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Performance analysis of Power Allocation Schemes for Cognitive Radios

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Abstract:

Coexistence of one or more cognitive radios with a primary radio where the cognitive radios transmit in a spectrum allocated to the primary radio has been investigated in this paper. We consider two distinct scenarios: one in which the cognitive radios give higher priority to one of the cognitive radios and a second in which all the cognitive radios compete to get maximum possible data rates for themselves. In first scenario, the cognitive radio with higher priority gets a choice to decide how much of available resources it wants to use, and rest of the cognitive radios scavenge the left-over resources. In this paper propose power allocation strategies to be used by the radios under both scenarios. we show that proposed power allocation strategy to be used in the first and cooperative scenario leads to overall system capacity improvement. In both cases the cognitive radios ensure that sum of interference caused by them in the spectrum remains below interference threshold.

I. INTRODUCTION:

Spatial considerations for frequency reuse have been ex-tensively studied in cellular systems. However, these systems largely differ from the cognitive radio (CR) systems . As the command-and-control structure of frequency allocation for traditional wireless communications, the within-system interference is the dominant interference to the users operating with the same operator. This kind of interference can be well controlled through planning. For these systems, power control has been studied in SIR-based, and information-theoretic contexts for fading and non-fading channels, for instance. However, in cognitive radio networks, th e interference is caused not only by the secondary users (SUs), or cognitive users, sharing the same spectrum, but also by the primary users (PUs), or licensed users, who share the spectrum. Additionally, the secondary users should not cause unacceptable interference to the primary users. In this paper we focus on the information-theoretic approaches, i.e., reviewing the optimal power allocation ap-proaches for the SUs to maximize the achievable rate under certain constraints. The framework employed to evaluate the power allocation schemes and other performance matrices is mainly based on information theory. There is a growing body of literature on power control/allocation in CR systems, power control for one pair of secondary users coexisting with one pair of primary users is considered. The secondary transmitter adjusts its transmission power to maximize its data rate without increasing the out-age probability at the primary receiver. The authors in Manuscript submitted June 20, 2014.The authors are with Communications and Systems Engineering Group, University of Vaasa, Finland.(emails: ruifeng.duan@ieee.org; {moel, rvir}@uva.fi).

The content of this paper is part of Duan's thesis, and is reprinted with the permission of the University of Vaasa. This work was supported in part by the SMACIW (Statistical Modeling and Control of Aggregate Interference in Wireless Systems, Decision no. 265077) project funded by the Academy of Finland. Proposed the optimal power control schemes based on the soft sensing information, and the capacity of the secondary user was maximized under a peak power constraint at the primary receiver. Power control for opportunistic spectrum access (OSA) in TV bands is investigated, where the primary users transmit all the time and spatial (rather than temporal) spectrum opportunities are exploited by secondary users.

For the interference control of the secondary users over television white spaces, Koufos *et al.* in proposed the power density and deployment based transmit power control of the secondary users such that the quality of the TV services is not violated by the aggregated interference.A comprehensive study of cognitive radio and associated challenges have been presented in [1]. The author in [1] considers a two-user interference channel where two cognitive radios compete to get best rate for themselves keeping in mind that the interference due to first radio at second radio receiver and vice versa is below the maximum allowed interference power. However the cognitive radios transmit in different spectrum holes.

A distributed power allocation algorithm was proposed for a TDD (time-division duplex) uplink scneraio where a primary radio and a cognitive radio talk to a single base station over the same frequency band. The authors have shown that the total capacity of the system improves in comparison to single-user case. The primary transmitter waterfills available transmit power against a virtual noise power level where the virtual noise power depends on cognitive radio's channel gains. The primary radio is assumed to know the cognitive radio's channel gains.

In this paper we consider two scenarios of coexistence of a primary radio with one or more cognitive (secondary) radios. In first scenario, the cognitive radios cooperate with each other. The first scenario can be divided into three cases. The first one is a multiple access case where two additional cognitive radios try to talk to a receiver using a band of frequency when a first cognitive radio is already talking to the same receiver using that band. We propose a power allocation algorithm for the three transmitters; the proposed power allocation algorithm results in an increase in total capacity of the multiple access system, compared to single cognitive radio case, at all interference power levels. The second and third case deal with a two-user channel where a first cognitive radio and a second cognitive radio send independent messages to respective receivers over the same frequency band.

In second case, the first cognitive radio is allowed to use the available power first; the second cognitive radio tries to get best rate for itself from the left-over resources. We call this scenario as preferential mode of transmission.

In third case, we find the power allocation strategies that two cognitive radios will follow to guarantee a minimum data rate for one of the two radios. We call it guaranteed data rate scheme. We show that, in second case and in third case, the total capacity of the two-user channel improves in comparison to single-user case at low interference power levels. We argue that the second case and third case have practical applications and thus worth studying. In second scenario, we again consider a two-user channel. The two users are two cognitive radios that operate over same frequency band and try to achieve individual target data rates simultaneously. We call this mode of data transmission as greedy approach.

An iterative water-filling algorithm applica-ble to digital subscriber lines was proposed by Wei Yu et al. [3]. Haykin proposed an iterative water-filling algorithm appli-cable to a two-user interference channel in [1]. We show that the two cognitive radios can attain the individual target rates using an iterative power allocation algorithm and we determine the necessary and sufficient conditions for convergence of the iterative power allocation algorithm. In both scenarios, since the cognitive radios transmit in presence of primary radio, they ensure that interference tem-perature limit is not violated at the intended receivers of the cognitive radios. Ideally interference temperature limit should not be exceeded at primary receiver. Satisfying the constraint at all probable locations of the primary receiver in absence of any knowledge about its location is not possible.

The interference temperature limit at measurement points must be thus set sufficiently lower than interference temperature actually tolerable by the primary receiver. A typical example of interest is coexistence of a WiMAX (Worldwide interoperability for Microwave access) radio that uses 3.5 GHz band for data transmission and an OFDM (Orthogonal Frequency Division Multiplexing) based UWB (Ultra-wideband) radio that uses 3.168 GHz to 4.752 GHz band (band-group 1) for data transmission [4]. The WiMAX radio is the primary radio and the UWB radio is the cogni-tive radio that can detect presence of WiMAX transmission. WiMAX transmission will interfere with typically two to four subcarriers of the OFDM based UWB. The cognitive UWB radio can choose to not send data on these couple of subcarriers or use channel coding to protect data on these subcarriers.

We are interested in the scenario where two or more UWB radios try to use the spectrum (band-group 1) at the same time. However, our study is not limited to WiMAX-UWB coexistence; it is applicable to all cases where the cognitive users use multicarrier modulation technique for data transmission. Throughout the analysis, the cognitive radios are assumed to know the noise power spectral density. j:j denotes modulus operation.

II. SINGLE USER SCENARIO:

A radio uses multicarrier modulation to send messages to its receiver over a frequency selective fading channel. The messages sent by the transmitter can be thought of passing through N parallel frequency flat subchannels of bandwidth W each. The subchannels fade slowly in comparison to length of the transmitted codewords so that we can consider the subchannel gains to remain constant over the time interval of interest. The input-output equation is: p

$$y^i = h^i \quad \overline{P\ ^i} x^i + n^i \;\; 8\ i \qquad (1)$$

x^i is unit-power symbol transmitted transmitter on subchannel i, y^i is symbol received by the receiver on subchannel i, h^i is complex gain of the ith subchannel between the transmitter and the receiver; P ^{i} is power transmitted by transmitter on ith subchannel; n^i is complex Gaussian noise on the ith subchannel with power spectral density (PSD) $^{N}{}_{2}{}^{0}$. Noise is assumed to have same PSD over all subchannels. The transmitter ia assumed to know the subchannel gains. The power allocation scheme across the subchannels that will maximize the radio's capacity under a total transmit power constraint is the well known water-filling solution. In cognitive networks, in addition to the total transmit power constraint, the interference temperature must not exceed the allowed upper limit, T_{max}, at any of the receivers [5]. The power allocation scheme that will maximize the radio's capacity under a total transmit power constraint and interference temperature con-straint ([1], pg 214) is solution of the following maximization problem.

$$\underset{P^1 \ldots P^N}{Max} \sum_{i=1}^{N} log_2 \left(1 + \frac{P^i \left|h^i\right|^2}{N_0 W}\right) \qquad (2)$$

subject to

$$\sum_{i=1}^{N} P^i \le P_{tot}, \;\; P^i \ge 0 \;\forall\, i,$$

and

$$\sum_{i=1}^{N} \left(P^i \left|h^i\right|^2 + N_0 W\right) \le F$$

Ptot is total transmit power; T_{max} is maximum allowed interference temperature in Kelvins; F = T_{max} k W N is interference temperature bound (ITB); k is Boltzmann's constant. The communication system can either be a TDD or a FDD (frequency-division duplex) system. The transmitter needs to receive the channel gain values from its receiver in an FDD system. F comprises desired receive signal power, receive noise power and undesired receive signal power from interferer(s) (in this paper, receive signal power from cognitive radio(s)).

III. MULTIPLE ACEESS SCENARIO:

A secondary user or cognitive radio is talking to a receiver using a frequency band licensed to the primary radio. A second and a third cognitive radio intend to talk to the same receiver using the aforea said frequency band along with the first cognitive radio. This is a multiple access scenario where three radios intend to transmit independent messages to a single receiver. The three cognitive radios decide to cooperate so that each one gets some resource. The input-output relation is given by:

$$y^i = h_1^i \sqrt{P_1^i}\, x_1^i + h_2^i \sqrt{P_2^i}\, x_2^i + h_3^i \sqrt{P_3^i}\, x_3^i + n^i \forall i \quad (3)$$

h_j^i is complex gain of the ith subchannel between the jth Transmitter and the receiver; P_j^i is power transmitted by jth Transmitter on ith subchannel; x_j^i is symbol transmitted by jth Transmitter on ith subchannel. Each of the transmitted symbols Has unit power. n^i is complex Gaussian noise on ith sibchannel With PSD $\frac{N_0}{2}$. Each of the three radios knows the channel gain between it and the receiver. We propose a power allocation scheme wherein the second and third cognitive radios transmit power that is inversely proportional to their respective channel gains. Such a channel inversion technique is not the best way to utilize available transmit power, but this power allocation technique ensures that the interference caused by the second and third cognitive radio transmissions to the first cognitive radio remains same for all subchannels. The second and third k3, to the first cognitive radio. k2 and k3 may be sent to the first cognitive radio via the receiver. Transmission of k2 and k3 does not consume large bandwidth particularly when the three radios are geographically close to each other [6].

$$P_j^i = \frac{k_j}{\left|h_j^i\right|^2}, \sum_{i=1}^{N} P_j^i = P_{tot}, \; P_j^i \geq \; 0, \; j = 2,3, \; i = 1 \cdots N \tag{4}$$

The first cognitive radio cooperates with the newly arrived second and third cognitive radios by trying to maximize its instantaneous capacity against an increased noise power level

$$\left(P_2^i \left|h_2^i\right|^2 + P_3^i \left|h_3^i\right|^2 + N_0 W\right)$$

instead of $(N_o W)$. The first Cognitive radio's transmit power is thus solution to the following maximization problem. And

$$\underset{P_1^1 \ldots P_1^N}{Max} \sum_{i=1}^{N} log_2 \left(1 + \frac{P_1^i \left|h_1^i\right|^2}{P_2^i \left|h_2^i\right|^2 + P_3^i \left|h_3^i\right|^2 + N_0 W}\right) \tag{5}$$

$$\sum_{i=1}^{N} \left(P_1^i \left|h_1^i\right|^2 + P_2^i \left|h_2^i\right|^2 + P_3^i \left|h_3^i\right|^2 + N_0 W\right) \leq F$$

The receiver is assumed to be capable of decoding the messages sent by the three cognitive radios using successive interference cancellation. We assume, without loss of generality, that the receiver decodes message sent by the first cognitive radio first, followed by messages sent by the second and the third cognitive radios. The first cognitive radio's data rate suffers as compared to single-user case (2). However, as shown in section VII, the total data rate attained by the three radios is more than the single-user data rate at all interference temperature bound-to-noise ratios (ITBNR), thus proving that transmission by multiple cognitive radios as per proposed power allocation scheme in the frequency band allocated to primary user improves system capacity.

IV. PREFERENTIAL MODE SCENARIO

A first cognitive radio is talking to its receiver over a frequency band that is licensed to the primary user. A second cognitive radio that intends to talk to a second receiver wishes to use the same frequency band. This is a two-user channel scenario. The input-output relation is given by:

$$y_1^i = h_{11}^i \sqrt{P_1^i} x_1^i + h_{21}^i \sqrt{P_2^i} x_2^i + n_1^i \;\forall\, i \tag{6}$$

$$y_2^i = h_{12}^i \sqrt{P_1^i} x_1^i + h_{22}^i \sqrt{P_2^i} x_2^i + n_2^i \;\forall\, i \tag{7}$$

h_{jk}^i is channel gain of the ith subchannel between the jth Transmitter and kth receiver; P_j^i is power transmitted by jth Transmitter on ith subchannel. n_1^i and n_2^i are complex Gaussian Noise, each with power spectral density $\frac{N_o}{2}$. The first cognitive Radio knows the channel gain between it and its receiver. We propose a power allocation scheme wherein the first cognitive radio allocates power across the N subchannels such that its capacity gets maximized under a total transmit power constraint and 80% of the maximum interference temperature bound constraint (similar to equation (2)). Transmission at 20% below the ITB ensures that the second cognitive radio stands a chance to transmit. However, the above restriction reduces the capacity of the first cognitive radio. The first cognitive radio is thus indirectly assisting the second cognitive radio to attain a positive data rate in its presence. The second cognitive radio knows the channel gain between its transmitter and its receiver (h^i_{22}) the channel gain between the first transmitter and the second receiver (h^i_{12}) and the interference due to the first transmitter at the second receiver for all subchannels.

The second receiver can measure h^i_{12} by listening to pilot symbols sent by the first transmitter. For that the second receiver must know when the first cognitive radio is transmitting pilot symbols and signature of the first cognitive radio's pilot symbols. The first cognitive radio needs to provide these information to the second cognitive radio thereby indicating that cooperation between first cognitive radio and second cognitive radio is necessary.Once the first cognitive radio decides its power allocation scheme, the second cognitive radio tries to get best rate out of the remaining power. The second cognitive radio allocates power across the N subchannels such that the interference temperature constraint is neither violated at the first receiver nor at the second receiver. The second cognitive radio's transmit power is obtained by solving the following maximization problem.

$$\underset{P_2^1 \ldots P_2^N}{Max} \sum_{i=1}^{N} log_2 \left(1 + \frac{P_2^i \left|h_{22}^i\right|^2}{P_1^i \left|h_{12}^i\right|^2 + N_0 W}\right) \tag{8}$$

subject to

$$\sum_{i=1}^{N} P_2^i \leq P_{tot}, \; P_2^i \geq \; 0 \;\forall\, i,$$

$$\sum_{i=1}^{N} \left(P_1^i \left|h_{11}^i\right|^2 + P_2^i \left|h_{21}^i\right|^2 + N_0 W\right) \leq F$$

and

$$\sum_{i=1}^{N} \left(P_1^i \left|h_{12}^i\right|^2 + P_2^i \left|h_{22}^i\right|^2 + N_0 W\right) \leq F$$

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The first cognitive radio is given priority over the second cognitive radio for using the available power. The first cognitive radio, in presence of the second cognitive radio, operates at a lower ITB. Thus it is not expected to get as much data rate as it gets when it operates at a higher ITB. In return, the second cognitive radio gets a positive data rate, however small it may be, at all noise power levels. This preferential mode of transmission is useful when the second cognitive radio needs to transmit emergency information to its receiver. The preferential mode of power transmission does not guarantee a minimum data rate for the first cognitive radio.Throughout the simulation, we assumed the sub channels to be symmetric, i.e., $h^i_{jk} = h^i_{kj}$.

V. GUARANTEED DATA RATE APPROACH

The system model is identical to that described by equations (6) and (7). We propose a power allocation scheme which is suitable for a scenario where the first cognitive radio has to attain a minimum data rate R even in presence of the second cognitive radio. The objective is to, instead of maximizing capacity of the first cognitive radio, minimize the probability that first cognitive radio data rate falls below R.Using the theory of majorization [7], we know that the power allocation $P^i_j = P/N$.

$$\underset{P_1^1 \dots P_1^N}{Min} \; Prob\left(\sum_{i=1}^{N} log_2\left(1 + \frac{P_1^i \left|h_{11}^i\right|^2}{I^i + N_0 W}\right) < R\right) \quad (9)$$

subject to

$$\sum^{N} P_1^i \leq P_{tot}, \; P_1^i \geq \; 0 \; \forall \; i,$$

I^i is interference seen by the first receiver on i^{th} sub channel. This interference is due to the presence of the second cognitive radio's transmission. Once the first cognitive radio distributes the available power equally among the N sub channels, the second cognitive radio maximizes its capacity under a total transmit power constraint and interference temperature constraint. The second cognitive radio's power allocation scheme is such that it does not violate the interference temperature limit at the first receiver and at the second receiver (8). The second cognitive radio transmitter is assumed to know the channel gain between it and its receiver (h^i_{22}, the channel gain between the first transmitter and the second receiver (h^i_{12}) and the interference due to the first transmitter at the secondary receiver for all sub channels. The total data rate achieved by the first cognitive radio and the second cognitive radio is more than the single-user case only at low ITBNRs. It is to be noted that the first cognitive radio' need not know the channel gain between it and its receiver in the guaranteed data rate approach.

VI. GREEDY APPROACH

We consider a two-user channel where the first cognitive radio and the second cognitive radio send independent messages to respective receivers over the same frequency band. The system model is described by equations (6) and (7). The aim of each radio is to get best data rate for itself. We use an iterative power allocation algorithm in which the two radios try to increase individual data rates simultaneously while treating interference caused by the other radio as noise. We show that the above algorithm converges and hence a solution exists. The algorithm comprises of two loops, an inner loop and an outer loop [3]. We set target data rates for the two radios. The algorithm iterates through the loops until the radios attain respective target data rates.

Inner Loop

Step I: The first cognitive radio maximizes its capacity subject to interference temperature constraint at the first receiver assuming that the second cognitive radio is silent. The first transmitter knows the channel gain between it and its receiver and noise power spectral density.

Step II: For the first transmitter power calculated in step I, the second transmitter maximizes its capacity subject to interference temperature constraint at the second receiver. The second transmitter knows the channel gain between it and its receiver, noise power spectral density and the interference power due to the first transmission at the second receiver.

Outer Loop

The first radio calculates data rate achieved by it. If the achieved data rate is less (more) than the target rate then the first transmitter increases (decrease) its transmit power by x percent. Next the second radio calculates data rate achieved by it. It increases or decreases its transmit power by x percent depending on its data rate. The first radio recalculates its data rate. If both the first and second radios' data rates are less than their respective target data rates, the algorithm goes back to inner loop.

From the second iteration onwards, interference due to the second transmitter is taken into account while calculating the first transmittter's power. A solution to the iterative algorithm exists if

$$\alpha_i\beta_i < 1 \,\forall\, i \qquad (10)$$

Where

$$\alpha_i = \frac{|h^i_{21}|^2}{|h^i_{11}|^2}, \qquad \beta_i = \frac{|h^i_{12}|^2}{|h^i_{22}|^2}$$

For given first radio's power $P_1^1 \ldots P_1^N$, the second

Radio's transmit power is solution to the following maximiza-

Tion problem:

$$\underset{P_2^1 \ldots P_2^N}{Max} \sum_{i=1}^{N} log_2\left(1 + \frac{P_2^i\left|h^i_{22}\right|^2}{P_1^i\left|h^i_{12}\right|^2 + N_0W}\right) \qquad (11)$$

Subject to

$$\sum_{i=1}^{N}\left(P_1^i\left|h^i_{12}\right|^2 + P_2^i\left|h^i_{22}\right|^2 + N_0W\right) \le F,\ P_2^i \ge 0 \,\forall\, i \ (12)$$

The solution to the above problem is

$$P_2^i = \left(\frac{K_2 - N_0W}{\left|h^i_{22}\right|^2} - \beta_i P_1^i\right)^+ \forall\, i \qquad (13)$$

Where K2 is a positive constant. By fixing $P^1_2 \ldots P^N_2$ obtained from the above step, the first radio's transmit power can be similarly determined.

CONCLUSION:

The cognitive radio operates in co-operative and the aim of present project is to allow multiple CR transmitters, send independent messages over the same frequency band. we evaluated performance of the distributed algorithm as studied the power management for secondary users in the presence of varying data rate requirements of the Secondary Users in general we conclude that as the data rate of the Secondary Users increases then the capacity and throughput of active SU significantly reduces.

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