A Spectrum Decision Framework for Scheduling and Primary User Emulation Attack in Cognitive Radio Network

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Abstract: ***A scheduling problem that includes different hardware delays experienced by the secondary users (SUs) while switching to different frequency bands in a centralized cognitive radio network (CRN) is formulated. A polynomial-time suboptimal algorithm is proposed to reduce the scheduling problem. The impact of varying switching delay, number offer quencies, and number of SUs is evaluated. The simulation results signify that our proposed algorithm is robust to changes in the hardware spectrum switching delay.***

Keywords: Network, GSM, X band, simulation, spectrum, Cognitive radio Network

1. Introduction

When a cognitive radio (CR) device changes its operation frequency, it experiences a hardware switching delay to tune to its new frequency before it can fully utilize it. This delay in general depends on the wideness between the two frequency bands. For occurrence, the delay incurred while switching from the central frequency belonging to one GSM operator to the frequency of another GSM operator might be small; however, switching from a GSM band to X-band takes longer time. When the range of frequencies that the cognitive radio network (CRN) operates in is narrow, this delay difference might be negligible. Therefore, spectrum allocation and scheduling algorithms designed for CRNs have to take into account different delays that occur while switching to different frequency bands. Some works in the literature use the term channel switching latency to refer to the delay encountered while searching for an idle channel, whereas some other works use the term to refer to the hardware switching delay of the frequency synthesizer given that the CR device has already determined the idle channel to switch to. The primary goal in most of these works is to minimize the number of channel switching along the route; hence, they do not differentiate between switching to different frequencies and assume that all of the channel switching cause a certain delay irrespective of the frequency separation distance. This is thet study on scheduling in CRNs that takes into account the hardware switching delay depending on the separation distance between the current and subsequent frequency bands.

2. Problem Formulation

A scheduling problem that makes frequency, time slot, and data rate allocation to the SUs in a CRN cell by maximizing the total average throughput of all SUs in the CRN cell is formulated, while at the same time ensuring that reliable communication of the SUs with the centralized CBS is maintained, no collisions occur among the SUs, and the PUs are not disturbed. The centralized time-slotted CRN cell that the scheduling framework in focuses on is illustrated in Fig. 1.

The work in considers the case where SUs possibly have multiple interfaces for data transmission. The first step of the solution consists of determining the values for Uif, which stands for the maximum number of packets that can be sent by SU i using frequency f in any time slot during the entire scheduling period consisting of T time slots. These values are determined such that the transmission power of the SUs does not violate the maximum tolerable interference power limits of the PUs, and reliable communication of the SUs with the CBS is maintained. The simulation results indicate that high throughput performance are achieved even when number or CR users is as small as 10. Assume that the network conditions, i.e., the PU and SU Assume that the network conditions, i.e., the PU and SU locations, the PU spectrum occupancies, and all the channel fading coefficients, are small enough not to have any impact on the Uif values for a duration of T time slots in the considered centralized CRN cell.

The value of T, in general, depends on the characteristics of the spectrum environment. For instance, a slowly varying spectrum environment like the TV broadcast bands utilized by an IEEE 802.22 network allows T to have spectrum environment. For instance, a slowly varying spectrum environment like the TV broadcast bands utilized by an IEEE 802.22 network allows T to have a fairly large value. Given the Uif values determined in the first stage, the work in reference paper solves in the second stage the following binary integer linear program (ILP) to maximize the total throughput using certain formulas.

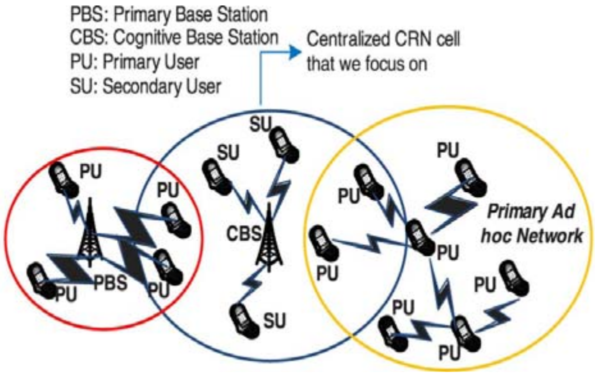

Figure 1: The centralized CRN architecture

$$\max\left(\sum_{i=1}^{N}\sum_{f=1}^{F}\sum_{t=1}^{T}\frac{U_{if}X_{ift}}{T}\right), \quad (1)$$

$s.t.$

$$\sum_{f=1}^{F}\sum_{t=1}^{T}X_{ift} \geq 1;\ \forall i \in \mathcal{N}, \quad (2)$$

$$\sum_{i=1}^{N}X_{ift} \leq 1;\ \forall f \in \mathcal{F}, \forall t \in \mathcal{T}, \quad (3)$$

$$\sum_{f=1}^{F}X_{ift} \leq a_i;\ \forall i \in \mathcal{N}, \forall t \in \mathcal{T}, \quad (4)$$

where N denotes the set of a total number of N SUs in the CRN cell, F denotes the set of a total number of F frequencies in the CRN cell, and T denotes the set of a total number of T time slots in a scheduling period. In addition, Xift is a binary decision variable such that Xif t ¼ 1 if SU i transmits with frequency f in time slot t and 0 otherwise, and ai is the number of interfaces of SU i. In this formulation, (2) guarantees that at least one time slot is assigned to every SU, and hence providing a temporal notion of fairness. Without this temporal fairness constraint in the problem formulation, some SUs with bad channel conditions may end up with being unable to send any packets for a long time. Some transport layer protocols such as TCP close the connection if no packets are received for a certain amount of time. Constraint (2) gives each SU the opportunity to send at least something and therefore avoids this undesired disconnection situation caused by transport layer protocols. Besides, (3) ensures that at most one SU can transmit in a particular time slot and frequency, and hence obviating collisions between the SUs. Moreover,(4) represents the fact that an SU i cannot transmit at the same time using frequencies more than the number of its transceivers (interfaces), ai, because each transceiver can tune to at most one frequency at a time. The goal of this assumption is to evaluate the impact of the number of interfaces more effectively. In this paper, we follow the same assumption. However, in reality, some portion of the subsequent time slot is inevitably wasted to tune to the new frequency; therefore, only the remaining portion of the next time slot can be used for actual data transmission. It may even be the case that the time it takes to switch to the new frequency is greater than or equal to the time slot length, which means that no packets can actually be sent using the new frequency. Since the scheduling decisions are known in advance by SUs, they should not waste time and energy in vain to switch to the new frequency; they should instead stay in the same frequency. On the other hand, the new frequency band might be more advantageous in terms of throughput by having a higher Uif value. The question is whether the delay incurred while switching to the new frequency band offsets this throughput advantage or not. If the throughput advantage of the new frequency band outweighs the disadvantage of throughput losses due to switching delay, then the SU may still prefer switching to the new frequency. Therefore, there is a tradeoff here; i.e., switching track of the information about which interface is assigned to which frequency since each interface experiences different switching delays depending on the frequency that it was assigned to in the previous time slot. In this paper, we extend the work in account for the spectrum switching delay, which depends on the distance between the used frequencies. This assumption enables us to effectively evaluate the performance of the scheduling algorithms by avoiding the possible influence of the traffic arrival process In practice, channel gains can be estimated by the SUs for instance by employing sensors near all receiving points and can be made available at the central controller, which is the CBS. Let us denote by Ciat the frequency that interface a of SUi is assigned to in time slot t. Note that the interfaces do not have to be assigned some frequency in every time slot; in other words, it is possible for an interface not to be assigned any frequency in some time slot. If interface of SU i has not been assigned some frequency for time slot t, then we say that t is a silent time slot for the interface a of SU i. Otherwise, we say that t is a busy time slot for the interface a of SU i. A time slot t may be a silent time slot for some interface but a busy time slot for another interface. Let us denote by miat the index of the busy time slot before time slot t. If t is the first busy time slot in the scheduling period, then miat ¼ 0. In other words,

$$miat = max\{j, 0\}$$

Then the number of silent time slots between the current time slot t and the previous busy time slot for interface a of SU i equals t − miat − 1. If miat = ¼ 0, i.e., if t is the first busy time slot for interface a of SU i in the scheduling period. In other words the interfaces are pretuned to the first used frequency is assumed. In practice, this delay in the first used time slot may depend on various other factors such as MAC protocol. If a single interface is used for both data transmission and control traffic, the interface may have to tune to the frequency band of the common control channel (CCC) during the time between consecutive scheduling periods. How frequently the tuning to the CCC is performed and which frequency the CCC uses depends on the protocol implementation. To isolate us from the possible influence of these factors, The interfaces are pretuned to the first used frequency. On the other hand, if a frequency f is not the first used frequency for interface a of SU i and there are silent time slots preceding time slot t, i.e., 0 < miat < t − 1, then interface a uses these silent time slots to switch to the new frequency f. Scheduling decisions are made by the CBS for the duration of a scheduling period, which consists of T time slots. Scheduling decisions for all T number of time slots are made by the scheduling algorithm but it is not the case that the scheduling algorithm is executed in each time slot. The decisions for all time slots of that particular scheduling period are made once and this is before the actual scheduling period for data transmission of that scheduling period starts. In other words, ours is a "frame based" scheduling discipline rather than a "slot-based" scheduling discipline. These scheduling decisions (Xiaft values) are then sent by the CBS to the SUs through the CCC. Therefore, SUs know the scheduling decisions (which frequencies are assigned to them in which time slots) before the beginning of the first time slot of the scheduling period. Because the scheduling decisions are known by SUs in advance, they can use these silent time slots to switch to the new frequency. If the numbers of silent time slots are enough to achieve the entire frequency switching, SU becomes ready to use the new frequency in the upcoming busy time slot.

$$\max\left(\sum_{i=1}^{N}\sum_{a=1}^{a_i}\sum_{f=1}^{F}\sum_{t=1}^{T}\frac{B_{iaft}X_{iaft}}{T}\right), \tag{5}$$

$$s.t.$$

$$\sum_{a=1}^{a_i}\sum_{f=1}^{F}\sum_{t=1}^{T}X_{iaft} \geq 1;\ \forall i \in \mathcal{N}, \tag{6}$$

$$\sum_{i=1}^{N}\sum_{a=1}^{a_i}X_{iaft} \leq 1; \forall f \in \mathcal{F}, \forall t \in \mathcal{T}, \tag{7}$$

$$\sum_{f=1}^{F}X_{iaft} \leq 1; \forall a \in \mathcal{A}_i, \forall i \in \mathcal{N}, \forall t \in \mathcal{T}, \tag{8}$$

$$C_{iat} = \sum_{f=1}^{F} f\ X_{iaft}; \forall i \in \mathcal{N}, \forall a \in \mathcal{A}_i, \forall t \in \mathcal{T}, \tag{9}$$

$$m_{iat} = \max_{\substack{\exists f s.t. X_{iafj}=1 \\ j<t}}\{j, 0\}, \tag{10}$$

$$\Delta_{iaft} = \begin{cases} 0, & \text{if } m_{iat} = 0 \\ \left(|f - C_{iam_{iat}}| - \frac{(t-m_{iat}-1)T_s}{\beta}\right)^+, & \text{o.w.,} \end{cases} \tag{11}$$

$$B_{iaft} = \left\lfloor \left(1 - \frac{\beta \times \Delta_{iaft}}{T_s}\right)^+ V_{if} \right\rfloor, \tag{12}$$

In this case, SU does not waste any portion of the busy time slot for frequency switching and hence it can use the entire busy time slot for data transmission. Otherwise, SU utilizes the silent time slots to achieve some portion of the frequency switching. The remaining switching is completed at the beginning of the next busy time slot. If the silent time slots and portions of the busy time slot are still not enough to achieve the frequency switching and no available time means that no packets can be sent by the SU using the new frequency in the busy time slot. Where N, Ai, ai, F, and T are as defined previously. The objective function in (5) maximizes the total average throughput of all the SUs in the CRN cell, whereas constraint (6) guarantees that each SU is assigned at least one time slot. Moreover, (7) represents the constraint that at most one interface can use a frequency in a specific time slot, and (8) denotes that each interface can tune to at most one frequency in a time slot. In other words, purposes of the constraints (6), (7), and (8) are the same as purposes of the constraints (2), (3), and (4), respectively. The focus of this paper is on spectrum switching delay rather than providing temporal fairness. The reason for having the temporal fairness constraint in (6) is to ensure comparability of the results with the problem formulation outlined in (1)-(4) from our previous work in [13]. In other words, the reason for having the same constraints in (6), (7), and (8) is because our goal is to evaluate the impact of the spectrum switching delay awareness more effectively by comparing our spectrum switching delay-aware scheduler with the scheduler in [13, (1)-(4)]. To be able to make an effective comparison, all other features of both schedulers except switching delay awareness have to be the same. Therefore, we have constraints (6), (7), and (8). Furthermore, the constraints (9), (10), (11), and (12) are as explained previously. Note here that because Biaft values depend on the frequency assignments in the previous time slots, the objective function in (5) is nonlinear.

3. Proposed Algorithm

In this section, A polynomial time heuristic algorithm to address the problem in the remainder of this paper is proposed. The proposed algorithm is referred by S^2 DASA. The main step of S^2DASA in Algorithm is outlined. The set ∓ = N symbolizes the set of SUs which have not yet been assigned any time slot during the execution of the algorithm. B'_{iaf} represents the benefit (in terms of the maximum number of packets that can be transmitted) that interface a of SU i receives for using frequency f in that particular time slot. In Step 1, S2DASA initializes the set 0 to N since none of the SUs have been assigned a time slot at the beginning of the algorithm. Moreover, Step 1 initializes the benefit values B'_{iaf} for the first time slot to |Vif| since no switching delay occurs in the first time slot. S^2DASA makes the frequency assignment sequentially for each time slot. At the beginning of each time slot, the algorithm chooses the set Ψ , which is the set of SUs that have to be assigned at least one frequency in that particular time slot. B'_{iaf} indicates the maximum number of packets that can be sent by interface a of SU i if it is tuned to frequency f in that particular time slot. To determine the set Ψ, we introduce a metric called Γ i to select the SUs with relatively good B'_{iaf} values averaged over all of their interfaces. Step 3 of S^2DASA assigns the Γi value by determining the average benefit value per interface for each SU in the set ∓ In each time slot, the set Ψ€∓ with relatively high Γi values is selected, and every SU in this set Ψ is guaranteed to be assigned with a frequency in that time slot. Steps 4 and 5 of S2DASA assign all the SUs in the set Ø to the set Ψ if the number of SUs in the set Ø is less than or equal to[N/t] Otherwise, in Step 7,[N/T] number of SUs that have the largest Γi values are selected and added to the set Ψ.

where X'iaf is a binary

$$\max\left(\sum_{i=1}^{N}\sum_{a=1}^{a_i}\sum_{f=1}^{F} B'_{iaf} X'_{iaf}\right), \tag{13}$$

$$s.t. \quad \sum_{a=1}^{a_i}\sum_{f=1}^{F} X'_{iaf} \geq 1; \forall i \in \Psi, \tag{14}$$

$$\sum_{i=1}^{N}\sum_{a=1}^{a_i} X'_{iaf} \leq 1; \forall f \in \mathcal{F}, \tag{15}$$

$$\sum_{f=1}^{F} X'_{iaf} \leq 1; \forall a \in \mathcal{A}_i, \forall i \in \mathcal{N}, \tag{16}$$

y decision variable that equals 1 if interface a of SU i transmits using frequency f, and 0 otherwise. At the end of the decision for every time slot, B'iaf values are calculated and updated (in Steps 15-17) for the subsequent time slot. Notice here that B'iaf values are input variables rather than decision variables in the optimization problem in . Constraint ensures that the SUs in the set Ψ € ∅ are assigned at least one frequency, which meets the constraint in for the SUs in Ψ. As in and, constraints and ensure that at most one interface can use a frequency, and each interface can tune to at most one frequency.

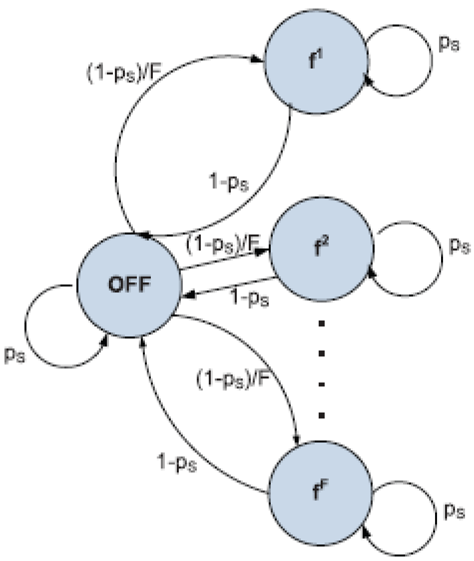

Figure 2: PU spectrum occupancy model

4. Simulation Results

As in simulation result is a centralized CRN cell with600 meters of radius, PIFmax =10 milliwatts, T =10 slots, and Ts = 100 ms. Besides, additive white Gaussian noise (AWGN) channels are assumed. The dynamicity of the spectral environment stems from two factors: Physical mobility of the SUs and PUs and the changing spectrum occupancy behavior of the PUs. Uif values for each scheduling period are possibly different due to the changes in the physical mobility and PU spectrum occupancies. If an SU becomes closer to another PU due to physicalmobility, it may need to change its operation frequency in order not to disturb the PU. Likewise, if a PU in the vicinity of the SU starts using a frequency that SU was using, the SU needs to switch to another band. Both the PUs and the SUs move within the CRN cell according to the random waypoint mobility model with constant velocities of Vp and Vs, respectively, and a staying duration of 10 s between the movement periods. Spectrum usage behavior of the PUs is also as in reference. Where a finite state model is used. Fig. 2 illustrates the finite state model used to simulate the PU spectrum occupancy behavior. Each PU is either in the ON state or OFF state. The ON state encompasses one of the F substates, each corresponding to being active using a frequency among a total of F frequencies. The superior throughput performance of S2DASA calls for techniques that quantify its worst case performance analytically. As a future work, we plan to derive an analytical lower bound for the throughput performance of our proposed algorithm S2DASA. To this end, we plan to utilize algorithmic graph theory and approximation algorithms. The probability of staying in the ON or OFF states is pS. At the end of each scheduling period, each PU either stays in the same state with probability pS or changes its state with probability 1- pS. While switching from the OFF state to the ON state, the probability of selecting each frequency is equally likely; therefore, probability of transition from OFF state to any frequency F. In a slowly varying spectral environment, pS value is usually high; hence, we selected the pS value as 0.9 in our simulations. Hence, our simulation results demonstrate that switching delay is an important factor even in a slowly varying spectral environment.

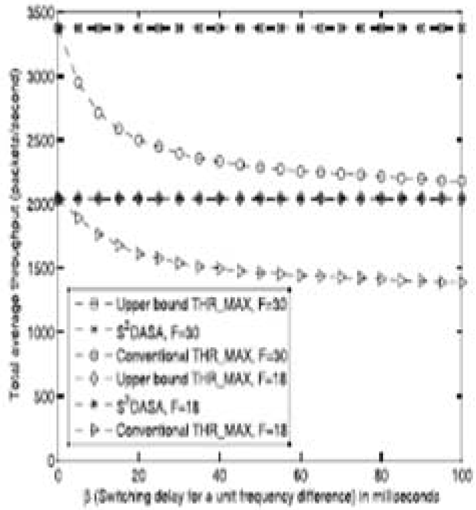

Fig. 3. Average total throughput of all schedulers for varying β.

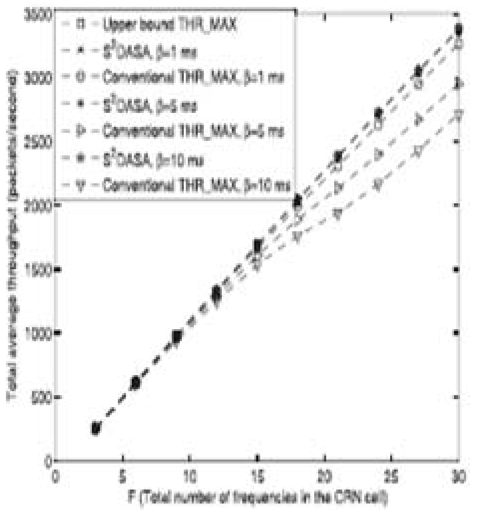

Fig. 4. Average total throughput of all schedulers for varying number of frequencies (F).

5. Conclusion

A scheduling problem that considers different hardware delays that occur during switching to different frequency bands is formulated in this paper. A polynomial time heuristic algorithm called S2DASA to solve our formulated problem is formulated. The simulation results show that the throughput that S2DASA yields is very close to its upper bound. Moreover, S2DASA is robust to changes in the hardware spectrum switching delay. Furthermore, throughput savings it achieves increase as the number of frequencies in the CRN cell (F) and the hardware switching delay for a unit frequency difference (β) increases. Furthermore, the throughput savings of our algorithm are significant even when there are a small number of SUs, an the savings remain significant as the number of SUs increases. Simulation results demonstrate that our idea of taking into account different hardware delays that occur during switching to different frequency bands is essential for CRNs since the assumption of constant switching delay can lead to low throughput performance. The superior throughput performance of S2DASA calls for techniques that quantify its worst case performance analytically. As a future work, we plan to derive an analytical lower bound for the throughput performance of our proposed algorithm S2DASA.

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