A NOVEL MODULATION-CLASSIFICATION TECHNIQUE FOR SOFTWARE-DEFINED RADIO APPLICATIONS

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ABSTRACT

The technique discussed here is being designed for a real-time SDR system using General Purpose Processors and SDR development boards and it is robust and efficient with a processing time overhead low enough to allow the software radio to maintain its real-time operating objectives. A decision-theoretic approach is being used in this technique. The method uses the waveforms' I–Q diagrams and, by employing pattern-recognition techniques on them, determines the type of modulation being transmitted. This new Modulation Classification method will be capable of determining the type of modulation scheme among different PAM, QAM, PSK and OFDM modulations.

1. INTRODUCTION

By definition, cognitive radios (CRs) are radios that can intelligently sense the radio environment, interpret it, plan the most appropriate system response (according to preset rules), and react accordingly [1]. A more specific and application-related definition would be that CRs provide a method of wireless communication in which the wireless node modifies its reception and transmission parameters to communicate with efficient use of bandwidth and to avoid interference with other users. Using this definition, the three steps that are critical for the functioning of the CR are frequency sensing, modulation classification, and, at a higher level, protocol analysis. Modulation classification (MC) is the process of recognizing the type of signal modulation in use with minimum or no *a priori* knowledge [2]. Software-defined MC automatically detects the type of modulation and applies the necessary demodulation techniques to the signal in order to retrieve the message. Most of the current modulation classifiers only cover a few modulation schemes and generally a few single-carrier signals. But today, the ever increasing applications of multi-carrier modulations, such as OFDM (orthogonal frequency-division multiplexing), require the design of classifiers that would automatically detect a vast number of modulations without having any *a priori* information about them.

There are three main steps in every MC process:

1. measurement,
2. feature extraction, and
3. decision.

Modulation detection algorithms usually can be categorized into the following:

1. Likelihood-based (LB), which includes
   a. average likelihood ratio test,
   b. generalized likelihood ratio test, and
   c. hybrid likelihood ratio test;
2. Feature-based (FB), which includes
   a. instantaneous amplitude, phase, and frequency,
   b. wavelet transform, and
   c. signal statistics [3].

Many issues concerning the implementation of these methods more or less have been solved. For most of these methods, however, accurate preprocessing is required for effective implementation of MC algorithms. Thus, devising low complexity blind algorithms and MC methods that rely less on preprocessing will be the next step in this research domain. Also, new MC issues are occurring as a result of new wireless technologies such as OFDM and MIMO (multiple in–multiple out).

The method that we propose here uses a tree structure (i.e., hierarchical) and uses a series of check points to identify the type of modulation. The proposed structure can be seen in **Figure 1**. The first step is to determine whether we have a single-carrier or multi-carrier signal. If the answer is multi-carrier, a number of processes are performed to identify the parameters of the OFDM signal. In the case of single-carrier, further classification methods are performed to determine the exact type of modulation [2]. For single-carrier MC, we use pattern recognition techniques on I–Q (in-phase–quadrature) diagrams of the received signals. Some of the digital modulation schemes that are discussed here are presented mathematically as follows [3]:

PSK (phase-shift keying):

$$x_{\mathrm{PSK}}(t) = A\mathrm{Re}\left\{\sum_k C_k e^{j2\pi f_c t} g(t - kT_s)\right\},$$

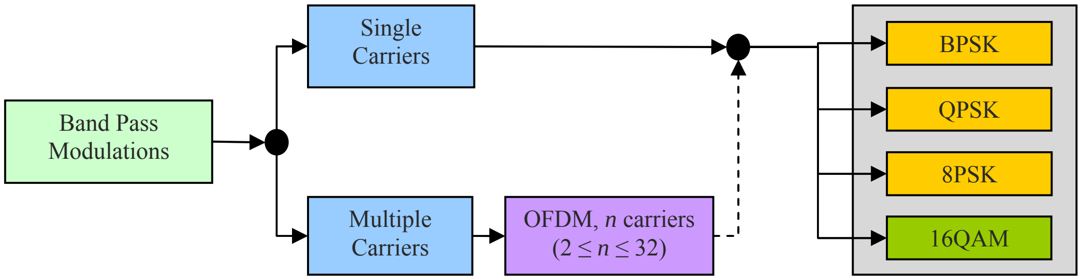

Figure 1. Tree structure for modulation classification

$$C_k = e^{j\frac{2\pi i}{M}};\ i = 0,1,\dots,M-1$$

QAM (quadrature amplitude modulation):

$$x_{\text{QAM}}(t) = A\text{Re}\left\{\sum_k C_k e^{j2\pi f_c t} g(t - kT_s)\right\},$$

$$C_k = a_k + jb_k\,; a_k, b_k = 2i - M - 1; i = 0,1,\dots,M-1$$

OFDM

$$x_{\text{OFDM}}(t) = A\text{Re}\left\{\sum_k \sum_{n=0}^{N_p-1} C_{n,k} e^{j2\pi n\Delta f t}\right\},$$

$$C_{n,k} \in \boldsymbol{C}\,; E\{C_{n,k}\} = 0\,.$$

where A depends on the power of received signal; C_k and $C_{n,k}$ map the transmitted symbols; T_s is the symbol period; f_c is the carrier frequency; N_p is the number of OFDM subcarriers; M is the modulation level; $g(t)$ is a finite energy signal with a T_s duration; $E\{\cdot\}$ is the expected value operator; and **C** is the set of the complex numbers. Simulation results of different modulation schemes show that constellation shape (i.e., the I–Q diagram) is a global and stable signature for different modulations, making it a reliable way to classify different modulation schemes [5].

In this paper, we first describe in Section 2 the method used for determining multi-carrier from single-carrier signals. In Section 3, we focus on methods designed for single-carrier classification. Section 4 presents some of the initial results we have achieved so far. Finally, we present some concluding remarks and future direction of this project.

2. MULTI-/SINGLE-CARRIER CLASSIFICATION

The first step in the classification process is the estimation of the number of carriers that are involved. So, the first step in the process determining whether we have a multi-carrier or a single-carrier signal.

In an OFDM modulation, all orthogonal subcarriers are transmitted simultaneously. In other words, the entire allocated channel is occupied with the aggregated sum of the narrow orthogonal sub-bands. Thus, since it is a combination of multiple carriers, the OFDM-modulated signal can be considered to be composed of a great number of independent identically distributed (IID) random variables. Therefore, using the central limit theorem, we can claim that the amplitude distribution of the sampled signal can be approximated with a Gaussian. However, this cannot be said of the case of a single-carrier modulated signal [6]. Hence, multi-/single-carrier classification can be made with a simple Gaussianality (normality) test.

Normality tests have been discussed in the literature [2,4,5] and a few of them have been proposed for this task. Although there are a vast number of tests available, some of them, such as Chi-square test or Epps test, are not well suited for digital modulation due to their high noise sensitivity.

The approach we have taken to find the best suitable test has been to try them in simulations under different conditions of noise and different types of channels: AWGN (additive white Gaussian noise), Rician, and Rayleigh channels. The tests that have been tried are Jarque–Bera, Giannakis–Tsatsanis, Epps, Albertson–Darling, Shapiro–Wilk, Kolmogorov–Smirnov, Lilliefors, D'Agostino–Pearson, Cramer–von Mises, and Shapiro–Francia. It must be noted that some of these tests are special forms of other tests; for example, Jaque–Bera and D'Agostino–Pearson are modified versions of Chi-square test and Lilliefors and Anderson–Darling are different versions of Kolmogorov–Smirnov test.

3. MULTI-CARRIER CLASSIFICATION

Passing the normality test indicates that we have Gaussianality in our received signal. However, this can be due to the presence of plain additive white Gaussian noise in AWGN channels. It has been shown that an OFDM signal is cyclo-stationary. So, in the next step a cyclo-stationarity test is used to confirm if we indeed have an OFDM signal or it is just AWGN.

A by-product of this process is the estimation of the OFDM symbol rate [6]. After this test, other processes are performed to extract parameters such as symbol duration, cyclic prefix duration, and number of subcarriers. As mentioned above, the cyclo-stationarity test will give an estimation of OFDM symbol duration. OFDM symbol duration consists of two parts: the data duration and cyclic prefix duration. After we acquire symbol duration we need to estimate the cyclic prefix duration.

Estimation of cyclic prefix duration is important for ISI elimination. For the cases of Rician and Rayleigh channels, there is multipath fading that may result in ISI. To eliminate any ISI without changing the orthogonality of its subcarriers, the last cyclic prefix of the useful signal is copied to the front of the symbol as shown in Figure 2. If we take T_s to be the duration of one OFDM signal, we can write it as

$$T_s = T_b + T_{cp} ,$$

where T_b is data duration and T_{cp} is cyclic prefix duration. Since copying of cyclic prefix is performed, there is an extremum in the signal's autocorrelation, which indicates the duration of this cyclic prefix. So, a simple correlation test will help to perform the task of estimation of cyclic prefix[5].

Finally, to estimate the number of carriers, which in our simulations we have assumed to be less than or equal to 32, we use a bank of fast Fourier transforms (FFTs). We assume that the number of subcarriers is a power of 2 since OFDM signals are made using inverse FFTs. This FFT bank consists of different lengths of FFTs based on powers of 2 and uses the concept of normality of the OFDM signal one more time to determine the number of subcarriers. It utilizes the fact that if the output in one of the FFT branches is perfectly demodulated, then it will have only useful data and will no longer possess a normal distribution. On the other hand, all the other branches will still show Gaussian property. By increasing the number of OFDM symbols processed in this FFT bank, a more accurate result can be obtained, but accuracy would be a traded off with an increase in time to make the decision.

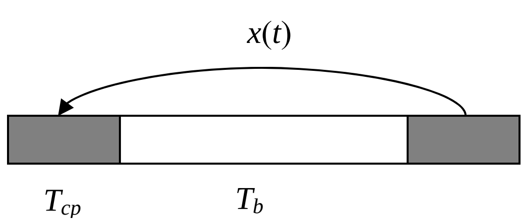

Figure 2. Cyclic prefix copied to eliminate ISI

4. SINGLE-CARRIER CLASSIFICATION

A failed normality test will indicate a single-carrier signal, which will branch the process to that of classifying the single-carrier signal. Also, after extracting the OFDM signal's parameters, we will need to demodulate each carrier present in the multi-carrier signal. We have developed a procedure for classifying the single-carrier modulations using its constellation shape and some pattern recognition techniques. First, we are developing an algorithm that estimates the number of symbols in the signal and then, by using methods such as *k*-means clustering, we find the overall shape of the modulation via the I–Q diagram, making it possible to automate the complete MC process.

This procedure involves finding the cluster centers on the constellation shape, which gives us first the number of symbols in the modulation and second the placement of these symbols on the I–Q diagram. After finding these points, comparing them with a database of possible modulations will determine the type of modulation we have received or we can calculate the distance between the symbols and determine the type of modulation by further using pattern recognition techniques.

5. SIMULATION RESULTS

For simulating an OFDM signal, we have used the models available in Simulink to create OFDM–16QAM, –BPSK, -QPSK, and –8PSK signals. The block diagram of the model is shown in Figure 3. The transmitted signal and the received signal for the model are depicted in Figure 4 and their I–Q diagrams in Figure 5. The simulation first uses a block to convert data from series to parallel format. The next blocks ensure that the frequency domain representation has FFT Hermitian symmetry. The Hermitian symmetry means that the following relation is ensured between carriers:

$$g_i = g_{n-i}^{*} ,$$

where n is the total number of carriers and * indicates the complex conjugate.

There are two methods for implementing different single-carrier modulations. The straight-forward method is to use the modulation blocks already implemented in Simulink's Communications toolbox. The other method is to use QAM blocks and use its signal constellation criteria to define different constellations on it by defining a constellation vector.

As discussed above, for single-carrier modulations, a simple image-recognition process is used. Examples of this algorithm applied to 16QAM and 8PSK modulations can be seen in Figure 6. As shown in Figure 5(a), there are rare cases when one of the clusters is missing due to a special symbol configuration in the modulation, which may cause an error in the process. This algorithm can also detect these conditions and reconfigure itself to work with these conditions. This effort will be briefly addressed in Section 6 below.

6. FUTURE WORK

Since this project is still underway, there are some parts that are still under development. The next steps will be additional work on single-carrier modulation classification method and to refine it. The distance between clusters should be normalized before classification. When a signal is received, its I–Q diagram will partly be defined by its power in the receiver. So, in order to compare the received signal with a database of modulation types, it needs to be normalized to have a standard I–Q diagram with a unit received power. This requires the design of a PLL-like device that would take the received signal and equalize its power level.

In addition, the issue of how to deal with missing clusters must be taken into consideration. When a cluster or a number of clusters are missing, it can cause an error in our algorithm. But, since the number of clusters to be found is predetermined, the algorithm will try to find the missing cluster center in other areas, which in turn will cause some cluster centers to be too close to each other. An example of this can be seen in Figure 6(a) where, because of a missing cluster, the algorithm has found two very closely adjacent cluster centers. To solve this error, a solution is to set a threshold for the minimum distance between cluster centers. When two cluster centers are too close to each other (i.e. below the threshold we set), this will indicate that a cluster is missing and the algorithm will take this into consideration when comparing the modulation structure to the database, thus avoiding an error in the decision making.

Noise and ISI thresholds will be also studied for this single-carrier MC technique. It will be determined how much noise in the received signal can be tolerated before there is an error in the decision. It is evident that this noise level will cause more error in certain modulations compared to others. A parametric study will determine the allowed level of noise for each modulation. In OFDM modulation, for which we need to determine the modulation type for subcarriers, we will need to determine the amount of ISI tolerable. Since cyclic prefix has been used to eliminate ISI in a previous step, the study will show whether an extra step in this level is required or not.

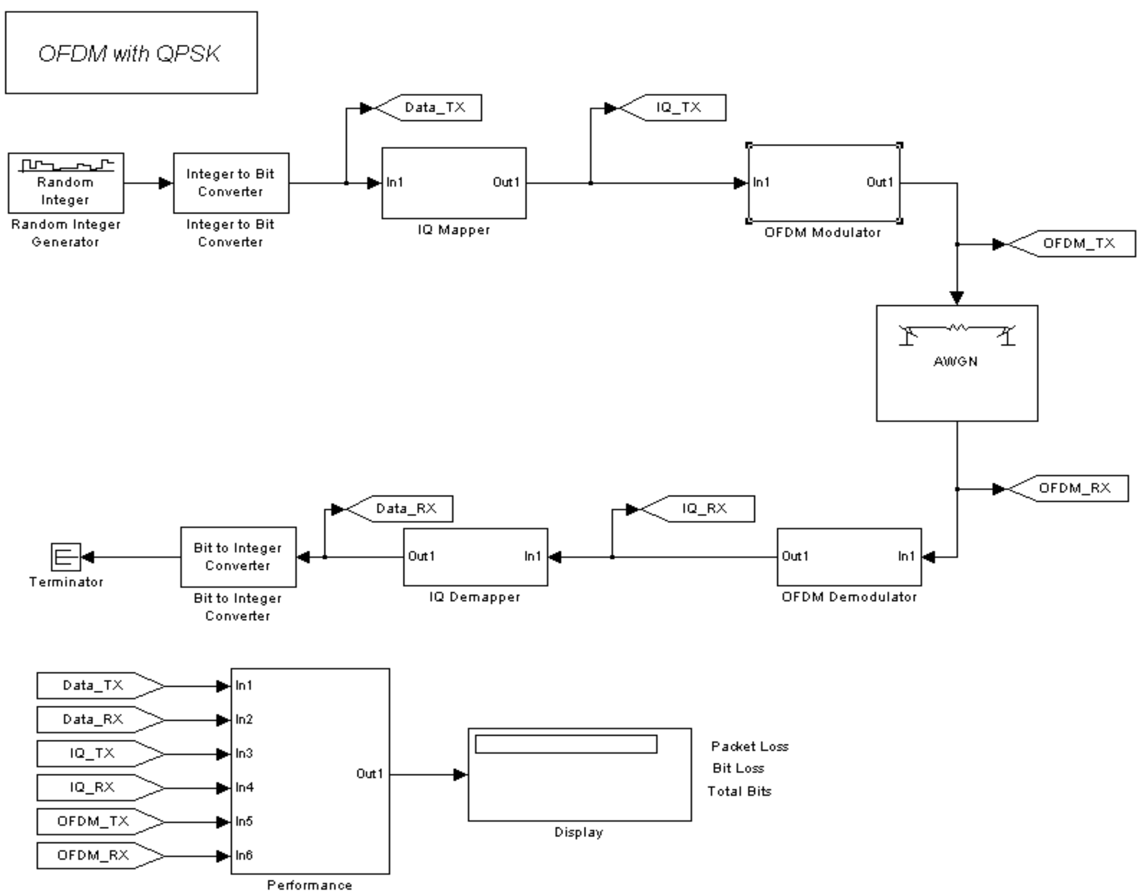

Figure 3. Simulink model of OFDM signal transmitter/receiver

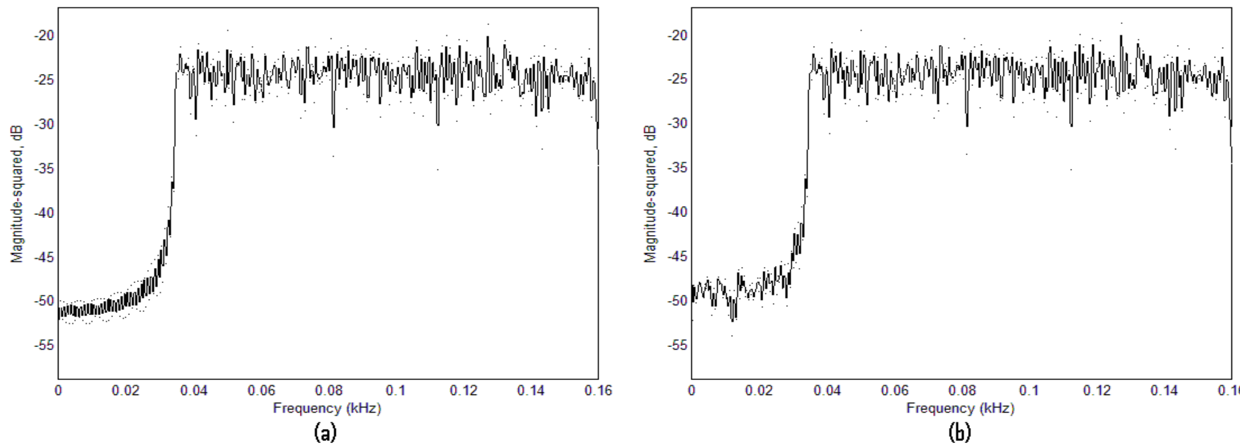

Figure 4. (a) Spectrum of transmitted signal and (b) spectrum of received signal

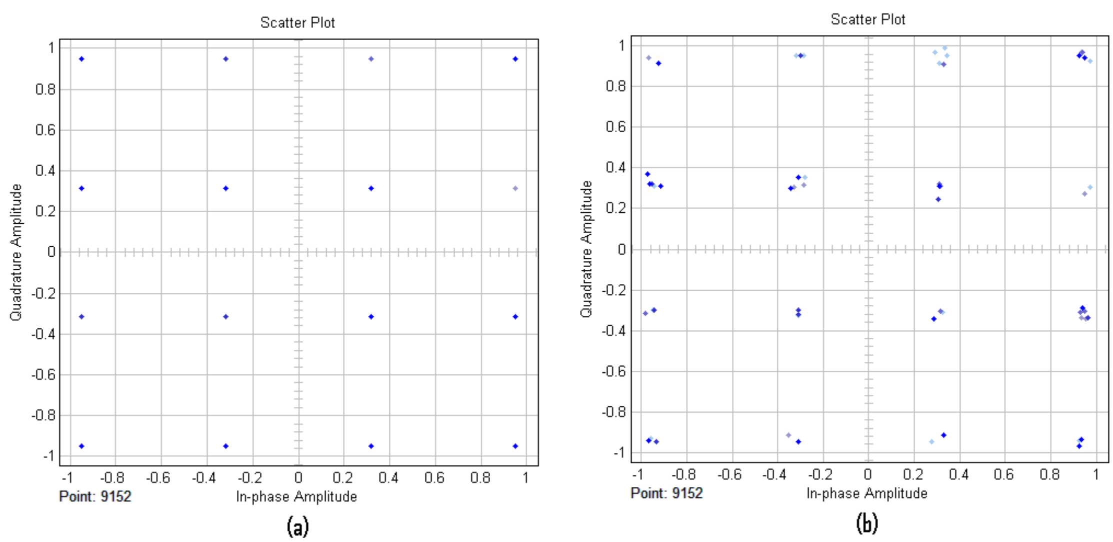

Figure 5. I-Q diagrams of (a) transmitted and (b) received signals for OFDM–16QAM modulation

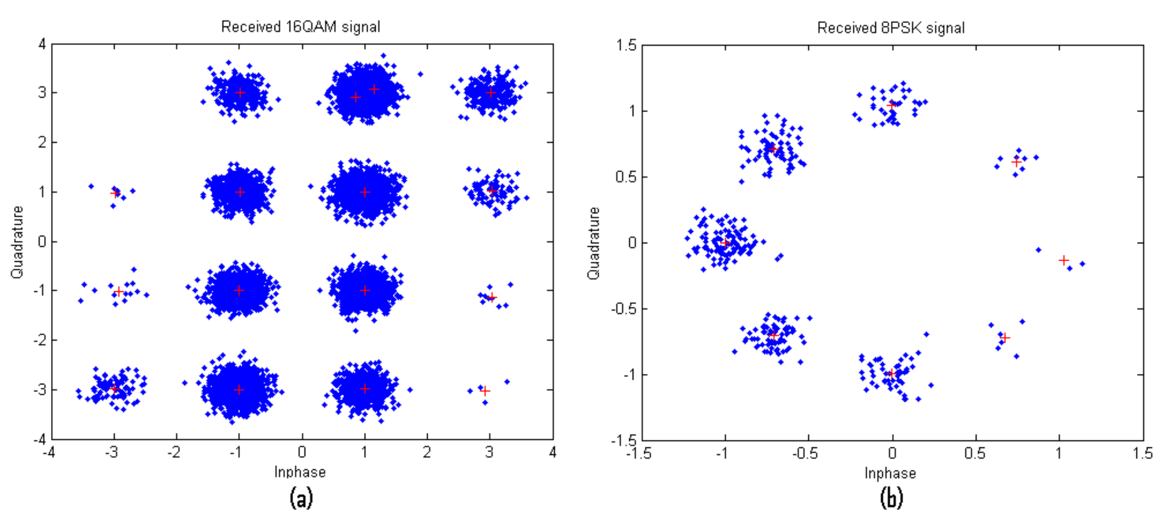

Figure 6. Clustering on (a) 16QAM and (b) 8PSK signals. The + signs show the center of each cluster.

In addition, carrier recovery and synchronization also should be considered for inclusion in the complete model. Specifically for the case of OFDM signals, frequency offset and phase errors between the transmitter carrier and the receiver carrier cause intercarrier interference (ICI); hence, there is more severe performance degradation on OFDM than on single-carrier systems. The method we used to correlate the cyclic prefix with its replica in the end of OFDM symbol can also used for synchronization [9].

7. CONCLUSION

The goal of this project is to design a comprehensive modulation classification system to address the increasing needs of cognitive radio designers. A tree structure has been proposed that combines an initial normality test to differentiate between multi-carrier signals such as OFDM and single-carrier signals with a combination of other tests and methods to further extract parameters and determine the exact type of modulations to apply the necessary demodulation method to the signal. To this end, I–Q diagrams have been used as a unique signature of the single carrier modulations to classify different types of modulation schemes. Some initial simulation results using this new method are presented as a proof of its capabilities.

8. REFERENCES

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