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Opportunistic Interference Cancellation Evaluation in Cognitive Radios under Power Control Strategies

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***Abstract*—This work considers a cognitive radio (secondary system) that operates under the interference of a WiMAX-like legacy (primary) system. The secondary terminals have knowledge of the codebooks used in the primary system and can apply Opportunistic Interference Cancellation (OIC): if the channel conditions allow, the secondary system can decode and subsequently cancel the interference from the primary system. Contrary to the previous works that utilize the concept of OIC, in this paper we consider practical packet coding, rather than optimal random codebooks in an information-theoretic setting.**

The key contribution is the mechanism for power control, whose objective is to protect the primary users from a harmful secondary interference. As a dividend, it is seen that in certain regions the proposed power control creates channel conditions that enable the secondary receiver to take advantage of the OIC mechanism. Several power control algorithms have been considered and evaluated in a single and multi-channel scenario. The results clearly indicate the advantage of using power control in conjunction with the OIC concept for achieving spectrally-efficient secondary operation.

***Index Terms*—Cognitive Radio; power control; OIC; power adaptation**

I. Introduction

Cognitive radio (CR) represents one of the best solutions to solve the problem of spectrum scarcity, as a CR device can make autonomous and rapid decisions about how to access the spectrum. CR users adapt to the variations in the licensed spectrum usage and utilize the spectrum resources without causing unacceptable interference to licensed users [1]. Consequently, CR technology has gained increasing attention and is, currently, viewed as one of the most promising technologies for the next generation wireless networks [2]. It is possible to use the cognitive radio concept for secondary systems (unlicensed users) that use a given spectrum simultaneously with a primary system (licensed users), without causing harmful interference to the communication within the primary system.

There are two spectrum usage models, the Overlay and the Underlay model, respectively. In both models spectrum sensing is required to determine whether the licensed band of interest has already been occupied by any licensed user.

The Overlay Model is an opportunistic one, in which the secondary users exploit the on/off activity of the primary users. In this case the spectrum is shared and available for usage whenever the primary users do not use it. The secondary systems try to find the spectrum holes automatically, and utilize them while avoiding interference towards the primary system.

The second model for the coexistence between the primary and secondary system is the Underlay Model, in which secondary users can access the spectrum simultaneously with a primary user, provided that no harmful interference is caused to the latter. The secondary system might be under interference from the primary system. In principle, a cognitive receiver can possibly try to decode and cancel the primary interference, if the channel conditions allow. This approach is called Opportunistic Interference Cancellation (OIC) [3].

In this paper we consider an Underlay model and propose a power adaption technique based on the PER estimated on the primary system. Our concept of cognition involves two aspects: the knowledge of the primary codebooks in order to cancel the primary interference and knowledge of the acceptable levels of interference caused to the primary users within the range of the cognitive users. The latter one sets a basis for proposing algorithms for power adaptation.

It is viable to assume that a cognitive device knows the primary codebooks, as the primary devices are legacy devices, while a cognitive device represents a more capable, evolved device. Note that this knowledge does not pose security problems, as secrecy is not in the transmission techniques, but is rather introduced through cryptographic operation on the data at the higher layers.

The main contribution of the paper is secondary dynamic power control that avoids harmful interference to the primary users, while offering throughput performance for the secondary system.

The paper is organized as follows: Section II reviews the related works on power control strategies applied in Cognitive Radio. In Section III, we discuss the OIC method [3] and its application to a scenario considering WiMax-like as the primary system. In Section IV the proposed power control adaptation and strategies are described, while the simulation results are presented in Section V. Finally, the conclusions are drawn in Section VI.

II. Related works

Our work differs from the previous works dealing with power management in Cognitive Radio in at least one of the

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following aspects: 1) we consider WiMax-like system as a primary system, considering the Kitao propagation model [4] as well as multipath fading; 2) we only consider the Underlay Model, taking advantage of OIC concept from [3], exploiting the interference caused by Primary System to transmit; 3) our power control algorithms avoid harmful interference to primary system, but they also improve the secondary throughput within the OIC framework.

There is a large body of works that consider sensing of the primary, e.g. [5], which uses a listen-before-talk strategy that is common in many traditional cognitive radio access schemes. In [6] secondary users have been allowed a dynamic control access and power adaption, based on inherent feedback mechanisms, particularly the ACK/NACK feedback from a primary receiver (PU-Rx) to a primary transmitter (PU-Tx) upon receiving a data packet.

Several power control strategies are given in [7] and [9].

III. System Model and Opportunistic Interference Cancellation

Compared to these related works, some of which consider protection of a primary user that operates on multiple channels, here the power control for protecting the primary is integrated with the OIC mechanism. We exploit the feedback mechanism of the primary system to sense and learn the primary transmission features, such that the secondary system is able to adapt its power to the receiving conditions in the primary system.

The scenario used in this work is shown in Fig. 1. The secondary transmitter (SU-Tx) can transmit opportunistically applying OIC in one of the primary channels, selecting the channel that offers the highest secondary throughput.

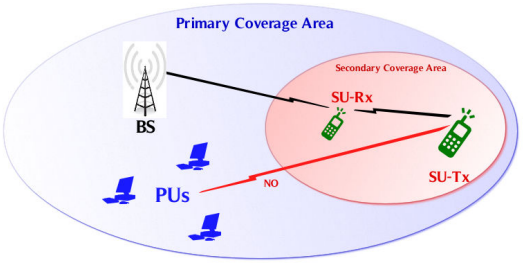

Fig. 1: The target scenario. All terminals are fixed, except SU-Tx, which is mobile and its interference to the primary users (PUs) varies in time.

A cognitive receiver can utilize OIC to decode/cancel the interference from a primary system (e. g. a Wimax BS) and thus decode its desired signal in more favorable decoding conditions. Such a decoding can be applied whenever opportunity is created by the transmitting powers and the channel conditions used in both the primary and the secondary system.

Initially (SU-Rx) checks if it is able to successfully decode the secondary signal from the received signal (eq. 1):

$$y_2 = x_1 h_{12} s + x_2 h_{22} + n \tag{1}$$

If x_1 is the signal that is coming from (PU-Tx) and it is received with a low power, then (SU-Rx) could be able to decode the desired signal x_2. But if (SU-Rx) cannot successfully decode x_2, then it tries to decode x_1 (undesired signal). If the receiver is able to decode x_1, then it can re-code it and subtract it from the received signal y_2 (eq. 1), obtaining the following signal

$$y_2 - x_1 h_{12} s = x_2 h_{22} + n \tag{2}$$

which is then used to decode the desired signal x_2. This decoding is also subject to errors due to noise.

Initially we assume that both transmitters, (PU-Tx) and (SU-Tx), are kept fixed, while the secondary receiver (SU-Rx) is moved. If the interference is very strong, then it is possible to decode the desired signal only using the OIC method. On the other hand, in the absence of interference, the secondary signal can even be decoded with a relatively low channel gain between (SU-Tx) and (SU-Rx).

In such a setting, it is convenient to distinguish three regions, called respectively *OIC*, *normal* and *critical* region, as shown in Fig.2, where we plot an example of regions division, highlighting the importance of secondary receiver (Cognitive node) position considering no dynamic power in the secondary transmitter.

The differences between the regions arise due to the way in which OIC method is applied.

In the *OIC* region the primary signal is stronger than the secondary, such that OIC can be successfully used. In the *normal* region, the secondary signal is stronger than the primary, such that SU-Rx is able to decode the secondary signal without being disturbed by interference from the primary. Finally, in the *critical* region the SU-Rx cannot decode either the primary nor the secondary signals, as both are strongly interfering with each other and a high percentage of the packets is dropped. If the secondary adapts the power in order to avoid harmful interference to (PU-Rx), then this power control also changes the actual region at (SU-Rx) with respect to the application of OIC.

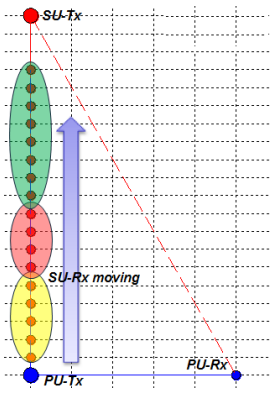

Fig. 2: Example of regions: a)OIC(blue), b)critical(red), c)normal (yellow)

Depending on the position and transmission power of the primary and secondary, these regions can change and therefore a mechanism of power control is needed to get the maximum throughput in the secondary ensuring primary protection.

Previous works on OIC provide an information-theoretic treatment of the interference, such that it is either completely cancelled, or treated as noise.

On the contrary, in this work we consider a practical setting related to WiMax physical model (802.16d), and we want to achieve a major advantage combining the OIC method with power control strategies.

Considering certain channel conditions (based on SNR values) the secondary receiver is able to correctly decoded and cancel primary interference, but sometimes the primary interference is decoded with errors and not removed; in this work we want to reduce this case increasing the decoded packet percentage of WiMax system due to the integration of our power control strategies in OIC.

IV. Power Control Strategy

A dynamic power management can produce different results, that can change the previous view of the three regions (OIC, normal and critical), so even if a node is in the critical region, it can be considered in another one because its power changes according to a certain power-control agorithm.

Thanks to this strategy (SU-Rx) can receive a stronger signal from its transmitter when the primary signal is weak and it has to adapt power to avoid harmful interference to the primary; on the other hand (SU-Rx), receiving a strong primary signal, can regulate its power, for example decreasing it, so it can be in the OIC region (when the primary signal is stronger than the secondary), can be easily decoded.

We propose *Packet Error Rate* (PER) based and *power-aware* algorithms that try to adapt secondary transmission power in order to reduce harmful interference to PUs and to respect PER thresholds on the secondary system, as shown in Fig. 3.

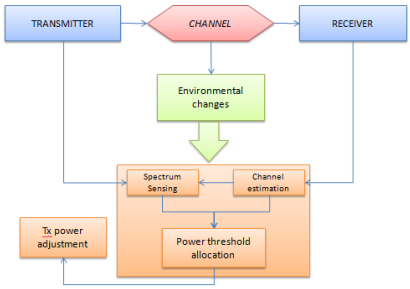

Fig. 3: Sensing operation

From the system perspective, the power threshold allocation block is obviously a critical component of the transceiver.

In next section we will describe how to make sensing operation and power adaptation in order to maximize secondary relays without producing the harmful interference issue to the primary system.

A. Sensing operation for PER estimation

Exploiting feedback messages overhearing from primary system, (SU-Tx) can learn CSI (Channel State Information).

Assuming that (SU-Tx) is able to overhear *ACK/NACK* packets sent by the primary system, and considering an observation time interval t_i, useful to estimate the PER value, it is possible for (SU-Tx) to exploit a power adaptation. The PER estimation is computed according to eq. 3.

$$PER(i) = \frac{M(i)}{N(i)} \tag{3}$$

where N is the total number of packets sent and M is the number of erroneously received packets.

In this way we present two types of sensing: in the first we consider the current sensed value to adapt the power (described in the subsection IV-C1), while in the second type we consider a smoothed PER, based on the average of previous PER values (subsection IV-C2).

Let us define a sensed PER variable as μ^k_{PER}, in which k represents the number of considered previous PER values (as in eq. 4).

$$\mu^k_{PER}(n) = A_1 \cdot \mu^k_{PER}(n-1) + A_2 \cdot \mu^k_{PER}(n-2) + ... + A_k \cdot \mu^k_{PER}(n-k) \tag{4}$$

in which $A_1, A_2, ..., A_k$ are the coefficient of linear regression about previously measured $\mu^k_{PER}(n)$ samples, and the term n represents the current simulation step. The linearity can be useful for having a smoothed estimation, as suggested in [10].

B. Power Adaption Strategies

Two power adaptation strategies are proposed in the following paragraphs. The first one tries to use fixed power levels allowing to fix the power level on the basis of the minimum BER to be respected on the primary system.

The second technique is based on a step by step power adaptation where a power budget is added or subtracted to the reference power level in order to reduce the interference on the primary system but allowing the secondary to increase its throughput.

Both techniques have the common goal to improve the secondary throughput respecting the QoS constraints on the primary system. It is possible to obtain this objective such proved in the following extending the application area of OIC and reducing the occurences in which the primary system cannot decode the signal due to the interference produced by secondary users.

Secondary node starts to transmit only after primary sensing and it uses a power in which the increment/decrement is based on PER thresholds as those mapped in the table II.

Let us define ΔP_i as corresponding power levels associated to each threshold (th_i). Thus ΔP_i will be expressed in eq. 5.

$$\Delta P_i = \{\Delta P_i(x) | Pr(\mu^k_{PER}(n) < th_i) = 1\} \tag{5}$$

in which the variable x represents our sensed PER variable, $\Delta P_i(x)$ refers to Fig. 4 and follows a linear trend; while the variable th_i represents the thresholds at which a power adjustment is expected (as shown in Fig. 4).

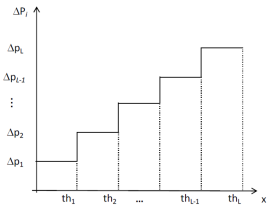

Fig. 4: Function ΔP_i

C. Proposed power control algorithms

1) Discrete Power Level Based Algorithm: This simple algorithm deals with the possibility to adapt the power level according to PER sensing and based on $L = 3$ fixed levels. It is made without considering any prediction models, in this case we refer to $k = 0$, as previously considered values.

If μ^0_{PER} is equal to zero, after primary sensing, (SU-Tx) can use the maximum power value available; otherwise it has to adapt based on three power levels defined before. The calculated power at $n-th$ step, as refered in7,is described in eq. 6.

$$P(n) = \begin{cases} P_{th1}, & \mu^0_{PER} \leq th_1 \\ P_{th2}, & th_1 < \mu^0_{PER} \leq th_2 \\ P_{th3}, & th_2 < \mu^0_{PER} \leq th_3 \end{cases} \quad (6)$$

The variables th_1, th_2, th_3, with $th_1 < th_2 < th_3$, represent fixed thresholds used in this kind of algorithm; they depend on the QoS constraints applied on the primary system. We expand the campaigns of simulations until $L = 6$ levels of thresholds.

2) Prediction based Adaptive Algorithm: It is possible to improve the previous algorithm (section IV-C1) by exploiting the autoregressive model, that is a simple prediction model; the power adaptation level depends on the previous estimated PER values on which the strategy is focused.

To estimate the predicted value of power $P(n)$, we exploit the autoregressive linear model based on k previous values (as described in eq. 4). For each step $n > k$, the power is described in eq.7.

$$P(n) = \begin{cases} P(0) & n = 0 \\ P(n-k) \pm \Delta P_i|_{i=1\ldots L} & n \geq 1 \end{cases} \quad (7)$$

in which L is the number of considered thresholds, while ΔP_i is a function of estimated PER, as shown in Fig. 4.

In our case the thresholds (th_i) have been chosen heuristically and we fix the PER value to satisfy primary QoS constraints, such that for every threshold a ΔP_i is associated, as described in Table II.

This means that for each step there is a power budget ΔP_i increment/decrement associated. To estabilish the quantity of power to increase/decrease, we assuming $\Delta\mu^k_{PER}(n)$ as the variation of $\mu^k_{PER}(n)$, shown in eq. 8.

$$\Delta\mu^k_{PER}(n) = \mu^k_{PER}(n) - \mu^k_{PER}(n-k) \quad (8)$$

Furthermore we are able to know if there is an increment/decrement of power (Fig. 4): if $\Delta\mu^k_{PER}(n) > 0$ (i.e. the current value is greater than the previous one), this means that there is a worsening of channel conditions due to an increment of interference, so it is necessary to decrease ΔP_i; on the contrary if $\Delta\mu^k_{PER}(n) < 0$ there is an improvement because the interference is low.

V. Performance Evaluation

A. Simulation scenario

We consider two scenarios: in the first we easly show an evaluation of proposed algorithms considering easily one primary channel, also used by the secondary; while in the second one, shown in Fig.1 we refer to a multichannel scenario, considering $M = 3$ channels, so that the secondary can use the best one to transmit according to the channel selection policy.

The channel selection policy is fixed and is based on optimizing secondary throughput, trying not to create harmful interference to the primary, and thus maintaining a required signal to interference plus noise ratio (SINR) for all primary receivers. On the other hand, the choice of the optimal channel selection policy is outside the scope of this paper.

We made two kinds of simulations of *Discrete Power Level Based* algorithm differentiating the two cases on the number of ΔP_i used, respectively $L = 3$ and $L = 6$ levels (shown in Table II).

Other secondary parameters used in the simulation are available in table I.

Secondary System parameters	
Secondary System	*802.16d/e*
Physical layer	*OFDM(256)*
Frequency	*5 GHz*
Bandwidth	*3.5 MHz*
Path Loss model	*Kitao[4]*
Tx power	*0dBm-43dBm*
Max cell range	*2000m*

TABLE I: Simulator parameters of Secondary System

$PERthresholds(th_i\|_{i=1..6})$	0	10^1	10^2	10^3	10^4	10^5
ΔP_i [dBm]	1	3	6	10	15	23

TABLE II: Example of emipirical thresholds and corresponding power level budgets

The power adaptation with discrete power levels is called *Fixed Power Levels based* algorithm; conventionally we call *LPC(k)* a predictive adaptive algorithm with $k = 1, 2, 3$, respectively.

B. Single channel case

Initially we are only interested in the evaluation of the primary system in a manner to ensure that the quality of primary transmissions is respected. This allows us to perceive the power control effectiveness (Fig. 5 and Fig. 6).

Having established that, we evaluate how power control effectively acts also in the secondary (Fig. 7 and Fig. 8) and permit obtaining maximum throughput while guaranteeing primary protection.

In Fig. 5 we can see a comparison between algorithms in a scenario with a single PU and only one channel. It is thus possible to observe PER trends of the primary system in function of the distance between (SU-Tx) and the PUs.

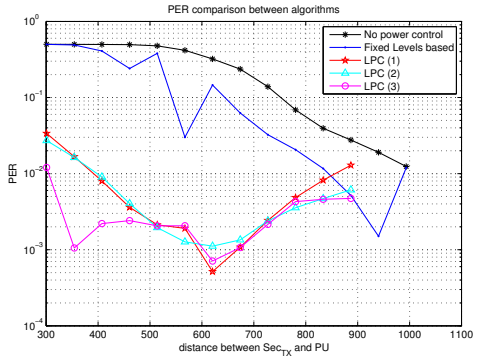

Fig. 5: Comparison between algorithms versus secondary users distances

If no power control is applied, the PER trend is linear, and decreases when distance increases.

Considering the *Discrete Power Level Based Algorithm*, the trend improves, but contains some peaks where there are power switchings; this depends on the region where the cognitive node is placed.

In the case of predictive algorithms, $k = 3$ is the maximal coefficient value used to estimate the PER values and it achieves the best results.

This dynamic power management reduces the *critical* region (in which the secondary signal cannot be decoded) at the expense of an increment of *OIC* and *normal* regions (as shown in Table III), so even the percentage of succesfully decoded packets is improved.

	Operating Region	
	critical (failed)	OIC or normal (decoded)
No power control	79.27%	20.73%
Fixed/Discrete	13.23%	86.77%
LPC(k)	11.6%	88.4%

TABLE III: Percentage of regions utilization

C. Multichannel case

Even in the multichannel scenario the power adjustment causes an improvement in the secondary system, because there is a reduction of the *critical* region, thus when the secondary node moves, it will be frequently in the *OIC* region or *normal* region and its transmission is better than the case in which no power adaptation strategy is adopted. In this way, when a secondary system manages its power, the channel choice is influenced by power management, so the throughput value is optimized.

In Fig. 6 it is possible to see the behaviour of primary PER comparing the *LPC* algorithms with the case in which no power control is applied.

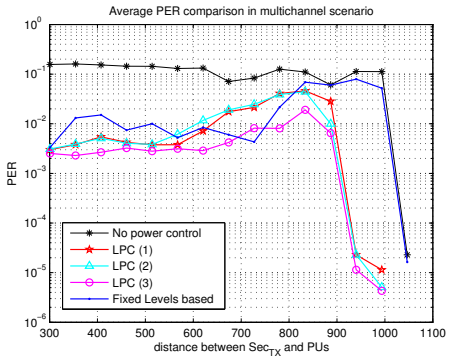

Fig. 6: Comparison PER in multichannel scenario ($M = 3$ channels)

There are improvements in terms of PER, so we reduce harmful interference to PUs, thanks to a SINR change in the secondary system that allows the receiving of a stronger signal from the primary by applying the OIC method more effectively. When (SU-Tx) reduces its power, (SU-Rx) can successfully decode its own, since OIC leads to the correct removal of the interference from the primary, as shown on Fig. 7.

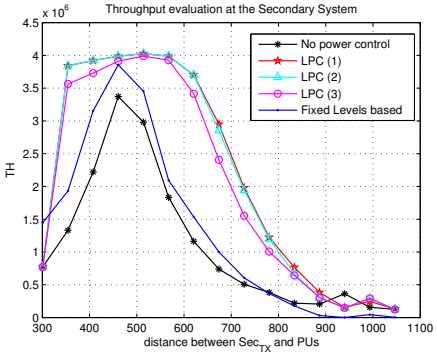

Fig. 7: Secondary throughput

These trends show the improvement to the secondary system, above all throughput in the OIC region, associated with a better percent of PER. The secondary PER is shown in Fig. 8, where we observe improvements due to power adaptation. In particular, the *LPC* method leads to the best results due to its flexibility.

D. Convergence time analysis

The convergence time of proposed power adaptation strategies is particularly useful for enhancing the performance of a cognitive system.

The proposed algorithms are probably convergent to the global optimal during the whole simulation time, in particular it needs a trade-off between the time to converge and the number of switchings made in terms of power (DP_i).

The Fig. 9 shows the different convergent power steps for each proposed algorithm, in particular the *Discrete Power*

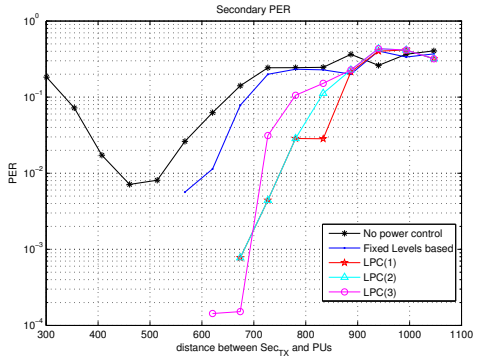

Fig. 8: PER evaluated in (SU-Rx)

Level Based algorithm is evaluated in two different cases, the first using only $L = 3$ levels of ΔP_i (*Discrete1*), while the second case is evaluated with $L = 6$ levels (*Discrete2*).

Both *Discrete Power Level Based* algorithms reported in the plot are the best ones in term of convergence time and they could be suitable for practical implementation in real systems; if we are interested in cost/effective solutions for enhancing system performance *LPC* algorithms can be good candidates.

By using *LPC* algorithms the cognitive system can mostly exploit the advantages of prediction models, versus a waste of power switchings, that reach the maximum in the middle of the simulation time.

On the other side, the *Discrete Power Level Based* algorithm one has a longer convergence time, but applies a lower number of adaptations.

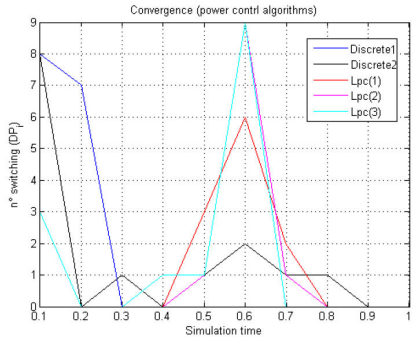

Fig. 9: Convergence of proposed algorithms

These schemes present desirable fairness properties and are also extensible to a multichannel environment, as shown in Fig. 10.

In this case the difference between the *Discrete Power Level Based* algorithms and the *Prediction Based* ones (*LPC*) is more evident; in fact in our simulations LPCs reach a steady state only in 0.7s against 0.3s.

It is clear that these considerations are only valid under certain channel conditions; if the SNR changes all the sensing and adaption procedures have to be taken into account again.

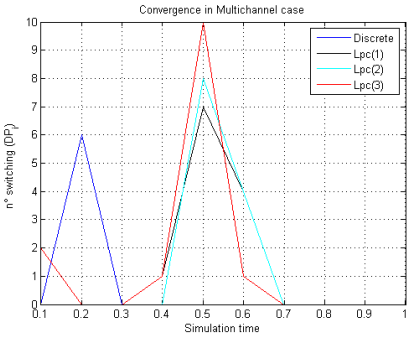

Fig. 10: Convergence in Multichannel case

VI. Conclusions

A power management in Cognitive Radio, under interference from a WiMax like primary system, is proposed. We have shown that power control schemes can effectively provide optimal secondary users performances while protecting primary system.

The numerical results confirm that the best improvements have been made using a PER value based algorithm with prediction (*LPC*), compared to the fixed one; mostly they can be shown in the region in which (SU-Tx) is closer both to (SU-Rx) and to PUs.

Through simulations it is possible to see the enhancements of the secondary system in terms of throughput and PER, after a power adaptation, so that the two goals of minimizing primary interference and optimizing secondary relays have been achieved.

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