Paper

Theoretical Investigation of Different Diversity Combining Techniques in Cognitive Radio

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https://doi.org/10.26636/jtit.2018.124618

Abstract—In this paper, the performance of an energy detector in cognitive radio, using different diversity combining techniques, is evaluated. Among many diversity combining techniques, maximal ratio combining (MRC) gives the best results but at the cost of the highest complexity. To design a simpler receiver, it is suggested to use less complex combining techniques, i.e. switched diversity, which provides one of the least complex solutions to combat fading. The paper analyzes two switched diversity schemes, switch examine combining (SEC), and switch examine combining with post examining selection (SECp). A closed form expression determining the probability of detection using MRC, SEC and SECp is derived for various numbers of branches. Detection performance with different diversity combining techniques is compared and the complexity trade-off is observed.

Keywords—cognitive radio, complementary ROC, post examining selection, probability of detection, probability of false alarm, switch and examine combining.

1. Introduction

Cognitive radio (CR) is gaining attention in wireless scenarios as it enables the secondary user (SU) to efficiently utilize the free spectrum licensed to the primary user (PU), at a time when the spectrum is not being used [1]–[5]. This unoccupied or unutilized frequency band is known as a spectrum hole [6]. To find these holes, different sensing techniques are used [3], [7]. But fading is a problem in the wireless environment and due to this phenomenon the performance of PU detection degrades significantly.

In literature [8]–[15], space diversity is one of the solutions to mitigate the effect of fading. Diversity combining techniques [16] are then used to receive multiple copies of the signal generated by space diversity. Switched diversity and selection combining (SC) [17] are two most popular less complex diversity combining techniques. Selection of the diversity branch in SC is based on choosing the best signal among all which are received from different branches at the receiver [18]. The use of SC requires SNR estimation of all branches, hence switched diversity can be a simpler option for diversity combining. Switching from one diversity branch to another only when needed reduces receiver complexity [19]. There are two different strategies that can be used in switched diversity. One is switch and stay combining (SSC), in which the receiver selects another branch only if SNR of the current branch falls below the required threshold. The other strategy is switch and examine (SEC). The classic switch and SEC are used to take advantage of multiple diversity paths. SEC is also used with post examining selection (SECp) [20]. This scheme is similar to SEC, except one difference – it chooses the best path when no acceptable path is found after all paths have been tested.

In this paper the complexity detection performance of cognitive radio, using with different diversity combining techniques is compared and the complexity trade-off is observed. General expressions for probability of detection over the Rayleigh fading channel using MRC, SEC and SECp diversity combining techniques are derived.

2. System Model

In this paper the energy detection method is applied to the PU which is discussed in [21]. The received signal $r[n]$ can be defined as a binary hypothesis test as [21]:

$$r[n] = \begin{cases} z[n] & , \; H_0 \\ Hx[n]+z[n] , & H_1 \end{cases} , \quad n = 1,2,\ldots,N , \tag{1}$$

where H is the channel coefficient that is considered as constant for a particular observation, i.e. for N samples. H_0 is the hypothesis test when noise only is present and H_1 is the hypothesis test when both noise and signal are present. $x[n]$ is the primary user signal component which is assumed to be an unknown deterministic signal, and $z[n]$ is the noise component which is assumed to be an additive white Gaussian noise (AWGN) having zero mean and variance σ^2.

3. Probability of Detection, Misdetection and False Alarm

3.1. Probability of False Alarm

As derived in [21] the probability of false alarm in AWGN channel is:

$$P_{fa} = \int_{\frac{\lambda}{\sigma^2}}^{\infty} \frac{1}{2^{\frac{N}{2}}\Gamma\left(\frac{N}{2}\right)} t^{\frac{N}{2}-1} \mathrm{e}^{-\frac{t}{2}} \mathrm{d}t = Q_{x_N^2}\left(\frac{\lambda}{\sigma^2}\right), \ \frac{\lambda}{\sigma^2} \geq 0, \quad (2)$$

$Q_{x_N^2}\left(\frac{\lambda}{\sigma^2}\right)$ can be written as [22]:

$$Q_{x_N^2}\left(\frac{\lambda}{\sigma^2}\right) = \begin{cases} 2Q\sqrt{\frac{\lambda}{\sigma^2}} & , \ N = 1 \\ 2Q\sqrt{\frac{\lambda}{\sigma^2}} + \frac{\mathrm{e}^{-\frac{\lambda}{2\sigma^2}}}{\sqrt{\pi}} & \\ \times \sum\limits_{k=1}^{\frac{N-1}{2}} \frac{(k-1)!\left(\frac{2\lambda}{\sigma^2}\right)^{k-\frac{1}{2}}}{(2k-1)!} & , \ N \text{ odd} \\ \mathrm{e}^{-\frac{\lambda}{2\sigma^2}} \sum\limits_{k=0}^{\frac{N}{2}-1} \frac{\left(\frac{\lambda}{2\sigma^2}\right)^k}{k!} & , \ N \text{ even} \end{cases}, \quad (3)$$

where $Q(.)$ is the complementary cumulative distribution function defined as:

$$Q(x) = \int_{x}^{\infty} \frac{1}{\sqrt{2\pi}} \mathrm{e}^{-\frac{t^2}{2}} \mathrm{d}t .$$

In the same work the probability of detection in AWGN channel is defined by:

$$P_d = Q_{\chi^2_{N(\gamma)}}\left(\frac{\lambda}{\sigma^2}\right) = \int_{\frac{\lambda}{\sigma^2}}^{\infty} \frac{1}{2}\left(\frac{1}{\gamma}\right)^{\frac{N-2}{4}} \mathrm{e}^{\frac{1}{2}(t+\gamma)} I_{\frac{N}{2}-1}\sqrt{\gamma t}\, \mathrm{d}t , \quad (4)$$

where λ is a predetermined threshold and instantaneous received SNR γ is defined as $\gamma = |H|^2 \frac{\xi}{\sigma^2}$. Equation (4) can also be written using [23] for an even number of degrees of freedom as:

$$P_d = Q_{\frac{N}{2}}\left(\sqrt{\gamma}, \sqrt{\lambda'}\right), \quad (5)$$

where $\lambda' = \frac{\lambda}{\sigma^2}$ and $Q_m(.)$, the m-th generalized Marcum Q function [24] which is given by:

$$Q_m(\alpha,\beta) = \frac{1}{\alpha^{m-1}} \int_{\beta}^{\infty} x^m e^{-\frac{x^2+\alpha^2}{2}} I_{m-1}(\alpha x)\, \mathrm{d}x . \quad (6)$$

Equation (6) cannot be used for an odd degrees of freedom. For this case, it can be defined as [21]:

$$\begin{aligned} Q_{\chi^2_{N(\gamma)}}\left(\frac{\lambda}{\sigma^2}\right) &= \sum_{k=0}^{\infty} \frac{\mathrm{e}^{-\frac{\gamma}{2}}\left(\frac{\gamma}{2}\right)^k}{k!} \int_{\lambda'}^{\infty} \frac{t^{\frac{N}{2}+k-1}\mathrm{e}^{-\frac{t}{2}}}{2^{\frac{N}{2}+k}\Gamma\left(\frac{N}{2}+k\right)} \mathrm{d}t \\ &= \sum_{k=0}^{\infty} \frac{\mathrm{e}^{-\frac{\gamma}{2}}\left(\frac{\gamma}{2}\right)^k}{k!} \underbrace{Q_{\chi^2_{N+2k}}\left(\lambda'\right)}_{\text{Second term}} . \quad (7) \end{aligned}$$

The second term is the right-tail probability of a central chi-square having $N+2k$ degrees of freedom.

3.2. Average Detection Probability

The probability of false alarm remains the same as given by Eq. (2) under any fading channel because it is formulated for the no signal transmission case and is independent of SNR. Hence the same formula can be used for upcoming sections as well. But to find out the probability of detection under the fading channel, Eq. (5) is averaged over the probability density function (PDF) of that particular channel. So, if the signal amplitude follows the Rayleigh distribution, then SNR γ follows an exponential PDF given by [25]:

$$f(\gamma) = \frac{1}{\overline{\gamma}} \mathrm{e}^{-\frac{\gamma}{\overline{\gamma}}}, \ \gamma \geq 0, \quad (8)$$

where $\overline{\gamma}$ is the average received SNR.
The probability of false alarm remains the same as given by Eq. (2) under any fading channel because it is formulated for the no signal transmission case and is independent of SNR. So, the same formula can be used for upcoming sections as well. In the Rayleigh fading channel, the average probability of detection P_D for this case is evaluated by integrating Eq. (5) over Eq. (8) [25]:

$$\begin{aligned} \overline{P}_{d_{Ray}} &= \int_0^{\infty} Q_{\frac{N}{2}}\left(\sqrt{\gamma}, \sqrt{\lambda'}\right) f(\gamma) \mathrm{d}\gamma \\ &= \frac{1}{\overline{\gamma}} \int_0^{\infty} Q_{\frac{N}{2}}\left(\sqrt{\gamma}, \sqrt{\lambda'}\right) \mathrm{e}^{-\frac{\gamma}{\overline{\gamma}}} \mathrm{d}\gamma, \quad (9) \end{aligned}$$

where $\overline{\gamma}$ is average SNR, and $f(\gamma)$ denotes the PDF of the fading channel (here PDF of the Rayleigh fading channel is taken).
Equation (9) can be written in the closed form [26]:

$$\begin{aligned} \overline{P}_{d_{Ray}} &= \mathrm{e}^{-\frac{\lambda}{2}} \sum_{k=0}^{u-2} \frac{1}{k!}\left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\overline{\gamma}}{\overline{\gamma}}\right)^{u-1} \\ &\times \left(\mathrm{e}^{-\frac{\lambda}{2(1+\overline{\gamma})}} - \mathrm{e}^{-\frac{\lambda}{2}} \sum_{k=0}^{u-2} \frac{1}{k!} \frac{\lambda\overline{\gamma}}{2(1+\overline{\gamma})}\right) . \quad (10) \end{aligned}$$

For maximal ratio combining, scaling as well as cophasing of the signals is required and all the paths are optimally combined at the receiver. The output SNR γ_t of the MR combiner is $\gamma_t = \sum_{l=1}^{L} \gamma_l$, where L is the total number of diversity branches and γ_l is the SNR of the individual branch. In MRC, the average probability of detection for AWGN channel is:

$$P_{dMRC} = Q_{LN/2}\left(\sqrt{2\gamma_t}, \sqrt{\lambda}\right). \tag{11}$$

The PDF of γ_t over i.i.d. Rayleigh branches for MRC is given by [9]:

$$f_{\gamma_{MRC}}(\gamma_t) = \frac{1}{(L-1)!\overline{\gamma}^{L}} \gamma_t^{L-1} \mathrm{e}^{-\frac{\gamma_t}{\overline{\gamma}}}. \tag{12}$$

The average probability of detection for MRC diversity scheme $\overline{P}_{dMRC}$ will then be calculated by averaging Eq. (11) over Eq. (12) and that comes out to be in closed form as:

$$\overline{P}_{d_{Ray_{MRC}}} = \alpha_1 \left[Z_1 + \rho \sum_{n=1}^{L} \frac{\left(\frac{\lambda}{2}\right)^n}{2(n!)} {}_1F_1 \times \left(L; n+1; \frac{L\lambda\overline{\gamma}}{2L(1+\overline{\gamma})}\right)\right], \tag{13}$$

where:

$\alpha_1 = \frac{1}{L!2^{L-1}} \overline{\gamma}^{-L}$,

$$Z_1 = \frac{2^{L-1}(L-1)!\overline{\gamma}^{L+1}}{1+\overline{\gamma}} \mathrm{e}^{-\frac{\lambda}{2(1+\overline{\gamma})}} \left[\left(1+\frac{1}{\overline{\gamma}}\right)\left(\frac{1}{1+\overline{\gamma}}\right)^{L-1} \times \Im_{L-1}\left(-\frac{\lambda}{2(1+\overline{\gamma})}\right) + \sum_{n=0}^{L-2} (1+\overline{\gamma})^n \Im_n \left(-\frac{\lambda}{2(1+\overline{\gamma})}\right)\right],$$

$\rho = (L-1)!\left(\frac{2\overline{\gamma}}{1+\overline{\gamma}}\right)^L \mathrm{e}^{-\frac{\lambda}{2}}$.

The $\Im_n$ is Laguerre polynomial of degree n.
The probability of detection in the AWGN channel is defined by Eq. (5). The PDF of γ over L number of i.i.d. Rayleigh branches for SEC is given by Eq. [9]:

$$f_{\gamma_{SEC}}(\gamma) = \begin{cases} \left(1-\mathrm{e}^{-\frac{\gamma_T}{\overline{\gamma}}}\right)^{L-1} \frac{1}{\overline{\gamma}} \mathrm{e}^{-\frac{\gamma}{\overline{\gamma}}}, & \gamma < \gamma_T \\ \sum_{j=0}^{L-1} \left(1-\mathrm{e}^{-\frac{\gamma_T}{\overline{\gamma}}}\right)^j \frac{1}{\overline{\gamma}} \mathrm{e}^{-\frac{\gamma}{\overline{\gamma}}}, & \gamma \geq \gamma_T \end{cases}, \tag{14}$$

where γ_T is the switching threshold. The average probability of detection of switch and examine combining can be obtained by averaging Eq. (5) over Eq. (14) and comes out to be:

$$\overline{P}_{d_{SEC}} = \frac{1}{\overline{\gamma}} \mathrm{e}^{-\frac{\gamma}{\overline{\gamma}}} \left[\int_0^{\gamma_T} \left(1-\mathrm{e}^{-\frac{\lambda_T}{\overline{\gamma}}}\right)^{L-1} Q_{fracN2}\left(\sqrt{\gamma}, \sqrt{\lambda'}\right) \mathrm{d}\gamma + \int_{\gamma_T}^{\infty} \sum_{j=0}^{L-1} \left(1-\mathrm{e}^{\frac{\gamma_T}{\overline{\gamma}}}\right)^j Q_{\frac{N}{2}}\left(\sqrt{\gamma}, \sqrt{\lambda'}\right) \mathrm{d}\gamma \right]. \tag{15}$$

In the closed form Eq. (15) comes out to be:

$$\overline{P}_{d_{SEC}} = \left(1-\mathrm{e}^{-\frac{\gamma_T}{\overline{\gamma}}}\right)^{L-1} \left(\overline{P}_{d_{Ray}} - C\right) + \sum_{j=0}^{L-1} \left(1-\mathrm{e}^{-\frac{\gamma_T}{\overline{\gamma}}}\right)^j C, \tag{16}$$

where

$$C = \mathrm{e}^{-\frac{\gamma_T}{\overline{\gamma}}} Q_u\left(\sqrt{\gamma_T}, \sqrt{\lambda}\right) + \left(\frac{1+\overline{\gamma}}{\overline{\gamma}}\right)^{u-1} \times \mathrm{e}^{-\frac{\lambda}{2(1+\overline{\gamma})}} \left[1 - Q_u\left(\sqrt{2\gamma_T \frac{1+\overline{\gamma}}{\overline{\gamma}}}, \sqrt{\frac{\lambda\overline{\gamma}}{1+\overline{\gamma}}}\right)\right]. \tag{17}$$

3.3. Average Detection Probability for SECP

In CR, when no acceptable path is found after examining all the possibilities, the best path among all these unacceptable routes (with the highest SNR for data reception) is selected. Whereas in classical SEC, the switching-examining process is repeated until an acceptable path is found (i.e. with SNR greater than the threshold) or until all the routes have been examined. If all the paths are examined and no acceptable route is found, the receiver selects, in most cases, the last examined path [20]. In SECp, there is a predetermined threshold γ_T and any diversity path having SNR greater than this threshold is accepted. If no path is found having SNR greater than γ_T, the SECp receiver selects the path having the highest SNR. As such, SECp needs less path switching and fewer path estimations which results more complexity compared to the classic SEC method. But it shows a better performance that is proved later in this paper.
The PDF of γ over L no. of i.i.d. Rayleigh branches for SECp is given by [9]:

$$f_{\gamma_{SEC_p}}(\gamma) = \begin{cases} L\left(1-\mathrm{e}^{-\frac{\gamma}{\overline{\gamma}}}\right)^{L-1} \frac{1}{\overline{\gamma}} \mathrm{e}^{-\frac{\gamma}{\overline{\gamma}}}, & \gamma < \gamma_T \\ \left[1-\left(1-\mathrm{e}^{-\frac{\gamma}{\overline{\gamma}}}\right)^L\right] \frac{1}{\overline{\gamma}} \mathrm{e}^{-\frac{\gamma-\gamma_T}{\overline{\gamma}}}, & \gamma \geq \gamma_T \end{cases}. \tag{18}$$

The average detection probability of SECp can be obtained by averaging Eq. (5) over Eq. (18):

$$\overline{P}_{d_{SEC_P}} = I_1 + I_2, \tag{19}$$

where I_1 is given by:

$$I_1 = \frac{L}{\overline{\gamma}} \sum_{k=0}^{L} (-1)^k \frac{(L-1)!}{k!(L-k-1)!} [X_1 - X_2], \tag{20}$$

having

$$X_1 = \frac{\overline{\gamma}}{k+1} \mathrm{e}^{\frac{-\lambda'}{2}} \left[\left(1+\frac{2(1+k)}{\overline{\gamma}}\right)^{\frac{N}{2}-1} \left(\mathrm{e}^{\frac{\lambda'}{2(1+\frac{2(1+k)}{\overline{\gamma}}}} - \sum_{n=0}^{\frac{N}{2}-2} \frac{1}{n!} \frac{\lambda'}{2\left(1+\frac{2(1+k)}{\overline{\gamma}}\right)} \right) + \sum_{n=0}^{\frac{N}{2}-2} \frac{1}{n!} \left(\frac{\lambda'}{2}\right)^n \right], \tag{21}$$

$$X_2 = \frac{\overline{\gamma}}{1+k} \mathrm{e}^{-\frac{(1+k)\gamma_T^2}{\overline{\gamma}}} Q_{\frac{N}{2}} \left(\gamma_T, \sqrt{\lambda'}\right) + \frac{\overline{\gamma}}{2\,(k+1)}$$
$$\times \left(1 + \frac{2(1+k)}{\overline{\gamma}}\right)^{\frac{N}{2}-1} \mathrm{e}^{-\frac{\lambda'}{2} \frac{2(1+k)}{2(1+k)+\overline{\gamma}}}$$
$$\times \left[1 - Q_{\frac{N}{2}} \left(\gamma_T \sqrt{1 + \frac{2(1+k)}{\overline{\gamma}}}, \frac{\sqrt{\lambda'}}{\sqrt{1 + \frac{2(1+k)}{\overline{\gamma}}}}\right)\right], \quad (22)$$

and I_2 has the expression given by:

$$I_2 = \left[1 - \left(1 - \mathrm{e}^{-\frac{\gamma_T}{\overline{\gamma}}}\right)^L\right] \mathrm{e}^{\frac{\gamma_T}{\overline{\gamma}}} C, \quad (23)$$

where C is defined by Eq. (17).

4. Results and Discussion

Here, the probability of detection for both SEC and SECp is evaluated using Monte Carlo simulation for the threshold SNR $\gamma_{th} = 18$ dB. Figure 1 illustrates SNR vs P_D over the Rayleigh fading channel for different diversity combining techniques (SEC, SECp, MRC) along with no diversity case. Here, the variation in probability of detection with respect to SNR is observed, and one may see from the graph that the probability of detection is higher for SECp than in the case of conventional SEC. Figure 2 also illustrates the same results for different numbers of samples, i.e. SECp performs better than SEC. Another finding of Fig. 2 is that the performance improves upon increasing N. In Fig. 3, a graph showing the probability of misdetection and the probability of a false alarm is plotted for a constant value of SNR. This graph is known as the complementary receiver operating characteristic (ROC) curve. Complementary ROC curves for different diversity combining techniques also show a better performance of the SECp technique, which is verified for different N in Fig. 4.

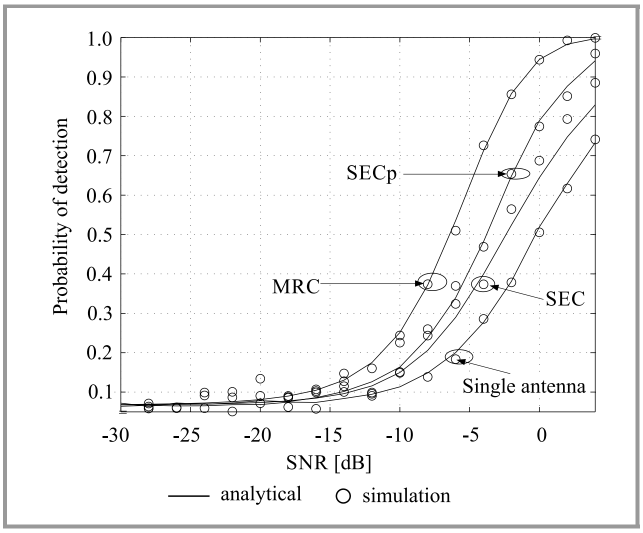

Fig. 1. SNR vs P_d curves over the Rayleigh fading channel for a single antenna and SEC, SECp, MRC diversity combining techniques for $L = 2$ with $\gamma_{th} = 8$ dB and $N = 10$.

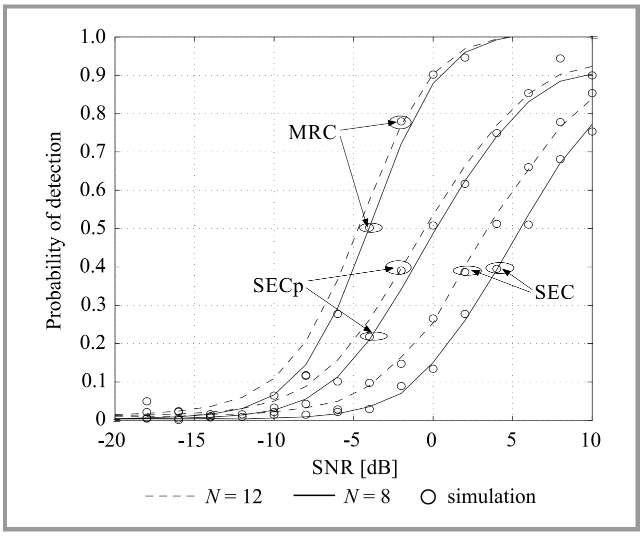

Fig. 2. SNR vs P_d curves over the Rayleigh fading channel with a single antenna and SEC, SECp ($L = 2$) diversity combining techniques having $\gamma_{th} = 8$ dB for different N.

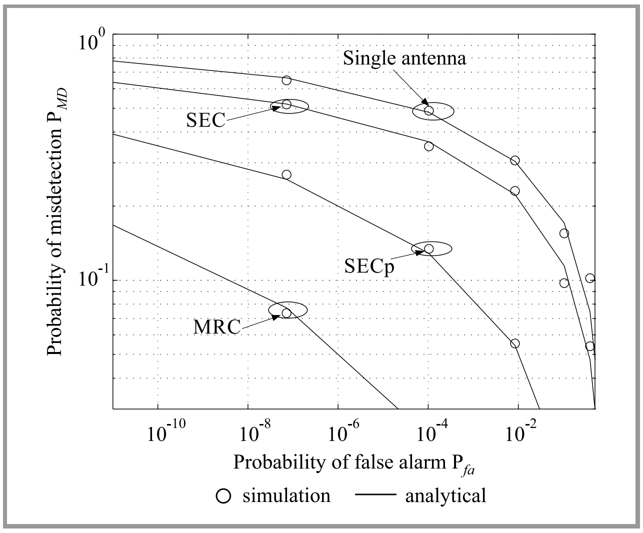

Fig. 3. Complementary ROC curves over the Rayleigh fading channel for a single antenna and SEC, SECp diversity combining techniques for $L = 2$ with $\gamma_{th} = 8$ dB, $\overline{\gamma} = 6$ dB, $N = 8$.

5. Conclusion

In this paper, performance analysis of different diversity combining techniques is conducted for cognitive radio scenarios. General formulas for the probability of detection using MRC, SEC and SECp diversity combining techniques over the Rayleigh fading channel are derived and results are cross-verified. Though MRC gives the best results, its hardware design is quite complex. If a less complex receiver design is required, switched diversity techniques may prove to be a better option. The performance of MRC is slightly better than SECp but the design of SECp is much simpler. It is shown that the same results are repeated for different numbers of samples. It is illustrated with the help of SNR vs probability of detection curves, as well as with

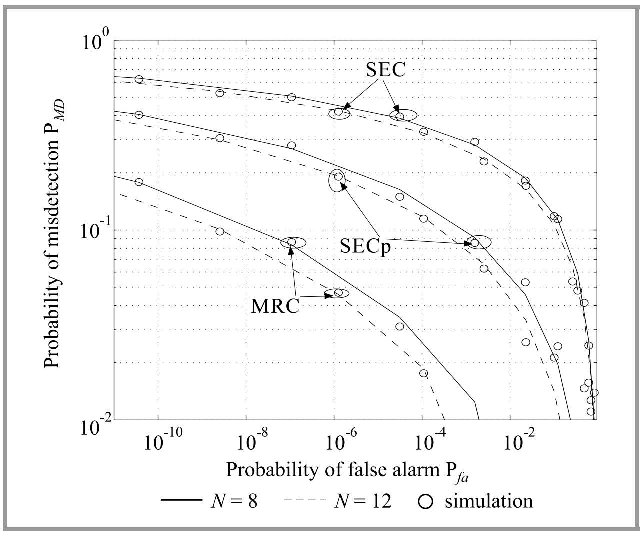

Fig. 4. Complementary ROC curves over the Rayleigh fading channel for a single antenna and SEC, SECp ($L = 2$) diversity combining techniques with $\gamma_{th} = 8$ dB, $\bar{\gamma} = 5$ dB for different N.

complementary ROC curves, that performance improves on increasing the number of samples. Performance improves also with additional branches. Performance of cognitive radio with no diversity is the lowest, and improves with the implementation of diversity combining techniques.

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