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Resource Allocation Protocol for Hybrid Overlay/Underlay Transmission for Improved Primary User Throughput

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Abstract

One of the fundamental assumptions while deploying a cognitive radio network is that the primary users are willing to tolerate additional interference generated by secondary users and are willing to share their spectrum resource with secondary users. So, the general question that arises here is that why the primary users should tolerate additional interference and share resources? In this paper, we presented a new scheme that can provide additional SNR for the primary users by allowing secondary users to coexist. Hybrid overlay/underlay strategy is the proposed scheme in which the idle secondary users are used to maximize the throughput of the primary users. The features of both underlay and overlay are incorporated into this hybrid transmission technique such that the both the licensed and unlicensed users get benefited, as their communication link is uninterrupted. Also, we presented a resource allocation algorithm for the hybrid overlay/underlay transmission method and the performance of the opportunistic and partial relay selection is investigated. This resource allocation algorithm is used for selection of the best relay, power allocated to the relay and best channel from relay to destination. Simulation results are presented to demonstrate the performance of the proposed hybrid technique over the traditional methods. The effectiveness of usage of the partial and opportunistic relay selection techniques is compared and the conclusions are drawn. The simulations show that the proposed hybrid overlay/underlay transmission scheme gives optimal performance when paired with partial relay selection

Key words

Cognitive radio, hybrid CR scheme, underlay, overlay, partial relay selection, opportunistic relay selection, resource allocation.

1. Introduction

With the widespread wireless communication technologies and demand for excessive spectrum, the need of intelligent wireless system that change their mode of operation by being aware of its surrounding environment, for better spectrum utilization, is inevitable. The need of such a system is because of the inefficiency of the traditional spectrum management for efficient spectrum utilization. The spectrum allocated in traditional spectrum management for various wireless standards or licensed users is done on an exclusive base. One of the technology that has caught the attention of many researchers is cooperative spectrum sharing systems. Cognitive Radio (CR) and cooperative diversity (CD) are the two techniques that are used in this technology. Efficient spectrum utilization is provided by CR and CD improves the reliability of communication. Usually in such cooperative communication systems there are several nodes in between destination and source to be chosen as the relay node. Performance of such system can be improved by selecting one of the node as the best relay, based on a criterion for relay selection. Classification of the relay selection schemes can be done into two types, partial relay selection and opportunistic relay selection. In the partial relay selection, a relay is chosen as best relay based on signal to noise ratio (SNR) at the first hop or at the second hop. The relay that has highest SNR at any one of the hop is chosen as best relay. In the opportunistic relay selection, the relay is selected based on the end to end SNR value. The best relay is the relay with best end to end SNR.

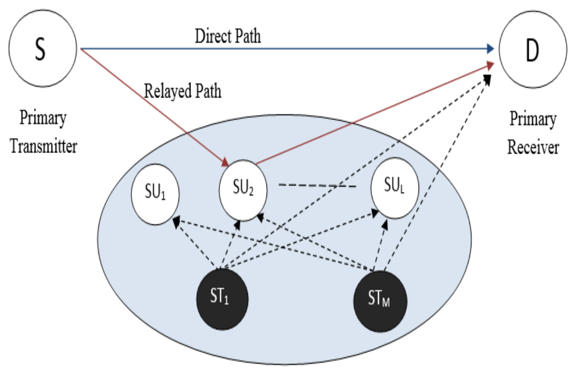
In order to utilize the free spectrum bands that are licensed to the primary users (PU), the secondary users (SU) employ two spectrum access strategies, underlay and overlay strategies. In underlay cognitive radio strategy, an interference level that is tolerable is set at the primary user. The unlicensed user is allowed to use the spectrum as long as interference generated by the SU is below this predetermined interference threshold (Interference Temperature). In overlay cognitive radio strategy, the data between two PU's is relayed using the SU node. The SU node can use majority of its power to transmit PU data and the rest of power to transmit its own data. The interference generated at the PU due to the transmission of SU data is compensated by the additional SNR offered by using SU node as relay. The combined access strategy in cognitive radio have been a topic of interest recently. This is done to exploit the advantages of both overlay and underlay access strategies. These combined access strategies are predominantly called as hybrid cognitive radio systems. A hybrid underlay/overlay transmission scheme with the aim of achieving better statistical delay QOS provisioning is presented in [1]. The CR is designed to switch between underlay and overlay based on operating condition of PU in [2-5]. In [6] the authors have presented a hybrid CR scheme with energy harvesting ability. A distributed power allocation algorithm in which the multiple SU's use a common node as relay and compete for the power of relay to transmit their signals is presented in [7]. In [7] the SU's transmit with different spectrum sharing modes. The opportunistic relay selection performance has been analyzed for the case of dual hop transmission in [8], [9]. Partial relay selection performance in dual hop communication with semi blind relaying is studied in [10]. The end to end performance of the cooperative AF relaying by using opportunistic relay selection and partial relay selection has been detailed and selection criterions have been presented in [11].

Unlike the previous hybrid CR algorithms, instead of switching between the overlay and underlay transmission modes, we consider combining the feature of both the modes and propose a novel transmission technique. This hybrid overlay/underlay method beneficiates both the PU's and SU's. This technique uses the idle secondary users as the relay node for the transmission of the PU signals. The SU's that have data to send will transmit in underlay mode without causing any interference to PU's. We consider the selection of best node, interference from the active SU's, transmission power of the best relay selected to improve the throughput of the primary user. The PU's are benefited with the extra SNR provided after utilizing idle relays and the SU's are benefited as they are able to utilize the PU band in underlay mode. Also, analysis on selection of the best relay using opportunistic and partial relay selection is presented.

The remainder of this paper is organized as follows. In section II, we introduce the cognitive radio system with the primary and secondary users in which the opportunistic and partial relay selection must be implemented. In section III, we investigate the performance of the hybrid CR scheme and relay selection techniques. Specifically, the analysis is done on the selection of best relay using partial or opportunistic relay selection, power allocated to best relay and efficient channel from relay to destination. Section IV presents the simulation environment and the performance comparisons of the selection techniques. Finally the concluding remarks are drawn in section V.

2. System Model

Fig.1. System Model



Consider a CR network that comprises of one primary transmitter (source), one primary receiver (destination), ‘M’ active SU’s and ‘L’ idle SU’s. Initially the source has direct link with destination. The relayed path is chosen when one of the relays among the ‘L’ idle SU’s can give higher SNR than the direct path. This model is depicted in Figure-1. The proposed technique can identify the best relay amongst the idle SU’s, the active SU’s operate in usual underlay mode. This operation of the active SU’s in underlay mode causes additional interference to idle SU’s and primary receiver. This is shown by a dotted line in Figure-1. The number of available channels between SU relays and PU destination are ‘K’.

In the proposed hybrid overlay/underlay transmission mode the active SU’s operate in underlay transmission mode, the selected relay node also works in underlay mode so that the other PU transmissions in the vicinity don’t get disturbed. The PU sender and receiver will use the idle SU’s as the relay to transmit their signals. This idle secondary user will use its entire power for PU transmission. In the ordinary overlay transmission, the SU uses only part of its power for PU transmission.

The benefits of using the underlay and overlay are jointly present in the proposed hybrid scheme. Here the unlicensed and licensed users can transmit their signals with full potential, since we have utilized the idle SU’s for PU transmission.

Reactive relay selection [12] is performed at the PU receiver. The signals from ‘L’ relays over the ‘K’ channels arrive at the PU destination. The PU destination node selects the best pair of channel and relay based on the SNR over the link. The pair with the higher SNR is selected to be best relay path. Let the first hop SNR is γ_{sr} and the second hop SNR is γ_{rd}. The selection criterion in partial relay selection technique to select best channel and relay is

$$(J, K) = \arg\max_{J,K}\{\gamma_{RD}\} \qquad (1)$$

The end to end SNR is given by $\gamma = \gamma_{sr}\gamma_{rd}/(\gamma_{sr}+\gamma_{rd})$. The selection criterion in opportunistic relay selection technique to select best channel and relay is

$$(J, K) = \arg\max_{J,K}\{\gamma\} \qquad (2)$$

3. Hybrid Overlay/Underlay Relay Selection Protocol

The process of selection of the best relay, power to be used by best relay and best channel for the proposed hybrid CR technique is given by this protocol. The various parameters such as interference threshold, PU transmitter power, distance between secondary users and primary users and the spectral distances between SU and PU channels are considered in the protocol. Let $\alpha_{PT_x-PR_x}$, $\alpha_{ST_i-PR_x}$, $\alpha_{PT_x-SU_j}$, $\alpha_{SU_j-PR_x}$ and $\alpha_{ST_i-SU_j}$ are the link gains over links $PT_x \rightarrow PR_x$, $ST_i \rightarrow PR_x$, $PT_x \rightarrow SU_j$, $SU_j \rightarrow PR_x$, and $ST_i \rightarrow SU_j$[13].Based on the SNIR over the direct link between PU receiver and transmitter, we first formulate the primary target rate. Let the distance dependent path loss factor be ‘n’. When P_{PT} is the power transmitted by the PU source, the power received P_{PR} at the PU receiver PRx is given by

$$P_{PR} = \frac{\alpha_{PT_x-PR_x} P_{PT}}{(d_{PT_x-PR_x})^n} \qquad (3)$$

The distance in the middle of PR_x and PT_x is denoted by dPTx-PRx. If ST_i (i=1,2,...M) are the active secondary users and PST_i is their transmitted power then the interference power strength P' at the PR_x is expressed as

$$P_i^{'} = \frac{\alpha_{ST_i-PR_x} P_{ST_i}}{(d_{ST_i-PR_x})^n} \qquad (4)$$

Where dSTi-PRx is the distance between secondary transmitter STi and primary receiver PR_x. The SNIR over the link PT_x-PR_x at the primary receiver is defined as

$$SNIR_{PT_x-PR_x} = \frac{P_{PR}}{\sum_{i=1}^{M} P_i^{'} + \sigma_p^2} \qquad (5)$$

Where σ_p^2 is the variance of AWGN on primary transmitter to receiver link. The achievable rate Rtarget bits/s/Hz for the links PTx-PRx is given by

$$R_{target} = log_2(1 + SNIR_{PT_x - PR_x}) \quad (6)$$

This is the target rate achieved over direct path. The following steps describe the calculation of data rate achieved over relayed path and the selection of best relay. One of the idle secondary user Re_j among the 'M' idle relays act as a best relay. Power received at relay SU_j, if P_{P_T} is the PU source transmitted, is given by

$$P_{SU_j} = \frac{\alpha_{PT_x - SU_j} P_{P_T}}{(d_{PT_x - SU_j})^n} \quad (7)$$

Where $d_{PT_x - SU_j}$ is the distance between the primary transmitter and the idle secondary user. The idle SU's face additional interference because of active secondary users. The additional interference power p'_{ij} at SU_j due to active SU's is expressed as [14]

$$p'_{ij} = \frac{\alpha_{ST_i - SU_j} P_{ST_i}}{(d_{ST_i - SU_j})^n} \quad (8)$$

Where p'_{ij} is the interference from user 'i' to user 'j' and the distance between the active SU and the idle SU is $d_{ST_i - SU_j}$. The primary transmitter sends the data to the relays on separate channels. The rate with which the data arrives at the idle secondary users is given by

$$R_{P,SU_j} = \frac{1}{2}\log(1 + \frac{P_{SU_j}}{\sigma_j^2 + \Sigma_{i=1}^{M} p'_{ij}}) \quad (9)$$

Where σ_j^2 is the variance of AWGN on primary transmitter to idle secondary user's link. For every relay SU_j paired to every subcarrier k calculate the power required to get the same rate of source to relay link in relay to destination link.

$$p_{j,k}^{rate} = \frac{\left(2^{\left(2R_{P,SU_j}\right)} - 1\right)\left(\sigma_k^2 + \Sigma_{i=1}^{M} p'_{ij}\right)(d_{SU_j - PR_x})^n}{\alpha_{SU_j - PR_x}} \quad (10)$$

Where $d_{SU_j-PR_x}$ is the distance between idle SU and the primary user receiver and σ_k^2 is the variance of AWGN on idle SU's to PU receiver link. The maximum power than can be allocated to each relay for all the combinations of (j,k) is calculated using the following expression

$$p_{j,k}^{max} = \frac{I_{th}}{\Omega_{j,k}} \qquad (11)$$

Where I_{th} is the interference threshold and $\Omega_{j,k}$ is the interference factor of the channel. The interference factor $\Omega_{j,k}$ is given by

$$\Omega_{j,k} = \alpha T_s \int_{d_k-B/2}^{d_k+B/2} \left(\frac{\sin \pi f T_s}{\pi f T_s} \right)^2 df \qquad (12)$$

Where the PU channel bandwidth is B, [15] channel gain is α, sampling time is T_s and the frequency distance between PU channel and subcarrier k is d_k. The final power allocated to each relay SU_j over the channel k is [16]

$$power_{j,k} = \min(p_{j,k}^{max}, p_{j,k}^{rate}) \qquad (13)$$

The power of the signal received at PU destination from the relay is given by

$$power_{j,k}^{Re} = \frac{\alpha_{SU_j-PR_x} Power_{j,k}}{(d_{SU_j-PR_x})^n} \qquad (14)$$

The optimal channel and relay pair can be selected using opportunistic or partial relay selection.

A. Partial Relay Selection

The optimal channel and relay is selected using the expression (15). The (j,k) pair which gets highest value with this expression is required optimal pair

$$(j^{opt}, k^{opt}) = \arg\max_{J,K}\{power_{j,k}^{Re}\} \qquad (15)$$

The rate of the signal that is received by the PU destination from this optimal pair is given by[17]

$$R_{PR_x} = \frac{1}{2}\log(1 + \frac{power^{Re}_{j^{opt},k^{opt}}}{\sigma_k^2 + \sum_{i=1}^{M} p_i^{\prime}}) \qquad (16)$$

B. Opportunistic Relay Selection

In this relay selection criterion the optimal pair (j^{opt}, k^{opt}) is selected based on the end to end SNR. To perform this the PU destination must be aware of full channel state information. The optimal pair is given by [11]

$$(j^{opt}, k^{opt}) = \arg\max_{J,K} \left\{ \frac{P_{SU_j} power^{Re}_{j,k}}{\left(P_{SU_j}\alpha_{PT_x - SU_j}\sigma_j^2 + power^{Re}_{j,k}\alpha_{SU_j - PR_x}\sigma_k^2 + \sum_{i=1}^{M} p_{ij}^{\prime}\right)} \right\} \qquad (17)$$

The rate of the received signal at PU destination by using the optimal pair obtained in opportunistic relay selection is given by

$$R_{PR_x} = \frac{1}{2}\log\left(1 + \frac{P_{SU_j} power^{Re}_{j^{opt},k^{opt}}}{\left(P_{SU_j}\alpha_{PT_x - SU_j}\sigma_j^2 + power^{Re}_{j,k}\alpha_{SU_j - PR_x}\sigma_k^2 + \sum_{i=1}^{M} p_{ij}^{\prime}\right)}\right) \qquad (18)$$

The communication is moved over to relayed path by neglecting the direct path under any one of the following 2 conditions.

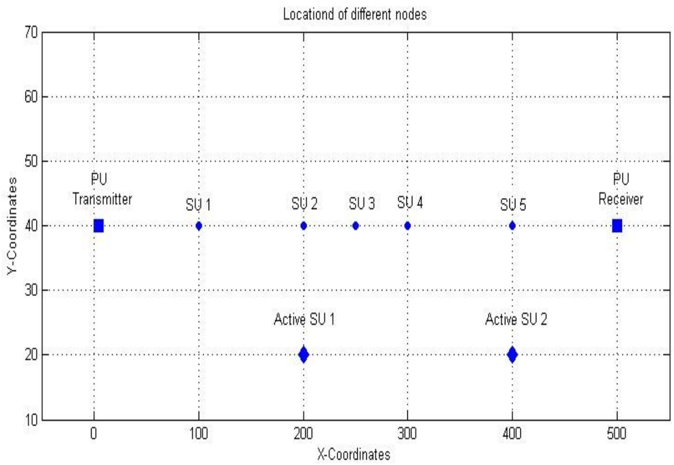
1. If rate over the relayed path (R_{PR_x}) obtained in either partial relay selection or opportunistic relay selection is greater than the rate over the direct path (R_{target}), i.e., $R_{PR_x} > R_{target}$
2. If the shadowing or fading is severe and the direct link from PU transmitter and PU destination is broken.

The received power from the PU source to PU destination over the direct link is evaluated by using (1). The interference at the PU destination because of SU's that are active is given by (2). The target data rate R_{target} upon direct path is obtained from (3). To find the relayed link data rate, we first need to recognize the best relay and channel. The signal power received from the PU transmitter to the SU's that are idle is given by (4). The interference by the active SU's to idle

SU's is given by (5). From these values we evaluate the data rate of the signal from SU source to idle SU's using (6). To achieve maximum throughput the data rate over the two hops must be equal [18]. To attain the same data rate over hop 1 and hop 2, the power needed by relay is given by (7). The relays maximum usable power is given by (8). The minimum of the two powers obtained in (7) and (8) is the power allocated to the relay, expressed in (9). The power of the signal that reaches from idle SU's to PU destination is given by (10). The partial relay selection criterion is expressed in (11). This gives the optimal pair of channel and relay between PU destination and SU relay. Rate over relayed path is given by (12). The opportunistic relay selection criterion is expressed in (13) and the rate over the relayed path selected by opportunistic relay selection is given by (14).

4. Simulation Results

In order to validate the proposed transmission technique, simulations were carried out and the results are presented in this section. Simulations were carried out on MATLAB. The primary user source and destination are situated at (4, 40) and (500, 40) respectively in a cartesian coordinate system. Two active SU's are located at (200, 20) and (400, 20). [19]The 5 idle SU's are positioned at (100, 40), (200, 40), (250, 40), (300, 40) and (400, 40) on the cartesian coordinate system. The scenario we considered assumes the power of PU source $P_{PT} = 10dB$ and the power of active secondary transmitter is$P_{ST_1} = P_{ST_2} = 10dB$. Link gain α and path loss



factor n are taken as $(0.097/d^2)^{1/2}$ and 2. To prevent the loss of generality, we assume $\sigma_p^2 = \sigma_j^2 = \sigma_k^2 = \sigma^2 = 10^{-13}$.

Fig.2. Location of nodes in simulated model

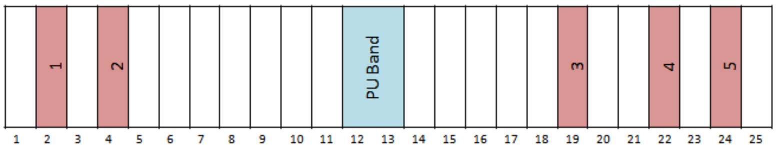


Fig.3. Spectrum Allocation

Figure-2 presents the simulation model of the system, it presents the 5 idle secondary users, 2 active secondary users and PU source and destination. The setup taken in Figure-2 is considered by us, where there is one PU sender and receiver, two active SU's and five idle SU's. Figure-2 helps in identifying the distances between the nodes. Figure-3 shows the five vacant channels between SU relay and Primary user receiver and their spectrum allocation. Figure-3 helps in finding the spectral distances between the channels. Bandwidth of the PU channel is 2MHz is the PU channel bandwidth and 1MHz is the relay channels bandwidth.

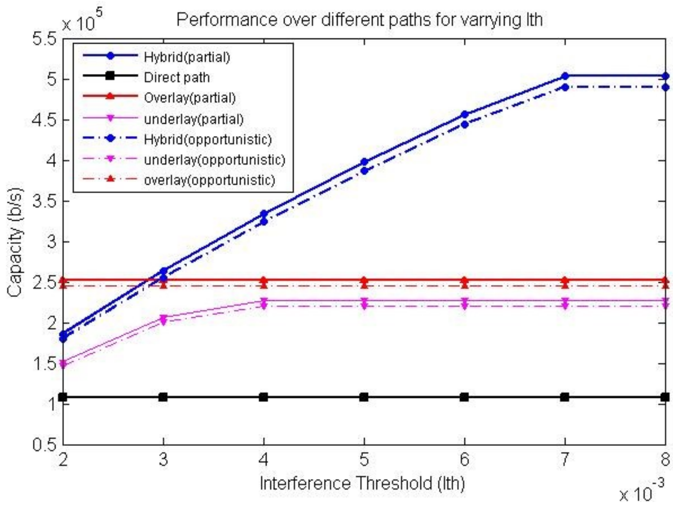


Fig.4. Capacity over different paths with partial and opportunistic relay selection and fixed PU transmitting power.

The performance comparison over the direct path and relayed by using the different transmission schemes is shown in Figure-4. The capacity is plotted by varying the interference threshold and power of the PU transmitter is fixed at 10dB. Since the influence of changing interference threshold (Ith) is not present on overlay transmission and direct path, the capacity response of them is flat. The response with partial relay selection is represented with a dotted line and the response of opportunistic relay selection is represented with a straight line. Figure-4 shows that the capacity over the relayed path, chosen by using partial relay selection gives better performance than the path chosen by using opportunistic relay selection. When the interference threshold is less than 3mw, overlay transmission gives better capacity than the proposed scheme. From Figure-4, it is evident that the proposed scheme gives good performance than the traditional overlay and underlay techniques at an interference threshold Ith≥3mw, with the relayed path selected using partial relay selection.

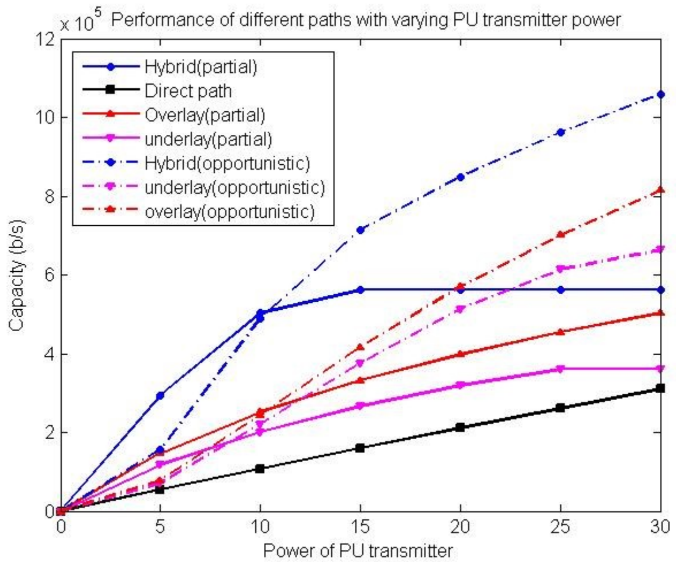


Fig.5. Capacity over different paths with partial and opportunistic relay selection and fixed Interference threshold.

The capacity over the direct path and relayed path with varying transmitting power of PU source is studied in Figure-5. The proposed hybrid CR scheme has better performance than the traditional overlay and underlay at various values of the PU transmitting power. The capacity reaches a saturation value at a power of 15dB and after this the capacity is constant. It is previously observed in Figure-4, that capacity over the relayed path by the use of partial relay selection is better when compared to opportunistic relay selection. Figure-4 is plotted with the PU transmitter power up to 10dB. In Figure-5, it can be observed that above the 10dB of PU transmitting power, the capacity achieved by opportunistic relay selection is higher than the partial relay selection. It is evident from Figure-5, that significantly better performance is achieved by opportunistic relay selection at higher SNR levels.

Conclusion

A novel hybrid overlay/underlay strategy for primary user throughput maximization is presented. We have analyzed two different relay selection schemes. An algorithm to allocate various resources in such hybrid CR scheme is presented. We have shown from the simulations that the hybrid overlay/underlay technique that we proposed has better performance over the traditional underlay and overlay methods. The throughput achieved by the use of the proposed technique is higher than the throughput achieved on the direct path.

This is a very useful incentive for the licenced users to cooperate with the unlicensed users. We have also presented the performance comparison between two relay selection criterions. Partial relay selection is preferable until the PU transmission of 10dB. Beyond 10dB, opportunistic relay selection gives best performance. The opportunistic relay selection has good performance at high SNR, but it is complex, as it needs the channel state info of the first hop. Partial relay selection is more preferable, as it is simple and the usual transmission power level of PU is commonly 10dB. At the PU transmission power of 10dB, the proposed hybrid overlay/underlay transmission scheme gives optimal performance when paired with partial relay selection.

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