AN OPTIMUM RELAY SELECTION FOR COOPERATIVE TRANSMISSION AND SPECTRUM SENSING IN COGNITIVE NETWORKS

Hasan Kartlak1, Cengiz Bektas2, Niyazi Odabasioglu1, and Aydin Akan1

1 Department of Electrical and Electronics Eng., Istanbul University
Avcilar, 34320, Istanbul, Turkey, hasank@ieee.org, {niyazioakan}@istanbul.edu.tr

2 Department of Satellite Communication and Remote Sensing
Istanbul Technical University, Istanbul, Turkey, cengizbektas@itu.edu.tr

ABSTRACT
In this paper, we propose a jointly optimized relay selection scheme for both cooperative transmission and spectrum sensing purposes for cognitive radio networks. Our aim is to select a relay to achieve the sufficient performances of cooperative transmission and spectrum sensing for the secondary network while ensuring the quality of service (QoS) of primary user. We present error performance of transmission and probability of detection for spectrum sensing via computer simulations. Results show that our jointly optimized scheme provides encouraging performance for both transmission and spectrum sensing in cognitive radio networks.

Index Terms—cooperative communication, cognitive radio, spectrum sensing, relay selection.

I. INTRODUCTION
Cognitive radio is the state of the art wireless communication technique which allows unlicensed users to utilize licensed users’ assigned but unused radio spectrum. As such, it provides efficient usage of radio spectrum resources [1]. For the implementation of cognitive radio, interference temperature is proposed as a metric to quantify and manage the interference between primary user (PU) and secondary user (SU) [2]. If the interference from SU to PU is less than a threshold, the SU can access the licensed spectrum together with the PU. Meanwhile, the desired quality of service (QoS) of primary transmissions will be satisfied [2]. Eventually, very low transmit power level is allowed for SUs, and thus throughput of SU will be very limited to satisfy high QoS for the PU. In order to cope with these constraints, improved transmission techniques as well as sensing the available spectrum of the PU are necessary to achieve the desired communication performance in cognitive radio networks.

Cooperative communication improves the system throughput over fading channels [3]. In cooperative communication, a key issue is how to choose which terminal in the network will be used as a relay. Therefore vast amount of studies have been conducted and still undergoing on relay selection problem in cooperative communication systems. A pioneering study on relay selection is proposed in [4] which shows the effect of relay selection into the system performance. Recently, other relay selection schemes with improved performance have been proposed [5]-[6]. Relay selection problem becomes much more complicated in cognitive radio networks compared to the classical cooperative communication systems, because of interference limitations from SU to PU. In some recent studies, cooperative transmission techniques have also been proposed for cognitive radio systems [7]-[8].

An important component of cognitive radio networks is sensing the availability of the radio spectrum. Spectrum sensing improves the efficiency of the frequency spectrum by detecting assigned but unused frequency bands of the radio spectrum. SU can communicate over these unused frequency bands of PU. In recent years, different spectrum sensing methods have been proposed [9]. Literature covers energy-based spectrum sensing techniques, higher-order statistics based methods, and cyclo-stationarity based methods [10]-[11]. Sensing time is a key issue in spectrum sensing as well as sensing the spectrum correctly. Energy based techniques are mostly preferred due to their low computational complexity.

Computational load of the spectrum sensing technique effects the duration of the sensing. From this point of view, energy-based spectrum sensing technique using Wavelet Transform (WT) is advantageous compared to other approaches. WT based techniques have computational complexity of order $N [10]$ for $N$-sample long sequence, whereas fast Fourier transform based techniques have computational complexity of order $N(\log_2 N)$. Therefore, WT based spectrum sensing has widely been applied [12]-[13]. Recent studies show that performance of spectrum sensing can be improved with the assistance of a relay [14]. Similar
to cooperation for transmission, a relay in the network also senses the spectrum in addition to SU and transmits the result to SU. Then SU combines these results using a soft or hard decision method and reaches the final result.

In this paper, we propose a jointly optimized relay selection scheme for both cooperative transmission and cooperative spectrum sensing in cognitive radio networks, aiming to reduce the computational burden of the selection procedure. Hence, we select an optimum relay with only one selection algorithm for two tasks. In energy based spectrum sensing algorithm, WT is used because of its low computational load. The transmission and sensing performances of the proposed method are presented by means of computer simulations. Results demonstrate that our proposed method gives sufficient performance for both cooperative spectrum sensing and transmission tasks.

Rest of the paper is organized as follows. The cognitive radio network system model is explained in section 2, simulation results are given in section 3, and section 4 concludes the paper.

II. RELAY SELECTION FOR COGNITIVE RADIO NETWORKS

In this section we present our jointly optimum relay selection scheme for both cooperative communication and spectrum sensing in cognitive radio networks. Our selection algorithm combines two steps: (i) choosing the “best relay” for cooperative transmission, (ii) choosing the “best relay” for spectrum sensing, and obtains only a single relay to perform both tasks. Clearly, the selected relay will be sub-optimal for either transmission or spectrum sensing. In the following, we briefly explain our cognitive radio network model with cooperation, relay selection for cooperative transmission and cooperative spectrum sensing.

II-A. Cognitive Radio Network Model

In the cognitive radio system, we consider two networks as shown in Fig. 1: the first one is a primary network and the second one is an amplify-and-forward (AF) cooperative communication secondary network. When the primary user sends data to a primary destination (PD), secondary transmitter (ST) sends its data to a secondary destination (SD) at the same time.

In order to implement the cooperation, we consider the “receive diversity protocol” presented in [3]. We assumed that the transmitters, PT, ST, destinations, PD, SD, and relay terminals, R1, R2, · · · , RM have one transmit and one receive antennas. In the first phase of this protocol, the ST transmits the data to both relay and the SD. Then in the second phase, the ST stays silent, while the relay amplifies and transmits the data. In cognitive radio systems with no spectrum sensing task, the transmit power of secondary transmitter should be limited to maintain a desired QoS of primary transmissions.

Fig. 1. Cognitive radio network model.

PT transmits the signal xP to PD where the transmit power of PT is denoted by PP and data rate by RPT. Similarly, ST transmits the signal xST to SD with transmit power PST. The outage probability of primary transmissions is limited by a threshold PTbr, because we need to guarantee that QoS of primary transmissions will not be decreased.

II-B. Relay Selection for Cooperative Transmission

In our study, a static method is used to control the ST’s PST and relay’s transmit powers PSTR, as in [15]:

\[ P_{ST} = \frac{\sigma^2_{SR-PD}PP}{\sigma^2_{ST-PD}PPT} \Theta + \rho \] (1)

\[ P_{STR} = \frac{\sigma^2_{SR-PD}PP}{\sigma^2_{ST-PD}PPT} \Theta - \rho \] (2)

where \( \sigma^2_{ST-PD} \), \( \sigma^2_{SR-PD} \) and \( \sigma^2_{ST-PD} \) are the fading variances of the channels from PT to PD and from ST to PD respectively. \( \Theta = 2^{\rho_T} - 1 \), \( \rho^+ = \max(\rho, 0) \), \( \rho = (1/(1 - PTbr))exp(-\Theta/\sigma^2_{ST-PD}PPT) \) - 1 and \( \gamma_{PT} \) is the transmit signal-to-noise ratio (SNR) at PT.

In first phase, signals received at relay i and the destination SD are given respectively by the following:

\[ r_{SR} = \sqrt{P_{ST}h_{ST-SR}x_s} + \sqrt{P_{PT}h_{PT-SR}x_p} + n_{SR} \] (3)

\[ r_{SD} = \sqrt{P_{ST}h_{ST-SD}x_s} + \sqrt{P_{PT}h_{PT-SD}x_p} + n_{SD} \] (4)

where i shows the index of selected relay. Considering path losses and the shadowing effects in these channels, \( \sqrt{P_{ST}} \) and \( \sqrt{P_{PT}} \) show the signal powers at the relay and the destination respectively, \( h_{ST-SR} \), \( h_{PT-SR} \), \( h_{ST-SD} \) and \( h_{PT-SD} \) represent the complex Gauss fading coefficients for ST and PT, Source → Ri and Source → SD channels respectively, where \( n_{SR} \) and \( n_{SD} \) show zero mean complex Gaussian noise with \( N_0/2 \) variance per dimension.
In the second phase, selected relay normalizes the received signal by $\sqrt{E[|r_{SR_i}|^2]}$ and transmits to the destination receiver. The signal at the destination in second phase:

$$r_{RD_i} = \sqrt{P_{SR} h_{ST-RD_i}} \frac{r_{SR_i}}{\sqrt{E[|r_{SR_i}|^2]}} + n_{RD_i}$$  \hspace{1cm} (5)

$\sqrt{P_{SR}}$ represents the received signal power at the destination, considering path losses and the shadowing effects in $R_i \rightarrow SD$ channel. $h_{ST-RD_i}$ represents the complex Gauss fading coefficients for this channel, where $n_{RD_i}$ is the zero mean complex Gaussian noise with $N_0/2$ variance per dimension.

Now let’s consider the relay selection procedures to optimize only transmission, only spectrum sensing, and finally both transmission and spectrum sensing tasks.

(i) The “best relay” for transmission is selected as follows: In the secondary network transmission, the best relay amplifies the ST’s signal and achieves the highest received instantaneous signal-to-noise ratio (SINR) at SD. For transmission, the best relay selection criterion is given as:

$$R_b = \arg \max SINR_{RS_{SD}}$$

$$= \arg \max \frac{|h_{SR_i-SD}|^2}{\sigma_{SR_i-PD}^2}$$  \hspace{1cm} (6)

where $R_b$ shows the selected relay. $ST \rightarrow R_i$ and $R_i \rightarrow SD$ cases are considered in selection criterion.

(ii) The “best relay” for spectrum sensing is selected as follows: The best relay to sense the spectrum of PU is the relay having the largest channel coefficient. For spectrum sensing, the best relay selection criterion is given by the following:

$$R_b = \arg \max \frac{|h_{PT-SR_i}|^2}{\sigma_{SR_i-PD}^2}$$  \hspace{1cm} (7)

(iii) The “best relay” for both cooperative transmission and spectrum sensing: In this study, we propose the following criterion to select a single relay in the secondary network to perform both transmission and spectrum sensing tasks: The selected relay amplifies the ST’s signal, achieves the highest received instantaneous signal-to-noise ratio (SINR) at SD and detects the PU. For this optimum solution, the relay selection criterion is given by the following:

$$R_b = \arg \max \frac{|h_{SR_i-SD}|^2 + |h_{PT-SR_i}|^2}{\sigma_{SR_i-PD}^2}$$  \hspace{1cm} (8)

In section 3, we present computer simulations to show the performance of our joint relay selection algorithm.

**II-C. Cooperative Spectrum Sensing**

The discrete dyadic wavelet transform giving the wavelet coefficients is given by the following for a discrete-time signal $x(n)$ [16]:

$$x^b_a = \sum_n x(n) \psi^b_a(n)$$  \hspace{1cm} (9)

Hence, $x(n)$ can be written as [16]:

$$x(n) = \sum_{a=1}^{M} \sum_{b=1}^{N} x^b_a \psi^b_a(n)$$  \hspace{1cm} (10)

$M$ shows the scale number ($M = \log_2(N)$), $N$ shows the data length, $a$ and $b$ show dilation (scale) and translation indices, respectively. $\psi^b_a(n)$ shows normalized dilations and translations of the mother wavelet function $\psi(n)$. The cutoff frequencies of the initial filters are $\pi/2$, and divided by 2 in every step, until a desired resolution is reached. Six level wavelet analysis is used in our simulations.

In our energy-based spectrum sensing technique, as shown in Fig. 2, we calculate the received signal’s energy by the WT. PU is detected by calculating the total energy of the wavelet coefficients in every band and the energy of the signal in different frequency bands are obtained. If the PU is silent, the received signal will have a low energy containing only noise. We experimentally determined a threshold which enables us to detect when the PU is transmitting or not.

![Fig. 2. Spectrum sensing algorithm.](image)

where $\hat{\sigma}_r^2$ and $\hat{\sigma}_w^2$ are the estimates of the normalized variances of the received signal, and only noise in each scale, respectively. We calculated the normalized variances of the wavelet coefficients to determine the threshold and estimated $\hat{\sigma}_w^2$ for each SNR ranging from -1 to -10 dB in the case of noise only. Then we calculate wavelet coefficients of the received signal and calculate normalized variances of the wavelet coefficients $\hat{\sigma}_r^2$. Finally we compare $\hat{\sigma}_r^2$ and $\hat{\sigma}_w^2$: when $\hat{\sigma}_r^2$ is higher than $\hat{\sigma}_w^2$, we decide that PU is transmitting in that frequency band.

In the cooperative spectrum sensing approach, we calculate the normalized variances of the wavelet coefficients at both ST and selected the relay $R_i$. The normalized variances of the wavelet coefficients are calculated as

$$\hat{\sigma}_r^2 = \frac{|h_{PT-ST}|^2 \hat{\sigma}_{r-ST}^2 + |h_{PT-SR_i}|^2 \hat{\sigma}_{r-ST-SR_i}^2}{|h_{PT-ST}|^2 + |h_{PT-SR_i}|^2}$$  \hspace{1cm} (11)

where $\hat{\sigma}_{r-ST}^2$ is the normalized variance of the wavelet coefficient for ST. $\hat{\sigma}_{r-ST-SR_i}^2$ represents the normalized variance of the wavelet coefficient for $SR_i$.

In the third section, we illustrate the probability of detection $P_d$ of the proposed method by means of computer simulations.

$$P_d = P_r(M > \lambda_E | H_1)$$  \hspace{1cm} (12)
Here, $M$ shows the normalized variance of the wavelet coefficients obtained from the received signal, $\lambda_E$ shows the threshold calculated by the normalized variances of the noise using Monte Carlo trials, $H_1$ is the case when the primary user exists in the received signal. In the next section, we illustrate the performance of the proposed joint relay selection for multiple-relay cognitive radio network by means of computer simulations.

III. SIMULATION RESULTS

In this section, we present numerical tests by means of computer simulations via Monte Carlo iterations. We tested our algorithm using for different scenarios:

1) One of the available relays in the secondary network is “randomly chosen” for both cooperative transmission and spectrum sensing.
2) The “best relay” for transmission is selected and used for both transmission and spectrum sensing tasks.
3) The “best relay” for spectrum sensing is selected and used for both tasks.
4) The proposed method of selecting “best relay” for transmission and spectrum sensing.

We use a frame size of 130 symbols, and assumed the channel fading coefficients are constant during one frame period. We assume that channel state information is known at the ST, transmitted from the SD to the ST by a feedback, all channels between Source-Destination, Source-Relays, Relays-Destination are Rayleigh fading, and QPSK modulation is considered for the data symbols.

We investigate the performance of the cognitive network model shown in Fig. 1 and demonstrate by means of “bit error rate (BER)” plots given in Fig. 3.

It is clearly observed from Fig. 3 that scenario (2) has better error performance than others and scenario (3) has the worst error performance for transmission. However, the proposed method, i.e., scenario (4) has a better error performance than random relay selection, best relay selection for spectrum sensing, and it achieves a close performance to best relay for transmission. Performance of the spectrum sensing is tested for the above scenarios by means of probability of detection and the results are given in Fig. 4.

Probability of detection values of random selection method are higher than scenario (2), the best relay for transmission. On the other hand, our proposed optimal solution has better $P_d$ values than random relay and best relay for transmission. Finally, $P_d$ values of the proposed best relay selection for transmission and spectrum sensing are closer to those of the best relay for spectrum sensing than others. As such, we conclude that the proposed relay selection approach provides sufficient $P_d$ values.

IV. CONCLUSIONS

In this study, we present a jointly optimum relay selection scheme for cooperative communication and spectrum sensing for multiple-relay cognitive radio networks. The most important advantage of the proposed relay selection method is that the jointly selected relay yields sufficient error performance for transmission and sufficient probability of detection for spectrum sensing. Simulation results show that the proposed method provides an optimum system throughput in multiple-relay cognitive radio networks. In conclusion, our algorithm selects a relay that performs sufficiently in terms of secondary network data transmission as well as spectrum sensing of the primary network.

V. REFERENCES

Fig. 4. Probability of detection for spectrum sensing.
