Best Relay Selection Using SNR and Interference Quotient for Underlay Cognitive Networks

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Abstract—Cognitive networks in underlay settings operate simultaneously with the primary networks satisfying stringent interference limits. This condition forces them to operate with low transmission powers and confines their area of coverage. In an effort to reach remote destinations, underlay cognitive sources make use of relaying techniques. Selecting the best relay among those who are ready to cooperate is different in underlay settings than traditional non-cognitive networks. In this paper, we present a relay selection scheme which uses the quotient of the relay link signal to noise ratio (SNR) and the interference generated from the relay to the primary user to choose the best relay. The proposed scheme optimizes this quotient in a way to maximize the relay link SNR above a certain value whereas the interference is kept below a defined threshold. We derive closed expressions for the outage probability and bit error probability of the system incorporating this scheme. Simulation results confirm the validity of the analytical results and reveal that the relay selection in cognitive environment is feasible in low SNR regions.

I. INTRODUCTION

Emerging wireless applications and consumer expectations fueled an endless desire for higher data rates. The enabling technologies for these high data rate services have consumed almost all the available and accessible spectrum. On the other hand, inefficient utilization of huge chunks of licensed spectrum forced regulatory authorities, industry and academia to look for and devise methods to access this unused spectrum in cognitive manner \cite{1}, \cite{2}. Generally, it is suggested that if the licensed or primary user is not using the dedicated spectrum or part of it, the secondary or cognitive user can exploit this unused spectrum \cite{1}, also referred to as spectrum hole. Once the primary user starts its transmission, the secondary user either switches off or moves to another spectrum hole if available. Co-existence in this fashion requires spectrum sensing and detection and generally known as interweave approach. Simultaneous in-band co-existence is possible in overlay settings where the secondary user avoids interference to the primary user by using advanced signal processing techniques. Another simpler way to access the spectrum simultaneously is the underlay approach in which the secondary user strictly follows the interference limit \cite{1}.

In order to obey the interference threshold, secondary users in underlay mode are required to transmit at low powers which limits their area of coverage. Hence, to reach distant destinations, relaying may be an attractive option. There exist various techniques and protocols for relaying a signal in cooperative networks among which amplify and forward (AF) is the most popular one due to its simplicity. As the name suggests, in this technique the received signal at the relay is just amplified and forwarded to the destination \cite{3}. Another better performing but computationally expensive approach is decode and forward (DF) in which the relay decodes and reproduces the received message before forwarding it to the destination or next node \cite{3}. A general advantage of relaying is to improve diversity order which can be further enhanced by using multiple relays in the system \cite{4}, \cite{5}. The relays involved in such a transmission, in most cases, must transmit on orthogonal channels making this approach inefficient in terms of spectrum utilization. Selective relaying was recently proposed as an alternative for better spectrum efficiency \cite{6}.

Selective relaying has been a topic of great interest recently in non-cognitive cooperative networks. Most commonly, a relay is picked up to forward the source’s message on the basis of signal to noise ratio (SNR) it could provide for the transmission. Contrarily in underlay cognitive networks, a relay which could provide the maximum SNR to the communication link may also be a source of strong interference to the primary user or even violate the interference threshold. Hence, the selective relaying defines an entirely different problem in underlay cognitive settings due to the stringent interference thresholds. It is also obvious that the maximum SNR can not be used as the only criterion for the relay selection.

Selective relaying has recently been studied in a couple of papers. A modified relay selection criterion is proposed in \cite{7} which takes into account the interference constraint and the relays in the network are assumed to be operating in DF mode. Main contribution in this paper is the derivation of outage probability. Another relay selection criterion scheme is proposed in \cite{8} which selects the best relay under the constraint of satisfying a required outage probability of the primary network. The outage probability of the secondary network is derived where the relays are operating in DF mode. In both of these papers, the secondary nodes are assumed to adapt their transmission power in order to always satisfy the interference constraint. However, this capability may not always be available.

In this paper, we consider an underlay secondary network with multiple relays operating in AF mode near a primary
user. The secondary nodes have fixed transmission powers at their discretion. We propose a new best relay selection criterion which defines a quotient of end-to-end SNR offered by a relay to the interference it produces to the primary user. A relay which could maximize this quotient while maintaining the interference threshold and offering end-to-end SNR above a certain value is selected by the destination. We derive closed form expressions for the cumulative distribution function (CDF) of the total SNR at the destination using moment generating function (MGF) approach. We also derive closed form expressions for the outage probability and average bit error probability of the system.

II. SYSTEM MODEL

Our system model is comprised of a secondary source $S$ which is transmitting its signal to a secondary destination $D$ with the help of $L$ secondary relays represented by $R_i, i = 1, 2, \cdots, L$, in Fig. 1. This whole network is operating in underlay mode near a primary user $P$. A traditional two time slot communication procedure is followed in AF mode. The source $S$ with transmission power $E_s$ broadcasts its signal in the first time slot. This signal is received by the destination, all the relays and the primary user with channel gains $h_0, h_{1i}$ and $h_{SPi}$, respectively. We assume that each relay is aware of the interference channel $h_{iP}$ form itself to the primary user. The relays can gather this information either when the primary user is transmitting or when it is acknowledging any received signal. They also share this information with the destination over some dedicated feedback channels.

The relays are allowed to transmit at fixed power $E_r$; therefore, they adjust their amplification factor in order to reciprocate previous hop’s channel gain. We assume that each hop in the system, either communication or interference link, is subjected to additive white Gaussian noise (AWGN) with zero mean and variance $N_0$. Hence, each relay sets its amplification factor to $g_i = \frac{E_r}{E_s|h_{1i}|^2 + N_0}$. The channel gain from the $i^{th}$ relay to the destination is $h_{2i}$ which we assume is known at the destination.

Underlay cognitive networks are required to operate under stringent interference limits which guarantees that the primary network is not affected by the secondary communication. Let $\lambda$ be the interference threshold; however, for some relays the interference channel may be strong enough that they would not satisfy this threshold. Therefore, the destination who has the channel state information (CSI) available through the relays excludes such relays from the group it is going to pick the best relays, no matter what SNR they could provide over the secondary relay link.

Let us assume that a certain number of relays out of $L$ satisfies the interference threshold. So, we define a set $U$ which contains the indexes of all the relays, another set $A \subseteq U$ which contains the indexes of the relays satisfying interference threshold whereas $B = U - A$ contains the remaining indexes.

Relay selection takes place in the second time slot and the destination chooses the best one based on a criterion explained in the next section. The chosen best relay then forwards the source’s message to the destination in AF mode. We assume that all the channels are Rayleigh distributed and therefore their squared amplitudes have exponential distribution.

The end-to-end SNR of the $i^{th}$ relayed link (secondary SNR) can be given as

$$\gamma_{SRiD} = \frac{\gamma_1 \gamma_{2i}}{\gamma_1 + \gamma_{2i} + 1},$$

where $\gamma_1 = \frac{E_s |h_{1i}|^2}{N_0}$ is the SNR of the first hop and $\gamma_{2i} = \frac{E_r |h_{2i}|^2}{N_0}$ is the SNR of the second hop. The above value of $\gamma_{SRiD}$ is tightly upper bounded by $\min(\gamma_1, \gamma_{2i})$ which makes it a function of just one random variable (RV) and makes the later analysis simple and more mathematically tractable [9].

$$\gamma_{SRiD} \leq \gamma_i = \min(\gamma_1, \gamma_{2i}).$$

III. THE QUOTIENT BASED RELAY SELECTION SCHEME

The best relay selection in underlay cognitive networks is entirely different from the traditional non-cognitive cooperative networks where, in most cases, the best relay is selected on the basis of maximum end-to-end SNR. Contrarily, in cognitive networks, a relay which could maintain maximum secondary SNR may also create more interference to the primary user in the absence of transmit power adaptation. Hence, the criterion for selecting the best relay in underlay cognitive networks should include the interference a relay is creating on the primary user. So, first we quantify the interference from the source to the primary in the first time slot and from the $i^{th}$ relay to the primary in the second time slot, respectively, as follows

$$I_{SP} = E_s |h_{SP}|^2 \quad \text{and} \quad I_{iP} = E_r |h_{iP}|^2.$$  

The whole transmission procedure described above could not begin if $I_{SP}$ is more than $\lambda$ and thus the proposed scheme could not be analyzed. In such a case, the source would wait until it satisfies the interference limit and qualifies for the transmission. Hence, to analyze the proposed scheme, we assume a situation when $I_{SP} \leq \lambda$. Now, to pick up the best relay, we propose a quotient of the $i^{th}$ secondary relay link SNR $\gamma_i$ to the interference caused by the $i^{th}$ relay $I_{iP}$, i.e., $Z_i = \frac{\gamma_i}{I_{iP}}$. The best relay should maximize this quotient with two important constraints. First, as mentioned above,
the interference level should be below the given threshold, i.e., $I_{iP} \leq \lambda$. Secondly, the secondary SNR should be above a certain value, i.e., $\gamma_i \geq \eta$. The second constraint avoids a situation when a relay is somehow hidden from the primary user and causing very little interference to it, but does not provide the maximum secondary SNR. In this case, the value of $Z_i$ becomes extremely large due to the very small denominator term and that particular relay would always be picked up, though it is not providing the maximum secondary SNR. Hence, the proposed best relay selection criterion can be stated as

$$i^* = \max_i Z_i = \max_i \frac{\gamma_i}{I_{iP}} \text{ such that } \gamma_i \geq \eta, I_{iP} \leq \lambda,$$

where $i^*$ is the index of the selected relay.

With the secondary SNR constraint, we need to define another subset $C$ in $A$, which contains the indexes of the relays satisfying the secondary SNR condition. Thus, the best relay for the above criterion lies in $A \cap C$. There exists a non zero probability that none of the relays satisfies both constraints and the destination only receives the direct signal from the source.

As mentioned earlier, both $\gamma_i$ and $I_{iP}$ are independent and exponentially distributed RVs with PDFs as follows

$$p_{\gamma_i}(\gamma_i) = \frac{1}{\bar{\gamma}_i} e^{-\frac{\gamma_i}{\bar{\gamma}_i}} \text{ and } p_{I_{iP}}(x) = \frac{1}{\sigma_{I_{iP}}} e^{-\frac{x}{\sigma_{I_{iP}}}},$$

where $\bar{\gamma}_i$ and $\sigma_{I_{iP}}$ are the average values of the secondary SNR and interference strength through the $i$th relay, respectively.

If the cardinality of $A \cap C$ is $\ell$ then the PDF of the SNR of the selected relay according to the proposed criterion can be given as

$$p_{\gamma_i}(\gamma_i|\ell) = p_{\gamma_i}(\gamma_i)p_{\gamma_{iP}}(\gamma_{iP})\left[p_{\gamma_{I_{iP}}}(\gamma_{I_{iP}} < \gamma_i)\right]^{\ell-1}.$$  

To simplify the above, we can assume that the average values of the secondary SNRs and interference strengths are the same for all the relays. Hence, $\bar{\gamma}_1 = \bar{\gamma}_2 = \cdots = \bar{\gamma}_{\ell} = \bar{\gamma}$ and $\sigma_{I_{iP}} = \sigma_{I_{iP}} = \cdots = \sigma_{I_{iP}} = \sigma$. With this assumption, (6) can be written as

$$p_{\gamma_i}(\gamma_i|\ell) = \ell p_{\gamma_i}(\gamma_i)\left[p_{\gamma_{I_{iP}}}(\gamma_{I_{iP}} < \gamma_i)\right]^{\ell-1},$$

where $\gamma_i = \max_i \frac{\gamma_i}{I_{iP}}$ evaluated at $\gamma_i$. This CDF can be derived in two steps. First, we consider $\frac{\gamma_i}{I_{iP}}$, which is $Z_i$ for all the relays not selected by the destination but $i \in A \cap C$. The conditional CDF of $Z_i$ with secondary SNR and interference constraints can be evaluated as

$$P_{Z_i}(z; \gamma_i \geq \eta, I_{iP} \leq \lambda) = \int_0^\lambda \left[ \int_{\eta}^z p_{\gamma_i}(\gamma_i)d\gamma_i \right] p_{I_{iP}}(x)dx,$$

$$= P_{\gamma}P_{\lambda} - \left[ 1 - \frac{1 - \beta e^{-\alpha z}}{\mu z + 1} \right].$$

where $P_{\gamma} = Pr(\gamma_i \geq \eta) = e^{-\frac{-\gamma}{\bar{\gamma}}}$, $P_{\lambda} = Pr(I_{iP} \leq \lambda) = 1 - e^{-\frac{-\lambda}{\sigma}}$, $\alpha = \frac{\bar{\gamma}}{\lambda}$, $\beta = e^{-\frac{-\lambda}{\mu z + 1}}$ and $\mu = \frac{\sigma_{I_{iP}}}{\sigma}$. Differentiating the above gives us the PDF of $Z_i$

$$p_{Z_i}(z; \gamma_i \geq \eta, I_{iP} \leq \lambda) = \frac{\mu z}{(\mu z + 1)^2},$$

where $a = \alpha\mu \beta$ and $b = (\alpha + \mu)\beta$.

Now, we consider $Y_i = Z_i I_{iP}$, in which $I_{iP}$ is the interference produced by the selected relay to the primary user and it should be less than $\lambda$. The CDF of $Y_i$ with all the constraints can be evaluated as

$$P_{Y_i}(y; \gamma_i \geq \eta, I_{iP}, I_{iP} \leq \lambda) = A + \frac{y}{\gamma} e^{-\frac{y}{\gamma}}\left[ \frac{\gamma}{\gamma} e^{-\frac{y}{\gamma}}\Delta(\gamma) \right]^{\ell-1},$$

where $A = \frac{\mu \bar{\gamma}}{\mu z + 1}$ and $\Delta(\gamma)$ is the exponential integral.

Replacing (11) with $y = \gamma$ in (7) we get

$$p_{\gamma_i}(\gamma_i|\ell; \gamma_i \geq \eta, I_{iP}, I_{iP} \leq \lambda) = \ell e^{-\frac{\gamma}{\bar{\gamma}}} \left[ A + \frac{\gamma}{\gamma} e^{-\frac{\gamma}{\gamma}}\Delta(\gamma) \right]^{\ell-1},$$

where, for the ease of notation, $\Delta(\gamma) \equiv \text{Ei}(\frac{\gamma}{\gamma} - \frac{\gamma}{\gamma}) - \text{Ei}(\frac{\gamma}{\gamma})$.

We note that $\Delta(\gamma)$ is infinitesimally small quantity, specially at higher SNR, and its higher powers could be neglected. Therefore, the above PDF could be approximated to

$$p_{\gamma_i}(\gamma_i|\ell; \gamma_i \geq \eta, I_{iP}, I_{iP} \leq \lambda) \simeq \frac{\ell A^{\ell-1}}{\gamma} e^{-\frac{\gamma}{\gamma}}.$$  

It is worthy to note that the above PDF is conditioned over $\ell$, i.e., the number of relays satisfying both constraints. The value of $\ell$ may vary from 0 to $L$. If $\ell = 0$, the destination only receives the direct signal from the source. In case $\ell = 1$, still there would be no relay selection, rather, the destination could combine the direct and the only relayed signal. A choice among the relays becomes available to the destination when $\ell \geq 2$ and the destination could select the best relay according to the proposed scheme. Each relay in the system can satisfy these constraints with a probability $P_c = P_{\ell}P_{\lambda} = e^{-\frac{-\gamma}{\gamma}}(1 - e^{-\frac{-\lambda}{\mu z + 1}})$. Hence, the probability of $\ell$ relays available for selection out of $L$ follows a binomial distribution

$$p_\ell(\ell; L, P_c) = \binom{L}{\ell} P_c^\ell (1 - P_c)^{L-\ell},$$

where $\binom{L}{\ell} = \frac{L!}{\ell!(L-\ell)!}$.

The unconditional PDF of $\gamma_\ell$ can be found by averaging (13) using (14) for $\ell = 1, 2, \cdots, L$. Therefore

$$p_{\gamma_\ell}(\gamma_\ell; \gamma_i \geq \eta, I_{iP}, I_{iP} \leq \lambda) = \sum_{\ell=1}^{L} \binom{L}{\ell} \ell A^{\ell-1} P_c^\ell (1 - P_c)^{L-\ell} e^{-\frac{\gamma_i}{\gamma}},$$

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Since the end-to-end SNR maintained by the selected relay should be above $\eta$, we can evaluate a truncated moment generating function (MGF) of $\gamma_s$ as follows

$$M_{\gamma_s}(s; \gamma_i \geq \eta, I_{iP}, I_{iP} \leq \lambda) = \int_{\eta}^{\infty} e^{-s\gamma} p_{\gamma_s}(\gamma; \gamma_i \geq \eta, I_{iP}, I_{iP} \leq \lambda) d\gamma$$

$$= \sum_{\ell=1}^{L} \left( \frac{L}{\ell} \right) \ell A^{L-\ell} P_c^\ell (1-P_c)^{L-\ell} P_{\eta} e^{-s\gamma}$$

$$\frac{1}{\gamma(s+1/\ell)}.$$  

(16)

The direct link SNR is also exponentially distributed with its average value $\bar{\gamma}_0$ having a well known MGF $\frac{1}{1+s\bar{\gamma}_0}$. Since the direct and the selected relay link SNRs are completely independent, the CDF of the total SNR at the destination, $\gamma_T = \gamma_0 + \gamma_s$, can be given as

$$P_{\gamma_T}(\gamma) = \mathcal{L}^{-1} \left[ \frac{M_{\gamma_0}(s)M_{\gamma_s}(s)}{s} \right]_{s=\gamma}$$  

(17)

where $\mathcal{L}^{-1}(\cdot)$ represents the inverse Laplace transform and again, to simplify the notation, we have dropped the constraint descriptions; however, it should be reminded that all the PDFs, CDFs and MGFs which follow are the truncated versions due to the posed constraints.

Replacing (16) in (17) and solving by [10, Table 17.13.25], we get

$$P_{\gamma_T}(\gamma) = \sum_{\ell=1}^{L} \left( \frac{L}{\ell} \right) \ell A^{L-\ell} P_c^\ell (1-P_c)^{L-\ell} P_{\eta} \times$$

$$\left[ \frac{\bar{\gamma}_0 e^{-\bar{\gamma}_0 (\gamma-\eta)} - \bar{\gamma}_0 e^{-\bar{\gamma}_0 (\gamma-\eta)} + (\gamma - \bar{\gamma}_0)}{\bar{\gamma} - \bar{\gamma}_0} \right]$$  

(18)

IV. PERFORMANCE ANALYSIS

A. Outage Probability

According to the conventional definition of outage probability, it represents the probability of having the received SNR below a certain threshold. Hence, the outage probability could be directly derived through the CDF of the total SNR above by replacing $\gamma = \gamma_{th}$, where $\gamma_{th}$ is the outage threshold SNR. The CDF of the total SNR in (18) is for the situations when at least one relay satisfies the imposed constraints. However, as mentioned earlier, it is possible that none of the relays satisfies the imposed constraints and the destination receives the direct signal only. The probability of this event is $Pr[\ell = 0] = (1-P_c)^L$. Furthermore, the probability of having the SNR less than $\gamma_{th}$ with the direct signal only is $(1 - e^{-\frac{\gamma_{th}}{\bar{\gamma}_0}})$. Hence, the outage probability of the system can be evaluated as

$$P_{out} = P_{\gamma_T}(\gamma_{th}) + (1-P_c)^L(1 - e^{-\frac{2\gamma_{th}}{\bar{\gamma}_0}}).$$  

(19)

B. Average Bit Error Probability

In order to find the average bit error probability, we first express the error probability conditioned over a given SNR in AWGN. This could be written terms of standard $Q$ function which could then be averaged over the derived total SNR PDF.

We assume that the modulation scheme used in the network is linear in nature.

$$P_e = Pr[\ell = 0] \int_{0}^{\infty} P_e(\epsilon|\gamma_0)P_{\gamma_0}(\gamma)d\gamma + \int_{0}^{\infty} P_e(\epsilon|\gamma_T)P_{\gamma_T}(\gamma)d\gamma,$$

(20)

where $P_e(\epsilon|\gamma) = Q(\sqrt{\beta}\gamma)$ and $\beta$ is a constant depending upon the modulation scheme.

Instead of deriving the PDF of $\gamma_T$, we can use the technique given in [11] to evaluate $P_e$ using the derived CDF.

$$\int_{0}^{\infty} P_e(\epsilon|\gamma)P_{\gamma}(\gamma)d\gamma = \frac{1}{\sqrt{2\pi}} \int_{0}^{\infty} P_\gamma(\frac{\epsilon^2}{\beta})e^{-\frac{\epsilon^2}{2\beta}}dt.$$  

(21)

Replacing (18) and the CDF of the direct link SNR in (20) and solving using [10, Eq. 3.321.2-3], we obtain

$$P_e = \frac{(1-P_c)^L}{2} \left[ 1 - \sqrt{\frac{\beta \gamma_0}{2(1+\gamma_0)}} + \sqrt{\frac{\pi P_\eta}{2}} \sum_{\ell=1}^{L} \left( \frac{L}{\ell} \right) A^{L-\ell} \right]$$

$$\times P_c^\ell (1-P_c)^{L-\ell} - \frac{\bar{\gamma}_0 e^{-\bar{\gamma}_0 q_0}}{(\gamma - \bar{\gamma}_0)q} \times \text{erfc}(q_0) - \frac{\gamma e^{-\gamma q_0}}{(\gamma - \bar{\gamma}_0)q} \times \text{erfc}(q) + \sqrt{2} \text{erfc}(\frac{\eta}{\sqrt{2}}),$$  

(22)

where $q_0 = \sqrt{\frac{\bar{\gamma}_0 \beta + 2}{2\bar{\gamma}_0^2}}, q = \sqrt{\frac{\gamma + 2}{2\gamma}}$ and erfc($\cdot$) is the complementary error function.

V. SIMULATION RESULTS

Simulation results are obtained by varying the average per hop SNR $\bar{\gamma}$ whereas the interfering channels are generated with parameter $\sigma = 0.9\bar{\gamma}$ and the direct link is simulated with $\bar{\gamma}_0 = 0.8\bar{\gamma}$. The noise in each hop is considered to be unit variance AWGN with zero mean. The transmission power at the source and the relay is also assumed to be $E_s = E_r = 1$. Binary phase shift keying (BPSK) with $\beta = 2$ is used as the modulation technique. System configurations with different number of relays are compared with equal power conditions. The bit error probability (BER) of the system is presented in Fig. 2 with $\lambda = 10$ and $\eta = 1$ for different
number of relays. BER performance of the system when it is operating on the direct link only i.e. none of the relays satisfies the imposed constraints is shown for comparison purposes. Similarly, the BER of the traditional non-cognitive relay network with best relay selection is also plotted for comparative analysis only. In non-cognitive networks, the best relay is chosen amongst the $L$ relays and hence the diversity order of the system remains $L$ at any SNR. On the other hand, in the considered cognitive network, the selection takes place out of $\ell$ relays, where $\ell \leq L$. Hence, on average, the diversity order of the non-cognitive network is higher than that of cognitive network where the relays are “short listed” based on the imposed constraints. This phenomenon results in better BER of non-cognitive networks at any value of $L$ and SNR. If we concentrate on the performance of the considered cognitive network, we observe that from low to medium SNR the interference to the primary is not an issue and the BER performance follows a normal trend. Increasing per hop SNR causes more and more relays to satisfy the value of $\eta$ and the BER gradually reduces. However, from medium to high SNR, the relays start violating the interference threshold $\lambda$ and get excluded from the selection pool. This causes a degradation in the performance and eventually at high SNR none of the relays could satisfy the interference constraint and system operates on the direct link only.

To study the effects of interference and SNR constraints on the proposed scheme, we simulate the system with four relays under different sets of constraint values, as shown in Fig. 3. The values of $\lambda = 10$ and $\eta = 1$ serve as comparison benchmark. Increasing the SNR constraint or reducing the interference limit makes it difficult for the relays to qualify for the selection and the BER of the system increases. It is also evident that more relays could be available for the selection reducing the BER if the constraints are relaxed, i.e., $\eta$ is reduced and $\lambda$ is increased. These variations also suggest different optimal operating points of the system in different settings to achieve the minimum BER.

Outage probability of the system is depicted in Fig. 4. Similar trends as seen in the BER are also visible here in outage probability due to the same reasons. It is clear from these results that the relay selection improves the system performance in low to mid SNR range for underlay cognitive networks. Whereas, in non-cognitive cooperative networks, it is feasible at all SNR values.

VI. CONCLUSION

We proposed a relay selection scheme based on SNR and interference quotient for a cognitive network operating near a primary user. The proposed scheme maximizes the relay link SNR while keeping the interference to the primary below the defined threshold. We derived the closed form CDF of the total SNR at the destination using MGF approach and then used it to derive BER and outage probability of the system in closed forms. We showed that relay selection is only feasible at low SNR in underlay cognitive networks. Analytical formulae are verified through simulations.

REFERENCES