communicating with each others and each SU is defined by its power transmitted, received signal strength indicator (RSSI), and data rate request. The spectrum of interest is divided into *ch* channels and these channels are licensed to the P Primary Users. Assuming that communication between any two SUs requires only one channel, we define the spectrum utilization as the total BW requests of the SUs served on the licensed spectrum. SUs that will get to operate on the PU licensed spectrum will be offered non-overlapping channels. In other words, each newly assigned channel is orthogonal to the adjacent assigned channels. Knowing the transmitted power at each SU, RSSI, and data rate request, the objective is to maximize the number of SUs served on the PU licensed spectrum such that the data rate request of each SU is met while not exceeding a set interference threshold at the P PUs.

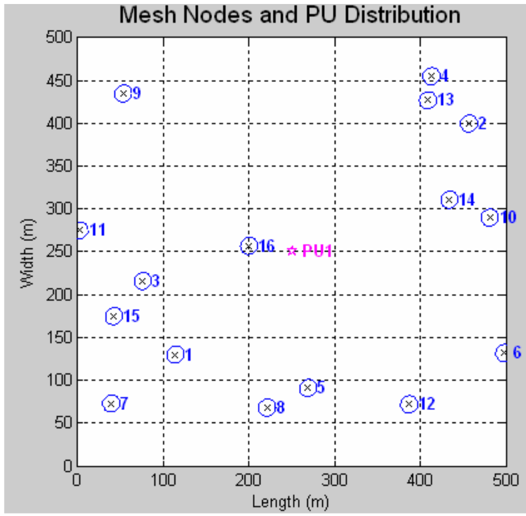

Figure 1. Deployment of cognitive radio network and PU

B. *Requirements*

Certain requirements need to be defined before we proceed further. The propagation model is based on the free space path loss model in [8]:

$$PL = 32.44 + 20Log(f) + 20Log(d) \qquad (1)$$

Where PL is the path loss or power attenuation as the signal propagates between the transmitter and receiver. f is the frequency in MHz and d is the distance between the transmitter and receiver in Km. It is important to note that the transmitter and receiver antennae of all nodes are omni-directional with a gain of 1 dB.

C. *Problem Formulation*

The problem at hand is formulated mathematically as a Non-Linear Integer Program (NLIP). Let c denotes the channel assigned for communication between SU transmitter i and SU receiver r, and u^c_i be a binary variable denoting whether or not a channel c is assigned to the communication between SU transmitter i and SU receiver r.

$$\text{objective} \quad \max_{u_i^c \in \{0,1\}} \sum_{i=1}^{N} u_i^c \qquad (2.1)$$

$$\text{such that} \quad \sum_{c=1}^{ch} u_i^c \le 1 \qquad (2.2)$$

$$\sum_{i=1}^{N} I_{PU_P} u_i^c \le I_{threshold} \qquad (2.3)$$

$$P_{lower} \le P_{SU_i} \le P_{upper} \qquad (2.4)$$

$$I_{PU_P} = P^c_{SU_i} - PL^c \qquad (2.5)$$

$$\sum_{i=1}^{N} BW_i^c \leq BW_P \quad (2.6)$$

$$\forall i \in \{1,2,3,...,N\}$$
$$\forall P \in \{1,2,3,...,M\}$$
$$\forall ch \in \{1,2,3,...,c\}$$

Objective (2.1) maximizes the total number of SUs on the channel used by the PU. Constraint (2.2) states that each SU user must be assigned one and only one channel. u_i^c is 1 if channel *c* is assigned to the SU transmitter-receiver link and 0 otherwise. The constraint stated in (2.3) defines that the sum of interference at the *Pth* PU should not exceed $I_{threshold}$. Constraint (2.4) defines the transmitted power restriction on the SU transmitter *i*. i.e., the transmitted power of the SU *i* has to be in the range between P_{lower} and P_{upper} in order to support the particular data rate requested by the SU receiver *r*. The power transmitted by SU *i* is directly proportional to the RSSI at receiver *r*. Constraint (2.5) shows the calculation of the interference at the *Pth* PU. Finally, constraint (2.6) reveals that the total requested BW of all SUs should not exceed the total available BW of the PU, BW_P.

It is important to note that when executed in real time, each SU *i* is assumed to periodically updates a central server which could be represented at an access point, base station, or computer server. The algorithm runs at the central server and decisions are multicasted to intended SUs in order to instruct them about their respective frequencies or channels (along with the BW allocation on the licensed spectrum), and their transmitted power levels. However, the present scenarios in this paper do not involve user mobility. They are set up with a fixed number of SUs and a PU and an average data rate over the study period. The purpose of the displayed scenarios is to show that the locations of nodes, their BW requests, and level of interference at the PU are what make them a potential candidate in accessing the licensed spectrum.

One can think of our model as representing the scenario in a time slice, for a particular user distribution. It is important to mention that exchanging of control information and signaling between SU nodes is beyond the scope of this paper and the information about the existence of the PU at the particular frequency and time is already known and detection of PU existence by SUs is absolutely accurate. The model can be executed for all time slices sequentially in which information is updated for each time slice.

III. Summary of the Proposed Algorithm

We present a heuristic algorithm that achieves good performance and can be obtained at lower complexity than the optimal algorithm. Intuitively, we try to serve the SUs with the highest data rate requests. This can be justified by assuming that SUs with higher data rate requests have higher priority than others. The steps of the heuristic algorithm can be summarized as follows:

1. Input the positions of *N* randomly SUs and *P* PUs.
2. Generate average data rate requests for all SUs based on a normal distribution of a mean μ and standard deviation σ. Knowing the SNR and data rate of each SU, a BW request can be estimated using Shannon-Hartley theorem in [9]:

$$C = B \log_2(1 + SNR) \quad (3)$$

Where *C* is the channel capacity in bits/second, *B* is bandwidth of the channel in Hz, and *SNR* is the signal to noise ratio of the communication signal as a linear power ratio.

3. Sort SUs in descending order according to their average data rate. It is obvious that we prefer to serve SUs with higher data rate first.
4. Compute RSSI at each SU receiver *r* from its corresponding SU transmitter *i*.
5. Decrement transmitted power of SU transmitter *i*. Does the RSSI level at the SU receiver *r* still support the communication data rate if to be served at the PU licensed spectrum?
    a. Yes: Compute interference at PU from the SU transmitter *i*.
    b. No: move to the next SU and repeat step 4 and 5.
6. Repeats steps 4 and 5 while interference at PU does not exceed the $I_{threshold}$ and BW requests of accepted SU receivers do not exceed the total available BW of the PU.

In theory, let us assume continuity among time slides, in that states transition smoothly from one time slice to another. Also assume that the central unit server is fast enough to obtain current information, the algorithm can ensure efficient operation of a cognitive mesh network.

IV. Numerical Results

The system model used in our numerical studies is as follows. We consider a square service area of size 500m x 500m in which a cognitive mesh network is deployed. The total number of SUs is *N* = 16. The total number of PUs is 1 (*P*=1). All SUs are randomly distributed across the service area with a uniform distribution while the PU is located at the center. The maximum transmit power at each SU and

PU is 20 dBm (100mW). The interference threshold that can be tolerated at the PU is -80 dBm. All SUs are assumed to be operating on the IEEE 802.11 b/g (2.4 GHz spectrum) while the PU is operating on the 700 MHz TV spectrum and occupies a 12 MHz bandwidth. The scenario can be depicted in Fig. 1. Table I shows a summary of the communication links between the different SU transmitters-receivers while Table II shows the lower and upper RSSI values that support different data rates. Each SU could be equipped with dual-radios in order to switch between different spectrums. The switching process between spectrums is considered very smooth and no interruption in service.

Table I. Communication between SU mesh nodes

SU Transmitter Number	SU Receiver Number	SU Transmitter Number	SU Receiver Number
1	16	9	6
2	12	10	14
3	1	11	3
4	8	12	7
5	2	13	11
6	15	14	13
7	10	15	5
8	4	16	9

Table II. Lower and upper RSSI bounds for the given data rates

Lower RSSI (dBm)	Upper RSSI (dBm)	Data Rate (Mbps)
-95	-93	1
-93	-91	2
-91	-89	5.5
-89	-87	11

The entire bandwidth is modeled as an orthogonal frequency division multiple access (OFDMA) system and is divided into 48 subcarriers. Each SU may occupy one or more subcarriers based on its BW request. The channels are picked by the central server that governs the whole mesh network.

In this paper, we provide two different scenarios of mesh nodes and PU distribution to show the effect of the SUs' locations on the decision of the algorithm. In all scenarios, the PU is deployed at the center of the study area and the communications between SU nodes is fixed.

A. *Scenario 1*

In scenario 1, the SU and PU distribution in Figure 1 is employed. After running the NLIP model in equation (2), the following results were obtained. Figure 2 summarizes which SU transmitter-receiver link can access the PU licensed spectrum.

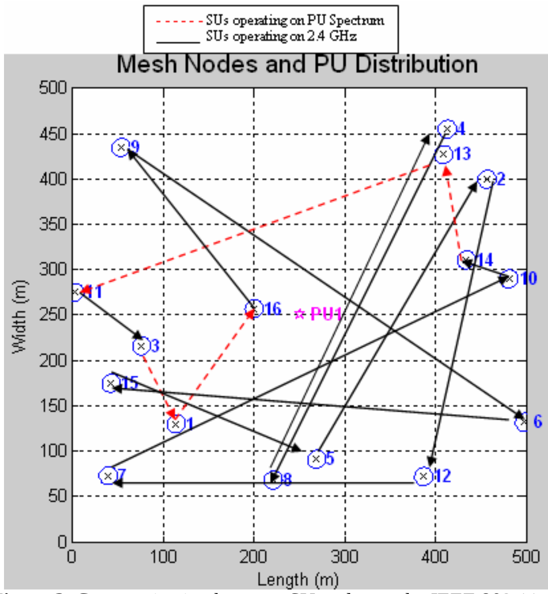

Figure 2. Communication between SU nodes on the IEEE 802.11 and licensed spectrums (scenario 1).

Table III shows which SU transmitters (along with their respective receivers) got the permission to access the PU licensed spectrum, their respective transmitted power, and BW reserved for each link. According to the results, only four SU transmitters were allowed to join the PU licensed spectrum while the interference tolerated at the PU is below -80.57 dBm. In addition, these communications only utilized about %50 of the available PU spectrum. Even though the BW is not fully utilized, however, any additional SU node will result in breaking the interference constraint on the PU node. Therefore, that is the highest possible BW achieved under the following constraints.

Table III. Summary of results (scenario 1)

SU Transmitter/Receiver Number	SU Transmitter Power (dBm)	SU Bandwidth Request (MHz)
3 / 1	8	2
14 / 13	2	1.9
13 / 11	11	1.8
1 / 16	6	0.4

B. Scenario 2

In this scenario, the SUs distribution is changed around while keeping the PU in the center. Also, communication between nodes is still fixed. This gives us a different insight on how the SU distribution affect the algorithm's decision on which SU communications should be moved to the PU licensed spectrum. Figure 3 displays which SU transmitter-receiver link pair were allowed to access the PU spectrum.

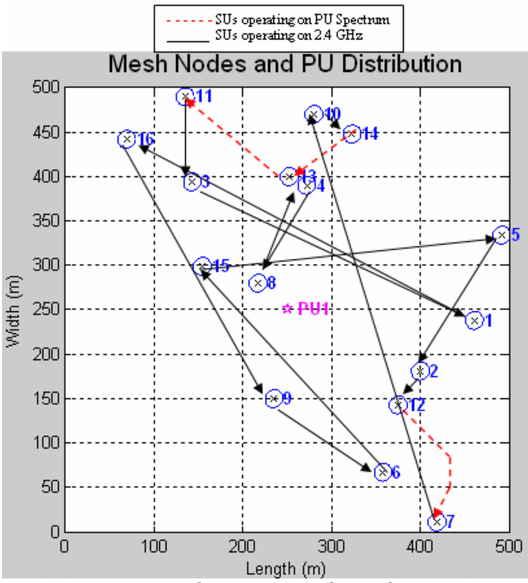

Figure 3. Communication between SU nodes on the IEEE 802.11 and licensed spectrums (scenario 2).

Table IV summarizes which SU transmitters got the permission to access the PU licensed spectrum, their respective transmitted power, and BW reserved for them.

Table IV. Summary of results (scenario 2)

SU Transmitter/Receiver Number	SU Transmitter Power (dBm)	SU Bandwidth Request (MHz)
12 / 7	3	4.80
14 / 13	3	4.10
13 / 11	7	3.00

However, it is important to note that in this particular scenario the PU can still tolerate additional interference from SUs since the interference level at the PU is -82.36 but it is the PU spectrum constraint that limits adding any additional SU since BW utilization achieved in this scenario is %99.17. Therefore, any additional SU can not be accepted at this time.

Finally, the results show that the algorithm can work and adapt under different user distribution scenarios. The reason behind placing the PU in the center is not to show any biased correlation between the SUs uniform distribution and the PU location. Therefore, in a real-time scenario, the central server will be collecting control information periodically from the mesh nodes and updating them periodically in the upcoming frames about their action (s), that is, assuming a perfect and accurate decision has been made concerning the PU presence (or detection) on the licensed spectrum and pre-existing knowledge about the BW it occupies.

V. Performance Evaluation

In Figure 4, we plot the number of SUs served versus the number of PUs when three algorithms are employed. First, the proposed power management algorithm, then the no power management algorithm, and, finally, the random algorithm. The no power management algorithm is based on selecting the same SU served by our proposed algorithm but transmitted power stays the same on all SUs, i.e. 20 dBm. As for the random algorithm, the algorithm picks random SUs to serve. The results show the average values of more than 200 simulations in order to obtain the average performance of each algorithm. Figure 5 shows the BW utilization of each algorithm.

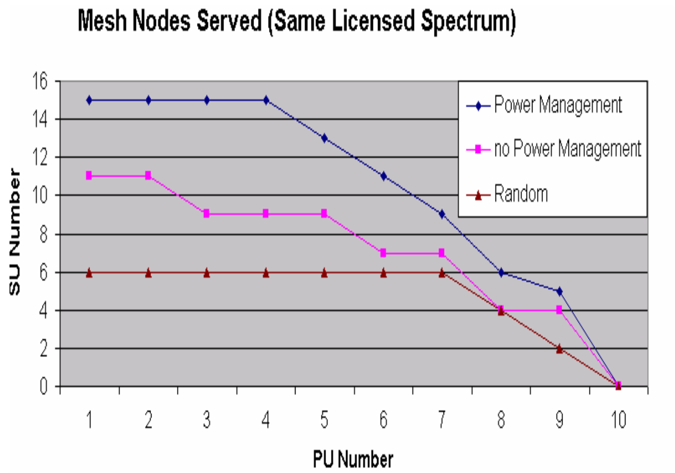

Figure 4. Performance evaluation of the proposed algorithm.

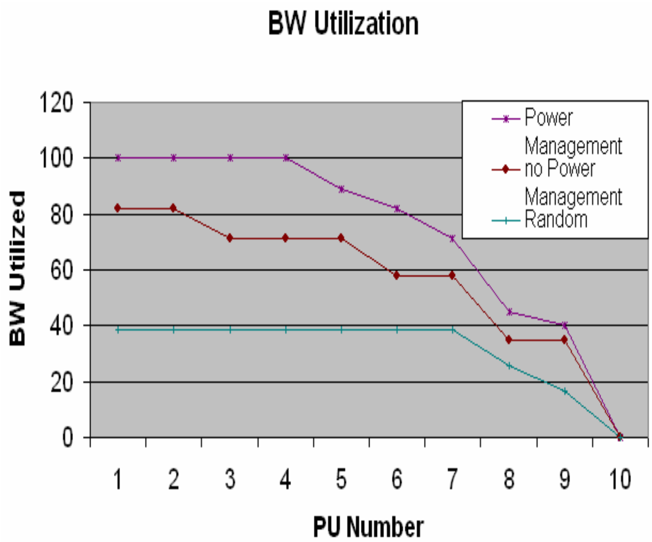

Figure 5. BW utilization performance of the algorithm.

It is important to mention that for all algorithms and scenarios tested, the number of SUs, as well as, BW utilization decrease as the number of PUs increase. This is expected since as more PUs occupy the same spectrum, less spectrum is available for opportunistic access by SUs.

Results show that the proposed power management and BW utilization algorithm outperforms other algorithms. In all simulations, the random scheme performed the worst. The performance gain of our proposed algorithm with respect to the second best was able to provide about 15% increase in the number of SUs served and 20% increase in BW utilization.

VI. Conclusion

In this paper, a power management and spectrum utilization algorithm has been presented in order to allow secondary users in a cognitive mesh network in the vicinity of a PU, which is operating on a licensed spectrum, to opportunistically access the licensed spectrum while not causing harmful interference at the PU. It has been shown that the interference levels, as well as, the bandwidth requests of secondary users govern which SU nodes should opportunistically access the licensed spectrum. When compared to other algorithms, the proposed algorithm outperformed other common algorithms.

Future work is undergoing to introduce signaling between mesh nodes in a cooperative distributed environment in order to see how signaling could affect the delay and throughput of the network. Moreover, switching time between the dual radios could be another topic of interest to be investigated further.

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