Optimal Energy Allocation Scheme for Throughput Enhancement in Cooperative Cognitive Network

Imen Sahnoun*, Ines Kammoun**, Mohamed Siala*
*Higher School of Communication of Tunis, University of Carthage, Tunisia
**National School of Engineers of Sfax, University of Sfax, Tunisia
imen.sahnoun@supcom.tn, ines.kammoun@ieee.org, mohamed.siala@supcom.rnu.tn

***Abstract*—In this paper, a cognitive radio scenario is proposed, where secondary users are allowed to communicate concurrently with primary users provided that they do not create harmful interference to the licensed users. Here, we aim to improve the throughput of unlicensed system. For this aim, we propose a selective relay cooperative scheme to assist the secondary transmission. Moreover, an adaptive modulation is used in order to compensate the throughput loss due to the relaying. The main contribution of this work is to combine a selection scheme where only one "best" relay is chosen with an energy allocation scheme for source and relay nodes to maximize the achievable throughput under the system constraints. A variety of simulation results reveals that our proposed energy allocation method combined with adaptive modulation offers better performance compared with the classical cooperation scheme where energy resources are equally distributed over all nodes.**

***Index Terms*—Cognitive network, cooperation, adaptive modulation, interference cost constraint, Amplify and forward, energy optimization**

I. Introduction

Radio spectrum is a precious and limited resource for wireless communication networks. With the emergence of new wireless applications, the currently deployed spectrum is becoming extremely saturated [1]. Cognitive radio (CR) [2] is a promising technology to deal with this frequency scarcity caused by the current inflexible spectrum allocation policy. Different paradigms for the CR scenario have been discussed in [3]. More specifically, we focus in this paper on the underlay paradigm allowing the SU to transmit concurrently with the PU. During its transmission, the SU has to guarantee that the interference power it causes to the PU receiver is kept below a certain threshold. Under such constraint, throughput maximization stills a key challenge in such cognitive radio where the secondary users transmit power must be limited. One possible solution is to use the cooperative relaying techniques [4]. In a few recent works, optimal power allocation schemes for various cooperative systems were investigated considering different relaying schemes and optimization criteria. In [5] and [6], an optimal power allocation scheme that minimizes the obtained outage probability under a total power constraint is given. In [5], the author consider dual-hop transmission systems with and without diversity employing DF and AF protocols. In [7], the total power consumption in a DF multi-hop transmission is minimized subject to achieving a target end-to-end bit error rate. For [8], the author propose an optimal power allocation scheme that maximize the instantaneous received signal-to-noise ratio (SNR) in an AF multi-hop transmission system for two kinds of power constraints, namely, the short-term (ST) and longterm (LT) power constraints. Cooperative communication with single relay selection is a simple but effective communication scheme for energy constrained networks [9]. Further, in most of the existing research activities on relaying, the cooperative diversity is used to reduce the bit error rate. However, this reduction comes at the expense of the amount of required resources since additional channels are needed for relaying. Therefore, the throughput is reduced in cooperative networks. For this reason, we propose to use an adaptive modulation technique in order to compensate the throughput loss due to the relaying [10] [12]. Our contribution consists in combining selective-relay cooperative communication with optimal energy allocation scheme for both source and relay nodes that maximize the instantaneous received signal-to-noise ratio (SNR) without causing interference to the PU. Numerical results show the superior performance of adaptive amplify-and-forward based on Alamouti ST code system with optimized energy allocation over those with uniform energy allocation.

The rest of this paper is organized as follows: In section II, we introduce the system model and the adaptive cognitive cooperative network based on Alamaouti AF protocol and best relay selection. Then, we derive in section III the analytical formulation for our constraint imposed on secondary users. In section IV, the formulation of our proposed energy allocation problem is detailed. Then, in section V, we provide some simulation results for the proposed system performance in terms of throughput. Finally, we end the paper with a brief conclusion.

II. System Model

As shown in Figure 1, we consider N primary base stations denoted by $\mathrm{BSp}^{\mathrm{k}}$ where $k = 1, ..N$ and a secondary radio network consisting of one terminal, one base station and M relays denoted respectively by SU, BSs, and R^{m} where $m = 1, ..M$. All links between terminals are assumed to be independent. Each link consists of Rayleigh, slow fading channel, so that we can consider its coefficients as constant during the transmission of at least one frame. Furthermore, to investigate the effect of the path loss into the channel model, the coefficients L_{ij} corrupting respectively the channel link between node i and j, follow a propagation model of

$1/d^{\alpha}$, where α denotes the path loss exponent. The shadowing contribution of the link between node i and j is also considered and expressed by $S_{ij} = S_i + S_j$, where S_i is the shadowing effects near the node i and follows a log-normal distribution with parameter σ. For our model, we assume that the shadowing effects near the differents nodes are as follow: $\mathrm{var}(S_{BSs}) = \mathrm{var}(S_{BSpk}) = \mathrm{var}(S_{R^m}) = (1-\beta)\sigma^2$ and $\mathrm{var}(S_{SU}) = \beta\sigma^2$, where β is the correlation factor.

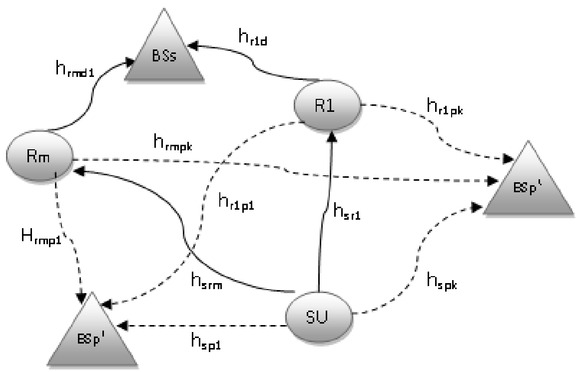

Figure 1. The proposed cognitive system model.

A. Selection relay criterion

Selecting a single relay for information forwarding simplifies the receiver design. Moreover, it ensures better ressources allocation since the available energy will be only used by the more suitable relay. In our study, the best relay selection is based on maximization of received signal quality at the secondary base station and minimization of the received interference at the primary users. Our selection criterion is expressed as follows

$$R = \begin{array}{c} arg\ max \\ m=1..M \end{array} \left[\frac{\frac{|h_{r^m d}|^2}{L_{r^m d} S_{r^m d}}}{\sum_{k=1}^{N} \frac{\left|h_{r^m p_k}\right|^2}{L_{r^m p_k} S_{r^m p_k}}} \right]. \quad (1)$$

B. Cooperation based on Alamouti ST code

In this paper, we consider an adaptive AF protocol based on the Alamouti space-time code. This protocol requires 4 channels uses to send 2 symbols. As schematized in Table I, in the first cooperative phase, the secondary source sends successively the first line of the code matrix: a_1 and $-a_2^*$. In the second phase, the selected relay sends an amplified version of the received signal, and the source sends the second line of the code matrix: a_2 and a_1^*.

Table I
ALAMOUTI AF PROTOCOL

Instant	t_1	t_2	t_3	t_4
SU	a_1	$-a_2^*$	a_2	a_1^*
R	y_{r1}	y_{r2}	γy_{r1}	γy_{r2}
BSs	y_1	y_2	y_3	y_4

At the output of the MRC combiner, the final total SNR expression for Alamouti cooperative protocol can be written as follows:

$$SNR_T = \frac{E_s}{N_0} \frac{\frac{|h_{sd}|^2}{\sqrt{L_{sd}S_{sd}}} + \gamma^2 \frac{|h_{sr}|^2}{\sqrt{L_{sr}S_{sr}}} \frac{|h_{rd}|^2}{\sqrt{L_{rd}S_{rd}}}}{1 + \gamma^2 \frac{|h_{rd}|^2}{\sqrt{L_{rd}S_{rd}}}}, \quad (2)$$

where $\gamma = \sqrt{\frac{E_r}{\frac{|h_{sr}|^2}{L_{sr}S_{sr}} E_s + N_0}}$ is the amplification factor of the relay. To provide a fair comparison platform, we will consider the same total energy consumed in both cooperative and non-cooperative schemes. Then, $E_a = E_s + E_r$ where E_a is the available symbol energy of the source in direct transmission.

III. GENERATED COST DUE TO SECONDARY NETWORK TRANSMISSION

We propose a cognitive radio scenario where concurrent primary and secondary communications are allowed only if primary transmission is protected. To address this problem, we define a maximum cost power at the BSp denoted by C_{max} so that secondary transmissions are possible only if their aggregate interference does not exceed this critical threshold. The expression of the overall cost function C_T in non-cooperative case as well as the considered threshold C_{max} are given in previous work [11]. In fact, in the presence of several primary base stations, the overall cost function C_{AF} will be the maximum of cost values at the different primary base stations. For simplicity sake, we assume here the presence of one BSp. For the cooperation based on Alamouti ST code, at the first and second time slots, only the secondary user is transmitting, so we have

$$C_s = \frac{E_s G \left|h_{sp}\right|^2}{L_{sp} S_{sp}}, \quad (3)$$

where $G = 1/T_s$ denotes the symbol rate. For the third and fourth time slots, both SU and R are transmitting to the secondary destination. Thus, the cost function at the primary destination will be the sum of these two transmissions'costs

$$C_r = \frac{E_s G \left|h_{sp}\right|^2}{L_{sp} S_{sp}} + \frac{E_r G \left|h_{rp}\right|^2}{L_{rp} S_{rp}}. \quad (4)$$

Finally, the overall cost function will be as follows

$$C_T = max\left(C_s, C_r\right) = \frac{E_s G \left|h_{sp}\right|^2}{L_{sp} S_{sp}} + \frac{E_r G \left|h_{rp}\right|^2}{L_{rp} S_{rp}}. \quad (5)$$

IV. SOURCE AND RELAY ENERGY OPTIMIZATION

In this section, we derive the adopted optimization approach. In fact, the optimization aims at finding out the appropriate energy repartition of both source and relay nodes in order to enhance the cognitive system performance. However, the interference cost generated at the PU must be kept below a prescribed threshold. Besides, the SU and R adapt their energies while keeping a fixed total available energy E_a.

Therefore, our optimization problem can be formulated as follows

$$\begin{aligned} \text{maximize} \quad & SNR_T \\ \text{subject to} \quad & E_s + E_r \leq E_a, \\ \text{and} \quad & C_T \leq C_{max} \end{aligned} \tag{6}$$

That can be written with refer to (5) as

$$\begin{aligned} \text{maximize} \quad & SNR_T \\ \text{subject to} \quad & E_s + E_r \leq E_a \quad , \\ \text{and} \quad & H_s E_s + H_r E_r \leq C_{max} \end{aligned} \tag{7}$$

where

$$H_s = \frac{G\,|h_{sp}|^2}{L_{sp} S_{sp}} \tag{8}$$

and

$$H_r = \frac{G\,|h_{rp}|^2}{L_{rp} S_{rp}}. \tag{9}$$

For the optimization, we propose to use graphical (or geometrical) method that presents an attractive way for solving nonlinear problems involving two parameters with a minimum amount of computational effort [12]. First, we have to trace the graph in two dimensions of the problem constraints as it is shown in Figures 2 and 3 where the SU and the R energies are presented on the x-axis and the y-axis respectively. Because of the non-negativity energies restrictions, the feasible region is restricted to the positive quadrant. The candidat solutions are the intersection area on the valid side of each constraint line that is drawn in Figures 2 and 3 as continous lines. In fact, the point of the segment which yields the maximum value of the objective function will be the optimal solution to our problem. This is equivalent to annul the derivative function of SNR with respect to E_s as follows

$$\frac{\partial}{\partial E_s}\left\{\frac{E_s}{N_0}\left(\frac{|h_{sd}|^2}{L_{sd}S_{sd}} + \frac{(E_a - E_s)\frac{|h_{sr}|^2}{L_{sr}S_{sr}}\frac{|h_{rd}|^2}{L_{rd}S_{rd}}}{E_s\frac{|h_{sr}|^2}{L_{sr}S_{sr}} + (E_a - E_s)\frac{|h_{rd}|^2}{L_{rd}S_{rd}} + N_0}\right)\right\} = 0. \tag{10}$$

Developping this expression yields to solve the following quadratic equation

$$AE_s^2 + BE_s - C = 0, \tag{11}$$

where

$$A = \frac{|h_{sr}|^2}{L_{sr}S_{sr}} - \frac{|h_{rd}|^2}{L_{rd}S_{rd}}, \tag{12}$$

$$B = 2\left(\frac{|h_{rd}|^2 E_a}{L_{rd}S_{rd}} + N_0\right) \tag{13}$$

and

$$C = \frac{|h_{sd}|^2}{L_{sd}S_{sd}}\frac{L_{sr}S_{sr}}{|h_{sr}|^2}\frac{L_{rd}S_{rd}}{|h_{rd}|^2} + E_a\left(\frac{|h_{rd}|^2}{L_{rd}S_{rd}}E_a + N_0\right). \tag{14}$$

In the case of positive discriminant $B^2 - 4AC \geq 0$, we denote by $E_s^{'}$ the potential solution of (13) that yields a maximum value of SNR. Since H_s and H_r values depend on a randomly varying environment, we have to study the following two cases illustrated in Figures 2 and 3 respectively.

1. $\frac{C_{max}}{H_s} \leq \frac{C_{max}}{H_r}$

In such condition, we can obtain three different cases depending on E_a value as presented in Figure 2 by 1.(a), 1.(b) and 1.(c).

- 1.(a): $E_a \leq \frac{C_{max}}{H_s}$

If $E_s^{'}$ exists and $E_s^{'} \epsilon\, [0, E_a]$, then the optimal solution is $(E_s^{'}, E_a - E_s^{'})$. Otherwise, the optimal solution will be at the segment boundary $(E_a, 0)$ which means that the SU uses the whole available energy to transmit.

- 1.(b): $\frac{C_{max}}{H_s} \leq E_a \leq \frac{C_{max}}{H_r}$

If $E_s^{'}$ exists and $E_s^{'} \epsilon \left[0, \frac{C_{max}}{H_s}\right]$, then the optimal solution is $(E_s^{'}, E_a - E_s^{'})$. Otherwise, the optimal solution will be one of the segment boundary namely $(\frac{C_{max}-H_rE_a}{H_s-H_r}, \frac{C_{max}-H_sE_a}{H_r-H_s})$ or $(\frac{C_{max}}{H_s}, 0)$ which yields the maximum SNR value.

- 1.(c): $E_a \geq \frac{C_{max}}{H_r}$

For this case, and as shown in Figure 2, no solution is possible. So, the secondary transmission is not allowed.

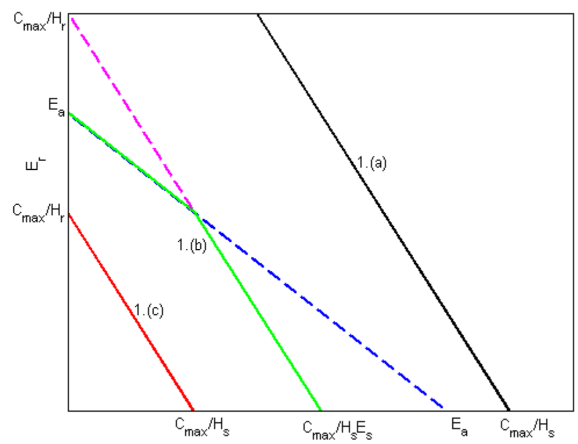

Figure 2. Different cases illustration where $\frac{C_{max}}{H_s} \leq \frac{C_{max}}{H_r}$

2. $\frac{C_{max}}{H_s} \geq \frac{C_{max}}{H_r}$

In such condition, we can obtain three different cases depending on E_a value as presented in Figure 3 by 1.(a), 1.(b) and 1.(c).

- 2.(a): $E_a \leq \frac{C_{max}}{H_r}$

If $E_s^{'}$ exists and $E_s^{'} \epsilon\, [0, E_a]$, then the optimal solution is $(E_s^{'}, E_a - E_s^{'})$. Otherwise, the optimal solution will be at the segment boundary $(E_a, 0)$ which means that the SU uses the whole available energy to transmit.

- 2.(b): $\frac{C_{max}}{H_r} \leq E_a \leq \frac{C_{max}}{H_s}$

If $E_s^{'}$ exists and $E_s^{'} \epsilon \left[0, \frac{C_{max}}{H_s}\right]$, then the optimal solution is $(E_s^{'}, E_a - E_s^{'})$. Otherwise, the optimal solution will be one of the segment boundary namely $(\frac{C_{max}-H_rE_a}{H_s-H_r}, \frac{C_{max}-H_sE_a}{H_r-H_s})$ or $(E_a, 0)$ which yields the maximum SNR value.

- 2.(c): $E_a \geq \frac{C_{max}}{H_s}$

For this case, and as shown in Figure 3, no solution is possible. So, the secondary transmission is not allowed.

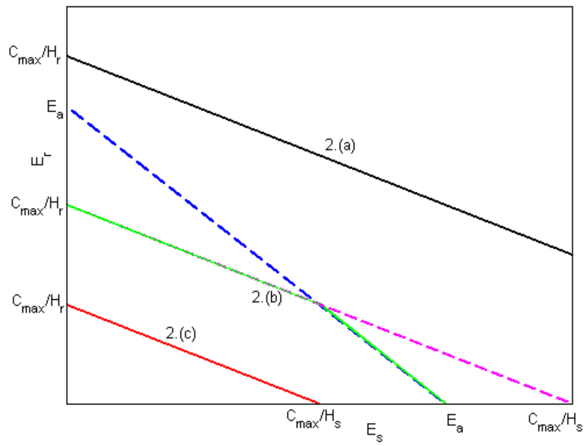

Figure 3. Different cases illustration where $\frac{C_{max}}{H_s} \geq \frac{C_{max}}{H_r}$

V. Simulation results

For the adaptative modulation technique, we propose to use a decision criterion based on throughput maximization that has been detailed in a previous work [11]. For the simulations, we use a path loss exponent of $\alpha = 4$ and a shadowing correlation coefficient between channels $\beta = 0.5$. We assume that the maximum cost tolerable at the primary receiver C_{max} is known at the secondary source. To study our proposed scheme with more general view, we consider a rectangular pattern where nodes are located as it shown in Figure 4. First of all, we consider the presence of one primary base station BSp1, and we present in Figures 5 the throughput behavior as a function of $(E_a/N_0)(d_0/d)^{\alpha}$for each of the relay location then when applying our selective cooperative schema, in the other words when the best relay transmit. We notice that d is the distance between the source and the secondary destination where $d_0$is a reference distance. Figure 5 approves once again our selection critireon and shows that worst throughput is seen when SU becomes near to BSp and distant to BSs. We also notice that our proposed a selective cooperative relay combined with an energy allocation scheme. A preliminary comparaison with other shemes, Figure 6 is plotted. For the fixed energy allocation scheme, we will consider the same transmitted energy in both relay and source nodes that is equal to $E_a/2$. Moreover, we assume that the SU is located at the center of the line connecting the secondary and primary base stations. More precisely, Figure 4 illustrates the system throughput as a function of $(E_a/N_0)(d_0/d)^{\alpha}$ for different cognitive schemes. We clearly depict from these curves that our selective cooperative transmission combined with an energy allocation scheme outperforms the other schemes, and that our optimization strategy improves significantly the cognitive transmissions. Moreover, we notice that the achievable throughput at the BSs decreases sharply at higher transmission energy values, since more and more the interference generated at the BSp increases and the SU will not be authorized to transmit. Next, we study the impact of the considered cost threshold on the throughput of our proposed optimized scheme. Figure 7 plots the system normalized throughput as a function of $(E_a/N_0)(d_0/d)^{\alpha}$ for different values of C_{max}. In fact, it is logical that a higher authorized C_{max} provides significant gain in terms of throughput when compared to the cases of more stringent interference constraints. Finally, we would like to study the effect of detecting more than one BSp in the secondary network. In fact, Figure 8 shows the throughput behavior as a function of $(E_a/N_0)(d_0/d)^{\alpha}$ for several number of primary base stations NBSp. In particuler, we consider three BSp located as shown in Figure 4. It is observed from Figure 8 that, with increasing the number of BSps, the achievable data rate decreases significantly.

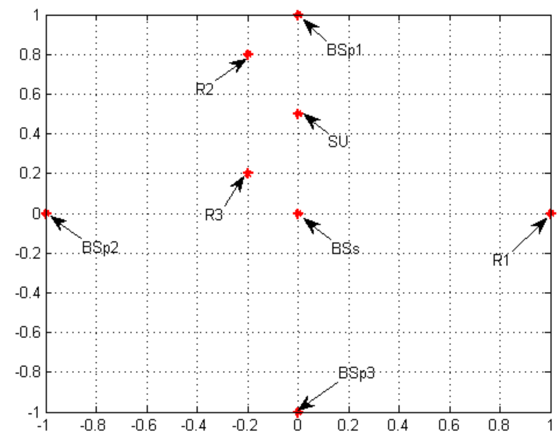

Figure 4. Positions of differents nodes.

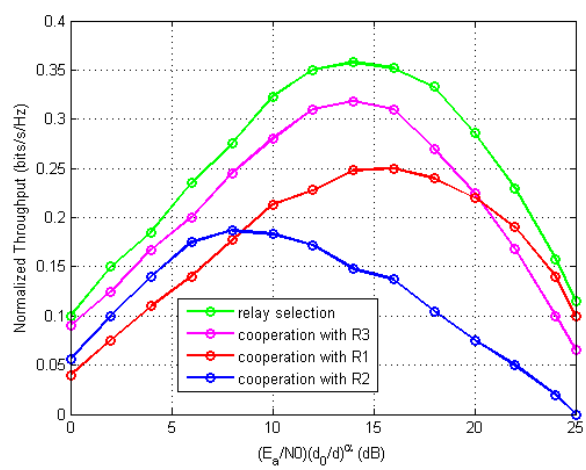

Figure 5. Throughput behavior of the proposed scheme as a function of $(E_a/N_0)(d_0/d)^{\alpha}$ for different relay locations.

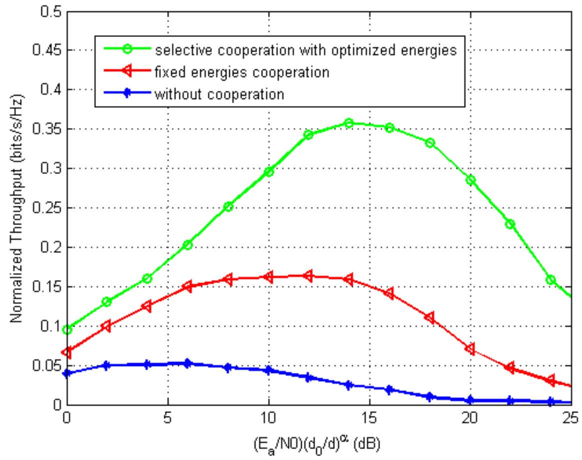

Figure 6. Throughput behavior of the proposed scheme as a function of $(E_a/N_0)(d_0/d)^{\alpha}$ for different schemes.

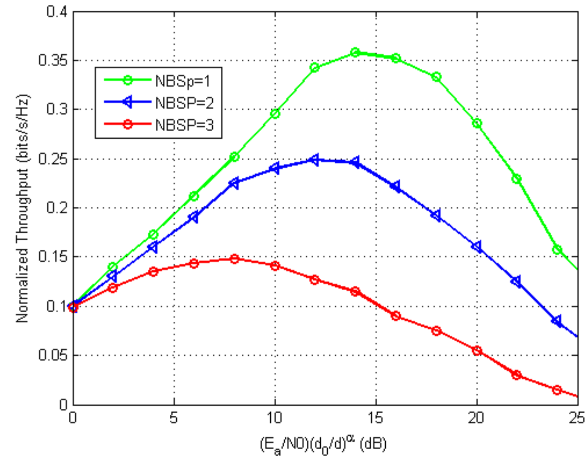

Figure 8. Troughput behavior as a function of $(E_a/N_0)(d_0/d)^{\alpha}$ for different numbers of BSp.

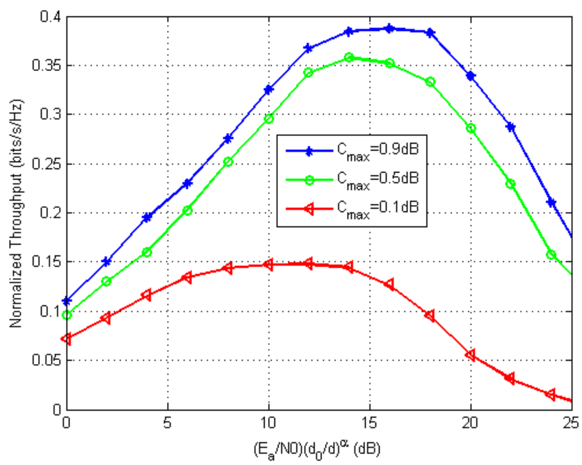

Figure 7. Troughput behavior as a function of $(E_a/N_0)(d_0/d)^{\alpha}$ for different schemes when $C_{max} = 0.5dB$.

VI. Conclusion

In this paper, we proposed a selective cooperative relay combined with an energy allocation scheme in an adaptive cognitive network based on cooperation. In fact, an optimization of the SU and the relay transmitted symbol energies is carried on to ensure the highest performance provided that the interference cost generated at the PU is below a prescribed threshold. We conclude that the system throughput is proportional to several parameters such as the SU location, the relay location, their transmission energies and the maximum tolerable cost at the primary network. Using numerical results, we proved that our proposed strategy shows a significant performance improvement in terms of throughput compared to the conventionnel fixed allocation scheme where energy is uniformly distributed to each node. This work can be extended by carrying out the optimization with multiple secondary users and carrying out an analytical optimization for the network resources.

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