Filtered OFDM System Improvement Using Hamming Code

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***Abstract*—Orthogonal Frequency Division Multiplexing (OFDM) technique is widely adopted for broadband Forth Generation (4G) wireless communication systems at present, owing to its ability to combat multi-path interference. Nevertheless, it suffers from a large Peak to Average Power Ratio (PAPR) and Out Of Band Emission (OOBE), making it unsuitable for a high-speed transmission system. On the other hand, the Filtered-OFDM (f-OFDM) system is suggested to overcome the traditional OFDM system's disadvantages and maintain its advantages. Nowadays, the developments and growing communications systems are rapid, especially on their applications such as wireless networks, internet, satellite communications, mobile telephony, etc. This increases the demand for raising the bit rates with decreasing power consumption and the bit error rates (BER). In this paper, Hamming codes are proposed to improve the f-OFDM system performance, while the presence of the subband filter in system architecture could decrease the values of OOBE than the familiar OFDM system. The outcomes showed that utilizing interleaver with Hamming code considerably improves the proposed system performance, while the OOBE values were lower than the conventional OFDM system.**

***Keywords*—hamming, OOBE, PAPR, OFDM, f-OFDM, MIMO**

I. INTRODUCTION

Due to the increase in the number of mobile users and the request for different types of new business, the rapid growth of wireless communication led to considering the wireless communication system to be hot spot research [1]. In contrast, the increasing demand for high data rates led to seeking new technologies to meet these demands. The fifth Generation (5G) is promising to introduce all these requirements [2]. Since 2020 and beyond, 5G of mobile communication that provides lower power consumption and greater spectral efficiency has been introduced. Among different features, it achieves a considerably improving user experience, transmission rate and resource utilization ratio better than (4G) Fourth Generation [3]. OFDM technology is currently adopted widely for broadband 4G wireless communication systems, owing to its ability to combat multi-path interference. Nevertheless, it suffers from high OOBE and PAPR, making it unsuitable for a high-speed transmission system. In contrast, Filtered-OFDM (f-OFDM) system is suggested to overcome the traditional OFDM system’s disadvantages and maintain its advantages. For instance, the f-OFDM system is characterized as the superior performance of OOBE and spectrum utilization, making it one of the contender candidate waveforms for 5G. The whole bandwidth of the system in f-OFDM is divided into different subbands by subband filter. It is regarded to each subband as non-overlapping, thus achieving very low spectrum leakage, effectively coexisting to another waveform using a discrete spectrum [4]. The aims of designing the 5G new radio (5G-NR) system are to have massive connecting devices, ultra-large transmission rate, massive capacity, Ultra-Reliable Low Latency Communication (URLLC) services and enhanced mobile broadband (eMBB). Thus, advanced wireless communication technologies such as massive Multi Input Multi Output (MIMO) antenna technologies and forward error correction codes (FEC) have been proposed and investigated. This is to support different specifications and challenges to help the flexible design of the 5G system [5].

II. RELATED WORKS

In recent years, the developments of mobile communication systems led to limiting the radio spectrum, which make it an expensive resource. Thus, techniques based on spectrum unlicensed access are needed. So, looking for a new modulation technique that minimizes OOBE and provides better spectral localization is necessary compared to the OFDM system. The authors evaluate the adjacent signals interference for MIMO with both OFDM and f-OFDM systems. They concluded that in case the power amplification is not an issue, the f-OFDM systems outperformed the OFDM systems. Hence, the f-OFDM system is considered a superior candidate for the next wireless network generations [2].

OFDM has been widely used as a multicarrier waveform in several wireless systems including 4G networks. Moreover, it has several features like high capacity and simplicity of implementation. However, it is suffering from high PAPR and OOBE led to make the OFDM is inappropriate for 5G applications. In contrast, f-

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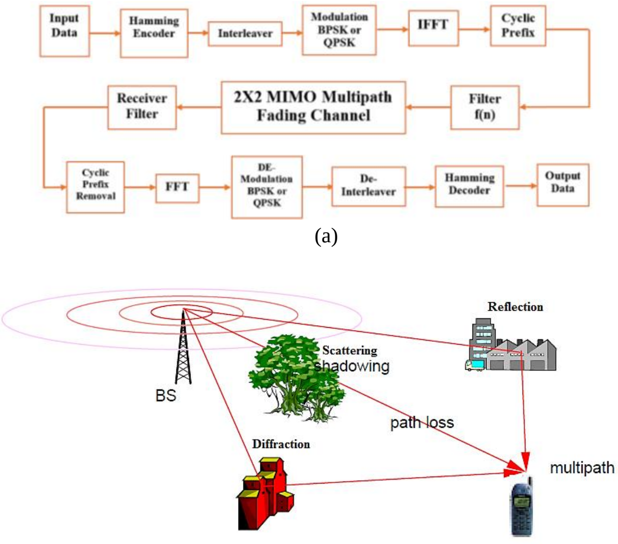
OFDM system is recommended for 5G communications as a waveform candidate [6], [7].

The developments and growth of communication systems nowadays are rapid, especially on their applications such as wireless networks, internet, satellite communications, mobile telephone, etc. This increases the demand for raising the bit rates with decreasing power consumption and the bit error rates (BER) [8]. Hence, different FEC techniques, including polar, LDPC, BCH and RS codes, have been suggested in [9–18] to improve the reliability of 5G systems. Several renewal codes and flaw identifications are suggested in communication systems such as longitudinal redundancy, check sum and Hamming codes. Due to its uncomplicated design, hamming codes are widely used. In Hamming codes, the redundant bits are attached to the message. It is considered one of the most effective codes among the error renewal codes [19]. In this paper, hamming codes have been suggested for the f-OFDM system to improve the BER performance. Meanwhile, both OOBE and PAPR values have been discussed to display the impact of utilizing Hamming codes on the performance of the proposed system.

The rest of the paper consists of a system diagram that explains the used parameters and the block diagram of the suggested system. After that, results and discussion are presented to show the simulation results and compare them results with conventional OFDM system. Finally, the conclusion is presented in the last section of this paper.

III. SYSTEM MODEL

The proposed system diagram using Hamming code is presented in this section as shown in Figure 1.



(b)

Figure 1. a) The proposed system Block diagram, b) Propagation Component [20].

The simulation of the suggested system is performed by MATLAB using a 2X2 MIMO system for Binary Phase-Shift Keying (BPSK) and Quadrature Phase-Shift Keying (QPSK) modulation schemes in the presence of a multi-path fading channel. The input binary data is encoded using Hamming encoder, which goes to the interleaver to distribute randomly before transmitting using the f-OFDM system. In the receiver, the transmitted data passed through a multipath fading channel using a 2X2 MIMO system is demodulated and rearranged using a de-interleaver before decoding using Hamming decoder. The proposed system performance will be compared with the performance of a familiar OFDM system. This shows the effect of use subband filter on minimizing OOBE level, as well discuss using Hamming codes on the system performance for both systems. Furthermore, the impact of using interleaver/de-interleaver in transmitter and receiver, respectively, has been studied in this paper.

TABLE I: SYSTEM PARAMETERS

	Bandwidth	20MHz
	Channel	Multipath Fading
	IFFT/FFT	2048
	CP	144
	Modulation	BPSK, QPSK
	Sub. Spacing	15 kHz
Filter Design	B.W.	19.83MHz
	Sampling Rate	30.72MHz
	Type	Root-Raised-Cosine (RRC) Windowed-Sinc
	Roll-off factor (a)	0.6
	Length	513
	Coding Techniques	(7,4) Hamming Codes

A. *Hamming Code*

In 1950, Richard Hamming was the first to suggest linear error correction (7,4) Hamming code. To obtain good image visual quality, Hamming code was widely used as an effective steganography manner. In (7,4) code, one error bit can be detected and corrected inside one code consisting of (4 origin bits) with (3 bits of parity check) using a parity check matrix [21]. Assume, a_1, a_2, a_3 and a_4 are the original bits and r_1, r_2 and r_3 are the parity check bits. Thus, (7,4) Hamming code is obtained by multiplying the original bits with the G generator matrix as follows [21]:

$$C = a \times G \tag{1}$$

$$= a_1, a_2, a_3, a_4 \times \begin{bmatrix} 1110000 \\ 1001100 \\ 0101010 \\ 1101001 \end{bmatrix} \tag{2}$$

These three parity check bits are obtained using exclusive- OR operation ⊕ as follows [21]:

$$r_1 = a_1 \oplus a_2 \oplus a_4 \tag{3}$$

$$r_2 = a_1 \oplus a_3 \oplus a_4 \tag{4}$$
$$r_3 = a_2 \oplus a_3 \oplus a_4 \tag{5}$$

For instance, if (a_1, a_2, a_3, a_4) is binary (0101) so, (r_1, r_2, r_3) will be binary (010) and the Hamming code as follows [21]:

$$C = (0100101)_2 \tag{6}$$

In the receiver, the decoding will be performed using the same parity check matrix H to detect and correct any errors detected as follows [21]:

$$z = H \times R^T \tag{7}$$

where R is the received message and z is the syndrome vector which is used to indicate whether there are errors or not. Here, it gives zero when there are no errors; otherwise, it indicates there are errors. For example, if the Hamming code $C = (0100101)_2$ is transmitted, then the received message is $R = (0100001)_2$. Hence, the syndrome vector will be calculated as $z = (101)_2 = 5$, which indicates there exists an error for the 5^{th} bit and should be corrected to get the original $C = (0100101)_2$ [21].

B. *Interleaver*

The interleaver is a technique used to reorder the data or the sequences of bits randomly in the form of one-to-one. In contrast, the de-interleaver retrieves the received data sequences as before the interleaver [8]. Thereby, interleavers are considered an essential component to improve the capability of error correction techniques such as turbo codes. The interleavers were used to achieve high values of spread factor and dispersion. High dispersion values imply the randomness of the bit positions interleaved [22]. In this paper, the interleaver/de-interleaver has been used with Hamming code to increase correction ability. The interleaver rearrange the encoded data before sending it through the channel. Consequently, the received data is restored using the de-interleaver in the receiver. This process distributes the random and burst errors which may create through the channel, thereby making the decoding process and correcting the errors easy.

IV. RESULTS AND DISCUSSION

To assess the proposed system performance using Hamming codes. Three important criteria, namely BER, OOBE and PAPR, will be discussed and analyzed for both modulation schemes. In this paper, the conventional OFDM system will be used as the baseline for comparison purposes. PAPR values of the proposed and familiar OFDM systems are the first parameter that will be evaluated and compared to show the effect of using Hamming codes with both systems. Table II shows the PAPR values for both systems (the OFDM against the f-OFDM).

The results showed that the values of PAPR for both systems don't look significantly different. However, the proposed system recorded higher values of PAPR than the conventional OFDM system for both BPSK and QPSK. Thus, it can be concluded that the proposed system still needs to be reviewed in terms of the PAPR parameter to look for another technique to decrease its PAPR values more than the familiar OFDM system. Meanwhile, in the second criteria, OOBE has been discussed for both systems, as shown in Fig. 2 and Fig. 3.

TABLE II: PAPR VALUES OF THE OFDM AGAINST THE F-OFDM SYSTEMS

System	BPSK	QPSK
Conventional OFDM system	9.2773 dB	9.4114 dB
The proposed System	9.6858 dB	10.0769 dB

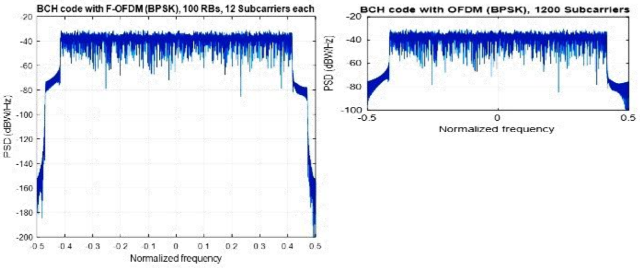


Figure 2. Power spectrum density / BPSK.

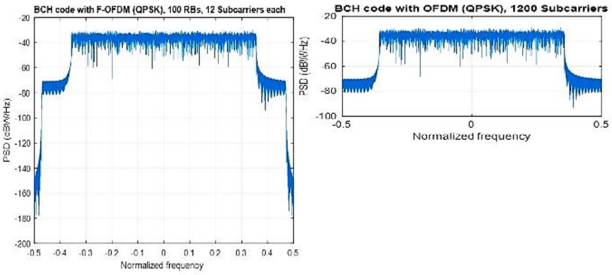


Figure 3. Power spectrum density / QPSK.

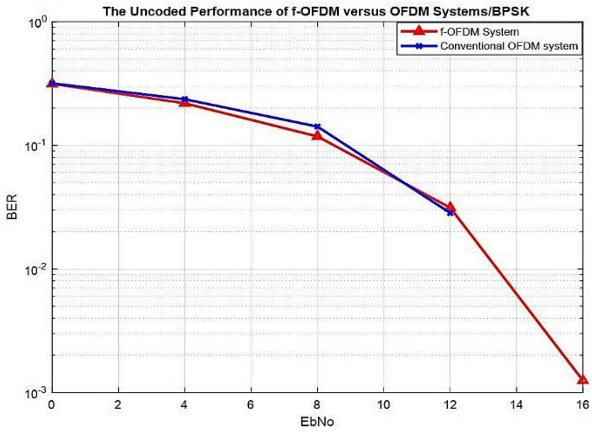


Figure 4. BER performance of uncoded systems/BPSK.

The results depicted that the OOBE for the conventional OFDM system is significantly higher than the proposed system for both BPSK and QPSK as shown in Fig. 2 and Fig. 3. The OOBE was around -80 dB for the conventional OFDM system against around -180 dB for the suggested system for both modulation schemes. Thereby, the suggested system could significantly decrease the values of OOBE to be around 100 than the conventional OFDM system for both BPSK and QPSK. That is due to using the subband filter's in the proposed system architecture, unlike the familiar OFDM system. The last criterion studied in this section is the BER performance of the suggested system against the familiar OFDM system. The impact of using interleaver with Hamming codes will be discussed regarding the BER system performance.

The uncoded system /BPSK is depicted in Fig. 4. Although the uncoded f-OFDM system performance looks better than the conventional OFDM system at low Signal to Noise Ratio (SNR) values, the conventional OFDM system outperformed the f-OFDM system after 12 dB SNR. Here, it recorded a lower number of errors compared to the f-OFDM system for BPSK.

In contrast, both OFDM and f- OFDM systems performances were close to each other in QPSK as depicted in Fig. 5 with a minor enhancement for OFDM. However, both BER performance curves were not smoothly decreasing given the errors with increased SNR values. Thereby, for both modulation schemes, the uncoded f-OFDM system was not better than the conventional OFDM system in BER performance.

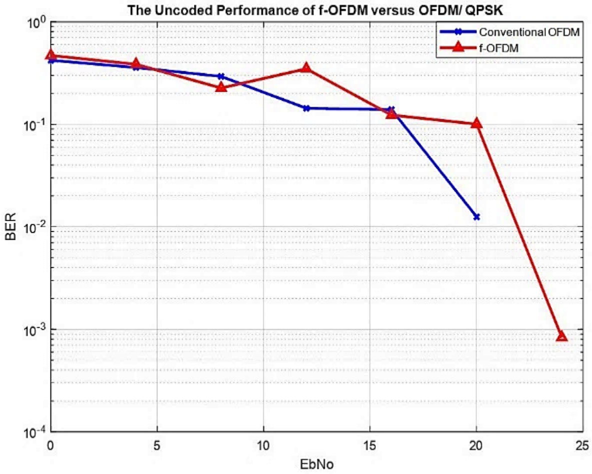


Figure 5. BER performance of uncoded systems/ QPSK.

On the other hand, the BER performance of the familiar OFDM versus f-OFDM systems using Hamming codes are depicted in Fig. 6 and Fig. 7 for BPSK and QPSK, respectively. Unexpectedly, the results of using Hamming codes with both conventional OFDM and f-OFDM systems were not well. In BPSK, the uncoded OFDM system significantly outperformed the OFDM system with Hamming codes. Even in QPSK, using Hamming codes with the OFDM system cannot improve its system performance. In contrast, the f- OFDM system performance for the uncoded case has significantly outperformed the performance using Hamming codes for BPSK modulation schemes. On the other hand, the performance of the f-OFDM system for both uncoded case and using Hamming codes are close to each other for the QPSK modulation scheme, with slight improvement for the uncoded case. Thereby, it can be concluded that, in both modulation schemes, using Hamming codes with both systems does not improve their systems.

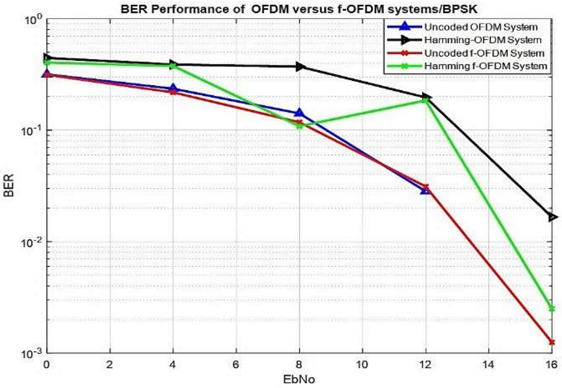


Figure 6. BER performance for using Hamming codes in both systems /BPSK.

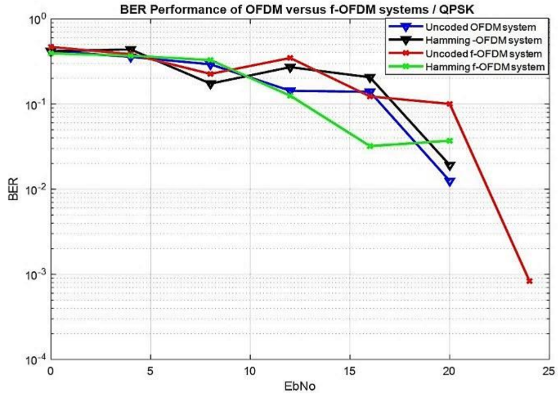


Figure 7. BER performance for using hamming codes in both systems /QPSK.

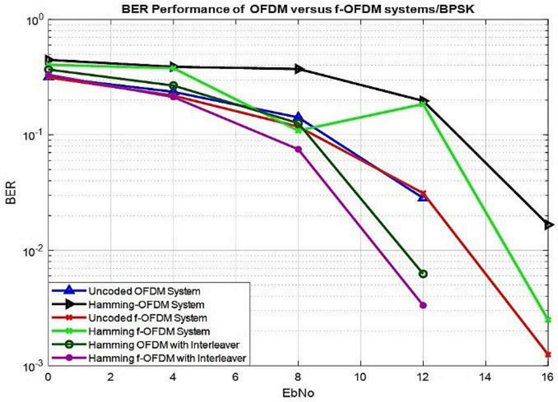


Figure 8. BER performance of using Interleaver in both systems/ BPSK.

On the contrary, the uncoded systems were better than using Hamming codes with their systems. Hence, the interleaving process has been used in this paper to enhance the system performance as depicted in Fig. 8 and Fig. 9 for modulation schemes, respectively. For the BPSK modulation scheme, using interleaver with both systems significantly improves their system performance more than uncoded systems. It also makes their BER performance curve smooth in reducing errors against increasing SNR values. On the other hand, the performance of the proposed system considerably improves than the conventional OFDM system, as depicted in Fig. 8. For the BPSK modulation scheme, 0.8 dB coding gain has been achieved at $6X10^{-3}$ BER against the familiar OFDM system for the proposed system. Using interleaver/de-interleaver with both OFDM and f-OFDM systems has also significantly improved the BER performances of these systems for the QPSK modulation scheme as depicted in Fig. 9.

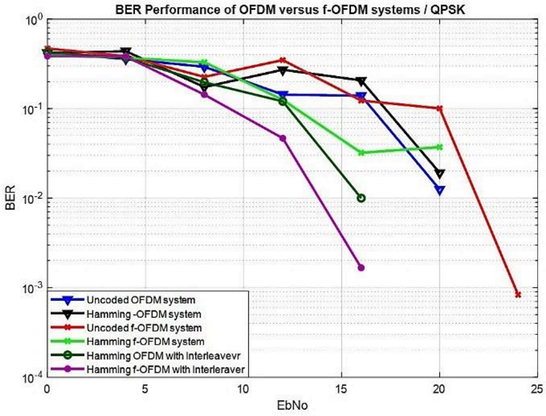


Figure 9. BER performance of using Interleaver in both systems / QPSK.

It is clear that the BER performance curves for both systems are considerably enhanced using the interleaving process than using the Hamming codes alone. The proposed system performance is considerably enhanced by using the interleaving process compared to the familiar OFDM system for the QPSK. Around 2.5 dB coding gain has been achieved at 10^{-2} BER for the proposed system against the conventional OFDM system for the QPSK modulation scheme. Therefore, the results proved the importance of using the interleaver/de-interleaver with channel coding in randomizing the encoded data. Thus it distributes the random and burst errors, improving the error correction ability of channel code. Using Hamming codes alone without the interleaving process lead to system performance deterioration, possibly due to exposure of the encoded data in the channel of the random and burst errors. Hence, it has difficulty in performing the decoding process in the receiver. Unlike using the interleaving, which contributes in combating the burst errors which may occurred for the transmit data via the channel and thus helping the decoder in correcting the errors. In conclusion, using the Hamming codes with interleaver in the proposed system significantly improves the BER performance better than the uncoded case or Hamming-OFDM system for both modulation schemes.

V. CONCLUSIONS

This paper proposes Hamming code for the f-OFDM system, while the conventional OFDM system is used as the baseline for comparison purposes. MATLAB executes the simulation over a 2X2 MIMO system in the presence of a multipath fading channel for BPSK and QPSK modulation schemes. The impact of using interleaver with Hamming codes on the system performance has been studied. The evaluation is performed for three important parameters, namely BER, OOBE and PAPR. The results show that the proposed system's PAPR values are still high compared to conventional OFDM and do not reduce. Thus, this parameter still needs to review and searching for another solution to decrease it. On the other hand, because of using a subband filter in the system architecture, the proposed system was able to decrease the values of OOBE significantly to around 100dB lower than the conventional OFDM system for BPSK and QPSK. Although using interleaver with Hamming code in both systems improved the BER systems performance better than uncoded and using Hamming codes without interleaver. However, the suggested system performance is considerably improved better than the familiar OFDM system. The suggested system achieved 0.8 and 2.5 dB coding gain at 10^{-2} and $6X10^{-3}$ BER against the familiar OFDM system for both schemes, respectively. Therefore, the proposed system can be presented as an alternative solution to the OFDM system because it outperforms in terms of OOBE and BER performance.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

First author made the design, analysis and writing the paper, while both other authors help in writing and reviewing the paper; all authors had approved the final version.

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