Transactions on Engineering and Computing Sciences - Vol. 13, No. 05
Publication Date: September 16, 2025
DOI:10.14738/tmlai.1305.19340.

Issa, W. A., Ojo, S. I., Abolade, R. O., Oyedokun, O. O., & Fawole, A. O. (2025). Interference Reduction in a Dynamic Spectrum Sharing Technique Using an Eigenvalue Detector over the Kapa-Mu Shadow Fading Channel. *Transactions on Engineering and Computing Sciences*, 13(05). 68-80.

Interference Reduction in a Dynamic Spectrum Sharing Technique Using an Eigenvalue Detector over the Kapa-Mu Shadow Fading Channel

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ABSTRACT

Wireless communication systems are crucial for modern telecommunications and are expected to be a key in national development. However, the systems often do not fully use the available radio spectrum due to the traditional fixed spectrum, making the frequency spectrum a valuable yet limited resource. Dynamic Overlay and Underlay Spectrum Sharing (D-OUSS) used to address the problem suffered from high interference due to inadequate switching between the overlay and underlay spectrum sharing. Therefore, in this study, interference reduction in D-OUSS was performed using the Eigenvalue Detector (EVD). The energy detector in the existing D-OUSS technique was replaced with EVD to improve accurate detection of white and brown spaces. The received signals, over the kappa-mu shadow fading channel, were used to form a covariance matrix to determine the ratio of the maximum to the minimum eigenvalues and to identify the presence of white and brown spaces. The proposed spectrum management system switches to the overlay approach when white space is present and instantly switches to the underlay approach when brown space is present. The proposed D-OUSS improved the performance of the existing D-OUSS with reduced interference and increased throughput.

Keywords: Overlay spectrum sharing, Underlay spectrum sharing, Eigenvalue detector, interference and signal to interference ratio.

INTRODUCTION

The explosive growth of wireless communication requires a more efficient use of network resources to enhance service quality. The increasing number of wireless users makes the frequency spectrum a valuable (Ojo *et al*., 2020). The current measurements revealed that the assigned radio spectra are largely underutilized, which is a consequence of fixed spectrum access. The traditional method of assigning spectrum, which grants exclusive access to authorized users to prevent interference, results in considerable periods of spectrum inactivity, with some bands experiencing usage rates below 15% (Ojo *et al*., 2021; Pawel *et al*., 2022; Goswami and Kumar, 2021). Due to the high cost and time required to acquire a new spectrum, maximizing the use of existing assigned spectrum is crucial. Cognitive Radio (CR) technology, which enables dynamic spectrum access, presents a viable solution by allowing unlicensed users to use spectrum when it is not in use. These systems involve two users: primary users (PUs), who hold licensed access, and secondary users (SUs), who opportunistically use the spectrum when PUs are inactive (Ojo *et al*., 2022; Abolade *et al*., 2020; Abbass *et al*., 2021). The accessibility of SU to the assigned spectrum is a function of the presence of white or brown space. The white space is the idle spectrum due to the idleness of the PU, while the brown spaces are the unused spectrum by the authorized user during its busy period. Therefore, overlay and underlay are the two major approaches in SS. Overlay SS (OSS) is a technique in which an unauthorized user makes use of the assigned spectrum when white space is present, while, Underlay SS (USS) is a technique in which a SU makes use of the assigned spectrum when brown space is present (Ahmed *et al*., 2019; Kehinde *et al*., 2020).

In the overlay approach, SUs can only transmit when the PU is inactive, requiring them to immediately vacate the spectrum upon PU activity. Conversely, the underlay approach allows simultaneous PU and SU transmission, provided that PU interference remains within acceptable limits. While this enables concurrent access, the underlay method often suffers from limited spectrum utilization due to power restrictions imposed on SUs to control interference (Ridhima and Avtar, 2019; Dinh-Thuan *et al*., 2020). To enhance the performance of OSS and USS, Dynamic Overlay and Underlay SS (D-OUSS), in which the cognitive radio system switches between overlay and underlay approaches, was proposed. The system uses the overlay approach when there is white space and switches to the underlay approach when brown space is present. D-OUSS overcomes the challenges of OSS and USS approaches but suffers from high interference if the switching between the overlay and underlay is inadequate (Hakan, 2020; Abbass *et al*., 2021; Deemah *et al*., 2022; Bag *et al*., 2022). Adequate switching in D-OUCR is a function of the accurate detection of white and brown spaces. The Energy Detector (ED) is commonly used in the literature to detect white space and brown space due to its simplicity and non-coherence in signal detection. However, ED suffers from noise uncertainty, resulting in a poor detection rate, and the selection of the threshold in ED depends on the noise variance, which cannot be accurately estimated, resulting in unreliable detection (Sarwar and Monirul, 2015; Kailas and Siddarama, 2021; Deemah *et al*., 2023).

Several studies have explored the use of D-OUCR for optimal spectrum management in communication systems using ED. In Kechen *et al*. (2022), throughput maximization for multi-channel energy harvesting CR networks with hybrid overlay and underlay transmission was performed to improve the energy and spectrum efficiencies of existing energy harvesting CR networks. The proposed technique focuses on power allocation and joint time in energy harvesting with MCRNs. However, the technique is characterized by inaccurate detection of white and brown spaces, resulting in high interference due to inadequate switching between the overlay and underlay CR. Yan *et al*. (2022) also developed a method to improve energy efficiency in hybrid overlay and underlay CR networks. Their goal was to address high energy consumption and low user access rates. Furthermore, Poonguzhali *et al*. (2024) introduced a horse herd-based (H-hb) Elman method for spectrum sharing in GCR networks. This study showed that the H-hb Elman approach led to reduced energy usage and faster and more efficient spectrum sharing. However, the existing dynamic CR transmission systems often struggle with the inaccurate detection of white and brown spaces. This leads to significant interference because they do not switch effectively between the overlay and underlay modes. Therefore, in this study, interference reduction in the existing D-OUSS was performed by improving the detection rate of white and brown spaces using EVD. The contributions of this paper are as follows:

1. establishing a new D-OUSS technique with reduced interference due to the accurate detection of white and brown spaces, resulting in adequate switching between overlay and underlay approaches.
2. derivation of the SIR, TP, and PD expressions for the proposed D-OUSS technique over the kappa mu shadowing fading channel.

PROPOSED TECHNIQUE

The detection of white and brown spaces was first performed using an eigenvalue detector. Multiple copies of the transmitting signal of the licensed user were received at the cognitive user using multiple antennae. The received signal 'V' from cognitive user's antennas for the proposed D-OUSS technique is obtained as follows:

$$V = \sum_{i=1}^{P_a} \sum_{j=1}^{Q_l} S_i(j) + N_i(j) \tag{1}$$

where:

P_a is the number of antennae,
Q_l is the number of branches received by the individual antenna,
$S_i(j)$ is the ith LU signal from the jth branch
$N_i(j)$ is the AWGN on the LU link

Using Equation (1), the received signal in matrix form for the proposed technique '**V**' is obtained as

$$\boldsymbol{V} = \begin{bmatrix} S_{1,1} & S_{1,2}\ldots\ldots & S_{1,Q_l} \\ S_{2,1} & S_{2,2}\ldots\ldots & S_{2,Q_l} \\ & & \vdots \\ S_{P_a,1} & S_{P_a,2} & S_{P_a,Q_l} \end{bmatrix} + \begin{bmatrix} N_{1,1} & N_{1,2}\ldots\ldots & N_{1,Q_l} \\ N_{2,1} & N_{2,2}\ldots\ldots & N_{2,Q_l} \\ & & \vdots \\ N_{P_a,1} & N_{P_a,2} & N_{P_a,Q_l} \end{bmatrix} \quad (2)$$

According to Ojo *et al*. (2022), covariance V_C of the signal received is given as follows:

$$\boldsymbol{V_C} = \frac{1}{P_a}(\boldsymbol{V})\boldsymbol{V}^T \quad (3)$$

where: $\boldsymbol{V^T}$ is the transpose of the received signal

The maximum eigenvalue, τ_{max} and the minimum eigenvalue, τ_{min} ,were obtained using Equation (4)

$$det\begin{bmatrix} V_{C1,1} - \tau & V_{C1,2}\ldots\ldots\ldots & V_{C1,Q} \\ V_{C2,1} & V_{C2,2} - \tau \ldots\ldots & V_{C2,Q} \\ & & \vdots \\ V_{CP,1} & V_{CP,2} & V_{CP,Q} - \tau \end{bmatrix} = 0 \quad (4)$$

Therefore, τ with the highest value is the maximum eigenvalue, while τ with the lowest value is the minimum eigenvalue. Therefore, the test statistics 'Z' for the detection of white or brown space for the proposed technique is obtained as follows:

$$Z = \frac{\tau_{max}}{\tau_{min}} \quad (5)$$

The probability 'φ' of detecting white or brown space for the proposed technique is given as follows:

$$\varphi = \Pr(Z = 1) \quad (6)$$

Therefore, in the proposed technique, if $Z = 1$, white space is present; otherwise, brown space is present. Hence, the system switches to the overlay approach when white space is present and instantly switches to the underlay approach when brown space is present based on the D-OUCR switching algorithm presented in Algorithm 1.

Algorithm 1: D-OUCR switching algorithm
1: **Begin**
2: Initialize $P_a, Q_l, V_i(j), N_i(j)$
3: Receiving antenna = multiple antennas
4: The square matrix of the received signals is obtained using Equations (1) and (2)
5: The covariance matrix of the received signal '$\boldsymbol{V_C}$' using Equation (3)

6: The maximum and minimum eigenvalues of the received signal are obtained using Equation (4)
7: The ratio of max to min eigenvalues 'z' of the received signal is estimated using Equation (5)
8: The probability of detecting white or brown space 'φ' using Equation (6)
7: **if** $(z = 1)$ **then**
8: white space is present
9: apply the overlay approach
10: **elseif** $(z \neq 1)$ **then**
10: brown space is present
11: apply the underlay approach
12: continue until $(z = 1)$ **then**
13: apply the overlay approach
17: **else**
18: apply the underlay approach
19: **End**

Probability of Detection

In this paper, the probability of detection is the probability of accurately detecting brown or white space. The probability of detecting white or brown space for the proposed technique '$PD_{W/B}$' is expressed as follows:

$$PD_{W/B} = \Pr(Z = 1) \tag{7}$$

Substituting Equation (5) into Equation (7) gives the probability of detection (PD) for the proposed D-OUCR technique, as presented in Equation (8)

Throughput of the Modified Technique

In this paper, TP is the rate at which messages are delivered successfully over the kappa-mu shadow fading channel. The expression for throughput 'TP' is obtained as follows:

$$\mathrm{TP} = \mathrm{B} \times \log_2(1 + \mathrm{SNR})(1 - \mathrm{OP}) \tag{8}$$

However, the SNR in this work is the SNR of the received signal at the receiving end of the secondary user, which is given as follows:

$$SNR = \frac{P_{tSU}|h|^2}{N_{SU}} \tag{9}$$

where:

P_{tSU} is the power of the signal transmitted to the secondary user
$|h|^2$ is the channel gain
N_{SU} is the noise at the SU transceiver.

Therefore, using Equations (8) and (9), the expression for TP is obtained as follows:

$$\mathrm{TP} = \mathrm{B} \times \log_2\left(1 + \frac{\mathrm{P_{tSU}}|\mathrm{h}|^2}{\mathrm{N_{SU}}}\right)(1 - \mathrm{OP}) \quad (10)$$

The OP for the proposed technique was obtained by comparing the SNR of the received signal with the set threshold of 2 dB. If the SNR of the received signal falls below the set threshold, a signal outage occurs at the SU destination; otherwise, no outage occurs at the destination.

Signal-to-interference Ratio

The expression for Signal to Interference Ratio (SIR) 'SIR'for proposed technique is obtained as

$$SIR = 10log_{10}\left(\frac{P_s}{\frac{1}{J}\sum_{j=1}^{J} P_{in}(j)}\right) \quad (11)$$

Using the average power of the desired signal, the SIR for the proposed technique is obtained as follows:

$$SIR = 10log_{10}\left(\frac{P_{tu} * h^2}{\frac{1}{J}\sum_{j=1}^{J} P_{in}(j)}\right) \quad (12)$$

SIMULATION RESULTS AND DISCUSSION

PD, TP, and SIR were the performance metrics used to evaluate the performance of the proposed D-OUSS. The probability of detection (PD) was used to evaluate the accuracy of the proposed D-OUSS system in detecting white and brown spaces, comparing its performance to an existing D-OUSS. The signal-to-interference ratio (SIR) was also employed to quantify the reduction in interference, and the throughput (TP) was used to confirm the messages that successfully reached the CU receiver. This study gathered results at various numbers of propagation paths (L = 2, 3, and 4) and with different modulation constellation sizes to observe their influence. Figs. Figures 1 and 2 illustrate the PD versus SNR for both the proposed and existing D-OUSS across varying path numbers and constellation sizes, respectively. 1 present PD values obtained at different SNR values with L of two. The PD values obtained at an SNR of 4 dB and 4QAM modulation scheme were 0.4518 and 0.2496 for the proposed and existing D-OUSS, respectively, while the corresponding PD values obtained at 8QAM modulation scheme were 0.3217 and 0.2489. The results obtained revealed that, at all the SNR considered, the proposed D-OUSS gave the highest PD values, indicating the accuracy of the proposed technique. The accurate detection rate of the proposed technique is due to the use of an eigenvalue detector and the avoidance of setting a threshold based on noise variance. Noise variance cannot be accurately estimated at a low signal strength, thereby resulting in poor detection rate. In addition, for the two techniques, PD increases as SNR increases, and this is due to the increase in detection rate as signal strength increases.

Fig. 2 shows the PD versus SNR for the proposed and existing D- OUSS at L of 4 with different constellation size Kappa-mu shadowing fading channels. At an SNR of 4 dB, the PD values obtained using the 4-QAM modulation scheme were 0.6330 and 0.4702 for the proposed and existing D- OUSS, respectively, while 0.4017 and 0.2407 were the corresponding PD values obtained at the 8-QAM modulation scheme were 0.4017 and 0.2407. The results revealed that the proposed technique performed better with a higher detection rate than the existing technique. This is due to the independency of the threshold setting on the noise variance, thereby improving the detection rate. Furthermore, the results revealed that for the two techniques, PD reduces as the constellation size of the modulation increases because the signal with a low constellation size is robust in the channel compared with the signal with a higher constellation size, though at the expense of a low transmission rate. The results also revealed that at all the SNR considered, the detection rate reduces as the constellation size of the modulation increases, and this is due to the signal's robustness at a lower constellation size, at the expense of a low transmission rate. Furthermore, the results showed that for both the modified D- OUSS and the existing D- OUSS, PD increases with the increase in SNR due to the increase in signal strength, which increases the detection rate.

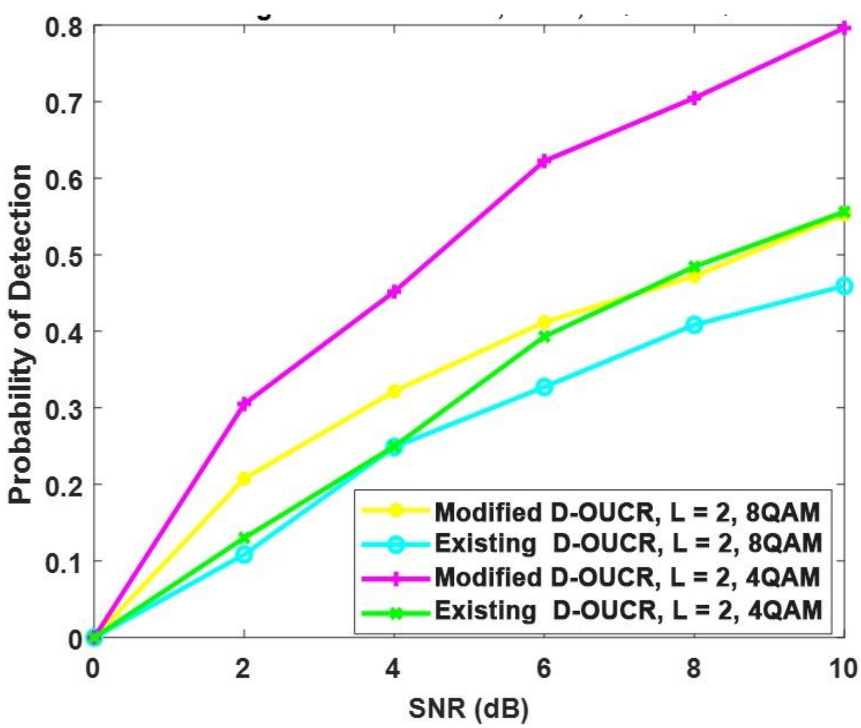

Fig 1: PD versus SNR for the modified and existing D-OUSS at L = 2 with different constellation sizes over the Kappa-mu shadowing fading channel

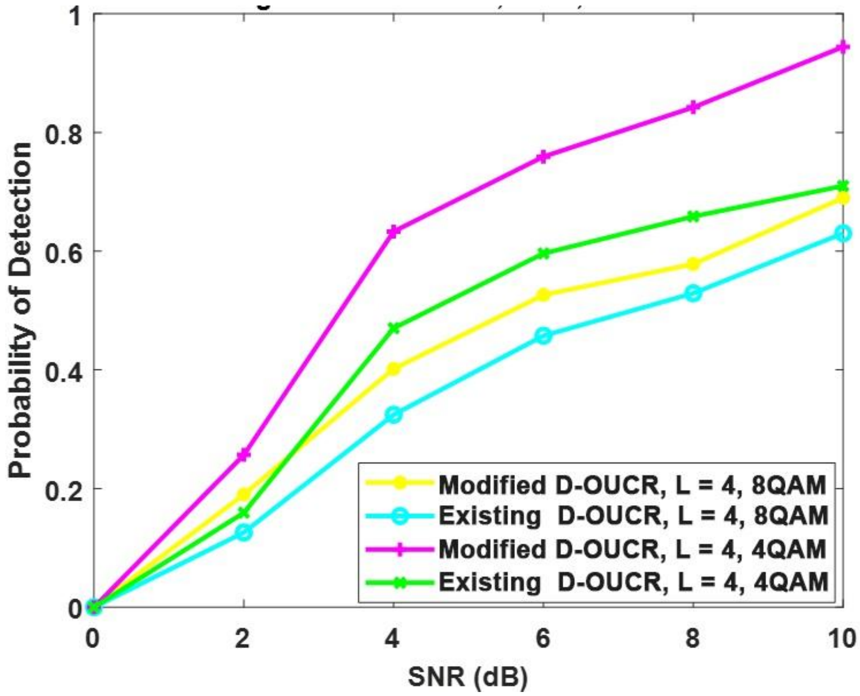

Fig 2: PD against SNR for the proposed and existing D- OUSS at L of 4 with different constellation sizes over the Kappa-mu shadowing fading channel

Figs. 3 and 4 present the SIR against SNR for the proposed and existing D- OUSS at varying modulation paths and constellation sizes. Fig. 3 depicts the SIR values versus SNR for the proposed and existing techniques at L = 2 and different constellation sizes. The SIR values obtained at an SNR of 4 dB were 0.6588 and 0.3487 for the proposed and existing D- OUSS, respectively, using the 4-QAM modulation scheme, while 0.4117 and 0.2179 were the corresponding PD values obtained using the 8-QAM modulation scheme were 0.4117 and 0.2179. The results revealed that, at all the SNR considered, the proposed technique gives the best SIR values, indicating a reduction in interference. This is due to the accurate detection of white and brown spaces, which results in accurate switching and reduces the interference between the SU and PU. The results also revealed that SIR increases as SNR increases, and this is due to the increase in detection rate and signal strength as SNR increases. Similarly, Figure 4.6 depicts the SIR values obtained versus the SNR at L = 4 using different constellation sizes. At an SNR of 4 dB, SIR values of 0.9515 and 0.6973 were obtained for the modified and existing D- OUSS using the 4-QAM modulation scheme, whereas the corresponding SIR values obtained using the 8-QAM modulation scheme were 0.5947 and 0.4358 for the modified and existing D-OUSS, respectively. The results obtained revealed that the value of SIR increases as the number of paths increases for the two considered techniques, justifying the accurate detection at a higher number of paths. However, in all the cases considered, the results revealed that the modified technique gave a high SIR value, which justified the reduction in the interference level in the modified technique. The high SIR value in the modified technique is due to the accurate detection of brown and white space, which reduces the interference between the PU and SU.

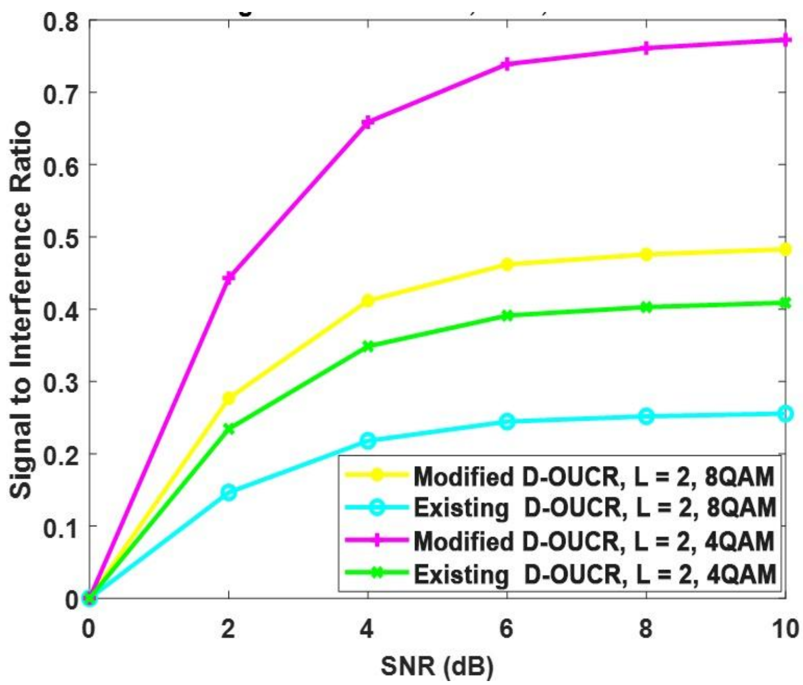

Fig 3: SIR versus SNR for the proposed and existing D-OUSS techniques at L = 2.

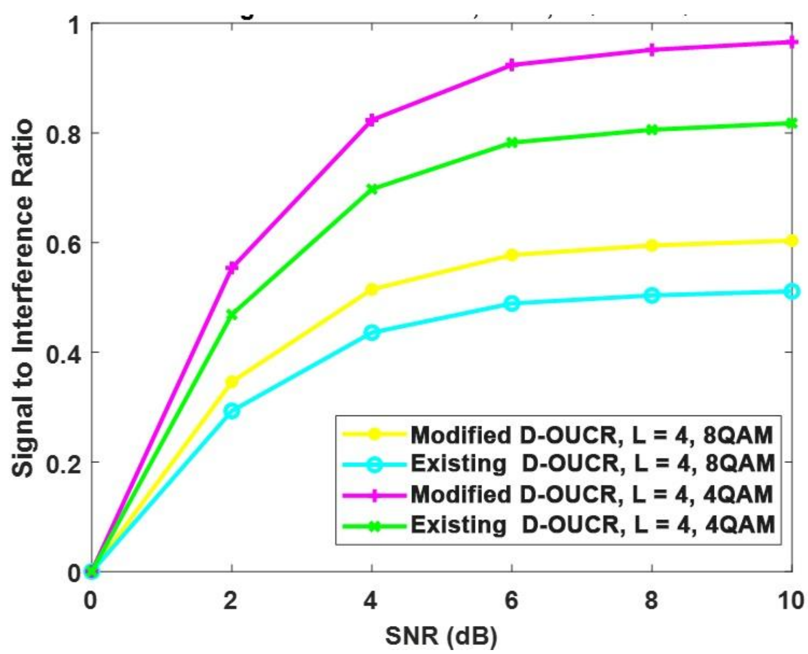

Fig 4: SNR vs. SIR for the proposed and existing D- OUSS techniques at L = 4.

Figs. 5 and 6 present the TP against SNR for the proposed and existing D- OUSS techniques at varying paths and constellation sizes. Fig. 5 shows the TP against SNR for the proposed and existing D- OUSS at L = 2 and different constellation sizes. The TP values obtained at SNR of 4 dB and 4-QAM were 7.68 and 4.80 Mbps for the proposed and existing D- OUSS, respectively, while the corresponding TP values obtained at 8-QAM modulation scheme were 9.60 and 3.00

for the proposed and existing technique, respectively. The results revealed that, at all the SNRs considered, the proposed technique gave the highest TP values, indicating the highest number of information that successfully arrives at the receiving end of SU. The highest TP values obtained for the proposed technique are due to the spectrum band that is fully exploited by the SU with little or no interference between the PU and SU. The results also reveal that TP increases as SNR increases due to the increase in the number of signals that successfully arrive at the SU receiving side as the SNR increases. Similarly, Fig. 6 shows the TP versus SNR at L = 4 for the proposed and existing D-OUSS techniques. The TP values obtained at an SNR of 4 dB and 4-QAM modulation scheme were 9.60 and 6.72 Mbps for the proposed and existing D- OUSS technique, respectively, while the corresponding values obtained using the 8-QAM modulation scheme were 6.00 and 4.20 Mbps. The results revealed that TP increases as the number of paths increases, and this is due to the increase in signal strength as the number of paths increases. However, the results obtained revealed that at all the number of paths considered, the proposed D-OUCR technique gave the best performance with the highest number of information that successfully arrived at the receiving end of SU due to reduction in interference between PU and SU during switching between the two techniques. The accurate switching in the proposed technique is due to the accurate detection of white and brown spaces resulting from the use of an eigenvalue detector.

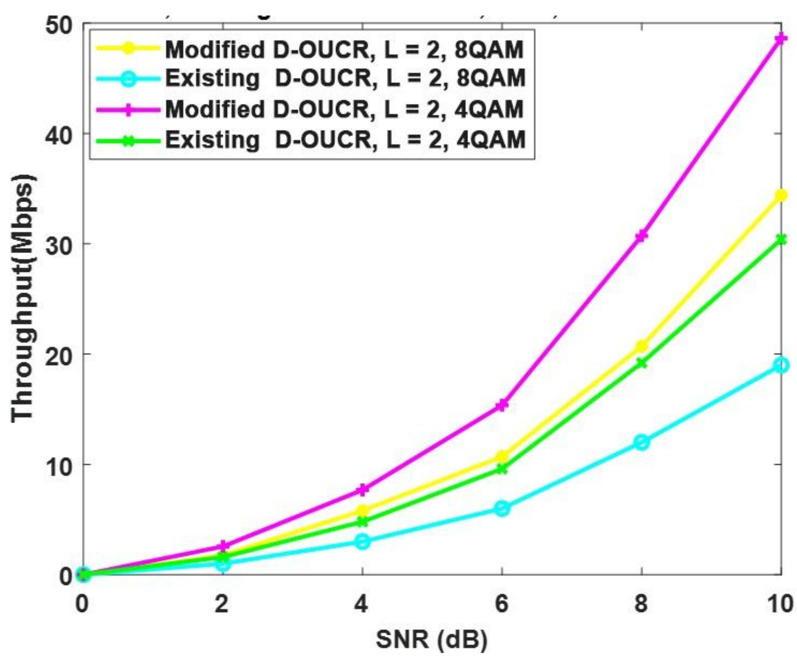

Fig 5: TP against SNR for the proposed D-OUSS technique at L = 2

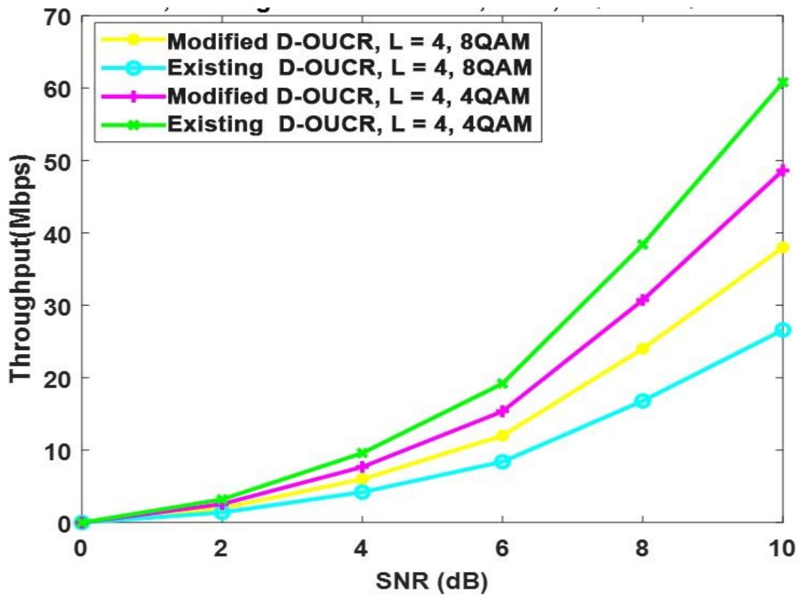

Fig 6: TP versus SNR for the proposed D-OUSS technique at L = 4

CONCLUSION

This study modified the existing D-OUSS for spectrum management in a wireless communication system over the Kappa-mu shadowing fading channel. The modification was carried out by replacing the ED in the existing D-OUSS with an eigenvalue detector to improve the accuracy of the detection of white and brown spaces, thereby improving the switching accuracy between the overlay and underlay SS. In the simulation process where MATLAB R2024a software was used, the system model for the received PU signal at the SU was designed in the presence of the Kappa-mu shadowing fading channel, while the noise was modeled as AWGN. The coefficient of the fading envelope was multiplied using the M-QAM signaling scheme with the addition of AWGN. Multiple copies of PU signals were received at different propagation paths 'L' (2 and 4) to investigate the effect of increasing the number of paths on the proposed technique. The proposed D-OUSS technique was evaluated using PD, TP, and SIR and compared with the existing D-OUSS to validate its performance. The PD, TP, and SIR values for the proposed and existing D-OUSS were obtained at different SNRs with different numbers of paths. The performance of the proposed and existing D-OUSS has been evaluated at different number of paths 'L' with different SNRs using PD, TP, and SIR as performance metrics. The results revealed that the proposed D-OUSS showed better performance with higher detection rate, high throughput, and reduced interference. The improved performance of the proposed technique is due to the use of an eigenvalue detector in setting the decision threshold and avoiding dependency on the noise variance, which is always uncertain. In addition, for the proposed and existing D-OUSS techniques, PD, TP, and SIR increase as SNR increases. This is due to the increase in the detection rate of the presence of white or brown space as the SNR increases. Consequently, the proposed technique effectively reduces the interference between the PU and SU, thereby improving the throughput at the receiving side of the SU over the Kappa-mu shadowing fading channel with a high signal-to-interference ratio.

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