ECE 233 Wireless Communications System Design, Modeling, and Implementation.

Classification of unknown received signal into modulation types

By:

Akshay Joshi, UCLA

ABSTRACT

In standardized wireless systems, modulation classification can be performed through exhaustive search of known signal features. Most commonly used classifiers are based on the detection of cyclostationary features, which are second-order moments of a signal, related to its carrier and symbol rate. Blind modulation classifiers are vital in the sense that when signal parameters are not known, it becomes difficult for the normal methods to demodulate the signal without knowing the modulation type and modulation level. This project deals with the implementation and obtaining the results of the algorithms presented in the paper. The paper proposes techniques to classify any linearly modulated signal into different modulation schemes viz. M-QAM, M-PSK, M-ASK, and GMSK in addition to multi-carrier signals and spread spectrum signals. Although the paper provides extensive techniques to work on various modulation types, this project focuses primarily on multi-carrier/MC (OFDM), and single-carrier/SC (M-QAM, M-PAM) classification. Once it is classified into SC, the algorithm then further classifies the SC signal into M-QAM or M-PAM, and further breaks down to the modulation level i.e. 4-QAM, 16-QAM, or 2-PAM, 4-PAM. The project deals with the implementation of the algorithms and visualization of the results and performance in terms of probability of correct classification at various signal-to-noise ratios at each stage independently as well as of the entire classifier as an overall measure of performance.

SYSTEM MODEL

The system model includes a transmitter, a receiver, and an AWGN channel. The transmitter side comprises following blocks:

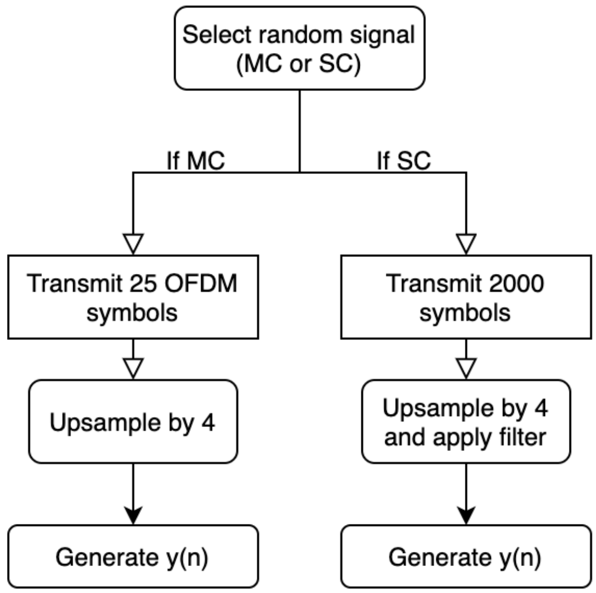

Fig. 1: Transmitter side

The transmitter randomly transmits one of the two types of signals; multi-carrier (MC) and single-carrier (SC). The MC signal is an OFDM signal with 64 subcarriers and cyclic prefix of 16 samples, and with a subcarrier spacing of 15.625 kHz. The SC signal can randomly be any one of the following types:

(a) 4-QAM
(b) 16-QAM
(c) BPSK / 2-PAM
(d) 4-PAM

A raised cosine filter is applied to the SC signal. The bandwidth of this transmitted signal $x(n)$ is 1 MHz. The symbol duration T is 1 µs and the symbol duration of 1 OFDM symbol is 80 µs. This $x(n)$ is upconverted to 2 MHz using the equation $y(n) = x(n)e^{j2\pi fcnTs} + w(n)$ with T_s being the sampling duration, $1/T_s$ = 4 MHz, and $w(n) \sim CN(0, \sigma^2)$ is the Gaussian noise. $y(n)$ is then transmitted across the AWGN channel. The received signal $y(n)$ is observed for 2ms at the receiver. From this information the number of SC symbols and OFDM symbols to be transmitted were found out to be 2000 and 25 respectively. Following is the receiver block diagram:

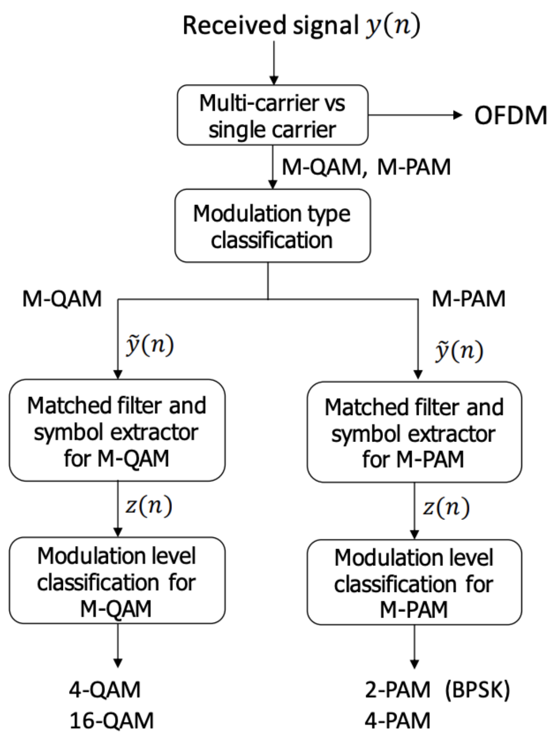

Fig. 2: Receiver side

The received signal is first classified as OFDM or SC by the MC-SC block. If it is classified as SC, it is further classified into its modulation type i.e. M-QAM or M-PAM by the modulation type classifier (MTC) block. From there, the modulation level classifier (MLC) block is used to identify the modulation level for either QAM (4-QAM or 16-QAM) or PAM (2-PAM or 4-PAM).

MAIN PART (ALGORITHMS & TECHNIQUES):

The receiver architecture is mainly divided into 3 blocks, MC-SC block which classifies between multicarrier and single carrier signals, MTC block which distinguishes between M-QAM and M-PAM signals if the input to the block is a SC signal, and the MLC block which behaves as a modulation level classifier, i.e., it classifies whether the input signal is 4-QAM or 16-QAM if it's a M-QAM signal or whether the input signal is 2-PAM or 4-PAM if it's a M-PAM signal.

1) MC-SC

The MC-SC block is based on a fourth-order cumulant which is like a Gaussianity test. The cumulunt C_{42} is computed as:

$$C_{42} = \frac{1}{N_m} \sum_{n=1}^{N_m} |y[n]|^4 - \left|C_{20}\right|^2 - 2{C_{21}}^2$$

where N_m is the number of samples used for distinguishing MC and SC signals, $y[.]$ is the received signal, $C_{20} = \frac{1}{N_m} \sum_{n=1}^{N_m} y[n]^2$, $C_{21} = \frac{1}{N_m} \sum_{n=1}^{N_m} |y[n]|^2$.

The property of cumulant C_{42} is that it tends to zero if the input samples are approaching Gaussian distribution. Since OFDM is a mixture of many subcarrier waveforms, its C_{42} statistic approaches zero. For other SC signals, C_{42} approaches a non-zero value. Using this technique, C_{42} is calculated which is a scalar quantity. Comparing this value with a threshold, the signal is classified as MC or SC. Following is a table that states the ideal C_{42} values for the different modulation types with a transmit filter of roll-off factor of 0.5:

OFDM	4-QAM	16-QAM	2-PAM/BPSK	4-PAM
0	-0.82	-0.52	-1.69	-1.1

Comparing the value of the obtained C_{42} with a certain threshold, it was possible to distinguish MC signals from SC signals, given that MC signals' C_{42} value approaches zero.

2) MTC block:

When the signal is classified as an SC signal, this block further classifies the received signal into modulation type; whether M-QAM or M-PAM. It uses cyclic-autocorrelation (CAC) function to determine their cyclostationary features. The conjugate and non-conjugate CACs can be computed as follows:

$$R_{x^*}(\alpha, v) = \frac{1}{N} \sum_{n=0}^{N-1} x[n]\, x^*[n-v]\, e^{-j2\pi\alpha n T_s}$$

$$R_{x}(\alpha, v) = \frac{1}{N} \sum_{n=0}^{N-1} x[n]\, x[n-v]\, e^{-j2\pi\alpha n T_s}$$

where v is the lag variable, T_s is the sampling period, α is the cyclic frequency, and N is a finite number of samples over which the CAC is to be calculated. Different modulation classes can be determined by the CAC function because the CAC has peaks at different locations of cyclic frequencies α which is a function of symbol rate (1/T) and carrier frequency (f_c). The modulation types are divided into 3 classes depending on the peak locations and cyclostationary properties. Class 1 consists of M-PSK (M>2) and M-QAM. Class 2 consists of M-ASK. And Class 3 comprises GMSK. Since this project is concerned with QAM and PAM modulations, Class 3 is not considered. Following is a table that states the location of the peaks of the CAC of each class in terms of T and f_c:

Modulation Class	Peaks at (α, v)
Class 1 (M-QAM)	$(1/T, 0)^*$
Class 2 (M-PAM)	$(1/T, 0)^*$, $(2f_c, 0)$, $(2f_c \pm 1/T, 0)$
Class 3	$(1/T, 0)^*$, $(2f_c \pm 1/2T, 0)$

Thus, combining these theoretical/ideal values, a feature vector of length 6 can be obtained as follows:

$$F = [\ |R_{x^*}(1/T,0)|, |R_{x^*}(2fc-1/T,0)|, |R_{x^*}(2fc-1/2T,0)|, \\ |R_{x^*}(2fc,0)|, |R_{x^*}(2fc+1/2T,0)|, |R_{x^*}(2fc+1/T,0)|\ ]$$

Because each element in the feature vector is proportional to the received signal power, feature vector is normalized to unit power, and compared to asymptotic/ideal normalized feature vectors V_i, $i \in [1,2,3]$ for each of the classes. For example, the normalized asymptotic feature vector for Class 1 (M-QAM) is $V_1 = [1,0,0,0,0,0]$, for Class 2 (M-PAM) is $V_2 = [0.5,0.5,0,0.5,0,0.5]$, for Class 3 is $V_3 = [0.5774,0,0.5774,0,0.5774,0]$ with peaks at the respective positions as stated in the table above represented appropriately in the respective feature vectors. The resulting feature vector calculated using the received signal is compared to each feature vector V_i, and the classifier picks the modulation class whose feature vector is closest to the one of the received signal in the least square sense. In this way, the MTC block classifies between M-QAM or M-PAM signals.

3) MLC block:

Once the signal is classified as M-QAM or M-PAM, MLC block, further breaks down the signal into its modulation level; whether 4-QAM, 16-QAM or 2-PAM, 4-PAM. This block calculates the CDF (empirical CDF) of the received signal and compares it with theoretical CDFs of available modulation types and then chooses the one with the smallest distance from it. The CDF is calculated as

$$F_N(t) = \frac{1}{N} \sum_{n=1}^{N} I(z(n) \leq t)$$

where z(n) is the received signal, N is the number of samples, t is a threshold range (-1.5 to 1.5) and I(.) is 1 if the condition inside is true, 0 otherwise. Theoretical CDFs of every modulation type were calculated by replacing z(n) with the corresponding input signal x(n) without any noise.

The modulation classification was carried out using the blocks described above. Probability of classification at block level alone at various SNRs was used as a metric to judge the performance of each block. The performance of the entire classifier was judged as well. The following section includes plots, figures which visualize the performance metrics like probability of classification as well as a confusion matrix to gauge the potential of the classifier as a whole.

RESULTS:

The performance of the MC-SC block was measured by evaluating the probability of detection and probability of false alarm by varying the threshold used to compare C_{42} values. Probability of detection (Pd) is the probability that the receiver classifies the received signal as MC given the transmitted signal was MC. Probability of false alarm (Pfa) is the probability that the receiver classifies the received signal as MC even though the transmitted signal was not MC. It was observed that as the threshold (γ) was increased, the probability of detection also increased. And so did the probability of false alarm. Thus, there is a tradeoff between Pd and Pfa. The number of samples (Nm) used to calculate C_{42} was found out to be a crucial parameter as well. Higher the value of Nm, greater was the performance. At the same time, it is desirable to perform this computation as fast as possible which also puts a limit on the value of Nm. Following are the two plots obtained for Nm=100 samples and Nm=8000 samples. As expected, as Pd increases, Pfa also increases. Also, when Nm=100, MC-SC block doesn't perform well at SNR=10 dB. But as Nm is increased to 8000, performance increases.

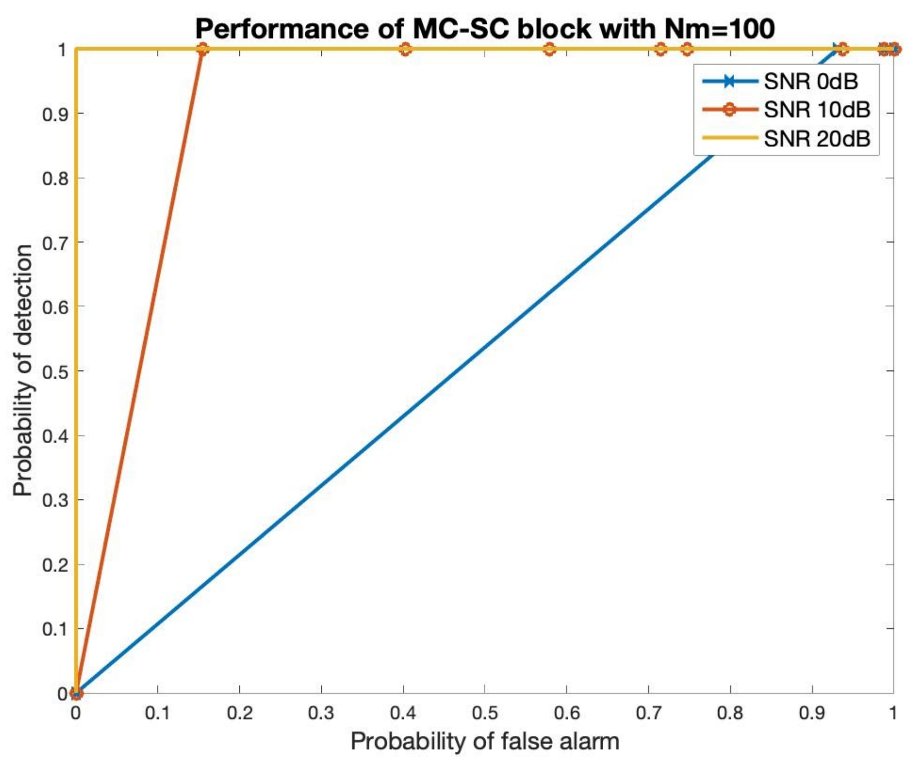

Fig. 3: Performance of MC-SC block (Nm=100)

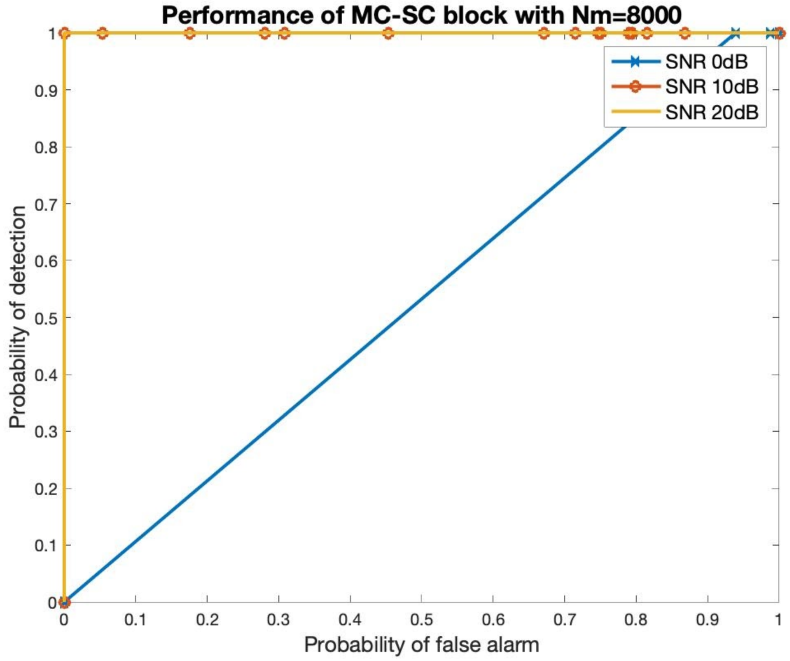

Fig. 4: Performance of MC-SC block (Nm=8000)

The C42 values calculated in each trial at the 3 SNR values were recorded and the 3 histograms were plotted. As expected, at 0dB SNR, the C42 values were way off the charts. At 20dB SNR, the C42 values were close to the ideal values.

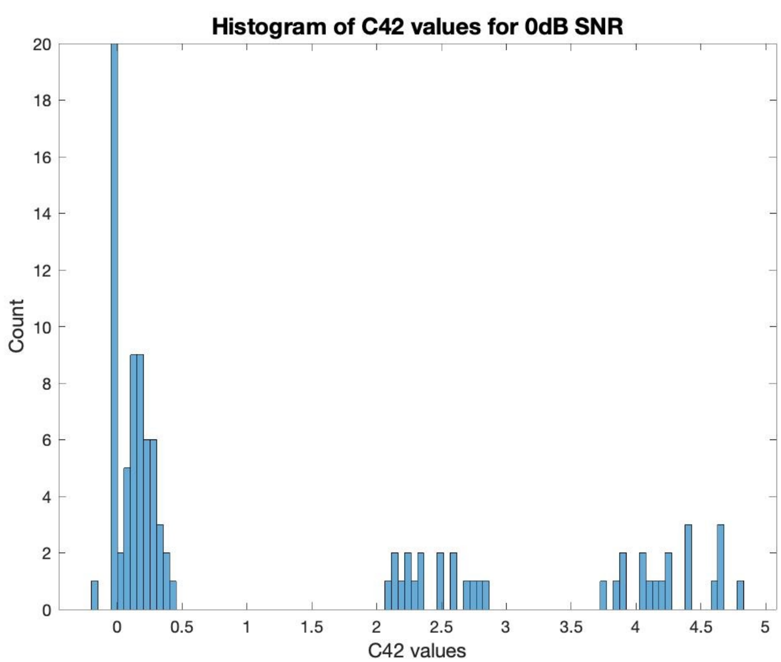

Fig. 5: Histogram of C42 values at 0dB SNR

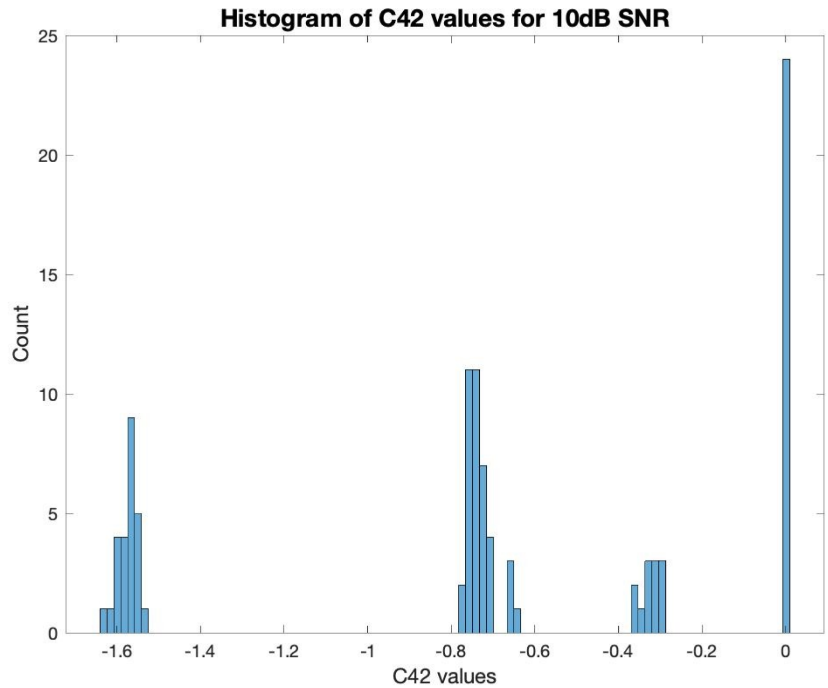

Fig. 6: Histogram of C42 values at 10dB SNR

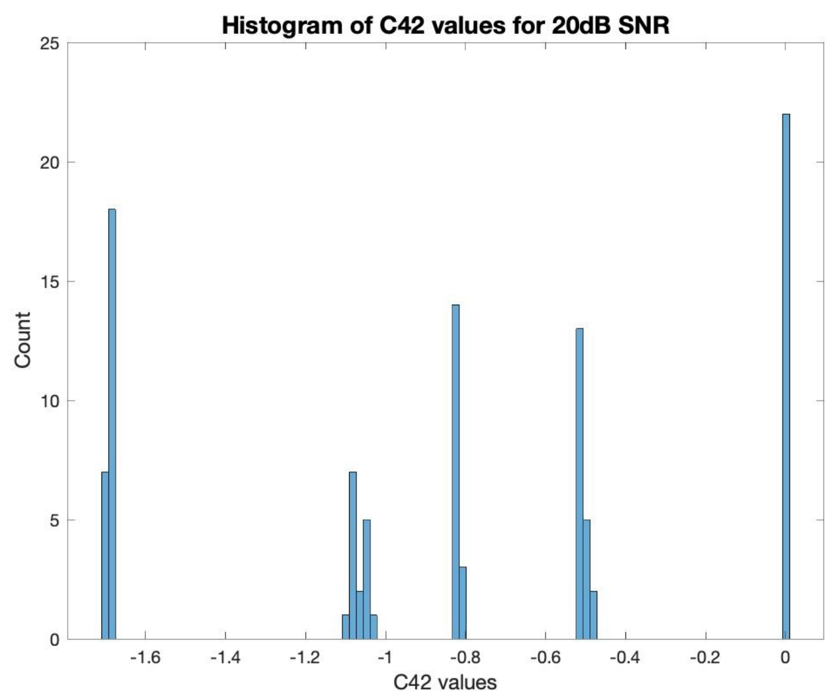

Fig. 7: Histogram of C42 values at 0dB SNR

Following plots depict the performance of MTC block in terms of probability of classification. Here as well, the performance increases with increase in the number of samples to perform computations.

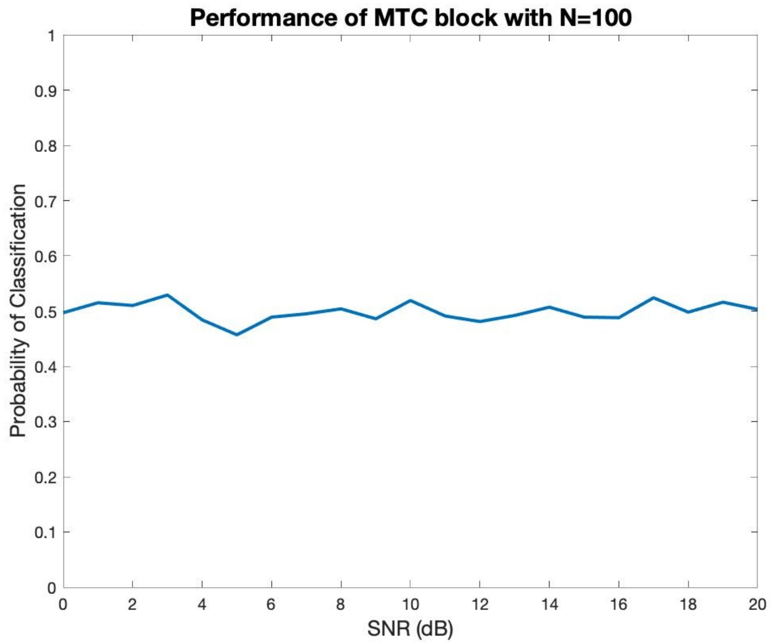

Fig. 8: Performance of MTC block (N=100)

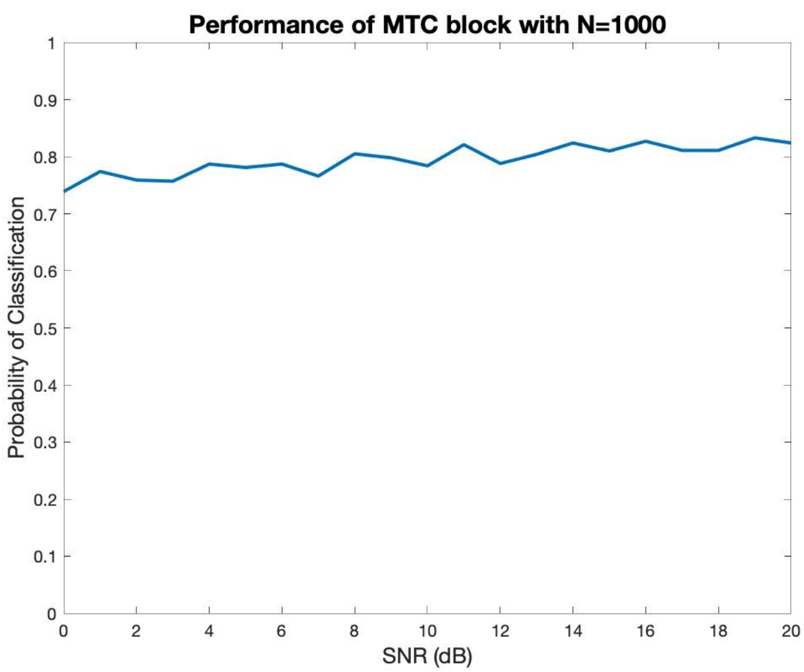

Fig. 9: Performance of MTC block (N=1000)

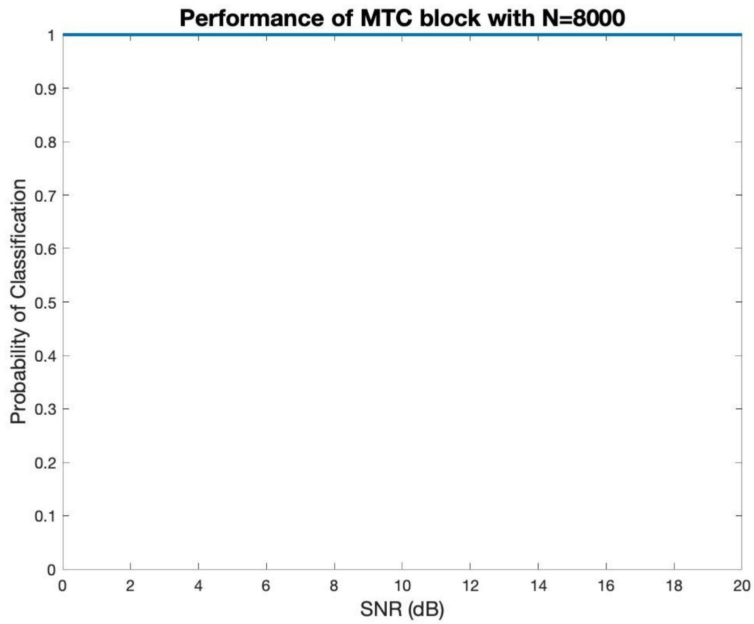

Fig. 10: Performance of MTC block (N=1000)

Following plots show the performance at the MLC block level. According to the plots, it can be seen that the PAM classifier performs better than the QAM classifier. The reason may be that at low SNR, the transmitted QAM signal's empirical CDF lies between the theoretical CDF of both level's signal causing the classifier to misclassify.

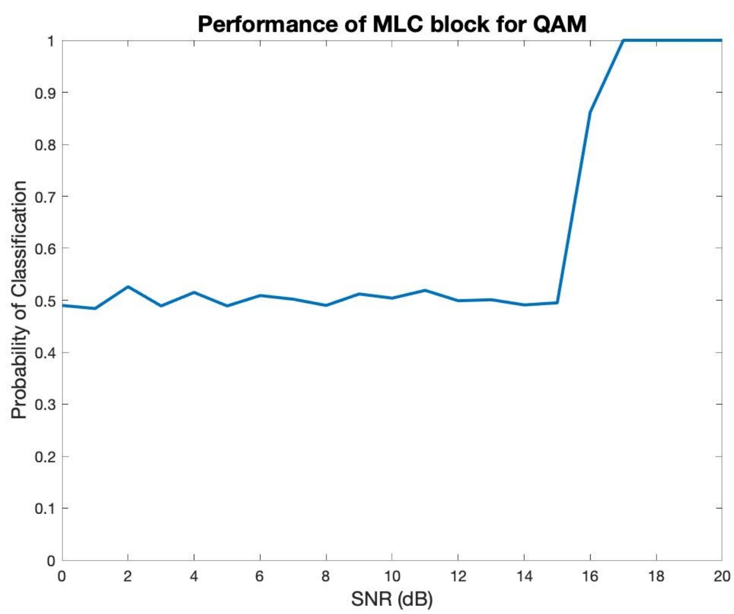

Fig. 11: Performance of QAM MLC block

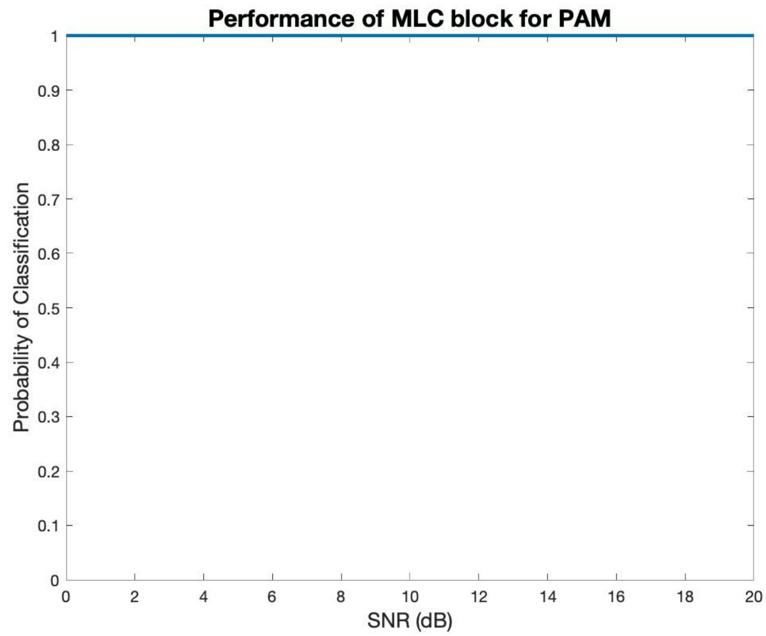

Fig. 12: Performance of PAM MLC block

The performance of the entire classifier was judged using a confusion matrix and the probability of correct classification at various SNR values. The MC-SC block's threshold value was also varied which resulted in significant performance differences.

The results with γ = -0.8 are:

The confusion matrix for SNR 0 dB and γ=−0.8 is

	OFDM	4–QAM	16–QAM	2–PAM	4–PAM
OFDM	1	0	0	0	0
4–QAM	1	0	0	0	0
16–QAM	1	0	0	0	0
2–PAM	1	0	0	0	0
4–PAM	1	0	0	0	0

Fig. 13: Confusion matrix (SNR = 0 dB, γ = -0.8)

The confusion matrix for SNR 10 dB and γ=−0.8 is

	OFDM	4–QAM	16–QAM	2–PAM	4–PAM
OFDM	1	0	0	0	0
4–QAM	1	0	0	0	0
16–QAM	1	0	0	0	0
2–PAM	0	0	0	0.84615	0.15385
4–PAM	1	0	0	0	0

Fig. 14: Confusion matrix (SNR = 10 dB, γ = -0.8)

The confusion matrix for SNR 20 dB and γ=−0.8 is

	OFDM	4–QAM	16–QAM	2–PAM	4–PAM
OFDM	1	0	0	0	0
4–QAM	0.11111	0.88889	0	0	0
16–QAM	1	0	0	0	0
2–PAM	0	0	0	1	0
4–PAM	0	0	0	0	1

Fig. 15: Confusion matrix (SNR = 20 dB, γ = -0.8)

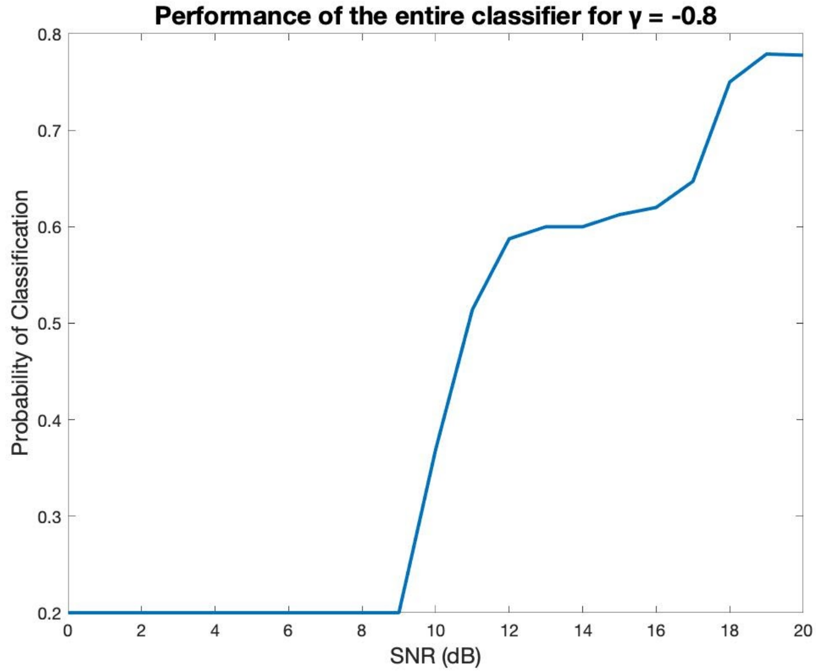

Fig. 16: Performance of entire classifier (γ = -0.8)

The results with γ = -0.5 are:

The confusion matrix for SNR 0 dB and γ=−0.5 is

	OFDM	4−QAM	16−QAM	2−PAM	4−PAM
OFDM	1	0	0	0	0
4−QAM	1	0	0	0	0
16−QAM	1	0	0	0	0
2−PAM	1	0	0	0	0
4−PAM	1	0	0	0	0

Fig. 14: Confusion matrix (SNR = 0 dB, γ = -0.5)

The confusion matrix for SNR 10 dB and γ=−0.5 is

	OFDM	4−QAM	16−QAM	2−PAM	4−PAM
OFDM	1	0	0	0	0
4−QAM	0	1	0	0	0
16−QAM	1	0	0	0	0
2−PAM	0	0	0	0.95652	0.043478
4−PAM	0	0	0	0	1

Fig. 17: Confusion matrix (SNR = 10 dB, γ = -0.5)

The confusion matrix for SNR 20 dB and γ=−0.5 is

	OFDM	4−QAM	16−QAM	2−PAM	4−PAM
OFDM	1	0	0	0	0
4−QAM	0	1	0	0	0
16−QAM	0.77273	0	0.22727	0	0
2−PAM	0	0	0	1	0
4−PAM	0	0	0	0	1

Fig. 18: Confusion matrix (SNR = 20 dB, γ = -0.5)

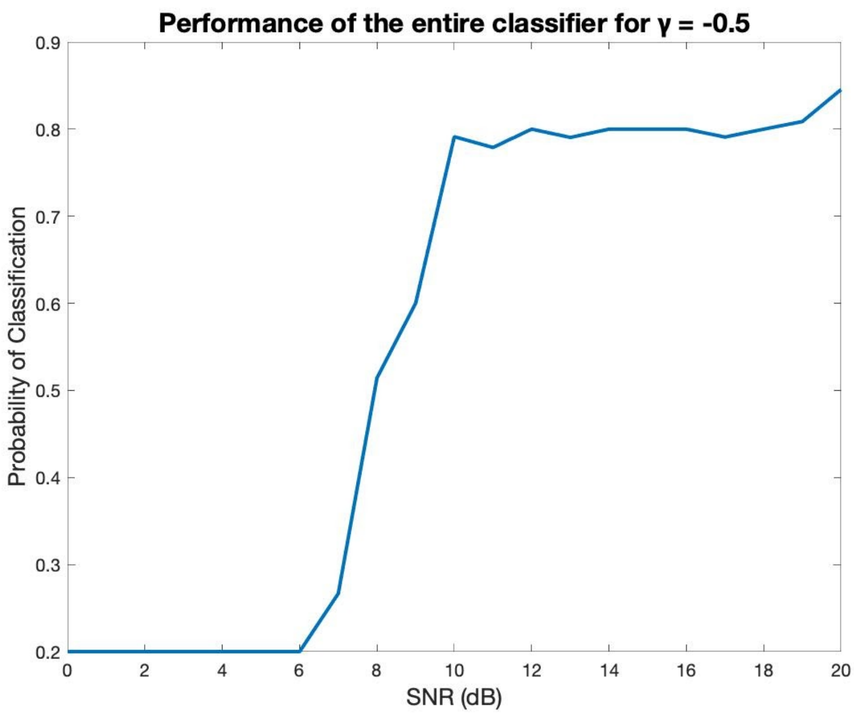

Fig. 19: Performance of entire classifier (γ = -0.5)

The results with γ = -0.2 are:

The confusion matrix for SNR 0 dB and γ=−0.2 is

	OFDM	4−QAM	16−QAM	2−PAM	4−PAM
OFDM	1	0	0	0	0
4−QAM	1	0	0	0	0
16−QAM	1	0	0	0	0
2−PAM	1	0	0	0	0
4−PAM	1	0	0	0	0

Fig. 20: Confusion matrix (SNR = 0 dB, γ = -0.2)

The confusion matrix for SNR 10 dB and γ=−0.2 is

	OFDM	4−QAM	16−QAM	2−PAM	4−PAM
OFDM	1	0	0	0	0
4−QAM	0	1	0	0	0
16−QAM	1	0	0	0	0
2−PAM	0	0	0	0.86667	0.13333
4−PAM	0	0	0	0	1

Fig. 21: Confusion matrix (SNR = 10 dB, γ = -0.2)

The confusion matrix for SNR 20 dB and γ=−0.2 is

	OFDM	4−QAM	16−QAM	2−PAM	4−PAM
OFDM	1	0	0	0	0
4−QAM	0	1	0	0	0
16−QAM	0	0	1	0	0
2−PAM	0	0	0	1	0
4−PAM	0	0	0	0	1

Fig. 22: Confusion matrix (SNR = 20 dB, γ = -0.2)

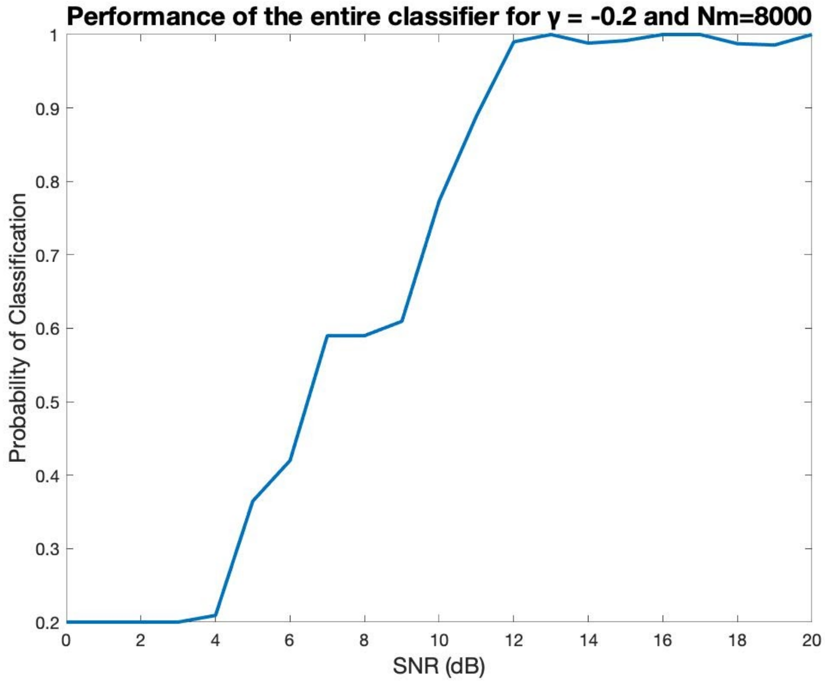

Fig. 23: Performance of entire classifier (γ = -0.2, Nm=8000)

It was found that performance was better when the threshold was -0.2. Further, the number of samples used to calculate C_{42} were reduced from 8000 to 100 and performance degradation was observed.

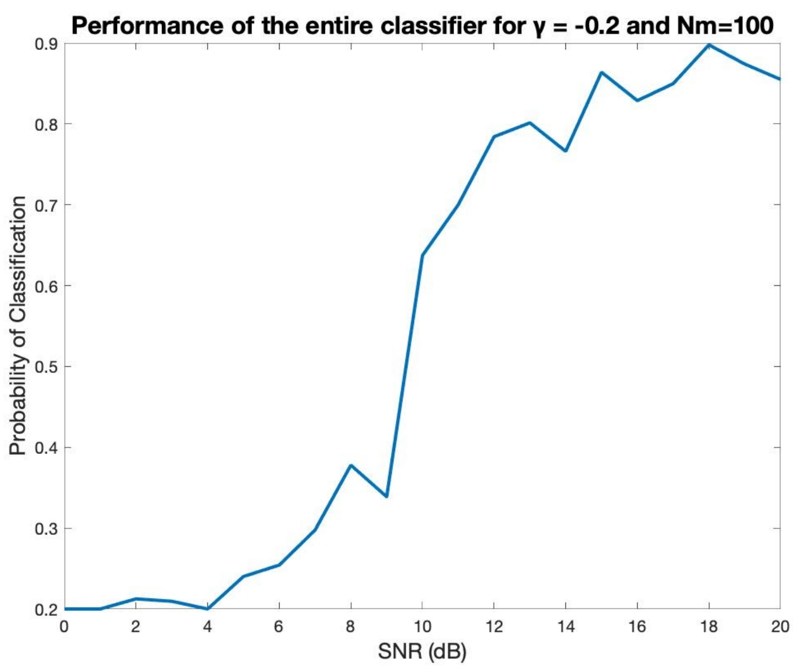

Fig. 24: Performance of entire classifier (γ = -0.2, Nm=100)

CONCLUSION:

A blind modulation classifier presented in the paper was implemented in this project. The transmitter and the receiver architectures were studied. The algorithms and techniques to perform various types of classification schemes at every stage viz. multi-carrier/single-carrier, modulation type classifier, and modulation level classifier were implemented. The tradeoffs between probability of detection and probability of false alarm were studied by varying the threshold value. The number of samples were also changed to observe the change in performance of MC-SC block. Furthermore, modulation type classification was carried out using comparison of normalized asymptotic feature vectors to the one of the received signal. The next step was modulation level classification. Using theoretical CDFs and empirical CDFs, classification at modulation level was carried out. The threshold, SNR value, the number of samples to perform computations proved to be important factors in determining the performance of the system at independent block levels as well as of the entire system.