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Energy-aware resource allocation for cooperative cognitive radio dynamic spectrum access networks

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Abstract. The resource allocation problem is investigated for cooperative cognitive radio networks, considering energy efficiency of the primary users (PUs) and spectrum efficiency of the secondary users (SUs). The cooperation framework involves a PU selecting a SU as the relay and allocating the spectrum access intervals for the selected SU as a reward. The above sequential decision procedure is formulated as a Stackelberg game. Based on the knowledge of the effects of PUs decision on the behavior of a SU, the leader (PU) determines a fraction of the time slot duration to be used for the primary. The follower (SU) is allowed to transmit its own data to the corresponding receiver in the remaining duration and determines its optimal transmission power. The outcomes of the proposed cooperative resource allocation scheme, including primary user and secondary user power control, as well as dynamic access spectrum, are analyzed. Numerical results demonstrate that, with the proposed resource allocation scheme, the PU can achieve high energy saving by cooperation with the SU.

Keywords: Cognitive radio, Stackelberg game, energy efficiency, resource allocation

1. Introduction

Cognitive radio (CR) is a promising paradigm, which can overcome the dilemma of spectrum scarcity. There are licensed users referred to as primary users (PUs) and secondary users (SUs) in CR networks. Traditionally, SUs carry out spectrum sensing continuously in order to access idle spectrum bands, and must terminate their transmission as soon as they sense activity of a PU. Spectrum sensing is a very challenging task, while most primary users assume non-licensed transmissions as interference.

Spectrum sensing is an energy consuming process and might not be accurate due to shadowing [3]. In this paper, we focus on a cooperative cognitive radio network (CCRN), where primary users are interested in selecting some of SUs to behave as cooperative relays, and in return CR users are awarded a certain portion of their access time for secondary transmission. A new framework in which the PU may lease its given bandwidth for a fraction of time to the SUs in exchange for the SUs acting as relays was proposed in [14] and further investigated in [15]. Cooperative networking in which SUs perform a service for PUs to gain spectrum access opportunities as a reward appears to be a suitable replacement for spectrum sensing [6,17], mainly because spectrum sensing consumes excessive energy.

The authors in [6] proposed a protocol where a SU applies decode-and-forward technology to transmit the primary signal, and the secondary transmissions did not affect the outage performance of the primary system. The

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PU decides whom it selects to cooperate with and chooses optimal parameters to maximize its energy efficiency [17]. The selected SU determines the optimal power for transmissions as a Stackelberg game. The risk-aware cooperative spectrum access schemes for multi-channel CRNs were studied [16]. Based on the conclusions of the single channel network, two schemes were proposed for the PUs and SUs cooperation on multiple channels scenario.

With the cooperation of one SU, the primary system can tolerate interference lower than a certain threshold. The other SU is selected to access the spectrum band, while the SU satisfies the interference constraint [5]. The evaluator arranges the real time and non-real time service flows in two sub-queues and then sorts them by their priority levels, so that the measured channel utilization is better [4]. A QoS-based spectrum allocation framework that supports real time and non-real time users in distributed cooperative CRNs was analyzed [1].

Green communication is one of the most active research problems in wireless communication systems [2]. Motivated by the idea of cooperative communication, energy awareness in wireless networks can be improved by using relays for coverage extension [9,10]. Cooperative communication is considered as a cost effective way to improve performance, which requires minimum modification in the existing network infrastructure [9]. Relays provide differentiated transmission paths from source to destination, improving transmission quality, reliability and energy efficiency [7,8].

We make an effort to improve the performance of cooperative networks. Since the PU has priority in accessing spectrum, it may have a concern with energy efficiency due to huge overhead cost [11–13]. By the similar reason, the SU may concern for its transmission rate more since it might not have much opportunity to transmit. Thus, the PU and the SU have different concerns, which need to be taken into consideration. In this paper, we investigate the energy consumption in primary communication networks, develop a scheme which tries to minimize the power demand of PU and maximize the throughput of SU.

2. System model

We consider a system model of spectrum leasing based on cooperation, as depicted in Fig. 1. The system consists of a primary infrastructure-based network and a secondary ad hoc network. In the primary network, the base station (BS) allocates the resource to mobile stations that are referred to as PUs. In secondary network, the SU transmits data to intended receiver. The PU leases the use of the bandwidth for a fraction of time to the cooperative SU,

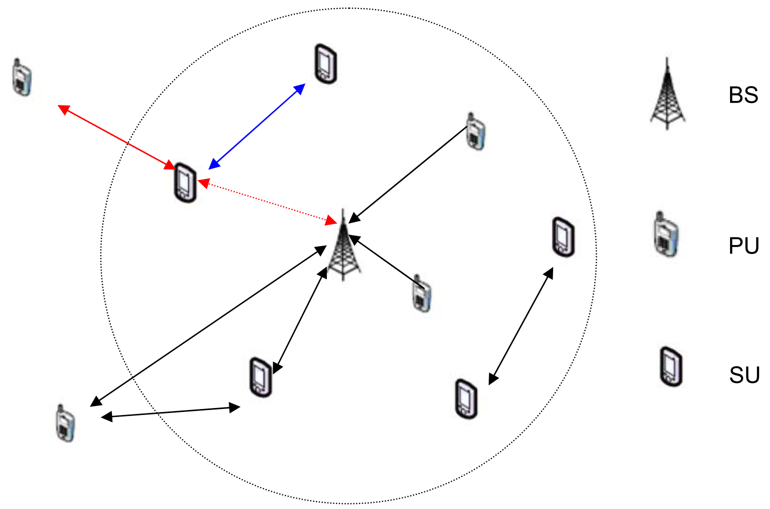

Fig. 1. The proposed framework of CCRN. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-150513.)

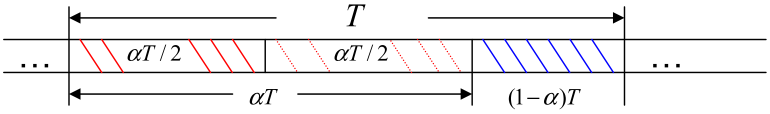

Fig. 2. Time slot allocation between a PU and a SU. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-150513.)

the selected SU assists the PU source transmitter to reach the PU destination receiver, the decode-and-forward cooperative protocol is considered, so as to improve the energy efficiency of the primary network.

Let T be the transmitting time slot duration for primary user. A fraction α of the time slot duration of T is used for the cooperative transmission. In the first $0.5\alpha T$ time interval, the PU transmits data to the SU. The follower (SU) relays the received data to the BS in the second $0.5\alpha T$ time interval. The selected SU is allowed to transmit its own data to the corresponding receiver in the remaining duration $(1-\alpha)T$ and determines its optimal transmission power. A common control channel is assumed for exchanging channel state information among PU, SU and BS, broadcasting the time slot allocation decision of BS.

The cooperation transmission is carried out in a three-phase way, as shown in Fig. 2. In particular, the leader decides whether to use the partial time slot for cooperation transmission or the entire time slot for direct transmission. In the first case, the partial time slot is further divided into two equal sub-time slots. In the first sub-time slot, the primary transmitter broadcasts its signal to the secondary transceiver and primary destination. In the second sub-time slot, the selected SU processes the received signal according to the relaying protocol and forwards it to the primary destination. The selected secondary user is allowed to transmit its own data in the last fraction of the time slot.

The channel gain from PU to the base station, from PU to SU, from SU to the base station, from SU to the corresponding secondary receiver are denoted respectively by h^p_{sd}, h^p_{sr}, h^s_{rd} and h^s_{sd}. The transmission power of SU is denoted by P_r. Shannon proved that the capacity limit of a communication channel with bandwidth B and SNR of is $B\log_2(1+SNR)$ for AWGN channel. The PU chooses power P_d for the primary transmission. The data rate of the direct transmission schemes can be written as:

$$R_{\mathrm{sd}} = B\log_2\left(1+\frac{P_d|h^p_{\mathrm{sd}}|^2}{N_0}\right). \tag{1}$$

3. Energy-aware radio resource allocation

We analyze spectrum leasing based relay cooperation within a game framework between PU and SU under the assumption of instantaneous channel state information.

3.1. Ad hoc cognitive radio network

The interaction between the PU and the SU can be modelled as a game, which provides the SU with the optimal transmission power allocation. PU and SU have different priorities for spectrum access, PU is a leader and SU is a follower, so Stackelberg game is suitable for describing the cooperation procedure.

As a follower in the game, SU selects the optimal transmission power to maximize utility, being aware of SU spectrum access time duration. Assuming each SU is behaving honesty, it uses the same power level P_r for two transmissions. Assuming that the PU uses α time slot for cooperation, the SU tries to maximize its utility. The achievable rate $R_s(\alpha)$ for secondary transmission is given by:

$$R_s(\alpha) = (1-\alpha)B\log_2\left(1+\frac{P_r|h^s_{\mathrm{sd}}|^2}{N_0}\right). \tag{2}$$

Moreover, the total cost is $c(1-0.5\alpha)T * P_r$, c is the weight of per unit transmission energy. From (2), the utility function of SU is given by $U_s(\alpha)$. The objective of SU in the game is to maximize its utility by the best strategy in choosing the optimal transmission power P_r.

The utility of SU in the game cooperating with the PU is:

$$\max_{P_r} U_s(\alpha) = (1-\alpha)B \log_2\left(1 + \frac{P_r |h_{\mathrm{sd}}^s|^2}{N_0}\right) - c * \left(1 - \frac{\alpha}{2}\right) * P_r. \tag{3}$$

Solving the problem (3), the optimal transmission power is:

$$P_r = \left\{\frac{(1-\alpha)B}{c(1-\frac{\alpha}{2})\ln 2} - \frac{N_0}{|h_s|^2}, P_{\max}\right\}, \tag{4}$$

where $P_{\max}$ is the maximum of SU transmission power.

The first order derivative of the best response function is negative. Therefore, the best transmission power of SU decreases with the increase of α. The SU is willing to spend more transmission power to forward PU's data if the PU allocates more resource for the SU's transmission.

3.2. *Energy-aware resource allocation for primary user*

Game theory can be applied to model the relations between PU and SU. In the Stackelberg game, the PU acts as the leader and the SU acts as the follower. As the leader, the PU can choose the best strategies in the relay selection process, aware of the effect of its decision on the strategies of the SU, while the SU can just select its own strategies given the fixed parameters of the PU.

In this section, a resource allocation scheme based on a cost function which depends on energy consumption is proposed. Each PU selects a SU, minimizing the cost while guaranteeing a minimum require rate. The problem of cost minimization-based power allocation at the source and relay node while guaranteeing the PU QoS can be formulated as:

$$\min 0.5\alpha P_s, \tag{5}$$

$$R_{\mathrm{DF}} = R_{\mathrm{sd}}^p. \tag{6}$$

A fraction α of the time slot duration is used for cooperation. The cost function of the PU is defined by (5), cooperating with SU in Stackelberg game.

The maximum error-free data rates of decode-and-forward (DF) relay schemes at the destination terminal are calculated as following:

$$R_{\mathrm{DF}} = 0.5\alpha \min\left[\log_2\left(1 + \frac{P_s |h_{\mathrm{sr}}^p|^2}{N_0}\right), R_c\right]. \tag{7}$$

The MRC combiner at the destination combines the received signal from the source and the relay. The first term in (7) is the achievable rate of the PU → SU link, and the second term is the achievable rate by maximum ratio combining between the PU → BS link and SU → BS link,

$$R_c = \log_2\left(1 + \frac{P_s |h_{\mathrm{sd}}^p|^2}{N_0} + \frac{P_r |h_{\mathrm{rd}}^s|^2}{N_0}\right). \tag{8}$$

Overall, the considered framework is characterized by a hierarchical structure, where one primary user optimizes its strategy based on the knowledge of the effects of its decision on the behavior of a secondary user. The optimization problems (3) and (5) may be interpreted as a Stackelberg game: The primary link is the Stackelberg leader, that optimizes its strategy (α, P_s) in order to minimize its cost according to (5), being aware that its decision will affect the strategy selected by the secondary ad hoc network.

The SU relays PU's data in the second phase and transmits its own data in the last phase of the time slot. DF relaying is a technique which requires more time overhead and hardware expense. DF relay decodes the received signal from the PU and performs error-correction on the decoded signal. The SU then re-transmits the correctly decoded signal to the BS.

The instantaneous *SNR* of the DF relaying scheme at the base station is the sum of the received SNRs from the direct and the relaying links and can be written as:

$$SNR_c = \frac{P_s|h^p_{\mathrm{sd}}|^2}{N_0} + \frac{P_r|h^s_{\mathrm{rd}}|^2}{N_0}. \tag{9}$$

4. Simulation results and discussions

In this section, we present numerical results so as to provide insight into the proposed energy aware resource allocation scheme. Similar to [17], by normalizing the distance between PU and BS, the SU is approximately placed at the distance $d \in (0, 1)$ from the PU and $1 - d$ from the BS. Considering a path loss model, the average power gains between the PU and SU, and between the SU and BS, are $|h^p_{\mathrm{sr}}|^2 = \frac{1}{d^\xi}$, $|h^s_{\mathrm{rd}}|^2 = \frac{1}{(1-d)^\xi}$, respectively, where $\xi = 2$ is the path loss coefficient. In order to reduce the system parameters, the maximum secondary transmission power $P_{\max}$ is normalized to 1 and we choose $P_{\max}/N_0 = 0$ dB and $\frac{B}{c \ln 2} = 2$.

Figure 3 shows the trends of PU transmit power with respect to α, for $d = 0.3$ and $|h^s_{\mathrm{sd}}|^2 = 10$ dB. It can be seen that SU is willing to spend more power when SU can obtain longer access time. The result demonstrates that there is linear relationship between the SU transmit power and the time allocation coefficient.

The optimal α and PU power for a given SU are shown in Figs 4 and 5. As it can be seen, PU power would be less than $P_d = 0.3$ when $\alpha \in [0.44, 0.91]$ which indicates a cooperation range in terms of α that the PU can

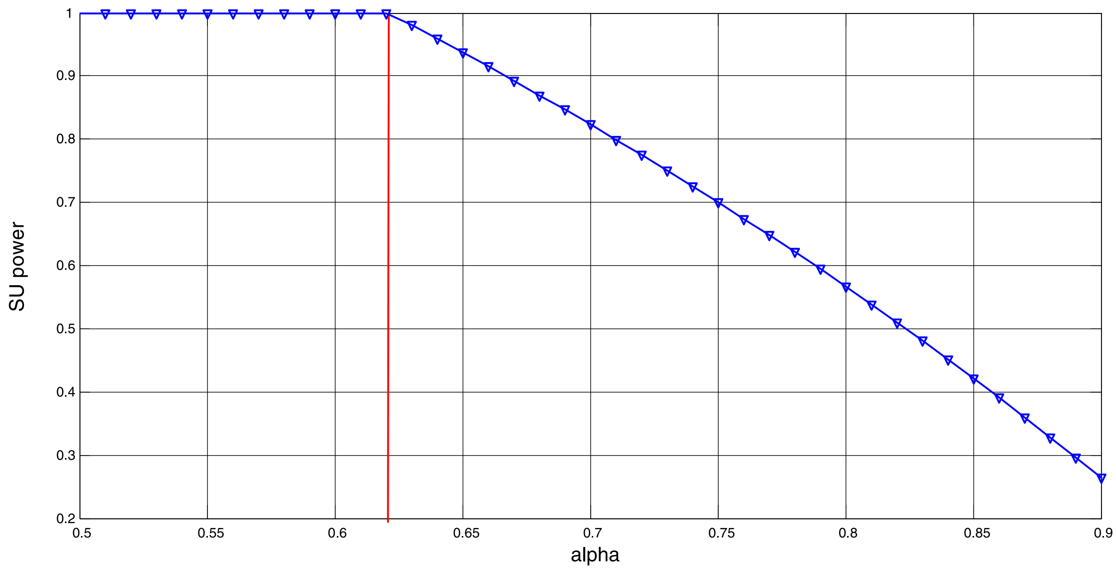

Fig. 3. SU transmit power versus the time allocation coefficient. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-150513.)

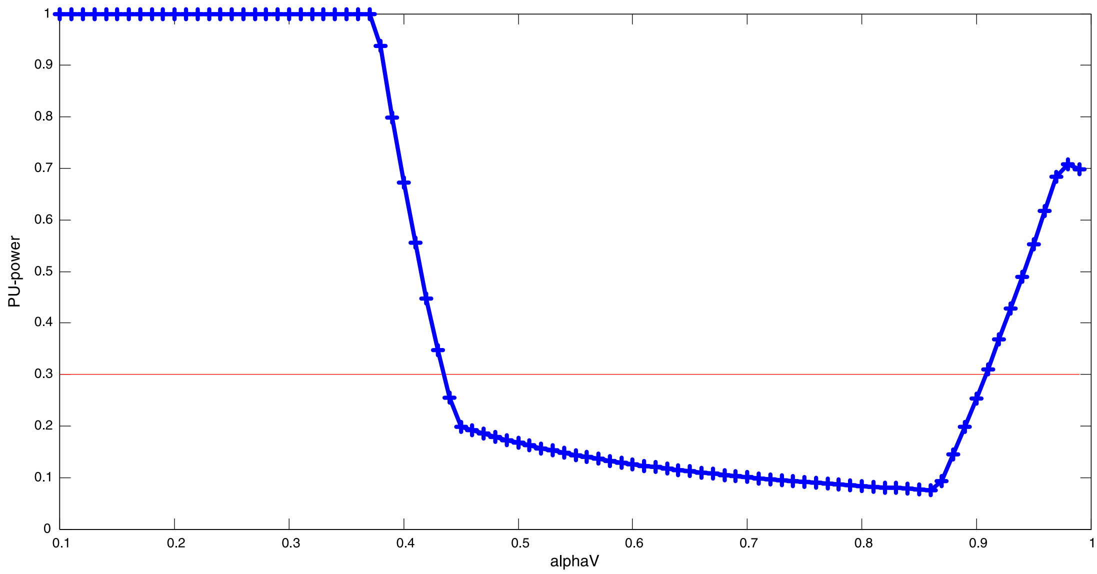

Fig. 4. PU transmit power versus the time allocation coefficient. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-150513.)

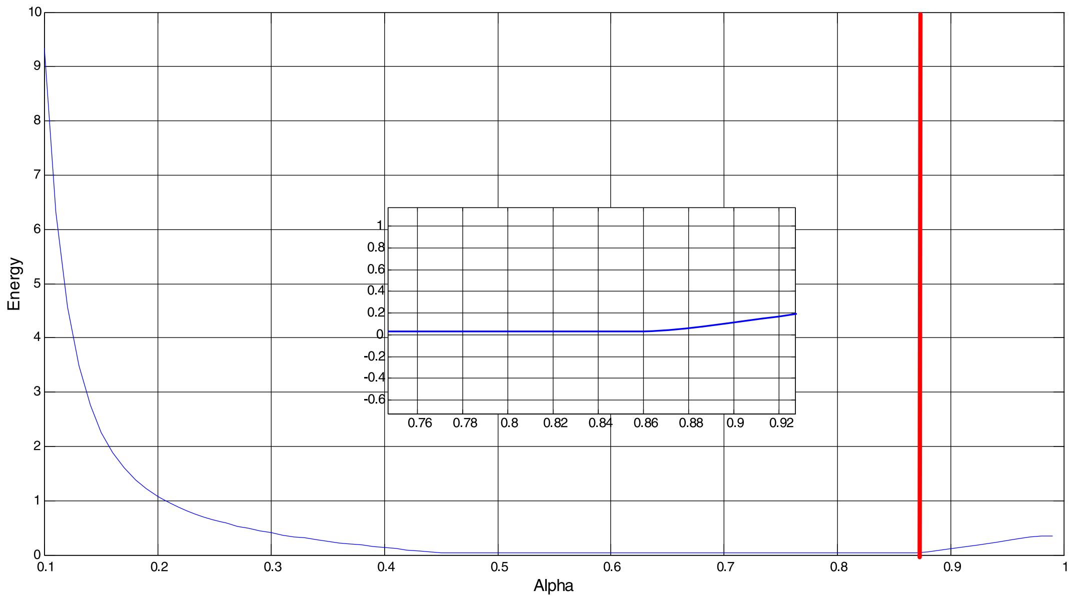

Fig. 5. PU energy versus the time allocation coefficient. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-150513.)

transmit in a smaller power than P_d through cooperation with the SU as long as the PU chooses α, in that range. The time allocation coefficient turns to be optimal when PU energy reaches its minimum value.

Figure 6 shows the optimal utility of SU versus the SU power according to different values of time allocation coefficient. It can be seen that there is a unique optimal SU power to the fixed parameter α, which is selected by PU for cooperation.

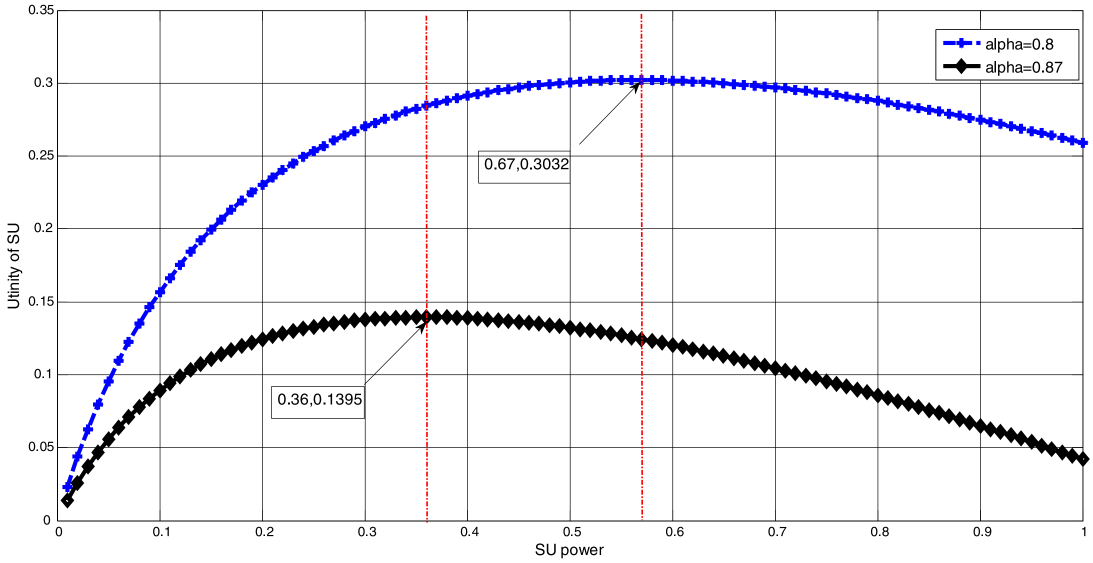

Fig. 6. Time slot allocation between a PU and a SU. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-150513.)

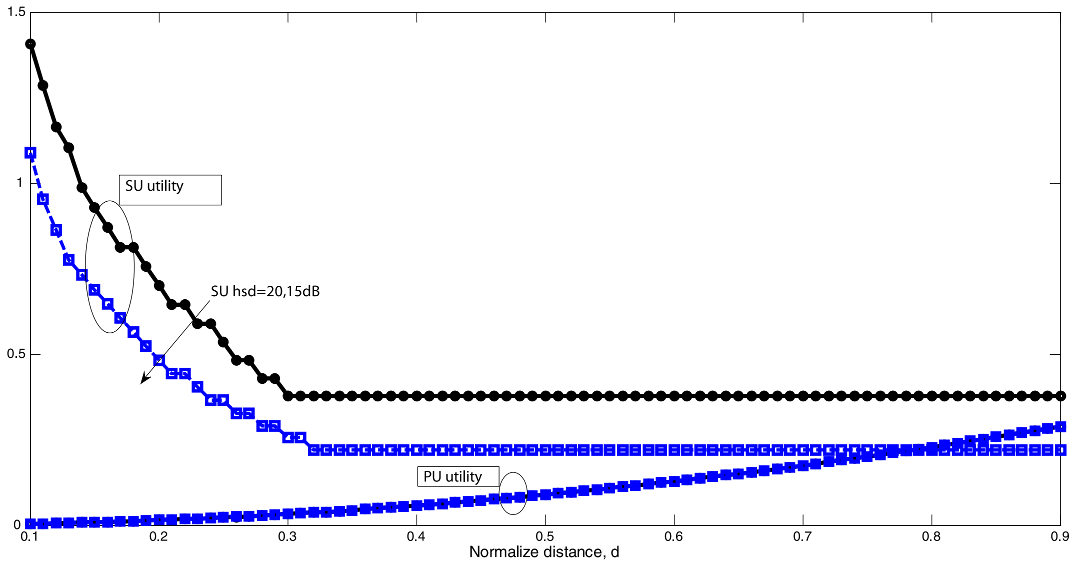

Fig. 7. PU and SU utility versus the normalized distance d given different channel power gains between secondary transmitter and receiver. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-150513.)

Figure 7 shows the PU cost function and the SU utility function, versus the normalized distance d according to different values of h^s_{sd}. It can be seen that the PU cost function tends to increase with distance d. The reason is that the channel gain decreases with increasing distance between the PU and the SU so that the PU requires a larger power for primary transmission. Moreover, with increasing d, the benefit that the PU can obtain from the cooperation (the energy saving) becomes less, resulting in the reduction of energy. It can also be seen that a better channel gain between the SU and its corresponding receiver comes with a better energy saving of the PU and a wider cooperation range in terms of the normalized distance d.

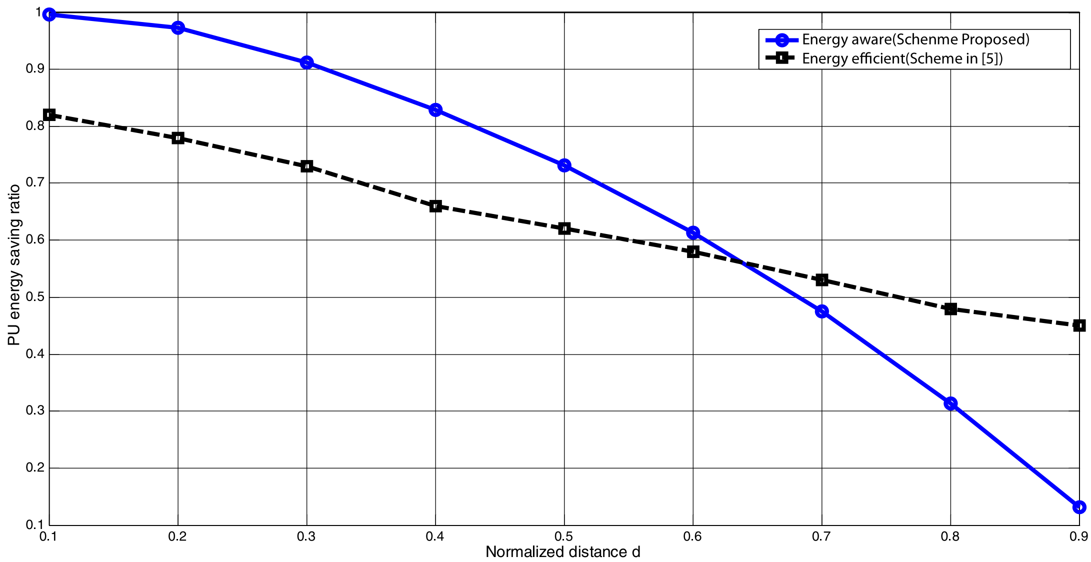

Fig. 8. Energy saving for the PU. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-150513.)

The energy saving for the PU is the ratio between the amount of energy reduction with cooperation and the total power dissipation without cooperation, which is shown in Fig. 8. We compare our energy-aware resource allocation algorithm with the Method in [17], which obtained the optimal total transmission power by AF cooperative communication between the PU and SU.

5. Conclusion

In this paper, we studied the decode-and-forward cooperative framework in CRN, considering energy efficiency of the PU. The PU chooses the best cooperative relay and optimal time slot allocation between a PU and a SU in order to maximize its energy efficiency, while the cooperative SU determines the optimal power for two transmissions. We model the procedure of decision making as a Stackelberg game. The analysis of the resource allocation scheme provides the PU with the best strategy for relay selection, spectrum access time allocation and transmission power determination. Numerical results have demonstrated that with the proposed framework, the PU can decrease the energy consumed through cooperation by selecting the most suitable SU, and the SU can obtain access spectrum by cooperation with the PU.

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