

# Physical Layer Considerations For Cognitive Radio: Modulation Techniques

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**Abstract**—Cognitive radio (CR) is one of the promising future possibilities for wireless broadcasting and communication. One of the key issues is the physical layer, where the modulation waveform best suitable for the CRs has to be chosen. In this paper we present the most promising modulation schemes with their advantages and disadvantages. Orthogonal frequency division multiplexing (OFDM) is the most favored modulation nowadays for high speed digital communications, but many other modulation techniques show advantages over it. Notably DFT-spread OFDM (DFTS-OFDM), Constant Envelope OFDM (CE-OFDM) and Filter Bank Multicarrier (FBMC). We give an overview of these schemes to see which is the most suitable with a given set of parameters or in a specific scenario. We compare these methods via spectral characteristics, signal metrics and system performance in the presence of non-linear distortions.

**Keywords**—Cognitive Radio, Physical layer, Orthogonal Frequency Division Multiplexing (OFDM), DFT-spread OFDM (DFTS-OFDM), Constant Envelope OFDM (CE-OFDM) and Filter Bank Multicarrier (FBMC), Multicarrier modulation schemes.

## I. INTRODUCTION

As the licensed and unlicensed communication bands become crowded, an increasing need is emerging for systems with smart and adaptive frequency allocation capability. Especially in licensed broadcast bands, where the spectrum is sparsely used, a secondary system is being considered, which could work without significantly disturbing the primary ones. Mitola's idea of cognitive radio (CR) [1] is a good candidate for this purpose, also the IEEE 802.22 standard [2], [3] is aiming at this target among other relevant standards.

Sensing the spectrum as well as choosing the most efficient data transmission technique for CRs is a challenging task. Currently, Orthogonal Frequency Division Multiplexing (OFDM) is the favored modulation technique due to its simplicity and robustness. It is especially favored in multiuser scenarios. Although many other promising techniques have been suggested, they still need to be investigated and their performance has to be evaluated.

In this paper we compare alternative candidates for OFDM. A comparison of the methods is given in terms of implementation complexity, bit error rate (BER), spectral characteristics and sensitivity to non-linear distortions. First,

the system architectures of OFDM and its most favored competitors including Constant Envelope OFDM (CE-OFDM) [4], DFT-spread OFDM (DFTS-OFDM) [5] and Filter Bank Multicarrier (FBMC) [8] are described. In section III., the simulation parameters are briefly introduced. In section IV the amplitude fluctuation of the transmission waveforms of the various methods are compared by means of peak-to-average power ratio (PAPR), cubic metric (CM) [6], [7] and spectral characteristics. In the next section, the bit error rates are investigated considering also the effects of non-linear distortions. We conclude our investigation with an overall evaluation of the methods described.

## II. SYSTEM ARCHITECTURE

The general transmitter block diagram of the four multicarrier modulation systems considered is depicted in Fig. 1. It can be seen that all transmitter schemes include an Inverse Fourier Transform (IFFT) block. The differences are mainly in the surrounding signal processing blocks. In the present section we introduce these signal processing blocks and then we compare their signal processing complexity.

### A. OFDM

The block diagram of an OFDM transmitter is depicted in Fig.1(a). The popularity of the system lies in the fact that the modulation and demodulation can be performed simply by using the Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT). The time domain samples of an OFDM symbol can be calculated using an  $N$  point IFFT as

$$x_n = \sum_{k=0}^{N-1} X_k e^{j \frac{2\pi}{N} nk}, \quad n = 0, 1, \dots, N-1, \quad (1)$$

where  $X_k$  is the complex modulation value for the subcarrier with index  $k$ . Then, prior to transmission, a Cyclic Prefix (CP) is added to each symbol. Although the channel equalization can be performed in a simple manner exploiting the CP, this method reduces the effective data rate of the system. On the other hand, OFDM has some well known drawbacks:

- To perform interference free demodulation the subcarriers have to remain orthogonal, otherwise system performance will degrade. Therefore, OFDM is very sensitive

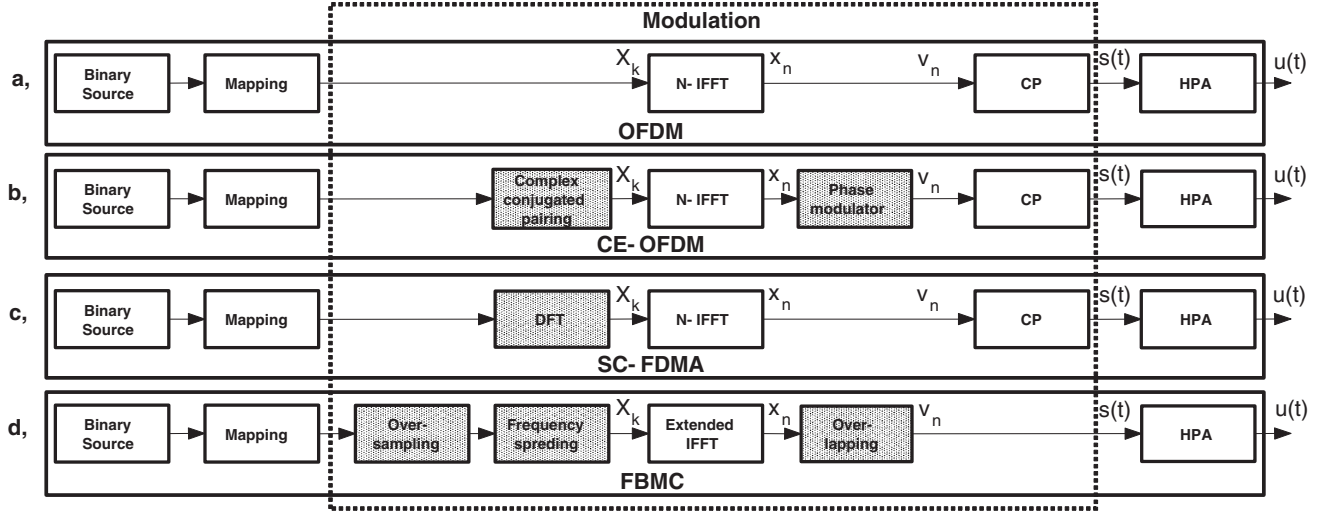


Figure 1. Block diagram of the presented transmitter schemes.

to frequency offset originating from the mismatch of transmitter and receiver local oscillators.

- The time domain OFDM signal is a sum of a large number of complex sinusoids, which means that, according to the central limit theorem, the amplitude distribution will be Gaussian, leading to a large PAPR of the signal. Hence, a power amplifier with a relatively large linear range is required, otherwise non-linear effects will severely degrade the system performance.

### B. CE-OFDM

CE-OFDM [4] targets to solve the high PAPR of the OFDM signal. The complex modulation symbols are aligned in a complex conjugated manner to achieve a real-valued IFFT output as depicted in Fig.1(b). Then, phase modulation is applied to the real-valued time domain signal and the CP is added to form the transmitted signal. One transmitted symbol before adding the CP can be expressed as:

$$v_n = e^{j2\pi h x_n}, \quad n = 0, 1, \dots, N-1, \quad (2)$$

where  $h$  is the modulation index of the phase modulator and  $x_n$  is defined in (1) but with the restriction of  $X_k = X_{N-k}^*$ . A noticeable disadvantage is that the complex conjugated pairing reduces the data rate by a factor of two. Then, the phase modulator can be driven with this real valued signal achieving a constant envelope output signal. The spectral distribution of the transmitted signal will be determined by the modulation index  $h$  of the phase modulator.

### C. DFTS-OFDM

In case of DFTS-OFDM systems [5], the complex modulation data set is preprocessed, the complex modulation values which will be transmitted are grouped and a Discrete Fourier Transform (DFT) is applied as it can be seen in Fig.

1(c). Then the output of the DFT is used to modulate the subcarriers. This technique can be viewed as a single carrier modulation scheme, where frequency spreading is applied through all subcarriers. The result is a slightly lower PAPR than OFDM signalling.

### D. FBMC

FBMC systems [8], [9] use a specially designed filter bank structure. First, the complex modulation values are spread over several carriers and filtered by a prototype filter. This will lead to the use of a larger FFT to construct the transmission signal. This can be visualized in Fig. 1(d). Due to the advantageous properties of the prototype filter bank, the spectral band allocation will be more efficient compared to the OFDM signal. With the use of offset-QAM modulation, where the real and imaginary data values are transmitted with a time shift of a half symbol duration, no data rate loss will occur. Finally, before transmission, the symbols are overlapped such that they can be separated at the receiver due to the fact that the filter bank is designed in a way that it fulfills the Nyquist criterion. Although the symbols are larger and they overlap, no data rate loss will occur. The other advantage of FBMC is that no CP has to be used to combat the channel-induced intersymbol interference. Conversely a more complex signal processing has to be applied, and the channel equalization in the receiver chain will be more complex than other schemes.

## III. SIMULATION PARAMETERS

This section deals with the comparison of the systems described above. First a comparison of the amplitude fluctuation of transmitted signal is made through signal metrics, then a bit error rate study is given based on simulations. The effects of a non-linear amplifier will be also shown.

Finally the spectral behavior of the transmitted signal will be also depicted. For the simulations we applied a 64-FFT with a cyclic prefix of 16 samples and an oversampling ratio of 4. We applied 16-QAM on 48 subcarriers from the maximally available 64, leaving out the DC subcarrier and some carriers on the edge of the transmission band. For the CE-OFDM modulation we have chosen a moderate modulation index of  $h = 0.8$ . The simulations were performed with normalized transmitted signal energy assuming AWGN channel. For the baseband equivalent of the high power amplifier (HPA) a Saleh-model [10] was applied which has the following amplitude transfer function  $A(r(t))$  and phase shift characteristics  $\phi(r(t))$ :

$$A(r(t)) = \frac{\alpha r(t)}{1 + \beta r(t)}, \quad (3)$$

$$\phi(r(t)) = \frac{\rho r(t)}{1 + \lambda r^2(t)}, \quad (4)$$

where  $r(t) = |s(t)|$  is the amplitude of the input signal  $s(t)$  and  $\alpha, \beta, \rho, \lambda$  are the parameters of the HPA. In the simulation scenario we used parameters similar to [11] but with slightly smoother non-linearity:  $\alpha = 1, \beta = 0.1, \rho = \frac{\pi}{32}, \lambda = 0.125$ . The output signal  $u(t)$  is formed as

$$u(t) = A(|s(t)|)e^{j(\varphi(s(t)) + \phi(|s(t)|))} \quad (5)$$

#### IV. PROPERTIES OF THE TRANSMITTED WAVEFORMS

##### A. Signal metrics

Two type of metrics are considered in the literature when describing the dynamics of the transmission signal  $s(t)$ : the PAPR and the CM. The PAPR is defined as:

$$\text{PAPR}(s(t))_{\text{dB}} = 10 \log_{10} \left( \frac{\max\{|s(t)|^2\}}{E_s} \right), \quad (6)$$

where  $|s(t)|$  is the amplitude of the transmission signal and  $E_s$  is the average energy of the signal. The CM is described as

$$\text{CM}_{\text{dB}} = \frac{\text{RCM}_{\text{dB}} - \text{RCM}_{\text{dB}}^{\text{ref}}}{K} \quad (7)$$

where  $\text{RCM}_{\text{dB}}$  is the raw CM of the analyzed signal and  $\text{RCM}_{\text{dB}}^{\text{ref}}$  is the CM of reference signal. The constant  $K$  and the reference signal is specified in [6]. For simplicity we will use the raw CM defined as:

$$\text{RCM}(s(t))_{\text{dB}} = 10 \log_{10} \left( E \left\{ \left( \frac{|s(t)|^2}{E_s} \right)^3 \right\} \right) \quad (8)$$

Using a HPA, the third order distortions dominate, so the CM gives a better insight of the dynamic behavior of the signal in presence of odd order non-linearities. First the PAPR values of the total entire transmission signal are analyzed in Fig. 2, where the complementary cumulative distribution functions (CCDF) of the PAPR values are depicted. It can be seen that CE-OFDM possesses the lowest PAPR value, being constant 0 dB. FBMC and OFDM performs worst,

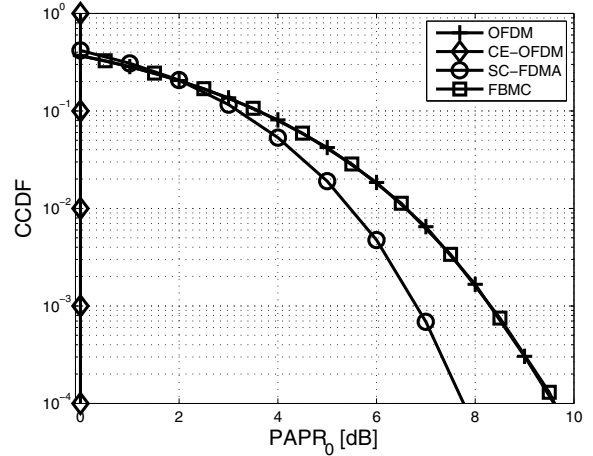


Figure 2. CCDF of the PAPR values of the transmitted signal

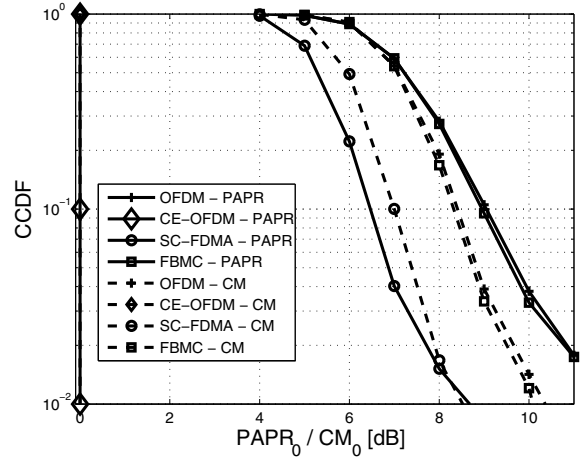


Figure 3. CCDF of the PAPR and CM values of the transmitted symbols

leading to an approximate PAPR value of 10 dB with the probability of  $10^{-4}$ . DFTS-OFDM, as mentioned earlier, has a lower PAPR figure, with a value of 8 dB at the same probability. Another type of analysis can be also made based on taking every transmission symbol separately, not looking at the entire transmission signal. The distribution function of PAPR and CM values for the four schemes regarding one symbol is depicted in Fig. 3. It can be seen that the metric values of OFDM and FBMC are fairly similar. This is due to the fact that both system use a sum of complex harmonics, resulting in Gaussian distributed amplitude values which can lead to high PAPR. The values for DFTS-OFDM are slightly lower due to the preprocessing of the complex modulation data. Again, CE-OFDM preforms the best, due to its constant envelope resulting in a constant PAPR and a CM value of zero. Although for FBMC and OFDM the CM curves lie below the PAPR curves, this is not true for DFTS-OFDM

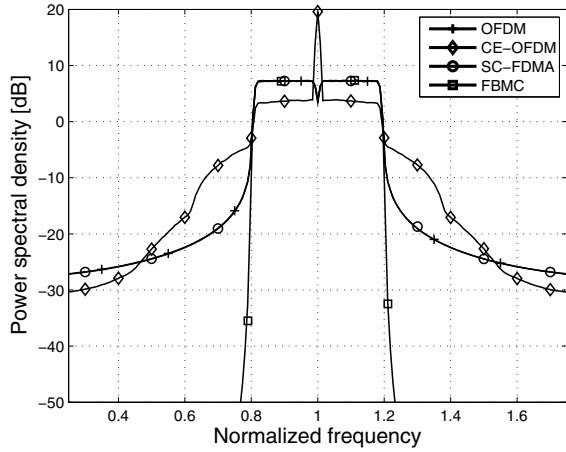


Figure 4. Power spectral density comparison of the transmitted signals with linear HPA

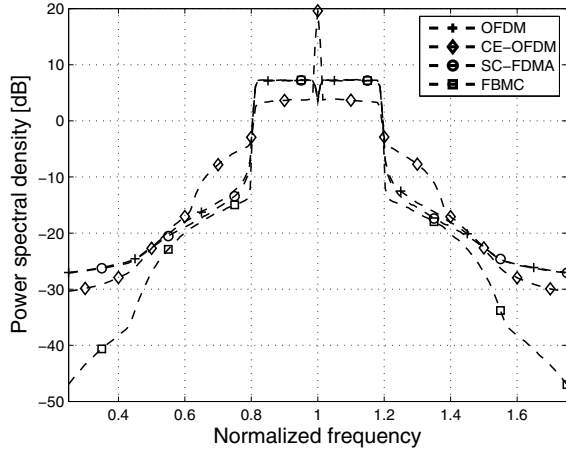


Figure 5. Power spectral density comparison of the transmitted signals with non-linear HPA

signals, but they are still significantly lower when compared to FBMC and OFDM. This can lead to better resistance to non-linear distortions as described in the next sections. It can be also concluded that all symbols of DFTS-OFDM, OFDM, FBMC have a PAPR and CM value higher than 4 dB.

### B. Spectral characteristics

Another important measure of the transmitted signal is its spectral behavior especially regarding to the out-of-channel leakage. These measures are especially important when dealing with CR scenarios. The power spectrum density functions of the transmitted signal with a linear HPA and with a non-linear HPA are depicted in Fig. 4 and Fig. 5 respectively.

The adjacent channel leakage of FBMC outperforms all

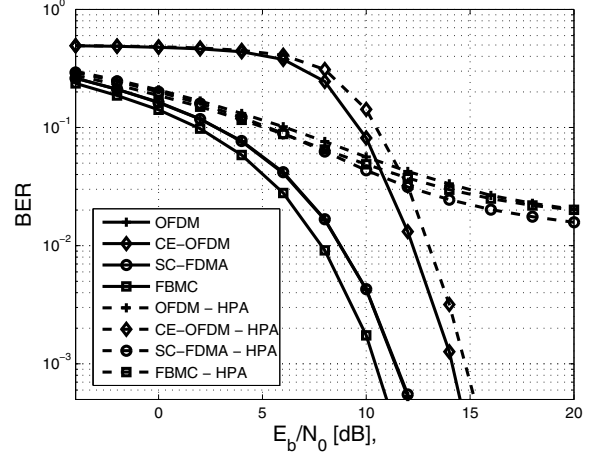


Figure 6. Bit error rate of the four schemes in AWGN channel with and without the effect of HPA

other modulation schemes, DFTS-OFDM and OFDM have fairly similar characteristics, but larger amount of out-of-channel leakage. CE-OFDM has the largest out of band radiation, with a large DC component. This DC component is not preferred in wireless transmissions. The effect of the HPA, on the out-of-band radiation can be also visualized. The non-linear amplifier adversely affects all modulations schemes, resulting in a similar spectral shape. The FBMC is severely affected by the non-linear distortion, but the resulting out-of-channel leakage is still lower compared to OFDM and DFTS-OFDM. The only exception is CE-OFDM which is resilient to the effect of the amplifier due to the constant envelope of the transmission signal. Especially in CR applications the low side radiation and the efficient band allocation can make FBMC the most suitable solution.

### V. SYSTEM PERFORMANCE

The system performances are compared via bit error rate as a function of signal to noise ratio (SNR). In our case the SNR values are defined as

$$\text{SNR}_{\text{dB}} = 10 \log_{10} \left( \frac{E_s}{N_0} \right) \quad (9)$$

$$= 10 \log_{10} \left( \frac{E_b N_c M}{OV(N+CP)N_0} \right), \quad (10)$$

with  $E_b$  being the bit energy,  $N_0$  the noise variance.  $N$  is the number of subcarriers available and  $N_c$  is the number of subcarrier used.  $CP$  is the length of the CP is samples,  $OV$  is the oversampling ratio and  $M$  is the number of bits transmitted over one subcarrier, in our case, due to 16-QAM,  $M = 4$ . The bit error rates are compared with the above mentioned simulation parameters, plotting the values in function of normalized to  $\frac{E_b}{N_0}$ . The results of the simulations are shown in Fig. 6. Without non-linear distortions the FBMC outperforms all modulations, because of the fact that it has no CP added to the transmission

Modulation name	System complexity	Transmission data rate	PAPR and CM metrics	Spectral behavior
OFDM	<b>Low</b>	$1 - \frac{CP}{N}$	High	Compact
CE-OFDM	Medium	$\frac{1}{2}(1 - \frac{CP}{N})$	<b>Low</b>	DC & Sidebands
DFTS-OFDM	Medium	$1 - \frac{CP}{N}$	Moderate	Compact
FBMC	High	<b>1</b>	High	<b>Very compact</b>

Table I  
COMPARISON OF THE FOUR MODULATION SCHEMES

signal, resulting in the best data rate. The worst bit error rate can be observed with CE-OFDM modulation, due to the fact that it has a data rate loss of  $\frac{1}{2}$  which is significantly smaller compared to the others, but it is almost resistant to the effect of the HPA. On the other hand, the gain can be observed when the non-linear HPA is introduced to the system. Now, over a given signal to noise ratio of 10 dB the CE-OFDM clearly outperforms all other techniques. But if we consider linear HPA, that means that the highest PAPR value of OFDM is also transmitted without distortion, so the the output power of the CE-OFDM system can be driven about 10 dB higher, resulting in an SNR gain of 10 dB which can give a significant advantage over all other modulation schemes. Another important observation that we can conclude is, as it was predicted before, DFTS-OFDM has a small gain over OFDM and FBMC in presence of the non-linearity.

## VI. CONCLUSIONS

In this paper we presented four modulation schemes which can be considered in CR scenarios. The schemes were compared in various aspects such as complexity, signal dynamics, spectra and bit error rate, also considering non-linear effects of the HPA. A summary of the comparison of the various schemes is shown in Table I, the best performance in each category is shown with bold letters. The lowest signal processing is needed in case of OFDM signalling, DFTS-OFDM and CE-OFDM require some extra computation and FBMC requires extreme amount of signal processing. CE-OFDM performs best in presence of non-linear distortions, in other words it has the best PAPR and CM metrics. Considering the spectral efficiency, FBMC has the best properties and the lowest neighboring band leakage. Although DFTS-OFDM is not the most desirable choice in any of the properties it can be a good compromise solution having a good performance in all categories. Generally, these aspects have to be considered in case of CR applications and the solution has to be chosen which fits best for the requirements. Some other aspects have to be also investigated in the future such as synchronization, channel equalization and the effect of other analog components to make the best choice regarding the waveform.

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