Performance Analysis of Selection Diversity Combining Using Improved Energy Detection over Rayleigh Fading Channel

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***Abstract*—Diversity schemes are powerful communication techniques that provide wireless link improvements at relatively lower cost and overcome deep fading scenarios. Also, Energy Detection is a technique for blind sensing of unused frequency bands, extensively used in Cognitive Radio and ultra wide-band applications due to its non-parametric and computationally low sensing ability. In this paper, by using an improved version of classical energy detection method, performance improvement of selection combining diversity scheme has been analyzed. The results demonstrate the significance of using Improved Energy Detection technique over existing methods, hence indicating remarkable improvement in the system performance. Based on the proposed algorithm, simulation results show a perfect agreement with analytical results, hence validating the proposed scheme.**

***Index Terms*—Cognitive Radio, Diversity, Improved Energy Detection, Rayleigh Fading, Selection Combining**

I. Introduction

The propagation of radio waves via wireless channels is a very complex phenomenon. It is characterised by different effects such as multipath fading and shadowing. The propagation of signal components involves randomly delayed, reflected, scattered and diffracted signal components. Multipath fading occurs due to the constructive and destructive combination of these components [1]. The signal power experiences significant variations resulting into critically affecting the performance of the wireless system due to such a dynamic nature of the radio environment [2].

A very promising approach to dulcify the various effects of wireless channels is diversity combining schemes. As an outcome of using these schemes, the overall capacity and coverage of wireless systems increases. The literature consists of humongous amounts of combining techniques, each having different levels of computational and hardware complexities and differing requirements for channel state information, some of the well-known diversity schemes being: Maximal Ratio Combining (MRC), Selection Combining (SC) and Equal Gain Combining (EGC) [3].

With increasing number of devices and advent of 5G wireless communications, the radio frequency spectrum is becoming insufficient [4]. A very low utilization of allocated spectrum has been observed using the conventional fixed spectrum allocation policy. According to a spectrum occupancy campaign in 2016, the overall usage of the spectrum band ranges from 7% to 34%, which is quite poor [5]. Spectrum allocation needs to be dynamic for efficient usage of spectrum and Cognitive Radio has turned out to be a promising approach for the scarcity problem. Spectrum sensing is an important countenance of Cognitive Radio for sensing the occupancy of Primary User's presence/absence. Various spectrum sensing techniques have been proposed in the literature [6]. However, majority of spectrum sensing techniques require apriori information about the signal, which is quite impractical in real life scenarios.

Energy detection is a very robust spectrum sensing technique which requires no apriori information about the signal and is a computationally efficient method as compared to other spectrum sensing techniques. Various improvements in Energy Detection have been proposed in the literature such as Modified Energy Detection (MED) [7] and Improved Energy Detection (IED) [8] which works upon reducing the false alarm ratio of Energy Detection or Classical Energy Detection (CED).

In this paper, the performance of selection combining diversity scheme has been analysed for the first time in literature using IED under Rayleigh Fading channels. The impact on performance of the system has also been studied by varying the number of antennas in the subsequent sections, hence proving the significance of diversity schemes. The proposed scheme significantly outperforms the existing scheme (using Energy Detection). The figures demonstrate a great agreement with the aforementioned assertion.

The remainder of this paper is structured as follows: Section II provides details on formulation of problem statement and system model which includes subsections on Selection Combining, Spectrum Sensing, Average Probability of Detection for Selection Diversity Combining using Classical Energy Detection (CED) and Improved Energy Detection (IED). Section III describes the proposed approach along with pseudo code of algorithm. Section IV showcases the Numerical Results of the proposed approach with the existing scheme followed by a comparison of computational complexities of both algorithms. Section V concludes the paper outlining the important takeaways and enumerates future scope of this research work followed by acknowledgement and references.

II. System Model and Problem Formulation

A. Selection Combining Diversity Technique

In this technique, the receiver selects the branch with the strongest signal.

$$h^* = \max\{h_l, l = 1, 2, 3, ..., L\} \tag{1}$$

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In (1), $h_1, h_2, ..., h_L$ indicate the channel magnitudes, where h_l represents the channel magnitude of l^{th} receiving antenna. Also, h^* represents the antenna with maximum SNR (Signal-to-Noise Ratio) value, which implies the selection of the corresponding receiving antenna.

The selection combining (SC) diversity technique has lesser complexity as compared to maximal ratio combining (MRC), since MRC requires complete knowledge of channel state information and on the contrary, only the knowledge of amplitude of branches is required when using SC diversity technique [1] in order to select the branch with highest SNR, due to which we assume complete information of channel state information (CSI). This assumption can be justified because the amplitude values may be achievable for cognitive sensors over a broadcast or control channel. [9].

B. Spectrum Sensing

A conventional cognitive spectrum sensing system has been considered in this work that tests a binary hypothesis. This hypothesis is used to decide the presence (busyness) or absence (idleness) of the primary user (PU) signal $x(n)$ based on the received signal $y(n)$ using IED technique, where $n = 1, 2, 3, ..., N$ represent N samples of the transmitted signal.

The hypothesis namely $\mathcal{H}_0$ (PU is idle) and $\mathcal{H}_1$ (PU is busy) have been defined for decision statistics of PU's signal respectively as:

$$y(n) = \begin{cases} w(n), & \mathcal{H}_0 \\ hx(n) + w(n), & \mathcal{H}_1 \end{cases}$$

Here, $x(n)$ represents the transmitted signal, h represents the channel coefficient between PU and SU and $w(n)$ indicates the Additive White Gaussian Noise (AWGN).

The Detection Probability (P_d) and Probability of False Alarm (P_{fa}) can be computed using the following test-statistic:

$$\mathcal{T}_i(x_i) = \sum_{n=1}^{N} |y(n)|^2 \tag{2}$$

The aforementioned test statistic is compared to a pre-defined energy threshold λ based on which a decision of the channel state as busy or idle is taken.

Probability of False Alarm (P_{fa}) and Detection Probability (P_d) for AWGN can be written as given in [10]:

$$P_{fa} = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)} \tag{3}$$

$$P_d = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{4}$$

Here, Upper Incomplete Gamma function: $\Gamma(a, x) = \int_x^\infty \mathrm{t}^{\mathrm{a}-1}\exp(-\mathrm{t})\mathrm{d}t$, Gamma function: $\Gamma(a) = \Gamma(a, 0)$, Generalized Marcum-q function: $Q_m(a, b) = \frac{1}{a^{(m-1)}}\int_b^\infty x^m \mathrm{I}_{\mathrm{m}-1}(\mathrm{ax})\exp\bigg(-\frac{(x^2+a^2)}{2}\bigg)\mathrm{d}x$, and nth order Modified Bessel Function of the first kind: $I_n(x) = \frac{1}{\pi}\int_0^\pi \cos(\mathrm{n}\theta)\exp(\mathrm{x}\cos(\theta))\mathrm{d}x$.

Moreover, $u = T \cdot W$ denotes product of Time (T) and Bandwidth (W). The value of *u* is always taken equal to half the number of samples considered.

C. Average Detection Probability for Selection Combining Diversity Scheme using Classical Energy Detection

Average Detection Probability ($\bar{P}_d$) for Selection Combining Diversity Scheme under uncorrelated Rayleigh Fading Channel can be calculated as [11] :

$$\bar{P}_{d,\alpha,\mu,sc} = \int_0^\infty Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) f_{SC}(\gamma)\mathrm{d}\gamma \tag{5}$$

where, f_{SC} denotes the probability density function (pdf) of SNR for Selection Diversity Combining obtained at the output of the combiner and is as shown below:

$$\begin{aligned} f_{SC}(\gamma) = &\left[\frac{L\alpha\mu^\mu}{2\Gamma(\mu)\bar{\gamma}^{-\frac{\alpha\mu}{2}}}\left(1 - \frac{\Gamma(\mu, \mu(\frac{\gamma}{\bar{\gamma}})^{\frac{\alpha}{2}})}{\Gamma(\mu)}\right)^{L-1}\right] \times \\ &\left[\gamma^{\frac{\alpha\mu}{2}-1}\exp\bigg(-\mu\Big(\frac{\gamma}{\bar{\gamma}}\Big)^{\frac{\alpha}{2}}\bigg)\right] \end{aligned} \tag{6}$$

According to [10], the Marcum-Q Function can be re-written as :

$$Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) = \sum_{n=0}^{\infty} \frac{\Gamma(n+u, \frac{\lambda}{2})}{n!\Gamma(n+u)}\gamma^n \exp(-\gamma) \tag{7}$$

Substituting (7) into (5) and solving the integral in (5) using the general Laplace transform [12, 2.2.1-22], we get the term $\left(1 - \frac{\Gamma(\mu, \mu(\frac{\gamma}{\bar{\gamma}})^{\frac{\alpha}{2}})}{\Gamma(\mu)}\right)^{L-1}$. Solving this term using multinomial expansion, we get (8) as below:

$$\begin{aligned} \bar{P}_{d,\alpha,\mu,sc} = &\left[C\sum_{n=0}^{\infty} a_n \sum_{i=0}^{L-1} (-1)^i \binom{L-1}{i}\right] \times \\ &\left[\sum_{m=0}^{i(\mu-1)} \frac{\mu^m \theta^{\frac{\alpha m}{2}+n}}{\bar{\gamma}^{-\frac{\alpha m}{2}}} \beta_{mi}(\mu) G_{\theta,\delta}^{\delta,\theta}\left(z;^{\triangle(\theta,-v)}_{\triangle(\delta,0)}\right)\right] \end{aligned} \tag{8}$$

where,

$$C = \frac{\alpha\mu^\mu L\sqrt{\delta}\theta^{\frac{\alpha\mu-1}{2}}}{2\Gamma(\mu)\bar{\gamma}^{\frac{\alpha\mu}{2}}(2\pi)^{\frac{\delta+\theta}{2}-1}}, a_n = \frac{\Gamma(n+u, \frac{\lambda}{2})}{n!\Gamma(n+u)}$$

$$z = \theta^\theta \left(\frac{(i+1)\mu}{\delta\bar{\gamma}^{\frac{\alpha}{2}}}\right)^\delta, v = \frac{\alpha(\mu+m)}{2} + n - 1$$

Here, $G_{\theta,\delta}^{\delta,\theta}\left(z;^{\triangle(\theta,-v)}_{\triangle(\delta,0)}\right)$ is the Meijer-G function, δ and θ are some integers such that $\frac{\theta}{\delta} = \frac{\alpha}{2}$.

Now, the detection probability for Classical Energy Detection with Selection Combining diversity reception under the assumption of Rayleigh fading channel can be obtained from (8) by setting α = 2 and μ = 1 as given in (9):

$$\bar{P}_{d,Ray,SC,L} = \left[\frac{L}{\bar{\gamma}}\sum_{r=0}^{\infty}\frac{\Gamma(r+u,\frac{\lambda}{2})}{\Gamma(r+u)}\right] \times \left[\sum_{j=0}^{L-1}(-1)^j\Big(\frac{1+j+\bar{\gamma}}{\bar{\gamma}}\Big)^{-1-r}\binom{L-1}{j}\right] \tag{9}$$

For the case of *No Diversity* scenario, $L = 1$, (9) reduces to:

$$\bar{P}_{d,Ray,SC,L} = \frac{1}{1+\bar{\gamma}}\sum_{r=0}^{\infty}\frac{\Gamma(r+u,\frac{\lambda}{2})}{\Gamma(r+u)}\Big(\frac{\bar{\gamma}}{1+\bar{\gamma}}\Big)^r \tag{10}$$

D. Improved Energy Detection

In order to avoid false alarms or rather reduce their ratio of occurence, an additional check is performed by IED algorithm on the basis of test-statistic of the preceding sensing event as illustrated in [8]. Let λ denote the predefined threshold which provides a basis for deciding upon idleness or busyness of the channel, $\mathcal{T}_i(\mathbf{y}_i)$ indicates test-statistic of the current sensing event, $\mathcal{T}_{i-1}(y_{i-1})$ denote test-statistic of previous sensing event and $\mathcal{T}_i^{avg}(\mathbf{T}_i)$ denote the average of previous S test-statistics and D_i denotes the decision taken. Improved Energy Detection says that:

- When $\mathcal{T}_i(\mathbf{y}_i) < \lambda$ and $\mathcal{T}_i^{avg}(\mathbf{T}_i) > \lambda$, the condition $\mathcal{T}_{i-1}(\mathbf{y}_{i-1}) > \lambda$ indicates that $\mathcal{T}_i(\mathbf{y}_i) < \lambda$ may result because of an instantaneous energy drop. In such case, hypothesis $\mathcal{H}_1$ must be considered.
- On the contrary, the condition $\mathcal{T}_{i-1}(\mathbf{y}_{i-1}) < \lambda$ suggests that $\mathcal{T}_i(\mathbf{y}_i) < \lambda$ may have occurred due to the channel release. In such a case hypothesis $\mathcal{H}_0$ must be the decision of CR.

For highly variable signals, the additional usage of $\mathcal{T}_i^{avg}(\mathbf{T}_i)$ has been shown in Algorithm 1 (line 9), which can robustly avoid miss-detections in cases where instantaneous energy drops may have affected certain consecutive sensing events.

Detection Probability of IED as a function of SNR as given in [8] is as follows:

$$P_d^{IED} = P_d^{CED} + P_d^{CED}\big(1 - P_d^{CED}\big)\cdot\varepsilon \tag{11}$$

Similarly,

$$P_{fa}^{IED} = P_{fa}^{CED} + P_{fa}^{CED}\big(1 - P_{fa}^{CED}\big)\cdot\varepsilon \tag{12}$$

where,

- For High SNR regime :

$$\varepsilon = Q\left(\frac{Q^{-1}(P_{fa})\sqrt{2N} - \frac{MN\bar{\gamma}}{S}}{\sqrt{\frac{2N}{S}\Big(1+\frac{M}{S}\big[(1+\bar{\gamma})^2-1\big]\Big)}}\right) \tag{13}$$

- For Low SNR regime,

$$\varepsilon = Q\left(Q^{-1}(P_{fa})\sqrt{S} - M\sqrt{\frac{N}{2S}}\bar{\gamma}\right) \tag{14}$$

Here, N indicates Number of Samples, S indicates the number of previous sensing events considered. Also, M represents the number of sensing events where a primary signal is actually present such that $M \in [0, S]$ and $\bar{\gamma}$ indicates average SNR (in linear scale).

As evident from (11), the value of Detection Probability will increase significantly. However, it is worth noting that IED algorithm improves at the cost of reduction in Probability of False Alarm, however, such a reduction is not as significant as the improvements demonstrated by the results in subsequent sections.

III. Proposed Scheme

At first glance, it might seem that our work is very similar to [8] and [11]. However, [8] is based entirely on AWGN channels and there is no consideration of fading scenarios. Also, [11] considers the effect of fading but only over the Classical version of energy detection, not Improved Energy Detection and the channel fading model is also different.

The proposed scheme involves using Improved Energy Detection instead of Classical Energy Detection for Selection Diversity Combining. The test statistic of IED owes its performance utility to the consideration of test statistics of instantaneous events, average test statistic of past S sensing events and test statistic of previous event.

Algorithm of Proposed Scheme (IED with Selection Combining Diversity) is given as below:

Algorithm 1 Proposed Scheme : IED with SC Diversity

1: **for** every sensing event i **do**
2: *choose* $h = \max\{h_l, l = 1, 2, 3, ..., L\}$
3: *choose* y corresponding to h
4: $\mathcal{T}_i(y_i) \leftarrow$ Energy of N samples
5: $\mathcal{T}_i^{avg}(\mathbf{T}_i) \leftarrow$ Mean of$\{\mathcal{T}_{i-S+1}(\mathbf{y}_{i-S+1}), \mathcal{T}_{i-S+2}(\mathbf{y}_{i-S+2}), \mathcal{T}_{i-S+3}(\mathbf{y}_{i-S+3}), .., \mathcal{T}_{i-1}(\mathbf{y}_{i-1}), \mathcal{T}_i(\mathbf{y}_i)\}$
6: **if** $\mathcal{T}_i(\mathbf{y}_i) > \lambda$ **then**
7: $D_i \leftarrow \mathcal{H}_1$
8: **else**
9: **if** $\mathcal{T}_i^{avg}(T_i) > \lambda$ **then**
10: **if** $\mathcal{T}_{i-1}(\mathbf{y}_{i-1}) > \lambda$ **then**
11: $D_i \leftarrow \mathcal{H}_1$
12: **else**
13: $D_i \leftarrow \mathcal{H}_0$
14: **end if**
15: **else**
16: $D_i \leftarrow \mathcal{H}_0$
17: **end if**
18: **end if**
19: **end for**

Detection Probability of IED as a function of SNR for Selection Diversity Combining Technique is as follows:

$$P_{d,Ray,SC,L}^{IED} = P_{d,Ray,SC,L}^{CED} + P_{d,Ray,SC,L}^{CED}\big(1 - P_{d,Ray,SC,L}^{CED}\big)\cdot\varepsilon \tag{15}$$

where $P_{d,Ray,SC,L}^{CED}$ is the probability of detection obtained in (8).

Since $Q(.) \in [0,1]$, $P_{d,Ray,SC,L}^{IED}$ is bounded by $P_{d,Ray,SC,L}^{CED} \leq P_{d,Ray,SC,L}^{IED} \leq 2P_{d,Ray,SC,L}^{CED} -$

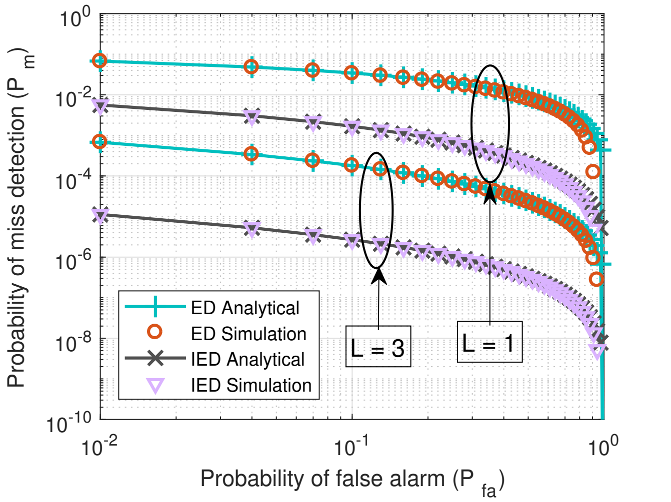

Fig. 1: Complementary ROC Curve for SC using ED and IED schemes ($N = 10$, $\bar{\gamma} = 20$ dB, $L = \{1, 3\}$, $M = 1$, $S = 3$)

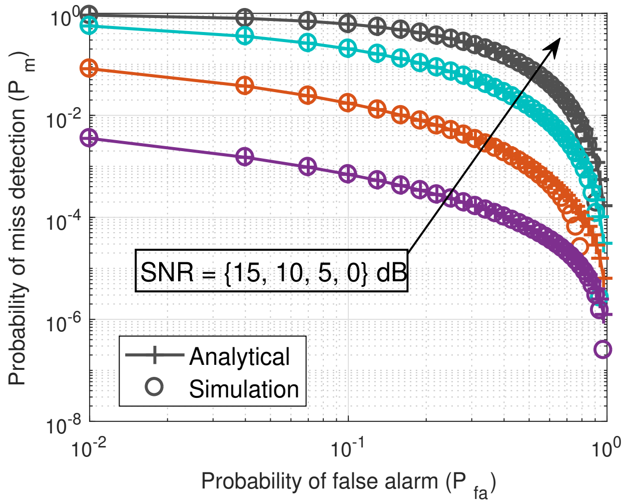

Fig. 2: Complementary ROC Curve for SC using IED ($N = 10$, $\bar{\gamma} = \{0, 5, 10, 15\}$ dB, $L = 2$, $M = 1$, $S = 3$)

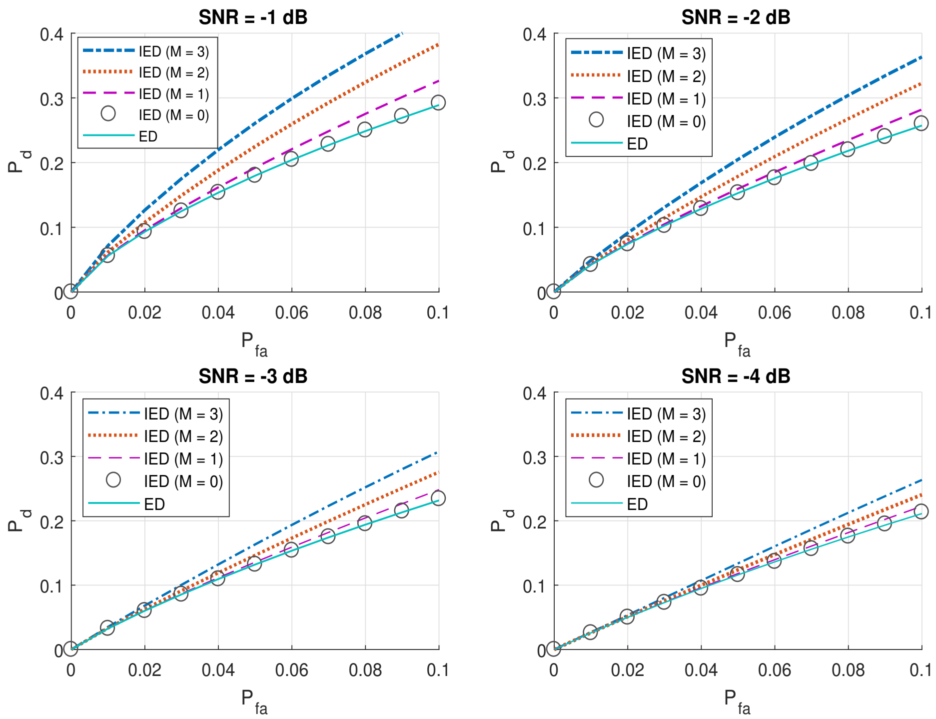

Fig. 3: ROC Curves for SC using ED and IED algorithms ($N = 10$, $L = 2$, $S = 3$, $M \in [0, S]$)

$(P^{CED}_{d,Ray,SC,L})^2$. Similar bound is applicable to the false alarm probability as well. Hence, the improvement in the detection probability occurs at the expense of false alarm probability as mentioned before. But according [8], this degradation is not as significant as in other algorithms like MED, yielding an improved performance in results using IED as evident in the next section.

IV. Numerical Results and Discussions

The metric used for evaluation of the performance of ED and IED algorithms is Complementary Receiver Operating Characteristics (ROCs) ($P_m = 1 - P_d$ versus P_f). Various fading distributions can be derived by substituting particular values of both α and μ, from the $\alpha - \mu$ fading distribution as given in [13] . However, in this work, we focus on performance analysis and comparison of ED and IED for Selection Combining diversity scheme under Rayleigh fading channel only.

Fig. 1 shows the complementary ROCs (P_m vs P_{fa}) depicting comparison in performance of ED and IED algorithms for $L = \{1, 3\}$. Here, the tuned parameters are number of samples (N = 10), number of previous sensing events ($S = 3$) and number of sensing events where a primary signal is acutally present ($M = 1$). For instance, consider the value of desired $P_{fa} = 0.01$, miss-detection probability for ED and IED techniques are 6.759×10^{-4} and 0.1127×10^{-4} respectively. As clearly evident, IED outperforms ED sensing technique and a significant reduction in probability of miss detection can be observed. Also, it is worth noting that $L = 1$ indicates *No Diversity* and $L = 3$ indicates *Diversity* scenario, as a result the scenario with *Diversity* scheme (SC) yields a lower probability of miss-detection than that of *No Diversity* scheme.

Fig. 2 shows the complementary ROCs (P_m vs P_{fa}) showing comparison in performance of IED at different values of SNR = 0 dB, 5 dB, 10 dB and 15 dB with SC Diversity branch, $L = 2$, $S = 3$, $M = 1$ and $N = 10$. It can be ascertained that as the value of SNR increases the probability of miss detection (P_m) decreases which implies increase in the value of detection probability.

Fig. 3 represents standard ROC curves for ED and IED techniques with various values of M and SNR for $L = 2$. All the four curves in Fig. 3 demonstrate ROC curves for low SNR regime using the approximation as shown in (14). As evident from the curves in Fig. 3, IED outperforms ED and the best performance of IED algorithm is achieved when the value of $M = S$, which is equal to 3 in this case, which is due to the reason that all the previous sensing events that have been considered (S), are the events where a primary signal is actually present (M).

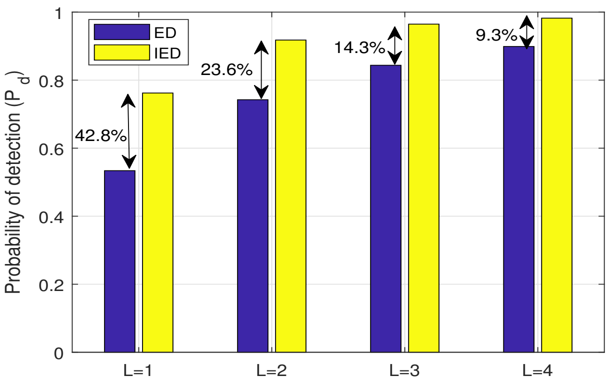

Fig. 4: Analysis of Improvement in Detection Probability of ED and IED schemes for SC diversity ($L \in [1, 4]$, $P_{fa} = 0.01$, $\bar{\gamma} = 10$dB, $M = 1$, $S = 3$)

Fig. 4 epitomizes the improvement in system performance by using IED instead of ED technique for different values of L. As observed from the figure, the increase in detection probability is maximum for *No Diversity* scenarios and decreases with increasing value of L. For *No Diversity* scenarios (L = 1), the detection probability for ED and IED schemes are 0.5339 and 0.7622 respectively giving a 42.8% performance improvement. Similarly, *Diversity* scenarios (L = 4), the detection probabilities for ED and IED schemes are 0.899 and 0.9823 respectively resulting in a 9.3% performance improvement. These percentage gain values shown in the figure above are subject to the tuned parameters, hence they will change on changing them. A superior performance can be expected nevertheless.

The comparison of computational cost in case of ED and IED can be explained as follows: The computation of $\mathcal{T}_i(\mathbf{y}_i)$ requires N multiplication operations and $N - 1$ sum operations, which, however, is required in both algorithms. Apart from that, IED algorithm computes $\mathcal{T}_i^{avg}(\mathbf{T}_i)$, which carries out $L-1$ sum operations and one division operation, performs two additional comparisons (lines 9 and 10). Furthermore, for each channel sensed by the CR, IED algorithm has a requirement of memory to store the last $L - 1$ test statistic values. However, the increase in the computational cost for IED algorithm in SC Diversity scheme can be considered as negligible, as compared to various conventional methods such as covariance-based detectors [16] or cyclostationary feature detectors [14], [15], which requires comparatively more computationally complex computations.

V. Conclusion and Future Work

Performance analysis and comparison of probability of detection for Classical Energy Detection and Improved Energy Detection methods over Rayleigh Fading Channels for Selection Diversity Combining Scheme has been demonstrated. Clearly, IED should be chosen owing to its better performance in all the cases. Also, it was shown that using higher diversity schemes will lead to a better performance in terms of probability of detection. Moreover, the figures of percentage improvement obtained by using IED indicated in Fig. 4 convincingly proves the superiority of algorithm. On increasing the value of diversity order, the value of detection probability increases. Various other fading channel models like Nakagami-m, $\kappa - \mu$, Gamma (Chi-Square), Weibull, Exponential can be considered for future work.

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