OFDM Modulation Classification and Parameters Extraction

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***Abstract*— A novel comprehensive classification system is proposed for recognizing the orthogonal frequency division multiplexing (OFDM) signal and extracting its parameters. An empirical distribution function -based Gaussianity test technique is first applied to distinguish OFDM from single carrier modulations. Cyclostationarity and correlation tests are then applied to estimate OFDM symbol duration and cyclic prefix duration. A bank of fast Fourier transform (FFT) bank filter is devised to detect the number of subcarriers. Numerical results are presented to verify the efficiency of the proposed scheme.**

I. Introduction

Recently, many state-of-the-arts communication technologies, such as orthogonal frequency division multiplexing (OFDM) modulations, have emerged [1]. OFDM has been adopted or proposed for a number of applications, such as satellite and terrestrial digital audio broadcasting (DAB), digital terrestrial television broadcasting (DVB), broadband indoor wireless systems, asymmetric digital subscriber line (ADSL) for high bit-rate digital subscriber services on twisted-pair channels, and fixed broadband wireless access [2]–[4]. The advantages of OFDM systems include immunity to multipath fading and impulsive noise [5]. Since for OFDM the individual subcarrier signal spectra is frequency-flat rather than frequency-selective fading, equalization is dramatically simplified.

The need for distinguishing OFDM signal from single carrier has become obvious for general military application as well as for software defined radio. Modulation classification problem has been studied for decades considering analog and digital modulation types. In comparison to the research on modulation classification for single carrier, however, much less attention has been paid to the modulation classification for these emerging modulation methods. Thanks to the accepted fact that the OFDM is asymptotically Gaussian we devised here a classifier based on a statistical test. The proposed Gaussianity test is based on the empirical distribution function (EDF) of samples of the received signal. Actually, it is a hypothesis test problem, in which $\mathcal{H}_1$ hypothesis (non-Gaussian process) is restricted to the single carrier modulation whereas $\mathcal{H}_0$ hypothesis (Gaussian process) is assigned to OFDM signals.

Besides distinguishing of OFDM signal from single carrier, some vital parameters of OFDM signal should be extracted for further processing. These parameters include, but not limit to, the number of subcarriers, OFDM symbol duration and cyclic prefix (CP) duration, etc. With those parameters at hand, one may further recognize the linear modulation type on each OFDM subcarrier by applying the conventional modulation classification methods. In this paper, a comprehensive classification system is devised for recognizing the OFDM signal and extracting its parameters.

The layout of the paper is as follows: In Section II the system model is described. Gaussianity test -based OFDM classification technique is addressed in Section III, followed by OFDM parameters extraction, discussed in Section IV. The concluding remarks are presented in Section V.

II. System Model

The module diagram of the proposed OFDM classification and parameter extraction system is depicted in Fig. 1. First, the incoming signals are pre-processed by down-conversion and sampling. Then, the type of signal, single carrier or OFDM (multicarrier), is determined using Gaussianity test. If the test failed, implying non-Gaussianity, it would suggest a conventional modulation classification method to be applied for further processing. A passed test indicates positive Gaussianity in the received signals and OFDM modulation exists at a certain significance.

However, plain additive white Gaussian noise (AWGN) can also pass the Gaussianity test. In order to distinguish the OFDM signal from AWGN, cyclostationarity test can be applied.[1] It has been proved that OFDM signal is cyclic stationary with period T_s [6] [7], where T_s denotes the interval of one OFDM symbol,

$$T_s = T_b + T_{cp}, \tag{1}$$

where T_b and T_{cp} are data, and cyclic prefix duration respectively. If the cyclostationarity test fails, then one may claim that there is no OFDM signals fed in and the positive

[1] In cyclostationary process, the statiscal properties (mean and autocorrelation), are not time independent, but periodic with time.

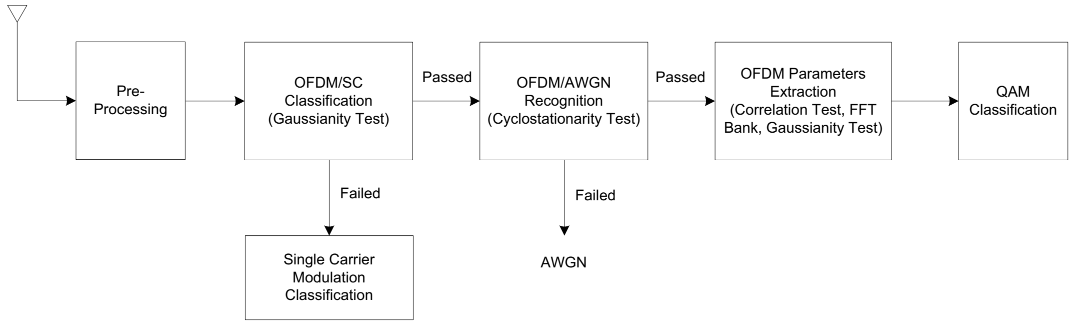


Fig. 1. System module diagram

Gaussianity test result of the preceding module is totally due to the AWGN. A beneficial by-product of this test is that, with the cyclic correlation based algorithm, the OFDM symbol rate ($1/T_s$) is estimated blindly [8] [9].

Once OFDM modulation is confirmed, a module is next used to extract the important system parameters. Inside this module, the classic correlation test method is used to determine the cyclic prefix interval T_{cp}. Moreover, a bank of Fast Fourier Transform (FFT) processors, followed by a Gaussianity test, has been designed to search the number of subcarriers. Finally, a QAM classifier is applied to identify the order of the QAM signals on each subcarrier. [2]

In subsequent sections, we will elaborate on each function of the module individually.

III. Gaussianity Test-Based OFDM Classification

In OFDM, all orthogonal subcarriers are transmitted simultaneously. In other words, the entire allocated channel is occupied with the aggregated sum of the narrow orthogonal subbands. The OFDM signal is therefore treated as composed of a large number of independent, identically distributed (i.i.d.) random variables. Hence, according to the central limit theorem (CLT), the amplitude distribution of the sampled signal can be approximated with Gaussian. On the other hand, the amplitude distribution of a single carrier modulated signal cannot be approximated with a Gaussian distribution. Therefore, the identification task of OFDM from single carrier becomes a Gaussianity test (or normality test).

A. Empirical Distribution Function -Based Gaussianity Test

The empirical distribution function (EDF) is a stair-wise function, which is calculated from the signal samples. The population distribution function can be estimated by the EDF. Assume a given random sample of size n is $\Omega_1, \Omega_2, \ldots, \Omega_n$ and arrange the sample in ascending order $\Omega_{(1)} < \Omega_{(2)} < \cdots < \Omega_{(n)}$, where $\Omega_{(\kappa)}$ denotes the order statistic. Suppose further that the cumulative distribution function of Ω is $F(\omega)$, then the definition of the EDF is given by

$$F_n(\omega) = \frac{\text{number of observations} \leq \omega}{n}, \quad -\infty < \omega < \infty. \tag{2}$$

Therefore, as ω increases, the EDF $F_n(\omega)$ takes a step up of height $1/n$ as each sample observation is arrived. We can expect $F_n(\omega)$ to estimate $F(\omega)$, and actually $F_n(\omega)$ is a consistent estimator of $F(\omega)$. As $n \to \infty$, $|F_n(\omega) - F(\omega)|$ decreases to zero with probability one.

Since in our case, a Gaussianity test is conducted, we assume the random samples belong to a Gaussian distribution

$$F(\omega) = \int_{-\infty}^{\omega} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t-\mu)^2}{2\sigma^2}} dt \tag{3}$$

with mean μ and variance σ^2, and suppose it null hypothesis $\mathcal{H}_0$. Furthermore, the hypothesized distribution has an incomplete specification, i.e., with mean and variance unknown. Then $\mathcal{H}_0$ becomes a composite hypothesis and we estimate parameters from the sample.

In order to measure the difference between EDF and CDF quantitatively, the so-called EDF statistics are introduced. They are based on the vertical differences between $F_n(\omega)$ and $F(\omega)$. The closer two curves, the smaller EDF test statistics. We resort to the Cramer-von Mises (CV) statistic, which is defined by

$$W^2 = n \int_{-\infty}^{\infty} \left[F_n(\omega) - F(\omega)\right]^2 dF(\omega). \tag{4}$$

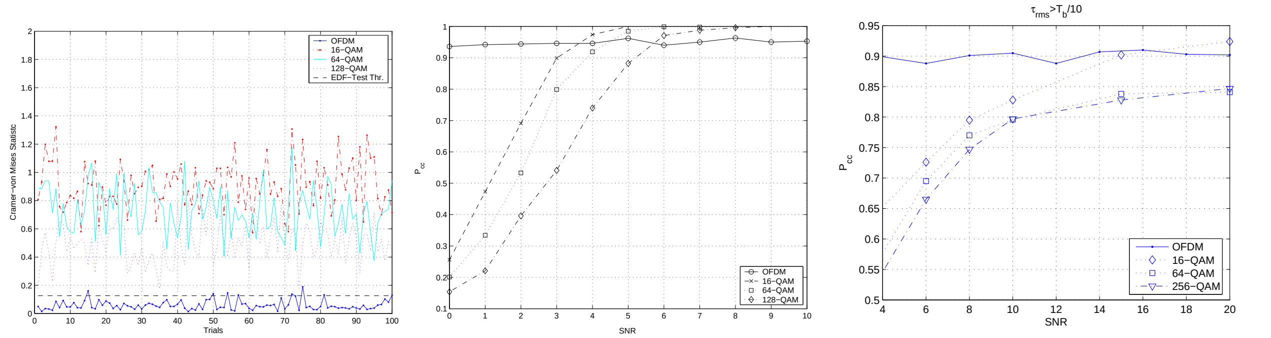
Thus, CV statistic is nothing but the integrated square error between the estimated cumulative distribution function and the measured empirical distribution function of the sample.

The computation of W^2 is carried out via the *Probability Integral Transformation* (PIT), $\Delta = F(\Omega)$. When $F(\omega)$ is the true distribution of Ω, the new random variable Δ is uniformly distributed between 0 and 1. Hence Δ has distribution function $U(\delta) = \delta$, $0 \leq \delta \leq 1$, $\Delta_\kappa = F(\Omega_\kappa)$, and let $U_n(\delta)$ be the EDF of the values Δ_κ. Thanks to the fact that

$$F_n(\omega) - F(\omega) = U_n(\delta) - U(\delta) = U_n(\delta) - \delta, \tag{5}$$

EDF statistic calculated from Δ_κ with the uniform distribution will take the same value as if it were calculated for the EDF of the Ω_κ. This yields the following formula to calculate the

[2]Generally speaking, in OFDM signals, the M-ary QAM is usually adopted for modulation type on every subcarrier.



(a) CV statistics for different modulations, SNR=10dB.

(b) Classification performance, no fading.

(c) Classification performance, frequency selective fading.

Fig. 2. EDF -based Gaussianity test.

CV test statistic [10]

$$W^2 = \sum_{\kappa} \left\{ \Delta_{(\kappa)} - (2\kappa - 1)/(2n) \right\}^2 + 1/(12n). \quad (6)$$

From the definition and derivation given above, the procedure of the CV Gaussianity test is summarized as follows:

- **step (a)** Sample the incoming signal, take the real or imaginary part of samples to obtain $\{\Omega_1, \dots, \Omega_n\}$;
- **step (b)** Arrange the sample in ascending order, $\Omega_{(1)} < \cdots < \Omega_{(n)}$;
- **step (c)** Estimate the sample mean $\overline{\Omega}$ and standard deviation S

$$\overline{\Omega} = \frac{\sum_{\kappa} \Omega_{\kappa}}{n} \quad \text{and} \quad S = \sqrt{\frac{\sum_{\kappa} (\Omega_{\kappa} - \overline{\Omega})^2}{n-1}}; \quad (7)$$

- **step (d)** Apply PIT, calculate the standardized value ζ_{κ}, for $\kappa = 1, \dots, n-1$, from $\zeta_{\kappa} = (\Omega_{(\kappa)} - \overline{\Omega})/S$, and further $\Delta_{(\kappa)} = \Phi(\zeta_{\kappa})$, where $\Phi(x)$ indicates the cumulative probability of a standard normal distribution;
- **step (e)** Calculate the CV test statistic via formula (6);
- **step (f)** Use the percentage points given in Table 4.7 of [10] and calculate the modified statistic [3]. If the modified CV statistic exceeds the appropriate percentage point at level α, $\mathcal{H}_0$ is rejected with significance level α. In other words, no Gaussianity is present in the incoming signal.

Note that *significance level* is a statistic expression, which corresponds to the *probability of false alarm* in engineering. Both belong to the so-called Type I error.

B. Simulations and Discussion on Gaussianity Test

The Gaussianity test for modulation classification with Cramer-von Mises statistics is simulated and numerical results are presented. Raised cosine pulse shaping is implemented with roll off factor set to 0.35. Without loss of the generality, CV test statistics of OFDM signal are compared with ones of single carrier modulation, say, M-ary QAM. In simulations, normalized constellations are generated to assure fair comparison. A 64-subcarrier OFDM signal has been generated, with 16-QAM modulation on each subcarrier.

The CV statistics for different modulations have been sketched in Fig. 2(a). The CV statistics are calculated from the in-phase or quadrature part of the tested signal for 100 trials. The value of the dashed line, 0.126, stands for the decision threshold at 5% significance level, which is given in Table 4.7 of [10]. If the statistic exceeds this threshold, $\mathcal{H}_0$ (Gaussianity hypothesis) is rejected at 5% probability that actually $\mathcal{H}_0$ is true. The CV statistics of all the single carrier modulations are above the threshold while the one of the OFDM keeps below the threshold, except for a couple of trials. This is due to the significance level set to 0.05, thus there is a little possibility that the CV statistic jumps over the threshold.

In Fig. 2(b), the probability of correct classification is employed to demonstrate the CV test performance in non-faded environment as a function of SNR. The correct classification only denotes successful decision if the signal is Gaussian (OFDM), rather than the identification of every modulation type. AWGN affects the test results for single carrier in low SNR region, whereas for an OFDM one, it does not affect the test result at all. This makes sense since with high additive noise power, even single carrier modulation behaves as Gaussian due to the overwhelming AWGN. Obviously, higher order QAM modulation suffers more than lower order one, as one might argue that higher order modulation presents more possible values, which leads to the fact that samples looks more similar to a normal distribution. Note that because of the 5% significance level, the P_{cc} performance curve for an OFDM fluctuates slightly around 0.95.

The performance of the proposed OFDM classification technique with frequency selective fading is plotted in Fig. 2(c), where the significance level is set to 0.1. The fading is present with $\tau_{rms} > T_b/10$ [11], and τ_{rms} denotes the root mean

[3]When the CDF is not completely specified and parameters are estimated, the Cramer-von Mises statistic should be modified to obey the asymptotic theory.

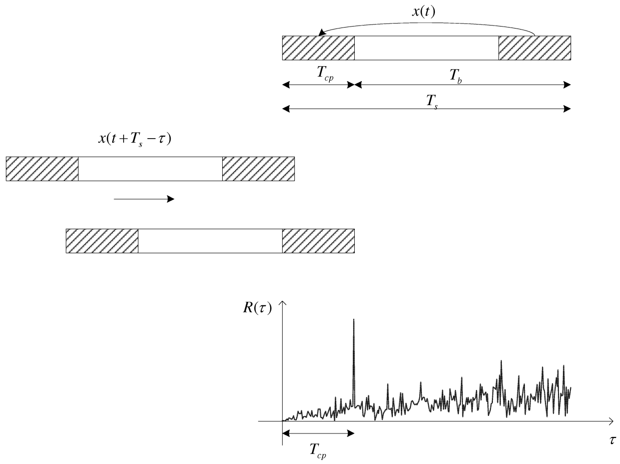


Fig. 3. Detection of cyclic prefix

square delay spread. Since frequency selective fading leads to inter-symbol interference (ISI), any sample of a single carrier signal contains overlapped neighboring symbols. Such mixture contributes somewhat Gaussianity behavior to single carrier signal. Moreover, the tail resulted from pulse shaping also cause deterioration in classification performance. It is shown that in the practical application environment, the proposed method can offer a probability of correct classification greater than 80% for distinguishing difference between OFDM and single carrier.

IV. OFDM Parameter Extraction

Once the incoming signal is classified as an OFDM modulation, parameter extraction is carried out. In this paper, these parameters include symbol duration, cyclic prefix duration and number of subcarriers.

A. Detection of the Symbol Duration (T_s)

First, a cyclostationarity test is applied to the incoming signal to detect the OFDM symbol duration T_s. According to [6] and [7], OFDM signal is cyclic stationary with period T_s. Therefore, a cyclic correlation based algorithm can be applied to estimate the OFDM symbol rate ($1/T_s$) blindly [8] [9]. If the test fails, in other words, no cyclostationarity is detected, then one may conclude that the incoming signal is not OFDM. Otherwise, the classifier truncate a single OFDM symbol based on the estimated T_s, and feed it into the cyclic prefix duration detection module.

B. Detection of the Cyclic Prefix Duration (T_{cp})

In wireless communications, multipath fading may result in the inter-symbol interference (ISI). In OFDM systems, to eliminate ISI while maintaining the orthogonality of its subcarriers, the last T_{cp} of the useful symbol period T_b, termed Cyclic Prefix (CP), is copied to the front of the symbol. Figure 3 depicts this structure. The principle of the T_{cp} detection is a classic correlation test, which is performed according to

$$R(\tau) = \int_0^{\tau} x'(t)x^*(t)dt, \quad 0 < \tau < T_s, \tag{8}$$

where $x(t)$ is a single OFDM symbol, $x'(t) = x(t + T_s - \tau)$ is the left-shift copy of $x(t)$, τ is delay, and $x^*(t)$ stands for the conjugate of $x(t)$. The detection procedure is also illustrated in Fig. 3. Since CP is identical to the last T_{cp} of an OFDM symbol, an extremum (local maximum) of $R(\tau)$ can be obtained when $\tau = T_{cp}$. As suggested in the IEEE 802.11a standards [2], the maximal length of the CP is limited to one fourth of the useful symbol time T_b. Therefore, one may reduce the search range for the CP to $T_s/4$ or $T_s/5$, in other words, the upper limit of τ in (8) can be reduced to $0 < \tau < T_s/4$.

However, as shown in Fig. 4, one may observe that although $R(T_{cp})$ is an extremum, other extrema nearby may have larger values for $0 < \tau < T_s/4$, when the T_{cp}/T_b becomes smaller. Hence, the maximum value of $R(\tau)$, may not be present at $\tau = T_{cp}$, The reason for such phenomena is that the sample values in one OFDM symbol are correlated due to the IFFT operation.

To avoid the effect of such correlation, a modified CP detector using multiple OFDM symbols is proposed in this work. First, multiple OFDM symbols are used in the CP detection module, and (8) is computed individually for each symbol. Then, multiple $R(\tau)$s are added together so that the extremum $R(T_{cp})$ is strengthened, whilst other extrema are weakened due to the fact that the original information bits are random. Fig. 5 shows results of the modified CP detector using multiple OFDM symbols, in which $R(T_{cp})$ in the first one fourth of T_s has been strengthened while other extrema weakened. Thus $R(T_{cp})$ is much easier to be detected.

C. Detection of the Number of Subcarriers

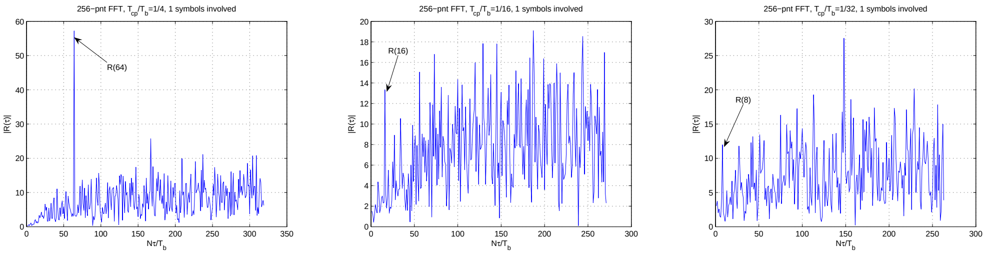
Suppose that the symbol duration is obtained, then as soon as the duration of the cyclic prefix is determined, it is removed from the OFDM symbol, and only useful symbol data is fed into the subsequent bank of FFT's module.

1) Bank of FFT's: As sketched in Fig. 6, it consists of several FFT processors in parallel. Each processor, termed FFT branch, has different length $\tilde{N}_p$, which is power of 2 multiple of $\tilde{N}_0$, a base FFT size, i.e.,

$$\tilde{N}_p = \tilde{N}_0 \cdot 2^{p-1}, p = 1, \ldots, P$$

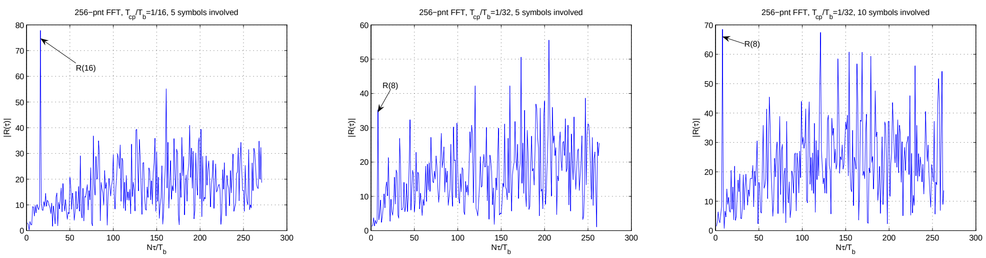
where P is the number of FFT branches.

It is reasonable to assume that the size of IFFT processing of the incoming OFDM signal, N, is in power of 2, and the value of N is in the set of $\{\tilde{N}_p\}_{p=1}^{P}$. Therefore, if $\tilde{N}_p = N$, the output of the p-th FFT branch are perfectly demodulated useful data bits. Just like a regular single carrier modulated signal, there is no Gaussianity in such demodulated OFDM data. On the other hand, if $\tilde{N}_p \neq N$, most output entries of the p-th FFT branch still shows Gaussianity property, whilst at certain equally spaced entries, there is no Gaussianity. The mathematic justification of this will be elaborated in the sequel.



(a) $T_{cp}/T_b = 1/4$ (b) $T_{cp}/T_b = 1/16$ (c) $T_{cp}/T_b = 1/32$

Fig. 4. Detection of T_{cp} using single OFDM symbol, $N_{FFT} = 256$.



(a) $T_{cp}/T_b = 1/16$, 5 symbols (b) $T_{cp}/T_b = 1/32$, 5 symbols (c) $T_{cp}/T_b = 1/32$, 10 symbols

Fig. 5. Detection of T_{cp} using multiple OFDM symbols, $N_{FFT} = 256$.

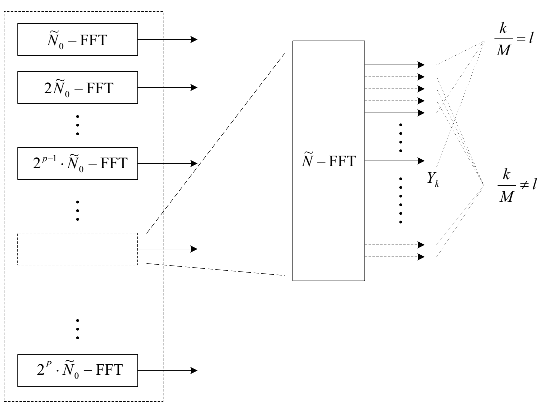


Fig. 6. Bank of FFT's.

Note that by increasing the number of OFDM symbols processed at FFT branches, a more accurate Gaussianity result may be obtained when $\tilde{N}_p \neq N$. But there would be a tradeoff as the delay in decision is increased.

2) Detection of the number of subcarriers: Suppose the transmitter IDFT size is N and the classifier DFT size $\tilde{N}$ satisfy $\tilde{N} = MN$ where $M \geq 1$ is a positive integer.

The input signal to the classifer DFT is

$$y_n^m = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k^m e^{j\frac{2\pi kn}{N}} \tag{9}$$

where X_k^m is the kth data symbol of the mth transmitted OFDM symbol, y_n^m is the nth IDFT output symbol of the mth transmitted OFDM symbol.

The classifier performs an $\tilde{N}$-point DFT hence the kth entry of the DFT output is given by

$$\begin{aligned} Y_k &= \frac{1}{\sqrt{\tilde{N}}} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} y_n^m e^{-j\frac{2\pi k}{\tilde{N}}(mN+n)} \\ &= \frac{1}{N\sqrt{M}} \sum_{m=0}^{M-1} \sum_{l=0}^{N-1} X_l^m e^{-j\frac{2\pi km}{M}} \sum_{n=0}^{N-1} e^{j\frac{2\pi n}{N}(l-\frac{k}{M})} \end{aligned} \tag{10}$$

where we substituted (9) in (10).

There are two cases. *Case I*: If $\frac{k}{M} = l'$ is an integer, i.e., $(k \bmod M) = 0$, we have

$$\begin{aligned} \sum_{n=0}^{N-1} e^{j\frac{2\pi n}{N}(l-\frac{k}{M})} &= \sum_{n=0}^{N-1} e^{j\frac{2\pi n}{N}(l-l')} \\ &= \begin{cases} N & l = l' \\ 0 & l \neq l' \end{cases}, \end{aligned} \tag{11}$$

Therefore, when $\frac{k}{M} = l$, expression (10) can be simplified as

$$\begin{aligned} Y_k &= \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} \sum_{l=0}^{N-1} X_l^m e^{-j\frac{2\pi km}{M}} \delta(l - \frac{k}{M}) \\ &= \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} X_{\frac{k}{M}}^m . \end{aligned} \tag{12}$$

The physical meaning of Eqn (12) is as follows; If k is a multiple of M, then Y_k, the k-th output of $\tilde{N}$-point FFT is the summation of M original data symbols. Those data symbols come from the k/M-th subcarrier of M transmitted OFDM symbols. Since M may not be a large number, Y_k shows only little Gaussianity.

Case II: If $\frac{k}{M}$ is not an integer, i.e., $(k \bmod M) \neq 0$, then

$$\sum_{n=0}^{N-1} e^{j\frac{2\pi n}{N}\left(l-\frac{k}{M}\right)} = \frac{1-e^{j2\pi\left(l-\frac{k}{M}\right)}}{1-e^{j\frac{2\pi}{N}\left(l-\frac{k}{M}\right)}}. \quad (13)$$

Substituting (13) into Eqn (10), we obtain

$$Y_k = \frac{1}{N\sqrt{M}} \sum_{l=0}^{N-1} \left[\frac{e^{j\pi\left(l-\frac{k}{M}\right)} \sin\left(\pi\left(l-\frac{k}{M}\right)\right)}{e^{j\frac{\pi}{N}\left(l-\frac{k}{M}\right)} \sin\left(\frac{\pi}{N}\left(l-\frac{k}{M}\right)\right)} \times \left(\sum_{m=0}^{M-1} X_l^m e^{-j\frac{2\pi k m}{M}} \right) \right], \quad (14)$$

which means that when k is not a multiple of M, the k-th output of $\tilde{N}$-point FFT is a mixture of MN data symbols $\{X_l^m\}_{l=0:N-1}^{m=0:M-1}$. In other words, every data symbols in the sampling interval contribute to the Y_k, and Y_k may show obvious Gaussianity.

According to derivations above, a successive approach to detect the number of subcarriers is devised as follows; First of all, with the incoming signal, we start a $\tilde{N}$-point FFT operation. The initial value of $\tilde{N}$ is set larger than the possible maximal value of the transmitter IFFT size N. Then we test the output of FFT for Gaussianity. If strong Gaussianity is shown, which means $\tilde{N} \gg N$, we divide $\tilde{N}$ by 2 and apply the new $\tilde{N}$-point FFT. Repeat this "$\tilde{N}$ FFT–Gaussianity test–$\tilde{N}/2$" cycle till the Gaussianity test is totally failed, which implies the fact that $\tilde{N} = N$. Therefore, the number of subcarriers is obtained.

D. Numerical Results

A two-phase searching scheme, is devised to detect the number of subcarriers. In the first phase, a coarse search is carried out iteratively. The exact number of subcarriers is determined by the fine tune search in the second phase. The implementation procedures are detailed in [12].

The overall performance of the proposed scheme for detecting the number of OFDM subcarriers is examined via Monte Carlo simulation. For each experiment, total number of trials is 5000. The size of receiver FFT is initialized at 4096. The number of IFFT at the transmitter side is randomly generated within the finite set $\{N|32, 64, 128, 256, 512\}$. The elements of the set are generated with equal probability. The performance is evaluated by the probability of correct detection P_D, which indicates that the classifier detects successfully the exact number of subcarriers.

Figure 7 plots the detection performance using probabilities of detection versus SNR. It shows that the proposed scheme offers acceptable performance ($P_D \geq 0.9$) when SNR is higher than 15dB.

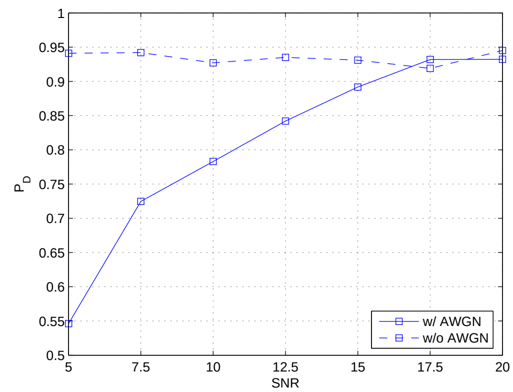


Fig. 7. Probabilities of the correct detection for the number of subcarriers.

V. Conclusion

In this paper, a comprehensive classification system is proposed to identify OFDM signal from single carrier, and to further extract some vital parameters for OFDM modulation. It is shown that the empirical distribution function -based Gaussianity test technique can distinguish OFDM from single carrier modulations and the correlation test can estimate the cyclic prefix duration effectively. A fast Fourier transform (FFT) bank is devised to detect the number of subcarriers. The efficiency of Gaussianity test module, correlation test module, and subcarrier number detection module is validated by computer simulations.

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