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Performance Improvement of f-OFDM Systems Using a Concatenated RS/LDPC Coding Scheme

Ghasan Ali Hussain*

Electrical Engineering Department, Faculty of Engineering, University of Kufa, Najaf, Iraq

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*Correspondence: Ghasan Ali Hussain
Email: ghasan.alabaichy@uokufa.edu.iq

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Abstract: *In wireless communication systems, transmission errors are inevitably generated due to interference and fading. Therefore, various approaches have been developed to enhance system reliability, including increasing the transmitted signal power and utilizing error detection and correction schemes. Among these approaches, channel coding is an important technique for reducing the Bit Error Rate (BER). Although LDPC codes are widely adopted in 5G wireless communication systems; achieving ultra-low BER values remains challenging in LDPC codes due to the error-floor phenomenon. To address this limitation, a modified concatenated RS/LDPC code is proposed for an f-OFDM system in this paper. It employs RS codes with LDPC codes followed by an interleaver, contrasting with traditional the conventional concatenated RS/LDPC codes that separated both codes by an interleaver. Simulation results demonstrate that the suggested system achieves superior BER performance compared with the conventional concatenated scheme and standalone RS and LDPC codes under both BPSK and QPSK. Furthermore, the suggested f-OFDM system provides superior Out-of-Band Emission (OOBE) suppression compared with the conventional OFDM system, while maintaining a Peak-to-Average Power Ratio (PAPR) performance comparable to that of the conventional OFDM system. Based on the results, the suggested f-OFDM system is considered a promising candidate for 5G and beyond systems.*

Keywords: *5G, f-OFDM, LDPC, RS, Concatenated*

Introduction

In physical layer design, Multicarrier Modulation (MCM) technology is vital for modern wireless communication systems, outperforming Single-Carrier Modulation (SCM) by providing spectral efficiency and data rates. MCM has been widely adopted in cellular networks owing because of its strong resilience to the Inter-Symbol Interference (ISI). Specifically, Orthogonal Frequency Division Multiplexing (OFDM) system has become the standard MCM scheme in Fourth Generation (4G) and Fifth Generation (5G) systems (Zhu et al., 2024), and its advanced enhancements remain leading candidates for Six Generation (6G) systems. However, its large values of Peak-to-Average Power Ratio (PAPR) and Out-Of-Band Emissions (OOBE) are major limitations, which is increasing its noise sensitivity at bad quality environments (Xiao et al., 2025). Consequently, conventional OFDM in its current form became unsuitable for the requirements of 5G heterogeneous service, especially, it provides a single set of waveform parameter for all services. In contrast, filtered-OFDM (f-OFDM) introduced as contender waveform for 5G systems and beyond.

It divides the entire bandwidth into multiple sub-bands and applies sub-band filtering to each, enabling various waveform parameters tailored to diverse service scenarios(X. Cheng et al., 2016). In mobile wireless communication systems, transmission errors are inevitably generated by interference and fading. Therefore, various approaches are developed to enhance system reliability, including increasing the transmitted signal power and utilizing error detection and correction schemes. Among these approaches, Error Correction Codes (ECC) is an effective method for reducing the Bit Error Rate (BER) (S. Cheng, 2019). Various ECCs are adopted to improve the 5G wireless communication system's reliability, including Low-Density Parity-Check (LDPC) codes, Reed-Solomon (RS) codes, Bose–Chaudhuri–Hocquenghem (BCH) codes and polar codes (Hussain & Audah, 2020c, 2020d, 2020b, 2021) (Chen et al., 2017; Dhuheir & "Ozt"urk, 2018) .

Both polar and LDPC codes have been introduced by 3GPP instead of convolutional and turbo codes with 4G/LTE for the standardized 5G New Radio (NR) Release 15(Bae et al., 2019) where, they are investigated in (Hui et al., 2018) for the 5G systems. The authors demonstrated that the LDPC code achieves performance comparable to that of the turbo code. Whereas, in terms of throughput and latency, the LDPC codes performed better than turbo codes. In contrast, the performance of turbo codes degrades at high code rates due to the error-floor phenomenon.

Different error correcting codes have been evaluated under Binary Phase Shift Keying (BPSK) modulation through Addictive White Gaussian Noise (AWGN) channel in (Hajiyat et al., 2019), 1/2 code rate of polar, turbo, LDPC and convolutional codes are discussed to find optimum codes for 5G system. They demonstrated that the convolutional codes outperform other coding techniques for short-length message transmission in terms of flexibility and reliability, whereas polar code exhibit lower decoding complexity.

In Channel coding, achieving ultra-high reliability is crucial for next- generation communication systems. For instance, 6G networks necessitate a frame error rate as low as 10-9 to satisfy the requirements of Ultra-Reliable Low Latency Communication (URLLC). In contrast, LDPC codes are commonly used in 5G systems; however, their performance encounters severe challenges in achieving such low error rates due to the error floor phenomenon (Kwak et al., 2025). Although various techniques to mitigate this issue, they introduced a clear trade-off, namely an increase in decoding latency as well as encoding and decoding computation complexity (Oh et al., 2016). Reed Solomon (RS) codes are robust error correction codes in terms of burst error (Stanescu & Brezeanu, 2025). To mitigate the error floor phenomenon without increasing the latency, RS codes are proposed as outer code with LDPC code in concatenated codes (Shi et al., 2024). Furthermore, concatenated RS/LDPC codes significantly improve decoding performance in addition to mitigating the error floor phenomenon down to 10^{-8} of BER (Qiu et al., 2020).

Concatenated coding schemes are widely employed as an effective error-correction approach in digital communication systems. It employs an interleaver in between two codes. The interleaver plays a crucial role in randomizing burst errors that may be generated by the inner decoder (Suls et al., 2017). A novel of BCH-RS (BCS) coding scheme was proposed in (Hussain & Audah, 2020a) based on the concept of concatenated coding. Unlike conventional concatenated approach, the authors employed a new interleaver placement strategy, where the interleaver is applied after both codes as illustrated in Figure 1. The authors demonstrated that the suggested method achieved better performance than the conventional concatenated coding scheme. The proposed method was subsequently extended to an f-OFDM system in (Hussain & Audah, 2022). The authors presented their system as a promising candidate for 5G systems because of the improvements achieved in BER performance, PAPR reduction and OOBE suppression.

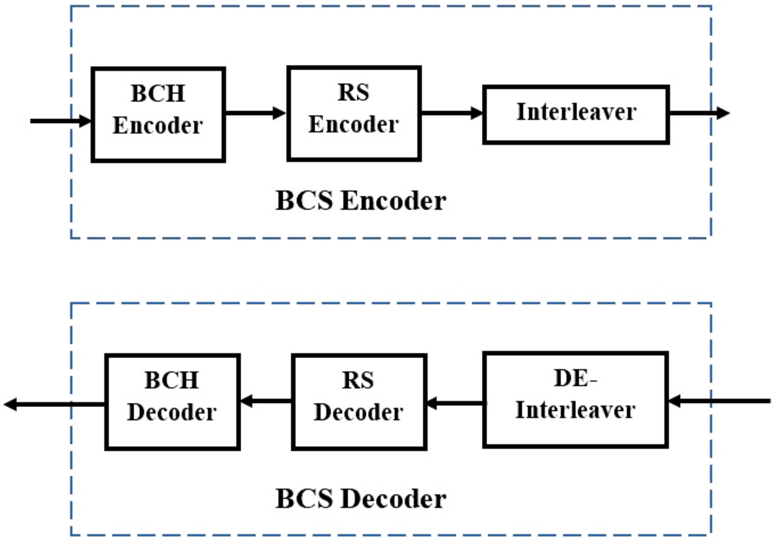

Figure 1. BCH-RS Code.

Although employing BCS codes in the f-OFDM system enhances BER performance, reduces PAPR, and suppresses OOBE, it relies on BCH coding as the inner code. Based on the previous studies, concatenated RS/LDPC codes can provide superior error-correction capability and effectively mitigate the error-floor phenomenon. Moreover, to the best of the authors' knowledge, employing a conventional RS/LDPC concatenated coding in the f-OFDM system has not yet been suggested. Therefore, it remains unclear whether combining RS/LDPC coding with f-OFDM can further enhance system reliability while preserving the waveform advantages of f-OFDM.

Inspired by the BCS coding approach presented in (Hussain & Audah, 2020a) and (Hussain & Audah, 2022) , this paper proposes a concatenated RS/LDPC coding scheme for an f-OFDM system. The proposed architecture employs an RS code and an LDPC code, followed by an interleaver, to exploit the complementary error-correction capabilities of both codes. The objectives of this work are to enhance BER performance with maintaining the features of the f-OFDM system regards to the OOBE suppression and PAPR reduction

Thereafter, the suggested system represents a viable solution for future 5G systems and beyond by achieving improved BER performance, suppress OOBE and reduced PAPR.

Methodology

The system diagram of the suggested system illustrates in Figure 2, which employs the concatenated RS/LDPC coding scheme in an f-OFDM system. The simulations were conducted using MATLAB software, and the system performance was evaluated over a 2X2 MIMO multipath fading channel under BPSK and QPSK modulation formats. The system and simulation parameters in this work are summarized in Table 1.

In this paper, the windowed Sinc approach was employed as the prototype filter in the f-OFDM system among various Finite Impulse Iesponse (FIR) filter design methods due to its simplicity and ease of online filters generation. Various window functions can be employed in f-OFDM systems, including Rooted Raised Cosine (RRC), Hanning and Kaiser. The RRC window is adopted in this paper because it achieves a good trade-off between frequency and time domain localization (Wu et al., 2016).

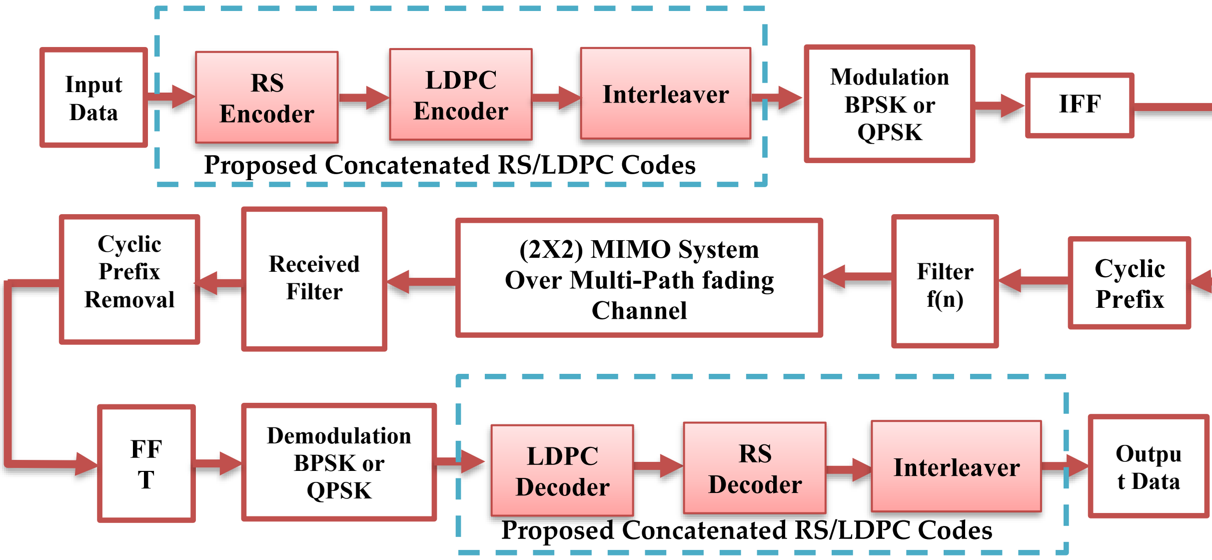

Figure 2. Proposed System Diagram.

First, the binary stream is fed into the external RS encoder. The RS encoded data are then sent to the inner LDPC encoder, followed by an interleaver that randomizes burst errors as well as enhances the error correction ability of both codes.

Thereafter, the modulator maps the LDPC encoder output data according to the selected modulation scheme. The OFDM signal is then generated by applying the Inverse Fast Fourier Transform (IFFT), followed by Cyclic Prefix (CP) insertion.

Finally, the OFDM signal is passed via an FIR filter to create the f-OFDM signal. Generally, the conventional OFDM symbol S(n) is given by (X. Cheng et al., 2016):

$$s(t) = \sum_{i=0}^{N-1} d_i \, rect\left(t - t_s - \frac{T}{2}\right) e^{i2\pi f_i (t-t_s)}, \qquad t_s \le t \le t_s + T \tag{1}$$

The number of subcarriers is represented as (N), the complex data symbol is represented by (d_i), the symbol duration is denoted by (T), the subcarrier frequency is represented by (f_i) and the rectangle function is denoted by $rect(t)$.

Table 1: Simulation Environment

PARAMETER		VALUE
B.W.		20MHz
Channel Model		(2X2) MIMO system with Multipath Fading
IFFT/FFT Size		2048
No. of Subcarrier		1200
C. P.		144
Modulation Schemes		BPSK or QPSK
Sampling Frequency		30.72MHz
Filter Parameters		
Filter Design	B.W.	19.83 MHz
	Sampling Frequency	30.72MHz
	Filter Type	RRC Windowed- Sinc
	Roll-off factor (α)	0.6
	Filter Length	513
Channel Coding Scheme		Modified Concatenated RS/LDPC Codes

Let,

$$\{s_{n,k}\}_{k=0}^{N-1} \text{ with } E\left|S_{n,k}\right|^2 = \sigma_s^2 \tag{2}$$

denote the complex baseband transmitted symbols in the nth OFDM block. The OFDM signal is given by (X. Cheng et al., 2016):

$$s_n(t) \sum_{k=0}^{N-1} s_{n,k}\, e^{j2\pi k \Delta f t}, \quad 0 \leq t \leq \mathrm{T_s} \tag{3}$$

The subchannels spacing is represented by Δf.

By applying the prototype filter $f(n)$, the filtered OFDM signal $\widetilde{s(n)}$ can be generated by using convolution operation as (X. Cheng et al., 2016):

$$\widetilde{s(n)} = s(n) * f(n) \tag{4}$$

The time-domain response of the prototype filter is given by [22]:

$$f(n) = f_{id}(n).w(n) \tag{5}$$

where ($f_{id}(n)$) denotes the ideal low pass filter, and ($w(n)$) represents the window function in time domain.

$$f_{id}(n) = \frac{1}{2}\int_{-w_c}^{w_c} e^{j\omega n}\, dw = \frac{\sin(w_c n)}{w_c\, n} \tag{6}$$

where (w_c) represents the cutoff frequency of the low pass filter, the RRC window in time domain can be expressed as follows (Wu et al., 2016):

$$w_{RRC}(n) = [0.5\left(1 - \cos\left(\frac{2\pi n}{N_f - 1}\right)\right)]^{\alpha} \tag{7}$$

where α denotes the roll-off factor that determines the window shape (α =0.6 for the RRC windowed FIR filter), while the filter length denoted by N_f.

Simulation Results and Discussion

The simulation results of the proposed modified concatenated RS/LDPC-coded f-OFDM system are evaluated in this section related to BER, PAPR and OOBE values, and compared with those conventional concatenated schemes.

First, the BER performance of different coding scenarios is examined to illustrate the effect of employing channel coding on the overall system performance. Figure 3 depicts the single LDPC-coded f-OFDM system's performance under the BPSK modulation scheme. The results show a smooth decrease in BER for both cases, with and without the use of an interleaver, up to 15dB of SNR. However, after this point, the error floor phenomenon starts to appear and dominates the system performance, where the BER remains almost constant and does not decrease despite increases in SNR. Consequently, although the interleaver effectively mitigates burst errors (Suls et al., 2017), thereby assisting the decoder in correcting errors, it does not improve the LDPC-coded f-OFDM system's performance in the error-floor region.

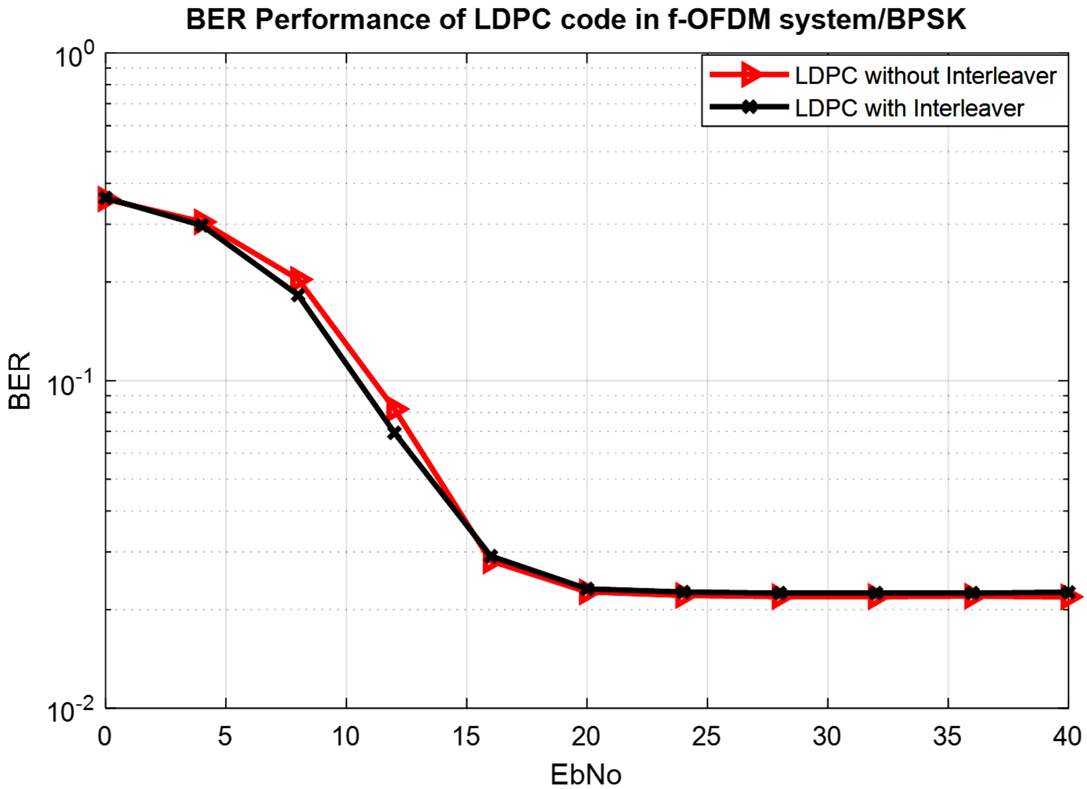

Figure 3. The LDPC-coded f-OFDM system's Performance-BPSK

Similarly, under the QPSK modulation scheme, Figure 4 illustrates the LDPC-coded f-OFDM system's performance. The outcomes indicate that employing an interleaver with the LDPC code fails to enhance its performance in the region of the error floor. It observed that the BER stops decreasing after SNR values of 20dB and 24dB for both cases with and without the interleaver, respectively. Therefore, under both modulation schemes, the LDPC code fails to mitigate the error-floor phenomenon, even when combined with an interleaver.

In contrast, Figure 5 illustrates the RS-coded f-OFDM system's performance under the BPSK. The results demonstrate that combining the RS code with an interleaver substantially improves the BER performance compared with using the RS code alone. Furthermore, the interleaver effectively mitigates the error floor phenomenon, which becomes clearly evident at an SNR of approximately 20 dB when using only the RS code. In contrast, the BER continues to decrease smoothly when employing the interleaver, and no error floor behavior is observed within the investigated SNR range. Moreover, employing an interleaver with the RS code achieves a coding gain of approximately 15 dB at a BER of 2×10^{-2} compared with standalone the RS-coded f-OFDM system under BPSK modulation scheme.

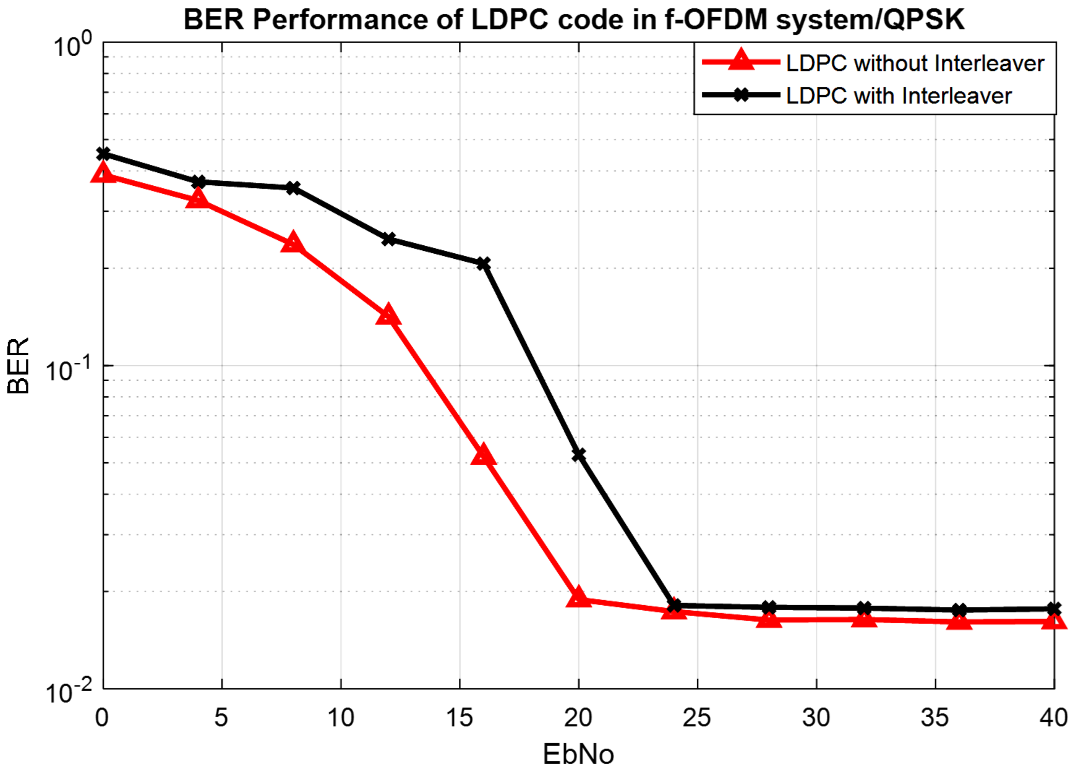

Figure 4. The LDPC-coded f-OFDM system's Performance -QPSK

The RS-coded f-OFDM system's performance is also significantly improved when an interleaver is employed under the QPSK modulation formats, as illustrated in Figure 6. Furthermore, no error floor phenomenon behavior observed within the investigated SNR range owing to the use of the interleaver with the RS code. Moreover, a coding gain of approximately 10 dB is achieved by using an interleaver at a BER of about 2×10^{-2} compared with using the RS alone with f-OFDM system under QPSK modulation scheme.

Therefore, unlike the LDPC-coded f-OFDM system's performance, which is not improved by using an interleaver, it is significantly improved when an interleaver is employed with the RS code under both modulation schemes. Furthermore, no error floor behavior is observed within the investigated SNR range due to the use of the interleaver with RS code, unlike its use with the LDPC code, where the error floor remains evident under both modulation schemes.

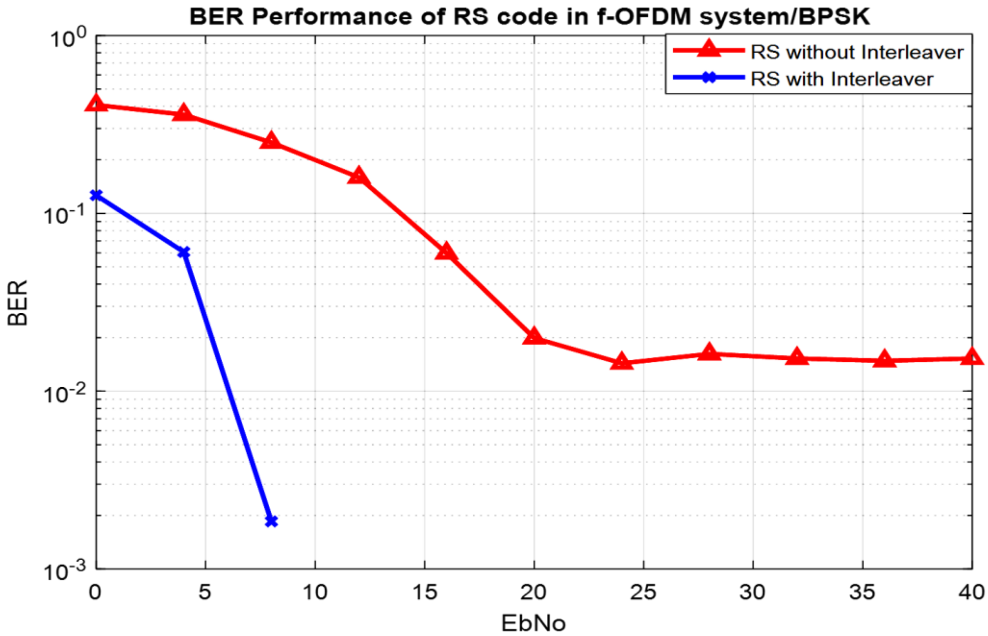

Figure 5. The RS-coded f-OFDM system Performance -BPSK

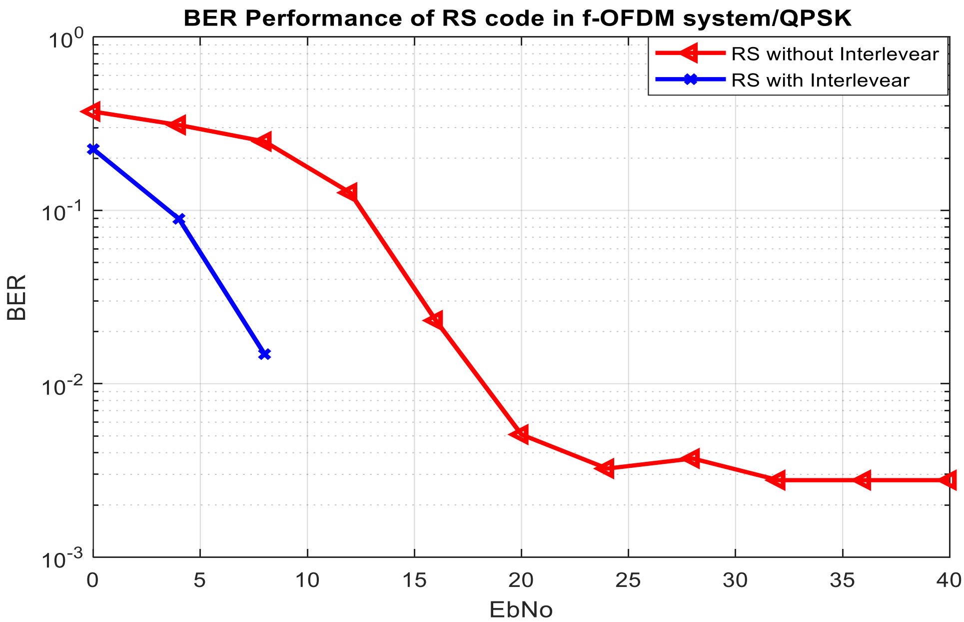

Figure 6. The RS-coded f-OFDM system Performance -QPSK

The BER performance comparison among the single RS and LDPC codes versus the conventional concatenated RS/LDPC coding schemes under both modulation formats is illustrated in Figures 7 and 8. It employes an interleaver between both codes. The results demonstrate the superiority of using the familiar concatenated RS/LDPC codes over both standalone RS and LDPC codes. The outcomes demonstrated that using conventional concatenated RS/LDPC codes achieves a coding gain of around 12 dB and 17 dB at a BER approximately 3×10^{-2} under both modulation formats, respectively.

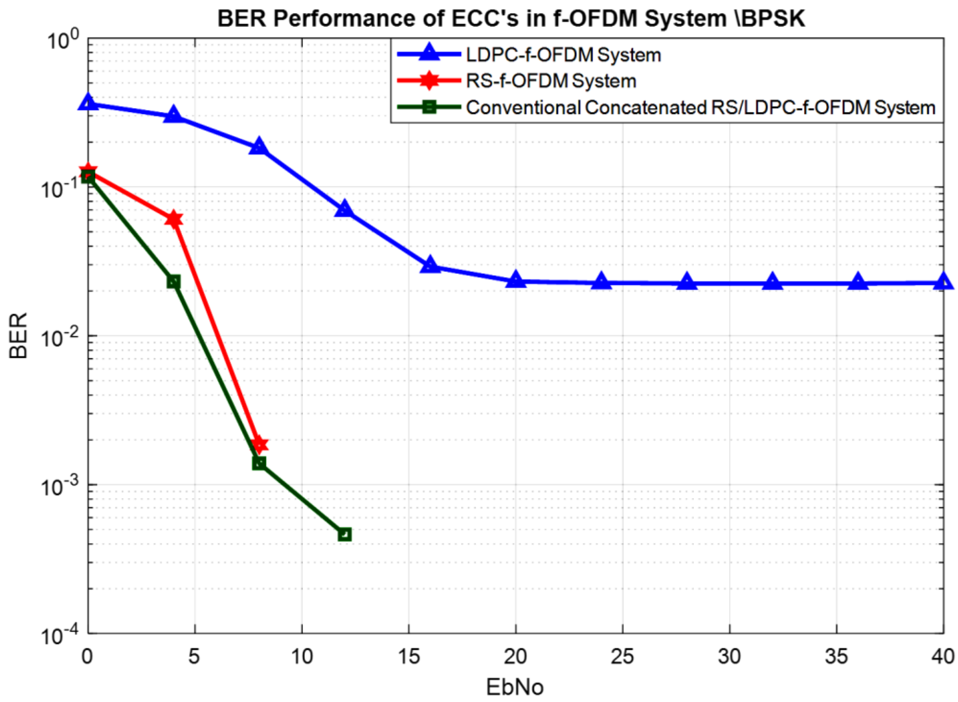

Figure 7. BER Performance of Various Coding approaches -BPSK

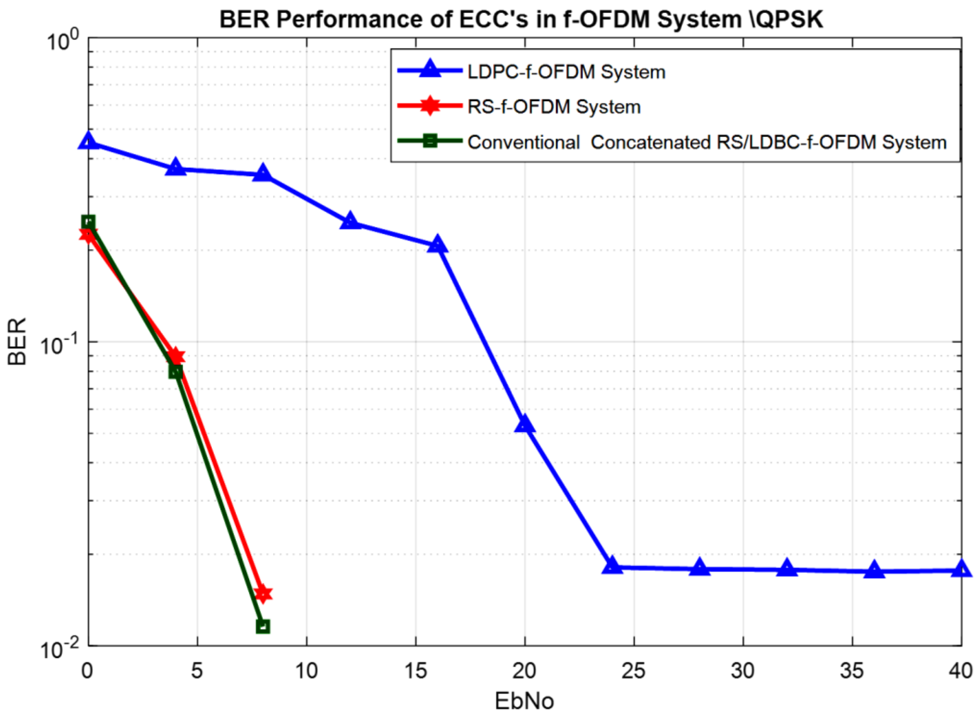

Figure 8. BER Performance of Various Coding approaches - QPSK

Figures 9 and 10 present the BER performance comparison between the suggested modified concatenated RS/LDPC-coded f-OFDM system and the conventional concatenated RS/LDPC-coded f-OFDM system under both modulation formats, respectively. Unlike the conventional concatenated RS/LDPC codes, the suggested approach employs an RS code with an LDPC code followed by an interleaver. The results demonstrate that, although the conventional concatenated scheme outperforms both the single RS and LDPC codes, the suggested approach outperforms the conventional scheme as well as the single RS and LDPC codes under both modulation schemes. Furthermore, no bit errors were observed in the proposed scheme at an SNR of about 8 dB compared to about 12 dB for the conventional concatenated scheme under BPSK. In contrast, the proposed scheme achieves lower BER values throughout the SNR range investigated compared with the conventional scheme under QPSK. This enhancement in BER performance can be attributed to the placement of the interleaver at the final stage of the proposed concatenated scheme, which helps both the RS and LDPC codes correct errors, thereby improving their error correction capability. Unlike the conventional scheme, the interleaver helps only the outer code correct errors.

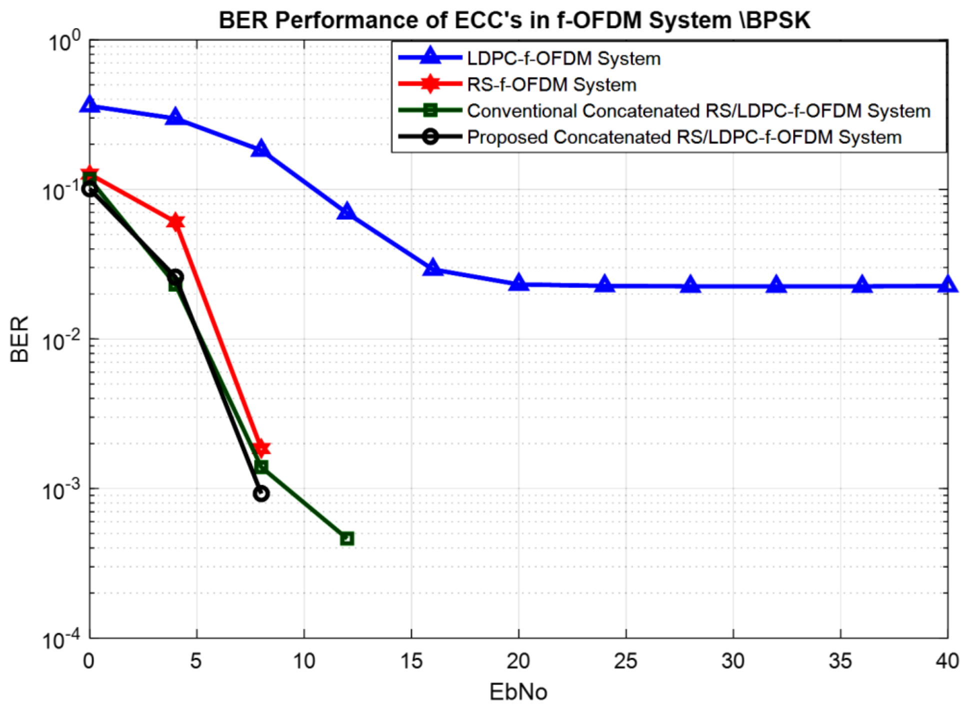

Figure 9. The proposed system Performance -BPSK

Therefore, based on the BER performance results, the conventional concatenated RS/LDPC coding scheme notably improves the f-OFDM system's performance better than both single RS and LDPC codes under both BPSK and QPSK modulation formats. However, the suggested modification, which uses the interleaver after both coding stages, achieves further improvements in the BER performance. As a result, the suggested modified concatenated RS/LDPC coding scheme outperforms the conventional concatenated RS/LDPC coding scheme as well as standalone RS and LDPC codes under both modulation formats.

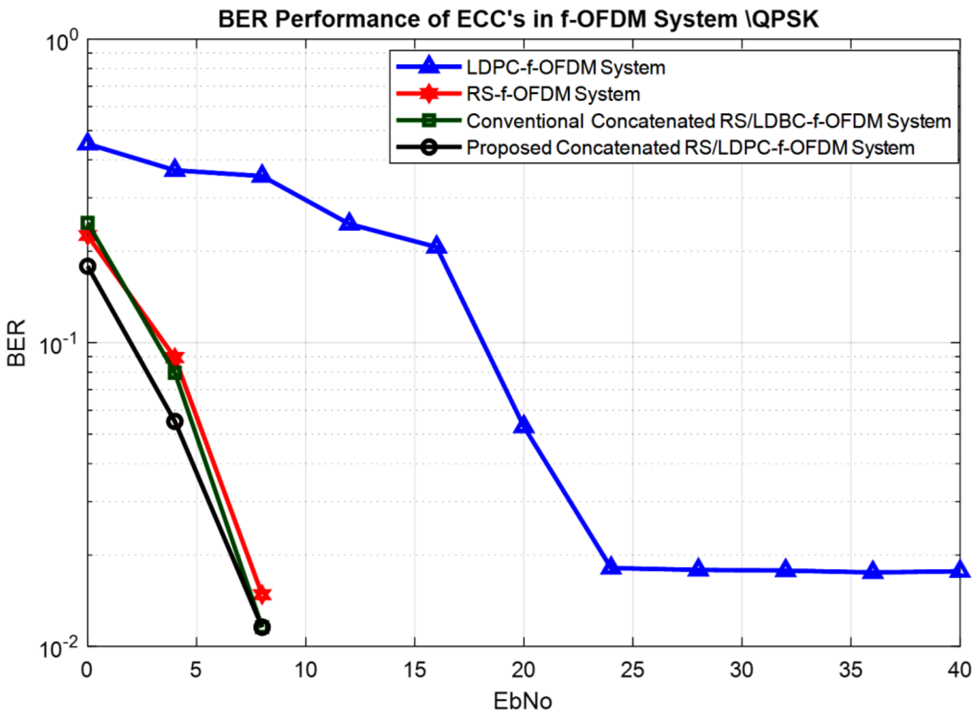

Figure 10. The proposed system Performance -QPSK

The second aspect of the evaluation is the OOBE suppression of the suggested system compared to the conventional OFDM system. Figures 11 and 12 present the Power Spectral Density (PSD) comparison between the suggested system and the conventional OFDM system under both modulation schemes. The outcomes demonstrate that the suggested system provides significantly improved OOBE suppression compared with the conventional OFDM system. Specifically, it achieves an OOBE reduction of about 100 dB for the proposed f-OFDM system compared with the conventional OFDM system in both modulation schemes. This improvement is attributed to the employment of a prototype FIR filter in the f-OFDM system.

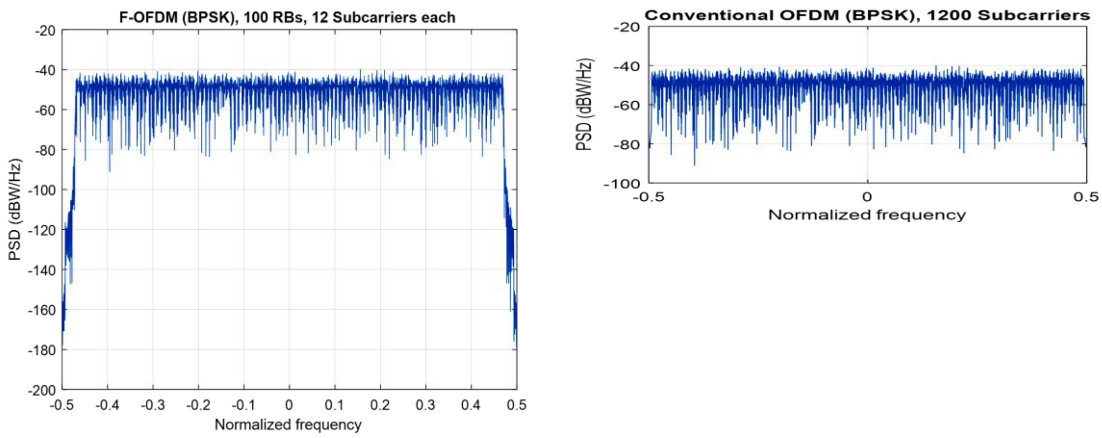

Figure 11. PSD of the Conventional OFDM versus suggested system -BPSK

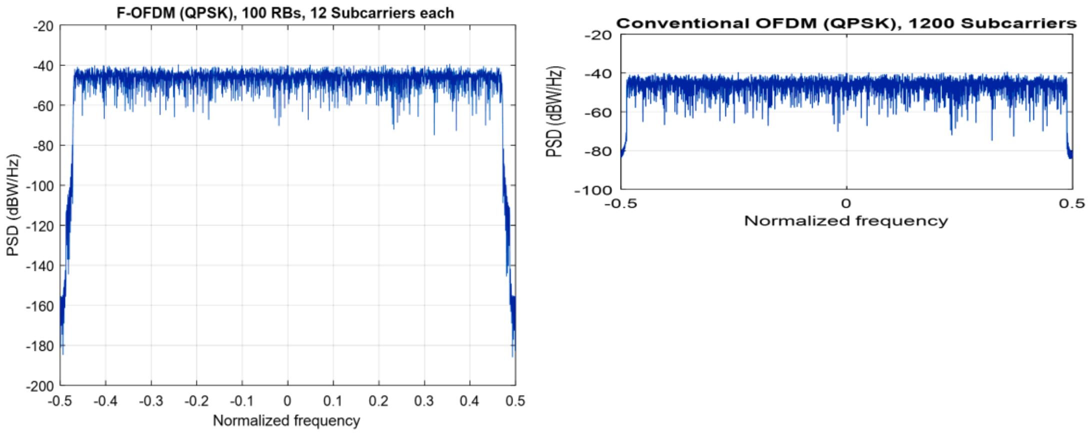

Figure 12. PSD of the Conventional OFDM versus suggested system -QPSK

Lastly, the PAPR performance is evaluated for both the suggested f-OFDM system and the familiar OFDM system, as shown in Table 2. The results indicate that the suggested system exhibits PAPR values comparable to those of the OFDM system under both modulation formats. Specifically, the suggested system recorded values of 10.5502 dB and 10.055 dB compared with 10.1926 dB and 10.1961 dB for the conventional OFDM system in both modulation formats, respectively.

Consequently, the PAPR performance of the suggested system remains at a level similar that of the conventional OFDM system while achieving substantial improvements in BER performance and OOBE suppression. Therefore, these advantages make the suggested concatenated RS/LDPC coded f-OFDM system an emerging solution for the next generation 5G systems.

Table 2. PAPR of the OFDM System and the Proposed System

Modulation Schemes	OFDM system (dB)	Suggested f-OFDM system (dB)
BPSK	10.1926	10.5502
QPSK	10.1961	10.055

Complexity, Latency, and Implementation Cost

A comprehensive theoretical analysis of computational complexity, decoding latency, and hardware implementation cost is presented in this section to assess the feasibility of the suggested system.

- **Computational Complexity**

  The computational complexity of the proposed concatenated RS/LDPC codes is determined by the decoding algorithms employed by both the RS and LDPC decoders. The computational complexity of the RS decoder, which utilizes the Berlekamp-Massey algorithm, is given by $(O(t^2))$, where t denotes the error correction capability (Majumder & Verma, 2015).

In contrast, the LDPC decoder, which utilizes the Belief Propagation (BP) or Min-Sum algorithm, has a computational complexity of $O(I_{max}.E)$, where (E) is the number of edges in the Tanner graph and I_{max} denotes the maximum number of decoding iterations. Accordingly, the total computational complexity grows linearly with both the maximum number of decoding iterations and the number of edges (Xu et al., 2024).

On the other hand, employing the interleaver in the final stage of the suggested architecture does not introduce any extra arithmetic operations (additions or multiplications). Its implementation only requires memory addressing and rearranging the encoded data for burst-errors randomization. Consequently, the overall computational complexity of the suggested system depends only on both RS and LDPC codes and remains identical to that of the conventional concatenated RS/LDPC codes.

Therefore, the total computational complexity is given by:

$$O(t^2) + O(I_{max}.E)$$

So,

$$Complexity\ (Proposed\ Method) = Complexity\ (Conventional\ Method)$$

- **Decoding Latency**

  The suggested method introduces a structured trade-off in terms of decoding latency. Unlike the familiar RS/LDPC codes, which employs the interleaver between the RS and LDPC codes, the suggested method employs the interleaver at the final stage after both codes. Consequently, the interleaver requires a buffering stage before transmission. However, this process doesn't introduce any additional decoding latency compared with the familiar concatenated method, where both schemes employ the same interleavers operation, with the only difference being its placement. Hence, the overall latency of the suggested scheme remains comparable to that of the familiar concatenated schemes.
- **Implementation Cost**

  From the hardware implementation standpoint, employing the interleaver at the final stage needs a standard RAM buffer, and modest memory addressing and data permutation operations, in order to store and permute the encoded data (Huo et al., 2022). However, the suggested concatenated RS/LDPC code remains highly cost-effective, where it needs only a standard memory buffer without introducing extra hardware modules or rising the computational complexity. Consequently, the hardware implementation cost in the suggested method remains comparable to that of the familiar concatenated RS/LDPC codes.

Conclusion

A modified concatenated RS/LDPC-coded f-OFDM system over a 2X2 MIMO multipath fading channel is proposed in this paper under both BPSK and QPSK modulation formats. The suggested concatenated scheme employs an RS codes with an LDPC codes followed by an interleaver, unlike the conventional concatenated scheme, which uses an external RS code and an internal LDPC code with an interleaver placed between them. The effect of employing the interleaver with standalone RS and LDPC codes is also investigated. The outcomes reveal that the use of an interleaver with the LDPC code does not provide noticeable performance enhancement or mitigate the error-floor phenomenon, whereas the RS code achieved significant improvement when combined with an interleaver, and no error floor behavior is observed within the investigated SNR range. Specifically, employing an interleaver with the RS code achieved coding gains of approximately 12 dB and 10 dB at a BER of 2×10^{-2}, compared with using the standalone RS code under both modulation schemes, respectively. In contrast, the conventional concatenated RS/LDPC coding scheme achieved significant BER performance improvements for the f-OFDM system compared with the standalone RS and LDPC codes. However, the suggested modified concatenated coding scheme outperformed the conventional concatenated scheme as well as the standalone RS and LDPC codes under both modulation formats. Under the BPSK, no bit errors were observed for the proposed scheme at an SNR of approximately 8 dB compared with approximately 12 dB for the conventional concatenated scheme. While achieved lower BER values throughout the investigated SNR range compared to the conventional approach under QPSK. Moreover, the proposed system achieved an OOBE reduction of approximately 100 dB compared to the OFDM system under both modulation schemes, while the PAPR performance of the suggested system remains at a level similar that of the OFDM system. Therefore, these advantages make the suggested concatenated RS/LDPC-coded f-OFDM system an emerging solution for the next-generation 5G systems.

Although the suggested modified concatenated RS/LDPC-coded f-OFDM system achieved considerable performance enhancements in terms of BER, PAPR and OOBE performance over multipath fading channels, this study is based on the simulation results. Therefore, the validation is limited to a theoretical and simulation-based framework. Consequently, extending the suggested system to hardware implementation is considered as future work, including FPGA implementation, which is based on the real time performance evaluation, and its validate under practical environments.

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