

Project: SENDORA	Deliv. ref.: D3.1
EC contract: 216076	Deliv. title: Spectrum Sensing Algorithm Evaluation
	Deliv. version: 1.1
	Submission date: 26/05/2010

4 SIMULATION RESULTS AND DISCUSSION

The evaluation framework for all simulations has been implemented in Matlab. Refer Section 3.2 for the evaluation framework. The Rayleigh and Rician flat fading channel models have been created with the help of the build-in functions "rayleighchan" and "ricianchan", respectively. The parameters have been chosen accordingly for the various scenarios. The AWGN channel is simulated by simply adding a complex Gaussian random variable to the sampled signal. The detectors are taken from the 'spectrum sensing algorithm library' created on the SENDRORA website under WP3 and the algorithms listed below are considered:

1. Energy detection (ED) refer Section 2.2.1
2. Cyclostationary based detectors
 - i. Single cycle (SingleCycle); refer Section 2.3.1.1
 - ii. Multi cycle (MultiCycle); refer Section 2.3.1.2
3. Cyclostationarity based robust sign detector (RSD); refer Section 2.3.2
4. Autocorrelation based detection (AC); refer Section 2.3.3
5. Cyclic prefix sliding correlation; refer Section 2.3.4
 - i. Maximum of absolute value test statistic (CPa)
 - ii. Maximum of real value test statistic (CPr)
6. DVB-T pilot based sliding correlation (DVB-T Pilot); refer Section 2.3.5.
7. Distribution analysis detection (DAD); refer 2.4.3

4.1.1 Simulator parameters and assumptions:

First we state the common assumption and parameters for the simulation. Next we list special assumptions and simulation parameters for each detector.

Common assumptions:

- i. For all simulation cases, discrete time baseband processing is assumed.
- ii. The SNR in decibels is defined as $SNR(dB) = 10 \log_{10}(SNR)$
- iii. Different non-idealities such as carrier frequency offset, dc offset, and non-Gaussian noise are not considered.
- iv. We assume that there is no interfering signal (only AWGN noise is considered).
- v. Finding out threshold values and noise power level are additional nuisance parameters for the detectors.

Common simulation parameters:

- i. **Detector:** Neyman Pearson detector with constraint on false alarm probability.
- ii. **Number of realizations to simulate the probability of detection:** 1000
- iii. Output of the signal generator is normalized such that signal has unit variance. For changing SNR, noise variance is varied accordingly.
- iv. Channel tap values are normalized such that the sum of channel tap powers is 1, on average.
- v. **Primary signal:** DVB-T signal , bandwidth: **8 MHz**, mode: **2K**, guard interval: $\frac{1}{4}$.
- vi. **Channel:**
 - a. **AWGN**
 - b. **Rayleigh:** frequency-flat ("single path"), maximum Doppler shift: **100Hz**
 - c. **Rician:** frequency-flat ("single path"), maximum Doppler shift: **100Hz** with **K=1** or **10**.
 - d. **Shadowing:** Location variability 10 dB.
- vii. **Sensing time:** 1.12ms or 10 ms.
- viii. **SNR Regime considered:** -30dB to 0dB without Shadowing; and -40 dB to 10 dB with Shadowing.
- ix. **Modulation:** 16 QAM; **Sampling interval :** $7/(8 \cdot \text{bandwidth})$

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Next, we present assumptions and parameters specifically for individual detectors.

4.1.1.1 Energy detector

Assumptions:

- i. Noise variance is known.
- ii. Noise distribution is Gaussian.

4.1.1.2 Autocorrelation based detection of OFDM signals

Assumptions:

- i. Lags T_d are known.
- ii. Noise distribution is Gaussian.

4.1.1.3 Cyclostationarity based single and multi cycle detector

Parameters:

- i. 1 Lag: T_d
- ii. **Single cycle detector:** 1 cyclic frequency $\alpha = 1/(T_d + T_c)$
- iii. **Multicycle detector:** 7 Cyclic Frequencies: $\alpha = (0, \bar{1}, \bar{2}, \bar{3})/(T_d + T_c)$

Assumptions:

- i. Lags and Cyclic Frequencies are known.

4.1.1.4 Cyclostationarity based robust sign detector

Parameters:

- i. 2 Lags: \bar{T}_d
- ii. 1 cyclic frequency: $\alpha = 1/(T_d + T_c)$

Assumption:

- i. Lags and Cyclic Frequencies are known.

4.1.1.5 Cyclic prefix sliding correlation detectors

- i. It is assumed that the noise variance is known.
- ii. As theoretical values for the decision statistics thresholds are not known, their calculation is performed empirically. It is done by passing a white noise signal of the corresponding variance to the signal detector, calculating the test statistics and finding the threshold for the given probability of false alarm. In our simulation we obtain proper approximation after 500 simulations. In a practical implementation of these algorithms the thresholds can be precalculated and stored in a table to be used directly by the algorithm.
- iii. In this case we also assume that the lags T_d and T_c are known.

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4.1.1.6 Pilot based sliding correlation detector

- i. As in the previous subsection we perform an empirical calculation of decision statistics thresholds.
- ii. In addition we assume that we have a perfect knowledge of the DVB-T signal parameters, i.e. its bandwidth, cyclic prefix length and mode.

4.1.1.7 Distribution analysis based detection

In the first step of the distribution analysis algorithm, we choose the size of the observed window in order to estimate Rayleigh and Rice parameters over this window using. In general, the size of the observed window depends on the type of the PU signals. As an example, the window is set to 200kHz for GSM signals, which is equal to the GSM bandwidth. In the presented simulations, we chose this size equal to 570 samples. There are total 18 sliding windows to cover the whole 8 MHz bandwidth.

In the second step, we compute the value of AIC and then Akaike weights using equations given in Section 2.4.2.

Assumptions:

- i. Detection is made in a perfectly blind way.
- ii. Noise distribution is Gaussian.
- iii. Signal envelope has Rician distribution.
- iv. Detection in frequency domain.

For this detector, authors [Zayen2008] assume that the received signal envelope obeys Rician distribution. This may not be necessarily true for many practical cases, e.g. complex circular signals. For example, in case of M-QAM or M-PSK modulation schemes where symbols have zero mean for both the real and imaginary part the envelope of the received signal is not Rician. Gaussian noise, on the other hand, leads to Rayleigh distributed envelope. See [Proakis 2001] for more detail for the validity of the assumption for various modulation schemes and receiver structures. However, in their simulation results authors [Zayen2008] illustrate that this detector has a high probability of detection even in case of M-QAM or M-PSK modulation schemes. See, [Zayen2008], [Zayen2010] for further clarifications by the authors.

4.1.2 Probability of detection vs SNR curves

4.1.2.1 AWGN Channel

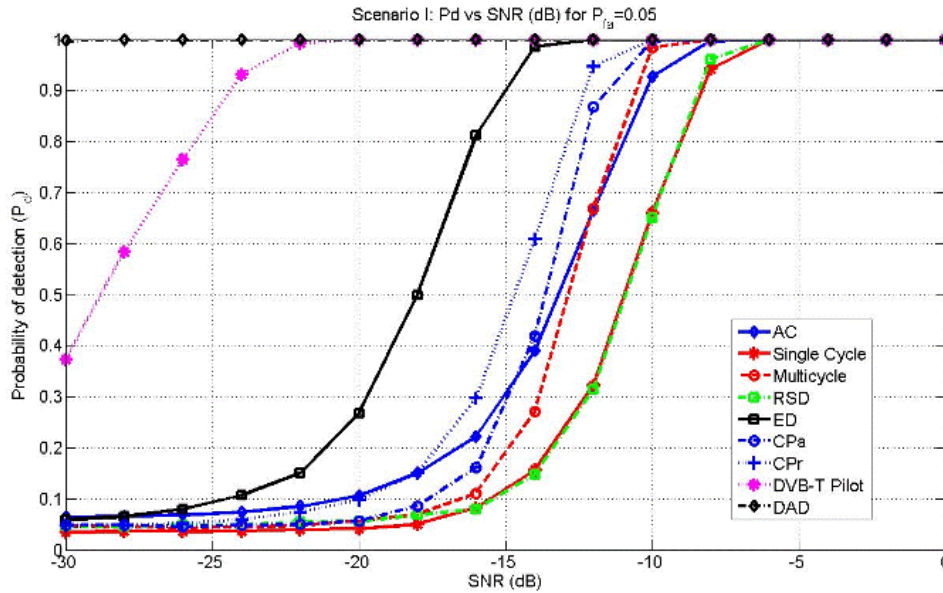


Figure 4. P_d vs. SNR (dB) curves for AWGN Channel and sensing time = 1.12 ms

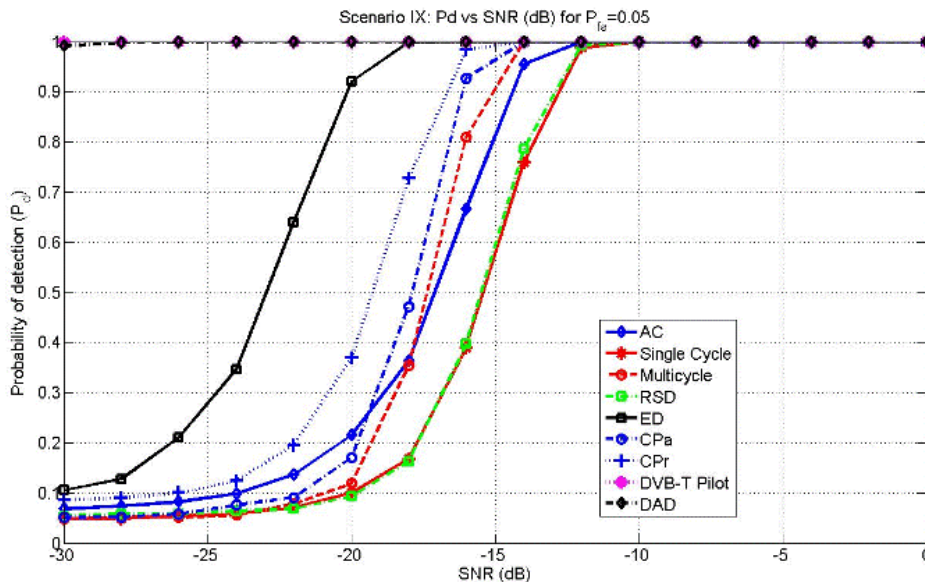


Figure 5. P_d vs. SNR (dB) curves for AWGN Channel and sensing time = 10 ms

Observations from Figure 4 and Figure 5:

- i. Detection performance improves for all detectors with sensing time.
- ii. Although DVB-T pilot and DAD detectors have highest probability of detection in the SNR regime of interest, they have equally serious issue of controlling false alarm rate.

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- iii. DAD detector assumes that PU signal envelope obeys Rician distribution. See [Proakis 2001] for more detail for the validity of the assumption for various modulation schemes and receiver structures. However, its probability of detection is very high, even higher than in the case of ED (which assumes noise variance) and DVB-T (a matched filter). Therefore the results for DAD looks inconclusive and interested readers should refer [Zayen2008], and [Zayen2010] for the details of the detector performance. Moreover, the remarks on false alarm probability above should be taken into account.
- iv. Energy detection has the next highest detection probability. However it also struggles somewhat to satisfy the false alarm constraint for longer sensing time.
- v. Detectors CPa, CPr, MultiCycle and AC have reasonable detection performance and are able to meet false alarm constraint.
- vi. RSD and SingleCycle detector have the lowest detection probability. However, it is not fair to compare RSD with other detectors in Gaussian noise, as the gain is only seen when the noise is non-Gaussian. This method trades off optimality for robustness.
- vii. Detectors, other than DAD, DVB-T pilot and ED, have excellent false alarm control.

4.1.2.2 AWGN + Shadowing

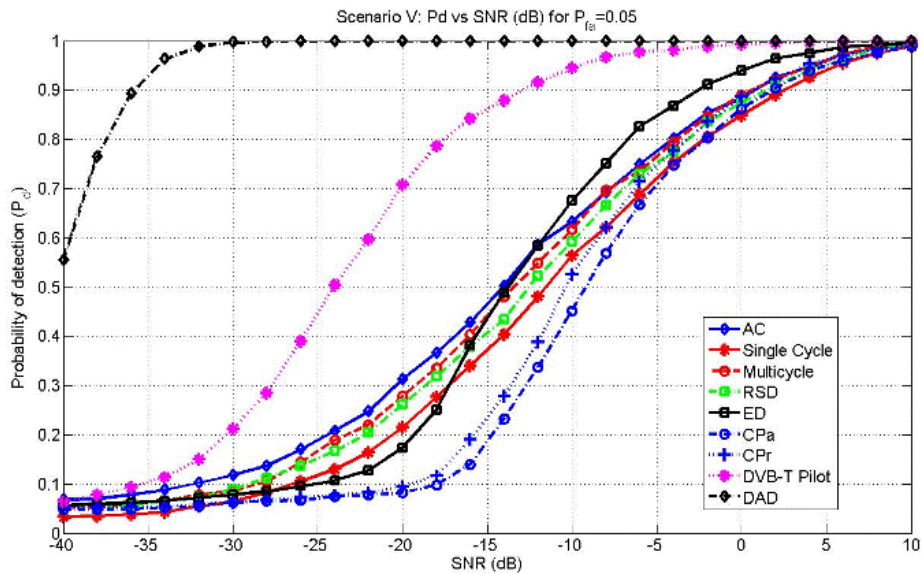


Figure 6. P_d vs. SNR (dB) curves for AWGN+Shadowing Channel and sensing time = 1.12 ms

Observations from Figure 6 and Figure 7:

- i. Detection performance of all detectors degrade in the presence of Shadowing. Therefore cooperative detection becomes necessary to overcome the shadowing effect.
- ii. Even in the case of Shadowing, DAD has the highest probability of detection. However again, it has serious issue with controlling false alarms

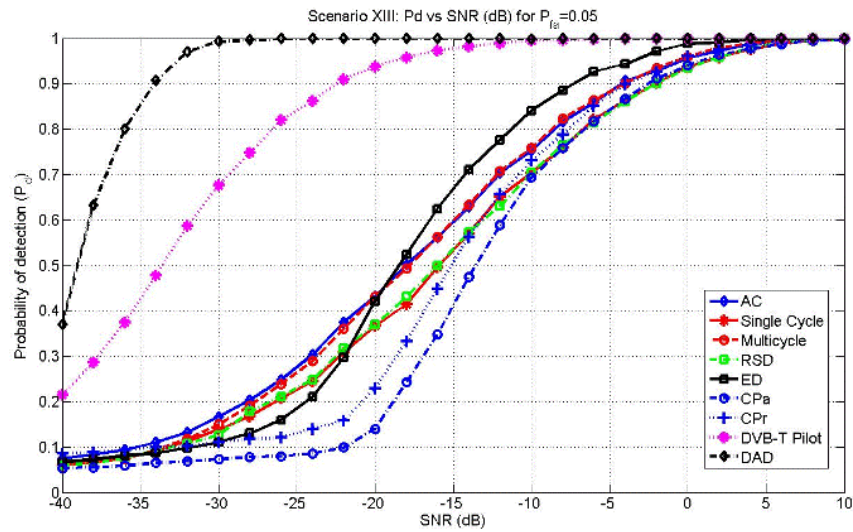


Figure 7. P_d vs. SNR (dB) curves for AWGN+Shadowing Channel and sensing time = 10ms.

- iii. DVB-T pilot has good performance in presence of shadowing. Even the false alarm rate is under constraint for low sensing time. However for large sensing time, false alarm constraint is not met.
- iv. ED is able to meet false alarm constraints in the presence of shadowing.

4.1.2.3 Rayleigh

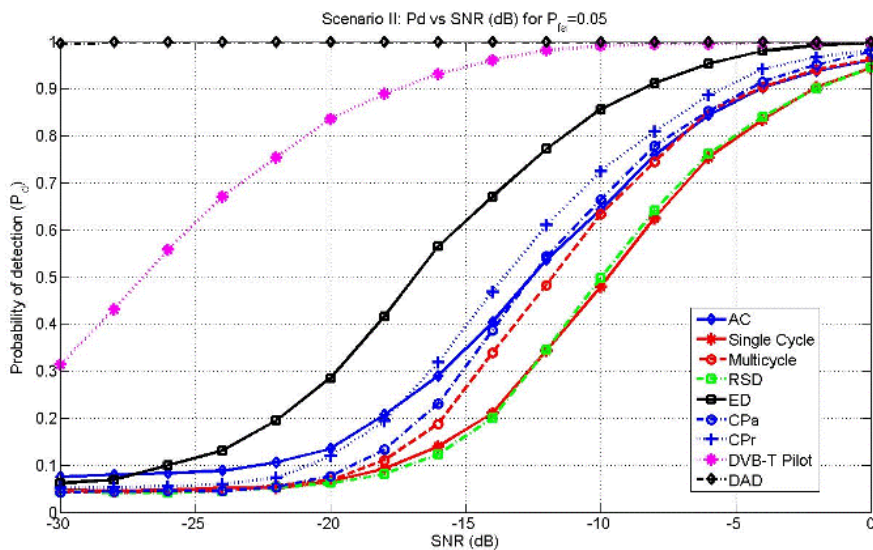


Figure 8 P_d vs. SNR (dB) curves for Rayleigh Channel and sensing time = 1.12 ms

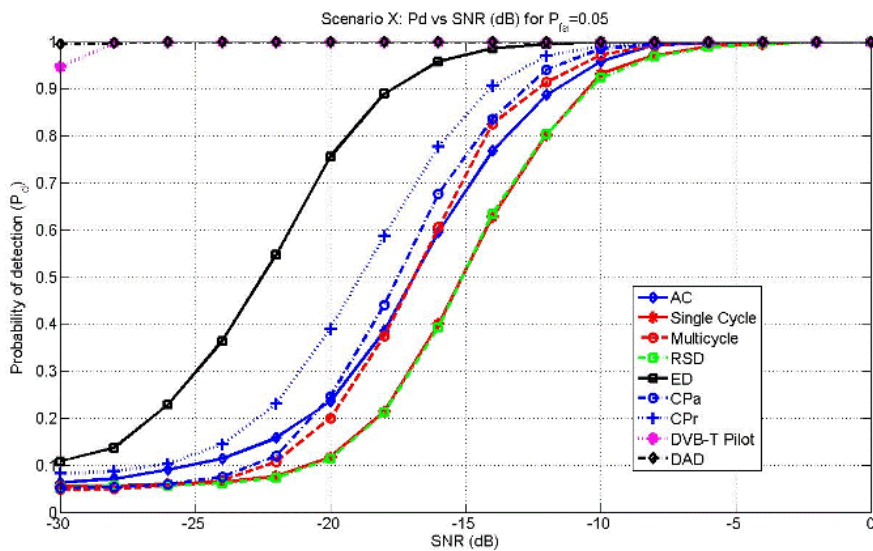


Figure 9 P_d vs. SNR (dB) curves for Rayleigh Channel and sensing time = 10 ms

Observations from Figure 8 and Figure 9:

- (i) There is significant deterioration in detection performance of all detectors except DAD and DVB-T pilot detector in presence of multipath. Therefore cooperation among the neighbouring sensors in network becomes important to mitigate the channel effect as is done in SENDORA.
- (ii) ED is not able to satisfactorily constraint false alarm rate in SNR regime of interest for sensing time 10ms.
- (iii) All other observations are similar to those made for Figs. 4 and 5.

4.1.2.4 Rayleigh + Shadowing

Sensing time: 1.12 ms

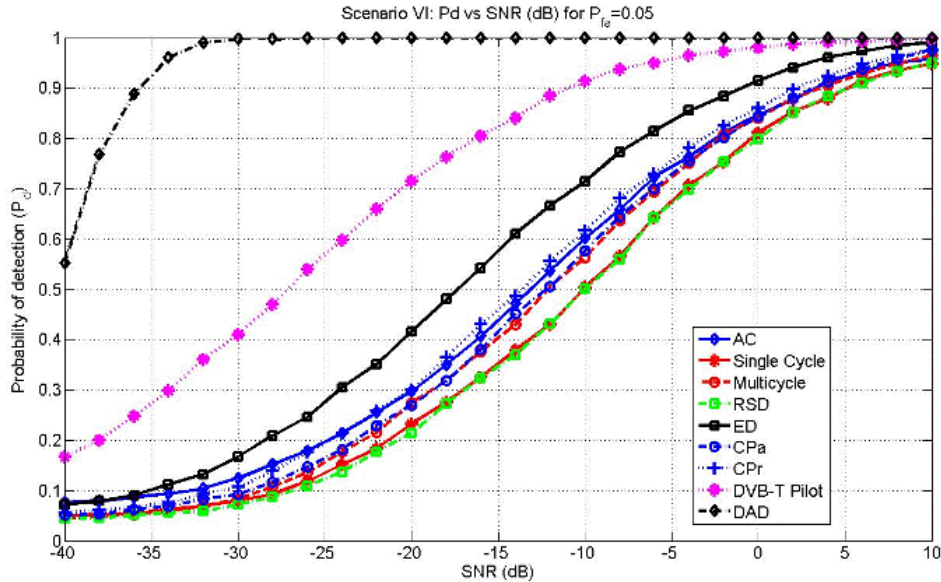


Figure 10 P_d vs. SNR (dB) curves for Rayleigh+Shadowing Channel and sensing time = 1.12 ms

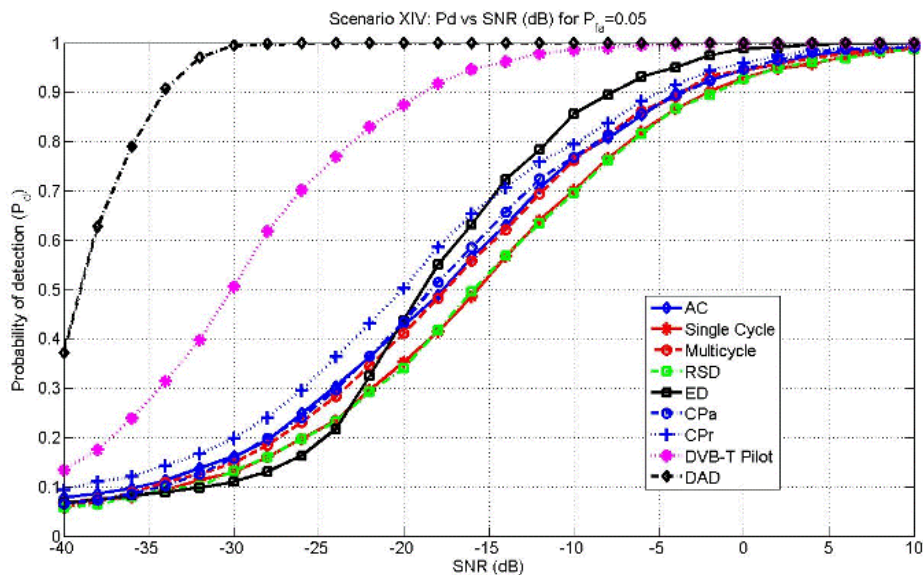


Figure 11. P_d vs. SNR (dB) curves for Rayleigh+Shadowing Channel and for sensing time = 10 ms

Observations from Figure 10 and Figure 11:

- (i) In presence of shadowing, the detection performances of all detectors degrade.
- (ii) ED is able to constraint false alarm rate in SNR regime of interest in the presence of shadowing.

4.1.2.5 Rician (K=1)

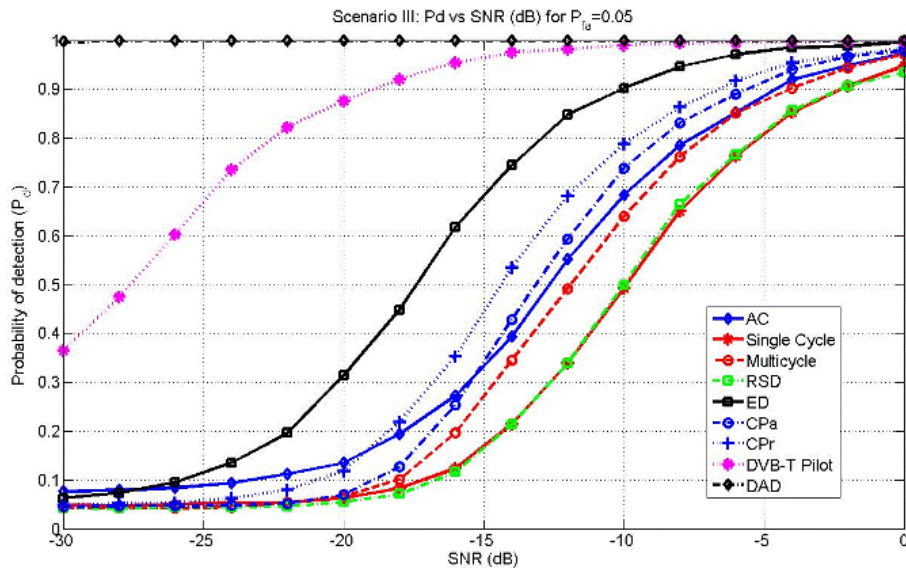


Figure 12 P_d vs. SNR (dB) curves for Rician (K=1) Channel and sensing time = 1.12 ms

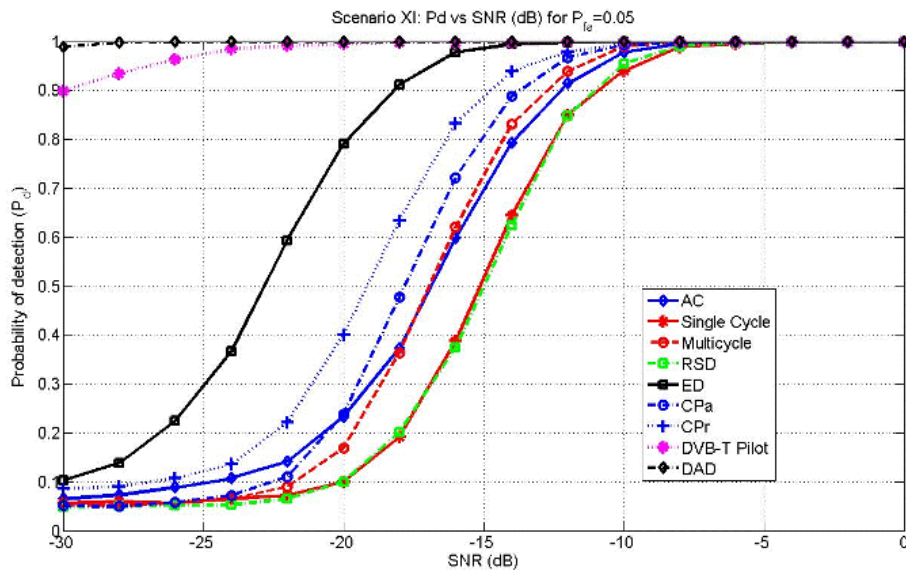


Figure 13. P_d vs. SNR (dB) curves for Rician (K=1) Channel and sensing time = 10 ms

Observations from Figure 13 and Figure 14:

- (i) Although the performance of all detection schemes, except DAD and DVB-T, is poor for low sensing time, the performance improves when sensing time increases to 10ms.
- (ii) ED is not able to constraint false alarm rate in SNR regime of interest for sensing time of 10ms.

4.1.2.6 Rician (K=1) + Shadowing

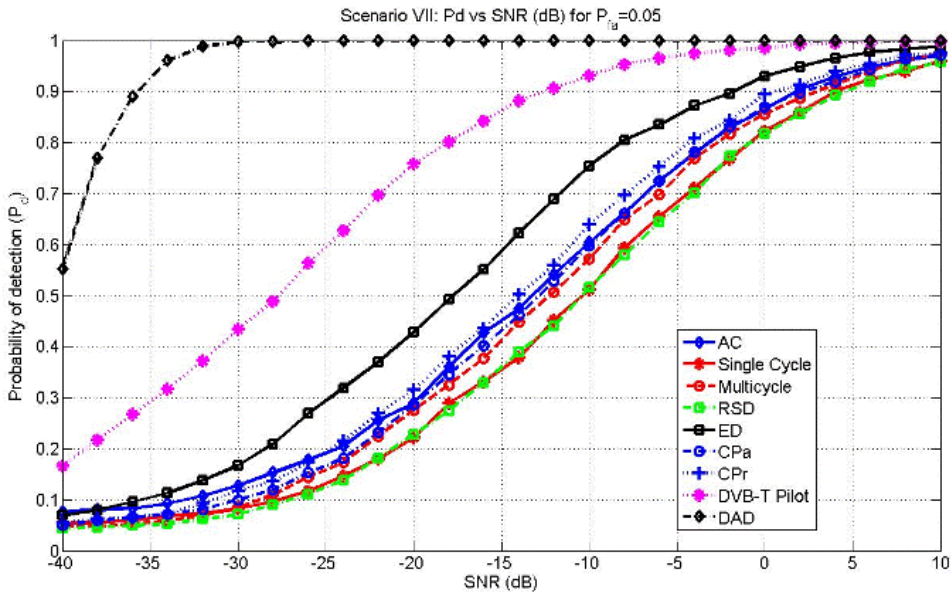


Figure 14. P_d vs. SNR (dB) curves for Rician (K=1)+Shadowing Channel and sensing time = 1.12 ms

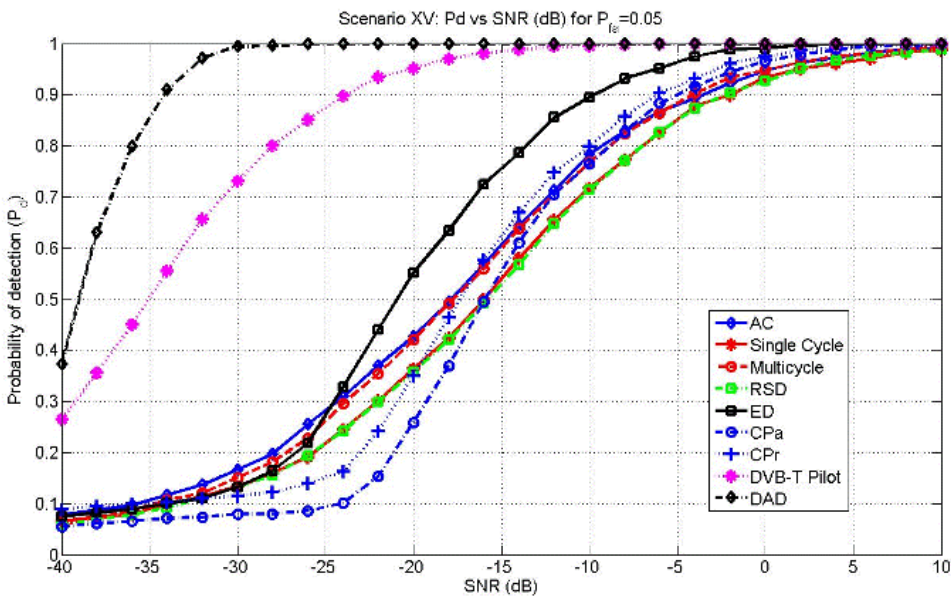


Figure 15 P_d vs. SNR (dB) curves for Rician (K=1) + Shadowing Channel and sensing time = 10 ms

Observation from Figure 14 and Figure 15:

- (i) Shadowing has a negative effect on the detection performance. Increasing sensing time helps overcome this effect. Another solution is to use cooperation.
- (ii) ED is able to constraint false alarm rate in SNR regime of interest in the presence of shadowing.

4.1.2.7 Rician (K=10)

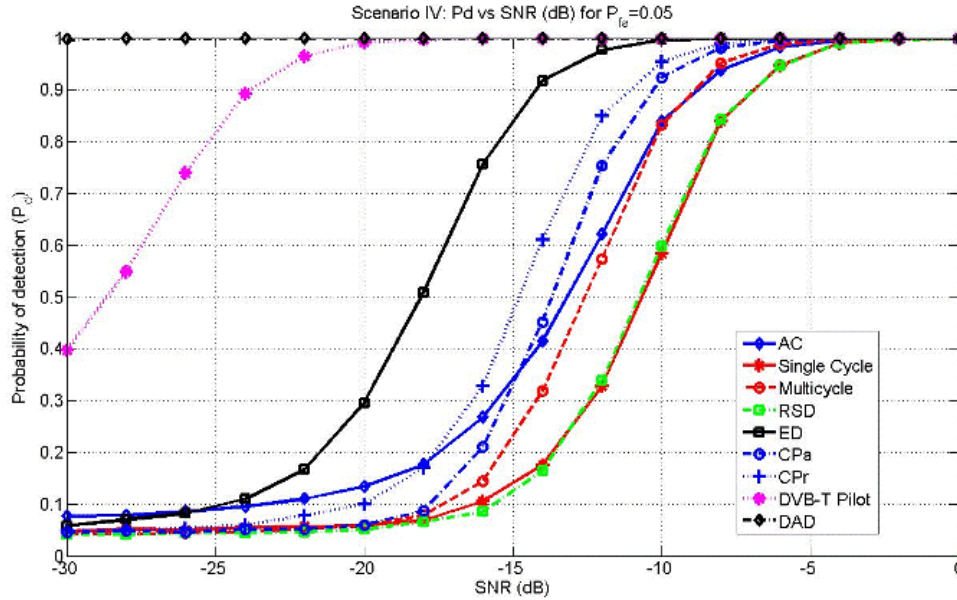


Figure 16 P_d vs. SNR (dB) curves for Rician (K=10) Channel and sensing time = 1.12 ms

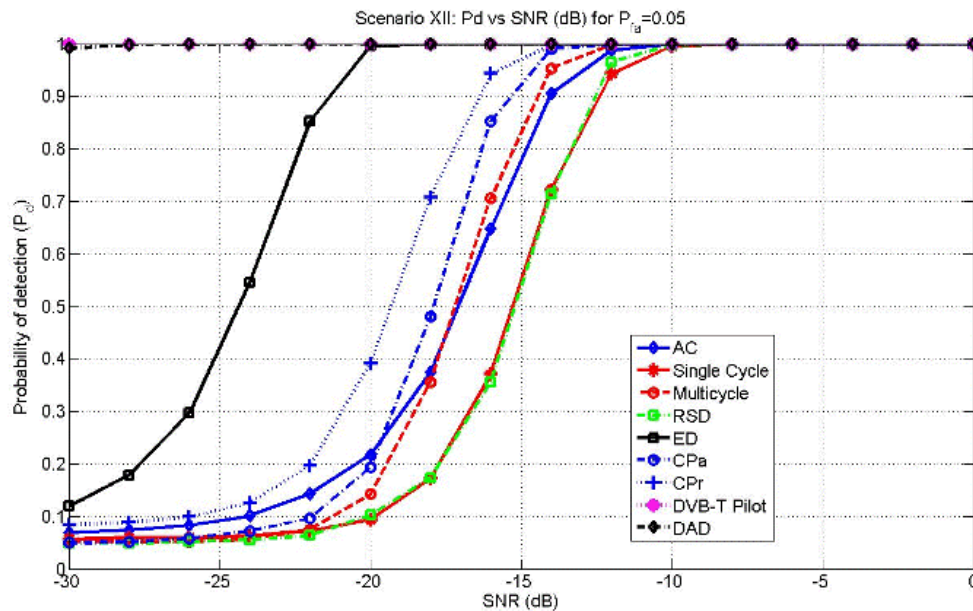


Figure 17 P_d vs. SNR (dB) curves for Rician (K=10) Channel and sensing time = 10 ms

Observation from Figure 16 and Figure 17 are similar to those for earlier figures.

4.1.2.8 Rician (K=10)+Shadowing

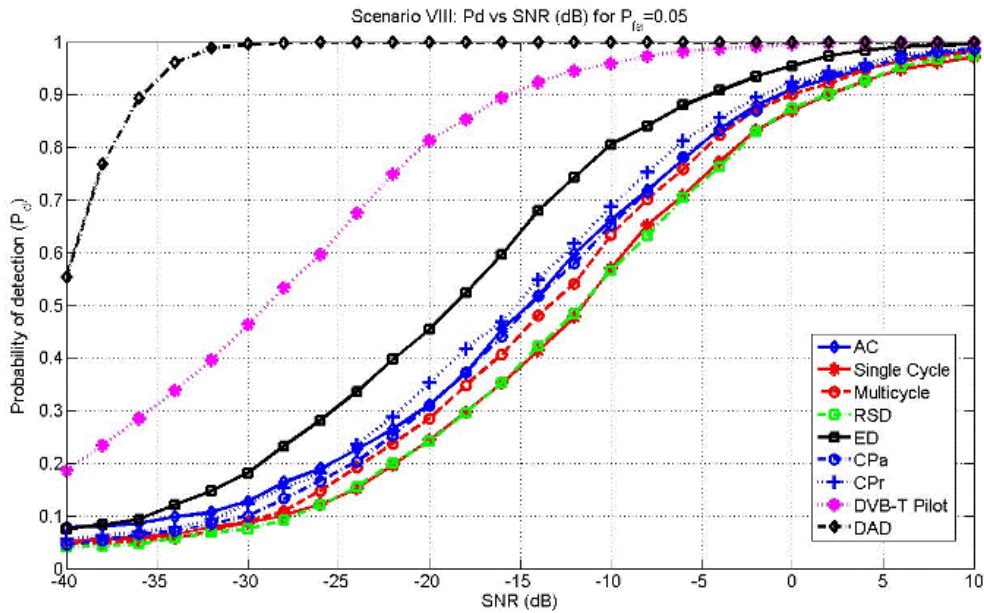


Figure 18 P_d vs. SNR (dB) curves for Rician (K=10)+Shadowing Channel and sensing time = 1.12 ms

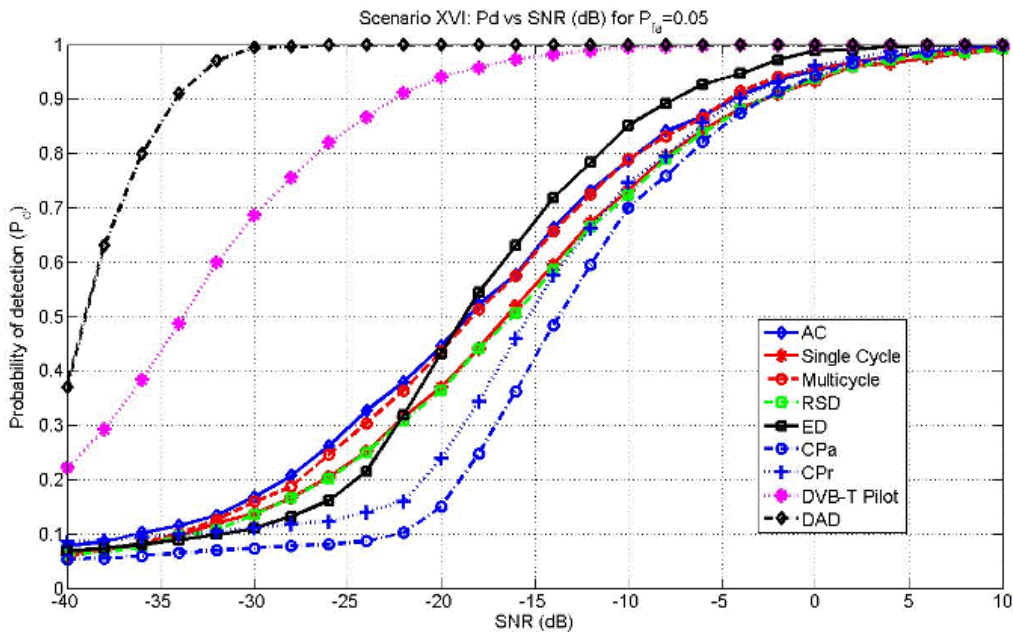


Figure 19 P_d vs. SNR (dB) curves for Rician (K=10) +Shadowing Channel and sensing time = 10 ms

Observation from Figure 18 and Figure 19 are similar to those for earlier figures.

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General Observations from Pd vs SNR Curves:

- (i) Detection performance improves with the increase in sensing time.
- (ii) Detection performance degrades in the presence of Multipath and Shadowing. However cooperation among different sensors in SENDORA sensor network will help in overcoming the channel effects. Cooperation also allows each sensor to be simpler without compromising the overall detection performance.
- (iii) DAD, DVB-T have the highest probability of detection followed by ED. These detectors are followed by detectors AC, Multicycle, CPa, CP_r which have comparable performance. RSD and SingleCycle have lowest probability of detection for the given scenarios.
- (iv) DAD, and DVB-T have serious issue of controlling false alarm in SNR regime of interest. ED also exhibits this issue slightly for sensing time of 10ms in the absence of shadowing. All other detectors have excellent ability of maintaining the constraint on false alarm.
- (v) From simulations results, authors [Zayen2008] claim that the DAD performs better than ED and DVB-T Pilot in terms of probability of detection. The DAD detector estimates the distribution of the primary user received signal to detect the existence/non existence of data signal. These results demonstrate that the DAD detector has very high probability of detection even at low SNR. According to [Zayen2008], the results also suggest that the Akaike information criterion (AIC) used as model selection tool for this detector have a very promising issues within the framework of blind sensing.

4.1.3 Receiver Operating Curves (ROC)

In this section, we present ROC curves (P_d vs. P_{fa}) for channel scenarios I-IV for SNR = -8, and -12 dB.

4.1.3.1 AWGN Channel

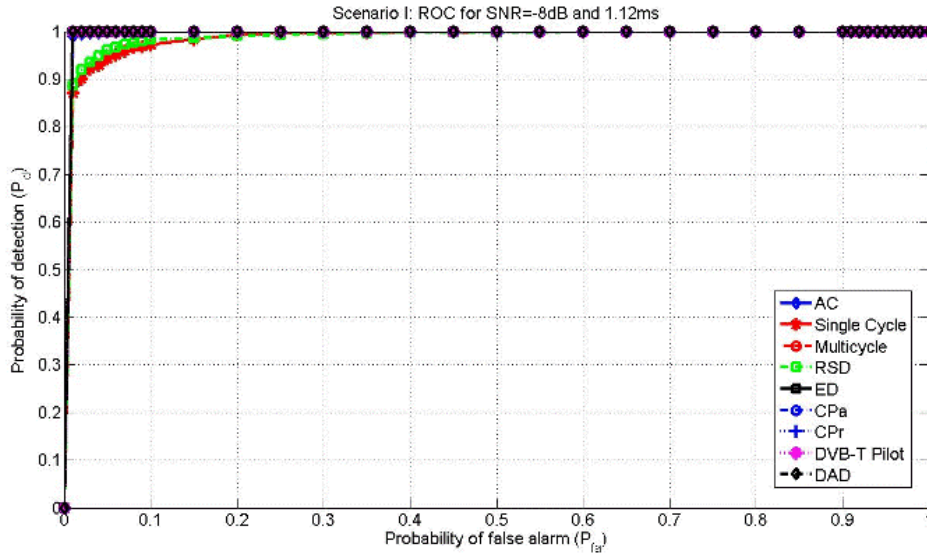


Figure 20 ROC Curves for AWGN Channel, SNR=-8, and sensing time = 1.12ms

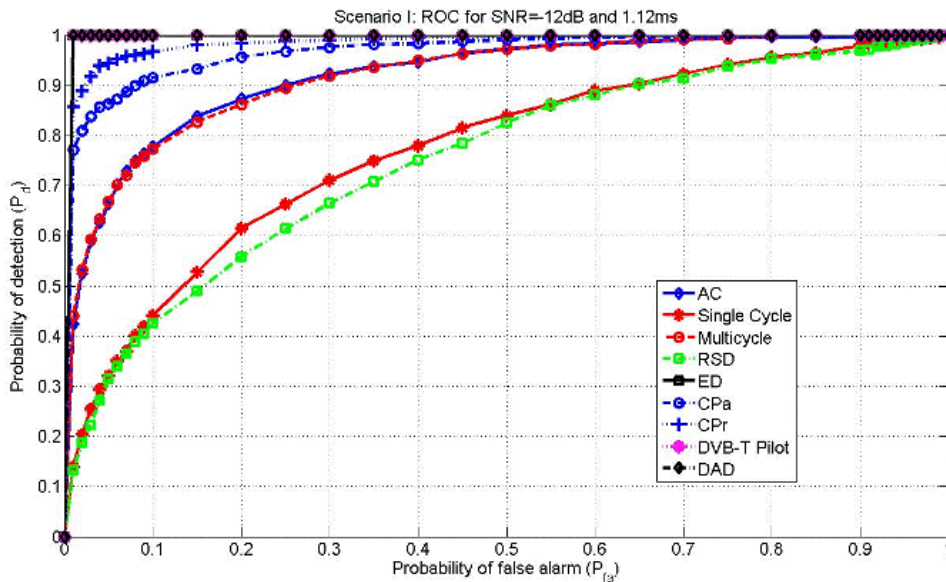


Figure 21 ROC Curves for AWGN Channel, SNR=-12 dB and sensing time = 1.12ms

From Figure 20 and Figure 21, it can be observed that all detectors perform quite well for SNR=-8dB and sensing time of 1.12 ms for AWGN scenario. However, the performance deteriorates with decrease in SNR for detectors AC, SingleCycle, MultiCycle, CPa, CPr and RSD. Comparative performance of the detectors is similar to P_d vs. SNR curves.

4.1.3.2 Rayleigh Channel

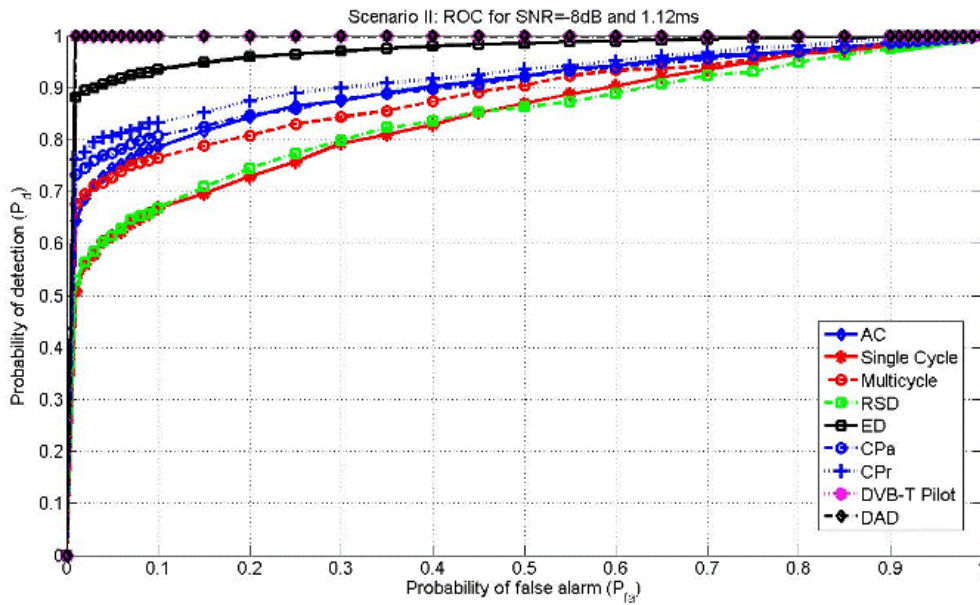


Figure 22 ROC Curves for Rayleigh Channel, SNR=-8dB and sensing time = 1.12ms

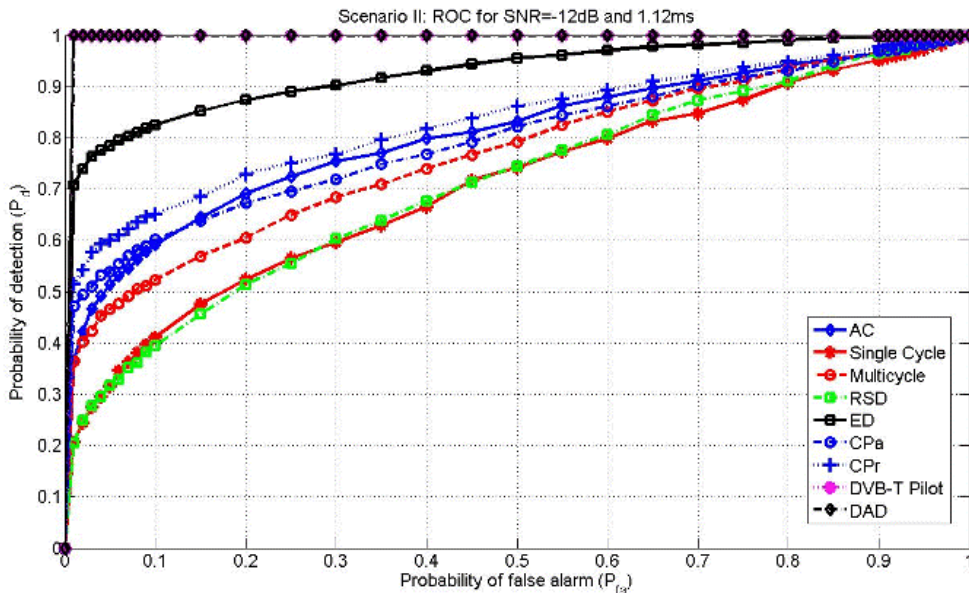


Figure 23 ROC Curves for Rayleigh Channel, SNR=-12 dB and sensing time=1.12ms

From Figure 22 and Figure 23, it can be observed that the performance of all detectors deteriorates in presence of Rayleigh channel.

4.1.3.3 Rician Channel (K=1)

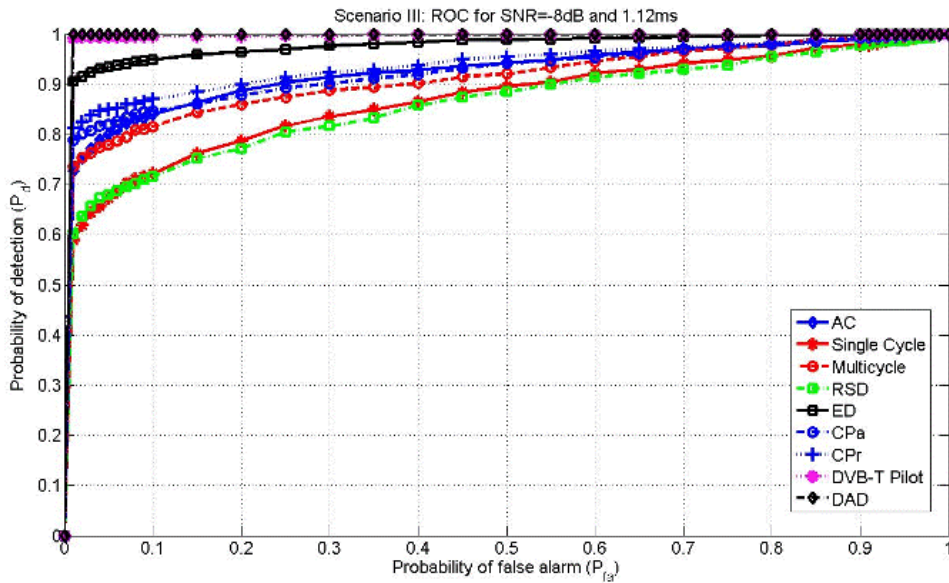


Figure 24 ROC Curves for Rician Channel (K=1), SNR=-8 dB and sensing time=1.12ms

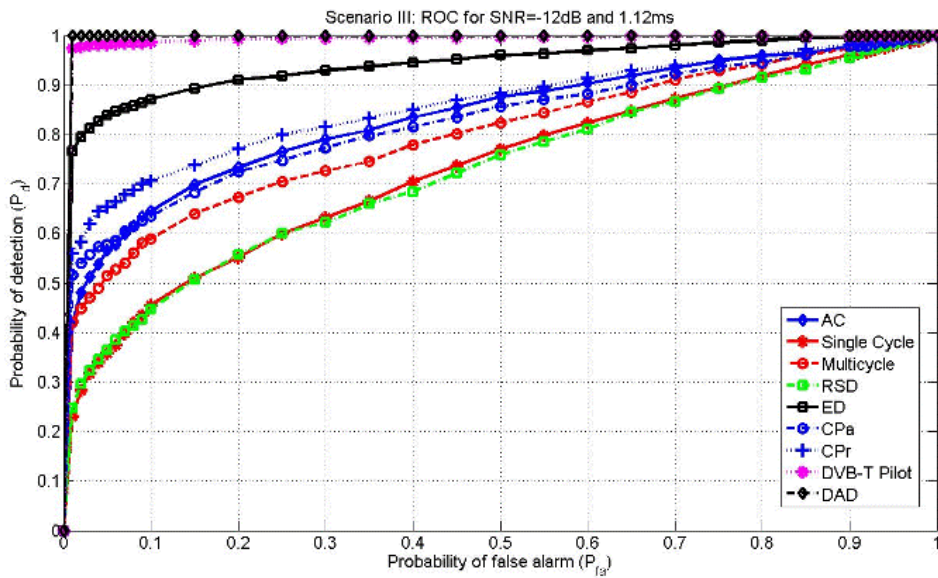


Figure 25 ROC Curves for Rician Channel (K=1), SNR=-12 dB and sensing time = 1.12ms

From Figs. 24 and 25, there is performance deterioration for Rician Channel (K=1) for detectors ED, CPa, CPr, specially for SNR=-12dB.

4.1.3.4 Rician Channel (K=10)

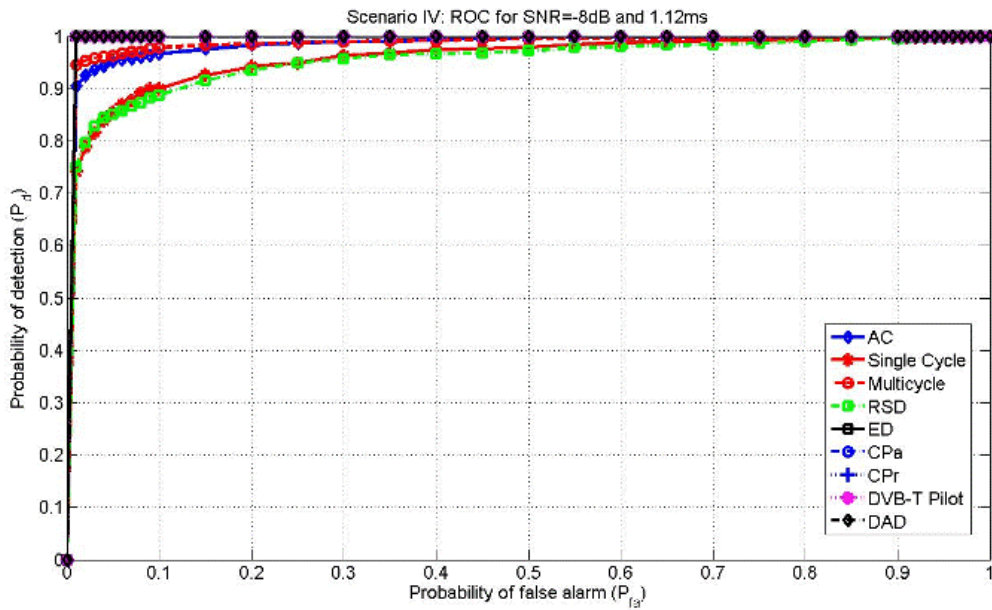


Figure 26 ROC Curves for Rician Channel (K=10), SNR=-8 dB and sensing time=1.12ms

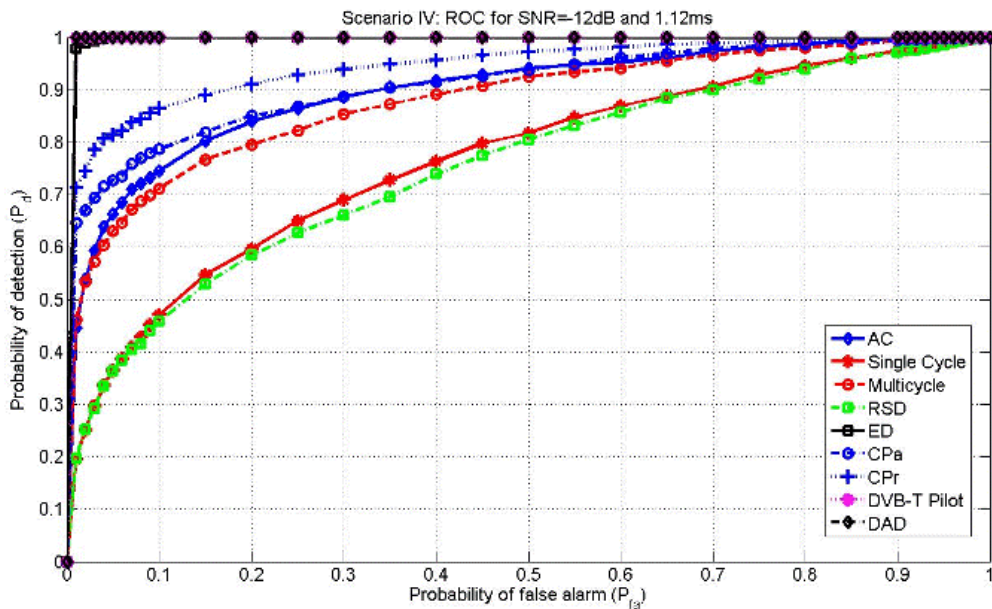


Figure 27 ROC Curves for Rician Channel (K=10), SNR=-12 dB and sensing time = 1.12ms

The general observations from figs. 26 and 27 for Rician Channel (K=10) are similar to that in case of Rician Channel (K=1). However, if we compare the curves in figs. 24 and 26, the performance of detection schemes are better for K=10 as compared to K=1.

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4.1.4 Noise Uncertainty

Noise uncertainty graphs are obtained for values of ρ (see Section 3.3.4) equal to 1 dB and 2 dB. To obtain curves usually the threshold is calculated for the least value of the noise variance and the detection is performed for the biggest value of the noise variance. Note that the uncertainty means that the noise variance can attain values in the interval $[\sigma_n^2 / \rho, \rho \sigma_n^2]$. For the algorithms which do not calculate the threshold for the test statistics based on the noise variance this uncertainty does not influence the performance. We have investigated the change of the performance for the ED, the CPa and CPv detectors as well as the DVB-T pilot detector. The curves for 0 dB (no noise uncertainty) are included for comparison. In the case of the DVB-T pilot detector we have also included a curve for the 10 dB noise uncertainty case to give a better idea of the value of the “SNR wall” of the algorithm.

Figure 28 shows that the ED suffers considerably by even small values of noise floor uncertainties. This makes this algorithm very unreliable in situations where good estimation of the noise floor is not available. The figure shows that the probability of detection vanishes when the SNR is becoming very small if the noise uncertainty is positive. The values of the SNR where a rapid transition from close to zero to close to one occurs indicate the “SNR wall” [Tandra2008] for the corresponding noise uncertainty level.

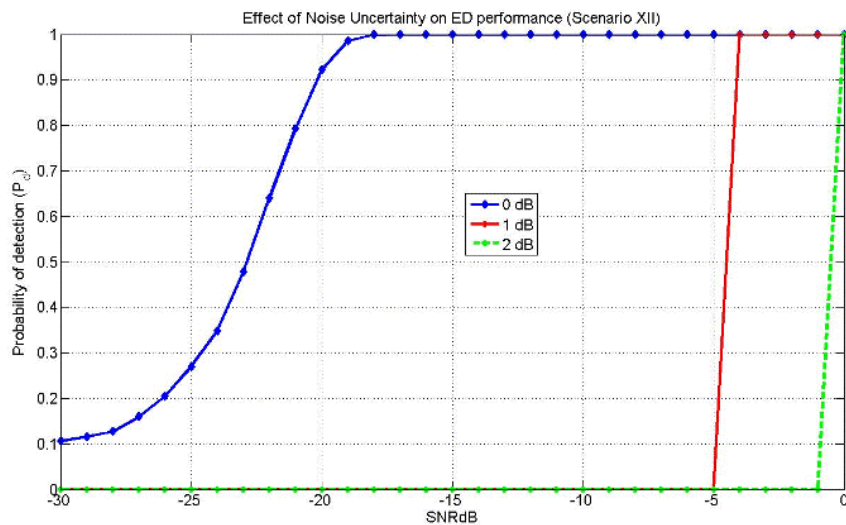


Figure 28 Effect of Noise Uncertainty for Energy Detector for AWGN Channel, Sensing time=10ms.

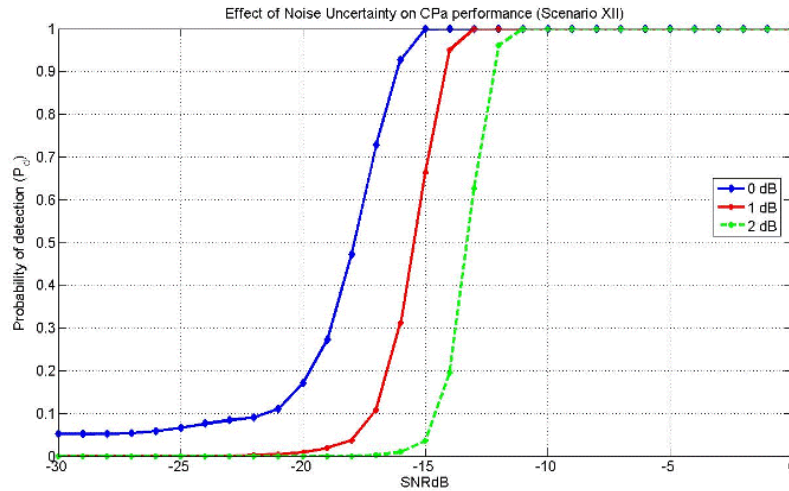


Figure 29 Effect of Uncertainty on CPa detector for AWGN channel and sensing time=10ms

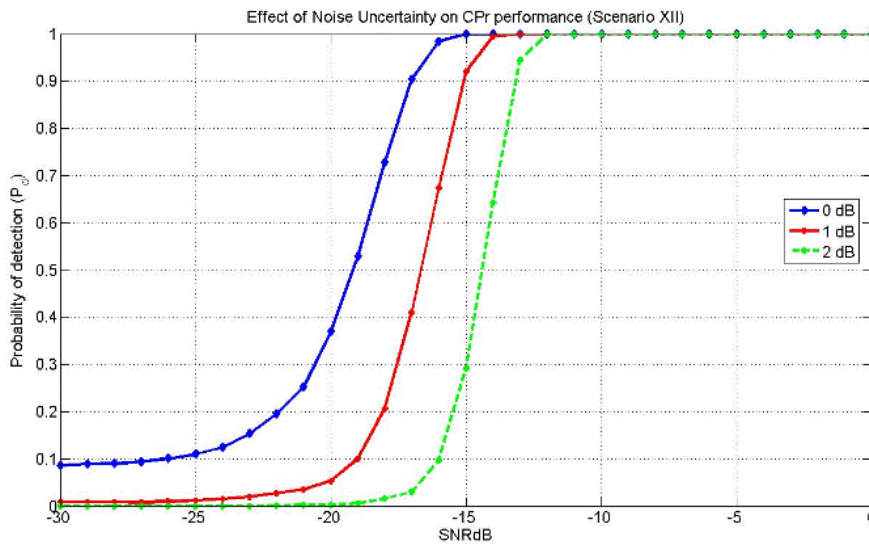


Figure 30 Effect of Uncertainty on CPr detector for AWGN channel and sensing time=10ms

Figs. 29 and 30 show that the losses in performance of the CPa and CPr algorithms are not severe which makes them more suitable choice for the detection purposes in the face of noise level uncertainty.

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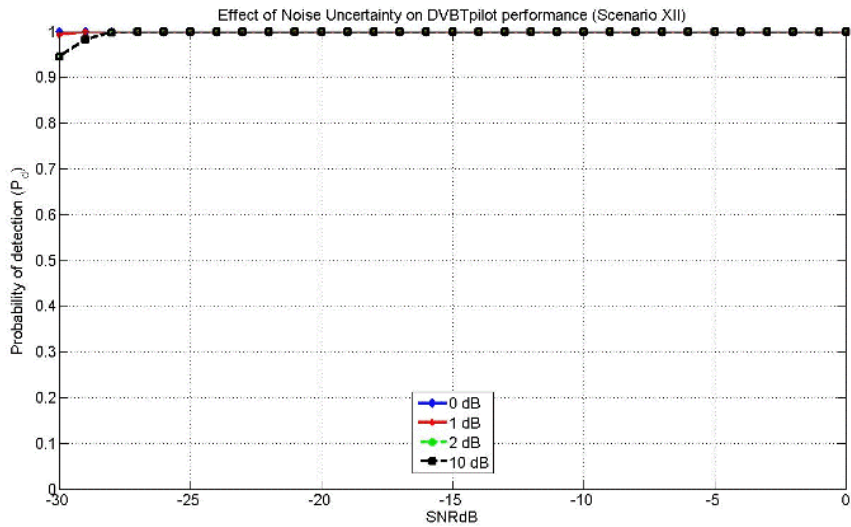


Figure 31 Effect of Uncertainty on DVBT Pilot detector for AWGN channel and sensing time=10ms

The DVB-T algorithm seems to be the most robust amongst the detectors which assume knowledge of noise variance. It can be mentioned that even at 10 dB of noise uncertainty this algorithm can detect signals for SNRs of around -15 dB.

Thus, it can be seen that the noise uncertainty leads to performance loss, the most severe case being ED. This emphasizes the need for estimating noise power from a signal free data for the detection methods ED, CPa, and CPr.

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4.1.5 Robustness

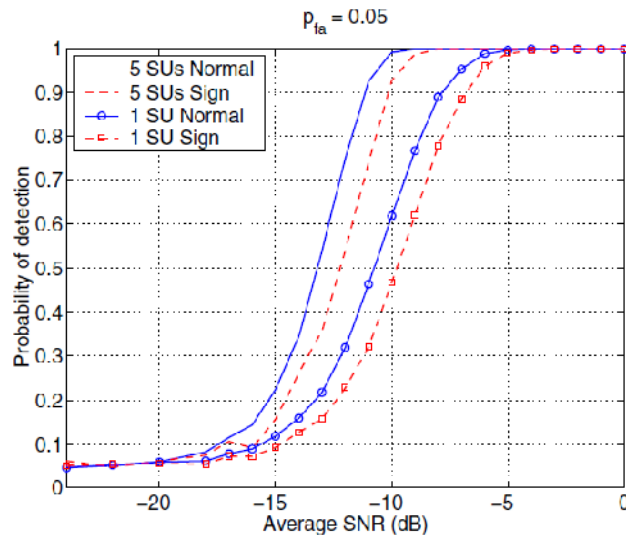


Figure 32 Probability of detection curve for Normal and Sign Cyclic Correlation detector for Gaussian Noise.

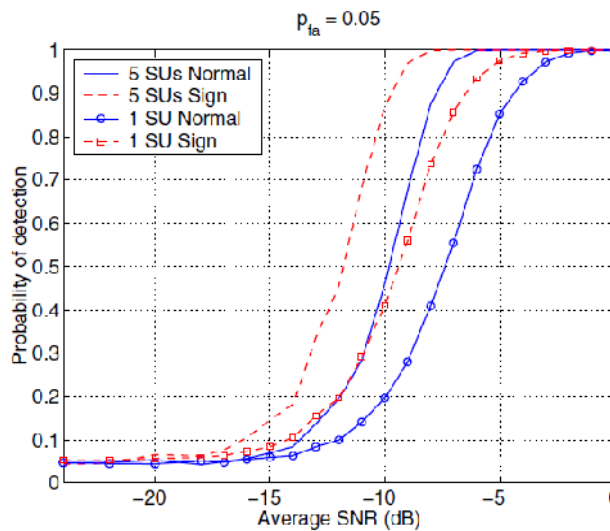


Figure 33 Probability of detection vs. SNR in presence of Gaussian noise corrupted by impulsive noise

In this section we present some results from [Lunden2008] to stress the importance of robustness issue. Fig. 32 shows the probability of detection curves as a function of average SNR in Rayleigh fading channel with AWGN. PU signal is OFDM Signal (DVB-T). The curves are for Normal Cycle detector and Robust Sign Detectors (RSD) for 1 and 5 SUs. Sign cyclic correlation suffers small degradation as compared to the classical cyclic correlation estimator in Gaussian noise. Fig. 33 shows probability of detection for the case when additive noise is contaminated Gaussian distribution $0.95N_c(0, \sigma^2) + 0.05N_c(0, 25\sigma^2)$. From the results, it is clear that RSDs are more robust to impulsive noise as compared to the classical cyclic detector. Robust detector is nonparametric method and maintains its performance and robustness regardless of the underlying noise distribution. It trades off optimality to robustness under uncertainty in noise and interference statistics.

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4.1.6 Complexity

In this report, the complexity of the algorithm is measured through the number of complex multiplications/divisions that the algorithm has to perform for the calculation of the test statistics. Algorithms where search or max/min functions are involved, their number is also indicated. Note that the complexity of estimating the nuisance parameters like noise variance is not included in this part and it may be significant. This is true for the detectors ED, CPa, CPr, and DVB-T pilot which assume that noise variance is known. In addition, the noise variance may be time varying and it is important to estimate this parameter reliably.

We assume that the number of the received samples during the sensing period is M . We also assume that in the case of detection of OFDM signals the length of the cyclic prefix is T_c and the length of the OFDM block is T_d . In order to give an idea of the complexity of the studied algorithms we provide a table with the corresponding values for the case of detection of the 8 MHz DVB-T signal. Note that this values are approximate. For the simulations, $M=10240$ for 1.12ms and $M=91429$ for 10 ms, $L=2049, T_c=512$, and $T_d=2048$. Number of Cyclic frequencies for Multicycle=7, and number of sliding windows corresponding to 8 MHz for DAD is 18.

Detector	Multiplications (complex)	Divisions	Search Operations
Autocorrelation Detector (AC)	$2(M - T_d)$	1 (real)	0
SingleCycle and Multicycle	$(2M + 4L) \cdot \text{Number of Cyclic Freqs.} + 0.5 \cdot M \cdot \log_2(M)$	0	0
Robust Sign Detector (RSD)	$4M$	M (complex)	0
Energy Detector (ED)	M	0	0
Cyclic Prefix Sliding Correlation (CPa and CPr)	$M - T_d$	0	1
DVBT Pilot	$4M(T_c + T_d)$	0	1
Distribution Analysis Detector (DAD)	$4M + 18 \cdot \log_2(M/18)$	0	0

4.1.7 Detecting different PU signals

Detectors such as ED, SingleCycle Multicycle, RSD and DAD can detect all kinds of PU signals. Detectors based on cyclic prefix like AC, CPa and CPr can detect all kinds of OFDM based PU signals like DVB-T, WLAN, and LTE. However they cannot detect CDMA based system like UMTS. The matched filter detector (DVB-T pilot) can detect only DVB-T signal.

4.1.8 Distinguishing different waveforms

Cyclostationarity based detectors like SingleCycle, Multicycle, and RSD can distinguish between different types of waveforms: PU signal, SU signal, noise, or interference. This is possible as each of them have different cyclostationarity features. Detectors like AC, CPa and CPr can differentiate between different OFDM signals as different OFDM standards have different values of symbol and cyclic prefix duration. Blind detectors like ED and DAD cannot distinguish between different waveforms at all.

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5 SUMMARY

In this section a summary of the spectrum sensing algorithm evaluation is provided. A qualitative rating denoted by '*' (*****-best to *-worst) is used in the evaluation instead of quantitative one because there is no feasible quantitative scaling of the performance that could be used for all the spectrum sensing techniques considered. The criteria used in the evaluation are

- Probability of detection
- False alarm control
- Complexity
- Underlying assumptions on PU signal
- Effect of noise level uncertainty
- Ability to distinguish among PUs and SUs
- Robustness
- Applicability to detect different PU signals

Probability of detection is an important criterion since it defines how weak signals can be detected and how much missed detections may take place. The ability to detect weak signals means that the detection distance may be longer and in the SENDORA scenario, fewer sensors would be needed in any specific area. Long detection distance is also useful in interference management since it allows identifying and avoiding areas of harmful interference more effectively. Missed detections, on the other hand will lead to collisions with PU transmissions and reduce the rate and quality of service (QoS). In order to strictly control the probability of detection or missed detection, analytical work in establishing the distribution of the decision statistics under is commonly required.

Controlling the false alarm probability is equally important criterion. If there are too many false alarms, the spectrum appears to be occupied and spectrum opportunities are overlooked. Consequently, the benefits of cognitive radio systems in terms of flexible spectrum use are not achieved. Therefore, high performance in detecting PU transmissions does not mean reliable performance for the spectrum sensing system unless the false alarm rate can be maintained at tolerable level. Controlling the rate of false alarms strictly requires commonly analytical work in establishing the distribution of the decision statistics. It is important to consider both the detection probability and false alarm probability simultaneously when designing spectrum sensing algorithms.

The underlying assumptions on PU waveforms may be very explicit, for example, we may be detecting known signal in noise. In such case, very weak signals may be detected rapidly. Obviously, such detectors are not applicable to other waveforms. This is important if PU system is using adaptive modulation and coding or has many different operating modes. Consequently, the detector may end up searching for a good number of different known signals in noise. In the other extreme case, we may have no prior information about the PU waveform and we are detecting random signals in noise. Accurate specification of the noise power level is crucial then in order to obtain reliable detector performance and avoid SNR wall phenomenon. Detector structures that rely on statistical or structural properties of PU signal are applicable to wide variety of PU waveforms.

In general, some detectors assume that noise distribution and its parameters are explicitly known and their performance is optimal or close to optimal when this assumption is valid. The performance of such detectors deteriorates rapidly even for small departures from the underlying assumptions. Nonparametric or robust detectors on the other hand make no such assumptions

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and maintain their reliable performance in all conditions. There is a trade-off between robustness and optimality and robust techniques exchange the optimality to reliability.

The ability to distinguish among different PU waveforms is necessary because many different types of signals may be sharing the spectrum or PU may use many different transmission modes depending on the channel conditions and the sensor should be able to decide whether PU is active, there is interfering signal present in the band of interest or there is noise only in the observed data. This is important also in the process of exploiting the underutilized spectrum since we need to ensure that the PU is protected from harmful interference whereas we may be competing for the spectrum with other secondary users.

Low complexity detectors are desirable since they are cheaper to manufacture and are typically more energy efficient. The latter is important especially if the spectrum sensors are battery operated, as in the ad-hoc mobile scenario considered in SENDORA.

Following table summarizes the quantitative performance of various detectors for different evaluation criteria for the same sensing time and SNR:

Detector-> Criterion	ED	AC	CPa	CPr	Multicy cle	DAD	DVB-T Pilot	RSD
Probability of Detection	****	***	***	***	***	*****	*****	**
False alarm control	***	*****	*****	*****	*****	*	*	*****
Complexity	*****	*****	****	****	**	**	*	***
Assumption of PU signal	*****	***	**	**	****	***	*	****
Effect of noise variance uncertainty	*	*****	***	***	*****	*****	****	*****
Distinguish between PU signals	*	***	***	***	*****	*	*	*****
PU that can be detected	*****	***	***	***	*****	*****	*	*****

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Based on the comparison table, we now discuss pros and cons of each detection scheme:

1. **Energy Detector:**

Pros:

- i. Simple detector
- ii. Optimal for random signal in noise when noise variance is known.
- iii. Detects all kinds of PU signals.
- iv. Does not need any information on PU signals.
- v. Threshold for the detector can be set theoretically.

Cons:

- i. Highly susceptible to noise variance uncertainty.
- ii. Cannot distinguish between different kinds of waveform: PU signal, SU signal, interference, or noise.

2. **Autocorrelation based detector**

Pros:

- i. Low complexity detector
- ii. Excellent false alarm control
- iii. Robust to noise uncertainty.
- iv. As distribution of test statistic is known for null hypotheses, threshold can be set theoretically.

Cons:

- i. Detects only OFDM based PU signal.

3. **Cyclic Prefix correlation based detectors CPa, CPr**

Pros:

- i. Low complexity detector
- ii. Good false alarm control.

Cons:

- i. Detects only OFDM based PU signal.
- ii. Slight deterioration in the presence of noise uncertainty.
- iii. Threshold has to be found empirically.

4. **Cyclostationarity based SingleCycle and Multicycle detectors**

Pros:

- i. Excellent false alarm control
- ii. Robust to noise uncertainty.
- iii. Can distinguish between different waveforms: PU signals, SU signals, interference and noise.
- iv. Can detect all kinds of PU signals.
- v. Threshold can be calculated offline using established distributions of test statistic under null hypothesis.

Cons:

- i. Although complexity is a issue, it is tolerable

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5. *Distribution Analysis Detector:*

Pros:

- i. Highest probability of detection in low SNR regime.
- ii. Can detect all kinds of PU signals.
- iii. Robust to noise uncertainty

Cons:

- i. High false alarm rate in SNR regime of interest.
- ii. High Complexity.
- iii. Cannot distinguish among different waveforms.

6. *DVB-T pilot detector*

Pros:

- i. Excellent probability of detection.

Cons:

- i. Can only detect DVB-T signal.
- ii. Highest complexity
- iii. Threshold has to be obtained analytically.

7. *Robust Sign Detector*

Pros:

- i. Robust to non-Gaussian noise.
- ii. CFAR detector.
- iii. Can detect all kind of PU signals.
- iv. Can distinguish different kind of waveforms
- v. Excellent false alarm control.
- vi. Threshold for the detector can be found theoretically.

Cons:

- i. Complexity is an issue, but tolerable.
- ii. Detection performance is poor as the detection scheme trades optimality to robustness.

It is clear from the performance comparison table and discussion on pros and cons of the detectors that no one detector is suitable for all scenarios. Instead, different detectors are suitable in different scenarios.

- i. Energy detection is best suitable when simpler detector is needed; noise variance is known and different kind of PU signals are to be detected.
- ii. DVB-T pilot detector is best suited only when DVB-T signal is to be detected.
- iii. AC detector is suitable when low complexity is required in presence of noise uncertainty to detect different OFDM signals reliably.
- iv. CPa and CPr detectors are performing similarly with a slight advantage for the CPr algorithm. They are suitable for detection of OFDM based signals in cases where the noise variance, the length of data duration and cyclic prefix are known.

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- v. Multicycle detector is suitable for the case when we need to distinguish different PU signals and with very less information on PU signals.
- vi. RSD detector is suitable for the case of detecting PU in presence of impulsive noise. It is also useful in distinguishing and detecting different waveform.
- vii. According to authors of [Zayen2008], DAD is best suitable when different kind of PU signals are to be detected in low SNR and in a blind way.

It has been observed from the simulation results that almost all the detection schemes are susceptible to channel conditions such as shadowing and multipath. The performance of a local detector degrades in the presence of such propagation effects. Cooperative detection helps mitigating these channel effects through multipath diversity. In case sensors are sufficiently displaced so that the channels have no correlation or the correlation is low, significant diversity gain may be obtained by the sensor network. The benefits of cooperative detection include: improvements in the detector performance, increase in the coverage, and simplification of the local detector design. Thus the need and the importance of cooperation among secondary users or sensors are evident which forms the basis of SENDORA architecture. The use of a sensor network with geographically displaced sensors for spectrum sensing is in the core of SENDORA framework because of the spatial diversity gains as well as fast sensing capability and energy efficiency benefits.

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