Journal of Engineering and Applied Sciences 11 (12): 2755-2763, 2016
ISSN: 1816-949X


# Improving the Performance of Generalized Frequency Division Multiplexing (GFDM) Modulation Scheme by Usingwalsh Hadamard Transform (WHT) Pre-Coded

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**Abstract:** The fourth Generation (4G) of cellular systems were designed and implemented to provide high data rate and reliable network coverage for mobile users. Now, the fithth Generation (5G) of cellular systems with a more diverse and broader practical purposes have been researching that some of the demands are data rates beyond the 4G systems up to 1G bit per sec, a slight delay time up to <11 m sec and even lower, very low consumption power, implementation of potential applications such as the Internet of Things (IoT) and all and all require a fundamental changes in the physical layer of network such as waveform and modulation scheme used in the next generation of mobile cellular systems. Modulation scheme of physical layer known as Generalized Frequency Division Multiplexing (GFDM) is a suitable option to respond to these demands and requirements for a technology leap to the next generation of cellular systems. In this study, the performance of GFDM modulation scheme is initially evaluated by Additive White Gaussian Noise (AWGN), Frequency Selector Channel (FSC) and Time-Varying Channel (TVC) and then, it is shown that GFDM modulation scheme brings more reliable transmission than FSC channels by using Walsh Hadamard Transform (WHT) pre-coded on data symbolsthat this functional improvement makes the above-mentioned waveform suitable for potential applications such as the internet of things in which the number of network interconnections is numerous and requires very low delay time because a slight delay time can be obtaineddue to transmission with low error probability. It should be noted that the important parameters of mobile networks such as Symbol Error Rate (SER) and Bit Error Rate (BER) are used for performance evaluation and comparison of method presented in this study.

**Key words:** Fifth-Generation (5G) networks, Generalized Frequency Division Multiplexing (GFDM), Walsh Hadamard Transform (WHT), Frequency Selector Channel (FSC), Symbol Error Rate (SER), Bit Error Rate (BER)

## INTRODUCTION

With the emergence of mobile communication technology in the past decade and providing 4th Generation (4G) of mobile system technology, there was a need to develop knowledge and break boundaries of mobile communication sciences. Therefore, it began with the aim of increasing productivity, speed of information exchange, reducing power consumption and moving to the fifth generation. Space interface is the path or link between the device used by user and the source station.The use of specific waveforms and also the use of some modulations change the way of exploiting the space interface. Although, some believe that 5G should not be changed in terms ofspace interface but it should also be noted thatone of the main reasons in the development of a new generation of a technology is incompatibility of system with previous generations. In 4G, one of the most important problems which shows itself between network and users during messaging, is the excessive use of power and network resources.

One of the key advantages of 4G systems which benefit from waveform or CP-OFDM modulation technique in its own physical layer (Fettweis, 2014) is a relatively simple implementation of the receiver because of orthogonal resource allocation. However, orthogonal systems have no desirable efficacy or the expected maximum of efficiency in terms of telecommunications capacity and spectral productivity. With the rapid development of mobile communication systems, conceptual discussion of non-orthogonal transmission for the fifth generation networks has attracted the attention of many researchers around the world and it can be said that the more debate is on new multiple access schemes and new techniques of multi-carrier modulation forthe fifth generation networks to meet the expectations as mobile internet with multi-Gbps data rate and dream of the internet of Things. Internet of Things (IoT) is a new concept in the world of technology and communication. In short, the "Internet of things" is a modern technology in which the ability to send data via communications networks whether Internet or an intranet, is provided for every creature (human, animal or objects). Internet platform of things is based on wireless radio waves which enables different devicesto communicate with each other via the Internet. The platform includes standards such as WiFi, Bluetooth and so on. Internet of things with its countless number of network interconnections has become one of the major research challenges for the design of the fifth generation mobile cellular networks. The waveform used for IoT networks should properly support the mass interconnection density of IoT devices and also should have very low latency for such a telecommunication potential applications (Wunder *et al*., 2014).

In addition, telecommunication coverage is acritical issue for connecting various IoT devices which can be said it is more reasonable that the telecommunication of IoT is done on the lower frequency bands, e.g., <6 Ghz. All of these issues have provided a background for IoT applications to optimize the physical layer of future cellular networks which is to achieve better network coverage and lower power consumption. CP-OFDM modulation technique is used as a physical layer modulation scheme in Long Term Evolution (LTE) systemsor in other words, 4G networks. As its name suggests, it uses Orthogonal Frequency Division Multiplex (OFDM) plus a Circular Prefix (CP) in its structure (Awoseyila *et al*., 2008). Theadded Circular Prefix (CP) caused the high resistance of this modulation scheme to multipath fading in channel emissions.Also, CP-OFDM-based systems are intended as MIM0-oriented systems due to its compatibility with Multi-Input Multi-Output (MIMO) technology and it can be said that MIMO will be a key technology for the future 5G networks, so that any potential scheme and innovation for 5G networks should have full compatibility with MIMO technology (Tadayon and Aissa, 2013). In addition to these benefits, CP-OFDM modulation scheme has obvious disadvantages whic happlying, it on 5G networks will faceto challenges. The traditional system of OFDM based on Fast Fourier Transform (FFT) faced with numerous defects. For example, it is very sensitive to the Doppler shift resulted from mobile users moving at high speed, reduced spectral productivity due to using Circular Prefix (CP) to deal with the effects of multipath fading in channel emissions as well as has substantially Peak to Average Power Ratio (PAPR) which is caused by linear superposition of modulated signals via subcarriers are other related drawbacks of OFDM-based systems (Bingham, 1990; Mirahmadi *et al*., 2013). To cope with the problems, the research team of Vodafone Chair Mobile Telecommunication System has proposed Generalized Frequency Division Multiplexing (GFDM) modulation scheme which uses the circular type for pulse shaping instead of linear filtering.GFDM has interesting features such as:The use of many spectrum white spaces in the band of UHF-TV which are in the neighborhood of assigned spectrum, has smaller PAPR than the OFDM and has incredibly small Out-Of-Band (OOB) radiation.It should be noted that smaller PAPR reducescosts resulting from the hardware implementation and consumption power which will be a turning point for future wireless telecommunication systems (Fechtel and Blaickner, 1999; Bravo, 2008; Farhang, 2011; Hossain *et al*., 2009). In Fig. 1 conceptual block of GFDM modulation scheme is illustrated.

The GFDM performs filtering function on each of the subcarriers in such a way that transmitted filters are obtained from circulating movement of a pulse shapingfilter in time and frequency axes. Various pulse shapes can be used for GFDM modulation scheme and the freedom and flexibility of this modulation scheme have become it to one of the best options for future wireless networks. Of course, the fine of this flexibility can be interpreted in non-orthogonality ofsubcarriers that leads to inter-carrierinterference in the receiver section and in other words, the cost of non-orthogonalitywill be in implementation complexity of the receiver (Kim *et al*., 2014).

The main objective of this paper is GFDM modulation scheme with WHT pre-coded method to achieve frequency diversity and improve performance against the FSC channels. The proposed schemewill be efficient and helpful especially in applications with slight delay time in which a huge volume of information had to be transmitted securely even if a subset of sub-carriers were severely weakened by channel. Also, it should be noted that the BER and SER parameters which are the key parameters for cellular networks in this research are used to assess and compare the discussed methods.

## MATERIALS AND METHODS

**GFDM waveform:** As can be seen in Fig. 1, GFDM modulation scheme consists of K subcarrier that each of them includes M complex data symbol $d_{k,m}$ which is known as sub-symbol. As a result, load capacity of GFDM block includes N = MK complex symbols. In this case, the data symbols are organized in a time-frequency grid as shown in Fig. 2. Subcarriers are filtered by transmitted filter

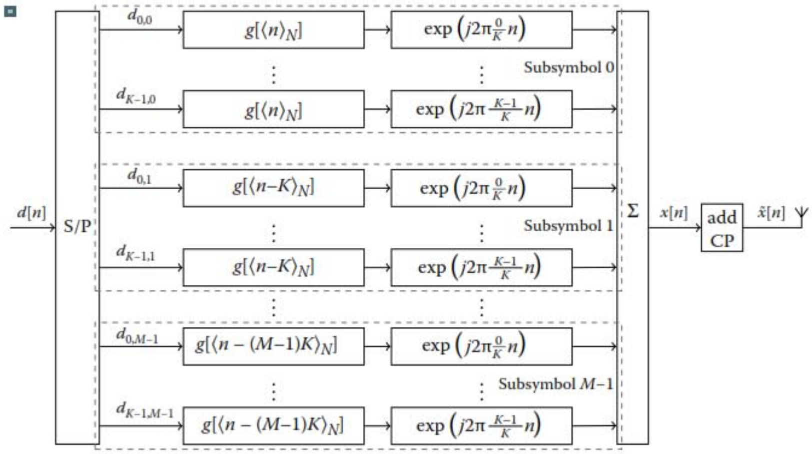


Fig. 1: Conceptual block of transmitter sectorin GFDM modulation scheme

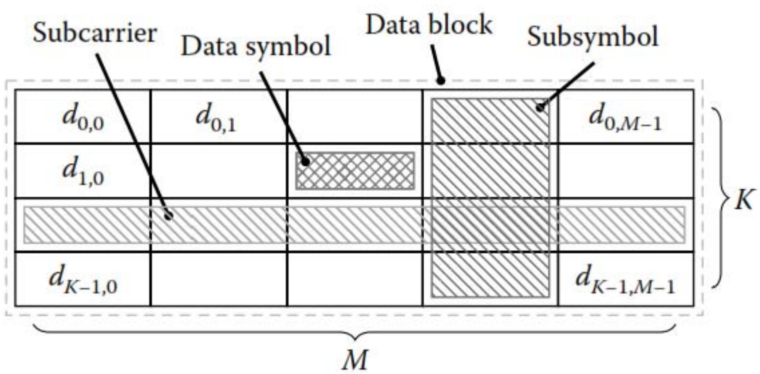


Fig. 2: Blockstructure of GFDM scheme

$g_{k,m}$ [n] that obtained from circulating displacement of a filter kind g[n] in time-frequency axes. As a result, we will have:

$$g_{k,m} = g[< n - mK_{>N}]\exp(j2\pi\frac{k}{K}n)$$

In which k = 0, 1, ...K-1 is sub-carrier index, m = 0,..., M-1 is sub-symbol index and n = 0,.... N-1 is sample index. Modulation between transmitted filters and symbol data is acircular convolution. That is:

$$x[n] = \sum_{k=0}^{k-1}\sum_{m=0}^{M-1} d_{k,m}\sigma[< n - mK_{>N} \otimes g[n]\exp j2\pi\frac{k}{K}n \quad (2)$$

$$\sum_{k=0}^{k-1}\sum_{m=0}^{M-1} d_{k,m}\, g_{k,m}[n]$$

Also, in GFDM modulation scheme, a CP is added to set with M symbol to deal with Inter-Frame Interference (IFI) generated by multipath channel that this leads to savings and greater efficiency from the spectrum resources compared to OFDM scheme in which a CP is added for each symbol (Lele and Legouable, 2010; Fettweis, 2004).

If x $\tilde{x}[n]$ is the output signal of the GFDM transmitter that CP was added to it, in a way that $N_{CP}$, then assuming the time-varying and multipath channels with impulse response h [n] to length L if $N_{CP} \geq L$ under these conditions, the GFDM signal in the receiver as seen in Fig. 3 would then be:

$$\tilde{y}[n] = ?[n] \times \tilde{x}[n] + \tilde{w}[n] \quad (3)$$

In which $\tilde{w}[n]$ is Additive White Gaussian Noise (AWGN) vector tolength $\tilde{N} = N + N_{CP}$. After removing CP, linear convolution operation becomes circular and we have:

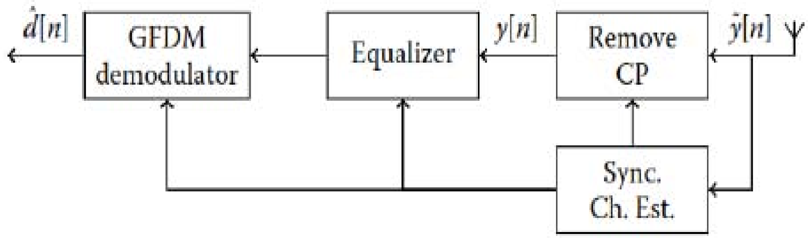


Fig. 3: Block diagram of GFDM receiver sector

$$y[n] = x[n] \otimes h[n] + w[n] \quad (4)$$

Because of this circular convolution, GFDM usesa simple equalization in frequency domain,and it can be written for received signal equalizer:

$$y_{eq}[n] = N^{(-1)} \frac{(N(y[n]))}{N(b[n])} \quad (5)$$

In which $F_N^{-1}$ and $F_N$ are Inverse Discrete Fourier Transform (IDFT) and point (NDFT) respectively. According to Fig. 3, data symbols can be retrieved by set of receiver filters which are described in the next section after equalization. In this case, the estimated data symbols are obtained in this way (Kay, 1998):

$$(\gamma^*)[<-n>_N] \otimes y_{eq}[n] \exp(-j2\pi \frac{k}{K} n) | n = mk) \quad (6)$$

**Matrix notation for GFDM:** Modulation and demodulation processes of GFDM are represented by the matrix operators that this notation would be very appropriate in the design of receiver filters.In this case, data symbols of GFDM block can thus be represented by a matrix N×1 in this way:

$$d = [d_{0,0} d_{1,0} - d_{K-1,0} d_{0,1} d_{1,1} - d_{K-1} M_{-1}]^T \quad (7)$$

Also, vector of transmitted filters can be displayed by following modulation matrix:

$$A = [g_{0,0}[n] ... g_{K-1,0}[n] g_{0,1}[n] ... g_{K-1,M-1}[n]] \quad (8)$$

As a result, transmitted vector of GFDM can be obtained as follows:

$$x = Ad \quad (9)$$

Now, transmitted vector $\tilde{x}$ is obtained with the addition of CP that in fact you add $N_{cp}$ of the last sample x to the beginning of it will be sent and transmitter sector is completed. In receiver sector, if h componential vector N×1 that $N_{ch}$ of its first element represents channel impulse response and N-$N_{ch}$ of its rest elements is zero, the received signal of receiver channel after removing the CP will be:

$$y = Hx + w \quad (10)$$

That vector H of rotation matrix obtained is based on the vector h and vector W is also N×1 samples related to channel AWGN. The received signal in the frequency domain can be expressed with the help of Fourier matrix N×N, $F_N$ in this way:

$$\begin{aligned} Y &= F_N y = F_N H x + F_N w \\ &= F_N H F_N^H F_N x + w = F_N H F_N^H + w \end{aligned} \quad (11)$$

That X and W aretransmitted vectors andAWGN in the frequency domain respectively (Xia, 1997). Here, $F_N H F_N^H$ is a diagonal matrix consisting of the channel frequency response on its original diameter and its rest elements are zero. Enjoying the frequency domain equalizer of receiver sector, we will have:

$$Y_{eq} = (F_N H F_N^H F_N)^{-1} Y = X + F_N H^{-1} F_N^H w \quad (12)$$

And received vector equalizer in the time domain can be obtained as follows:

$$Y_{eq} = F_N^H Y_{eq} = F_N^H X + F_N^H F_N H^{-1} F_N^H w = x + H^{-1} w \quad (13)$$

Finally, demodulation matrix B to retrieve the data symbols can be obtained from received vector equalized:

$$\hat{d} = B y_{eq} = Bx + BH^{-1} w = BAd + BH^{-1} w \quad (14)$$

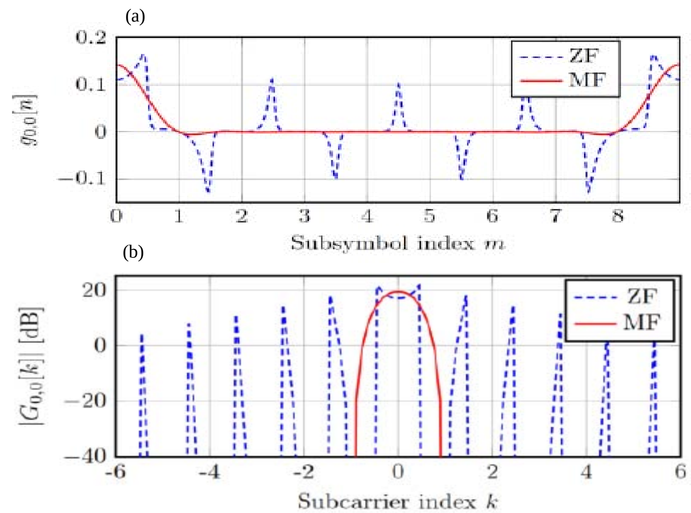


Fig. 4: Frequency and time characteristics of ZF and mffilters: a) Time impulse response and b) Frequency response

Here, different demodulation matrices can be considered in which type of receiver will be different corresponding to each them. The first and most obvious method for demodulation matrix is solving the equation BA = $I_N$ that leads to demodulation matrix ZF:

$$B_{ZF} = A^{-1} \tag{15}$$

Demodulator ZF removes interferences caused by non-orthogonal transmitted filters.But the drawback of this method is the accumulation of noise from other unwanted bandsand thus increases the noise level and performance degradation (Hossain *et al*., 2009). Other method for demodulation matrix B is:

$$B_{MF} = A^H \tag{16}$$

In which $(.)^H$ Represents the Hermitian operator. The demodulator maximizes the noise levels, but suffers from internal interferences (Sklar, 2001). Figure 4 shows the frequency and time characteristics of these two filters.

In contrast to these two demodulators, there is another filter called MMSE which creates a good balance between the two above methods. MMSE filter has a behavior like MF filter for low SNR level and has same performance of ZF filter for high SNR values. MMSEdemodulation matrix is calculated as follows:

$$B_{MMSE}(R_w + A^H A^H HA)^{-1} A^H A^H \tag{17}$$

In which $R_w = \sigma_w^2 I_N$ and $\sigma_w^2$ is the noise vector covariance matrix of Sklar (2001).

## RESULTS AND DISCUSSION

**Functional analysis of GFDM in terms of SER:** In this study, performance of GFDM modulation scheme in terms of Symbol Error Rate (SER) is evaluated and compared with signal to noise ratio ($E_s/N_0$) assuming ZF receiver under FSC and AWGN and TVC channels. Before addressing the channel characteristics and relationships needed for simulation, we initiallyexpress the Noise Enhancement Factor (NEF) which represents the ratio of signal to declining noise for ZF receiver:

$$\xi = \sum_{n=0}^{MK_{-1}} \left|[B_{ZF}]_{k,n}\right|_0^2 \tag{18}$$

**AWGN channel:** Under this type of channel, parameter of NEF is equivalent to SNR in receiver sector. And the Symbol Error Rate (SER) in these channels and for the GFDM modulation scheme is calculated as follows:

$$p_{AWGN} = 2\left(\frac{K-1}{k}\right)\mathrm{erfc}(\sqrt{\gamma}) - \left(\frac{k-1}{k}\right)\mathrm{erfc}^2(\sqrt{\gamma}) \tag{19}$$

Where:

$$\gamma = \frac{3R_T}{2(2^\mu - 1)} \times \frac{E_s}{\xi N_0} \tag{20}$$

$$R_T = \frac{KM}{KM + N_{CP} + N_{CS}} \tag{21}$$

So, μ is equal to number of bits per symbol QAM, QAM, $K = \sqrt{2^\mu}$, $N_{CP}$ and $N_{CS}$ are the lengths of circular prefixes and suffixes respectively. The $E_S$ is average energy to symbol and N0 is the noise power density.

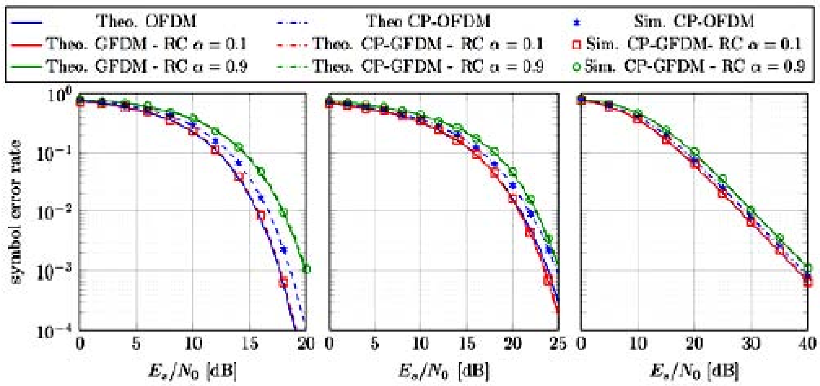


Fig. 5: Simulate the performance of GFDM-SER under different channel models: a) AWGN channel; b) FSC channel; c) TVC channel

**FSC channel:** The good performance of SER under FSC channels is essential for multi-carrier modulation. In this type of channel, situation of filters in the frequency domain changes NEF parameter because the channel frequency response is not smooth due to the multiplicity of paths. As a result, the probability of symbol error is obtained as follows:

$$p_{FSC}(e) = 2\left(\frac{k-1}{kK}\right)\sum_{l=0}^{K-1}\text{erfc}\left(\sqrt{\gamma_l}\right)-\frac{1}{K}\left(\frac{k-1}{k}\right)^2\sum_{l=0}^{K-1}\left(\sqrt{\gamma_l}\right) \quad (22)$$

Where:

$$\gamma r = \frac{3R_T}{2\left(2^{\mu}-1\right)}\times\frac{E_s}{\xi N_0} \quad (23)$$

**TVC channel:** In time-varying channels, both moment parameters of SNR and SER are random variables. So, we use average Symbol Error Probability (SEP) in TVC channels to express its performance. In this type of channel, we will have:

$$p_{TVC} = 2\left(\frac{k-1}{k}\right)\left(1-\sqrt{\frac{\gamma_r}{1+\gamma_r}}\right)-\left(\frac{k-1}{k}\right)^2\left[1-\frac{4}{\pi}\sqrt{\frac{\gamma_r}{1+\gamma_r}}\,a\tan\sqrt{\frac{1+\gamma_r}{\gamma_r}}\right] \quad (24)$$

In which:

$$\gamma_r = \frac{3\delta_r^2 R_T}{2^{\mu}-1}\times\frac{E_s}{\xi N_0} \quad (25)$$

To simulate these three types of channel, we use the mapping 16-QAM, transmitted filter RC, number of sub-carriers K = 64, number of sub-symbols M = 9 and length of circular prefix $N_{CP}$ = 16. The results of this simulation is depicted in Fig. 5.

**Pre-coding for GFDM:** Gaps in channel frequency response leads to considerable destruction in multi-carrier modulation systems on the total time of delay and output of the channel.In this section we want to reduce Bit Error Rate (BER) of GFDM transmitter-receiver under FSC channel by combining multi-carrier modulation of GFDM with WHT transform as a pre-coded methodon data symbols which takes place before modulation operation and sending to channel.

By combining the scheme of WHT with GFDM for a known sub-symbol each subcarrier sends a linear combination of K data symbol. In this case, even if a set of sub-carriers are heavily attenuated by the channel frequency response, it is possible that all symbols can be retrieved without errors. Figure 6 shows the aforementioned combination scheme of WHT-GFDM. WHT transform requires that the number of sub-carriers is a power of two but it has no this limitation for the number of sub-symbols. In this case, the transmitter output signal WHT-GFDM will be in this way:

$$X_{\Omega}[n] = \frac{1}{\sqrt{K}}\sum_{m=0}^{M-1}\sum_{k=0}^{K-1}\sum_{j=0}^{K-1}a_{j,k}d_{j,m}g_m[n]e^{-j2\pi\frac{k}{K}n} \quad (26)$$

In which $a_{j,k}$ are matrix elements WHT which are defined as:

$$\Omega_K = \begin{pmatrix}\Omega_{\frac{K}{2}} & \Omega_{\frac{K}{2}} \\ \Omega_{\frac{K}{2}} & -\Omega_{\frac{K}{2}}\end{pmatrix} \quad (27)$$

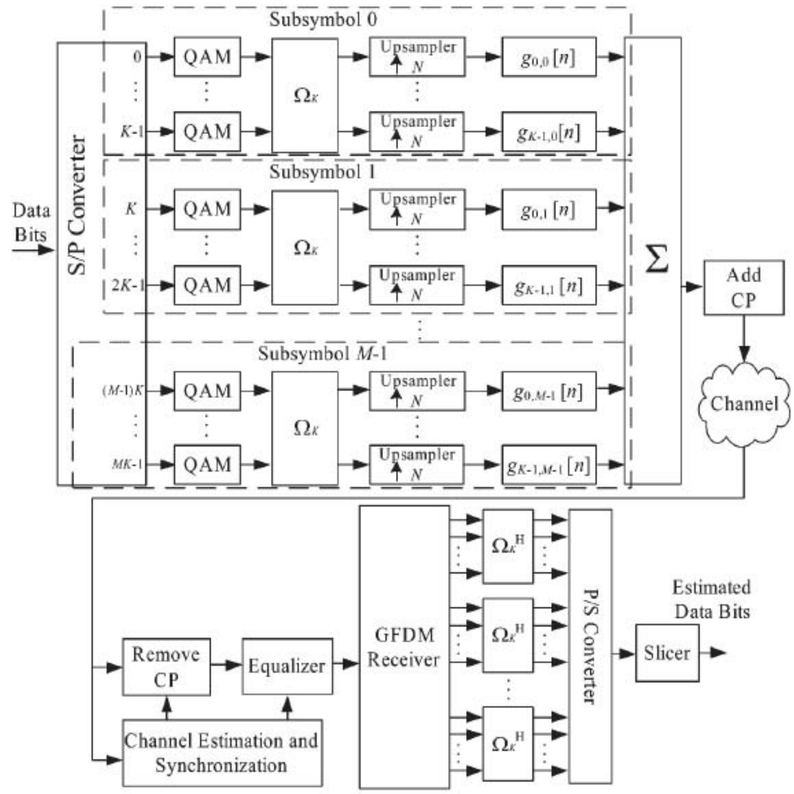


Fig. 6: Block diagram of combinedscheme WHT-GFDM

When, $\Omega_1$ = 1 WHT coefficientof data sequence for symbols is:

$$c_m = \frac{1}{\sqrt{K}}\Omega_K d_m \quad (28)$$

In which $d_m$ iscolumn vector of K transmitted symbol in m-th sub-symbol. Using the matrix display provided in section 3, here there isthe possibility of matrix display for transmitted symbols and we will have (Fig. 6):

$$X_\Omega = Ac = A\Theta d \quad (29)$$

Where:

$$\Theta = \frac{1}{\sqrt{K}} I_M \otimes \Omega_K \quad (30)$$

In which ⊗ represents the Kronecker matrix multiplication, $I_M$ single matrix with size M and:

$$c = \left[c_0^T c_1^T ... c_{M-1}^T\right]^T \quad (31)$$

After removing the CP in receiver sector, we will have:

$$y = (x \otimes h)_N + w \quad (32)$$

In which ⊗ is channel impulse response. By equalizer the frequency domain, we will have now:

$$y_e = F^{-1}[X + H^{-1}W] \quad (33)$$

Now, assuming the ZF receiver, the received symbol of WHT received is:

$$\hat{c} = A^{-1}y_e = c + w_e \quad (34)$$

Where We = $A^{-1}F^{-1}H^{-1}W$ is equivalent noises vector. Finally, retrieveddata symbols will be equal to:

$$\hat{d}_m = \frac{1}{\sqrt{K}}\Omega_K \hat{c}_m = d_m + \frac{1}{\sqrt{K}}\Omega_K w_{em} \quad (35)$$

In which $W_e$ is equivalent noise vector of mth symbol. It should be noted that the channel frequency response after applying WHT method would be equivalent to:

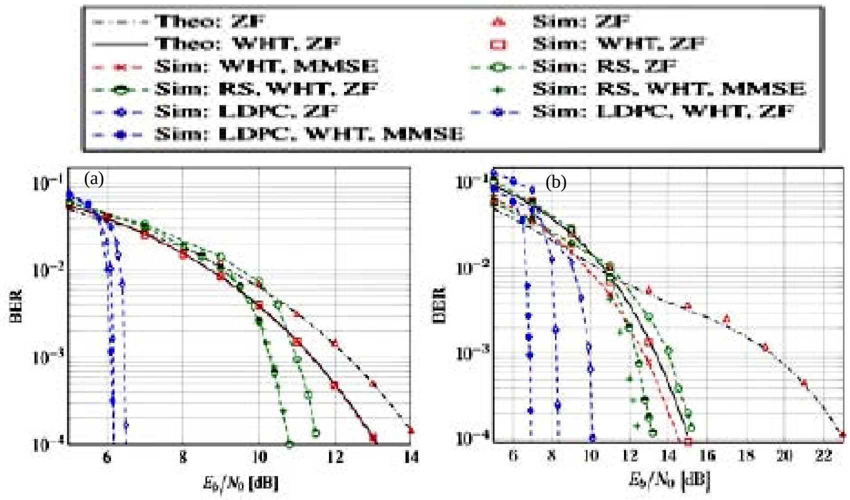


Fig. 7: Simulation of BER performance for combined scheme WHT-GFDM: a) Ch. A; b) Ch. B

$$H_{e=}\left(\frac{1}{K}\sum_{k=0}^{K-1}\frac{1}{|H[k]|^2}\right)^{\frac{-1}{2}} \quad (36)$$

Also, parameter WHT related to this combined scheme will be as follows:

$$\xi_k=\sum_{i=0}^{N-1}\left|\left[\theta A^{-1}\right]_{K,i}\right|^2 \quad (37)$$

Noting this point is essential that WHT can have a positive or negative impact on NEF. Using the equivalent frequency response and NEF, probability of error equationfor scheme WHT-GFDM with ZF receiver under Channel FSC with little change in Eq. 32 would be:

$$P_b\approx\frac{2(L-1)}{KL\log_2(j)}\sum_{k=0}^{K-1}\text{erfc}\left(\sqrt{\frac{3\backslash H_e\backslash^2}{2(j-1)}\frac{\log_2(j)E_b}{\xi_k N_0}}\right) \quad (38)$$

To simulate the combined scheme of WHT-GFDM, we use the mapping 16-QAM, transmitted filter RC, number of sub-carriers K = 64, number of sub-symbols M = 7 and length of circular prefix $N_{CP}$ = 16 under two channels A and B given in Fig. 1. Also, two channel coding methods of LDPC and RS have also been used in the simulation. LDPC coding is very powerful and has the best performance among other methods. But, it should be noted that itscodeword is long and has repeated decoding which itself leadsto increased latency. The RS coding is an interesting method to deal with errors and serious damages; so that, its decoding process is not repeatedand thus has slight time delay while does not need to know the channelparameters (Lee and Williams, 2000). The results of the simulations have been shown in Fig. 7 and Table 1.

Table 1: Specifications of two channels used in simulation

| Ch. A | | Ch. B | |
|---|---|---|---|
| Gain (dB) | Delay (µ sec) | Gain (dB) | Delay (µ sec) |
| 0 | 0.00 | 0 | 0.00 |
| -8 | 4.57 | -10 | 2.85 |
| -14 | 9.14 | -12 | 4.57 |
| - | - | -13 | 6.28 |
| - | - | -16 | 9.71 |
| - | - | -20 | 15.43 |
| - | - | -22 | 20.00 |

## CONCLUSION

Flexible and powerful physical layer should provide required areas for achieving the communication application with slight time delay. Since, slight time delay, namely the transmission under the secure and efficient communication is possible with negligible error probability, so it can be said that realization of the issue is no more than providing a powerful multi-carrier modulation scheme with the possibility to send and receive with low bit error rate. In this study, the GFDM modulation scheme which is one of the best suitable waveforms and alternative for fifth-generation networks was initiallyraised and its SER performance under AWGN and FSC and TVC channels was evaluated. Then, the proposed combined scheme called WHT-GFDM that benefitsfrom Walsh Hadamard transform pre-codedondata symbols is examined and its BER performanceis evaluated and compared, assuming ZF receiver and FSC channel.The results showed that the combined scheme of WHT-GFDM has a better performance compared to GFDM under intense RSC channel.

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