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Throughput Analysis of a Energy Harvesting Cooperative Cognitive Radio Network

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Abstract

In this paper, energy harvesting cooperative cognitive radio (CR) network is studied under a collision constraint of PU. Optimal numbers of CRs cooperate in transmission of primary user (PU), if it remains present in the given channel; otherwise all the CRs transmit their own data in time division scheme. The harvested energy at CR is divided into two parts, one part is allocated for cooperation in PU transmission and the other part is used for its own transmission. The allocation of energy is based on the targeted CR throughput. Influence of an energy allocation parameter and sensing time on throughput performance is studied under the random behaviour of PU.

1 Introduction

In recent time, CR technology has come up as a promising approach to resolve the spectrum scarcity problem in wireless communication. In CR technology, a CR user accesses the PU spectrum while it is found to be free. Thus, in a CR network, reliable spectrum sensing is a challenging task to protect the quality of service (QoS) of PU and maximizing the secondary network throughput. The sensing performance can be influenced by fading in the sensing channel [1]. The impact of fading on the sensing performance can be reduced significantly if the CRs in a cooperative network cooperate their decisions at the fusion centre (FC) for overall decision [1, 2]. It is also shown in [3] that there exists an optimal number of CRs among the cooperating CRs, for which the error in sensing performance becomes less [3]. In [4], a cooperative CR ad hoc network is studied where CR users cooperate in PU transmission. The cooperation of a CR to PU increases the network throughput. In [5], the authors studied the trade-off of throughput and sensing time keeping QoS of PU to a target level. It has been observed that the optimization of sensing period maximized the network throughput. On the other hand, in an energy constraint network, the energy efficiency of the network improves if the network throughput improves [6].

Energy harvesting scheme makes the wireless system free from energy constraints [7, 8, 9]. An optimal energy management policy for a sensor node is studied to maximize the throughput of an energy harvesting sensor network [10]. A decision policy to select the optimal mode to achieve the maximum the throughput based on non-RF energy harvesting has been proposed in [11]. A hybrid spectrum access model for an energy-harvesting CR network has been investigated in [12] where harvesting is done from a RF source as well as from other ambient sources. In [13], energy allocation parameter has been estimated for a CR network which consists of a pair of CR users. The CR user transmits its own data and also helps in PU transmission [13]. In this paper we consider cooperative CR network scenario with multiple CRs that transmit their own data in absence of PU and an optimal number of CR users cooperate in PU transmission.

The major contributions in this paper are as follows:

- When PU is present, optimal number CRs users are obtained by minimizing the total error and that optimal number of CRs relay the PU data on amplification and forward basis.
- The achievable total throughput (throughput from CR network plus the part of PU throughput obtained from CRs cooperation) of a cooperative CR network under a collision constraint of PU is analyzed.
- The CR transmitter harvests from non-RF and RF sources. An energy allocation ratio parameter is proposed to allocate energy judiciously to achieve the own targeted throughput of the CR system and to cooperate in PU transmission. The influence of energy allocation ratio parameter on total throughput is also studied.
- MATLAB simulation is carried out to show the efficacy of the proposed energy harvesting technique in a cooperative cognitive network.

The rest of the paper is organized as follows: In Section 2, a formal description of the system model is given. Next, an analytical framework for the considered network scenario is developed. In Section 3, results are presented. Finally we conclude in Section 4.

2 System Model

The network model of a CCR network is shown in Fig. 1 and consists of a PU transmitter (PU_{TX}) and a PU receiver (PU_{RX}); N number of CR transmitters (CR_{TX}), N number of CR receivers (CR_{RX}) and a fusion center (FC). The CR system uses the PU band opportunistically. Thus, all the CR transmitters (CR sources) of the CR system sense the PU channel and access the same in TDMA scheme when PU is found to be absent. It is considered that only optimal number CR users (n_{opt}, where $n_{opt} \leq N$), cooperate among each other in sensing and cooperate in PU transmission. During PU cooperation all the n_{opt} CRs act as Amplify and Forward (AF) relays. All the CR_{TX} harvest energy from non-RF sources as well as from RF source such as PU signal. The activity of PU is unpredictable. It is assumed that the

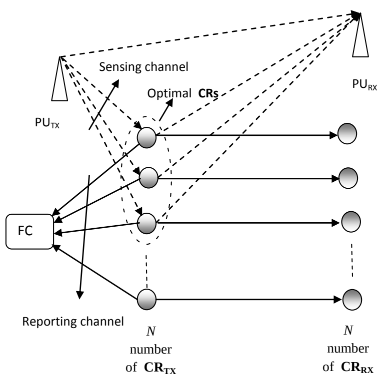

Figure 1. Cooperative energy harvesting CR network

busy period, i.e., H_1 and the ideal period, i.e., H_0 of PU are exponentially distributed with the mean values b_0 and a_0, respectively. The distribution of the busy period, i.e., $P_b(t)$ and the ideal period, i.e., $P_i(t)$ are considered as in [14]. Some important probabilities such as probability busy period (P_{busy}), probability of idle period (P_{idle}), probability of disappear from spectrum band (P_{dis}), and probability to re-occupy the spectrum band (P_{re}) are also considered as in [14]. All the CR_{TX} sense the presence of PU periodically. It is considered that the detection frame time for all the CR_{TX} are same and synchronized. The time length of the detection frame is T which consists of sensing time (t_s) and transmission time (t_r), i.e., $T = t_s + t_r$. During t_s, all the CR_{TX} sense the spectrum as well as harvest energy; during t_r, they continue harvesting from non-RF sources and transmit if PU is found to be absent. All the CR_{TX} harvest continuously from non-RF resources and also harvest from RF signal of PU while PU is present.

Each CR_{TX} consists of an energy splitter [15]. It divides the stored power P_s in the ratio of $\eta : (1-\eta)$ per unit time during t_s for harvesting and sensing. We also assume that the links exist between PU_{TX} - PU_{RX}, PU_{TX} - $CR_{TX,i}$, $CR_{TX,i}$ - PU_{RX}, and $CR_{TX,i}$ - $CR_{RX,i}$ are complex normal, i.e., $\mathcal{N}(0,1)$ and the respective channel coefficients are h_{pp}, $h_{pc,i}$, $h_{cp,i}$ and $h_{cc,i}$ where $i = 1,2,3,...N$. The instantaneous gains of the links are $G_{pp} = |h_{pp}|^2$, $G_{pc,i} = |h_{pc,i}|^2$, $G_{cp,i} = |h_{cp,i}|^2$, and $G_{cc,i} = |h_{cc,i}|^2$, respectively. The link gains are exponentially distributed with mean g_{hm}.

2.1 Sensing analysis

Each CR_{TX} starts its detection cycle with a residual energy, ξ_r. The observation statistic ($T_{CR,i}$), at the i-th CR_{TX}, can be written as [5]

$$T_{CR,i} = \frac{1}{N_s}\sum_{j=1}^{N_s} |y(j,i)|^2 \tag{1}$$

where $y(j,i)$ is the received signal at the i-th CR over sensing channel, $N_s = t_s f_s$ where f_s is the sampling rate. For a large number of samples, $T_{CR,i}$ can be approximated to a Gaussian distribution with the mean and variance, $\mu_0 = \sigma_w^2$, $\sigma_0^2 = \frac{1}{N_s}\sigma_w^4$ under H_0 condition and $\mu_1 = (1+\gamma_s)\sigma_w^2$, $\sigma_1^2 = \frac{1}{N_s}(1+2\gamma_s)\sigma_w^4$ under H_1 condition, respectively, as considered in [5]. Here σ_w^2 is the noise variance and $\gamma_s = d^{-n}\sigma_s^2/\sigma_w^2$, σ_s^2 is the signal variance, d is the distance between PU_{TX} and CR_{TX}, and n is the path loss exponent. The observation statistic is compared with a predefined threshold λ_s and $CR_{TX,i}$ gets a sensing decision about the presence of PU. Thus, for N number of CRs, the overall probability of detection ($Q_d(t_s)$), probability of missed detection ($Q_m(t_s)$) and probability of false alarm ($Q_f(t_s)$) for OR fusion rule can be expressed as

$$Q_d(t_s) = 1-(1-P_{d,i}(t_s))^N \tag{2}$$

$$Q_m(t_s) = 1-Q_d(t_s) \tag{3}$$

$$Q_f(t_s) = 1-(1-P_{f,i}(t_s))^N \tag{4}$$

where $P_{d,i}(t_s))$, $(P_{m,i}(t_s))$ and $(P_{f,i}(t_s)$ are the individual probability of detection, probability of missed detection, probability of false alarm, respectively, over faded channel [5]. It is necessary to optimize the number of CRs to limit the delay. Thus, the optimal number of CRs can be obtained if the total error is minimized. The optimal number of CRs can be obtained as [2],

$$n_{opt} = min(N, \lceil n \rceil) \tag{5}$$

where $n = \ln[Q_f(t_s)/(1-Q_m(t_s)))]/\ln[Q_m(t_s)/(1-Q_f(t_s))]$.

If the overall decision finds that the PU is present in the given channel, then the n_{opt} number of CR_{TX} forward the received PU signal to PU_{RX} after amplification with factor $\beta_{cp} = \sqrt{\frac{1}{|h_{cp}|^2 P_{CR,i}+\sigma_w^2}}$. Here, $P_{CR,i}$ is the i-th CR transmission power.

2.2 Harvested Energy from RF and non-RF resources

A CR_{TX} keeps on harvesting from non-RF signal during the entire detection cycle, it also harvests from RF signal of PU if PU is present (during t_r). It is assumed that the non-RF harvesting, i.e., $E_{NR,i}$, follows Poisson process with mean $E_{nr,i}$ (energy per unit time) [13]. Thus, energy is received in the form of packets, i.e., $E_{NR,i} = \{E_h^1, E_h^2 ... E_h^m\}$ [13]. The harvested energy from non-RF resources over T is $E_{s,i}$,

$$E_{s,i} = E_{nr,i}T \tag{6}$$

On the other hand, harvesting from RF signal of PU per unit time can be written as,

$$E_{hp,i} = \int_0^\infty P_{pu}|h_{pc,i}|^2 f_{g_{h,i}} dg_h = \frac{P_{pu}}{g_m} \tag{7}$$

where P_{pu} is the PU transmission power, and $f_{g_{h,i}}$ is the distribution of channel gain (channel between i-th CR and PU) which is assumed to be an exponential with a mean g_m. The harvested energy from RF signal of PU can be modeled under two states, H_1 and H_0 respectively. Under H_1 condition, the harvested energy can be expressed as,

$$\begin{aligned} E_{H_1} &= P(H_1)Q_d(t_s)(1-P_{dis})E_{hp,i}t_r \\ &+ P(H_1)(1-Q_d(t_s))(1-P_{dis})E_{hp,i}t_r \end{aligned} \tag{8}$$

In (8), the first part indicates the harvested energy while PU is detected correctly ($E_{H_1|H_1}$) and the second part is for missed detection ($E_{H_0|H_1}$). Under H_0 condition, the RF energy harvesting is possible only if PU re-arrives in the given channel. Hence, the harvested energy under this condition is given as,

$$E_{H_0} = P(H_0)(1-Q_f(t_s))E_{hp,i}t_{c,0} \tag{9}$$

where $t_{c,0}$ is the time for which PU remains in the given channel after re-arrival. The time duration $t_{c,0}$ can be modeled as $t_{c,0} = \rho_c t_r$ where ρ_c is the probability of collision, $\rho_c = \int_0^{t_{c,0}} P_b(t)dt = 1 - e^{t_{c,0}/b_0}$. To protect the quality of service of PU, ρ_c is considered to be low. Now combining (6), (8), and (9) the total harvested energy can be expressed as

$$E_{H,i} = E_{s,i} + E_{H_1} + E_{H_0} \tag{10}$$

2.3 Total network throughput

As in the considered network scenario, if PU is detected, n_{opt} number of CR_{TX} out of N, cooperate with PU transmission. If PU is found to be absent, all N CR_{TX} transmit to their respective destination, i.e., CR_{RX}. A CR_{TX} uses β amount of $E_{H,i}$ for its own and $(1-\beta)$ portion is used for PU cooperation. Under $P(H_0|H_0)$, the throughput of the CR network can be written as,

$$R_{CR}(t_s,\beta) = \frac{t_r}{T}P(H_0)(1-Q_f(t_s))C_{02}N \tag{11}$$

where, $C_{02} = \log_2\left(1 + \frac{E_{H,i}G_{cc,i}}{(t_r - t_{c,0})\sigma_w^2}\right)$. Hence, the total throughput CR network which includes a portion of PU throughput which is achieved with cooperation of CRs plus CRs own throughput. Hence, the total achievable throughput of the CR network is given as,

$$R_{CR,total} = R_{pcp}(t_s,\beta) + R_{CR}(t_s,\beta) \tag{12}$$

where $R_{pcp}(\tau_s,\beta) = \frac{t_r}{T}P(H_1)Q_d(t_s)C_{pcp}$ and $C_{pcp} = \frac{1}{2}\log_2\left(1 + \frac{\beta_{cp}G_{pc,i}G_{cp,i}P_{pu}}{\sigma_w^2(1+\beta_{cp}G_{cp,i})}\right)$.

3 Results and Discussions

In this section, numerical results are shown based on the above analysis. The performances is investigated for $P_{pu} = 1W$, $\sigma_s^2 = 1$, $\sigma_w^2 = 1$, $\alpha_0 = 0.65$, $\alpha_1 = 0.35$, $\rho_c = 0.01$, $E_{AF} = 0.0001J$, $P_{d,tar} = 0.9$, $d = 1\ m$, $\alpha = 3.5$ and $f_s = 6MHz$. Fig. 2 shows that the optimal number of CRs is

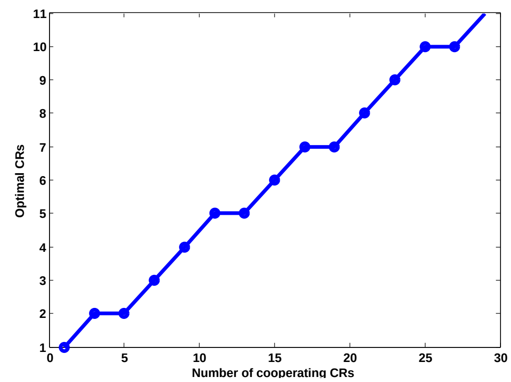

Figure 2. Optimal number of CRs in a cooperative scenario

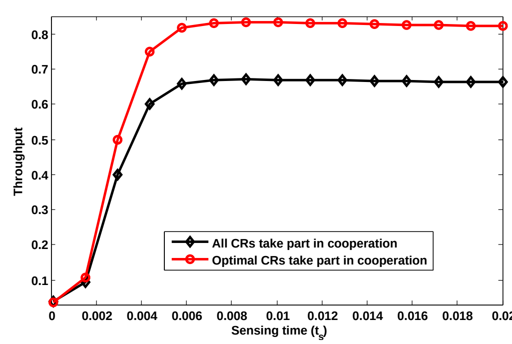

Figure 3. Comparison in achieved throughput

a function of number of cooperating CRs. It is observed that optimal number of CRs are increases as the number of cooperative CRs increases. Fig. 3 shows the comparative useful throughput performance of all number of CRs as well as optimal number CRs. From the figure it is clear that the useful throughput will be improved when optimal number of CRs take part in cooperation. If optimal number of CRs take part in cooperation, energy consumption decreases and improves the throughput. In Fig. 4 shows that throughput as a function of optimal number of CRs. Impact of (β) on throughput is investigated for optimal number of CRs. It is found that for a particular value of β, the useful throughput decreases as the optimal number of CRs increases. It is also observed that for a particular value of optimal number of CRs, the throughput increases as β increases.

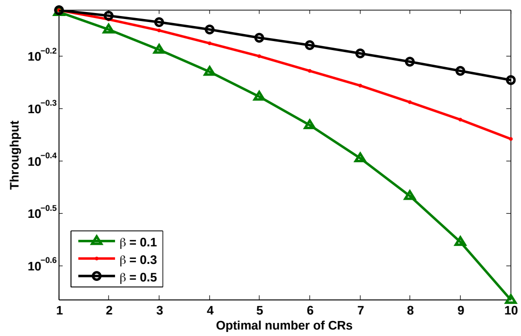

Figure 4. Throughput is a function of optimal number of CRs

4 Conclusions

The total achievable network throughput (CR throughput plus cooperative PU throughput) for an energy harvesting cooperative CR network is studied. A collision constraint of PU is considered to make the analysis model more realistic and to protect the QoS of PU. The CR transmitter harvests from RF signal of PU and non-RF signal. The spectrum sensing helps the CR system to know the availability of PU where optimal number of CRs take part in cooperation. The harvested energy at CR is divided into two parts, one part is allocated for cooperation in PU transmission and the other part is used for its own transmission. The allocation of energy is based on a targeted CR throughput. The impact of sensing time and energy allocation ratio parameter on throughput is also investigated. It is observed that the cooperation of optimal number of CRs improves the network throughput. Increase in energy allocation ratio parameter also increases the network throughput.

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