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MULTI-HOP RELAY SELECTION FOR COOPERATIVE SENSING IN COGNITIVE RADIO NETWORKS

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Spectrum sensing is one of the essential blocks of the cognitive radio (CR) system. Cooperative spectrum sensing (CSS) enhances sensing performance by exchanging information among secondary users (SUs). The paper addresses a situation where some SUs cannot communicate their local information with the fusion center (FC) due to real-time circumstances, i.e., shadowing, large distances, increased signal interference, etc. The issue can be resolved by introducing relay nodes to assist such SUs in transmitting local information to the corresponding destination (FC), making relay selection an essential component on which the system's performance depends. This paper proposes a critical path method (CPM) based multi-hop relay selection technique to select a set of relay nodes combined to form a relay with minimum path loss. The performance of the proposed scheme is compared with that of the existing methodologies to demonstrate its robustness and efficiency in terms of end-to-end path loss and reliability. In addition, a closed-form expression of outage probability is also developed to withstand the results.

1. INTRODUCTION

Cooperative spectrum sensing (CSS) is an effective approach to combat the practical challenges of single-node sensing and is being adopted in most cognitive radio (CR) systems [1,2]. It combats such issues by combining local observation from multiple secondary users (SUs) to detect the present state of the spectrum [3]. Based on the architecture of cooperative sensing networks, they are classified into three broad categories: centralized, decentralized, and relay-assisted [4]. In a centralized scheme, sensing performed at each SU is reported to a centrally located fusion center (FC), which combines the sensing information to produce a global decision and broadcast it back to all the cooperative SUs. In decentralized sensing, as the sensing is performed at each SU, they share their sensing results with other SUs within the cluster.

Based on the combination of all decisions received, a local decision is obtained on the current state of the spectrum. Relay-assisted cooperative sensing (RCS) occurs when some SUs within a cluster cannot share their local decision with the FC due to shadowing or a huge distance between SUs and the FC [5]. In this case, the SU, which can reach the FC without any distortion or disturbance, can be used as a relay node to assist in forwarding the sensing results from other SUs to the FC. Several intermediate nodes would be between the source and corresponding destination in any multi-hop network, including cognitive radio networks. Therefore, making "optimal relay selection" is integral to any multi-hop communication protocol [6].

In literature, optimal multi-hop relay selection is typically carried out based on certain metrics, *i.e.*, delay, trusted distance, weights, channel coefficient, status of relay buffers, signal-to-interference and noise ratio (SINR), and channel capacity, or a new adaptive relay is established by combining channels with maximum instantaneous signal to noise ratio (SNR) at each hop. In [7], several delay-based selection policies were proposed where a relay with minimum instantaneous delay was selected for data transmission.

A new metric, trusted distance/ weight, was introduced in [8,9], selecting the optimal relay with maximum trusted distance/ weight. Krikidis et. al. [10] compare the quality of the available relays and select the strongest relay based on channel co-efficient. The status of the relay buffer emerges as another parameter over which some of the new selection schemes depend. Authors of [11,12] build a probabilistic model with the status of a relay buffer as one of the constraints to select an optimal relay. A new methodology based on SINR/ channel capacity of relay selection is elaborated in [13,14]. Here, SINR/channel capacity is used as the selection criteria, where a relay with the highest SINR/ channel capacity is chosen for data transmission from source to destination. In the context of evaluating the existing relay selection algorithms, there were two key findings:

- To choose the best relay, selecting metrics must be determined for each potential relay combination. Hence, adding intermediate nodes increases the number of potential relay combinations, exponentially increasing the complexity of the existing methodologies.
- Most current research focuses on a dual-hop relay, leaving the rest unexplored.

Goel et al., in their paper [15], attempt to overcome the issues mentioned above by proposing a new methodology that does not compute the selecting metric for potential combinations of relays. This method successfully selects links with maximum instantaneous SNR at each hop to establish a relay between source and destination. Although the procedure is computationally simple, it is inefficient to select the optimal relay. Additionally, there are times when the system loses data. As a result, the system's performance deteriorates. In this paper, we extend the concept of Goel et al. and present a new optimal multi-hop relay selection scheme that is computationally simple and inherently capable of selecting optimal relays. The main contributions of the paper are summarized below:

- A new optimal multi-hop relay selection scheme is proposed. It is based on the critical path method, an approach conventionally used in project management [16]. The concept can be extended with minor modifications to multi-hop RCS, and the benefits of selecting optimal relays and maximizing cooperative gain can be realized.
- Analytical derivation of outage probability for the

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proposed algorithm is another contribution of the paper.

- Compared with the method used in [15], the proposed CPM-based multi-hop relay selection method showcases the extent of the improvement over relay selection.

The rest of the paper is organized as follows: Section 2 presents the CPM-based multi-hop relay selection algorithm. Section 3 presents the proposed scheme's mathematical derivation of outage probability by considering various real-time scenarios. Section 4 discusses the experimental setup and results. Finally, we conclude the paper with major findings in section 5.

2. PROPOSED ADAPTIVE COOPERATION WITH CPM-BASED MULTI-HOP RELAY SELECTION

Consider a cognitive radio system where Primary Users (PUs) coexist and share their licensed spectrum with Sus, as depicted in Fig. 1. Over such systems, the primary transmitter (PTx) transmits its data to the primary receiver (PRx). Meanwhile, the secondary/ cognitive transmitter (CTx) continuously scans the same channel to determine the current state of the PTx (busy/ idle). It transfers the same to the FC, also referred to as the secondary/ cognitive receiver (CRx), over the control channel. From Fig. 1, one can observe that there is a group of M SUs lying in between CTx and CRx and can act as a relay node to assist data transmission at an instant when CRx fails to receive data from CTx directly. For notation convenience, all M relay nodes are denoted as $RN_i|i = 1, 2, \ldots, M$. Various combinations of such relay nodes can come together to form a multi-hop relay to transfer data to the respective destination.

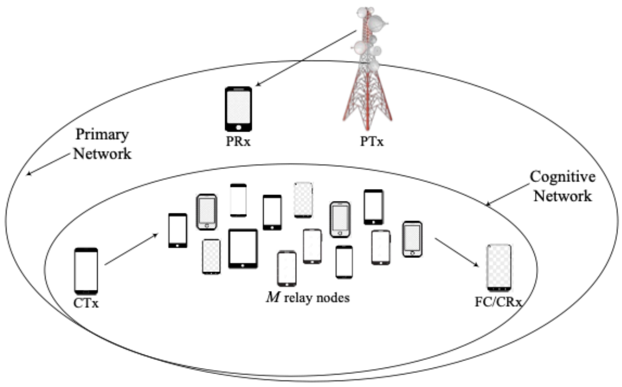

Fig. 1 – Coexisting primary and cognitive networks.

Let's consider CTx and PTx as transmitting x_{CTx} and x_{PTx} symbol at D_{CTx} and D_{PTx} data rate respectively. Moreover, P_{CTx} and $P_{PTx} represent$ the transmitted power of CTx and PTx, respectively. Thus, the signal received RN_i is represented as:

$$P_{CTx-RN_i} = h_{CTx-RN_i}\sqrt{P_{CTx}}x_{CTx} + h_{PTx-RN_i}\sqrt{\vartheta P_{PTx}}x_{PTx} + \\ +n_{RN_i}., i = 1, 2, \ldots, M, \quad (1)$$

where h_{CTx-RN_i} and h_{PTx-RN_i} the Rayleigh fading coefficient of the CTx to RN_i and PTx to RN_i channel respectively, n_{RN_i} represents Additive White Gaussian Noise (AWGN) with zero means and power spectral density N_0 and the parameter ∂ is defined as:

$$\vartheta = \begin{cases} 0, & H_0, \\ 1, & H_1, \end{cases} \quad (2)$$

whereas H_0 and H_1 represents the absence and presence of the primary user. Using (1) the capacity of the channel can be obtained as:

$$C_{CTx-RN_i} = \frac{1}{\xi - 1}\log_2\left(1 + \frac{\left|h_{CTx-RN_i}\right|^2 \gamma_c}{\vartheta\left|h_{PTx-RN_i}\right|^2 \gamma_p + 1}\right), \quad (3)$$

where $\gamma_c = \frac{P_{CTx}}{N_0}$, $\gamma_p = \frac{P_{PTx}}{N_0}$ and the parameter ξ represents the number of RN_i combined to form a multi-hop relay to assist transmission. To transmit data over a multi-hop network, initially the CTx broadcast its signal to relay nodes (RN_i) and CRx. All the entities to which the signal was transmitted try decoding it. However, only those entities can decode/receive the CTx's signal whose channel capacity is greater than the required data rate as specified by Shannon's coding theorem. RN_i, which receive the signal successfully, retransmit it, and the process continues till the source signal reaches CRx, which combined to form a relay constitutes a set R referred to as a relay set. A sample space for all possible relay sets can be denoted as:

$$R = \{R_j|\emptyset, R_1, R_2, \ldots, R_{2^m-1}\}, \quad (4)$$

where $\emptyset$ represents the null set for an instant when CRx successfully decodes the transmitted signal, and no relay is required between them. However, for an instant when CRx fails to decode the transmitted signal, one of the R_j helps in doing so.

Choosing the best relay is a crucial component of communication protocols in any multi-hop connection, including cognitive radio networks. Various characterizing features, such as negligible simulation time, optimal result, *etc*., of the critical path method motivate the exploration of the algorithm and modification so that it can be extended to relay selection for multi-hop RCS. The proposed CPM-based multi-hop relay selection algorithm determines the relay with the least path loss while forwarding the local sensing result.

The process of finding the optimal relay can be divided into three major steps: forward pass method, backward pass method, and optimal relay formation, which are described below.

2.1 FORWARD PASS METHOD

In this method, calculations begin at CTx and calculate a parameter, forward path loss (FPL), over each relay node while moving toward CRx. As we reach CRx, the computed *FPL* at the node indicates the minimum path loss of the entire network. The step-by-step procedure to calculate *FPL* in the forward pass method is:

a) The algorithm begins at CTx by initializing its FPL value to zero, *i.e.*,

$$FPL_{CTx} = 0, \quad (5)$$

b) While moving towards CRx, FPL over each relay node is calculated as:

$$FPL_{RN_y} = FPL_{RN_x} + pl_{xy}, \quad (6)$$

where, pl_{xy} represents path loss as the transmitted signal travels from RN_x to the relay node at the next hop, say RN_y, and variable $x, y \in M$.

c) If more than one relay nodes approach the same RN_y node, the relay node with minimum path loss will be considered and is represented as:

$$FPL_{RN_y} = \min_{x \in M}\{FPL_{RN_x} + pl_{xy}\}. \quad (7)$$

d) As the calculation reaches CRx, the FLP calculated for the node represents the minimum path loss for the entire network.

2.2 BACKWARD PASS METHOD

In this method, calculations begin at CRx, and backward path loss BPL is calculated over each relay node while moving backward toward CTx. As we reach CTx, the value of BPL is finalized for each relay node in the network. The step-by-step procedure to calculate BPL in the backward pass method is summarized as:

a) The algorithm begins at CRx by initializing its BPL parameter equal to its FPL value as determined in the previous step, *i.e.*,

$$BPL_{CRx} = FPL_{CRx}. \quad (8)$$

b) While moving in a backward direction towards CTx, the BPL parameter at each relay node is calculated as:

$$BPL_{RN_x} = BPL_{RN_y} - pl_{yx}\,. \quad (9)$$

where, pl_{yx} represents path loss as the transmitted signal travels from RN_y to the relay node at the next hop, say RN_x and variable $x, y \in M$.

c) If more than one relay node approaches the same RN_x node, the relay node with maximum path loss will be considered and is represented as:

$$BPL_{RN_x} = \max_{y \in M}\left\{BPL_{RN_y} - pl_{yx}\right\}. \quad (10)$$

d) As the calculation reaches CTx, the value of BPL is finalized for each relay node within the entire network.

2.3 OPTIMAL RELAY FORMATION

Relay nodes with an equal FPL and BPL together to form a multi-hop optimal relay with the least path loss.

3. OUTAGE PROBABILITY ANALYSIS FOR THE PROPOSED METHOD OVER FADING CHANNEL

It is known that outage probability occurs only when the channel capacity falls below the required data rate. Hence the outage probability (P) for the proposed model can be calculated as:

$$\begin{aligned}
\mathrm{P} &= \Pr(Outage, R = \emptyset|\mathrm{H} = \mathrm{H}_0) \\
&+ \Pr\left(Outage, R = R_j\middle|\mathrm{H} = \mathrm{H}_0\right) \\
&+ \Pr(Outage, R = \emptyset|\mathrm{H} = \mathrm{H}_1) \\
&+ Pr\left(Outage, R = R_j\middle|\mathrm{H} = \mathrm{H}_1\right) \quad (11)
\end{aligned}$$

$$\begin{aligned}
\mathrm{P} &= \Pr(Outage\,|R = \emptyset, \mathrm{H} = \mathrm{H}_0) \times \Pr(R = \emptyset, \mathrm{H} = \mathrm{H}_0) \\
&+ \Pr\left(Outage\,\middle|R = R_j, \mathrm{H} = \mathrm{H}_0\right) \times \Pr\left(R = R_j, \mathrm{H} = \mathrm{H}_0\right) \\
&+ \Pr(Outage\,|R = \emptyset, \mathrm{H} = \mathrm{H}_1) \times \Pr(R = \emptyset, \mathrm{H} = \mathrm{H}_1) \\
&+ \Pr\left(Outage\,\middle|R = R_j, \mathrm{H} = \mathrm{H}_1\right) \times \Pr\left(R = R_j, \mathrm{H} = \mathrm{H}_1\right) \quad (12)
\end{aligned}$$

Since outage probability occurs when channel capacity falls below the data rate. Hence, the occurrence of an outage can be represented using (3) as:

$$\frac{1}{\xi - 1}\log_2\left(1 + \frac{\left|h_{CTx-RN_i}\right|^2\gamma_c}{\vartheta\left|h_{PTx-RN_i}\right|^2\gamma_p + 1}\right) < D_{CTx} \quad (13)$$

$$\left|h_{CTx-RN_i}\right|^2 < \Lambda, \quad \mathrm{H}_0 \quad (14)$$

$$\left|h_{CTx-RN_i}\right|^2 < \Lambda\left(\left|h_{PTx-RN_i}\right|^2\gamma_p + 1\right), \quad \mathrm{H}_1 \quad (15)$$

where, $\Lambda = \left(2^{(\xi-1)D_{CTx}} - 1\right)/\gamma_c$ and ξ represents the number of RN_i combined to form a multi-hop relay. Using equations (14) and (15), (12) yields,

$$\begin{aligned}
P &= Pr(|h_{CTx-CRx}|^2 < \Lambda|R = \emptyset, H = H_0) \\
&\quad \times Pr(R = \emptyset|H = H_0) \\
&+ \sum_{y=1}^{\xi-1} Pr\left(\left|h_{RN_y-RN_{y+1}}\right|^2 < \Lambda|R = R_x, H = H_0\right) \\
&\quad \times \Pr\,(R = R_x|H = H_0) \\
&+ Pr\big(|h_{CTx-CRx}|^2 - |h_{PTx-CRx}|^2\gamma_p\Lambda < \Lambda|R = \emptyset, \\
&\quad H = H_1\big) \times Pr(R = \emptyset|H = H_1) \\
&+ \textstyle\sum_{y=1}^{\xi-1} Pr\left(\left|h_{RN_y-RN_{y+1}}\right|^2 - \left|h_{PTx-RN_{y+1}}\right|^2\gamma_p\Lambda < \right. \\
&\quad \left.\Lambda|R = R_x, H = H_1\right) \times \Pr\,(R = R_x|H = H_1) \quad (16)
\end{aligned}$$

As $\left|h_{RN_y-RN_{y+1}}\right|^2$ and $\left|h_{PTx-RN_{y+1}}\right|^2$ are exponentially distributed with parameters $1/\sigma^2_{RN_y-RN_{y+1}}$ and $1/\sigma^2_{PTx-RN_{y+1}}$ respectively, where $\sigma^2_{RN_y-RN_{y+1}}$ and $\sigma^2_{PTx-RN_{y+1}}$ are the fading variances of the channel from RN_y to RN_{y+1} and PTx to RN_{y+1}. Hence, we can obtain:

$$Pr(R = \emptyset|H = H_0) = \exp\left(-\frac{\Lambda}{\sigma^2_{CTx-CRx}}\right) \quad (17)$$

$$Pr(R = \emptyset|H = H_1) = \frac{\sigma^2_{CTx-CRx}}{\sigma^2_{CTx-CRx} + \sigma^2_{PTx-CRx}\gamma_p\Lambda} \times \exp\left(-\frac{\Lambda}{\sigma^2_{CTx-CRx}}\right) \quad (18)$$

$$Pr(|h_{CTx-CRx}|^2 < \Lambda|R = \emptyset, H = H_0) = 1 - \exp\left(-\frac{\Lambda}{(\xi-1)\sigma^2_{CTx-CRx}}\right) \quad (19)$$

$$\begin{aligned}
&Pr\left(|h_{CTx-CRx}|^2 - |h_{PTx-CRx}|^2\gamma_{\mathrm{p}}\Lambda < \Lambda|R = \emptyset, H = H1\right) \\
&= 1 - \left(\frac{(\xi - 1)\sigma^2_{CTx-CRx}}{(\xi - 1)\sigma^2_{CTx-CRx} + \sigma^2_{PTx-CRx}\gamma_P\Lambda} \times \exp\left(-\frac{\Lambda}{(\xi-1)\sigma^2_{CTx-CRx}}\right)\right) \quad (20)
\end{aligned}$$

$$Pr(R = R_x|H = H_0) = 1 - \left(\exp\left(-\frac{\Lambda}{\sigma^2_{CTx-CRx}}\right) \times \left(1 - \frac{pl_x}{\sum_{k=1}^{2^M-1} pl_k}\right)\right) \quad (21)$$

$$Pr(R = R_x|H = H_1) = 1 - \left(\frac{\sigma^2_{CTx-CRx}}{\sigma^2_{CTx-CRx} + \sigma^2_{PTx-CRx}\gamma_p\Lambda} \times \exp\left(-\frac{\Lambda}{\sigma^2_{CTx-CRx}}\right) \times \left(1 - \frac{pl_x}{\sum_{k=1}^{2^M-1} pl_k}\right)\right) \quad (22)$$

$$\Pr\left(\left|h_{RN_y-RN_{y+1}}\right|^2 < \Lambda | R = R_x, H = H_0\right) = 1 - \exp\left(-\frac{\Lambda}{\sigma^2_{RN_y-RN_{y+1}}}\right) \quad (23)$$

$$\Pr\left(\begin{array}{c}\left|h_{RN_y-RN_{y+1}}\right|^2 - \left|h_{PTx-RN_{y+1}}\right|^2 \gamma_p\Lambda < \Lambda | R = R_x, \\ H = H_1\end{array}\right) = 1 - \left(\frac{\sigma^2_{RN_y-RN_{y+1}}}{\sigma^2_{RN_y-RN_{y+1}} + \sigma^2_{PTx-RN_{y+1}}\gamma_p\Lambda} \times \exp\left(-\frac{\Lambda}{\sigma^2_{RN_y-RN_{y+1}}}\right)\right). \quad (24)$$

Finally, by putting (17)-(24) in (16), a closed-form expression of outage probability for the proposed multi-hop relay is given as:

$$\begin{aligned} P = &\left(1 - \exp\left(-\frac{\Lambda}{(\xi-1)\sigma^2_{CTx-CRx}}\right) \times \left(\exp\left(-\frac{\Lambda}{\sigma^2_{CTx-CRx}}\right)\right)\right) \\ &+ \left(\sum_{Y=1}^{\xi-1} 1 - \exp\left(-\frac{\Lambda}{\sigma^2_{RN_y-RN_{y+1}}}\right)\right) \times \left(1 - \left(\exp\left(-\frac{\Lambda}{\sigma^2_{CTx-CRx}}\right) \times \left(1 - \frac{pl_x}{\sum_{k=1}^{2^M-1} pl_k}\right)\right)\right) \\ &+ \left(1 - \left(\frac{(\xi-1)\sigma^2_{CTx-CRx}}{(\xi-1)\sigma^2_{CTx-CRx} + \sigma^2_{PTx-CRx}\gamma_p\Lambda} \times \exp\left(-\frac{\Lambda}{(\xi-1)\sigma^2_{CTx-CRx}}\right)\right)\right) \\ &\times \left(\frac{\sigma^2_{CTx-CRx}}{\sigma^2_{CTx-CRx} + \sigma^2_{PTx-CRx}\gamma_p\Lambda} \times \exp\left(-\frac{\Lambda}{\sigma^2_{CTx-CRx}}\right)\right) \\ &+ \left(\sum_{y=1}^{\xi-1} 1 - \left(\frac{\sigma^2_{RN_y-RN_{y+1}}}{\sigma^2_{RN_y-RN_{y+1}} + \sigma^2_{PTx-RN_{y+1}}\gamma_p\Lambda} \times \exp\left(-\frac{\Lambda}{\sigma^2_{RN_y-RN_{y+1}}}\right)\right)\right) \\ &\times \left(1 - \left(\frac{\sigma^2_{CTx-CRx}}{\sigma^2_{CTx-CRx} + \sigma^2_{PTx-CRx}\gamma_p\Lambda} \times \exp\left(-\frac{\Lambda}{\sigma^2_{CTx-CRx}}\right) \times \left(1 - \frac{pl_x}{\sum_{k=1}^{2^M-1} pl_k}\right)\right)\right). \end{aligned} \quad (25)$$

4. EXPERIMENTAL SETUP AND RESULTS

The experimental testbed developed using nine USRP 2942R placed a hundred meters apart is shown in Fig. 2 to illustrate a cooperative scenario. As per the defined scenario, CTx tries to contact CRx over 815 MHz via intermediary relay nodes. CTx and CRx were considered mobile entities, while others remained static. Hence, the network under consideration evolved, and simultaneously, the path loss of each channel was periodically collected. Further, the retrieved information was fed into the MATLAB software, over which the proposed multi-hop relay selection scheme was built to determine the optimal relay. The performance of the proposed method is compared with the minimum instantaneous delay (MID) method as proposed in [15].

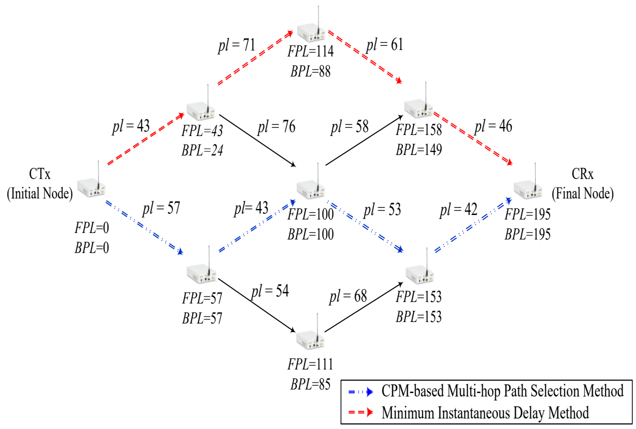

Fig. 2 – The experimental test bed.

Figure 3 shows one of the experimental iterations to illustrate the proposed method's efficiency over the MID scheme. One can see that both methods choose to select different paths with different path losses to reach the destination. It's been observed that the proposed method offers connectivity with lower path loss (195 dB) as compared to the MID technique (221 dB). Since the experimental setup was deployed over a small region, there is a small change in path loss between the two methods. However, the network's efficiency and reliability can be seen once deployed over a large geographical region.

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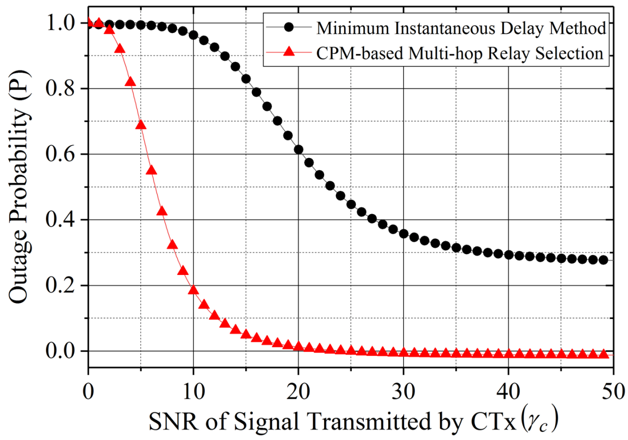

Fig. 3 – Outage probability *versus* transmitting SNR of CTx signal.

Further, we tried comparing both methods regarding outage probability using (25). To simplify the calculation of outage probability, the following parameters: $\sigma_{CTx-CRx} = \sigma_{RN_y-RN_{y+1}} = 1$, $\sigma_{PTx-CRx} = \sigma_{PTx-RN_{y+1}} = 0.1$, $\xi = 5$, and $\gamma_p = 10$ dB were considered while deriving the same. Figure 3 shows outage probability (P) versus γ_c.

The plot seems to follow this characteristic since outage probability decreases with increased SNR of the signal transmitted out of CTx (γ_c). To explain the plot more elaborately, let's divide it into its initial, transitional, and ultimate phases. In the initial phase, the outage probability appears excessively large (close to one) $\gamma_c \ll \gamma_p$. Due to high interference from the primary user, the transmitted signal fails to reach the intended destination. However, as γ_c it gets closer to the transitional phase.

In this plot phase, the outage probability decreases exponentially as the effect of the interfering signal diminishes, and the signal transmitted out of CTx may reach the intended destination. In the final stage, which is much greater than gamma sub p, the primary user has no impact on the signal transmitted by the CTx, and the plot eventually hits the outage floor in its final stage. From the figure, one can observe that the outage probability of the proposed method outperforms the MID method by a huge difference.

The reason for such a large deviation has been investigated thoroughly. It's been found that under certain iteration conditions in the simulation model, the MID method fails to reach the destination because it encounters a low SNR intermediate link, hence aborting transmission midway.

The resulting outage probability equals one. This upthrusts the average outage probability graph for the MID method, as depicted in the figure. In other words, the proposed scheme has superior outage performance over the MID method because, in contrast to the MID method, the proposed method computes the optimal path for transmission in situations where the MID method is forced to terminate the transmission due to poor links in the next hop.

5. CONCLUSION

The paper proposes a novel multi-hop relay selection scheme based on the CPM method, generally used for project management. The proposed scheme is analyzed and compared with the existing literature methods using the combination of the NI-USRP test-bed dataset and the MATLAB simulation platform.

The comparison establishes the reliability and efficiency of the proposed technique by choosing the optimal path. Strong results indicate that the proposed technique is very helpful for CRN and can be expanded to 5G communication systems.

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