ASM Sc. J., 16, 2021

https://doi.org/10.32802/asmscj.2021.786

A Novel PM-OFDM-CDMA System for 5G Wireless Communication with High Capacity and Low Energy Consumption

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Phase Modulation Orthogonal Frequency Division Multiplexing (PM-OFDM) and Code Division Multiple Access (CDMA) have distinctive advantages. On one hand, PM-OFDM is an attractive technique to combat multipath fading and reduce high PAPR in conventional OFDM. On the other hand, CDMA has the ability to serve multiple users at the same time and/or frequency. In this article, a new PM-OFDM-CDMA system that combines PM-OFDM and CDMA is proposed. The idea behind the proposed technique is to combine the advantages of these techniques in order to enhance the performance of the 5G system by serving multiple users simultaneously. The performance of the proposed system is analysed in terms of BER under different channel conditions. A Minimum Mean Square Equaliser (MMSE) scheme is used in order to avoid the effect of multipath effect and noise simultaneously. From the simulation results, we conclude that the proposed system has good performance that can improve 5G wireless communication networks, especially for battery-powered mobile devices. This amounts to the constant envelope of the proposed waveform which generates constant instantaneous power and therefore reduced PAPR.

Keywords: OFDM; PAPR; 5G; CDMA; BER

I. INTRODUCTION

5G is the future wireless communication system that has to support different applications under strict requirements. In recent years, progressive growth has been noticed in the development areas of wireless communication devices to satisfy the advanced requirements of high-speed data communication systems. To support these requirements, future mobile communication networks need to use different modulation and multiple access techniques.

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier waveform used in the implementation and development of the most important standards (Wi-Fi "IEEE 802.11", LTE "3GPP" and Wi-MAX "IEEE 802.16") (Ansar & Noor, 2018). In fact, the OFDM waveform addresses certain challenges in wireless communications systems, such as ensuring high data rate communication over wireless channels characterised by severe multipath fading. In addition, the execution of OFDM is simple by using Fast Fourier Transform (FFT) with a Digital Signal Processor (DSP). However, the OFDM signal is characterised by a high Peak-to-Average Power Ratio (PAPR) (Belkadid, Benbassou & El Ghzaoui, 2013). The high PAPR of OFDM causes nonlinear distortion at the power amplifier (PA) of the transmitter (Banelli, 2003). In the case where no input Back-off (IBO) power is used, the OFDM signal suffers from nonlinear distortions and Spectral regrowth and therefore, performance degradation (Singya, Kumar & Bhatia, 2017). As a result, OFDM is considered inefficient in terms of power consumption, which is undesirable especially for battery-powered devices. Many technics have been proposed to solve this problem (Mohammady *et al.*, 2019, 2020). However, the PAPR reduction technics proposed in the

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*Corresponding author's e-mail: j.mestoui@edu.umi.ac.ma literature suffer from increased complexity (El Ghzaoui *et al.*, 2020). Transforming the OFDM signal into a constant envelope signal is used to alleviate the problem of PAPR (Mestoui *et al.,* 2020). In this case, the PA can be used efficiently in the transmission chain based on the OFDM wave forme.

Besides, the MC-CDMA technique benefits from the multiple access possibilities specific to CDMA in direct sequence (DS-CDMA). A comparison of the systems shows the interest of MC-CDMA (Judson *et al.,* 2019). The association of a code with a user must theoretically allow the receiving terminal to recover the signal disturbed by neighboring transmitters. The notion of code induces the notion of the system's ability to manage a maximum number of users. In addition, MC-CDMA can is easily implemented in an FPGA (Nahar *et al.,* 2017). In addition, MC-CDMA is an appropriate technique for 5G applications (Razavi, Dianati & Imran, 2017). Maatouk *et al.* (2018) proposed OFDM-CDMA for 5G cellular networks. Gerzaguet *et al.* (2017) compared CDMA compared to Universal Filtered Multi-Carrier (UFMC), Filter Bank Multi-Carrier (FBMC), and Generalised Frequency Division Multiplexing (GFDM) over a wireless channel. The comparison is done by taking into account spectral efficiency, PSD, PAPR, and BER.

The objective of the work presented in this paper is the design of a transceiver for 5G communication bands meeting the constraints stated above, namely the high throughput, high channel capacity, low SNR, and Low PAPR which leads to low power consumption. To do that, some 5G waveforms such as FBMC, GFDM, UFMC, OFDM, and PM-OFDM are proposed and compared. Based on our simulation it has been demonstrated that the PM-OFDM offers a good compromise between BER and power consumption. That is why we decided to combine this waveform with CDMA in order to get high performance as well as to realise the multi-users concept by means of the CDMA technique. Based on simulation results, we realise a combination of OFDM and CDMA to obtain multi-user access. This technique, the MC-CDMA, is very simple to implement. Works by the separation of spreading blocks on the one hand and OFDM on the other hand. Some simulations were carried out in this work to validate the proposed model. A comparison between the proposed technique and the 5G waveforms is presented. Based on simulation results, we can conclude that the proposed system can be a good candidate for 5G application thanks to its low BER and low power consumption which is a critical issue in the 5G application.

II. PM-OFDM-CDMA SYSTEM

Conventional OFDM-CDMA systems, even with the use of effective PAPR reduction and/or power amplifier linearisation techniques, typically require more input power backoff than convention single carrier systems. Therefore, OFDM-CDMA is considered power inefficient, which is undesirable particularly for battery-powered wireless systems. The PM-OFDM-CDMA system is a new version of the OFDM-CDMA system. In this section we present the model of the new PM-OFDM-CDMA system and the model of the fading frequency selective channel.

A. System Model

PM-OFDM-CDMA is based on the modification of the OFDM modulator into a phase modulator which allows to phase modulate the OFDM-CDMA signal. In this way the resulting signal is characterised by its constant amplitude (constant peak power) which is equal to its mean value. Therefore the PM-OFDM-CDMA system has the lowest possible PAPR.

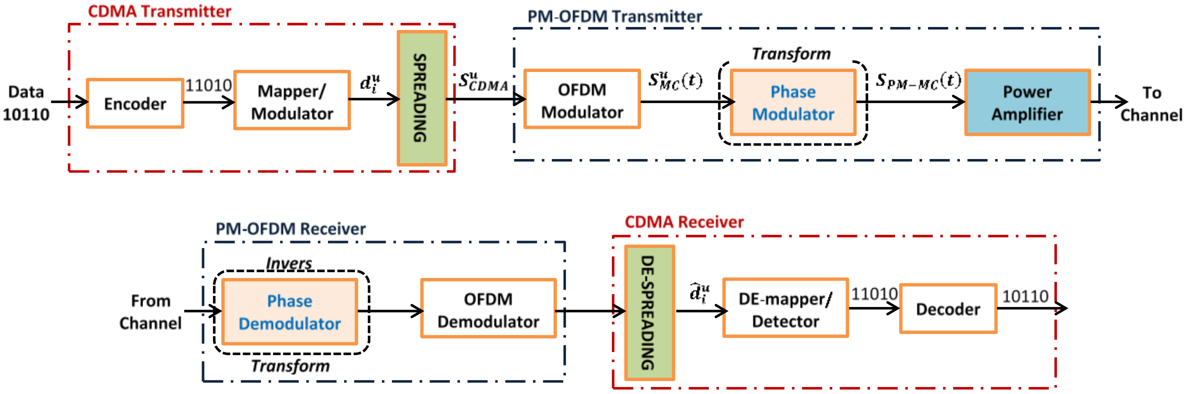

Figure 1. PM-OFDM-CDMA system structure

Figure 1 shows the simple PM-OFDM-CDMA uplink signal flow for the u-th user. Each information symbol $\mathrm{d_i^u}$ is multiplied by the frequency domain spreading sequence chip $\mathrm{CS_k^u}$, followed by OFDM modulation to form the OFDM-CDMA signal of Equation (1).

$$S_{MC}^u(t) = \sum_{k=0}^{N-1} d_i^u CS_k^u e^{2\pi(f_0+k\Delta t)} \delta(t-iT) \qquad (1)$$

where, N is the number of subcarriers, d_i^u is the *i-th* data symbol of the *u-th* user, $f_k = f_0 + k\Delta f$ is a frequency of *k-th* subcarrier, when f_0 is the fundamental transmission frequency and $\Delta f = 1/T$ is the space between two adjusted subcarriers.

CS_k^u, (k=0, 1, … N-1) is the code sequence of the *u-th* user and δ(t) is a rectangular pulse filter defined by

A transformation is applied to the resulting signal to modulate it in phase. In this way we obtain a constant envelope waveform which is characterised by a reduced PAPR.

The $S_{MC}^u(t)$ signal is passed in a phase modulator to obtain the $S_{PM-MC}^u(t)$ signal. The signal at the output of the PM-OFDM-CDMA transmitter is written as follows:

$$S_{PM-MC}^u(t) = Ae^{j\emptyset(t)} \qquad (2)$$

where A is the signal amplitude

The motivation for PM-OFDM is to eliminate the PAPR problem of the conventional OFDM system. So, the instantaneous power of the $S_{PM-MC}(t)$ signal is constant. Therefore, the PAPR of PM-OFDM signal is 0dB.

The phase signal during the *i-th* block for *u-th* user is written as:

$$\emptyset(t) = \theta_i + 2\pi h C_N \sum_{k=1}^{N} d_{i,k}^u \, sub_k(t-iT_B) CS_k^u, \qquad (3)$$

where $iT_B \le t < (i+1)T_B$, h is referred as the modulation index and θ_i is a memory term. The normalising constant, C_N, is

$$C_N = \sqrt{\frac{2}{N\sigma_d^2}} \qquad (4)$$

where σ_d^2 is the data symbol variance:

$$\sigma_d^2 = E\left\{\left|d_{i,k}^u\right|^2\right\} = \frac{M^2-1}{3} \qquad (5)$$

which is only a function of the modulation index. The signal energy is

$$\varepsilon_S = \int_{iT_B}^{(i-1)T_B} |S_{PM-MC}(t)|^2 dt = A^2 T_B \qquad (6)$$

and the bit energy is

$$\varepsilon_b = \frac{\varepsilon_S}{N\log_2 M} = \frac{A^2}{N\log_2 M} \qquad (7)$$

CE-OFDM requires a real-valued OFDM message signal. Therefore, the data symbols are real-valued:

$$d_{i,k}^u \in \{\pm 1, \pm 3, \dots \pm (M-1)\} \qquad (8)$$

This one-dimensional constellation is known as pulse-amplitude modulation (PAM). The subcarriers $\{sub_k(t)\}$must also be real-valued.

In this paper, the discrete cosines transform is used for simulation system.

For *k=1, 2, … N*, half-wave cosines is,

$$sub_k(t) = \begin{cases} \cos\left(\frac{2\pi kt}{T_B}\right), & 0 \le t < T_B \\ 0, & otherwise \end{cases} \qquad (9)$$

Note that the cyclic prefix is used in the OFDM symbol and therefore in the PM-OFDM-CDMA symbol in order to avoid the loss of orthogonality of the sub-carriers in multipath channels. The cyclic prefix is a copy of some final samples of the OFDM symbol which is appended to the data symbol. If the length of the cyclic prefix and the spread of the channel delay are in the same order, the inter symbol interference will be removed (Fazel & Kaiser, 2008). The cyclic prefix does not carry useful information and decreases the efficiency of the spectrum. For example, according to the IEEE802.16.3 standard, if the cyclic prefix is used, 20% of the bandwidth will be lost (Gupta & Tiwari, 2013).

B. Channel Model

The channel is time dispersive having an impulse response $h(\tau)$, that can be non-zero over $0 \leq \tau < \tau_{max}$, where τ_{max} is the channel's maximum propagation delay. The received signal is

$$\begin{aligned} r(t) &= \int_{-\infty}^{+\infty} h(\tau) S_{PM-MC}(t-\tau) d\tau + n(t) \\ &= \int_{0}^{\tau_{max}} h(\tau) S_{PM-MC}(t-\tau) d\tau + n(t) \end{aligned} \tag{10}$$

Where $S_{PM-MC}(t)$ is the CE-OFDM signal and $n(t)$ is the complex Gaussian noise term. The lower bound of integration in Equation (9) is due to the law of causality: $h(\tau)=0$ for $\tau<0$. The upperbound is τ_{max} since, by definition of the maximum propagation delay, $h(\tau)=0$ for $\tau> \tau_{max}$.

Mathematically, linear channels with stochastic temporal variations are described by Bello (Bello, 1963). The widely used assumption of WSSUS (broadly stationary uncorrelated scattering) is applied. In addition, it is assumed that the channel is composed of discrete paths, each having an associated gain and a discrete delay. The impulse response of the channel is

$$h(\tau) = \sum_{p=0}^{P-1} a_p \delta(\tau - \tau_p) \tag{11}$$

where a_p is the complex channel gain and τ_p is discrete propagation delay of the *p-th* path; the total number of paths is represented by P. The delay of the *0-th* path is defined as $\tau_0 \equiv 0$, thus

$$\tau_p = pT_{sa}, \quad p = 0, 1, \dots, P-1 \tag{12}$$

For each simulation trial, the set of path gains $\{a_p\}_{p=0}^{P-1}$ are generated randomly. Each gain is complex valued, has a zero mean and a variance

$$\sigma_{a_p}^2 = E\left\{\left|a_p\right|^2\right\}, \quad p = 0, 1, \dots, P-1 \tag{13}$$

Both the real and imaginary parts of the path gains are Gaussian distributed; thus the envelope $\left|a_p\right|^2$ is Rayleigh distributed. Also, the channels are normalised such that

$$\sum_{p=0}^{P-1} \sigma_{a_p}^2 = 1 \tag{14}$$

CE-OFDM is simulated over two channel models. The first channel is AWGN, but the second is a frequency selective channel. In the case of an AWGN channel, only the Gaussian additive noise n(t) is taken into account.

Frequency-selective fading channel has an exponential delay power spectral density:

$$\sigma_{a_{p,C}}^2 = \begin{cases} Ce^{-\tau_p/2\mu s}, & 0 \leq \tau_p \leq 125ns \\ 0, & otherwise \end{cases} \tag{15}$$

where

$$C_{Ch} = 1 / \sum_{l=0}^{255} \exp(-\tau_l \,/\, 2e-6)$$

is the normalising constant used to guarantee (14). Note that the maximum propagation delay is 125 *ns*.

At the receiver, $r(t)$ is sampled, the guard time samples are discarded, and the block time samples are processed. The discrete time model and the MMSE equaliser described in (Mestoui *et al.*, 2019)are used to simulate the performance of the system.

C. Discrete Model and Equalisation

CE-OFDM has the same block structure as conventional OFDM, with a block period, T_B, designed to be much longer than τ_{max}. A guard interval of duration $T_g \geq \tau_{max}$ is inserted between successive CE-OFDM blocks to avoid interblock interference. At the receiver, $r(t)$ is sampled at the rate $F_{sa} = \frac{1}{T_{sa}} samp/s$, the guard time samples are discarded and the block time samples are processed. Using the discrete-time model, the processed samples are

$$r[i] = \sum_{m=0}^{N_C-1} h[m] S_{PM-MC}[i-m] + n[i], \quad i = 0, \dots, N_B - 1 \tag{16}$$

Note that the eliminated samples are $\{r[i]\}_{i=-N_g}^{-1}$. Transmitting a cyclic prefix during the guard interval makes the linear convolution with the channel equivalent to circular convolution. Thus

$$r[i] = \frac{1}{N_{DFT}} \sum_{k=0}^{N_{DFT}-1} H[k] S_{PM-MC}[k] e^{j2\pi ik/N_{DFT}} \quad i = 0, \ldots, N_B - 1 \tag{17}$$

where {H[k]} is the DFT of {h[i]} and {S[k]} is the DFT of {s[i]}.

$$\hat{S}[i] = \frac{1}{N_{DFT}} \sum_{k=0}^{N_{DFT}-1} R[k] C[k] e^{j2\pi ik/N_{DFT}} \quad i = 0, \ldots, N_B - 1 \tag{18}$$

where {*R*[k]} is the DFT of the processed samples and {*C*[k]} are the equaliser correction terms, which are computed as (Sari, Karam & Jeanclaude, 1995). The MMSE criterion takes into account the signal-to-noise ratio, making an optimum trade between channel inversion and noise enhancement. Notice that the MMSE and ZF are equivalent at high SNR (Thompson, 2005):

$$\lim_{\varepsilon_b/N_0 \to \infty} C[k]|_{MMSE} = \lim_{\varepsilon_b/N_0 \to \infty} \frac{H^*[k]}{|H[k]|^2 + (\varepsilon_b / N_0)^{-1}} = \frac{H[k]}{|H[k]|^2} = \frac{1}{H[k]} = C[k]|_{ZF} \tag{19}$$

III. RESULTS

Performance of the proposed PM-OFDM-CDMA scheme was evaluated on AWGN and Rayleigh fading channel. We have simulated and examined the performance of system and the effect of code length Walsh Hadamard on these performances. The BER results are reported in Figures 2-5.

In this section an *N=128* PM-OFDM-CDMA system is considered, with a block period of $T_B = 500\,ns$. The modulation order is *M=16, 32, and 64*. The subcarrier spacing is $1/T_B = 2MHz$ and the mainlobe bandwidth is $W = N/T_B = 256\,MHz$. The guard period is $T_g = 125\,ns$, resulting in a transmission efficiency $\eta_t = \frac{500}{625} = 0.8 = 80\%$.

First, the PM-OFDM-CDMA system with M=16, 32 and 64 is simulated through an AWGN channel. The simulation uses an oversampling factor *J=8*; therefore, the sampling rate is $f_{sa} = JN/T_B = 4096\ Msamp/s$, and the sampling period is $T_{sa} = 1/f_{sa} \approx 0.244\ ns$. In Figure 2, the performances in terms of BER for the PM-OFDM-CDMA system for 2πh = 0.7 and J=8 are shown. It is clear that we are seeking to increase the bit rate, the performance of the system is all the less as the order of modulation M increases. For example, to have a BER of 10-4, for M = 16 we need an $SNR \approx 25dB$ while for M = 64 we don't need more energy with an $SNR \approx 35dB$.

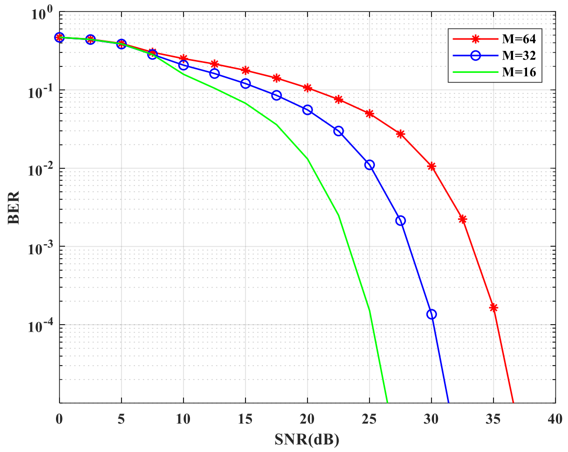

Figure 2. BER performance of PM-OFDM-CDMA for AWGN channel (2πh=0.7 and J=8)

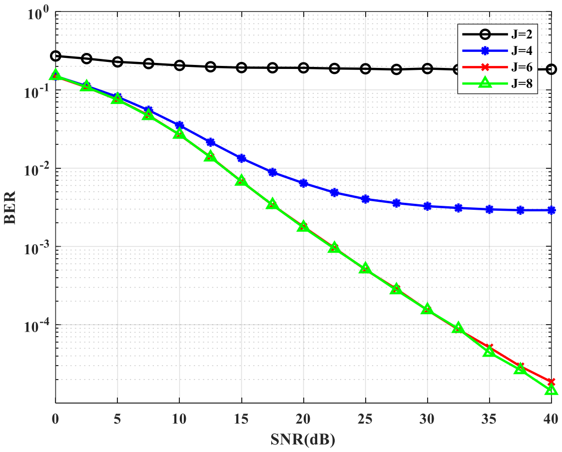

Figure 3. BER performance of PM-OFDM-CDMA for Rayleigh channel (2πh=0.7 and M=16)

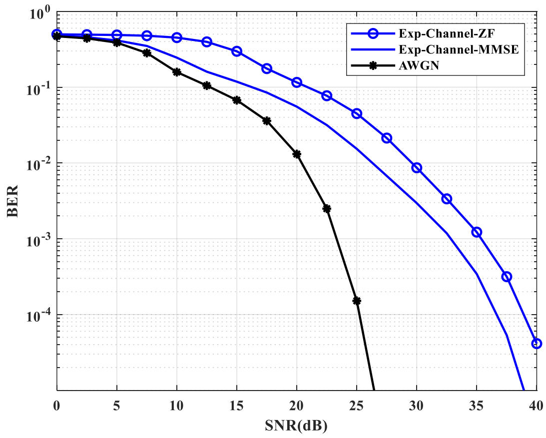

Figure 4. BER performance of PM-OFDM-CDMA (M=16) for AWGN channel and Exp_Channel with equalisation

In Figure 3, the performances in terms of BER for the PM-OFDM-CDMA system for M=16, 2πh = 0.7 and J = 2, 4, 6 and 8 are presented. This figure demonstrates the effect of the oversampling factor J on the performance of the system through a Rayleigh channel. It can be concluded that better performance is obtained as the J factor increases.

In Figure 4, BER versus mean SNR is plotted with and without estimation schemes for an exponential power density channel. The 16QAM modulation, a DFT of size NDFT = 1024 and 2πh=0.7are used in the simulation. The results of Figure 4 show that the system gives better performance for an AWGN channel. On the other hand, when using an exponential density channel, the performance of the system with MMSE equalisation is better than that of the ZF at high SNRs.

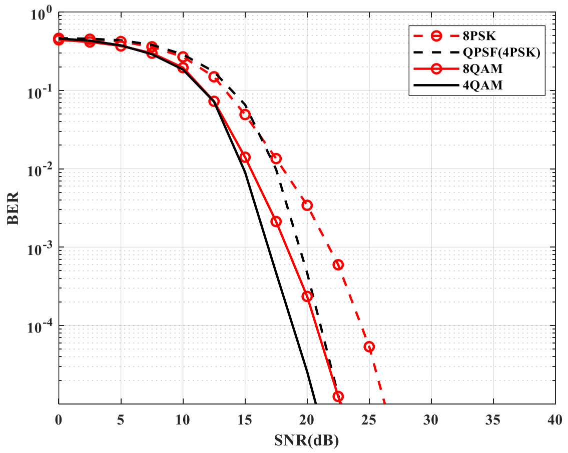

Figure 5. BER performance of PM-OFDM-CDMA (2πh=1.0) for Exp_Channel with equalisation

Figure 5 presents the performances in terms of Binary Error Rate for the M-PSK and M-QAM modulations of a PM-OFDM-CDMA system for a frequency-selective exponential power density channel with a Cyclic-Prefix duration of 125 ns. From Figure 5, it can be shown that the proposed system gives better results with an M-QAM constellation than with an M-PSK constellation.

Figure 6 compares the performance of a PM-OFDM-CDMA system with N = 512, M = 64 and h varying on a Rayleigh fading channel. If the desired BER is less than or equal to 10-3, with 2πh = 1.0 we only need an SNR = 21.5dB, on the other hand with 2πh = 0.2 we need more energy (SNR = 37.5dB).

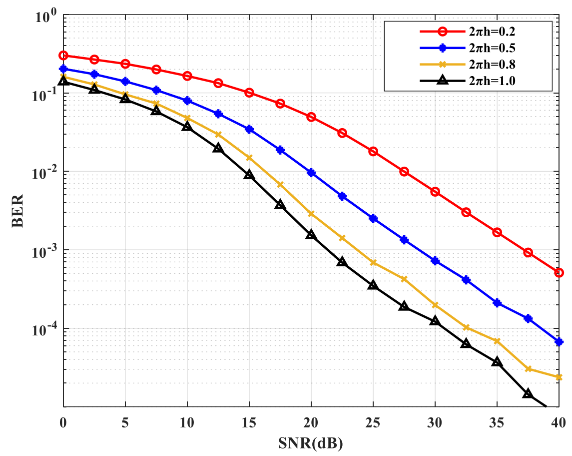

Figure 6. BER performance of PM-OFDM-CDMA for Rayleigh channel (M=64, N=512)

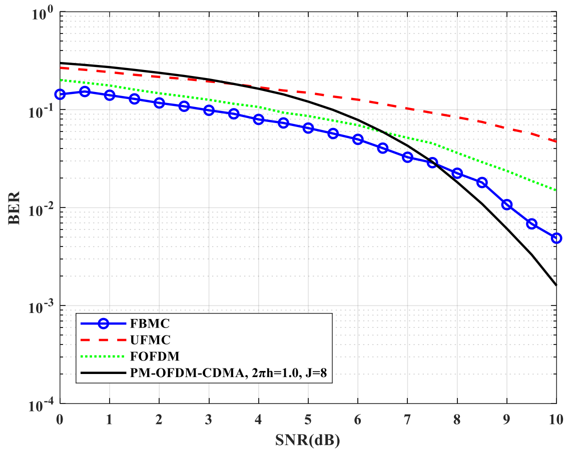

Figure 7. BER performance of PM-OFDM-CDMA vs. FBMC, UFMC and FOFDM on AWGN channel

In the simulation shown in Figure 7, a PM-OFDM-CDMA system with M = 4, 2πh = 1.0, N = 128 and J = 8 is considered, i.e., the number of NDFT points = 1024. The performance of this system is compared with that of the FBMC, UFMC and FOFDM schemes, respectively using the same simulation parameters (M = 4, N = 128 and NDFT = 1024). From these results, we can note that at low SNR, the FBMC waveform is the most efficient in terms of BER. However, PM-CE-OFDM gives the best performance at high SNR.

IV. CONCLUSION

In this paper, we have described a phase transform multiple access scheme based on the principle of code division multiple access (CDMA) and the OFDM orthogonal multicarriers signal waveform. This technique can be seen as an extension of MC-CDMA to accommodate a larger number of users. A very distinctive feature is that unlike many CDMA multicarrier approaches in the literature, the proposed scheme does not require any reduction in PAPR because the new waveform has a constant power which leads to the lowest possible PAPR. In addition, the fact that it combines the CDMA with the orthogonality characteristic of phase transforming subcarriers makes the proposed technique particularly attractive for multi-users concept with the advantage of better energy efficiency. Thus, PM-OFDM-CDMA technique is a suitable scheme for 5G applications.

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