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THROUGHPUT MAXIMIZATION IN COGNITIVE RADIO USING JOINT BEAMFORMING AND POWER CONTROL

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Abstract. *The reason for the birth of cognitive radio (CR) is to utilize the spectrum resources efficiently by allowing secondary (unlicensed) users to access licensed frequency bands without harmful inference to the licensed (primary) users. In this paper, we discuss the tradeoff among the spectrum sensing ability, the throughput of the CR system and the interference to the primary users. In conventional frame structure, the secondary system has to sense the licensed frequency bands within the allocated sensing time before data transmission. During spectrum sensing, the transmission of data is not allowed which makes the sensing-throughput tradeoff problem, in the cognitive system. To solve this tradeoff, this paper proposed joint beamforming and power control method with optimal target detection probability. The proposed approach ensures the protection to the primary system as well as overcoming the sensing throughput tradeoff problems in CR system. The simulation result demonstrates that the optimal transmit power and optimal target detection probability maximize the throughput.*

Keywords: Throughput optimization, Power control cognitive radio, Beamforming, Interference, Detection probability

1. **Introduction.** As most of the available bands have been licensed out and the unlicensed bands are filling up fast, we are facing spectral crisis. Moreover, fixed spectrum allocation for different services has caused inefficient utilization of spectrum because most of the time, the large portion of the bands remain unused. Therefore, to make better utilization of available spectrum, non-legitimate users are enabled to utilize licensed bands without causing significant interference to the primary users (PUs). This concept for wireless communication is termed as cognitive radio (CR). This intelligent radio can sense the idle band of the spectrum and transmit data through the band [1]. It can create awareness of RF, audio, video, temperature, acceleration, location and others of surrounding the environment to choose the best action among all the candidate actions [2].

In cognitive radio, the secondary system has to perform sensing the licensed frequency bands within the allocated sensing time before data transmission. Spectrum sensing plays a challenging role in the cognitive networks [4]. Its aim is to grab unused channel without interfering the licenses users. For the last few years, significant studies have been done on the spectrum sensing to improve the performance of spectrum sensing [3]. There are two parameters associated to the spectrum sensing – one is false alarm probability and the other one is detection probability. If the detection probability is higher, the transmission of PU will be protected. Conversely, the lower the false alarm probability, the more opportunities for CR users to reuse the spectrum band. In conventional frame structure, a specific sensing time slot is used for sensing licensed frequency band before data transmission. Confessing the classic detection theory [5,6], a reliable protection of PUs can be ensured if sensing time increases which in turn results in high detection probability. Then again, increased sensing time will provide a lower throughput of the secondary system in conventional frame structure. Hence, an intrinsic tradeoff exists between the throughput and the sensing time in CR system. To mitigate this problem, the transmit power of secondary users and sensing time are both optimized with conventional frame structure in [4]. In addition, a novel frame structure approach is presented to overcome this problem where both spectrum sensing and data transmission are performed at the same time [7]. In this paper, we have addressed the problem of determining the optimal power allocation strategy that maximizes the throughput of the cognitive radio system under some constraints. In practice, the perfect spectrum sensing may not be achievable due to the limitations of spectrum sensing techniques. Therefore, we additionally consider in this paper the case that frequency band is falsely detected to be idle, when in fact it is active. The joint beamforming and power control approach is proposed which jointly updates the set of beamforming vectors, w and power vector, p to converge optimal solution while satisfying the SINR constraints of SUs and interference constraints of PUs. The proposed approach gives a higher throughput in comparison to the existing approaches in [4,7] and reduces the interference to primary users that give us a better system performance.

The main contributions are summarized as follows:

- Propose an optimization framework for joint beamforming weights and power allocations at the BS to support minimum SINR requirements at user terminals;
- Propose an approach that acquires optimal detection probability and power allocation scheme using modified WLS that maximizes the throughput under some constraints.

The paper is structured as follows. Section 2 reports the related works in maximizing the throughput in cognitive radio network. In Section 3, the system model is described. The problem formulation is also described in this section. Section 4 discusses the throughput of the cognitive radio. Join beamforming and power control approach is presented in Section 5. Numerical results are presented and discussed in Section 6. Finally, conclusions are drawn in Section 7.

2. **Related Works.**

Throughput maximization for cognitive radio network is a challenging task under interference constraints. Y. Y. He and S. Dey examine the ergodic capacity maximization problem of SU in [14] that uses the same frequency band with a number of PUs in a narrowband spectrum-sharing CR framework under certain constraints. The secondary-user transmitters (SU-Tx) have the channel-state information (CSI) which transmit average power with limited peak interference at each primary-user receiver (PU-Rx). J. Zhang et al. [15] propose a joint uplink power and sub channel allocation algorithm based on particle swarm optimization (PSO) to diminish resource allocation problem and to maximize the uplink throughput of secondary users (SUs) in CR network under the constraints of the primary user (PU) interference. M. Zhan et al. propose a cross-layer channel assignment and routing (CCAR) algorithm for throughput maximization in [16] under the interference avoidance issue in cognitive radio networks (CRNs). M. Pan et al. propose in [17] a cross-layer approach to maximize the multicast throughput in multi-hop CRNs bearing in mind the availability of spectrum and sharing fairness. Y. Tsai and Y. C. Chao proposed a scheme in [18] that can simply find the prearranged optimal number of channels for data transmission in order to optimize the system throughput taking into consideration the tradeoff between the sensing time and the number of available channels. S. Li et al. present in [19] a series of algorithms to maximize the system throughput through cooperative sensing in cognitive radio network that consists of a single PU and several SUs. S. Khalili et al. [20] propose an optimal spectrum sensing approach to maximize the total throughput of the system under some constraints on the interference to the primary users (PUs). G. Nie et al. proposed a cluster-based cooperative spectrum sensing model [21] in order to reduce the reporting time. The optimal clustering rule is obtained through maximizing the transmission time of all SUs. Then, a low-complexity solution is proposed to overcome the sensing throughput tradeoff issue, which shows close-to-optimal performance.

In this paper, the authors present joint beamforming and power control scheme with full frame structure to maximize the throughput while overcoming the sensing-throughput tradeoff problem and protecting PUs from harmful interference.

3. **System Model.**

This paper is concerned with the data transmission in a single cell of the cellular network. A secondary CR network operates within the area of the primary cellular network is considered in the presented system model where N is the number of SUs, who opportunistically access the allocated primary frequency band with M number of PUs. Each SU and PU has been equipped with single antenna transceiver system. The communication between SUs has been done through a secondary BS (SBS) which is furnished with an adaptive uniform linear array of K antenna elements and is positioned at the center of the CR network as shown in Figure 1. The multiantenna BS supports simultaneous transmission of independent information to multiple single antenna mobile users at the same frequency. Due to simultaneous transmission at same frequency, the co-channel interference exists. The co-channel interference can be effectively pre-suppressed at the transmitter of the BS by applying joint beamforming and power control over different user data streams. Before accessing the frequency band and data transmission, cognitive system has to sense the status of the spectrum. The energy detection technique is used for sensing, which is the most popular spectrum sensing technique to decide the status of the primary users [8,9]. It is presumed that the SUs are aware of the environment and the SBS has the perfect knowledge about the transmission channel.

As both the primary and secondary network use identical frequency band, the received signal at the SBS is interfered by the primary users' data transmission. Also, the received signal at the PUs receiver is obstructed by the secondary users signal transmission. Bearing the noise in mind, the SINR, ξ_n of the SU_n and total interference δ_m at PU_m are given

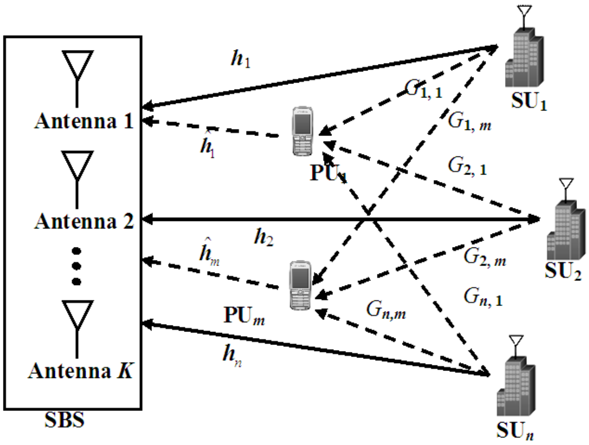


Figure 1. The diagram of system model [13]

correspondingly as [13]

$$\xi_n = \frac{|w_n h_n|^2 P_n}{\sum\limits_{\substack{i=1 \\ i \neq n}}^{n} |w_n h_i|^2 P_i + \gamma_n^2 \|w_n\|^2 + \sum\limits_{m=1}^{N} \left| w_n^H \hat{h}_m \right|^2 P_m}, \quad \forall n \in [1, N], \forall m \in [1, M] \tag{1}$$

$$\delta_m = \sum_{m=1}^{n} |X_{n,m}|^2 P_m, \quad \forall n \in [1, N], \forall m \in [1, M] \tag{2}$$

where, w_n denote the beamforming weights and are normalized as, $\|w_n\|^2 = 1, \forall n \in [1, N]$. The receiver noise power is expressed as γ_n^2. P_m is the transmit power of PU_m and a fixed value of P_m is chosen whereas P_n indicates SU_n transmitted power. h_n and $\hat{h}_m$ are being the channel response vector from SU_n to BS and PU_m to BS respectively.

The objective of the joint power control and beamforming problem is to find optimal beamforming weight vector in such a way that every SU attains its target SINR [13]. Thus, the interference level at PUs depends on both the gain between interfering SUs and PUs and the transmit power of SUs. Therefore, to gain reasonable performance of the SUs in the CR network without harmful interference to PUs, joint beamforming and power control method is optimized. The optimization is done in such a fashion that all the SUs have SINRs above the threshold value of ξ_0 while maintaining the overall interference at PUs within the maximum reasonable limit, μ_0. Accordingly, the joint power control and beamforming problem can be expressed as follows [13]

$$\begin{aligned} &\min_{w,p} \sum_{n=1}^{n} P_n \\ &\text{subject to } \xi_n \geq \xi_0 \text{ and } \delta_m \leq \delta_0, \forall n \in [1, N], \forall m \in [1, M] \end{aligned} \tag{3}$$

4. **Throughput Analysis of the Cognitive Radio.** In this section, the average throughput of the cognitive radio system is studied using the full-frame structure shown in Figure 2 instead of conventional frame structure. The conventional frame structure uses a limited amount of time for spectrum sensing but in case of full frame structure, the authors do both spectrum sensing and data transmission at the same time, thus possible to optimize the duration of both and hence, overcome sensing-throughput tradeoff. This allows increased data transmission with increased sensing time. As a result, throughput is maximized with improved sensing performance. In this paper, energy detection scheme is used for spectrum sensing. This is quite a popular technique in cognitive radio because it shows evidence of low complexity, also robust to unknown channels, fading and variation of the primary signal, and additionally it does not require any prior knowledge of the PU signal under detection.

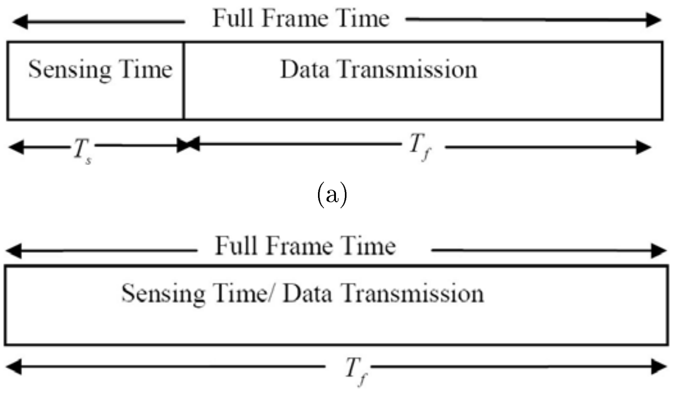
The probability of detection and the probability of false alarm in case of the energy detection scheme can be expressed as [11]

$$\text{Pr}_d = Q\left(\left(\frac{\varepsilon}{\sigma_n^2} - \xi_n - 1\right)\sqrt{\frac{T_s f_s}{2\xi + 1}}\right) \tag{4}$$

$$\text{Pr}_{fa} = Q\left(\left(\frac{\varepsilon}{\sigma_n^2} - 1\right)\sqrt{T_s f_s}\right) \tag{5}$$

where, ε denotes the decision threshold of energy detector and σ_n^2, the noise variance.

However, spectrum sensing with opportunistic spectrum access is not a perfect function caused by the limitations of the spectrum sensing techniques and the behaviour of wireless communications that include shadowing and fading phenomena. Therefore, either the



(a)

(b)

Figure 2. (a) Conventional frame structure and (b) full-frame structure

primary user might be miss-detected or a false alarm may occur. Thus, two different situations can be illustrated regarding the sensing decision (present or absent) and the actual status of the PU (active or idle) on each frequency band

(i) that is correctly detected as idle and the throughput of the cognitive radio network in this context is expressed by c_0 and

(ii) that is falsely detected as idle and the throughput of the cognitive radio network in this context is expressed by c_1.

$$c_0 = \log_2\left(1 + \frac{P_n h^2}{\sigma_n^2}\right) \tag{6}$$

$$c_1 = \log_2\left(1 + \frac{P_n h^2}{P_m g^2 + \sigma_n^2}\right) \tag{7}$$

where, h^2 and g^2 represent channel power gain between the SU_n Tx-Rx and PU_m Tx-Rx respectively. The average throughput of the cognitive radio for the opportunistic spectrum scheme can be written as:

$$C = \left(\frac{T_f - T_s}{T_f}\right)\left[\Pr\left(H_0\right)\left(1 - \Pr_{fa}\right)c_0 + \Pr\left(H_1\right)\left(1 - \Pr_d\right)c_1\right] \tag{8}$$

where, $\Pr(H_0)$ indicates the probability of the channel to be idle and $\Pr(H_1)$ indicates the probability of the channel to be active. Two probabilities are of interest for spectrum sensing: probability of detection, which correctly detects the presence of primary signal and probability of false alarm which falsely declares the presence of primary signal. $\Pr_d$ and $\Pr_{fa}$ are respectively represents the detection probability and false alarm probability. As of the primary user's point of view, the higher the detection probability, the better protection it receives whereas the secondary user's perspective, the lower the false alarm probability, the higher chances for secondary users of using available bands. Here, T_s denotes the sensing time whereas T_f, the frame duration. In the next section, joint beamforming and transmit power (P_n) of the secondary are optimized using our modified weighted least square (WLS) approach for throughput maximization with full frame structure. It provides better throughput than [22].

5. **Joint Beamforming and Power Control in Maximizing Throughput.** There is another trade-off between interference level and system throughput in CR system. With the increase of transmits power, system throughput increases but at the same time interference level also increases. Therefore, transmit power allocation is done in an optimized

manner for maximizing system throughput subject to the interference constraints. This is achieved through joint beamforming and power control approach. The minimum variance beamforming (MVB) method is chosen for the system as it is adaptive in nature and can improve system capacity by suppressing the co-channel interference induced by the transmission of SUs. The received SINR of the SUs also increases due to the use of MVB. The proposed joint beamforming and power allocation algorithm is implemented by using modified WLS power control with a full-frame structure of the secondary system. The throughput maximization is implemented under the following constraints

$$\begin{aligned}&\max_{w_n, P_n}\ C\\&\text{subject to } \xi_n \geq \xi_0 \text{ and } \delta_m \leq \delta_0,\ \forall n \in [1, N],\ \forall m \in [1, M]\end{aligned} \tag{9}$$

where, δ_0 is interference threshold to PU_n and ξ_0 is the SINR threshold of secondary user.

The transmission power of SU is derived from Equations (1) and (2) and maintains threshold interference and SINR level and can be written as

$$P_n = \frac{(\delta_0 + \xi_0)\left(w_n\gamma_n^2 + \left(w_n^\dagger R_m\right)^2 P_m\right)}{\left(I_N - \xi_0\left(\frac{|w_nR_n|^2}{|w_nR_m|^2}\right) + |X_{m,n}|^2\right)\left|w_k^\dagger R_k\right|^2}, \quad \forall n \in [1, N],\ \forall m \in [1, M] \tag{10}$$

where, $(.)\dagger$ is the hermitian transpose of the matrix. To optimize the transmit power of the secondary system, we have to maintain

$$\frac{\xi_0\left(w_n\gamma_n^2 + \left(w_n^\dagger R_m\right)^2 P_m\right)}{I_N - \xi_0 b} \leq P_{n,\max} \text{ and } |X_{m,n}|^2 \frac{\xi_0\left(w_n\gamma_n^2 + \left(w_n^\dagger R_m\right)^2 P_m\right)}{I_N - \xi_0 b} \leq \delta_0$$

for optimizing Equation (10). Taking into account the optimization problem, Equation (9) is optimized using modified WLS and can be expressed as

$$P_n = \frac{\Phi^\dagger\Phi\xi_0\left(w_n\gamma_n^2 + \left(w_n^\dagger R_m\right)^2 P_m\right)}{\Phi^\dagger\Phi\left(I_N - \xi_0\left(\frac{|w_nR_n|^2}{|w_nR_m|^2}\right)\right)\left|w_k^\dagger R_k\right|^2}, \quad \forall n \in [1, N],\ \forall m \in [1, M] \tag{11}$$

where, $\Phi = diag\left(1_M, \omega_n\right)$ is a diagonal weight matrix of size $(N + M) \times (N + M)$.

The power optimization using the above solution can provide us considerable protection to PU and better spectrum sensing as well as maximizing the throughput of CR system.

6. Results and Analysis.

This section presents the simulation result of throughput for the opportunistic spectrum access cognitive radio system using the energy detection scheme as a spectrum sensing technique. The frame duration is set to $T_f = 100$ ms and the sampling frequency is $f_s = 1$ MHz. To tackle the tradeoff between sensing-throughput, we consider a scenario of 3 secondary users and 5 primary users. The user terminals are uniformly placed over the area of service around a single base station. The base station has 10 antenna elements with a centre frequency of 600 MHz and receiver noise power is -120 dBm. In this paper, two sets of constraints are considered: interference power to the PUs and peak transmission power to the SUs. Based on these constraints, the initial transmit power of all secondary users is set 10 dB and the threshold value of SINR for all secondary users is 12 dB. The limit of acceptable interference to all primary users is -100 dBm to ensure QoS of the PUs. To measure the performance of our method, the values of the parameters are as follows [22]; the probability that the frequency band is idle, $P_r(H_0) = 0.8$, whereas, the probability that the frequency band is to be active, $P_r(H_1) = 0.2$, and $P_m = 10$ dB.

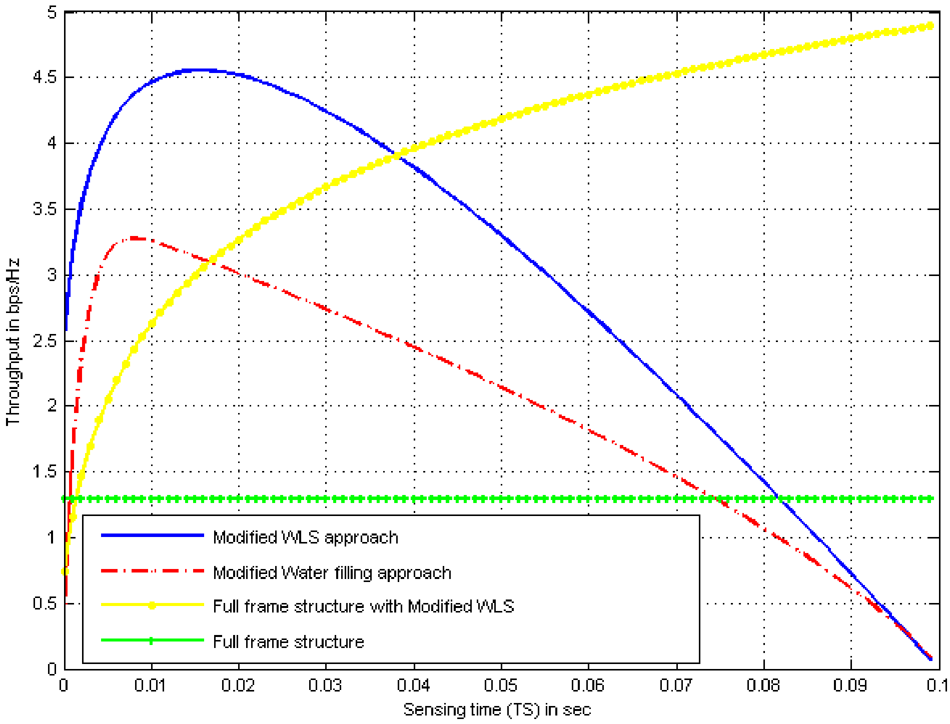


FIGURE 3. The throughput of the cognitive systems versus the sensing time

Figure 3 shows the comparison in terms of throughput of the cognitive users. The method of [22] is also simulated for comparison. From the figure, a noteworthy improvement is observed in throughput of the secondary system using the power optimization with modified weighted least square (WLS) approach. The proposed method using modified WLS solution jointly updates the set of beamforming vectors, w and power vector, p to converge optimal solution while satisfying the SINR constraints of SUs and interference constraints of PUs. This optimal power allocation strategy maximizes the throughput of the cognitive radio system. The simulation result presents throughput maximization with the increase in sensing time.

7. Conclusions.

This paper studies the problem of maximizing the throughput of the opportunistic spectrum access cognitive radio under both average transmit and interference power constraints. Furthermore, an optimization approach is presented for joint design of beamforming weights and power allocations to support QoS as well as maximizing throughput. Modified WLS approach confirms better protection to primary users with high SINR of secondary users. It is also observed that the optimal transmit power with modified WLS method with a full-frame structure maximizes the throughput of CR system as well, in comparison to the traditional method. This innovative method also guarantees improved spectrum sensing of the CR system as well as overcomes the sensing-throughput tradeoff.

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