Polynomial-Based Compressing and Iterative Expanding for PAPR Reduction in GFDM

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***Abstract*—GFDM (generalized frequency division multiplexing) is a non-orthogonal waveform that is being discussed as a candidate for the fifth generation of wireless communication systems (5G). GFDM is a multicarrier technique with circular pulse shaping that is designed in a way to address emerging applications in 5G networks such as *Internet of Things* (IoT) and *machine-to-machine* communications (M2M). The same as other multicarrier systems, GFDM suffers from a high peak to average power ratio (PAPR). To attack PAPR problem, in this paper, we propose a polynomial based companding method with iterative expansion that is called polynomial-based companding technique (PCT). Based on our simulation results, a great amount of PAPR reduction can be achieved through utilization of our proposed technique. Through simulations, we have also investigated the bit error rate (BER) performance of the system while adopting our PCT method. Our simulations reveal that there is a tradeoff between PAPR reduction and BER performance.**

***Keywords*—PCT method, GFDM, PAPR, companding.**

I. Introduction

Due to their robustness against multipath fading channels and the ease of equalization, multicarrier modulation techniques have been widely used in communication systems. In particular, orthogonal frequency division multiplexing (OFDM) has been the technology of choice for a large number of wired and wireless standards, such as asymmetric digital subscriber loop (ADSL), [1], power line communication systems, [2], LTE and WiMAX, [3]. However, OFDM has some limitations such as its large out-of-band emissions which is its limiting factor for utilization of non-contiguous spectrum and its sensitivity to synchronization errors specifically carrier frequency offset (CFO). The advent of new applications such as *machine-to-machine* communications (M2M), i.e., the massive wireless connectivity of machines with each other without human intervention, and *Internet of Things* (IoT), [4], in the fifth generation of wireless communication systems (5G) imposes some requirements to the network. For instance, in the uplink of a network with a large number of embedded devices or machines where freuency division multiple access (OFDMA) is deployed, a large amount of multiple access interference (MAI) is caused by multiple CFOs. To avoid this interference, stringent synchronization is required which imposes a large amount of overhead to the network. In order to relax the synchronization requirements and hence reduce the network overhead, the MAI problem can be tackled with a wide range of different solutions that are proposed in [5]–[8]. However, these techniques lead to a large amount of receiver complexity which makes OFDMA unattractive for such applications. Hence, waveforms with a more relaxed synchronization requirements and more localized signals in time and frequency are needed to suit the future 5G networks without the high MAI or receiver complexity penalty. To address these aspects, the innovative multicarrier systems have been candidate, namely Filter-bank Based Multicarrier (FBMC) [9], Universal Filtered MultiCarrier (UFMC) [10], Biorthogonal Frequency Division Multiplexing (BFDM) [11], and Generalized Frequency Division Multiplexing (GFDM) [12], which is the topic of interest in this paper.

Based on its appealing properties, GFDM has been recently discussed as a candidate waveform for 5G and has received a great deal of attention, [11]. GFDM is a flexible multicarrier modulation scheme that can be considered as a subset of “filtered multicarrier techniques” [13]. From filter bank point of view, GFDM is an FBMC system with circular filtering in subcarrier level rather than linear filtering which is the case in the conventional FBMC systems. In this system, a two-dimensional block comprised of data symbols spread over time-frequency resources is communicated through circular pulse shaping that is known as tail biting, [12]. Tail biting preserves circular properties across time and frequency domain in order to prevent rate loss incurred due to long cyclic prefix (CP) requirement [12]. In other words, GFDM removes the ramp-up and ramp-down of the filtered multicarrier signal, i.e., due to the transient of the prototype filter, through circular pulse shaping.

One of the major drawbacks of every multicarrier system is their high peak-to-average-power ratio (PAPR). To address this problem, essential features of GFDM such as possibility of reducing the number of subcarriers and changing the parameters of the pulse shaping filter, are considered in [12] and [13]. However, in any multicarrier system, reducing the number of subcarriers always leads to PAPR reduction and does not solve the issue. As a result, there still is the need for reducing the peak values to the lowest level possible while having a large number of subcarriers. Despite the large

978-1-4799-1972-7/15/$31.00

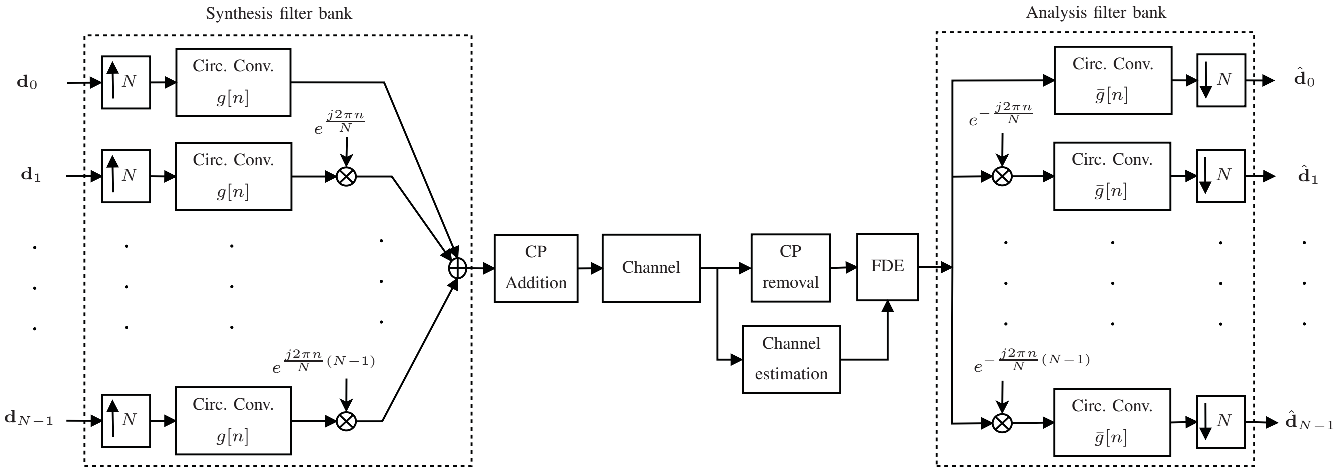


Fig. 1. Baseband block diagram of a GFDM transceiver system

number of PAPR reduction techniques that are available for the other multicarrier schemes, only one solution has been proposed for GFDM, [14] that translates one of the classic PAPR reduction techniques that has been proposed for OFDM to GFDM. Hence, these systems are still in their infancy and more research is needed to effectively attack the PAPR problem while keeping the performance degradation penalty at a satisfactory level.

To address the PAPR problem, in this paper, we extend the "polynomial-based companding technique" (PCT) that was previously proposed in [15] for OFDM to GFDM. The challenge in this paper is to modify PCT in a way to make it applicable to GFDM. In this technique, a polynomial-based compressing function is used at the transmitter side and an iterative algorithm is applied at the receiver as a dual of the transformation that is performed at the transmitter. This leads to a small increase in required signal to noise ratio (SNR) to reach at a given bit error rate (BER) in the expanding operation compared with other companding methods. In [15], expanding is combined with the fast fourier transform (FFT) block and hence is considered as a part of demodulation procedure. Accordingly, it is not straightforwardly applicable to GFDM or other multicarrier techniques. Hence, one of the main contributions of this paper is to generalize the expanding procedure at the receiver and make it applicable to any multicarrier modulation technique. Based on our simulation results, PCT can effectively reduce PAPR in GFDM while maintaining a satisfactory BER performance. Our numerical analysis reveals that there is a trade-off between computational complexity, PAPR reduction ability, and BER performance.

The rest of this paper is organized as follows. Section II is dedicated to GFDM system model. PAPR problem is explained in Section III and the proposed PAPR reduction method is described in Section IV. Simulation results and discussions are included in Section V. Finally, conclusions are drawn in Section VI.

II. GFDM System Model

The baseband block diagram of the GFDM transceiver is shown in Fig. 1 where the high rate data stream $\mathbf{d}$ is split into N low rate sub-streams, i.e., $d_k[m]$'s and transmitted over N subcarriers with circular pulse shaping. In GFDM, a group of overlapping symbols in time domain with circular pulse shaping are carrying information. Thus, it can be considered as a generalized form of OFDM, [16]. The following subsections briefly cover the GFDM transmission and reception.

A. Transmitter

From Fig. 1, GFDM transmitter can be thought of as a synthesis filter bank with circular filtering. In the first step, the high rate data stream, $\mathbf{d} = [\mathbf{d}_0^{\mathrm{T}}, \ldots, \mathbf{d}_{N-1}^{\mathrm{T}}]^{\mathrm{T}}$, consisting of quadrature amplitude modulation (QAM) symbols is split into a number of low rate sub-streams with the rate N times lower than $\mathbf{d}$. Therefore, $\mathbf{d}_k^{\mathrm{T}} = [d_k[0], \ldots, d_k[M-1]]$ where M is the number of data symbols that are carried over each subcarrier band. To put it differently, $d_k[m]$ is carried over the kth subcarrier and the mth time slot. In the second step, the data symbols $d_k[m]$ are over-sampled with the factor of N. In the next step, the over-sampled symbols are circularly convolved with the transmit filter $g[n]$, modulated with the corresponding carrier frequencies and added to each other. It is worth mentioning that the transmit filter $g[n]$, has the length MN samples. Finally, after addition of M symbols, a CP which contains the last N_{CP} samples of each GFDM block is added to the beginning of the signal to form the transmit signal.

To cast the aforementioned process into a mathematical formulation, the GFDM transmit signal in the baseband can be written as

$$x[n] = \sum_{m=0}^{M-1} \sum_{k=0}^{N-1} d_k[m] g[(n - mN) \bmod MN] e^{j\frac{2\pi kn}{N}}, \quad (1)$$

where $n = 0, \ldots, MN-1$. In order to avoid inter frame interference (IFI), a CP with the length $N_{\mathrm{CP}} \geq N_{\mathrm{ch}}$ is added to the resulting signal from (1), in the same way as in OFDM systems [17].

Gathering all the output samples from the GFDM modulator in an $MN \times 1$ vector $\mathbf{x} = [x[0], \ldots, x[MN-1]]^{\mathrm{T}}$, equation

(1) can be reformulated as multiplication of an $MN \times MN$ modulation matrix $\mathbf{A}$ to the vector $\mathbf{d}$, [18].

$$\mathbf{x} = \mathbf{A}\mathbf{d}. \quad (2)$$

Matrix $\mathbf{A}$ includes all the signal processing steps involved in GFDM modulation and its elements can be represented as

$$[\mathbf{A}]_{nm} = g[(n - mN) \bmod MN] e^{j\frac{2\pi n}{N}\lfloor \frac{m}{M} \rfloor}, \quad (3)$$

where $m, n = 0, \ldots, MN - 1$ and $\lfloor \cdot \rfloor$ is the round down operator.

B. Receiver

The received signal, after removing CP can be written as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{v}, \quad (4)$$

where $\mathbf{v} \sim \mathcal{N}\left(0, \sigma^2 \mathbf{I}_{MN}\right)$ is the additive white Gaussian noise (AWGN) vector with the variance σ^2 and $\mathbf{I}_{MN}$ is an identity matrix of the size $MN \times MN$. $\mathbf{H}$ is the channel matrix which circulant with the first column $\mathbf{h}$, where $\mathbf{h}$ is the time domain channel impulse response. Therefore, the channel distortions can be compensated using a frequency domain equalizer (FDE), [3]. In this paper, an AWGN channel is considered where $\mathbf{H} = \mathbf{I}_{MN}$. Thus, $\mathbf{y} = \mathbf{x} + \mathbf{v}$.

From Fig. 1, one realizes that the next step after the FDE block for each subcarrier, say, the k th one, is to down-convert the signal to the baseband using the carrier frequency $f_k = \frac{2\pi k}{N}$ and circularly convolve it with the receiver filter $\tilde{g}[n]$.

So far, three receiver methods have been proposed in the literature, [11], namely; matched filter (MF), zero forcing (ZF) and minimum mean square error (MMSE). In this paper, we consider the the ZF receiver that can be obtained as

$$\hat{\mathbf{d}} = \mathbf{A}^{+}\mathbf{y}, \quad (5)$$

where $\mathbf{A}^{+} = \left(\mathbf{A}^{\mathrm{H}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{H}}$ is the pseudo inverse of $\mathbf{A}$. It is worth noting that equation (5) is for the general case where the number of active subcarriers K is smaller than or equal to N and hence the matrix $\mathbf{A}$ is not square. In this case, $\mathbf{A}$ becomes an $MN \times MK$ matrix and the vector $\hat{\mathbf{d}}$ becomes $MK \times 1$. Therefore, the corresponding columns of the matrix A defined in (3) is removed.

III. PAPR Problem

Due to the constructive superposition of the subcarriers in multicarrier modulation techniques, large peaks often appear in the transmit signal. The ratio between the power of these peaks and the average power of the multicarrier signal is called PAPR. PAPR is a metric that defines the dynamic range or variations of the power of the transmit singal. Large PAPR can saturate the power amplifier (PA) and cause nonlinearity which creates a large amount of distortion and hence degradation in the BER performance, i.e., due to the interference among the adjacent channels, [19]. This is due to the appearance of inter-modulation products which leads to out of band radiation regrowth. PAPR of the transmit signal is defined as

$$\text{PAPR}(x[n]) = \frac{max|x[n]|^2}{\mathbb{E}[|x[n]|^2]}, \quad (6)$$

where $\mathbb{E}\left[\cdot\right]$ is the expectation operator.

The available PAPR reduction methods for multicarrier signals can be categorized into two main groups. The first group includes distortion-less techniques which are applied before the multicarrier modulation. However, such techniques suffer from a number of weaknesses such as high computational complexity, overhead due to side information, restrictions on system parameters and rate reduction, [15]. The second group is comprised of signal distortion methods that put a transformation on the signal after multicarrier modulation. The BER degradation is the main drawback of these techniques. Companding is one of the effective signal distortion methods with low complexity and no bandwidth expansion. PCT, which is of interest to this paper, is a type of companding techniques which aims at decreasing the computational complexity and BER performance loss at the same time, [15].

IV. The Proposed Method

A. Compressor at the Transmitter

In PCT, a compressor function is added at the output of the GFDM transmitter before any CP insertion. The main characteristics of this compressor function with the normalized input are highlighted in the following.

- It has one-to-one mapping, in order to be a reversible function. This enables the receiver to recover the desired samples by inverting the transformation that is performed at the transmitter.
- Increasing transform to keep the sign of the input.
- It has odd symmetry, in order to identically provide the same effect for both positive and negative data.
- It takes the minimum and maximum values at (-1,-1) and (1,1), respectively.
- It provides the steepest possible slope at the original and the lowest slope at the boundary points for effective PAPR reduction.
- The polynomial function is close to μ-law compressor.

Therefore, the arbitrary function of the order P can be derived directly from the above characteristics as

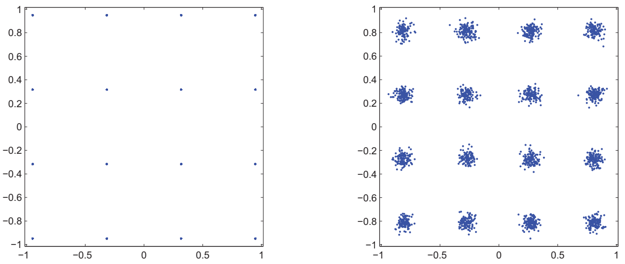
$$f(x) = a_p x^P + a_{P-2} x^{P-2} + \ldots + a_5 x^5 + a_3 x^3 + a_1 x, \quad (7)$$

where the coefficients of the polynomial, a_is, can be adapted by a variable change in the Daubechies wavelets [15]. The general form of the obtained compressor function can be obtained as

$$f(x) = 1 - (\frac{1}{2})^{\frac{P-1}{2}} (1-x)^{\frac{P+1}{2}} \sum_{n=0}^{\frac{P-1}{2}} (\frac{1}{2})^n \binom{\frac{P+1}{2}+n}{n} (x+1)^n. \quad (8)$$

B. Expander at the Receiver

In this subsection, we propose a generalized form of PCT expanding method which is applicable to all the multicarrier modulation schemes including GFDM. In the PCT expander, an iterative algorithm is employed rather than compressor reverse function. The aim is to find the expanded received vector, $\mathbf{y}_{\text{Expanded}}$, which is fed to the GFDM receiver.



(a) original signal (b) compressed signal

Fig. 2. Normalized constellation map of the GFDM signals for data block with a size of 256 in 16-QAM constellation

According to Fig. 2, the normalized distribution of constellation map does not change significantly for compressed data compare to original ones . So $\mathbf{y}$ is a defensible select as the initial value of the expanded received signal.

$$\mathbf{y}^{(1)}_{\text{Expanded}} = \mathbf{y}.$$

Starting from this initial value, $\mathbf{y}_{\text{Expanded}}$ of the $(m+1)$th step can be calculated based on its value in the previous step, (m), according to the following algorithm.

1) Calculate the compressed version of $\mathbf{y}^{(m)}_{\text{Expanded}}$, where $j = \sqrt{-1}$ and (m) denotes the iteration number

$$\hat{\mathbf{x}}^{(m)} = \sum_{k=0}^{\frac{P-1}{2}} a_{2k+1}\Big(\mathcal{R}\{\mathbf{y}^{(m)}_{\text{Expanded}}\}\Big)^{2k+1} + j\sum_{k=0}^{\frac{P-1}{2}} a_{2k+1}\Big(\mathcal{I}\{\mathbf{y}^{(m)}_{\text{Expanded}}\}\Big)^{2k+1}. \quad (9)$$

2) Calculate the estimated data, $\hat{\mathbf{d}}^{(m)}$, according to PCT method

$$\hat{\mathbf{d}}^{(m)} = \mathbf{A}^{+}\Big(\Big(\mathbf{y} - \hat{\mathbf{x}}^{(m)}\Big)/a_1 + \mathbf{y}^{(m)}_{\text{Expanded}}\Big). \quad (10)$$

3) Calculated $\mathbf{y}^{(m+1)}_{\text{Expanded}}$ according to estimated data

$$\mathbf{y}^{(m+1)}_{\text{Expanded}} = \mathbf{A}\hat{\mathbf{d}}^{(m)}. \quad (11)$$

It is clear that the last two stages can be performed together without the need of the matrix operation.

To assess the accuracy of the estimate in the second sentence, we note that regardless of the noise, $\mathbf{y}$ applies at the following approximate

$$\mathbf{y} \simeq \sum_{k=0}^{\frac{P-1}{2}} a_{2k+1}(\mathcal{R}\{\mathbf{Ad}\})^{2k+1} + j\sum_{k=0}^{\frac{P-1}{2}} a_{2k+1}(\mathcal{I}\{\mathbf{Ad}\})^{2k+1}. \quad (12)$$

Replacing equations (12) and (9) in equation (10) and use the first element of the summation as the approximation of the compressor function, will result

$$\hat{\mathbf{d}}^{(m)} \simeq \mathbf{A}^{+}\Big(\Big(a_1\mathbf{Ad} - a_1\mathbf{y}^{(m)}_{\text{Expanded}}\Big)/a_1 + \mathbf{y}^{(m)}_{\text{Expanded}}\Big) = \mathbf{d}. \quad (13)$$

By continuing algorithm $\hat{\mathbf{d}}^{(m)}$ more matched to $\mathbf{d}$.

It is noteworthy that the first step of this algorithm can be divergent if the range of the input data falls outside (-1,1), because of low SNR condition. Hence, the following function is applied to the inputs of (9)

$$T(x) = \begin{cases} x, & -1 \le x \le 1, \\ 1, & x > 1, \\ -1, & x < -1. \end{cases} \quad (14)$$

V. Simulation Results

In order to confirm the efficacy of the proposed technique, we have evaluated PAPR as well as BER performance of a GFDM system with the raised cosine (RC) pulse shaping filter. An RC filter with a roll-off factor of 0.1 is considered. PAPR performance of the proposed technique is evaluated trough transmission of 10^5 randomly generated set of data symbols with 64-QAM constellation. PAPR performance is presented based on the complementary cumulative distribution function (CCDF) graph. The BER performance of the system is also investigated.

A. CCDF of Required PAPR

The CCDF of the original and compressed GFDM signals with (M, K) = (1,1300), (13,100), and (65,20) are presented in Fig. 3 where the polynomial with the order of 25 is used for compressing. This figure confirms the better PAPR performance for the lower number of subcarriers and shows the effect of the proposed method in different conditions. As shown, although decrease in the number of subcarriers leads to a reduced PAPR, utilization of the proposed method can significantly reduce PAPR for all the cases.

Fig. 4 compares PAPR performance of the original signals, i.e., the plain OFDM and GFDM signals without PCT, with their compressed version. The polynomials of the orders 3, 11, 25 and 55 and total number of 256 subcarriers are considered for both OFDM and GFDM systems.

From Fig. 4, one realizes that in this case the PAPR of the OFDM is slightly less than GFDM. To investigate the reason, we note that OFDM signal is a summation of exponential terms limited with a rectangular window, while GFDM is a summation of the same exponential terms limited with the main lobe of an RC filter. Given the assumption of having a normalized filter, the average power of GFDM signal certainly decreases by applying windowing while it remains constant for OFDM. This is despite the fact that only in some cases a significant reduction in peak power of the GFDM is created. Therefore, PAPR is the same for the summation of exponential terms and OFDM signals, while it statistically grows for the GFDM.

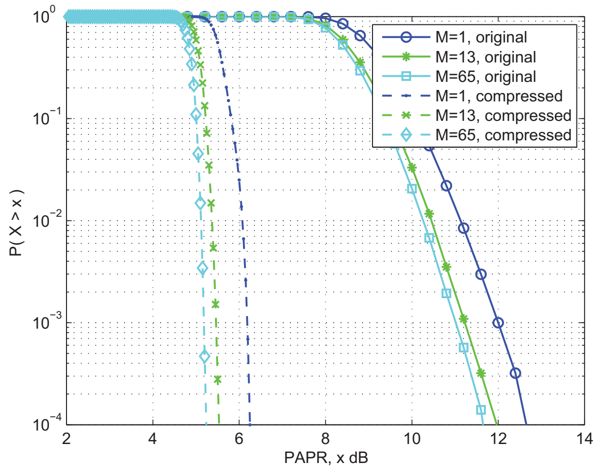


Fig. 3. The CCDF of PAPR of original and compressed GFDM signals with 1, 13, and 65 time slots

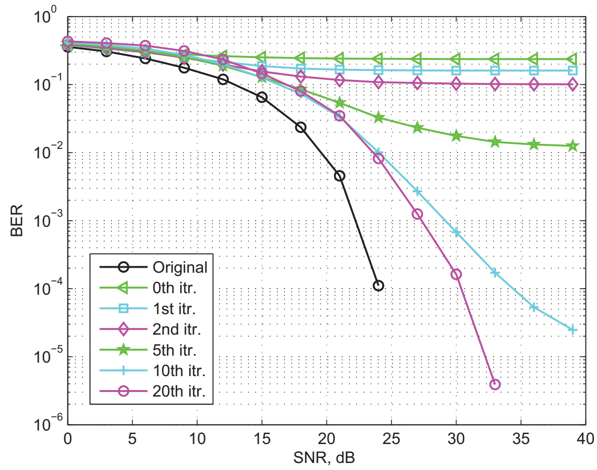


Fig. 5. Effect of iteration on system performance for the 7th order polynomial

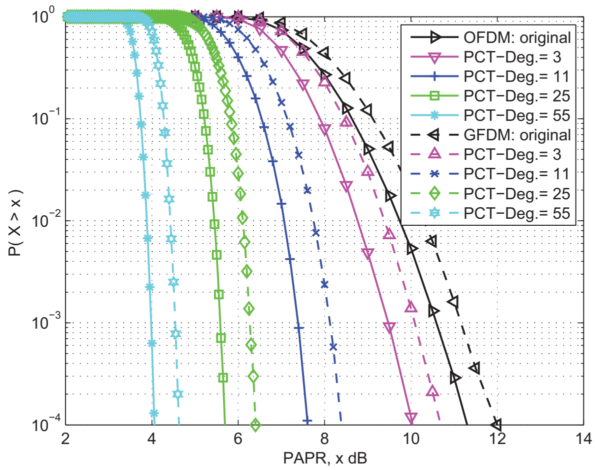


Fig. 4. The CCDF of PAPR of original and compressed signal for both OFDM and GFDM systems

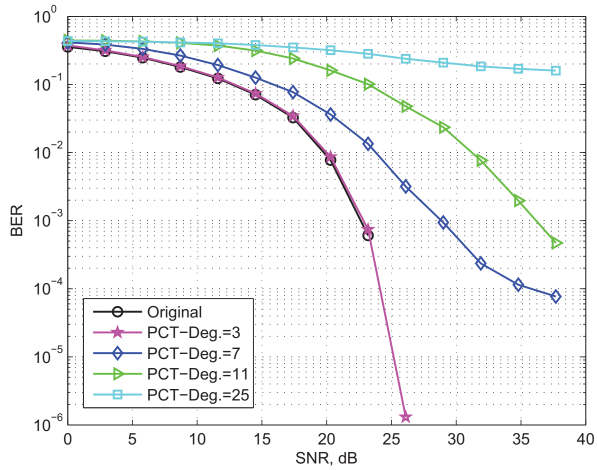


Fig. 6. System performance for original and compressed GFDM signals

In addition, Fig. 4 highlights the fact that the proposed algorithm reduces PAPR in both systems effectively and the reduction has a direct relationship with increasing the order of the polynomial.

B. BER

In this subsection, the BER performance of the receiver for different number of iterations is evaluated and compared to the original GFDM signal that is generated using an RC filter with the roll-off factor of 0.1. $M = 5$ time slots and $K = 256$ subcarriers for the 7th order polynomial is considered here. According to Fig. 5, the larger number of iterations the better the BER performance. Hence, there is a trade-off between the number of iterations and BER performance. As a result, a suitable number of iterations can be selected for every polynomial order.

Fig. 6 shows the effect of different polynomial orders where suitable number of iterations are chosen at the receiver. In this figure, 3, 9, 49 and 49 iterations are selected for the polynomial orders 3, 7, 11 and 25, respectively. By combining the results of both Figs. 6 and 4, it can be concluded that there is an inverse relationship between the PAPR reduction ability and BER Performance.

VI. Conclusion

In this paper, an effective PAPR (peak to average power ratio) reduction for generalized frequency division multiplexing (GFDM) is proposed. The proposed technique is based on application of a polynomial compressor at the transmitter and an iterative expander at the receiver side. This method is called "polynomial-based companding technique" (PCT) and was previously proposed for PAPR reduction in orthogonal frequency division multiplexing (OFDM), [15]. However, application of PCT to other multicarrier systems is not straightforward. Therefore, we have introduced a generalized version of PCT which makes it applicable to any multicarrier system. The efficacy of our proposed technique has been shown through simulation results. It was shown through our numerical analysis that increasing the polynomial order reduces the PAPR on one hand; on the other hand, it increases the complexity as well as bit error rate (BER) for a given signal to noise ratio. Thus, there is a trade-off between computational complexity, PAPR reduction capability, and BER performance.

In this paper, we have applied PCT to GFDM. In our future work, we will analyze the performance of PCT when applied to other candidate waveforms that are proposed for the fifth generation of wireless communication systems (5G). In our future study, we will investigate the BER performance in multipath wireless channels in addition to additive white Gaussian channels. Finally, detailed computational complexity analysis of the proposed technique will be included in our future work.

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