# An Optimal Relay Selection and Precoder Designing in MIMO Multi-Relay Cognitive Networks

Deepak Sahu
*PDPM-IIITDM Jabalpur, India*
1812602@iiitdmj.ac.in

Shikha Maurya
*NIT Agartala, India*
drshikha.ece@nita.ac.in

Matadeen Bansal
*PDPM-IIITDM Jabalpur, India*
mbansal@iiitdmj.ac.in

Dinesh kumar V.
*PDPM-IIITDM Jabalpur, India*
dineshk@iiitdmj.ac.in

***Abstract*—In this article, we propose a best relay selection scheme along with the impact of precoder designing for multi-input multi-output (MIMO) multi-relay cognitive networks (MCNs). Joint relay selection and precoder designing problem is studied to maximize the energy efficiency of the secondary network ($SN$) subject to a quality-of-service (QoS), power, and interference constraints at the relays and/or source. In this, amplify-and-forward inspired multiple relays are deployed randomly to facilitate the transmission between source and destination in the $SN$. These relays ($S_{R_i}$) help to reduce the power consumption requirements at the secondary transmitter ($S_{TX}$) while meeting the need for quality-of-service (QoS) for both networks, i.e., primary network ($PN$) and $SN$. This study introduces four different schemes for joint relay selection and precoder designing for $SN$. Simulation results show that the opportunistic relay selection scheme outperforms other schemes in terms of maximum end-to-end energy efficiency of the $SN$.**

***Index Terms*—Relay Selection, Multi-Relay Cognitive Network, MIMO, Energy Efficiency, Precoder Designing**

## I. Introduction

The explosive growth of recent technologies in information and wireless communication theory has increased the demand of high data rate [1]. These technologies have raised the demand for more spectrum and energy efficient communication systems with higher throughput and diverted the focus of researchers towards energy efficient systems while designing the next generation of communication system [2]. These challenges and demands can be attained by employing several promising technologies such as cognitive radio (CR) [3]- [5], multi-input multi-output (MIMO) [7], and cooperative relaying [8]. The former technology enables the unlicensed user to use licensed user's bands to enhance the spectrum efficiency [5]- [6]. The MIMO transmission technology allows secondary nodes to use multiple antennas to enhance the data rate and suppress the interference at the primary network ($PN$) [7]. Finally, CR with MIMO can significantly meet the challenges of spectrum scarcity of next-generation communication systems [3]. In addition to that precoding technique enhances the transmitter diversity at the secondary network ($SN$) and manages the interference at the $PN$. On the other hand, combining the relay technology can further improve the performance of unlicensed user [8].

In this paper, an underlay CR scenario is considered, where performance of the $PN$ should be maintained by keeping the interference from $SN$ to $PN$ below a tolerable limit. This limits the transmission range of the secondary nodes, which can be solved by employing a relay between secondary transmitter ($S_{TX}$) and receiver ($S_{RX}$). It limits the power requirement and interference at various nodes. Furthermore, in comparison with a single relay scenario, relay selection in multi relay scenario provides better performance. In literature, relay selection techniques in various scenarios, such as Cooperative CR [13], MIMO-Cognitive Relay Networks [14], device-to-device (D2D) [15] etc., have been recently explored to improve the transmission reliability and also to minimize the transmission power requirement of the $SN$ in long distance communication. In [13]-[14], researchers studied the impact of relay selection with single antenna nodes in various scenarios of wireless communication system, while the authors in [16]-[17] explored the relay selection with multi-antenna scenarios.

In this work, CR inspired multiple relay system is considered with MIMO technology. Various relay selection schemes are introduced along with the impact of precoders design to improve the energy efficiency of $SN$ subject to the power and interference, and quality-of-service constraints at the $S_{TX}$ and secondary relay ($S_{R_i}$), respectively. These constraints meet the need of maintaining the quality-of-service of both $SN$ and $PN$. This relay selection and precoder designing problem is solved in two phases. First phase deals with the precoder designing, whereas, in second phase, best relay is selected based on the designed precoders and obtained energy efficiency.

The rest of the paper is organized as follows: in Section II, system model and problem formulation with relay selection scheme and precoder designing are illustrated. while numerical results are presented in Section III. Finally, conclusions are drawn in Section V.

## II. System Model

This paper considers a MIMO-MCN, illustrated in Fig. 1. It includes two networks, $PN$ and $SN$, where $PN$ consists licensed users, i.e., a transmitter $P_{TX}$ and a receiver $P_{RX}$; all equipped with antennas $m_p$. The $SN$ works in an underlay mode, which includes a $S_{TX}$, a $S_{RX}$, and $K$ amplify-and-forward relays ($S_{R_i}$, $\forall i \in 1, 2, ..., K$). Let, $m_s$, $m_d$, and $m_r$ denote the number of antennas at the $S_{TX}$, $S_{RX}$, and

$S_{R_i}$, respectively. The channel matrices from $S_{TX}$ to $S_{R_i}$ and from $S_{R_i}$ to $S_{RX}$, are denoted by $\mathbf{H}_{SR_i} \in \mathbb{C}^{(m_r \times m_s)}$ and $\mathbf{H}_{R_iD} \in \mathbb{C}^{(m_d \times m_r)}$, respectively. While the interference channel matrices from $S_{TX}$ and $S_{R_i}$ to $P_{RX}$ are represented by $\mathbf{G}_{SP} \in \mathbb{C}^{(m_p \times m_s)}$ and $\mathbf{G}_{R_iP} \in \mathbb{C}^{(m_p \times m_r)}$, respectively. It is assumed that the $S_{TX}$ and $S_{RX}$ have the knowledge of channel state information (CSI) of all the links due to the feedback system between $SN$ and $PN$ [12].

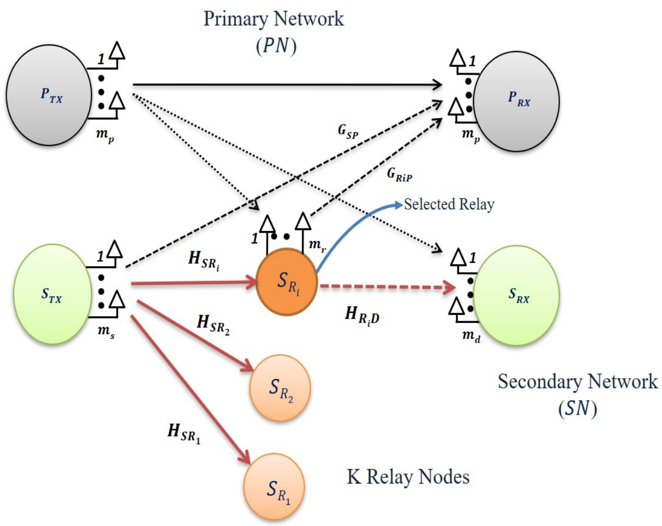


Fig. 1. Proposed System Model of a MIMO-MCN.

### A. Problem Formulation

In the $SN$, all relays operate in half duplex mode. Among these relays, one relay is selected to transmit the information from $S_{TX}$ to $S_{RX}$. Thus, $SN$ requires two time-slots for end-to-end transmission. In the first time-slot, $S_{TX}$ transmits the data stream $\mathbf{s}$ of length $d_u \times 1$ after multiplying it with a pre-coding matrix $\mathbf{U}_i \in \mathbb{C}^{m_s \times d_u}$, where $d_u = min(m_s, m_r, m_d)$ and $\mathbb{E}\{\mathbf{s}\mathbf{s}^H\} = I_{d_u}$. The received signal at $S_{R_i}$ ($i^{th}$ relay) is denoted by $\mathbf{y}_{R_i} = \mathbf{H}_{SR_i}\mathbf{U}_i\mathbf{s} + \mathbf{n}_{R_i}$. Further, $S_{R_i}$ forwards the signal $\mathbf{y}_{R_i}$, after multiplying it with a relay precoding matrix $\mathbf{Q}_i \in \mathbb{C}^{(m_r \times m_r)}$, to $S_{RX}$. Finally, the received signal at $S_{RX}$ is given by $\mathbf{y}_D = \mathbf{H}_{R_iD}\mathbf{Q}_i\mathbf{H}_{SR_i}\mathbf{U}_i\mathbf{s} + \mathbf{n}_1$. Here, $\mathbf{n}_1 = \mathbf{H}_{R_iD}\mathbf{Q}_i\mathbf{n}_{R_i} + \mathbf{n}_D$ represents the total noise plus interference caused by the $PN$ to the $SN$ with zero mean and covariance of $\mathbf{Z}_D = \sigma^2_{n_{R_i}}\mathbf{H}_{R_iD}\mathbf{Q}_i\mathbf{Q}_i^H\mathbf{H}_{R_iD}^H + \sigma^2_{n_D}\mathbf{I}_{m_d}$; $n_{R_i}$ and $n_D$ are the complex white Gaussian noise vectors having zero means with variances of $\sigma^2_{n_{R_i}}\mathbf{I}_{m_r}$ and $\sigma^2_{n_D}\mathbf{I}_{m_d}$, respectively.

This paper finds the best relay selection scheme along with the impact of precoder designing in relay selection. Both relay selection and precoder designing is done with the aim to maximize the energy-efficiency of the $SN$.

Now, the energy-efficiency of the $SN$ can be defined as the ratio of the average rate to the total consumed power, denoted as

$$\eta_i = \frac{Rate_i}{P_{total}}$$

$$\eta_i = \frac{\log_2[\det\{\mathbf{I} + \mathbf{H}_{R_iD}\mathbf{Q}_i\mathbf{H}_{SR_i}\mathbf{W}_i\mathbf{H}_{SR_i}^H\mathbf{Q}_i^H\mathbf{H}_{R_iD}^H\mathbf{Z}_D^{-1}\}]}{(P_{S_{TX}}/\rho_{S_{TX}} + P_{R_i}/\rho_{R_i} + P_{ckt})}, \tag{1}$$

where $P_{S_{TX}}$ and $P_{R_i}$ are the transmit powers at $S_{TX}$ and $S_{R_i}$, respectively, represented by

$$P_{S_{TX}} = tr(\mathbf{W}_i), \tag{2}$$

$$P_{R_i} = tr(\mathbf{Q}_i\mathbf{H}_{SR_i}\mathbf{W}_i\mathbf{H}_{SR_i}^H\mathbf{Q}_i^H + \sigma^2_{n_{R_i}}\mathbf{Q}_i\mathbf{Q}_i^H). \tag{3}$$

These transmit powers should be less than the maximum available transmit power $P_{max}$. $\rho_{S_{TX}}$ and $\rho_{R_i}$ represent the power amplifier efficiencies of $S_{TX}$ and $S_{R_i}$, respectively. The quantity $P_{ckt}$ is the total circuit power consumed by the $SN$.

Additionally, while transmission, $SN$ causes interference to the $PN$, which can be given as

$$I_{S_{TX}} = tr(\mathbf{G}_{SP}\mathbf{W}_i\mathbf{G}_{SP}^H), \tag{4}$$

$$I_{R_i} = tr(\mathbf{G}_{R_iP}\mathbf{Q}_i\mathbf{H}_{SR_i}\mathbf{W}_i\mathbf{H}_{SR_i}^H\mathbf{Q}_i^H\mathbf{G}_{R_iP}^H + \sigma^2_{n_{R_i}}\mathbf{G}_{R_iP}\mathbf{Q}_i\mathbf{Q}_i^H\mathbf{G}_{R_iP}^H), \tag{5}$$

where $\mathbf{W}_i = \mathbf{U}_i\mathbf{U}_i^H$. The interference powers at the $P_{RX}$ in both time-slots, i.e., $I_{S_{TX}}$ and $I_{R_i}$ should be less than a predefined threshold value $I_{max}$.

In order to find the joint precoders at $S_{TX}$ and $S_{R_i}$, i.e., $\mathbf{W}_i$ and $\mathbf{Q}_i$, an energy efficiency maximization problem is devised subject to the quality-of-service (QoS), interference, and transmit power constraints. Here, QoS constraint for $SN$ is used in the form of minimum rate requirement. Mathematically, the problem can be written as

Prob. 1:
$$\max_{(\mathbf{W}_i),(\mathbf{Q}_i)} \quad \eta_i \tag{6}$$

$$\text{s.t.} \quad I_{S_{TX}} \leq I_{max}, \tag{7}$$

$$I_{R_i} \leq I_{max}, \tag{8}$$

$$P_{S_{TX}} \leq P_{max}, \tag{9}$$

$$P_{R_i} \leq P_{max}, \tag{10}$$

$$Rate_i \geq Rate_{min}, \tag{11}$$

$$\forall i = 1, 2, ..., K.$$

### B. Relay Selection and Precoder Design Schemes

This section introduces four different schemes for relay selection and precoder designing for secondary nodes. These schemes are carried out in two phases. One phase is for precoder designing and second is for relay selection. Detailed explanation of the proposed four schemes are given below:

*1) Opportunistic Scheme:* In the first phase of this scheme, source and relay precoders are jointly designed by solving the given Prob. 1. The detailed solution of Prob. 1 can be obtained in [18]. In the second phase, the best relay $S_{R_i}$ is selected based on the maximum end-to-end achieved energy efficiency at $S_{RX}$, which can be mathematically presented as

$$(S_{R_{i^*}}, \mathbf{W}_{i^*}, \mathbf{Q}_{i^*}) = arg \max_{i \in \{1,2,...,K\}} \eta_i. \tag{12}$$

*2) Proactive Scheme:* In this criterion, the optimal energy efficient precoder weights at each relay ($\mathbf{Q}_i$) are designed, while considering the fixed precoder weight at $S_{TX}$. This can be done by solving Prob. 1 while assuming that $\mathbf{W}_i$ is known, i.e., Prob. 1 can be converted into single variable problem. After finding the precoder weights at relays, the best relay $S_{R_i^*}$ is selected based on the maximum end-to-end energy efficiency from $S_{TX}$ to $S_{RX}$. Relay selection criteria can be mathematically presented as:

$$(S_{R_{i^*}}, \mathbf{Q}_{i^*}) = arg \max_{i \in \{1,2,\ldots,K\}} \eta_i. \quad (13)$$

*3) Reactive Scheme:* The first phase of this criteria is to design the $S_{TX}$ precoder while considering the fixed precoder at all relay nodes. For this scheme, Prob. 1 can be modified and converted into single variable problem with unknown variable $\mathbf{W}_i$ along with the constraints (7), (9), and (11). In the second phase of this scheme, the best relay $S_{R_i}$ is selected based on the maximum end-to-end energy efficiency at $SN$, calculated using the designed precoder. Mathematically, it can be represented as:

$$(S_{R_{i^*}}, \mathbf{W}_{i^*}) = arg \max_{i \in \{1,2,\ldots,K\}} \eta_i. \quad (14)$$

*4) Random Scheme:* Here, both $S_{TX}$ and $S_{R_i}$ precoder matrices are jointly designed by solving Prob. 1. Afterwards, the relay $S_{R_i}$ is selected in random manner without taking the consideration of the obtained end-to-end energy efficiency.

## III. Numerical Results

This section depicts an experimental analysis and comparison of all the proposed joint relay selection and precoder designing schemes via MATLAB simulation. It is assumed that the channel parameters are independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian variables having zero means with variances of 1 for $\mathbf{H}_{SR_i}$ and $\mathbf{H}_{R_iD}$; variances of 0.3 for $\mathbf{G}_{SP}$ and $\mathbf{G}_{R_iP}$. We set the noise variances $\sigma^2_{n_{R_i}}$ and $\sigma^2_{n_D}$ at 1; $\rho_{S_{TX}} = \rho_{R_i} = 1$ and $P_{ckt} = 3$ dBm, $Rate_{min} = 0.4$ bits/sec/Hz.

The initial values assigned for $\mathbf{W}_i$ and $\mathbf{Q}_i$ are given as:

$$\mathbf{W}_i = \sqrt{\delta_1}\mathbf{I}_{(m_s,m_s)}, \quad (15)$$

$$\mathbf{Q}_i = \sqrt{\delta_2}\mathbf{I}_{(m_r,m_r)}, \quad (16)$$

where $\delta_1 = \min\left\{\frac{P_{max}}{m_s}, \frac{I_{max}}{tr(\mathbf{G}_{SP}{}^H\mathbf{G}_{SP})}\right\}$ and $\delta_2 = \min\left\{\frac{P_{max}}{\sigma^2_{n_{R_i}} m_r + \delta_1 tr(\mathbf{H}_{SR_i}{}^H\mathbf{H}_{SR_i})}, \frac{I_{max}}{\sigma^2_{n_{R_i}} tr(\mathbf{G}^H_{R_iP}\mathbf{G}_{R_iP}) + \delta_1 tr(\mathbf{G}^H_{R_iP}\mathbf{G}_{R_iP}\mathbf{H}_{SR_i}\mathbf{H}^H_{SR_i})}\right\}$. This ensures equal power allocation across antenna elements and transmission from the SU-Tx is within the interference limit of the PU. Simulation results are averaged over 500 channel realizations.

Fig. 2 shows the comparison of all the proposed schemes along with the variation of the energy efficiency with respect to the total transmit power. One can see, the energy efficiency of all the schemes increases with the transmit power and reaches at the peak and saturates afterwards. This behaviour occurs

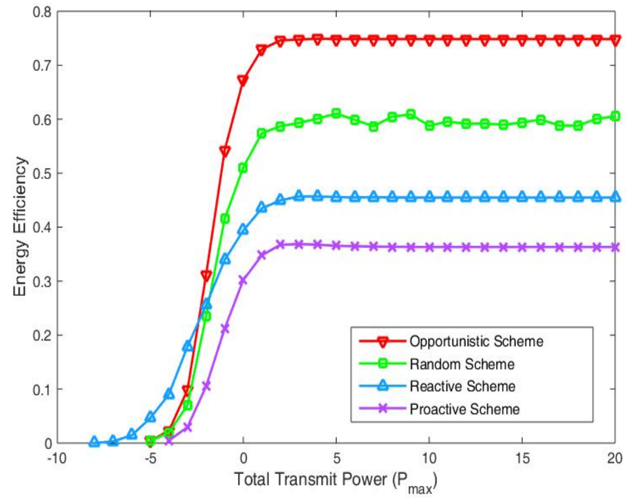


Fig. 2. Average EE versus $P_{max}$ (dBW) for various schemes; $m_s = m_r = m_d = m_p = 2$, $I_{max} = -1$ dBW.

because as we increase the transmit power level, secondary nodes can consume more power to improve the data rate, which also results in the increment of energy efficiency. However, after a certain point if we increase the transmit power, nodes can not utilize more power due to the limitation caused by the interference constraint. It results in the saturation of the achieved energy efficiency.

In addition, we can also analyse and compare the performance of all schemes using Fig. 2. As can be seen, Opportunistic Scheme provides better energy efficiency than any other schemes. It is by the fact that it designed both $S_{TX}$ and $S_{R_i}$ precoders as well as selects the best relay according to the maximum obtained energy efficiency. The other two proposed schemes, i.e., Proactive and Reactive Schemes also selects the best relay according to maximum obtained energy efficiency, however, in both of these schemes only one precoder is designed (i.e., either $S_{R_i}$ or $S_{TX}$ precoder), which resulted in the decreased energy efficiency. Finally, the performance of the fourth scheme, i.e., Random Scheme lies between these three schemes. This scheme designed both $S_{TX}$ and $S_{R_i}$ precoders, thus, it achieves better energy efficiency than the Proactive and Reactive Schemes. However, due to the random selection of relay for transmission, the achieved performance is less than the Opportunistic Scheme.

The feasibility of the proposed schemes are measured in terms of probability of feasibility. It is calculated by the ratio of simulation runs for which scheme is feasible to the total simulation runs. This factor is important as it validates the feasibility of the problem with respect to various parameters such as transmit power, interference power etc. Fig. 3 presents the probability of feasibility comparison for all the schemes. Among all schemes, Opportunistic Scheme has best probability of feasibility.

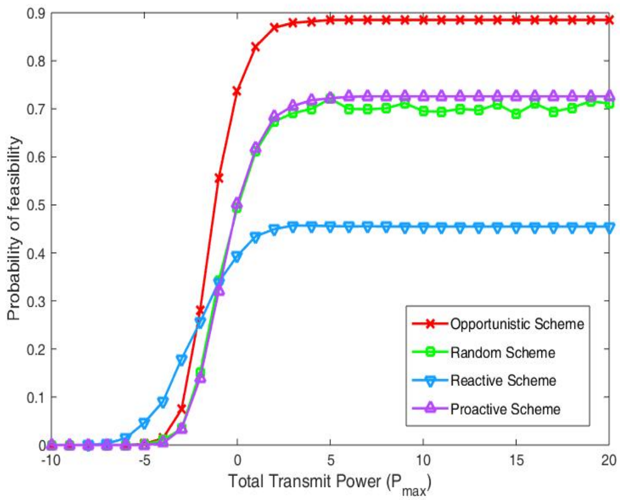


Fig. 3. Probability of feasibility versus $P_{max}$ (dBW) for various schemes; $m_s = m_r = m_d = m_p = 2$, $I_{max} = -1$ dBW.

## IV. Conclusion

In this article, we studied and compared the various joint relay selection and precoder designing schemes in MIMO-MCN. The proposed schemes were investigated with the objective to maximize the energy efficiency of $SN$ subject to different set of constraints to satisfy the quality-of-service of both $PN$ and $SN$. The schemes were analysed in terms of the achieved energy efficiency as well as the probability of feasibility. Numerical results have shown that the opportunistic scheme outperforms the other schemes in terms of maximum end-to-end energy efficiency for the $SN$.

## References

[1] A. Dogra, R. K. Jha, and S. Jain, "A Survey on Beyond 5G Network With the Advent of 6G: Architecture and Emerging Technologies", *IEEE Access*, vol. 9, pp. 67512-67547, 2021.

[2] L. Williams, B. K. Sovacool, and T.J. Foxon, "The energy use implications of 5G: Reviewing whole network operational energy, embodied energy, and indirect effects, Renewable and Sustainable Energy Reviews", vol. 157, 2022.

[3] W. S. H. M. W. Ahmad et. al., "5G Technology: Towards Dynamic Spectrum Sharing Using Cognitive Radio Networks", *IEEE Access*, vol. 8, pp. 14460-14488, 2020.

[4] Ian F. Akyildiz, et. al., "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey", *Computer Networks*, vol. 50, no. 13, pp. 2127-2159, 2006.

[5] S. Haykin, "Cognitive radio: brain-empowered wireless communications", *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201-220, 2005.

[6] Andrea Goldsmith, Syed Ali Jafar, Ivana Mari, and Sudhir Srinivasa, "Breaking spectrum gridlock with cognitive radios: An information theoretic perspective", *Proceedings of the IEEE*, vol. 97, no. 5, pp. 894-914, 2009.

[7] A. Deligiannis, A. Daniyan, S. Lambotharan, and J. A. Chambers, "Secrecy Rate Optimizations for MIMO Communication Radar", *IEEE Transactions on Aerospace and Electronic Systems*, vol. 54, no. 5, pp. 2481-2492, 2018.

[8] X. Chen, H.-H. Chen, and W. Meng, "Cooperative Communications for Cognitive Radio Networks-From Theory to Applications", *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1180-1192, 2014.

[9] D. Sahu, S. Maurya, M. Bansal, and Dinesh Kumar V., "Deep Learning Based Energy-Efficient Relay Precoder Design in MIMO-CRNs", *Elsevier Physical Communication*, vol. 50, pp. 1-8, 2022.

[10] D. Sahu, S. Maurya, M. Bansal, and Dinesh Kumar V., "Data-driven approach to design energy-efficient joint precoders at source and relay using deep learning in MIMO-CRNs", *Transactions on Emerging Telecommunications Technologies*, 2022.

[11] J. Perez-Romero, O. Sallent, R. Agusti, and L. Giupponi, "A novel on-demand cognitive pilot channel enabling dynamic spectrum allocation", *2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 46-54, 2007.

[12] S. Maurya and M. Bansal, "Energy Efficient Precoder Design for Non-Regenerative MIMO-CRN", *IEEE Wireless Communications Letters*, vol. 6, no. 5, pp. 646-649, 2017.

[13] P. Yan, Y. Zou, X. Ding, and J. Zhu, "Energy-Aware Relay Selection Improves Security-Reliability Tradeoff in Energy Harvesting Cooperative Cognitive Radio Systems", *IEEE Transactions on Vehicular Technology*, vol. 69, no. 5, pp. 5115-5128, 2020.

[14] P. Das, "Outage Performance of Cognitive Relay Networks with Optimal Relay and Antenna Selection", *2020 National Conference on Communications (NCC)*, pp. 1-6, 2020.

[15] M. H. Khoshafa, T. M. N. Ngatched, M. H. Ahmed and A. Ibrahim, "Enhancing Physical Layer Security Using Underlay Full-Duplex Relay-Aided D2D Communications," *2020 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1-7, 2020.

[16] Q. Li, Q. Zhang, R. Feng, L. Luo, and J. Qin, "Optimal Relay Selection and Beamforming in MIMO Cognitive Multi-Relay Networks", *IEEE Communications Letters*, vol. 17, no. 6, pp. 1188-1191, 2013.

[17] S. Maurya and M. Bansal, "Joint Relay Selection and Precoder Designing for Energy-Efficient MIMO-CRNs", *5th Conference on Information and Communication Technology (CICT)*, pp. 1-5, 2021.

[18] S. Maurya, M. Bansal, and A. Trivedi, "Joint source and relay precoder design for energy-efficient MIMO-cognitive relay networks", *IET Communications*, vol. 13, no. 15, pp. 2226-2234, 2019.