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Intelligent Optimization of PC-GFDM Transceiver

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Abstract: Generalized frequency division multiplexing (GFDM) presents an outstanding performance in out-of-band, latency, and peak-to-average power ratio, Thus, promoting it to be the most contender for the fifth generation and beyond. This paper evaluates the performance of the GFDM transceiver system with polar code (PC) and interleavers based on the bit error rate (BER). The proposed system is enhanced by artificial intelligence, which is the genetic algorithm (GA) used to optimize the parameters of the pulse shaping filter (G) and the artificial neural network (ANN) used in improving method-based least square (LS) channel estimation dataset. At each step of evaluating the performance computed based on BER vs. SNR. The optimized PC-GFDM enhances over standard GFDM by 0.0649 in BER at 28 SNR.

Keywords: ANN, Channel estimation, GA, GFDM, Interleaver, PC.

1. Introduction

Generalized frequency division multiplexing (GFDM) is an innovative multi-carrier waveform method. Offer exciting features, efficient PAPR, and low OOB [1]. Features flexible structure with subcarrier, sub-symbol, and G. When the subcarriers are filtering, the diverse pulses can be employed to adjust the BER and the spectral efficiency. GFDM is designed based on the time-frequency structure to approve the requirements of all kinds of applications. Thus, it is the next-generation candidate for communication systems [2, 3]. In order to optimize the GFDM transceiver, various types of technology and algorithms are added, such as polar code (PC), interleaver, genetic algorithm (GA), artificial neural network (ANN), estimation, equalization, Etc.

PC is the coding of the channels that first appeared by Arıkan in 2009. Its operation is based on channel polarization for binary input symmetric discrete memoryless channels and its present capacity-achieving channel with suitable complexity for the encoder and decoder. The code construction is based on channel polarization, generating extremal bits (noisy or noiseless) from independent uses bits. The data send over the perfect channel while frozen bits are specialized to the noisy channel [4].

The artificial intelligence present over performance which the ANN with different training methods for backpropagation algorithm used in channel estimation. ANN is required to train before making estimations, and this algorithm presents an active learning process to minimize the error [5]. The GA is a type of heuristic optimization algorithm that simulates the selection and evolution of the natural, which is used to search for the best parameters of the G [6]. Its operation is based on generating the initial operation and then repeatedly calculating the fitness function, the crossover, and mutation [7].

To evaluate the 5G and beyond of wireless communication, many researchers present scientific proposals for GFDM transceiver systems to improve the performance-based BER vs. SNR as follows: Dias et al. 2019 present a new receiver structure under frequency selective fading channel trade-off between the complexity and the performance. The new structure is applied under the frequency domain's MMSE sense [8]. SIM et al in 2020, present design of pulse shaping filter based quadratic programming approach, this approach gives numerical enhancement in BER, spectral efficiency and OOB [9]. Maras et al., in 2021, met the requirement of 5G by using walsh–hadamard transform- lifting wavelet transform (WHT-LWT), which presents the enhancement in BER, OOB, PAPR, and latency [10]. KIM et al. 2022 proposed two types of receivers based on minimum mean square error and -successive interference cancellation (MMSE-SIC) to enhance the out-of-band emission (OOBE), PAPR, and throughput and reduce the BER [11].

All the works presented above differ radically from the proposed scenarios, and this indicates the importance of this work.

This paper presents enhancement scenarios for GFDM system-based Rayleigh fading channel. The channel response is estimated based on LS. The enhancement of this system is presented based on PC, interleaver, GA, and ANN. The PC performs the coding system, and the interleaver support the PC by shuffling the bits hence converting burst error to random error. The GA is used to assign G parameters based on minimum BER, and the ANN performs the estimation-based dataset generated from LS estimation. All the enhancement steps are presented based on BER with respect to SNR.

2. Theoretical background

This section presents the theoretical background of GFDM, PC, interleavers, channel estimation, GA, and ANN.

2.1 GFDM

The primary motivation of preference for GFDM is the flexible use of a multi-carrier filter bank. The spectrum region is split into a set of non-orthogonally spectral segments by a developed method to reduce the emission [12]. Hence removed the orthogonality restrictions related to subcarrier spacing and applied the filtration at each subcarrier. The G is flexibly used over the subcarrier level of the waveform [13].

On the transmitter side, in the mapper, the binary stream is transformed into complex numbers in the frequency domain depending on the mapping order. The next step is entered to GFDM modulation, as in Fig. 1, by applying S/P and each subcarrier oversampled by the K factor (where K represent the total number of subcarrier). The demodulation steps are inverse to the GFDM modulation, [14].

In the filtration step, the oversampled subcarrier performs convoluted separately by the related filter. The orthogonality is no longer fulfilled for every frequency subcarrier; hence the characteristics of each subcarrier can be changed. In the GFDM, the data block has N size containing K frequency of subcarriers and M subsymbols time slot, which N=KM. The cyclic prefix adds after each block to reduce the ISI and increase robustness. This is done flexibly in assigning its length and becomes fitted with a variant range of applications. In the receiver, perform the opposite stage with an additional technique to increase the efficiency of receiving the signal well. Hence, improve the BER performance by interference cancellation and equalization techniques [15]. The mathematical model of the GFDM presents in Eqs. (1-3) [16].

$$x[n] = \sum_{m=0}^{M-1} \sum_{k=0}^{K-1} d_{m,k} g_{m,}[n] \quad (1)$$

$$g_m[n] = g[(n-mk)_{\mathrm{mod}\,N}] \exp\left(-j2\pi \frac{kn}{K}\right) \quad (2)$$

$$g[n] = \frac{\mathrm{sinc}(n) * \cos(\pi * a * n)}{1-(4 * a^2 * n^2)} \quad (3)$$

Where, $n = 0, \dots, N-1$, x[n] is the transmitted signal. [n] is the sampling index. $d_{(m,k)}$ is the complex data belonging to the kth subcarrier and mth sub- symbol. g is the prototype pulse filter. N is equal to MK. α is the roll-off factor.

2.2 Polar code

The transmitted data through wireless channels affect by noise and interference. Hence the channel coding is used to enable the receiver to detect and correct the errors that occur over the transmitter. Block codes are a significant type of channel codes, which fragment original data into blocks under a given length. PC is one type of block code promising in forwarding error correction codes. The encoder of PC is based on kernel matrix (F) as in Eq. (4) and Kronecker product as in Eq. (5). The m-bit polar encoder is present in Eq. (6) and Fig. 2. The mth Kronecker product of F ($F^{\otimes m}$) is defined in Eq. (7), Where $m = \log_2 n$ and n length of encoded bits [17].

$$F = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \quad (4)$$

$$[u_1 \;\; u_2]G_2 = u^{(2)} = [u_1 + u_2 \;\;\; u_2] \quad (5)$$

$$F^{\otimes m} = \begin{bmatrix} F^{\otimes m-1} & 0 \\ F^{\otimes m-1} & F^{\otimes m-1} \end{bmatrix} \quad (6)$$

$$u^{(m)} = uF_m \quad (7)$$

Where: + is XOR operation, $F^{\otimes 1}$ =F, u is the data.

The PC performs the demodulator in the receiver to recover the original data. The data cannot be

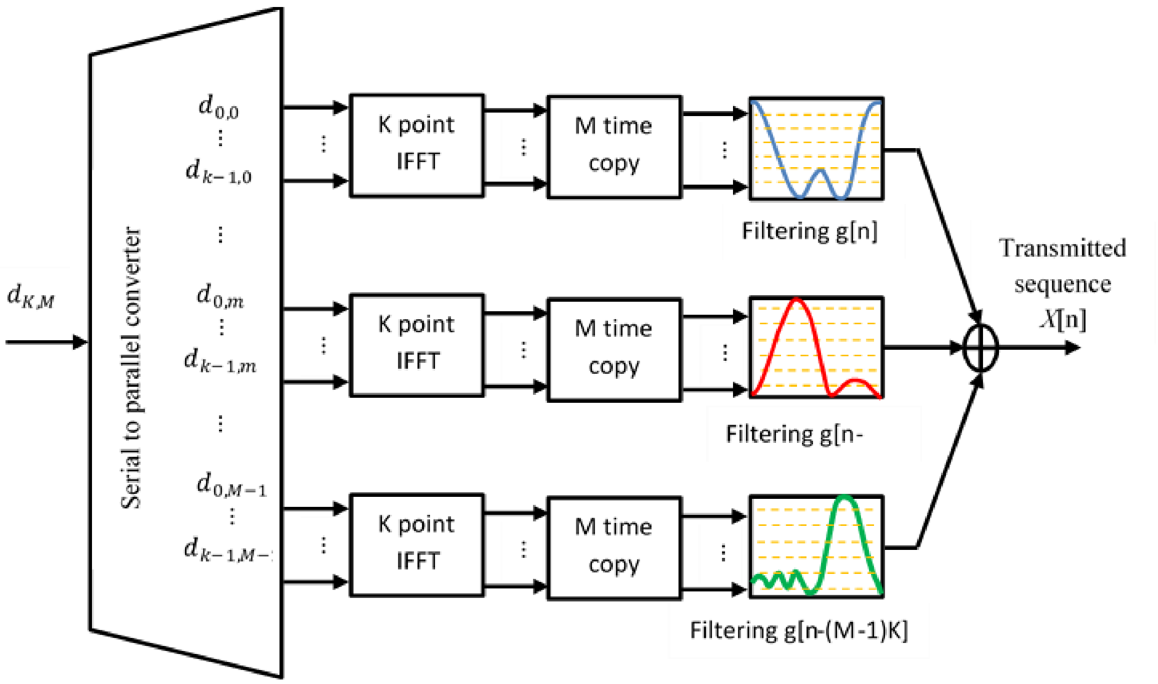

Figure. 1 GFDM modulation [17]

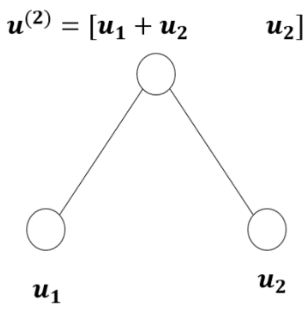

Figure. 2 polar encoder [18]

recovered with zero noise due to the wireless channel degradation. The demodulator performs based on the logarithmic likelihood ratio (LLR) as in Eq. (8). Where: the pr(bit=0) and pr(bit=1) indicate the bit probability of 0 and 1, respectively.

Bit zero is a higher probability when LLR is positive, while bit one is higher probably when LLR is negative [19].

$$\text{LLR} = \ln\left[\frac{\text{pr(bit=0)}}{\text{pr(bit=1)}}\right] \quad (8)$$

2.3 Interleaver

Interleaving is a simple and robust mechanism that enables the PC to detect and correct the error by transforming the burst error into a random error. Interleaving is a method to arrange the data in a particular order to be non-adjacent without losing or adding any bits to the stream [20]. There are many interleavers types, depending on the bits scatter methods. This paper used matrix, helical and random types. In matrix interleaver, the symbol fills the matrix in the input row by row, then sends it to the output column by column. In helical interleaver, permute the symbol by arranging the array in a helical fashion and sending row by row. The random interleaver arranges the element as a random permutation, then send and, at the receiver, re-arranges the permutation to recover the original stream vector [21].

2.4 Channel estimation

The transmitted signal is affected by multi-path with two tapes AWGN channel as Eq. (9). Then must apply channel estimation and equalization to recover the original signal [22].

$$y(n)=x(n)*h(n)+w(n) \quad (9)$$

Where y(n): is the received noisy signal, x(n) is the transmitted signal, * denotes linear convolution, h(n) is the channel vector that has two taps random values, and w(n) is the AWGN.

Channel estimation is recovering the transmission data at the receiver side by estimating the propagation characteristics in real-time [23].

This process required inserting the pilot symbol at the transmission side and then using this symbol to detect the channel parameters by the LS method [24]. The estimation by LS used the prior knowledge of transmitted pilot symbols with the received pilot to obtain the channel estimation as Eq. (10). The

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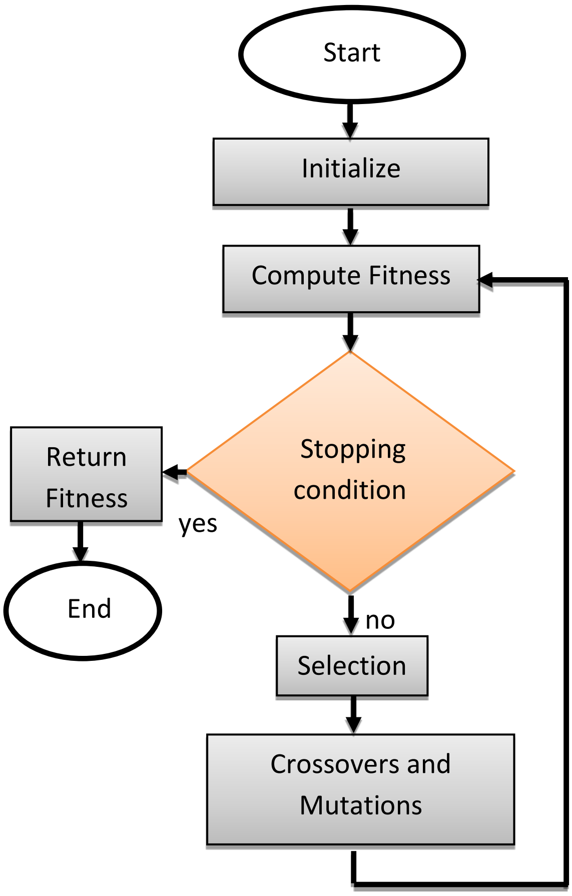

Figure. 3 GA block diagram [28]

interpolation concept is used to estimate the complete response of the channel parameters as in Eq. (11). The received signal is divided by channel estimation as in Eq. (12) to recover the transmitted signal [25].

$$LS_{es} = \frac{Y_p}{x_p} \tag{10}$$

$$H_{LS} = \text{interpolate}\ (LS_{es}) \tag{11}$$

$$Y_{es} = \frac{Y}{H_{LS}} \tag{12}$$

Where: LS_{es} is the *LS* estimation. Y_p is the received pilot signal. x_p is the transmitted pilot. H_{LS} is the channel estimation. Y_{es} is the recovered signal. Y is the received noisy signal.

2.5 Genetic algorithm

GA is a search algorithm that simulates the evolutionary process of natural selection for the population [26]. It performs the search-based operations on a population of solutions as chromosomes for several iterations, called generations. The operation was inspired form biological genetics: mutation, reproduction, fitness, and generations. The fitness function is used to classify the solutions and randomness of generations to provide diversity support [27]. The GA is Often used in the optimization process, which is used to solve problems for many disciplines. GA optimizes the G and searches for the best filter parameters based on its procedure. The block diagram of GA at each iteration is presented in Fig. 3.

The GA at the first of each iteration generates the initial population and then evaluates the fitness function. Crossover selects the population based on their fitness, which generates new individuals-based combine two chromosomes. Mutations are applied population randomly then the fitness function is re-evaluated. This process continues until it exceeds the maximum number of generations or the solution converges [29].

2.6 ANN

ANN computational network inspired biological nervous system. ANN is built from processing elements categorized in the form of layers, and each layer contains multi neurons for training the data and storing the knowledge for various tasks [30]. The basic structure is built from three layers: input, hidden, and output. The number of input and output layer neurons depends on the external sources and destinations connected with the network [31]. The block diagram of ANN present in Fig. 4.

In contrast, the hidden layer can contain multilayers with various numbers of neurons. The most significant advantage of ANN is the training process. In training, perform the adjustable weights depending on the training methods. The training processing is performed until arrived to the minimum error. The error computed between the actual output and desired that depending on the data set used in configuring the network to work with the specified application. Levenberg-Marquardt (LM), Bayesian regularization (BR), and scaled conjugate gradient (SCG) are the crucial ways of training the ANN [32].

The LM algorithm was built based on the Jacobian matrix without computing the Hessian matrix. When the solution is remote from the correct one, and the error is high, which requires slow operation but is guaranteed to converge, the algorithm operates based on gradient descent. When the error is low and the solution matches the correction, it operates like a Gauss-Newton method. The mathematical model of LM is present in Eq. (18) [29].

$$w_{t+1} = w_t - [\,J^T J + \zeta\, I\,]^{-1} J^T e \tag{18}$$

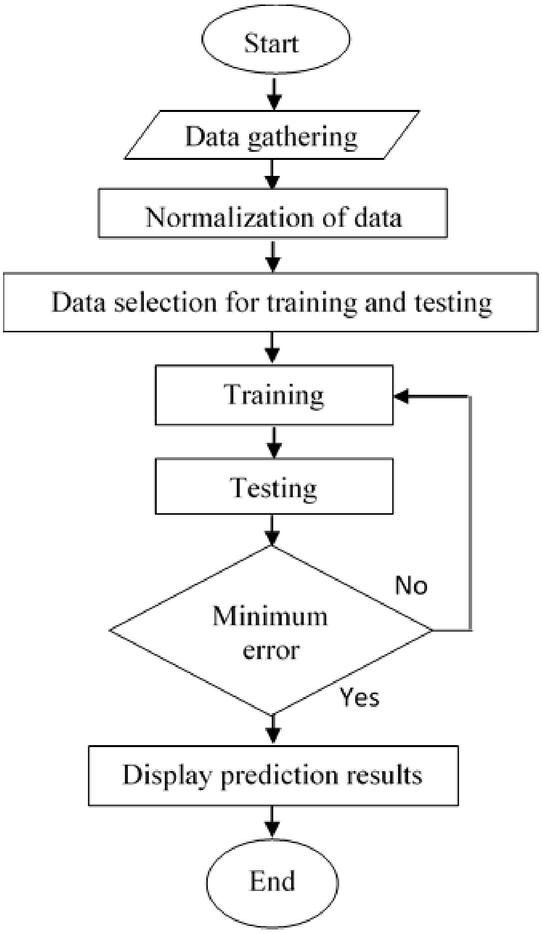

Figure. 4 ANN block diagram [33]

w_{t+1}:is the new weight vector. *J*: is the Jacobian matrix. ζ: is combination coefficient. *e:* is a vector of network errors between the desired and actual output.

BR operation based on reduced the square error and updates the weight based on LM optimization.

The performance of objective function F(w) present in Eqs. (19-21).

$$E_w = \sum_{i=1}^{n} w_i{}^2 \tag{19}$$

$$E_D = \sum_{K=1}^{n} e_k{}^2 \tag{20}$$

$$F_w = \lambda E_w + \beta\, E_D \tag{21}$$

Where E_w is the sum of squared weights and E_D is the sum of errors. λ and β are the parameters of the objective function.

In SCG, the algorithm combines the conjugate gradient and line search strategy to get a faster convergence speed. It used the learning rate to control the weight and thresholds updating step. Its function of the second-order method without saving the information of the second derivative. The objective function's gradient is calculated based on errors corresponding to input and output. As in Eq. (22), the objective function is reduced through the negative gradient, depending on the weights. The best distance is computed based on Eq. (23). The new steepest descent direction is obtained by conjugating the new and previous search directions as Eqs. (24, 25) [29].

$$p_0 = -g_0 \tag{22}$$

$$w_{k+1} = w_k + \Omega_k\, g_k \tag{23}$$

$$\beta_K = \frac{(|g_{K+1}|^2 - g_{K+1}{}^T)}{g_K{}^T\, g_K} \tag{24}$$

$$P_{K+1} = -g_{K+1} + \beta_K P_K \tag{25}$$

Where: p is the search direction vector, g is the gradient direction vector, w is the weight. Ω is the step size. k is the step index. $k + 1$ is the next step.

3. Simulation result

This section presents the simulation result of the proposed intelligent system, which presents the optimization of the PC-GFDM transceiver system based on different types of interleaver. The simulated result performs based on computer processor properties: 11th Generation, Core i7-11800H with 2.30GHz speed, and 16GB RAM, using MATLAB 2021b. The optimization performs the enhancement on G-based GA to get optimized G (opG) and channel estimation based on different types of ANN.

This optimization improves the system performance based on BER with different values of SNR. The general block diagram of the proposed system presents in Fig. 5. The adopted parameters are presented in Table 1.

The GA performs the searching about the G coefficient to arrive at minimum error. This search is bounded by upper and lower values. The BER performance at AWGN of the GFDM system with stG and opG is present in Fig. 6.

The enhancement at SNR = 22 dB is 0.0044, and at SNR = 28 dB is 0.0030. This performance is computed at AWGN channel. Then the system is degradant with a two-tape multi-path AWGN channel. Fig. 7 present the opG performance Rayleigh fading channel. Which the enhancement at 22 dB and 28 dB are 0.0092 and 0.0083, respectively. Using PC enhanced the performance after 18dB, as in Fig. 8, which

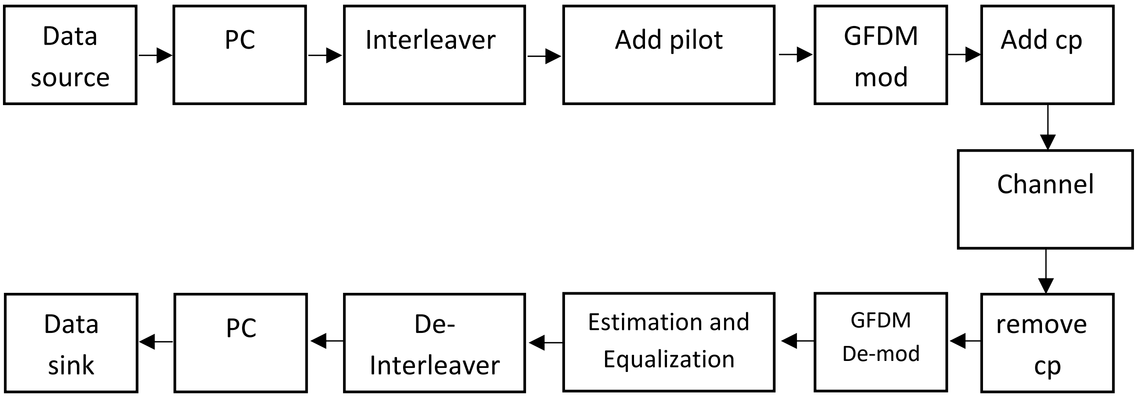

Figure. 5 proposed system block diagram

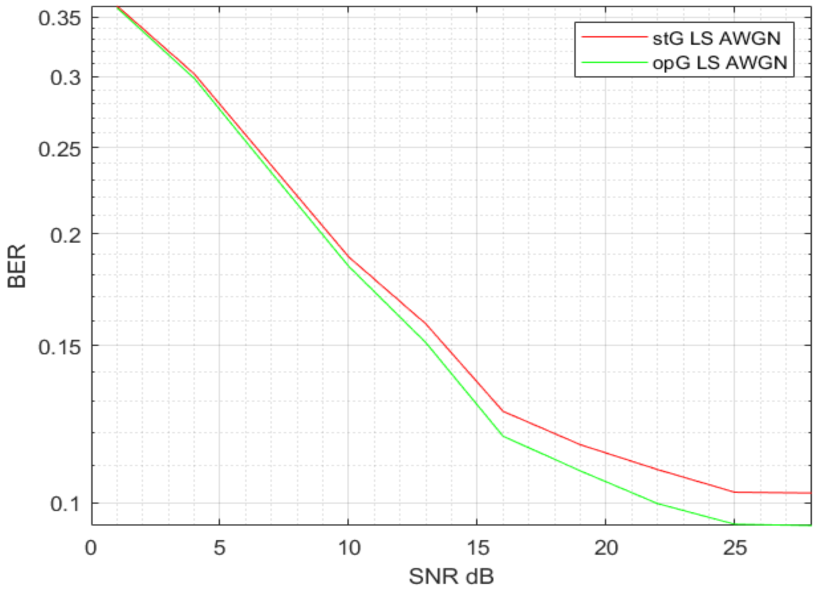

Figure. 6 Performance at AWGN

Table 1. System parameters

Parameters	Description
Number of samples per subsymbols (K)	20
Number of subsymbols (M)	15
Percentage of cyclic prefix	10%
Roll-off factor of the G (a)	0.1
Modulation	16-QAM
spacing pilot	4
Number of transmitted blocks	1000
SNR range	1:3:30
Channel	Rayleigh
Number of tapes	2

The interleaver added by three methods random, matrix and helical. it converts the burst error to random error hence improve the performance of PC. Fig. 9 present all enhanced step which the

Table 2 Performance comparison at 16dB

Ref.	BER at traditional	BER after Enhancement
[8]	0.225	0.220
[9]	4.5×10^{-2}	3×10^{-2}
[10]	2×10^{-2}	3×10^{-5}
[11]	0.75	0.6
proposed	0.129	0.088

interleavers, at 22dB, the enhancements are 0.0290, 0.0081, and 0.0257, respectively. While at 28 dB, the enhancement is 0.0307, 0.0126, and 0.0289 for random, helical, and matrix, respectively, the random interleaver is the best than helical and matrix. The SCG 25 present the ANN that train by SCG method based 25 neurons in hidden layer. Table 2 presents the numerical comparison between the proposed system with other works, which present the enhancement in BER at the 16 dB SNR.

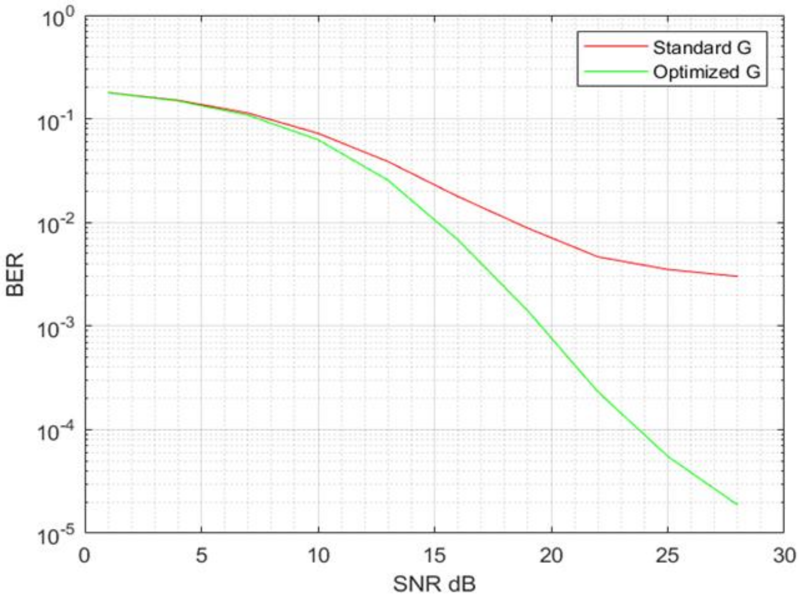

Figure. 7 Performance rayleigh fading channel

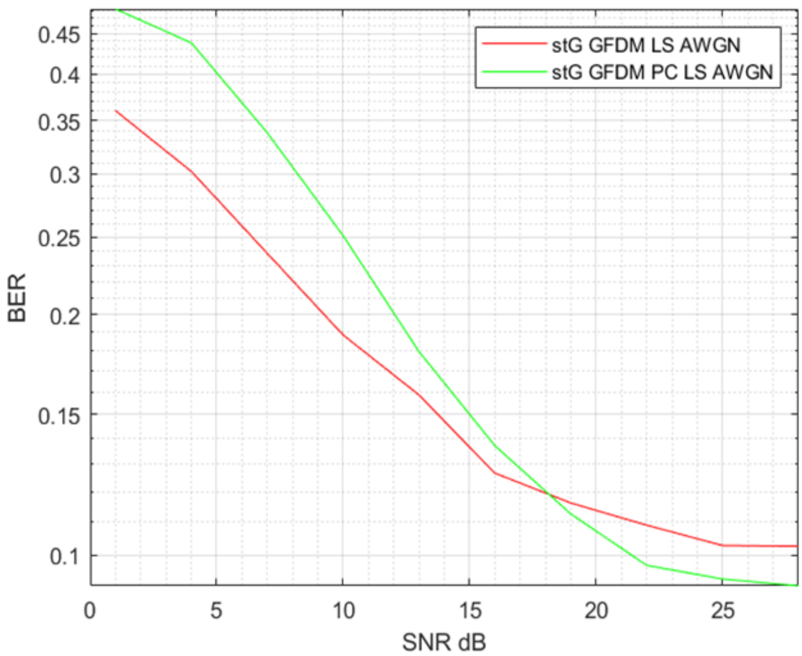

Figure. 8 Performance after adding PC to the system

4. Conclusions

The GFDM is considered a new communication system and has yet to be officially adopted in the generations of wireless communications. Thus, it is within the stage of development and improvement. Traditional GFDM is studied with AWGN and Rayleigh fading channels. The strong points were determined and compared with OFDM; weaknesses were found in the BER. This paper proposed new methods for developing the BER of the GFDM system.

The enhancement-based GA presents a new method of enhancement of the G of GFDM by assigning its parameters-based GA. This method presents high performance with the AWGN channel, but at Rayleigh fading channels, the enhancement is relatively less due to the randomness of the tapes in the channel. The estimation-based ANN presented new methods based on taking advantage of the high flexibility of the ANN in using it as an alternative to

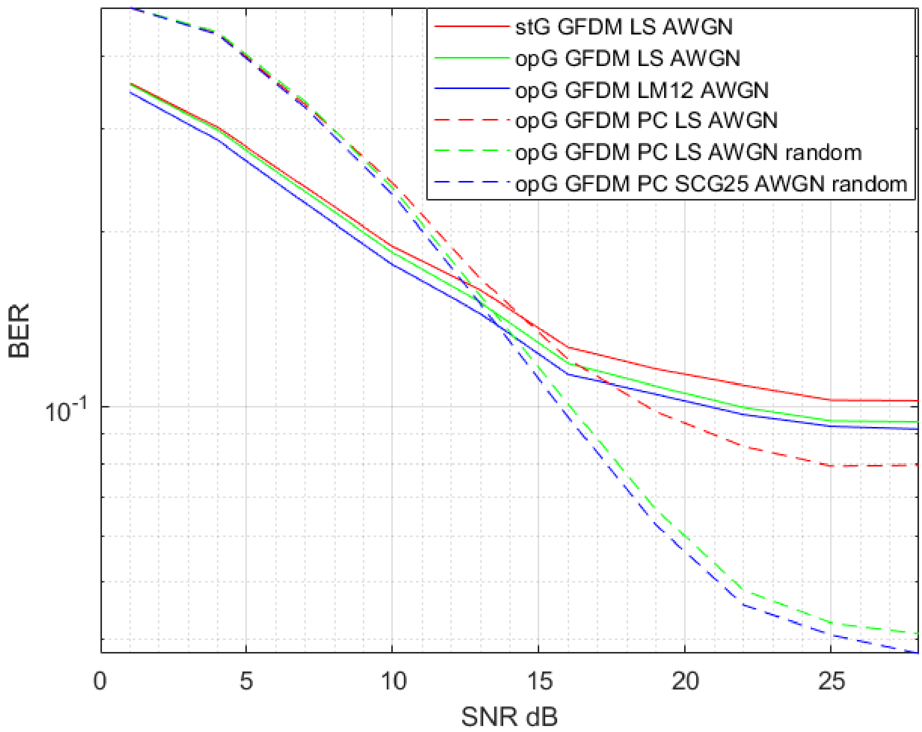

Figure. 9 Performance enhancement proposed system

any part of the system. The PC as a coding system combined with enhancement methods increased the enhancement despite the higher PC rate.

However, the amount of improvement remains interesting in the case of higher values of SNR. The added interleaver to the system increases the enhancement. This scenario presents the last step in the enhancement of the GFDM system. Hence the GFDM-based PC with random interleaver and the SCG with 19 neurons in the hidden layer gives the lowest BER to SNR.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

The paper conceptualization, methodology, software, validation, formal analysis, resources, data curation, writing original draft preparation, writing, review and editing, visualization, supervision, project administration and funding have been done by 1st and 2nd authors

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