

# Hybrid Overlay/Underlay Transmission with Partial and Opportunistic Relay Selection in Cognitive Radio Networks

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## Abstract

**Objectives:** In this paper, we consider a hybrid overlay/underlay strategy to maximize the throughput of primary users by use of idle secondary users as relays. Specifically, we focus on incorporating the advantageous features of underlay and overlay transmission methods into a hybrid cognitive radio technique. **Analysis:** By the use of the proposed technique both the primary and secondary users get benefited, as their communication link is uninterrupted. This scheme helps as an incentive for primary users to share their spectrum with the secondary users. **Findings:** The paper presents a resource allocation algorithm for the hybrid overlay/underlay transmission method. Also, the performance of the opportunistic and partial relay selection is investigated. This resource allocation algorithm is used to select the best channel from relay to destination, best relay and power allocated to best relay. 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. **Improvements:** The proposed scheme will eliminate the need to switching between the overlay and underlay techniques. The resource allocation along with proposed hybrid transmission scheme will give significant improvement in SNR of primary user.

**Keywords:** Cognitive Radio, Hybrid CR Scheme, Overlay, Opportunistic Relay Selection, Partial Relay Selection, Resource Allocation, Underlay

## 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 to utilize the spectrum efficiently. By use of traditional spectrum management, the spectrum is allocated for exclusive use to various wireless standards or licensed. One of the technology that has caught the attention of many researchers is cooperative spectrum sharing systems. Cognitive Radio (CR) and

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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<sup>1</sup>. Usually in such cooperative communication systems there are several nodes in between the source and destination to be chosen as the relay node. The performance of such system can be improved by selecting one of the node as the best relay, based on relay selection methods. The relay selection schemes can be classified into two types, opportunistic relay selection and partial relay selection. In the partial relay selection, a relay is chosen as the best relay based on the 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 elected to be best relay. In opportunistic relay selection the relay is selected based on the end to end SNR value. The relay with highest end to end SNR value is elected to be best relay.

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, a tolerable interference level is set at the PU. As long as the interference generated by the SU is below this predetermined interference threshold (Interference Temperature), the SU is allowed to use the spectrum. In overlay cognitive radio strategy, the primary users will relay data to other primary users using the SU node as relay. SU node must 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<sup>2</sup>. The CR is designed to switch between overlay and underlay based on the operating condition of PU in<sup>3-6</sup>. In<sup>7</sup> 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<sup>8</sup>. In<sup>8</sup> the SU's transmit with different spectrum sharing modes. The opportunistic relay selection performance has been analysed for the case of dual hop transmission in<sup>9,10</sup>. Performance of partial relay selection in dual hop communication systems with semi blind relaying is studied in<sup>11</sup>. 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<sup>12</sup>.

Unlike the previous hybrid CR algorithms, instead of switching between the overlay and underlay transmission modes, we consider combining the features 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 improved Signal to noise ratio provided after utilizing idle SU's 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 relay selection 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 secondary users and primary users in which the partial and opportunistic 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, efficient channel from best relay to destination and power allocated to the best relay. Section IV presents the simulation environment and the performance comparisons of the selection techniques. Finally, the concluding remarks are drawn in section V.

## 2. Results

Consider a CR network that comprises of one primary transmitter (source), one primary receiver (destina-

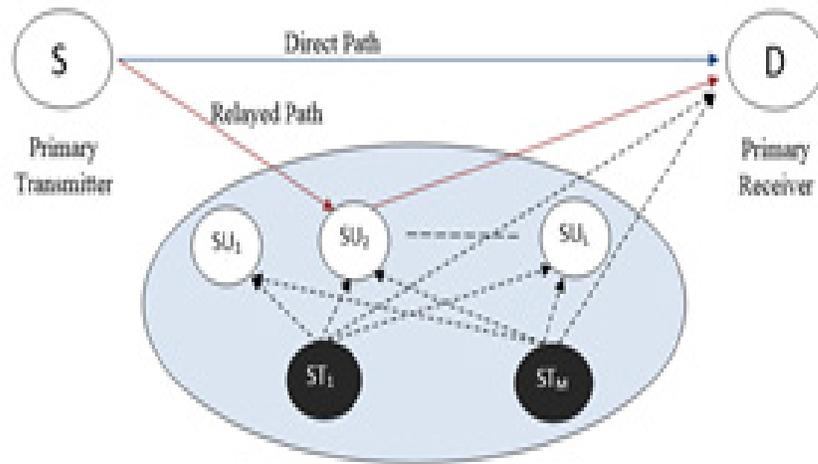


Figure 1. System Model.

tion), ‘M’ active SU’s and ‘L’ idle SU’s. Initially, 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 Figure1. 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 channels available between PU destination and SU relays is ‘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 advantageous features of both overlay and underlay are present in the transmission scheme that we proposed. Here SU’s and PU’s can both transmit their signals at full potential, since we have utilized the idle SU’s for PU transmission.

Reactive relay selection<sup>13</sup> 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<sup>14</sup>. The relay path is the pair with the highest SNR. Let the second hop SNR is  $\gamma_{rd}$  and the first hop SNR is  $\gamma_{sr}$ . The best relay selection criterion in the partial relay selection method is

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

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

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

### 3. Hybrid Overlay/Underlay Relay Selection Protocol

Selecting best relay in non-cognitive cooperative networks is totally deferent from the relay selection in hybrid CR network. The relay selection technique in hybrid CR technique must relay the data between two PU’s and the interference caused to other PU’s must be maintained at a minimum level. This section presents best relay selection procedure for such hybrid CR net-

works. This section presents selection procedure of power of the best relay, the best relay and the best channel for the hybrid overlay/underlay model presented in Figure 1. 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

$$\alpha_{ST_i-PR_x}, \alpha_{SU_j-PR_x}, \alpha_{ST_i-SU_j}, \alpha_{PT_x-SU_j}$$

and  $\alpha_{PT_x-PR_x}$  are the gains on the following links  $ST_i \rightarrow PR_x$ ,  $SU_j \rightarrow PR_x$ ,  $ST_i \rightarrow SU_j$ ,  $PT_x \rightarrow SU_j$  and  $PT_x \rightarrow PR_x$ . We first formulate the primary target rate over the direct link between PU transmitter and receiver. Let the factor for path loss be 'n' and it is distance dependent. When  $P_{PT}$  is the power transmitted by the PU source, let the power received at PU receiver  $PR_x$  be denoted by  $P_{PR}$ .  $P_{PR}$  is given by

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

The distance from  $PR_x$  to  $PT_x$  is denoted by  $d_{PT_x-PR_x}$ . If  $ST_i$  ( $i=1,2,\dots,M$ ) are the active secondary users and  $P_{ST_i}$  is their transmitted power, then the power of interference  $P'_i$  at PU receiver is expressed as<sup>15</sup>

$$P'_i = \frac{\alpha_{ST_i-PR_x} P_{ST_i}}{(d_{ST_i-PR_x})^n} \quad (4)$$

Where the primary receiver  $PR_x$  and secondary transmitter  $ST_i$  are separated by a distance  $d_{ST_i-PR_x}$ . The SNIR over the link  $PT_x-PR_x$  at the primary receiver is given by

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

Where the variance of AWGN over the link between PU receiver and transmitter is represented by  $\sigma_p^2$ . The rate that can be achieved over the direct path between PU's is denoted by  $R_{target}$  bits/s/Hz.  $R_{target}$  is given by

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

This is target rate achieved on the direct path. The following steps illustrate the evaluation of rate over the cooperative path and the best relay is selection. The best relay  $Re_j$  is one among the 'M' idle relays. The power

received at relay  $SU_j$ , if  $P_{PT}$  is the PU source transmitted, is given by

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

Where distance between idle secondary user and PU transmitter is denoted by  $d_{PT_x-SU_j}$ . Idle SU's receive additional interference from SU's that are active. The additional interference  $P'_{ij}$  at  $SU_j$  due to active SU's is expressed as<sup>16</sup>

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

Where the interference from user 'i' to user 'j' is denoted by  $P'_{ij}$  and distance between idle secondary user  $SU_j$  and active secondary user  $ST_i$  is  $d_{ST_i-SU_j}$ . The data is transmitted from PU transmitter to relay nodes over independent channels. Data rate of signal from PU transmitter to the idle SU's is given by the following equation

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

Where the AWGN variance over the link between PU transmitter and idle SU's is denoted with  $\sigma_j^2$ . The following expression (10) is used to calculate the required power for the relay node to generate same rate of information over hop 1 and hop 2

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

Where the variance of AWGN on link between PU destination and idle SU's is denoted with  $\sigma_k^2$ . Distance between PU destination and idle SU's is denoted by  $d_{SU_j-PR_x}$ . Maximum power that can be allocated to each relay for all the combinations of (j,k) is calculated using the following expression

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

Where the interference factor is represented by  $\Omega_{j,k}$  and interference threshold is denoted by  $I_{th}$ .  $\Omega_{j,k}$  is given by the following equation

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

Where PU channel bandwidth is  $B$ <sup>17</sup>,  $T_s$  is the sampling time, frequency distance between PU channel and subcarrier  $k$  is  $d_k$  and  $\alpha$  is the gain of the channel. For transmitting the signal from relay to destination over channel  $k$ , the power with which the relay can operate is given by the following expression<sup>18</sup>

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

The received signal power from the relay to PU destination is given by the following equation

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

The next step after finding the power allocated to relay and power received at PU destination is to identify optimal channel and relay pair. This can be done using opportunistic or partial relay selection.

### 3.1 Partial Relay Selection

The optimal channel and relay is selected using the expression (15). The (j,k)pair that achieves highest value using this expression is optimal pair

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

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

$$R_{PR_x} = \frac{1}{2} \log \left( 1 + \frac{power_{j^{opt},k^{opt}}^{Re}}{\sigma_k^2 + \sum_{i=1}^M p_i} \right) \quad (16)$$

### 3.2 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<sup>12</sup>

$$\max_{j,k} \left\{ \frac{R_{SU_j} power_{j,k}^{Re}}{\left( R_{SU_j} \alpha_{PT_x-SU_j} \sigma_j^2 + power_{j,k}^{Re} \alpha_{SU_j-PR_x} \sigma_k^2 + \sum_{i=1}^M p_i \right)} \right\} \quad (17)$$

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

$$R_{PR_x} = \frac{1}{2} \log \left( 1 + \frac{R_{SU_j} power_{j^{opt},k^{opt}}^{Re}}{\left( R_{SU_j} \alpha_{PT_x-SU_j} \sigma_j^2 + power_{j^{opt},k^{opt}}^{Re} \alpha_{SU_j-PR_x} \sigma_k^2 + \sum_{i=1}^M p_i \right)} \right) \quad (18)$$

The transmission is switched from direct link to relay link under any one of the following 2 conditions.

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

The power that is received from the PU source to PU destination over the direct link is evaluated by using (1). The secondary users that are active create interference at primary destination which is given by (2). The target rate  $R_{target}$  on direct channel is obtained from (3).(4) gives power of the signal received from the PU source to idle SU's. 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<sup>19</sup>. The required power for attaining the same data rate by the relay on hop 1 is given by (7). The relay can use a maximum power which 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 destination primary user receives a signal from idle SU's with a power that is given by (10). The partial relay selec-

tion criterion is expressed in (11). This gives the optimal pair of relay and link to be selected 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. 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 5 idle SU's are located at (100, 40), (200, 40), (250, 40), (300, 40) and (400, 40). The primary user source and destination are located at (4, 40) and (500, 40). The two active SU's are located at (200, 20) and (400, 20). The scenario we considered assumes the power of PU source  $P_{PT} = 10dB$

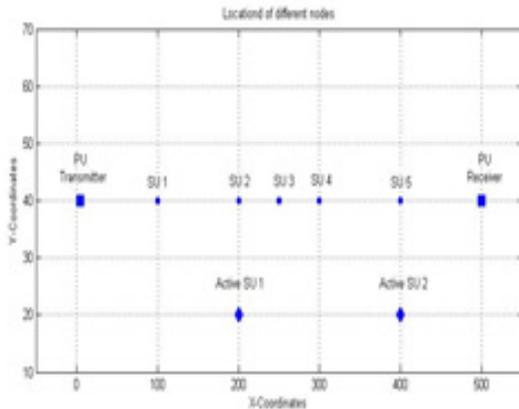


Figure 2. Location of nodes in simulated model.

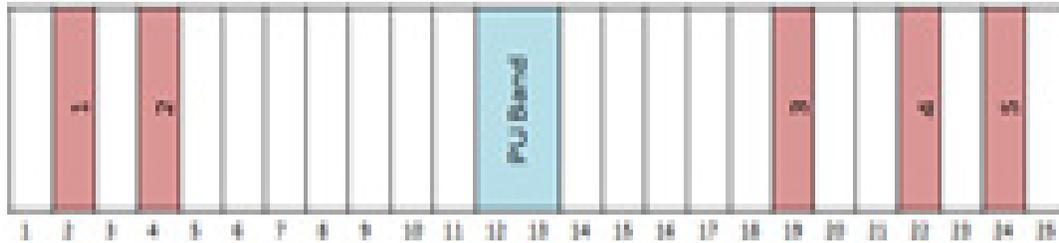


Figure 3. Spectrum Allocation.

and the power of active secondary transmitter is  $P_{ST_1} = P_{ST_2} = 10dB$ . Link gain  $\alpha$  and path loss factor  $n$  are taken as  $(0.097/d^2)^{1/2}$  and 2. To prevent the loss of generality, we assume  $\sigma_p^2 = \sigma_j^2 = \sigma_k^2 = \sigma^2 = 10^{-13}$ .

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. Figure 2 helps in identifying the distances between the nodes. Figure 3 shows the allocation of spectrum for the five existing channels between primary user receiver and SU. Figure 3 helps in finding the spectral distances between the channels. The PU channel bandwidth is 2MHz and bandwidth of the relay channels is 1MHz.

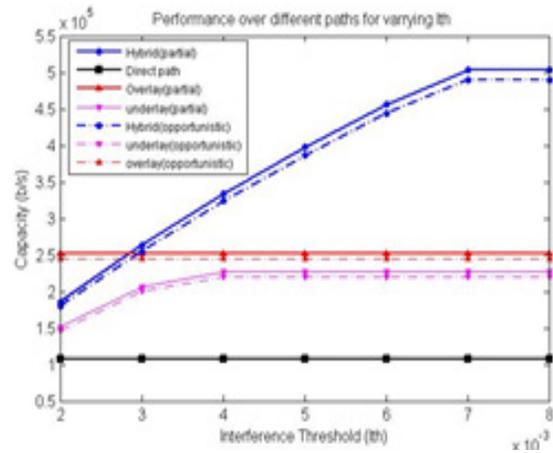
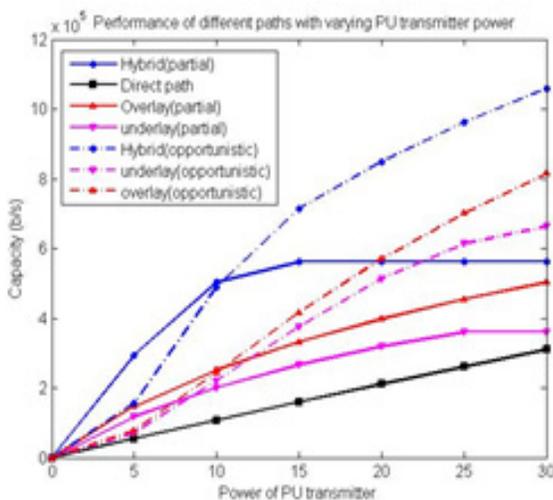


Figure 4. Capacity over different paths with partial and opportunistic relay selection and fixed PU transmitting power.

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 the power of PU transmitter is fixed at 10dB. Since there is no effect of varying interference threshold<sup>15</sup> 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. It is evident from Figure 4 that the proposed performs better than the traditional overlay and underlay techniques at an interference threshold  $I_{th} \geq 3\text{mw}$ , with the relayed path selected using partial relay selection.



**Figure 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 performance of the proposed hybrid CR scheme is better 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 higher performance is achieved by opportunistic relay selection at higher SNR levels.

## 5. Conclusion

A novel hybrid overlay/underlay strategy for primary user throughput maximization is presented. We have analysed 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 proposed hybrid overlay/underlay technique has better performance over the traditional overlay and underlay techniques. The throughput achieved by the use of the proposed technique is higher than the throughput achieved on the direct path. We have also presented the performance of two relay selection criteria. Partial relay selection is preferable up to 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 combined with partial relay selection.

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