Channel Switching Cost-Aware Resource Allocation for Multi-hop Cognitive Radio Networks with a Single Transceiver

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Abstract. Cognitive radio networks need to operate in a wide range of frequencies. This requirement brings up new challenges that do not exist in other wireless networks. Switching from a certain frequency to another frequency incurs a non-negligible cost in cognitive radio networks and depends on the distance between the previous and current frequencies. This cost is especially important in ad hoc cognitive radio networks when the cognitive devices have a single transceiver. Research studies related to green networks indicate the need for methods that address energy consumption in cognitive radio networks. In this paper, we analyze the impact of the channel switching cost in terms of energy consumption. We formulate an optimization problem that makes frequency and time slot allocation to the cognitive devices in an ad hoc cognitive radio network so that the energy cost related to frequency switching is minimized. We formulate our optimization problem as an integer linear program and comparatively evaluate the energy cost of varying switching energy consumption with constant switching energy consumption. Our simulation results indicate that taking into account the different energy consumption while switching to different frequency bands is vital for resource allocation in cognitive radio networks with a single transceiver.

Keywords: Cognitive radio · Ad-hoc networks · Energy efficiency · Channel switching · Frequency switching · Resource allocation

1 Introduction

Fixed spectrum assignment policy in current wireless networks leads to inefficiency in spectrum usage. To this end, researchers have proposed dynamic spectrum access concept, which refers to opportunistic usage of frequencies by intelligent devices called cognitive radios (CR) or secondary users (SU). Users who have exclusive rights to use the spectrum are called primary users (PU). SUs need to operate in such a way that the operation of PUs is not affected.

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Availability of a particular frequency to a particular SU depends on the spectrum usage behaviors of the PUs in the vicinity of the SUs [1].

An SU consumes energy to change its operation frequency. This energy consumption in general depends on the distance between the previous and current frequency bands [2]. For instance, switching from central frequency of 700 MHz to 10 GHz leads to larger energy consumption than switching from 700 MHz to 750 MHz. This behavior is directly related to the different channel switching delay while switching to different frequency bands [3] since spending more time for switching naturally consumes more energy. This energy consumption might be negligible in wireless technologies that operate in a narrow band; however, cognitive radios are expected to operate in a wide range of spectrum and hence the energy consumption due to channel switching is crucial for cognitive radio networks [2]. The emerging green networking paradigm that focuses on energy efficiency of both wired and wireless technologies puts emphasis on techniques that enhance the energy efficiency of new technologies such as cognitive radio networks [4].

Studies in the literature analyzed the impact of channel switching in CRNs mostly in terms of delay [5–10]. Most of these works focus primarily on minimizing the number of channel switchings along the routing path; in other words, they assume constant switching delay whenever channel switching occurs irrespective of from which frequency and to which frequency the channel switching has taken place. Only [5] and [6] consider the dependence of channel switching delay on the distance between the previous and current frequencies. The work in [3], on the other hand, focuses on scheduling in centralized cognitive radio networks and analyzes the impact of channel switching delay on throughput. The authors propose a scheduling algorithm that considers the different hardware delay that occurs while switching to different frequency bands. The work in [11] focuses on minimizing the service interruption by taking into account the dependence of switching delay on the frequency distance. To the best of our knowledge, the work in [2] is the only work in the literature that considers the impact of frequency distance-aware channel switching on energy efficiency in cognitive radio networks. However, unlike our work, the work in [2] concentrates on scheduling in centralized cognitive radio networks.

Most works about routing in cognitive radio networks consider the case where the CR devices have multiple transceivers/interfaces [11–15]. However, having multiple transceivers is costly and therefore, scenarios where CRs have a single transceiver are more realistic. There are some works in the literature that focuses on the case with single transceivers [16–18]. In a multi-hop CRN, channel switching cost becomes especially important when each CR has a single transceiver. However, unlike our work, none of the works in [16–18] focus on the energy cost related to the channel switching of the single transceiver.

The rest of this paper is organized as follows: In Section 2, we provide our optimization problem formulation as an integer linear program. In Section 3, we present our numerical evaluation and then conclude the paper in Section 4.

2 Problem Formulation

We represent the ad hoc CRN as a graph $G = (V, E)$, where the vertices in V correspond to the SUs and the edges in E corresponds to the communication links between the SUs. We consider the situation where the routing is predetermined; in other words, if a link exists between a pair of SUs, it means that link is used to carry data along some route. The scheduling period consists of T time slots. There are a total number of F frequencies. A subset of these F frequencies is available for each SU in each time slot. Availability of the frequencies is determined by the PU spectrum occupancy behavior in the geographical region of the ad hoc CRN. The goal of our integer linear programming (ILP) formulation is to assign a time slot and frequency to each SU so that the total energy consumption of the SUs due to frequency switching is minimized.

Table 1 and 2 present the decision and input variables, respectively, of our ILP formulation. If $x_{vft} = 1$, it means the single transceiver of the SU corresponding to vertex v is tuned to use frequency f in one of its incident links (an incident link e with $x_{eft} = 1$) in time slot t. Besides, $y_{vff't}$ is the main decision variable used in the calculation of the objective function. If at the beginning of time slot t, vertex v switches to frequency f from frequency f', then $y_{vff't} = 1$. y_{vft} is another decision variable needed to model the behavior of $y_{vff't}$ by taking into account the silent (idle) time slots (will be explained in the sequel).

Table 1. Table for decision variables

Varible	Description
x_{vt}	$= \begin{cases} 1, & \text{if vertex } v \text{ is assigned some frequency in time slot } t \\ 0, & \text{otherwise.} \end{cases}$
x_{eft}	$= \begin{cases} 1, & \text{if edge } e \text{ is assigned frequency } f \text{ in time slot } t \\ 0, & \text{otherwise.} \end{cases}$
x_{vft}	$= \begin{cases} 1, & \text{if vertex } v \text{ is assigned frequency } f \text{ in timeslot } t \\ 0, & \text{otherwise.} \end{cases}$
y_{vft}	$= \begin{cases} 1, & \text{if } x_{vft} = 1 \text{ or } x_{vf(t-1)} = 1 \\ 0, & \text{otherwise.} \end{cases}$
$y_{vff't}$	$= \begin{cases} 1, & \text{if } y_{vft} = 1 \text{ and } y_{vf'(t-1)} = 1 \\ 0, & \text{otherwise.} \end{cases}$

Table 2 shows input variables that are given to the ILP formulation. The value of switching cost $c_{ff'}$ denotes the energy consumption that occurs while switching from/to frequency f to/from f' and depends on the hardware of the cognitive nodes. Switching cost to/from the same frequency equals zero, whereas the switching cost between different frequencies has a nonzero and symmetric cost. Besides, the values of a_{vft} are determined by the spectrum usage behavior of the PUs.

Table 2. Table for input variables

Input Variable	Description
$c_{ff'}$	= Switching cost (in terms of energy consumption) to transition from/to frequency f to/from frequency f'
a_{vft}	$= \begin{cases} 1, & \text{if frequency } f \text{ is available for vertex } v \text{ in time slot } t \\ 0, & \text{otherwise.} \end{cases}$
G = (V,E)	= Network represented as a graph with vertex set V and edge set E
T	= Total number of time slots
F	= Total number of frequencies

Objective function of our ILP formulation is as follows:

$$\min \sum_{v=1}^{|V|} \sum_{f=0}^{F} \sum_{f'=0}^{F} \sum_{t=0}^{T} c_{ff'} \times y_{vff't} \tag{1}$$

The objective function in Equation (1) minimizes the switching cost of all vertices (nodes) in the graph (network). The decision variable $y_{vff't}$ indicates whether there has been a frequency switching at vertex v from f' to f at the beginning of time slot t; i.e., basically, $y_{vff't} = y_{vft} \times y_{vf'(t-1)}$. This relation will be modeled by the constraints and explained later.

Recall that routing is predetermined in our scenario. In other words, every edge $e \in E$ carries data and should therefore be assigned at least one time slot during the scheduling period. The following constraint achieves this behavior:

$$\sum_{f=1}^{F} \sum_{t=1}^{T} x_{eft} \geq 1; \forall e \in E \tag{2}$$

Since only available frequencies can be assigned to a particular vertex, we need the following constraint:

$$x_{vft} \leq a_{vft}; \forall v, f, t \tag{3}$$

Since each node (vertex) has a single transceiver, at most one incident edge can be given service in each time slot. Therefore, we need to ensure that $x_{vft} = \sum_{e \in E(v)}^{|E|} x_{eft}$. Furthermore, since the values of the decision variables $y_{vff't}$ depend on the frequency assignments in the previous time slot, in order to properly handle the situation in the first time slot, we define an auxiliary frequency $f = 0$ and an auxiliary time slot $t = 0$. The auxiliary frequency $f = 0$ is not assigned to any vertex for time slots $t \geq 1$. Besides, all vertices are assigned frequency $f = 0$ in time slot $t = 0$ (will be enforced in constraints (4) and (5)). The inputs $c_{ff'}$ are given such that the switching cost from frequency 0 to all other frequencies equals zero. This behavior is necessary in order to linearize our integer programming formulation and handle the border case in the first time slot. In other words, frequency $f = 0$ and time slot $t = 0$ are defined to handle the value of $y_{vff't}$ in the first time slot $t = 1$. All vertices are assigned frequency $f = 0$ in time slot $t = 0$. Switching cost between frequency $f = 0$ and any other frequency is zero. Frequency $f = 0$ cannot be used in other time slots $t \neq 0$. Hence, we need the following constraints:

$$x_{vft} = 1 \ ; \ \text{ for } f = t = 0 \text{ and } \forall v \tag{4}$$

$$y_{vft} = 1 \ ; \ \text{ for } f = t = 0 \text{ and } \forall v \tag{5}$$

$$x_{vft} = \sum_{e \in E(v)}^{|E|} x_{eft} = 0 \ ; \ \text{ for } f = 0 \tag{6}$$

$$x_{vft} = \sum_{e \in E(v)}^{|E|} x_{eft} \geq 1 \ ; \ \forall f \geq 1 \tag{7}$$

The following constraints ensure the multiplication of the decision variables such that $y_{vff't} = y_{vft} \times y_{vf'(t-1)}$. This way, if there is a switching between frequencies f' and f at vertex v, the variable $y_{vff't}$ is set to 1.

$$y_{vff't} \leq y_{vft}; \quad \forall v, f, t \geq 1 \tag{8}$$

$$y_{vff't} \leq y_{vf'(t-1)}; \forall v, f, f', t \geq 1 \tag{9}$$

$$y_{vft} + y_{vf'(t-1)} - 1 \leq y_{vff't}; \forall v, f, f', t \geq 1 \tag{10}$$

Notice that it is not a requirement that each vertex is assigned some frequency in every time slot; some vertices may not be assigned a frequency in some time slots. We refer to such a time slot as a *silent time slot* for that vertex. We assume that the transceiver of the node is tuned to the last used frequency in that time slot. When some other frequency is used in a tim eslot following the silent time slot(s), an energy consumption cost corresponding to frequency switching occurs. We need to make sure that the decision variable $y_{vff't}$ handles the silent time slots properly. To this end, we need to ensure the following set of nonlinear inequalities: a) If $x_{vft} = 0$, then $y_{vft} = y_{vf(t-1)}$ and b) If $x_{vft} = 1$, then $y_{vft} = 1$. These nonlinear constraints can be linearized as follows:

$$y_{vft} - y_{vf(t-1)} \leq x_{vft}; \ \forall v, f, t \geq 1 \tag{11}$$

$$y_{vf(t-1)} - y_{vft} \leq x_{vft}; \ \forall v, f, t \geq 1 \tag{12}$$

$$x_{vft} \leq y_{vft}; \ \forall v, f, t \geq 1 \tag{13}$$

Since each node has a single transceiver and a transceiver can tune to at most one frequency at a time, we need to ensure that at most one frequency is assigned to each vertex in each time slot:

$$\sum_{f=1}^{F} x_{vft} \leq 1; \ \forall v, t \tag{14}$$

We also need to model the relationship between the decision variables x_{vt} and x_{vft}. In particular, $x_{vt} = 1$ if and only if some frequency f is assigned to vertex v in timeslot t. We model this relation as follows:

$$\sum_{f=1}^{F} x_{vft} = x_{vt};\ \forall v, t \tag{15}$$

In order to increase the utilization in the network and achieve more throughput, less queueing delay and more realistic network behavior, we need to avoid the situation that two adjacent vertices are idle. To this end, we ensure in the following that at least one of two neighboring nodes is assigned some frequency in each time slot:

$$x_{vt} + x_{v't} \geq 1;\ \forall v, t, \forall v' \in N(v) \tag{16}$$

where $N(v)$ denotes the neighborhood of vertex v, i.e., the set of vertices that are adjacent to vertex v.

3 Simulation Results

In this section, we present our simulation results and comparatively evaluate our ILP formulation solutions with different input parameter settings. We have implemented our ILP formulation introduced in Section 2 by using CPLEX [19]. We have made performance evaluation under different number of frequencies, primary users and secondary users. In our simulation environment, PUs and SUs are distributed randomly in a 400 m^2 two dimensional Euclidean space. As in [11], we set the operation range of each SU to a radius of 110 m. If two SUs are within the operation range of each other, then there is an edge connecting the two vertices corresponding to these SUs in the input graph G fed into our ILP formulation. Likewise, we set the operation range of each PU to 170 m radius. An SU within the operation range of a PU cannot use the frequency used by that PU in that time slot. Furthermore, each scheduling period consists of 20 time slots, i.e., $T = 20$. All PUs are assigned a random frequency at the beginning of the simulation. In every time slot, each PU changes its frequency with a probability of $P_c = 0.1$. If a PU changes its frequency, the probability of selecting each frequency is equally likely.

In 2009 full power analog TV ceased operation and hence, the frequency range between 54 MHz and 806 MHz were cleared due to the transition to digital TV [20]. In accordance with these frequency bands that became available for cognitive radio operation, we set the frequency range in our experiments between 460 MHz and 700 MHz with the bandwidth of each channel being 20 Mhz. In other words, the highest number of frequencies used in our experiments is 13. According to the work in [2], switching latency is 0.1 ms/MHz. In the same article, channel switching power is assumed to be 1 W. In accordance with this information, we set in our model the energy consumption incurred due to switching between two frequencies with a difference of 20 MHz as 0.002 Joule.

We have evaluated the impact of the following three parameters in our simulations: number of primary users, number of secondary users and number of frequencies. Values of the other parameters remain constant in all experiments. As a result, we calculate two separate solutions corresponding to two different cost schemes. Notice that the energy consumption due to frequency switching is proportional to the time it takes to complete the frequency switching, i.e., switching delay. We refer to the first scheme as *varying cost*. Varying cost scheme relies on the fact that switching delay and hence the energy consumption due to frequency switching depends on the distance between the previous and current frequencies. We refer to the second scheme as *fixed cost*. Fixed cost scheme relies on the assumption that switching delay and hence the energy consumption due to frequency switching is the same (constant value) as long as the previous and current frequencies are different. We have taken this constant value as 0.002 Joule in our simulations.

Table 3 displays the range of values for the evaluated parameters. When investigating the impact of a particular parameter, we set the value of the other parameters to their middle values, which are also shown in Table 3. We take the sample mean of 15 random experiments in each setup.

Table 3. Parameter names and range of values evaluated in the experiments

Parameter	Range Min	Range Max	Middle Value
Frequency	5	13	10
Secondary User	5	13	10
Primary User	3	7	5

Figure 1 shows that varying cost scheme is advantageous when the number of frequencies in the CRN is less than 7. Furthermore, when the number of frequencies is high, the cardinality of the frequency set that is available for the SUs also increases. This increasing availability makes it possible to switch to closer frequencies and hence decreases the energy consumption due to frequency switching.

In Figure 2, we observe that the number of secondary users does not have a consistent and stable impact on the performance of the fixed cost scheme, which fluctuates and is hence unpredictable. In contrast, the switching cost of varying cost scheme increases linearly with number of secondary users. In some parts, fixed cost scheme performs better than varying cost. However, its unpredictability can discourage cognitive radio systems to rely on fixed switching cost in order to schedule their networks. As a result, predictable and consistent performance of varying cost scheme (in addition to the fact that it is more realistic) can make it preferable.

Figure 3 shows the impact of increasing number of PUs. Since the frequencies that are available for the SUs decrease as the number of PUs increases, SUs become obliged to make frequency switching more often and between increasingly distant frequencies. Especially when we have more than 5 primary users,

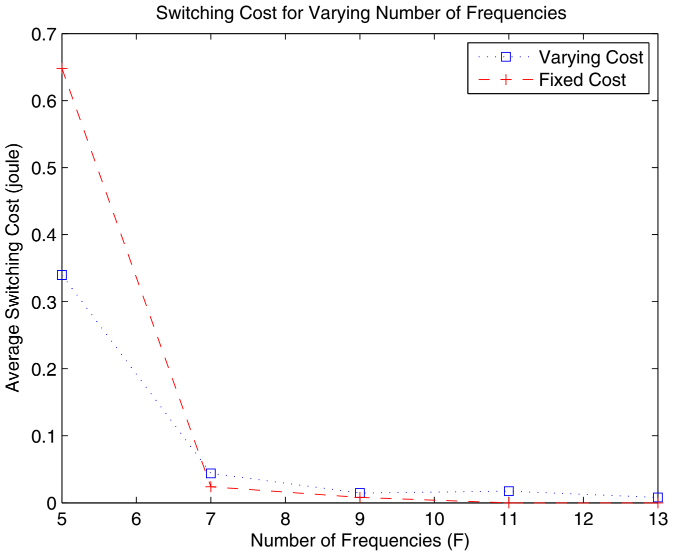

Fig. 1. Average switching cost for varying number of frequencies

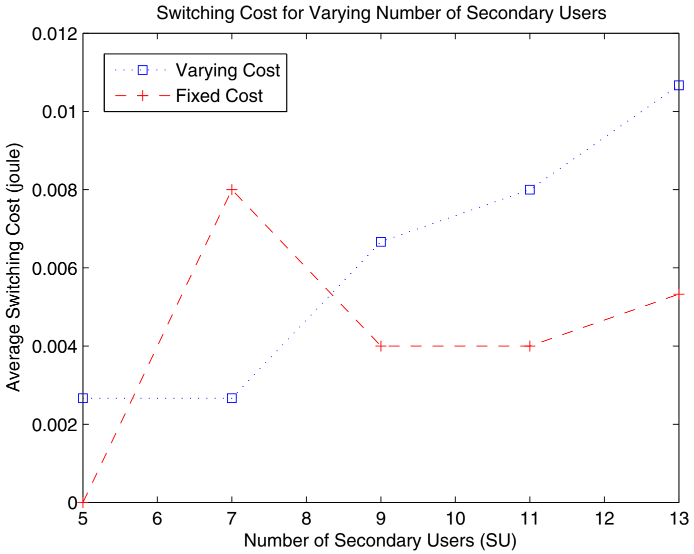

Fig. 2. Average switching cost for varying number of secondary users

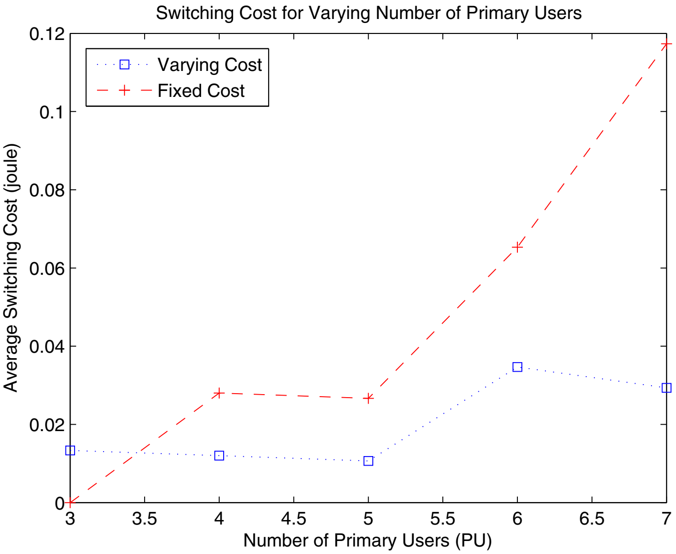

Fig. 3. Average switching cost for varying number of primary users

average switching cost of fixed cost solutions increases faster than varying cost solutions. This figure demonstrates the strength of our varying cost scheme since it outperforms the constant cost scheme especially when there are a high number of PUs.

4 Conclusion

In this paper, we present an optimization model in the form of an integer linear programming formulation that makes frequency and time slot allocation for ad hoc cognitive radio networks with a single transceiver. Our formulation aims to minimize the energy consumption due to frequency switching by taking into account the fact that energy consumption due to frequency switching depends on the distance between the previous and current frequencies. Our simulation results indicate that our idea of taking into account the different energy consumption that occurs during switching to different frequency bands is essential for ad hoc cognitive radio networks especially when there are a high number of primary users in the vicinity of the secondary users.

As a future work, we plan to analyze the performance of our algorithm with higher number of frequencies and secondary users. We believe that the difference between constant switching cost case and our suggestion of varying switching cost will be more evident in a network with a high number of secondary users and frequencies. Furthermore, we also plan to analyze the computational complexity of our integer linear programming formulation and propose a computationally efficient heuristic algorithm.

References

1. Akyildiz, I., Lee, W., Vuran, M., Mohanty, S.: Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey. Computer Networks **50**(13), 2127–2159 (2006)
2. Bayhan, S., Alagoz, F.: Scheduling in centralized cognitive radio networks for energy efficiency. IEEE Transactions on Vehicular Technology **62**(2), 582–595 (2013)
3. Gozupek, D., Buhari, S., Alagoz, F.: A spectrum switching delay-aware scheduling algorithm for centralized cognitive radio networks. IEEE Transactions on Mobile Computing **12**(7), 1270–1280 (2013)
4. Gur, G., Alagoz, F.: Green wireless communications via cognitive dimension: An overview. IEEE Network Magazine **25**(2), 50–56 (2011)
5. Cheng, G., Liu, W., Li, Y., Cheng, W.: Spectrum aware on-demand routing in cognitive radio networks. In: IEEE DySPAN (2007)
6. Cheng, G., Liu, W., Li, Y., Cheng, W.: Joint on-demand routing and spectrum assignment in cognitive radio networks. In: IEEE ICC (2007)
7. Filippini, I., Ekici, E., Cesana, M.: Minimum maintenance cost routing in Cognitive Radio Networks. In: IEEE MASS (2009)
8. Chowdhury, K., Felice, M.: SEARCH: A routing protocol for mobile cognitive radio ad-hoc networks. Computer Communications **32**(18), 1983–1997 (2009)
9. Chen, J., Li, H., Wu, J., Zhang, R.: STARP: A novel routing protocol for multi-hop dynamic spectrum access networks. In: ACM Workshop on Mobile Internet Through Cellular Networks (2009)
10. Krishnamurthy, S., Thoppian, M., Venkatesan, S., Prakash, R.: Control channel based MAC-layer configuration, routing and situation awareness for cognitive radio networks. In: IEEE MILCOM (2005)
11. Arkoulis, S., Anifantis, E., Karyotis, V., Papavassiliou, S., Mitrou, N.: On the optimal, fair and channel-aware cognitive radio network reconfiguration. Computer Networks **57**(8), 1739–1757 (2013)
12. Chen, K.-C., Cetin, B.K., Peng, Y.-C., Prasad, N., Wang, J., Lee, S.: Routing for cognitive radio networks consisting of opportunistic links. Wireless Communications and Mobile Computing **10**(4), 451–466 (2010)
13. Pyo, C.W., Hasegawa, M.: Minimum weight routing based on a common link control radio for cognitive wireless ad hoc networks. In: ACM International Conference on Wireless Communications and Mobile Computing, pp. 399–404 (2007)
14. Zhu, G.-M., Akyildiz, I.F., Kuo, G.-S.: Stod-rp: A spectrum-tree based on-demand routing protocol for multi-hop cognitive radio networks. In: IEEE Global Telecommunications Conference (GLOBECOM), pp. 1–5 (2008)
15. Wang, X., Kwon, T.T., Choi, Y.: A multipath routing and spectrum access (mrsa) framework for cognitive radio systems in multi-radio mesh networks. In: ACM Workshop on Cognitive Radio Networks, pp. 55–60 (2009)
16. Ma, H., Zheng, L., Ma, X., et al.: Spectrum aware routing for multi-hop cognitive radio networks with a single transceiver. In: IEEE International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom), pp. 1–6 (2008)

17. Zeeshan, M., Sattar, K., Shah, Z., Ullah, I.: Routing and spectrum decision in single transceiver cognitive radio networks. In: IEEE Vehicular Technology Conference (VTC), pp. 1–5 (2013)
18. Kamruzzaman, S., Kim, E., Jeong, D.G.: An energy efficient qos routing protocol for cognitive radio ad hoc networks. In: IEEE International Conference on Advanced Communication Technology (ICACT), pp. 344–349 (2011)
19. Cplex. In: CPLEX. http://www.ilog.com/products/cplex
20. FCC, E.: Fcc 10–174 (2010). https://apps.fcc.gov/edocs_public/attachmatch/FCC-10-174A1.pdf