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Burst Channel Error Reduction Based on Interleaving for Efficient High-Speed Wireless Communication

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Abstract: Recently, the demand for reliable and high-speed wireless communication has rapidly increased. Orthogonal frequency division multiplexing (OFDM) is a modulation scheme that is the newest competitor against other modulation schemes used for this purpose. OFDM is mostly used for wireless data transfer, although it may also be used for cable and fiber optic connections. However, in many applications, OFDM suffers from burst errors and high bit error rates. This paper presents the utilization of a helical interleaver with OFDM systems to efficiently handle burst channel errors and allow for Bit Error Rate (BER) reduction. The paper also presents a new interleaver, FRF, the initial letters of the authors' names, for the same purpose. This newly proposed interleaver summarizes our previous experience with many recent interleavers. Fast Fourier transform OFDM (FFT-OFDM) and Discrete Wavelet Transform OFDM (DWT-OFDM) systems are used to test the efficiency of the suggested scheme in terms of burst channel error removal and BER reduction. Finally, the general complexity of the FRF interleaver is different from that of the helical interleaver in terms of hardware requirements. The performance of the proposed scheme was studied over different channel models. The obtained simulation results show a noticeable performance improvement over the conventional FFT-OFDM and the FFT-OFDM systems with the helical interleaver. Finally, the disadvantage of the proposed FRF interleaver is that it is more complex than the helical interleaver.

Keywords: OFDM; FRF interleaver; helical interleaver; deterministic interleaver; FFT; DWT

1. Introduction

Wireless communication systems are extremely necessary to support high quality of service and high data rates. Channel frequency selectivity, multipath fading, and inter-symbol interference (ISI) often impair wireless channel communications. This substantially degrades both service quality and data rates [1]. OFDM is a multicarrier modulation technology that processes data using multiple orthogonal sub-carriers from the same source. The great spectral efficiency of orthogonality-based OFDM systems, their resistance to frequency-selective fading, and their easy equalizer implementation have recently sparked considerable interest. It has also become the widely recognized modulation scheme for high-data-rate communication over wireless connections [2]. The multiplexing is performed on the transmitter and receiver signals using inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) in the standard OFDM system. In addition, recent research on multicarrier modulation performance has explored the use of wavelet-based OFDM as an appealing alternative to the Fourier-based OFDM system [3–8]. Because there is no cyclic prefix requirement, the wavelet-based OFDM system offers better spectral efficiency, has very tight side lobes, and shows enhanced BER performance [9–12]. Another topic that will be considered in this work is the performance enhancement of data transmission in OFDM systems through data interleaving. It is known that data transmission over wireless channels may suffer from severe adverse conditions, especially burst errors, where errors are likely to occur in clusters. Interleavers have been used extensively in digital communication systems to disperse these burst errors [13,14]. Some simple interleaving techniques have been proposed [15–17]. The performance of such simple interleavers is limited. Therefore, there is a need for more powerful interleavers.

This work depends on using helical interleavers with OFDM systems to effectively manage burst channel errors and reduce BER. In addition, the paper presents a new interleaver, FRF, for the same purpose. This suggested interleaver summarizes our prior experience with several recent interleavers. There are two types of systems that are used to test the proposed interleaver: FFT-OFDM and DWT-OFDM. The FRF interleaver is more complicated than the helical interleaver in terms of hardware. It can also combat the channel effects with neither complicated coding schemes for error detection and correction nor adaptation of the modulation scheme. Another advantage of the proposed interleaver is that it achieves a degree of encryption in the transmitted data, which adds more security to the data transmission process.

Therefore, the contribution of this work could be summarized as follows:

1. Introducing a new interleaver that manages burst channel errors and reduces BER. Such an interleaver can be used in critical systems where power consumption is essential.
2. The new interleaver combats the channel effects with neither complicated coding schemes for error detection and correction nor adaptation of the modulation scheme.
3. The new interleaver achieves a degree of encryption in the transmitted data.

The paper is structured as follows. Section 2 introduces the OFDM and interleaver overview. Then, Section 3 describes the proposed interleaver. In addition, the proposed system model is described in Section 4. The simulation results are given in Section 5. Finally, the conclusions are presented in Section 6.

2. Burst Error, OFDM, and Interleaving

Adding redundancy to information sequences increases message delivery success rates in communication systems. Burst errors occur in a continuous portion of the received data. Burst errors represent a typical kind of interference in radio communications. For example, let u be an information sequence.

u = ABC

Let the error correction coding (ECC) duplicate each symbol as follows:

$v = A_1A_2A_3B_1B_2B_3C_1C_2C_3$

These data are now wirelessly sent. For a three-symbol-length burst of interference during transmission, this yields an error stream (X):

$R = A_1A_2A_3XXXC_1C_2C_3$

Despite the redundancies, symbol B is now irrecoverable due to the loss of all copies. If the error exceeds the repeated symbols, the error-correcting algorithm fails to retrieve the original data sequence. Let the redundant symbols be scrambled randomly within the stream, for example:

$V = A_2B_3C_2A_1B_1C_3A_2B_2C_1$

The same burst interference that results in the sequence can be as follows:

$R = A_2B_3C_2XXXA_2B_2C_1$

As a result, we obtain some duplicates of all the symbols, from which the original symbols and information sequence may be reconstructed. Therefore, interleavers are responsible for the scrambling of the message information. The detailed concept of interleavers will be stated in later subsections.

2.1. FFT-OFDM

As can be seen in Figure 1, depicting the OFDM transmitter, the data generator produces $\{d_k\}$ in a random binary form. Firstly, constellation mapping is implemented. The quadrature phase-shift keying (QPSK) modulator is used for this work to map the data to appropriate QPSK symbols X_m. The serial-to-parallel converter then transforms the high-speed information symbols into N sub-channel parallel information. The parallel data symbols are fed into IFFT to generate the multicarrier OFDM signal as follows [18]:

$$x_k = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} x_m e^{j2\pi km/N},\ 0 \le m \le N-1 \tag{1}$$

where $\{x_k \mid 0 \le k \le N-1\}$ is a sequence in the discrete time domain, and $\{X_m \mid 0 \le m \le N-1\}$ are complex numbers in the discrete frequency domain.

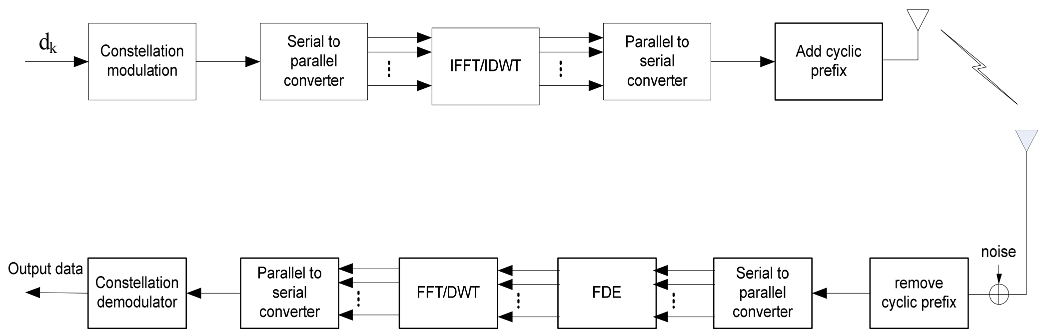


Figure 1. OFDM transceiver [18].

To prevent the ISI that happens in multipath channels, guard intervals are placed between frames. These intervals are either added zeros or a cyclic prefix (CP). The most commonly used strategy is the addition of a CP [19,20]. The CP is a copy of the IFFT last N samples at the start of the OFDM frame. The multipath versions of a symbol do not interfere with the next symbol by adding the CP to each OFDM symbol with a length longer than the channel length. Consequently, the impact of ISI is totally abolished, and at the same time, the channel appears to be circular, allowing a circular convolution to be implemented between the OFDM signal and the channel impulse response. This method is reversed at the receiver side to get the decoded information. The CP is detached, and the frequency domain equalizer (FDE) is used. The FDE relies on a CP guard interval between successive data blocks. The FDE can invert the channel completely. The benefit of FDE is that the complexity is comparatively low [21,22].

Equalizer coefficients are calculated by Minimum Mean Square Error (MMSE) or Zero Force (ZF) technique [23]. The MMSE equalizer requires the Signal-to-Noise-Ratio (SNR) estimation, which allows a trade-off between channel inversion and noise enhancement [24]. The FFT is applied at the receiver to reconstruct the signal as follows [18]:

$$X_m = \sum_{k=0}^{N-1} x_k e^{-j2\pi km/N},\ 0 \le k \le N-1 \tag{2}$$

2.2. DWT-OFDM

The inverse discrete wavelet transformation (IDWT) and the DWT take the place of the IFFT and FFT, respectively, in the DWT-OFDM system. The output of the IDWT can be represented as [25]:

$$s(k) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} S_m^n 2^{m/2} \psi(2_k^m - n) \tag{3}$$

where S_m^n are the wavelet coefficients and $\psi(t)$ is the wavelet function with compression factor m and shift n for each sub-carrier. The process is reversed at the receiver side. The output of the DWT could be formed as shown in Equation (4).

$$S_m^n = \sum_{k=0}^{N-1} s(k) 2^{m/2} \psi(2_k^m - n) \tag{4}$$

In the wavelet-based OFDM system, the MMSE equalizer achieves a significantly lower BER compared to that of the zero-forcing (ZF) equalizer. Therefore, it is considered in our work.

2.3. Interleavers

Bit errors are more likely to occur in bursts on wireless channels because of the fading nature of the channels and the impulsive noise. The goal of interleaving is to disperse bursts of errors throughout the data stream. It rearranges symbols to be transmitted in a certain order. The receiver uses the reverse rule to revert the sequence [26,27]. This section focuses only on the interleavers related to our proposal in this paper.

2.3.1. Helical Interleaver

The helical interleaver algorithm can be summarized as follows [28–31]:

(i) Primary interleaver generation: This refers to arranging the data sequence in a matrix with N_r rows and N_c columns, such that N_r. N_c = L. L, in this context, refers to the length of the primary interleaver, as given in Figure 2a.
(ii) Helical interleaver: It is constructed based on the primary interleaver through reading the interleaver indices column-wise, as given in Figure 2b.
(iii) By cyclically reading the interleaver indices from the diagonals of a matrix with decreasing slope, other interleavers can be generated, as indicated in Figure 2c.

The *ith* helical interleaver can be represented in Equation (5) as follows:
The *i'th* helical interleaver can be represented in Equation (5) as follows:

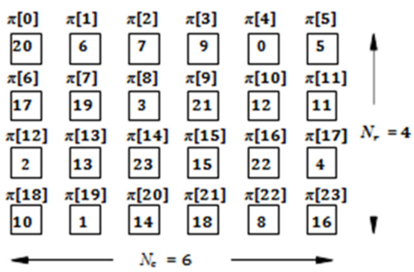
$$\pi[k] = \pi[l_{modL}],\ 0 \le k < L \tag{5}$$

where, $l = k_{modN_r}.N_c + \left(\left[\frac{k}{N_r}\right] + \left(k_{modN_r}.(i-1)\right)\right)$.

In Equation (5), it is seen that the helical interleaver can be managed in a very short time. If the parameters are chosen correctly, the interleaver indices can be spread out quite well. Now, the best way to even better optimize Equation (5) is to add layer-specific shifts to it, as given in Equation (6).

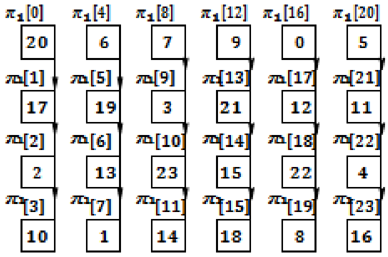
$$\pi[k] = \pi\left[(l + i.S)_{modN_c}\right] \tag{6}$$

where S is a constant integer, which describes the shift between the interleavers.

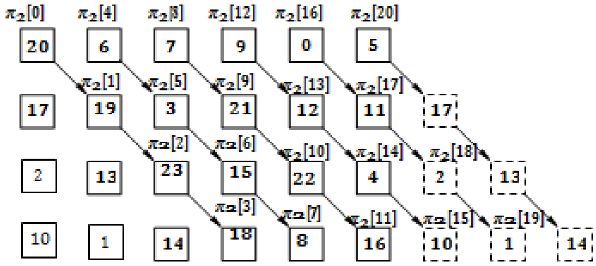


(**a**)

Figure 2. *Cont.*



(b)



(c)

Figure 2. Generation of 4 × 6 helical interleavers. (**a**) Master interleaver written in matrix form, π = [20, 6, 7, . . . , 8, 16]. (**b**) First helical interleaver written in matrix form, π_1 = [20, 17, 2, . . . , 4, 16]. (**c**) Second helical interleaver written in matrix form, π_2 = [20, 19, 23, . . . , 13, 14] [28,29].

2.3.2. Other Interleavers

There are many other interleavers based on the different standards summarized in Figure 3 [32]. In addition, Table 1 summarizes the interleaver algorithms.

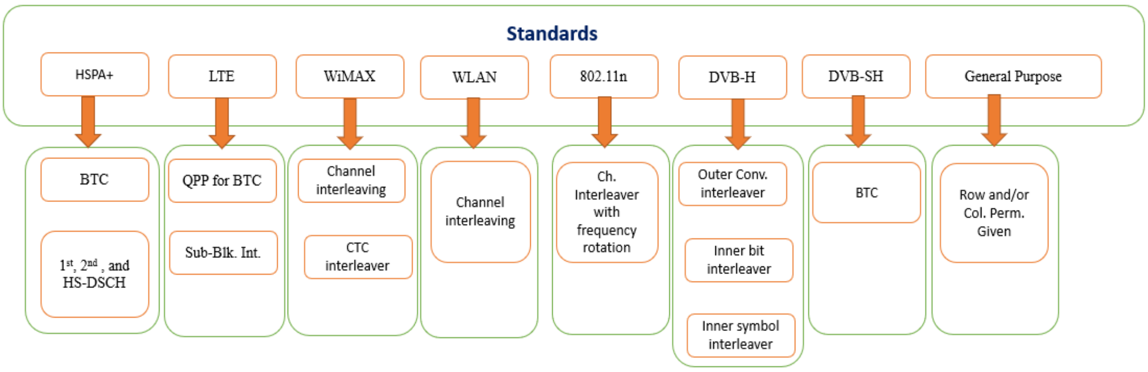


Figure 3. Other interleavers [32].

Table 1. Most of the current interleaver standards [32].

Interleaver Type	Algorithm
BTC	Multi-Step computation including intra-row permutation computation $S(j) = (\nu \times S(j-1))\ \%p;\ r(i) = T(q(i));$ $U(i,j) = S((j \times r(i)))\ \%(p-1);\ q\ mod(i) = r(i)\%(p-1);$ $RA(i,j) = \{RA(i,j-1) + q\ mod(i)\}\%(p-1);$ $I_{i,j} = \{C \times r(i)\} + U(i,j)$
1st, 2nd, and HS-DSCH	Standard block interleaving with different column permutations $\pi(k) = \left(p\left\lfloor \frac{k}{R} \right\rfloor + C \times (k\%R)\right)\ \%K_\pi$
QPP for BTC	$I_{(x)} = \left(f_1 \cdot x + f_2 \cdot x^2\right)\ \%$
Sub-Blk. Int.	Standard block interleaving with given column permutations

Table 1. *Cont.*

Interleaver Type	Algorithm
Channel interleaving	$Two - \text{step permutation } M_k = \left(\frac{N}{d}\right) \times (k\%d) + \left\lfloor \frac{k}{d} \right\rfloor$; and $J_k = s \times \left\lfloor \frac{M_k}{s} \right\rfloor \left(\left(M_k + N - \left\lfloor d \times \frac{M_k}{N} \right\rfloor \right) \%s \right)$
CTC interleaver	$I_{(x\%4=2)} = (P_0 x + 1 + P_1)\ \%N;\ I_{(x\%4=3)} = \left(P_0 x + 1 + \frac{N}{2} + P_3\right)\ \%N$
Ch. Interleaver with frequency rotation	Two step permutation as above, with extra frequency Interleaving i.e., $R_k = \left[J_k - \left\{ \left(((i_{ss} - 1) \times 2)\ \%3 + 3 \left\lfloor \frac{i_{ss} - 1}{3} \right\rfloor \right) \times N_{ROT} \times N_{BPSC} \right\} \right] \%N$
Outer Conv. interleaver	Permutation defined by depth of first branch (M) and number of total branches
Inner bit interleaver	Six parallel interleavers with different cyclic shift $H_e(w) = (w + \Delta)\ \%126;\ where\ \Delta = 0,\ 63,\ 105,\ 42,\ 21,$ and 84
Inner symbol interleaver	$y_{H(q)} = x_q$ for even symbols; $y_q = x_{H(q)}$ for odd symbols; where $H(q) = (i\%2) \times 2^{N_r - 1} + \sum_{j=0}^{N_r - 2} R_i(j) \times 2^j$;
BTC	$R_c(j) = \{R_c(j-1) + Inc(j)\}\ \%32;$ and $I(i,j) = \{T_{bas}(j) + M_1(i-1,j)\}\ \%C_T$

3. Proposed Interleavers

This section presents the proposed interleavers, including the two-dimensional prime interleaver and the newly proposed FRF interleaver.

3.1. TWO-Dimensional Deterministic Interleaver Design

The main idea behind this interleaver is expanding the 1-D deterministic interleaver into 2-D [33]. The proposed 2-D deterministic interleaver works as follows, assuming the case of N_r rows and N_c columns:

- First, interleaving is split into row-wise and column-wise cases.
- The seeds for row-wise and column-wise interleavers are assumed to be two prime numbers. After interleaving, bits will be located as follows:

$$\begin{array}{cc}
row - wise & column - wise \\
0 \to 0 & 0 \to 0 \\
1 \to (1 \times p_{row}) mod\ N_r & 1 \to (1 \times p_{col}) mod\ N_c \\
2 \to (2 \times p_{row}) mod\ N_r & 2 \to (2 \times p_{col}) mod\ N_c \\
\vdots & \vdots \\
N_r - 1 \to ((N_r - 1) * p_{row})\ mod\ N_r & N_c - 1 \to ((N_c - 1) * p_{col})\ mod\ N_c
\end{array}$$

  where p_{row} and p_{col} are row-wise and column-wise seeds, respectively.
- Finally, the new locations are mapped back into the two-dimensional interleaver, resulting in two-dimensional interleaved bits.

For instance, consider an 8 × 8 2-D deterministic interleaver with p_{row} = 3 and p_{col} = 5. The new locations of the bits will be as follows:

$$\begin{array}{cc}
row - wise & column - wise \\
0 \to 0 & 0 \to 0 \\
1 \to (1 \times 3) mod\ 8 = 3 & 1 \to (1 \times 5) mod\ 8 = 5 \\
2 \to (2 \times 3) mod\ 8 = 6 & 2 \to (2 \times 5) mod\ 8 = 2 \\
3 \to (3 \times 3) mod\ 8 = 1 & 3 \to (3 \times 5) mod\ 8 = 7 \\
4 \to (4 \times 3) mod\ 8 = 4 & 4 \to (4 \times 5) mod\ 8 = 4 \\
5 \to (5 \times 3) mod\ 8 = 7 & 5 \to (5 \times 5) mod\ 8 = 1 \\
6 \to (6 \times 3) mod\ 8 = 2 & 6 \to (6 \times 5) mod\ 8 = 6 \\
7 \to (7 \times 3) mod\ 8 = 5 & 7 \to (7 \times 5) mod\ 8 = 3
\end{array}$$

The arrangement of the bits prior to interleaving is seen in Figure 4a. By applying the new order of column- and row-wise interleaved bits acquired from the preceding calculation and mapping the locations, we get the bit arrangement shown in Figure 4b after interleaving.

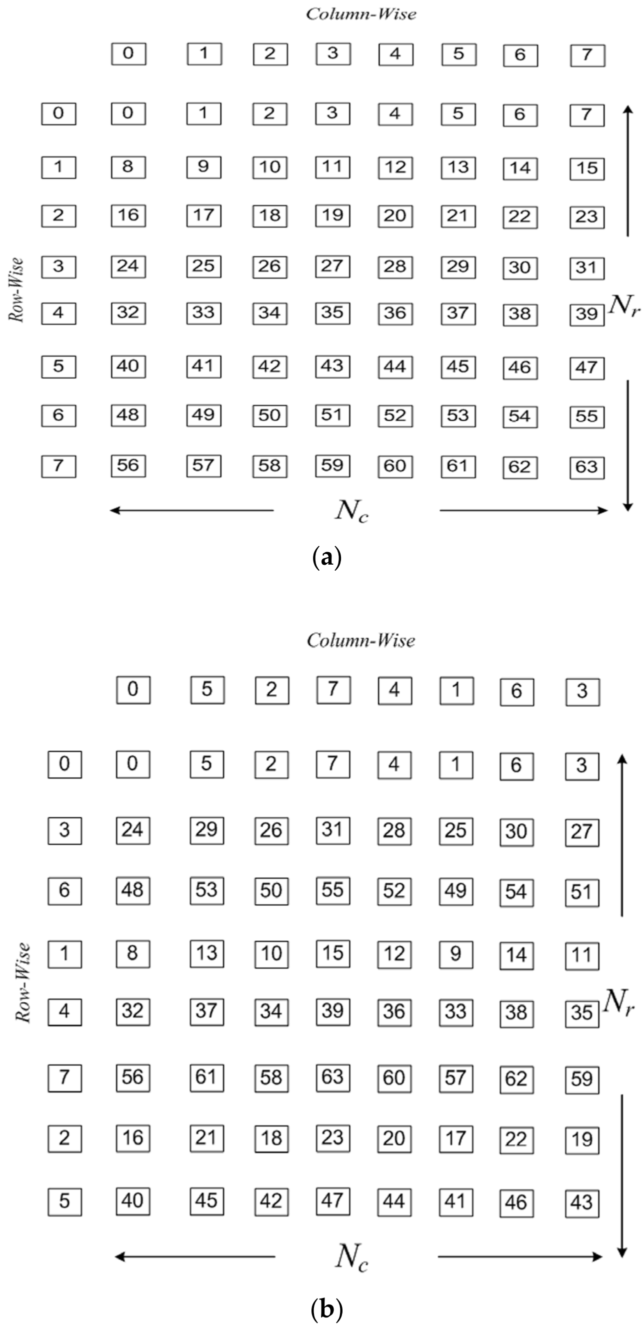


Figure 4. Arrangement of bits for an 8 × 8 channel (**a**) before interleaving and (**b**) after interleaving.

3.2. FRF Interleaver Design

Utilization of the proposed 2-D deterministic interleaver of size 8 × 8 with the helical interleaver produces highly strong randomization. In addition, based on our study, it has been found that the utilization of two-stage interleavers is not practical. Thus, this paper presents the novel FRF interleaver that can perform the task of two interleavers, but in a single stage.

The main concept of the proposed interleaver is stated as follows:

(i) First, we arrange the data in a matrix with N_r rows and N_c columns, such that $N_r \times N_c = L$, where L is the number of decoded bits, and each of them should be an integer and multiple of 8.

(ii) Using Equation (7), we obtain the new bit locations after interleaving:

$$\pi[k] = \pi[((ii + S \cdot jj) mod\ N_r) \cdot N_c + jj],\ 0 \leq k < L \tag{7}$$

where S is a constant integer, and

$$ii = ((i \cdot 3) mod\ 8) + (i\ mod\ 8) + 1\ , i = 0, 1, \cdots, N_r - 1$$
$$jj = ((j \cdot 3) mod\ 8) + (j\ mod\ 8) + 1\ , j = 0, 1, \cdots, N_c - 1$$

Now, we take a look at how the helical and FRF interleaving mechanisms can correct error bursts. An example of the interleaving of an (8 × 8) square matrix for S = 2 is given in Figure 5. Assume a burst of errors affecting four consecutive samples (1-D error burst) as shown in Figure 5b,c with shades. After helical and FRF de-interleaving, the error burst is effectively spread among four different rows, resulting in a small effect for the 1-D error burst as shown in Figure 5d,e. With a single error correction capability, it is obvious that no decoding error will result from the presence of such a 1-D error burst. This simple example demonstrates the effectiveness of the helical and FRF interleaving mechanisms in combating 1-D bursts of errors. Let us examine the performance of the helical and FRF interleaving mechanisms when a 2-D (2 × 2) error burst occurs, as shown in Figure 5b,c with shades. Figure 5d,e show that although the two interleaving mechanisms effectively spread the 2 × 2 error burst, the FRF interleaver has a stronger randomization ability than the helical interleaver. As a result, a better BER performance can be achieved with the proposed FRF interleaving mechanism.

S_{1}	S_{2}	S_{3}	S_{4}	S_{5}	S_{6}	S_{7}	S_{8}
S_{9}	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}
S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	S_{22}	S_{23}	S_{24}
S_{25}	S_{26}	S_{27}	S_{28}	S_{29}	S_{30}	S_{31}	S_{32}
S_{33}	S_{34}	S_{35}	S_{36}	S_{37}	S_{38}	S_{39}	S_{40}
S_{41}	S_{42}	S_{43}	S_{44}	S_{45}	S_{46}	S_{47}	S_{48}
S_{49}	S_{50}	S_{51}	S_{52}	S_{53}	S_{54}	S_{55}	S_{56}
S_{57}	S_{58}	S_{59}	S_{60}	S_{61}	S_{62}	S_{63}	S_{64}

(**a**)

1-D error burst

S_{1}	S_{18}	S_{35}	S_{52}	S_{5}	S_{22}	S_{39}	S_{56}
S_{9}	S_{26}	S_{43}	S_{60}	S_{13}	S_{30}	S_{47}	S_{64}
S_{17}	S_{34}	S_{51}	S_{4}	S_{21}	S_{38}	S_{55}	S_{8}
S_{25}	S_{42}	S_{59}	S_{12}	S_{29}	S_{46}	S_{63}	S_{16}
S_{33}	S_{50}	S_{3}	S_{20}	S_{37}	S_{54}	S_{7}	S_{24}
S_{41}	S_{58}	S_{11}	S_{28}	S_{45}	S_{62}	S_{15}	S_{32}
S_{49}	S_{2}	S_{19}	S_{36}	S_{53}	S_{6}	S_{23}	S_{40}
S_{57}	S_{10}	S_{27}	S_{44}	S_{61}	S_{14}	S_{31}	S_{48}

2-D error burst

(**b**)

Figure 5. *Cont.*

1-D error burst

S_1	S_{54}	S_{35}	S_{24}	S_5	S_{50}	S_{39}	S_{20}
S_{25}	S_{14}	S_{59}	S_{48}	S_{29}	S_{10}	S_{63}	S_{44}
S_{49}	S_{38}	S_{19}	S_8	S_{53}	S_{34}	S_{23}	S_4
S_9	S_{62}	S_{43}	S_{32}	S_{13}	S_{58}	S_{47}	S_{28}
S_{33}	S_{22}	S_3	S_{56}	S_{37}	S_{18}	S_7	S_{52}
S_{57}	S_{46}	S_{27}	S_{16}	S_{61}	S_{42}	S_{31}	S_{12}
S_{17}	S_6	S_{51}	S_{40}	S_{21}	S_2	S_{55}	S_{36}
S_{41}	S_{30}	S_{11}	S_{64}	S_{45}	S_{26}	S_{15}	S_{60}

2-D error burst

(**c**)

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}
S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	S_{22}	S_{23}	S_{24}
S_{25}	S_{26}	S_{27}	S_{28}	S_{29}	S_{30}	S_{31}	S_{32}
S_{33}	S_{34}	S_{35}	S_{36}	S_{37}	S_{38}	S_{39}	S_{40}
S_{41}	S_{42}	S_{43}	S_{44}	S_{45}	S_{46}	S_{47}	S_{48}
S_{49}	S_{50}	S_{51}	S_{52}	S_{53}	S_{54}	S_{55}	S_{56}
S_{57}	S_{58}	S_{59}	S_{60}	S_{61}	S_{62}	S_{63}	S_{64}

(**d**)

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}
S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	S_{22}	S_{23}	S_{24}
S_{25}	S_{26}	S_{27}	S_{28}	S_{29}	S_{30}	S_{31}	S_{32}
S_{33}	S_{34}	S_{35}	S_{36}	S_{37}	S_{38}	S_{39}	S_{40}
S_{41}	S_{42}	S_{43}	S_{44}	S_{45}	S_{46}	S_{47}	S_{48}
S_{49}	S_{50}	S_{51}	S_{52}	S_{53}	S_{54}	S_{55}	S_{56}
S_{57}	S_{58}	S_{59}	S_{60}	S_{61}	S_{62}	S_{63}	S_{64}

(**e**)

Figure 5. Helical and FRF interleaving of an 8 × 8 matrix. (**a**) The 8 × 8 matrix. (**b**) Data with error bursts after helical interleaving. (**c**) Data with error bursts after FRF interleaving. (**d**) Effect of error bursts after helical de-interleaving. (**e**) Effect of error bursts after FRF de-interleaving.

4. Proposed System Model

The main idea of the proposed system is to use a combination of (FFT/DWT)-OFDM with the proposed FRF interleaving mechanism. The FRF interleaver can be a potential candidate for practical OFDM systems due to its low computational complexity and good BER performance. The block diagram of the proposed (FFT/DWT)-OFDM with helical interleaving is shown in Figure 6. The conventional OFDM block is modified by adding an interleaving stage. Both the in-phase and quadrature fields of the OFDM signal (the output of IFFT/IDWT) are interleaved. *S* is supposed to be known by the receiver.

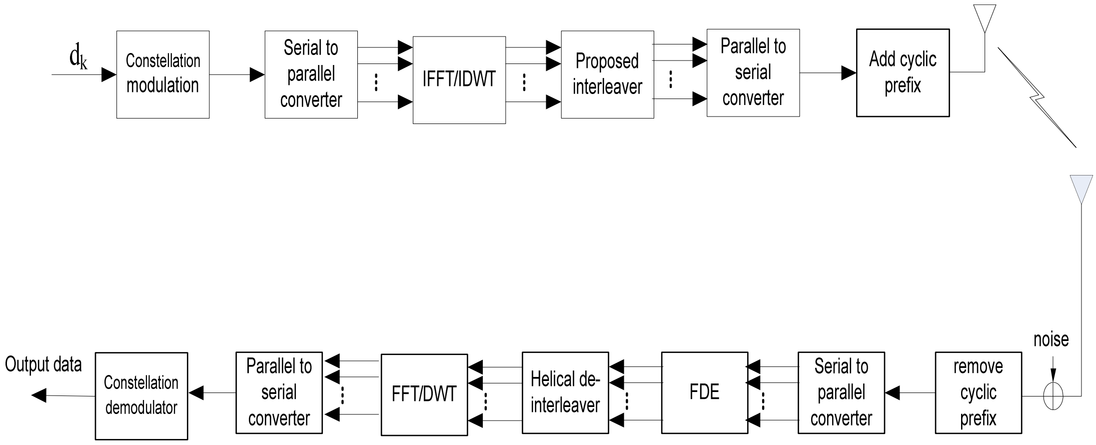


Figure 6. Block diagram of the proposed (FFT/DWT)-OFDM system model.

5. Simulation Results

The experiments in this section have been carried out using the MATLAB 7.5 program. Experiments have been conducted on an i5-2.3 GHz laptop running Microsoft Windows 7. In this section, computer simulations are presented to examine and evaluate the BER performances of different scenarios.

1. Different wavelet families are used in DWT- and FFT-OFDM.
2. Over the AWGN channel model, the proposed systems are compared to conventional (FFT/DWT)-OFDM systems.
3. With an exponential power delay profile Rayleigh fading channel without a Doppler effect, the proposed systems are compared to conventional (FFT/DWT)-OFDM systems.
4. In the presence of AWGN, the suggested systems are compared to conventional (FFT/DWT)-OFDM systems.
5. The suggested systems are compared to traditional (FFT/DWT)-OFDM systems over the AWGN outdoor channel.

To ensure the success of the proposed systems, we introduce the BER versus E_b/N_0 for all systems, where E_b is the energy per bit and N_0 is the noise power spectral density. The number of sub-carriers considered equals 512, with each sub-carrier having 16 symbols. The guard interval length is one-eighth of the symbol duration. QPSK or 4-QAM ($M = 4$) data symbols are used in the simulation experiments. In all later experiments except in the following subsection, we use the value of $S = 5$, where the evaluation results show that this value is the best for all experiments. Table 2 summarizes the simulation parameters.

Table 2. Simulation parameters.

Parameters	Values
Number of sub-carriers	512
Number of symbols with each sub-carrier	16
CP length	1/8 symbol duration
Modulation type	QPSK
Equalization	MMSE
Channel model	Rayleigh, SUI, and vehicular A outdoor channels

5.1. BER Performance Evaluation of DWT-OFDM and FFT-OFDM

An experiment was conducted in order to provide the wavelet with which the best performance in wireless communications can be obtained. In this experiment, the BER performances of (FFT/DWT)-OFDM systems have been evaluated with several mother wavelets such as Haar, Daubechies (db3), coiflets (coif1), symlets (sym3), biorthogonal (bior1.3), and reverse biorthogonal (rbio1.3) [34] over a multipath Rayleigh fading channel model in the absence of AWGN.

Figure 7 presents the BER vs. E_b/N_0. The figure shows that the DWT-OFDM outperforms the conventional OFDM for all chosen wavelet families. For instance, at BER = 2.4×10^{-4}, the DWT (Haar)-OFDM system provides E_b/N_0 gains of about 11 dB over the FFT-OFDM system. In addition, it can be seen that there is no significant difference between the kinds of wavelets except Haar, which performs slightly better than the other wavelets at high E_b/N_0 values. Therefore, the Haar mother wavelet will be the best choice for DWT-OFDM implementation. For instance, at BER = 1×10^{-7}, the Haar wavelet provides E_b/N_0 gains of about 1dB over coif1 and rbio1.3 and about 0.5 dB over bior1.3, db3, and sym3. After performing this experiment, we can recommend that the Haar wavelet gives better performance parameters for implementing DWT-OFDM.

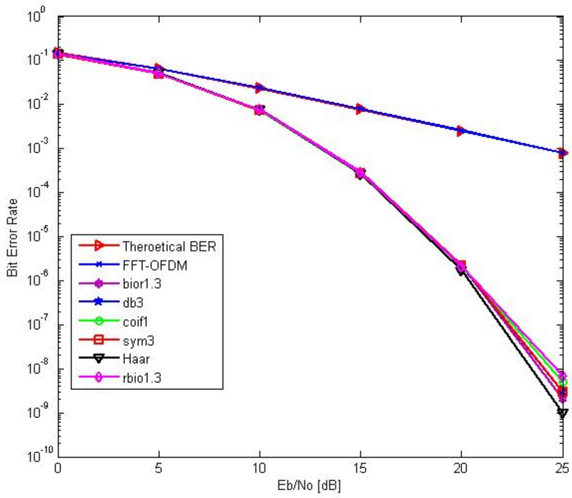


Figure 7. BER performance comparisons of the DWT-OFDM and the FFT-OFDM systems over Rayleigh channel model using several wavelets.

5.2. BER Performance Evaluation over AWGN Channel

This experiment evaluates the BER performances of the FFT-OFDM and the DWT (Haar)-OFDM with and without helical and FRF interleavers over the AWGN channel. Figure 8 shows the BER vs. E_b/N_0 for the helical (FFT/DWT)-OFDM and the FRF (FFT/DWT)-OFDM systems compared with the conventional (FFT/DWT)-OFDM over an AWGN channel. As shown in the results, there is no improvement, because there are no burst errors in the AWGN case. We can say that there is no need for the interleaver in this case.

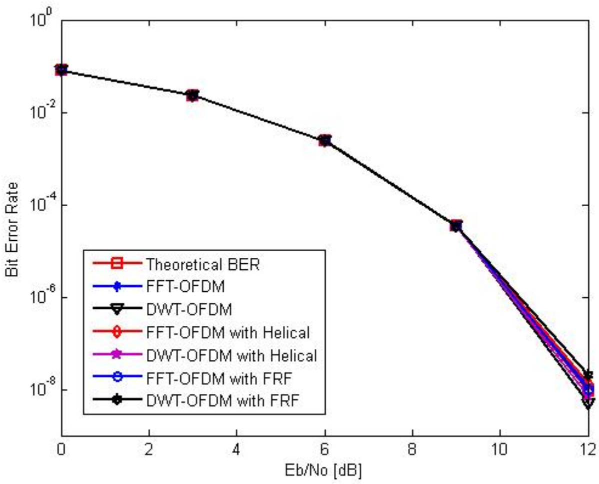


Figure 8. FFT−OFDM and DWT−OFDM BER performance over AWGN channel.

5.3. BER Evaluation over Rayleigh Fading Channel

In this experiment, the BER performances of the FFT-OFDM and the DWT (Haar)-OFDM with and without helical and FRF interleavers have been evaluated over a multipath Rayleigh fading channel with an exponential power delay profile and no Doppler effect in the presence of AWGN. Figure 9 shows the BER vs. E_b/N_0 for the helical (FFT/DWT)-OFDM and FRF (FFT/DWT)-OFDM systems compared with the conventional (FFT/DWT)-OFDM systems over a Rayleigh fading channel. It should be noted that the performance of the DWT-OFDM outperforms that of the conventional FFT-OFDM. This is justified as follows. The performance merit can be explained by the premise of the cyclic prefixing required in the FFT-OFDM system, which is not required in the DWT-OFDM modulation, since copying a certain portion of each of the transmit symbol lengths leads to some noise also being copied. This would lower the likelihood of decoding the transmitted bits correctly. Over the multipath channel, more orientation is imposed on the transmit signal by the channel impulse response, but the signals processed by the DWT scheme possess some sturdy flexibility in time and frequency coupled with the filtering mechanisms used in the wavelet transform. The wavelet filters decompose the signal into equal lengths of low-frequency band and high-frequency band, and likewise reconstruct them. Since the channel state is known to the receiver, the effect of the channel can be removed with some bearable error introduced by the system noise. Therefore, from Figure 9, we can see clearly that helical and FRF interleaving achieve the best results with DWT-OFDM and strong improvements with FFT-OFDM. The proposed FFT-OFDM system with FRF interleaving outperforms that with helical interleaving in terms of BER. The reason for this improvement can be explained as follows. As mentioned above, the FRF interleaver has better randomization capabilities than the helical interleaver; that is to say, the FRF interleaver generates permuted sequences with a lower correlation between their samples, which efficiently combats the channel effects without a need for complicated coding schemes for error detection.

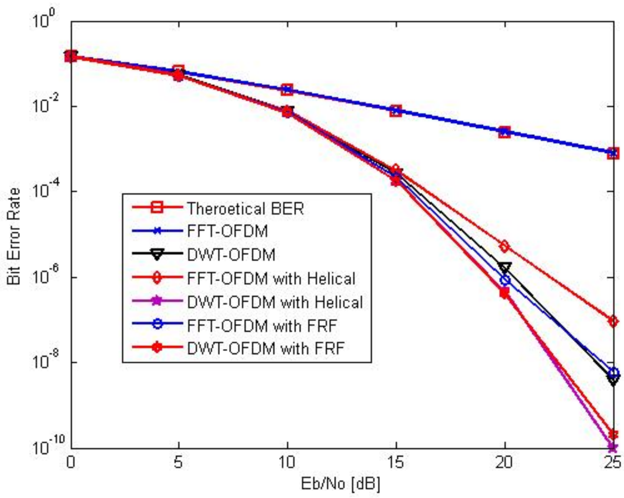


Figure 9. FFT−OFDM and DWT−OFDM BER performance over Rayleigh channel with exponential power delay profile channel without a Doppler effect.

On the other hand, the proposed DWT-OFDM system with the FRF interleaver provides approximately the same BER performance as that with the helical interleaver. In fact, the BER performance of communication systems can be improved due to the unique time–frequency localization feature of wavelets. As a result, there is no need to use interleavers with great randomization capabilities for the DWT-OFDM system. This is the reason why the FRF interleaver gives the same BER performance as that of the helical interleaver with the DWT-OFDM system. Thus, our recommendation is to use the proposed FRF interleaver for the FFT-OFDM system because of its ability to provide a good BER due to its inherent strong randomization ability. From the results shown in Figure 9, for example, at E_b/N_0 = 20 dB, the proposed FFT-OFDM system with the FRF interleaver achieves a

BER of about 8.8 × 10^{-7}. On the other hand, the BER value achieved in the FFT-OFDM system with the helical interleaver is 5.248 × 10^{-6}, while it is 2.557 × 10^{-3} in the case of the conventional FFT-OFDM system. This means that the proposed FRF interleaver can improve the BER performance compared to the BER achieved by the FFT-OFDM system with a helical interleaver and the conventional FFT-OFDM.

5.4. BER Performance Evaluation over Different Stanford University Interim (SUI) Channel Models

In this experiment, the BER performances of FFT-OFDM and DWT (Haar)-OFDM systems with and without helical and FRF interleavers are evaluated over different SUI channel models in the presence of AWGN. The SUI channel models considered are SUI-2, SUI-3, and SUI-6 [35]. The multipath profiles of the used SUI channels are summarized in Table 3.

Table 3. The multipath profiles of the used SUI channels.

Model	**Delay**	***L* (No. of Taps) = 3**			**Units**
	Gain	**Tap1**	**Tap2**	**Tap3**	
SUI-2		0	0.4	1.1	µs
		0	−12	−15	dB
SUI-3		0	0.4	0.9	µs
		0	−5	−10	dB
SUI-6		0	14	20	µs
		0	−10	−14	dB

Figures 10–12 show the BER vs. E_b/N_0 for the helical (FFT/DWT)-OFDM and FRF (FFT/DWT)-OFDM systems compared with the conventional (FFT/DWT)-OFDM systems over the SUI-2, SUI-3, and SUI-6 channel models. As seen in Figures 10–12, the DWT-OFDM achieves a better performance than that of the FFT-OFDM for the same reasons described above. In addition, the proposed (FFT/DWT)-OFDM systems outperform the traditional (FFT/DWT)-OFDM systems. In addition, helical and FRF interleaving achieve the best results with the DWT-OFDM system. Therefore, we can say that the proposed systems have a high immunity to burst errors. The figures also show that the proposed FFT-OFDM system with FRF interleaving provides a better BER performance than that with the helical interleaving, but the proposed DWT-OFDM systems with FRF and helical interleavers provide approximately the same BER performance for the same reasons described above. This indicates that the FRF interleaver is more suitable for the FFT-OFDM system due to its strong randomization capability that leads to a good BER. From the previous results obtained from Figures 10–12, for example, at E_b/N_0 = 30 dB, the proposed FFT-OFDM system with an FRF interleaver achieves BERs of about 1.22 × 10^{-6}, 9.78 × 10^{-7}, and 1.25×10^{-6} for the SUI-2, SUI-3, and SUI-6 channel models, respectively. On the other hand, the BER values achieved by the FFT-OFDM system with the helical interleaver are 4.44 × 10^{-6}, 2.11 × 10^{-6}, and 4.67 × 10^{-6}, while they are 0.1333 × 10^{-3}, 0.2354 × 10^{-3}, and 0.2562 × 10^{-3} for the conventional FFT-OFDM system over the SUI-2, SUI-3, and SUI-6 channel models, respectively. This means that the proposed FRF interleaver can improve the BER performance compared to those of the FFT-OFDM system with the helical interleaver and the conventional FFT-OFDM.

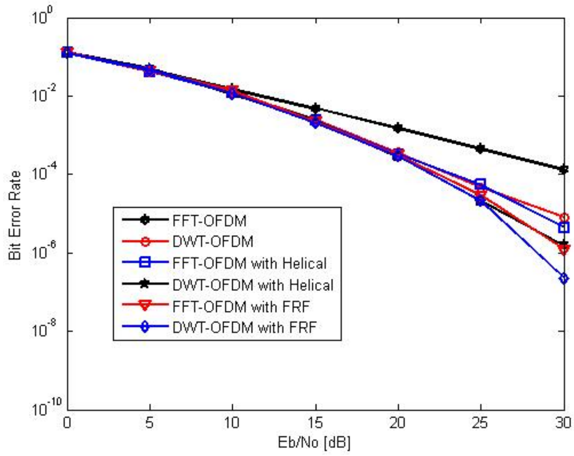


Figure 10. BER performance for the FFT−OFDM and DWT−OFDM systems over SUI-2 channel.

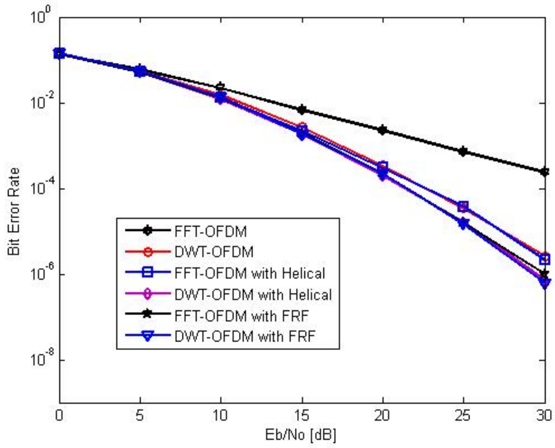


Figure 11. BER performance for the FFT−OFDM and DWT−OFDM systems over SUI-3 channel.

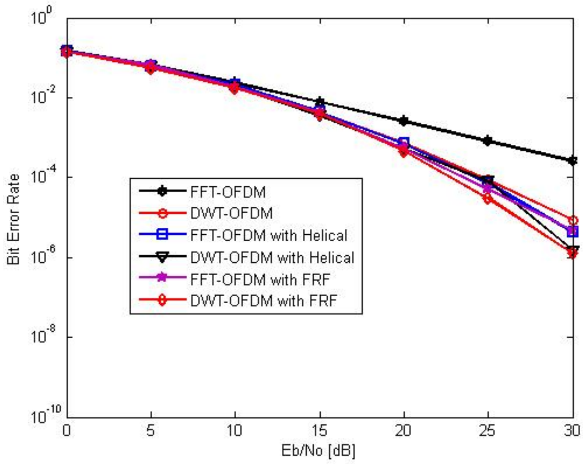


Figure 12. BER performance for the FFT−OFDM and DWT−OFDM systems over SUI-6 channel.

5.5. BER Performance Evaluation over Vehicular A Channel

In this experiment, the BER performances of FFT-OFDM and DWT (Haar)-OFDM with and without helical and FRF interleavers are evaluated over the vehicular A outdoor channel model in the presence of AWGN. The multipath profile of the vehicular A outdoor channel model is summarized in Table 4 [35].

Table 4. Multipath profile of the vehicular A outdoor channel model.

	Tap1	Tap2	Tap3	Tap4	Tap5	Tap6
Delay (ns)	0	310	710	1090	1730	2510
Power (dB)	0	−1	−9	−10	−15	−20

Figure 13 shows the BER vs. E_b/N_0 for the helical (FFT/DWT)-OFDM and FRF (FFT/DWT)-OFDM systems compared with the conventional (FFT/DWT)-OFDM over the vehicular A outdoor channel model. As can be seen in the figure, the proposed (FFT/DWT)-OFDM systems outperform the conventional (FFT/DWT)-OFDM systems. Hence, this confirms that the proposed systems have a high immunity to burst errors regardless of the channel models. From Figure 13, it is also clear that the proposed FFT-OFDM system with an FRF interleaver provides a better BER performance than that with the helical interleaver, but the proposed DWT-OFDM system with the FRF interleaver provides approximately the same BER performance as that with the helical interleaver for the same reasons mentioned above. Therefore, it is better to use the proposed FRF interleaver with the FFT-OFDM system for the same reasons described above. From the results obtained from Figure 13, at E_b/N_0 = 25 dB, the proposed FFT-OFDM system with an FRF interleaver achieves a BER of about 3.62×10^{-6}. On the other hand, the BER value achieved by the FFT-OFDM system with a helical interleaver is 1.335×10^{-5}, while it is 0.8369×10^{-3} in the case of the conventional FFT-OFDM system. This means that the proposed FRF interleaver can improve BER performance compared to those achieved by the FFT-OFDM system with the helical interleaver and the conventional FFT-OFDM system.

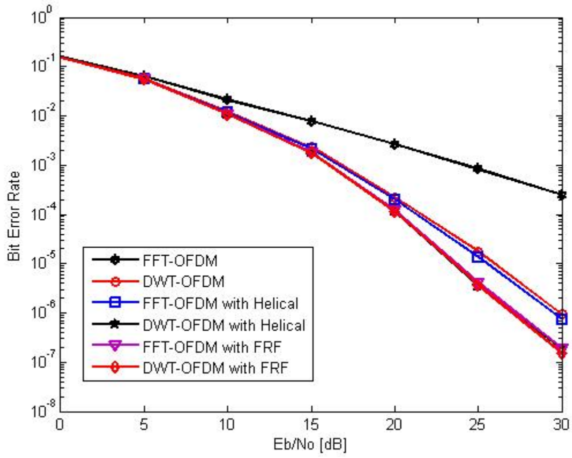


Figure 13. BER performance for FFT−OFDM and DWT−OFDM systems over vehicular A channel.

5.6. Overall Complexity Evaluation

In this set of experiments, the FRF interleaver is compared to the helical interleaver in terms of hardware complexity. The two interleavers were implemented in hardware using field-programmable gate arrays (FPGA) with a size of 128 × 128. Additionally, both interleavers were developed using Altera's Cyclone II FPGA board. Figures 14 and 15 indicate the overall complexity in terms of the total logic elements and memory bits. The FRF and helical interleavers' required logic elements were estimated using Altera's Quartus II tools. As indicated in the figures, the FRF interleaver needs more logic elements than the helical interleaver, but the total memory bits are almost the same for both of them. The FRF interleaver is, therefore, more complicated than the helical interleaver; that is to say, the FRF interleaver requires more energy in computations. However, in wireless networks such as wireless sensor networks, the energy consumption in communication is identified as the major source of energy consumption and costs significantly more than computation. Indeed, increasing the BER will increase the number of lost packets, leading to an increase in energy consumption due to packet retransmission that inevitably affects the network efficiency. Therefore, the FRF interleaver can improve the network throughput and energy efficiency compared with the others.

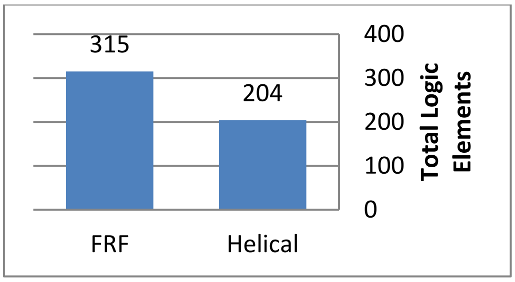


Figure 14. Total number of logic elements required for the FPGA implementation of the FRF and helical interleavers of size 128 × 128.

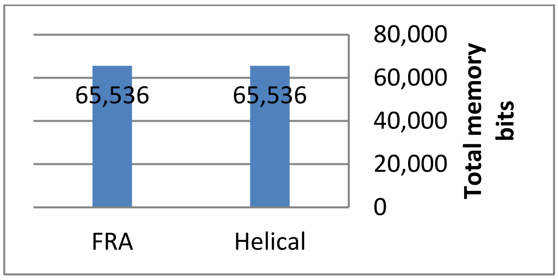


Figure 15. Total number of memory bits required for FPGA implementation of FRF and helical interleavers of size 128 × 128.

6. Conclusions

This research introduced an efficient helical interleaver and a novel FRF interleaver for OFDM systems to increase wireless communication reliability and data throughput. The proposed approach enhances the (FFT/DWT)-OFDM BER performance. The BER performance of the FFT-OFDM system was compared to that of the DWT-OFDM system for numerous wavelet families. The AWGN, multipath Rayleigh fading with exponential power delay spread and no Doppler influence, SUI-2, SUI-3, SUI-6, and vehicular A channel models have all been considered to assess the performance of the suggested approach. Finally, experimental findings indicate that higher-order M-QAM offers high data rates despite a weaker resilience to errors. The DWT-OFDM outperforms the traditional FFT-OFDM for all wavelet families. In addition, it is observed that the Haar wavelet is the best choice for DWT-OFDM implementation. Furthermore, according to the simulation results, it has been observed that the proposed FFT-OFDM system with FRF interleaving outperforms that with helical interleaving in terms of BER, as the FRF interleaver has better randomization capabilities than the helical interleaver. On the other hand, the proposed DWT-OFDM system with the FRF interleaver provides approximately the same BER performance as that of the DWT-OFDM system with the helical interleaver. As a result, our recommendation is to use the proposed FRF interleaver for the FFT-OFDM system. Finally, the proposed FRF interleaver is more complex than the helical interleaver, but the FRF interleaver can improve the throughput and energy efficiency of critical systems, where their power consumption is essential, compared with the others. The simulation results have shown that the performances of the proposed FRF and helical interleavers have noticeable improvements compared to that of the conventional (FFT/DWT)-OFDM. Finally, the proposed FRF interleaver is more complex than the helical interleaver. One possible future focus of this paper is a deep investigation of the performance of conventional interleavers compared to our proposed FRF interleaver.

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