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Concatenated RS/Hamming Code in f-OFDM System

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Abstract

With the appearance of Fifth Generation (5G) technology , its necessary to fast the enhancing of the current networks, because of the limitations of Fourth Generation (4G) in terms of data transmission. Although the benefits of the Orthogonal Frequency Division Multiplexing (OFDM) standard of the LTE systems, it has demerits such as rises the Peak-to-Average Power Ratio (PAPR) as well, high Out-Of-Band Emission (OOBE). Thus, it is considered unsuitable for 5G. In this paper, the filtered OFDM (f-OFDM) is proposed for 5G wireless communication systems as an alternative of OFDM because of its low OOBE. Nevertheless, a trade-off between minimize Bit Error Rate (BER) and OOBE and managing PAPR values are the challenge. One of the most important objectives in this paper is achieving balance among this trade-off through proposing concatenated Reed-Solomon (RS)-Hamming codes to improve f-OFDM systems performance. The proposed method utilizes an external RS (7, 1) code with an internal Hamming (7, 4) codes, then appended of an interleaver to combat random errors and help RS code in correcting errors. The results indicated that the proposed f-OFDM system significantly reduced OOBE values compared to familiar OFDM system owing to use FIR digital filter, while minimizes PAPR and improved BER performance due to combined with concatenated codes. Thereby, the suggested system is presented as a highly competitor candidate future wireless communication systems thank to these benefits.

Keywords
f-OFDM, OOBE, BER, PAPR, RS, Hamming.

I. INTRODUCTION

Because of the rapidly growth in the users numbers of smart phones with appearance the new types of businesses that based on modern technologies led to the wireless communication as an important and substantial active area research [1]. Cell phones are developed and passed via past years with millstones. First Generation (G1) is the first wireless generation which is transferring from fixed contact to the moving personal devices, followed by several enhancing of the services and battery life. While, in the second generation (G2) let to use the Short Message Services (SMS) which was the millstone at that period. High data rate and internet connectivity introduced in third generation (G3). In Fourth Generation (G4) improving efficiency and high storage by using smartphones which characterized by large screens and high-definition photos. Moreover, increasing throughput and easier and interactive the mobile interactions were the main objectives [2]. On contrast, because of the growth request of high data rate and low latency, many academic researchers still concentrate on Fifth Generation (5G) cellular communications [3].

Based on the research of the International Telecommunication Union (ITU), they predict annual growth in total mobile traffic around 55% and reaches to thousands exabytes by 2030 [4]. The rise of user requests led to seek of efficient solutions, concentrating on enhancing the geographic spectrum reusability [5]. Thereby, enhancing spectral efficiency is an important to accommodate the increasing growth data rates of networks [6]. While, with expanding the mobile traffic demand, prominent a trade-off between spectrum availability and capacity [7]. In contrast, billions of smart terminals con-

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nected to 5G IoT led to a broad requirements range and use cases [8]. Whereas, 5G wireless communication and beyond characterized of low latency, high throughput and reliability [9]. To boost the diverse requirements of 5G, it is important to effectively utilize the network slicing. Where, a multicarrier waveform such as Orthogonal Frequency Division Multiplexing (OFDM) is commonly utilized in several wireless systems especially in 4G networks, owing to its advantages including of simplicity implementation and high capacity. Nevertheless, rising the Peak-to-Average Power Ratio (PAPR) as well, high Out-Of-Band Emission (OOBE) are considered disadvantages of OFDM which make it unsuitable for 5G applications. On contrast, filtered OFDM (f-OFDM) system is a candidate for 5G systems as an alternative to OFDM system [10, 11]. Although, OFDM system characterized of simple equalization implementation, channel estimation and compatible to multi antenna techniques [12] but, due to the needs of wireless communication systems, LTE systems no longer satisfy the requirement of high data rates. Moreover, OFDM system produces high values of OOBE that cause interference with neighbor frequency bands. Hence, f-OFDM system that uses Finite Impulse Response (FIR) based on a window function scheme is a good choice for 5G communication systems [13]. While, different systems including of Universal Filtered Multicarrier (UFMC) and Filter Bank Multicarrier (FBMC) have been proposed from other researchers as alternative system of OFDM. However, these systems are difficult implementation and faced difficulties with MIMO channels [14]. So f-OFDM system strongly presents as promising candidate for 5G waveforms owing to lower OOBE, slight equalization complexity and handling lots of streams at one time [3]. Where, a good localized filter achieves very low OOBE levels, thus minimize the user's interference [15]. As a comparison between multicarrier systems such as Generalized Frequency Division Multiplexing (GFDM), UFMC and FBMC with f-OFDM; GFDM needs to high order filter with interference cancellation more than once, against the f-OFDM that utilize quasi-orthogonal subcarriers with filter length equivalent to half symbol length and thus less processing, moreover f-OFDM filters are highly efficient and low complexity. On the other hand, using FBMC with multi- antenna is a challenge and restrict their potential applications, while f-OFDM easy to implement and compatible with multiple antennas without complexity. Also, the circular prefix limits filter length to protect from OFDM's ISI from causing poor OOBE. Properly built filters may outweigh performance loss from longer filters [16]. f-OFDM system has been introduced to improve spectrum usage and flexibility in 5G systems which permit a non-synchronous transmitting between multiple users with lower interference, minimum OOBE leakage signaling noise [17]. So, f-OFDM is a vital technology for the 5G communication systems due to its similar to OFDM and lower OOBE and compatible to multiple antennas [18].

On the other hand, using Forward Error Correction (FEC) techniques including RS, BCH, LDPC and polar codes in 5G communication systems are effectively enhance the system reliability [19–21]. Using channel coding in modern communication systems has become essential particularly for 5G systems. Where, different Error Control Coding (ECC) techniques are proposed to improve system performance such as Turbo, LDPC, and polar codes [22]. In [23], proposed a hash-concatenated polar coding method to improve error correction performance and low false alarm rates. They indicated this approach outperformance than LTE turbo codes on high-speed train channels in a study on 5G control channels [23]. Whereas, polar and LDPC code are suggested for data and control channels in 5G [24]. Since, polar code is considered a great reliability promissing channel coding technique used in wireless communication systems. It uses in Enhanced Mobile Broadband (eMBB) for 5G systems [25]. However, its reliability decreased with increasing its code rate because of using more parts of incompletely polarized to accommodate extra information bits [26]. BCH codes are used in f-OFDM which is considered a contender waveform for 5G systems to improve the reliability via multipath fading channels [27]. It enhances OOBE in addition to BER performance outperforming to BCH-LTE system. Nevertheless, this proposed method un able to decrease PAPR levels owing to trade-off between enhancing SNR and decreasing PAPR. On the other hand, hamming codes are suggested to f-OFDM system to improve BER performance which outperformed than familiar OFDM system [9]. On contrast, RS code in [28] has been suggested for f-OFDM system to enhance its reliability through noisy multipath fading channel. Their outcomes indicated outperforming the suggested system than familiar OFDM system.

Concatenated RS/Hamming codes is suggested in this paper for f-OFDM system to improve its performance and achieve balance between enhancing BER and reducing PAPR and OOBE values. The suggested system introducing as an alternative system of OFDM has its advantages and addressing disadvantages, proposing it for 5G wireless communication systems.

The paper structure is consisting of the proposed system methodology and system diagram with all details of simulation parameters in Section II. In Section III, results and discussion have been presented which contains of evaluations to three parameters BER performance, OOBE and PAPR values. Lastly, conclusion and future works are introduced in Section IV.

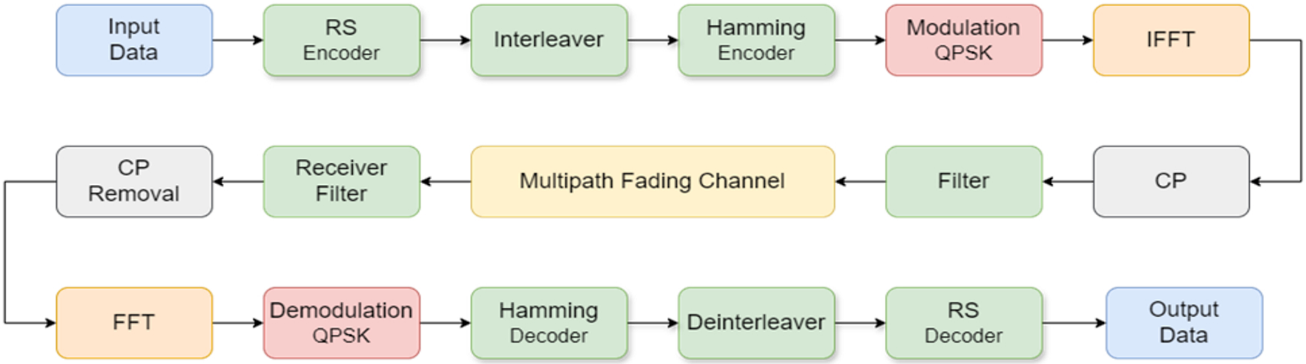

Fig. 1. System Block Diagram

II. PROPOSED METHOD

Block diagram of the proposed system which is used concatenated RS/Hamming codes in f-OFDM system is shown in Fig. 1. Whereas, the details of utilized simulation parameters is depicted in Table I. The proposed system was simulated using MATLAB to evaluate its performance.

First, the binary data is being encoded via the RS encoder then send to interleaver for random distribution (which increases the ability to correct burst errors). After that, it sends to Hamming encoder. These two encodes work together to increase the correction ability of the transmission errors. The f-OFDM system design reduces OOBE levels using FIR digital filter based on the window function procedure. At the receiver, the data is decoded via the RS than Hamming decoders after passing through the multipath fading channel.

TABLE I.
UTILIZED PARAMETERS

Bandwidth	20 MHZ
Channel	Multi-path fading channel.
IFFT/FFT points	2048
Occupied Sub-Carriers	1200
C.P	144
Modulation Scheme	QPSK,64QAM
Sub-carrier spacing	15 KHZ
Filter Design	
Bandwidth (B.W)	19.83 MHz
Sampling Rate	30.72 MHz
Type	Root-Raised-Cosine(RRC), Windowed- Sinc
Roll-off factor (α)	0.6 MHz
Length	513
FEC	RS (7,1) codes Hamming (7,4) codes

A. *Reed Solomon Codes*

The RS codes are developed by I. S. Reed and G. Solomon, which are robust error-correcting codes. They are extensively used in storage and data transfer applications because of the strong ability to correct burst errors [29]. It is also considered one of the codes have low encryption complexity.

The generator polynomial for an RS code (n,k) is represented by a simple equation. Since, n indicated to the number of symbols codeword, whereas k described the number of data symbols as following:

$$n-k=2t \tag{1}$$

since, $2t$ indicated to the number of symbols for parity, and t is the code's ability to fix symbol errors [30].

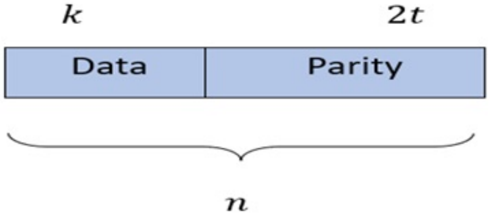

Fig. 2. System Block Diagram

The generating polynomial $g(x)$ of RS code is obtained as below:

$$g(X) = g_0 + g_1X + g_2X^2 + ...g_{(2t-1)}X^{(2t-1)} + X^{2t} \tag{2}$$

where the factors in $g(x)$ are consecutive roots in the Galois field [31]. The message that will encoded as one block can represent as following:

$$M(X) = M_{k-1}X^{k-1} + ... + M_1X + M_0 \tag{3}$$

The encoding involves multiplying $M(X)$ by X^{2t} and dividing it by the generator polynomial $g(x)$. By division by $g(x)$ produces, $q(x)$ this term represents the quotient obtained from the division operation and $r(x)$ this term represents the obtained from the division operation. The equation is structured as follows:

$$\frac{M(X)X^{2t}}{g(X)} = q(X) + r(X) \tag{4}$$

The transmitted codeword $T(X)$ can then be formed by summing the message polynomial with remainder polynomial.

$$T(X) = M(X)X^{2t} + r(X) \tag{5}$$

B. Hamming Code

It a kind of linear error-correcting code. It can find errors of one bit or two bits, or they can fix errors of one bit without finding errors that haven't been fixed. The best rate for codes with a block length and a minimum distance of three is achieved by hamming codes, which are perfect codes [32]. Which was discovered by Richard Hamming in 1950. It was distinguished by its simplicity and low complexity of encryption. Hamming code is widely used as an effective way to hide information [33]. Hamming displays more detail about its main idea and the Hamming (7,4) code, which takes four data bits into a 7-bit codeword by combine three parity bits to them [34]. The parameters used in Hamming code, Generator matrix G is the combination of identity matrix I and submatrix P. The generator matrix utilizes to generate the encoded message in the Hamming code [35].

$$G_{kXn} = [I_{kXk}|P_{kXr}] \tag{6}$$

G defines as a canonical generator matrix of a linear (n,k) code [36]. Where n is the codeword bits, r is the parity bits, and k is the message bits.

The parity check matrix H is employed to verify the presence of errors in the received message. H is the relationship between a negative transposed submatrix and an identity matrix [35].

$$H_{rXn} = [-P^T_{kXr}|I_{rXr}] \tag{7}$$

This is how G and H are constructed in a conventional, methodical manner. For linear block codes, G and H, regardless of form, must satisfy $GH^T = 0$ an all-zeros matrix [36]. A codeword in Hamming codes comprises both data and parity bits, arranged in a manner that enables the receiver to correct and detect errors.

$$Codeword_{n-bits} = mod_2(M_{k-bits} * G_{kxn}) \tag{8}$$

The syndrome S is calculated to ascertain the existence of any errors in the received message, where S is a zero vector, indicating the absence of errors. If S is not equal to zero, it indicates the error's position.

$$S_r = mod_2(C_{n-bits} * H^T_{rXn}) \tag{9}$$

In the proposed system, we will seek to merge two codes using the concatenated techniques to increase the ability of the correction of transmission errors to achieve higher reliability in wireless communications systems [35]. The two codes were use in 5G research for the f-OFDM system by [9] [28]. The suggested system will use concatenated techniques to integrate two codes, aiming to achieve higher reliability and include accurate transmission, where the $RS(7,1)$ code is suggested with the Hamming (7,4) to obtain a new code deals with the data digital binary.

C. Filter Design

To meet requirements of the 5G cell phone network, the filter utilized in f-OFDM. This filter is applied to sub-bands, which consist of groups of subcarriers. The bandwidth will divided into sub-bands of specific widths, then each one will separately filtered [37]. All these filtering sub-band are sending out based on the frequency resources that have been assigned to make better use of the spectrum [37–39]. The 5G system must provide enhanced services across various channel characteristics. Additionally, the f-OFDM system can minimize OOBE leakage, tolerate time-frequency misalignment, and overcome any system drawbacks [37, 38]. The steps for f-OFDM are the same as those for regular OFDM. The major different is in using filtering after the Cyclic Prefix (CP). Where, the interference between sub-bands are prevent through filtering in f-OFDM system. This OOBE has minimal performance loss [40]. The choice of filter depends on its ability to minimize OOBE radiation while maintaining a constant passband [37,41]. It is important that the filter has an impulse reaction length that is longer than the CP. If the tail of filter exceeds the length of the CP, the Inter-Symbol Interference (ISI) will occur, also in a flat channel [42]. The FIR filter has been selected in this paper due to its simple equations, making it quick, easy to use, and reliable [43]. FIR filters employ the windowing technique which have a finite lifetime [43] due to the fact that they reach zero after a finite period of time. It is possible to reduce the ISI without reducing efficiency. The f-OFDM system may reduce the PAPR values and improved BER performance, as it eliminates the most significant obstacle of the OFDM system, thereby increasing the system's efficacy.

1) *FIR Filter:*

It is determined by windowing of non-recursive digital filter [44]. As the order of the FIR filter increases during its design, its transfer function approaches that of an ideal filter [45]. These factors will make the filtration process of f-OFDM more time-consuming as well complex. The frequency response may show monotonic behavior through a frequency range, and the frequency response shape is typically influenced by the filtering scheme used [43]. This paper incorporates the windowing technique into its filtering framework within the f-OFDM system. The features of the transfer function based on the specific window function chosen. Various windowing configurations are supported, such as the Root-Raised-Cosine (RRC), Kaiser, and Hanning windows. The equations for these window types are provided in Table I. As shown in Fig. 3 and Table II, the time-frequency response of each window function, Kaiser, RRC, and Hanning were among the window function options to attain the acceptable trade-off between frequency and time localization [17]. Fig. 2 It is demonstrated that the RRC windowed filter exhibits a smoother impulse response compared to the Remez filter, that features a tighter transition region than the Hanning windowed filter. Consequently, the trade-off between frequency and time localization is more favorable for the RRC windowed filter [17].

TABLE II.
WINDOW TYPE EQUATION [27, 45, 46]

Window Type	Mathematical Equation
Root-Raised-Cosine (RRC)	$W_n = [0.5(1 - cos\frac{2\pi n}{N-1})]^{\alpha}$
Hanning	$W(n) = 0.5 - 0.5cos\frac{2\pi n}{M}$
Kaiser	$W(n) = \frac{I_0(\pi n)\sqrt{1-(\frac{2n}{M}-1)^2}}{I_0(\pi\alpha)}$

2) *Interleaver*

Using an interleaver, one can randomly rearrange data or bit sequences in a one-to-one fashion. As opposed to this, the de-interleaver restores the original order of the incoming data sequences, reversing the effect of the interleaver [47].

In this paper, to improve correcting capabilities, the interleaver/deinterleaver has been utilized with the RS/Hamming code. The encoded data is rearranged by the interleaver before transmission across the channel. As a result, the receiver's de-interleaver is used to restore the received data. This procedure disperses bursts and random mistakes that could arise over the channel, simplifying the decoding and error correction processes.

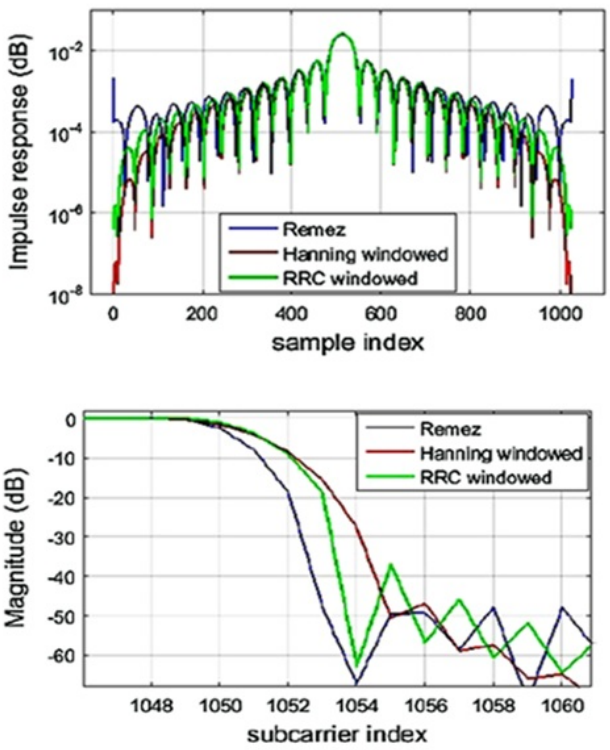

Fig. 3. Frequency and Time Response of FIR Window Filter [17]

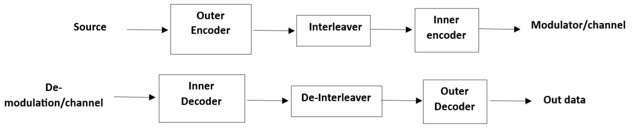

Fig. 4. Interleaver— De-interleaver During Channel Coding

The interleaver doesn't add any extra error correction code; it just starts moving the symbols that were made by the outer code around [48].

III. RESULTS AND DISCUSSION

The concatenated RS/Hamming code system was proposed for f-OFDM system. This system was simulated using MATLAB, and two primary standards were applied for evaluation. Firstly, the OOBE levels in f-OFDM were measured and compared to those in the OFDM. Secondly, the BER performance was assessed to determine the impact of using the concatenated

RS/Hamming code on the f-OFDM system, comparing it with the RS f-OFDM and Hamming f-OFDM systems. Finally, PAPR values of proposed system was compared to conventional OFDM system. The main goal is demonstrating the advantages of proposed system in this paper thus, introducing it as competitor candidate for future communication systems.

A. *OOBE*

In this section, the OOBE levels for proposed system and familiar OFDM system are discussed. The results indicated that familiar OFDM system gives OOBE values much higher than suggested f-OFDM system in QPSK modulation schemes. Where, the conventional OFDM system recorded -90 dB compared to -195 dB for proposed system (i.e, reduced of 105 dB). This reduction referred to use FIR digital filter with f-OFDM system as depicted in Figs. 5 and 6.

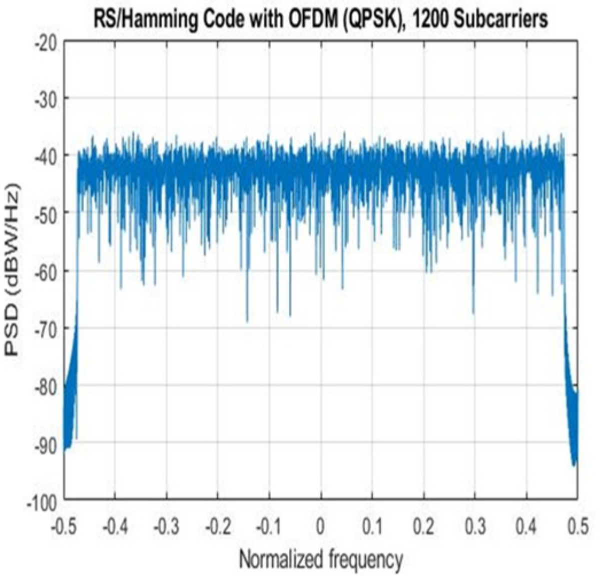

Fig. 5. Power Spectrum Density of RS/Hamming OFDM System/QPSK.

TABLE III.
PAPR OF SUGGESTED SYSTEM AGAINST FAMILIAR OFDM SYSTEM

Technique	PAPR (dB)
RS/Hamming OFDM	11.77
RS/Hamming f-OFDM	11.00

Both OFDM and f-OFDM have their PAPR values displayed in Table III, which compares the two systems. The findings showed that the RS/Hamming f-OFDM system achieves an enhancing in PAPR compared to the RS/Hamming OFDM system, reducing the PAPR value by approximately 0.77dB. This improvement can be beneficial in mitigating distortion effects in wireless communication systems that use OFDM.

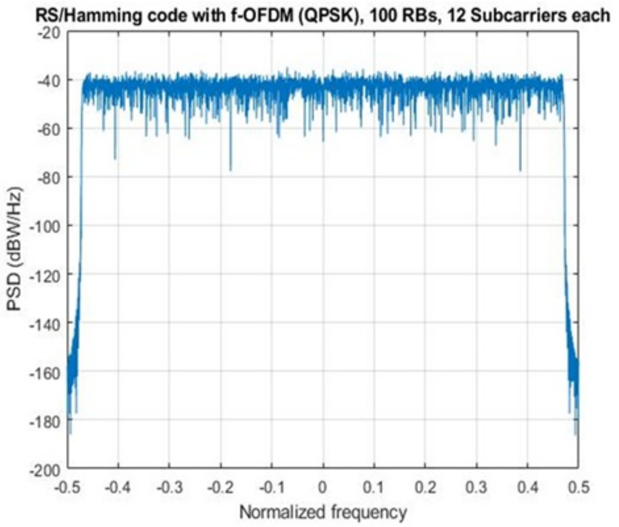

Fig. 6. Power Spectrum Density of RS/Hamming f-OFDM System/QPSK.

B. *BER*

In this section, Fig. 7 compares uncoded BER performance between f-OFDM and OFDM systems, focusing on higher Eb/No values. The oucomes indicate that the uncoded f-OFDM system performance does not show a substantial improvement over the uncoded OFDM system, with noticeable enhancement occurring only after an SNR of approximately 20 dB.

On contrast, Fig. 8 displays the performance for different codes in OFDM and f-OFDM systems using QPSK. The RS-Hamming f-OFDM shows the best performance across the range of Eb/No values, with a significant decrease in BER as Eb/No increases. The f-OFDM technique provides an improvement, but the BER stabilizes round 10^{-1} to 10^{-2} at higher Eb/No values. The RS-Hamming OFDM shows better performance than the Hamming code but worse than the concatenated RS-Hamming f-OFDM. The Hamming f-OFDM performs better than the RS f-OFDM scheme but not as well as the RS-Hamming f-OFDM. This good performance for RS-Hamming f-OFDM can be attributed to the combination of RS codes and Hamming codes with the f-OFDM system. The RS and Hamming codes provide robust error correction, while f-OFDM helps reduce inter-symbol interference and

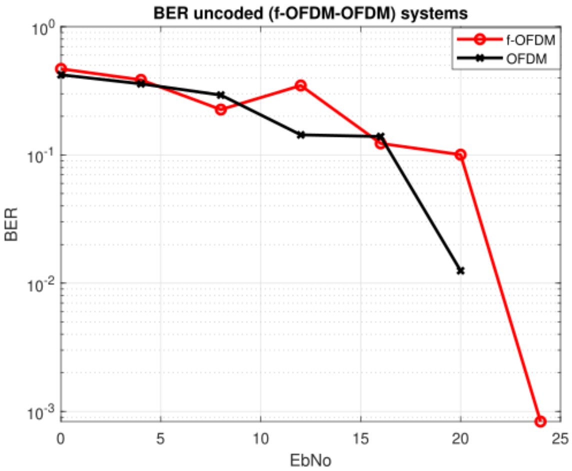

Fig. 7. BER (f-OFDM-OFDM) Uncoded Systems.

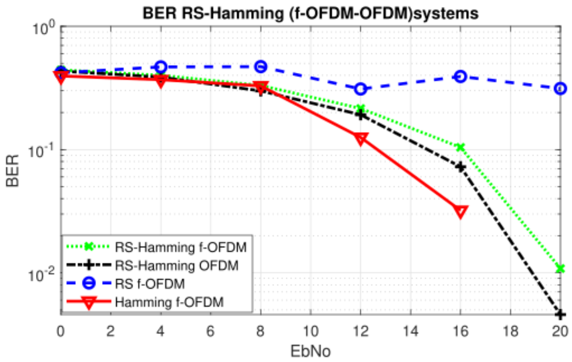

Fig. 8. BER RS-Hamming for (f-OFDM-OFDM) without Interleaver.

enhance spectral efficiency, resulting in lower BER.

Fig. 9 shows the performance of OFDM and f-OFDM systems in terms of BER. The system with the RS-Hamming f-OFDM and interleaver shows the best performance, with BER below $4X10^{-4}$ at around 12dB SNR. The Hamming f-OFDM with interleaver performs worse than the concatenated RS-Hamming code but better than non-interleaved systems. Interleaving is a technique used to rearrange the order of a data sequence so that burst errors are spread out over time. This makes correcting errors in error-correcting codes like RS and Hamming easier. Interleaving spreads errors caused by noise over multiple code blocks, preventing burst errors from overwhelming a single block. With interleaving, RS and Hamming codes can more effectively correct errors as they are dispersed rather than concentrated.

Fig. 10 displays the performance of an RS-Hamming f-OFDM system with different positions of interleaves in terms of BER. Three configurations are shown: interleave in middle, middle-end, and end. Interleave in the middle performs better in reducing the BER below $4X10^{-}4$ at 9dB SNR. This is due to the effective distribution of errors by the RS-Hamming code, leading to a significant reduction in BER. Middle-End performs moderately well but not as effectively, resulting in higher BER compared to the middle placement. End placement is less effective in distributing errors, resulting in less effective error distribution and higher BER.

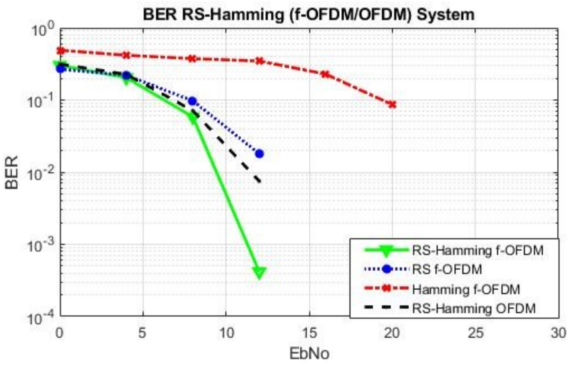

Fig. 9. BER RS-Hamming for (f-OFDM-OFDM) with Interleaver.

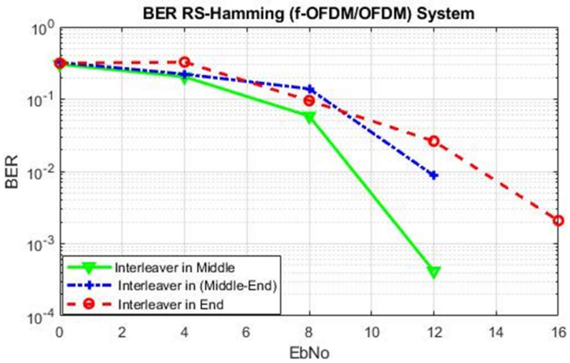

Fig. 10. BER (RS-Hamming) for f-OFDM with interleaver

Table IV shows a comparison among the proposed system and the RS f-OFDM and Hamming f-OFDM systems, where the outcomes show the superiority of the suggested system over the previous systems in three problems facing the communications system in 5G technology, including (OOBE, PAPR, PER). Where it was clear that when merging two codes together, higher results were obtained, and it outperformed the Hamming system in improving PAPR in addition to the rest of the factors. So we can say that the proposed system is better than the previous systems in mobile communication system.

TABLE IV.
COMPARISON AMONG CONCATENATED RS/HAMMING CODES WITH BOTH SINGLE RS AND HAMMING CODES FOR F-OFDM

Authors	Method.	Advantages	Disadvantages	Results (OOBE, PAPR, BER)
[28]	RS Codes with interleaver for f-OFDM System	-Strong codes and RS codes significantly improve the performance of downlink LTE systems compared to convolutional or turbo codes - Top-notch in rectifying burst errors. -low complexity.	It is not considered the best for correcting random errors	- Recorded 9.9763 dB PAPR versus 10.1419 dB. - Achieved almost 100 dB OOBE lower than familiar OFDM. - Achieved $8X10^{-2}$ BER at 14 dB.
[9]	Hamming code with interleaver for f-OFDM systems	-Hamming is characterized by the reduction of random errors. -low complexity	-Limited Error Correction Capability	-PAPR values are higher than familiar OFDM. - Minimize the OOBE values to around 100dB lower than familiar OFDM system with QPSK - The system achieved 10^{-2} BER at 16 dB.
P.Work	Concatenated RS/Hamming code with various positions of interleaves for f-OFDM system	The proposed system presents a promising alternative for improving BER and OOBE in future wireless communication standards.	facing challenges in practical implementation due to complexity.	- Recorded 11.0 dB PAPR against 11.77 dB for familiar OFDM system. -Achieved almost 105 dB OOBE lower than familiar OFDM system. - Achieved $4X10^{-4}$ BER at 12dB.

IV. CONCLUSION

In this paper, we propose using concatenated RS and Hamming codes to enhance data reliability in an f-OFDM system over a multipath fading channel. We conducted simulations using MATLAB software with a QPSK modulation scheme. A crucial element of our proposed system is the FIR digital filter, implemented through the window function method. We analyzed the performance impact of placing the interleaver at different points within the system. While, RS-f-OFDM and Hamming-f-OFDM systems have been used as benchmarks. The outcomes showed that the OOBE of suggested system largely minimized with 105 dB, while it reduces PAPR around 0.77dB compared to conventional OFDM system. On contrast, the proposed system achieved considerable enhancement of BER performance by using interleaver in middle between both codes.

Where, it records $4X10^{-4}$ BER by using interleaver in between codes compared to $1X10^{-2}$ by using two interleavers in between and in the end of codes and $3X10^{-2}$ by using it in the end, at 12 dB SNR. Furthermore, the proposed system outperforms in terms of BER both RS f-OFDM and Hamming f-OFDM systems. For example, it achieved $4X10^{-4}$ BER against $2X10^{-2}$ for RS f-OFDM and $3X10^{-1}$ Hamming f-OFDM at 12dB SNR. Therefore, based on these results, could present the suggested method as contender candidate waveform for future wireless communication standards.

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CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

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