Performance evaluation of MIMO DFT-Spread WR-OFDM system for spectrum efficiency and power efficiency

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ABSTRACT

It is important to design a spectrum-efficient and power-efficient wireless communication system, which is the main design target in cellular and wireless communication engineering. Basically, to make it, the desired system must have a low peak-to-average power ratio (PAPR), low-level of out-of-band (OOB) power emission and can provide a high throughput. In this paper, we propose a high-throughput cellular communication system, namely Discrete Fourier Transform-Spread Windowing and Restructuring Orthogonal Frequency Division Multiplexing (DFT-Spread WR-OFDM), which has considerably low PAPR and low OOB power emission for upcoming next-generation beyond 5G (B5G) and 6G cellular communication systems. High PAPR is still one of the challenging issues for the MIMO-OFDM system. The proposed system is an effective arrangement of DFT-Spreading and windowing techniques to reduce PAPR and OOB power emission, respectively. Multiuser diversity is obtained using localized subcarrier mapping. We take advantages of spatial multiplexing to enhance the data throughput significantly. Additionally, frequency-domain equalization (FDE)-minimum mean squared error (MMSE) is used to combat the inter-symbol interference (ISI) effect. Simulation results verify that the suggested system considerably lowers PAPR and OOB power emission compared to the conventional systems. Furthermore, the proposed scheme shows better bit error rate (BER) performance over the MIMO Rayleigh fading channel environment. Simulation results also confirmed that the channel capacity of our suggested system is better than the conventional multi-carrier systems.

1. Introduction

Multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) is an attractive technology to deliver higher data rates in future generation 5G/B5G mobile communication systems. In addition, the MIMO technique increases the channel's capacity through spatial multiplexing, the bit error rate performance, and increases...
the range of cells (Stuber et al., 2004; Zou & Wu, 1995). However, the OFDM transmission system suffers from a high peak-to-average power ratio (PAPR), which lowers the efficiency of a transmitter’s power amplifier (PA); as a result, in-band and out-of-band distortion effects can occur in the output signal (Jiang & Wu, 2008). A large input back-off (IBO) copes with the high power peaks of the OFDM signals and to keep away from the saturation point of the power amplifier. Providing IBO to the signal is not a satisfactory solution because the PA efficiency and spectrum efficiency (SE) decrease with IBO (Jiang et al., 2013; Ryu et al., 2004). Moreover, high PAPR creates inter-modulation among the different subcarriers and causes additional interference in the systems. The BER performance could be deteriorated due to the additional interference.

To meet the key performance indicators (KPIs) requirements of 5G and beyond, a new radio interface has been recommended for the 5G technology. The CP-OFDM system was the preference for the 5G new radio waveform, especially for the downlink transmission (3GPP TR 38.913, 2017; Chiuheh & Tsai, 2008; Maziar et al., 2016). The Single Carrier-Frequency Division Multiple Access (SC-FDMA) technique was proposed for uplink transmission due to its low PAPR (Myung, 2007; Myung et al., 2006). However, this system has high OOB power emissions. Different MIMO-OFDM systems have been used in the LTE-A standard. In addition, MIMO-OFDM is favoured as an attractive technology for the development of future next-generation 6G systems to deal with the rapidly growing demands for mobile data access. However, the candidate waveform for 6G networks, has not been finalised yet. The motivation behind this research is to suggest a waveform candidate for the efficient downlink and uplink transmissions for 5G and 6G systems. Filtering-based waveforms, such as Universal Filtered Multicarrier (UFMC), filtered-OFDM (f-OFDM), and Filter Bank Multicarrier (FBMC) (Abdoli et al., 2015; Bellanger et al., 2010; Schaich & Wild, 2014) can reduce the out-of-band power emissions significantly, but the system complexity is very high. Generalized Frequency Division Multiplexing (GFDM) technique based on filter bank multibranch multi-carrier concept facilities high degrees of spectrum fragmentation compared to OFDM (Fettweis et al., 2009; Michailow et al., 2012). Time Interleaved Block Windowed Burst-OFDM (TIBWB-OFDM) (Fernandes et al., 2016; Fernandes et al., 2018) gives superior spectral efficiency than the OFDM system. Like OFDM, these systems also have high PAPR because they are based on multi-carrier (Conceição et al., 2021; Vakilian et al., 2013). On the other hand, in window-based new waveform candidates, such as Weighted Overlap and Add based OFDM (WOLA-OFDM) and WR-OFDM (An et al., 2017; Zayani et al., 2016), the circuit size and complexity are almost the same as the conventional OFDM system. These systems are also multicarrier-based, and thus, high PAPR is inevitable. To get a sharper OOB spectrum, WOLA-OFDM adopted the windowing process. Long window length can get the sharper OOB spectrum; however, data will be damaged seriously, even before transmission. The damaged data cannot be recovered at the receiver. This is a serious problem with the WOLA-OFDM system. A simplified DFT-Spread WR-OFDM system was proposed (Hossain et al., 2018; Hossain et al., 2019) to reduce the PAPR at the transmitter. Low PAPR facilitates numerous improvements in power saving, channel capacity, and spectrum efficiency (Hossain & Shimamura, 2017; Jiang & Wu, 2008). The MIMO technology enhances the spectrum and energy efficiency when it is introduced to the OFDM-based systems (Bhamri et al., 2016). However, reducing the PAPR of the MIMO-OFDM system becomes a more challenging task, especially when more carriers are added to the LTE-A or 5G systems.
In this article, a new waveform is presented to reduce out-of-band emission (OOBE) and PAPR of the MIMO-OFDM scheme that can also provide a high throughput. The MIMO DFT-Spread WR-OFDM scheme is based on a combination of DFT-IFTF chain and windowing technique i.e. DFT-Spreading technique is utilized before IFFT operation, and time-domain windowing is utilized following cyclic prefix (CP) addition. The purposes of using the DFT-Spreading and windowing techniques are to lower the PAPR and OOB power emission of the OFDM system, respectively. To be precise, DFT precoding lowers the high peak of OFDM signals and the windowing technique lowers the high OOBE.

The rest of the paper is structured as follows. Section 2 describes the characteristics of OFDM signals and their PAPR. Section 3 illustrates the transceiver structure of the suggested MIMO DFT-Spread WR-OFDM method. The performance of the suggested method is evaluated in Section 4. In the end, the conclusion of this manuscript is given in Section 5.

2. Overview of the OFDM signal characteristics and its PAPR

The time-domain OFDM signal can be yielded from the frequency-domain signal using the inverse fast Fourier transformation (IFFT) as follows:

$$
x_n = \frac{1}{NL} \sum_{k=0}^{NL-1} X_k e^{j2\pi kn/L} \quad (1)
$$

where $n = 0, 1, 2, \ldots, NL - 1$ and $L$ is the oversampling factor. We consider $L = 4$, to improve the accuracy of the discrete PAPR. For the MIMO-OFDM system with $N_t$ transmit antennas using $N$ subcarriers, the PAPR of the $L$-time oversampled time-domain signals is defined as

$$
PAPR_{N_t} = \max(|x_n|^2)/E[|x_n|^2] \quad (2)
$$

where max(.) denotes the maximum value function, $n = 1, 2, \ldots, NL$ and $E[.]$ is the expected value. For the accurate statistical distribution of the PAPR, we consider the complementary cumulative distribution function (CCDF), which is the probability that the PAPR of a data block surpasses a certain threshold $PAPR_0$ (Prasad, 2004). The CCDF is defined as

$$
CCDF_{N_t} = \text{Prob}(PAPR_{N_t} > PAPR_0) = 1 - (1 - e^{-PAPR_0})^{\alpha N} \quad (3)
$$

The value of $\alpha = 2.3$ is found in (Han & Lee, 2004) for $L = 4$.

3. Proposed system model

Figure 1 shows the transceiver structure of the proposed MIMO-OFDM system based on DFT-Spreading and time-domain windowing techniques with $N_r \times N_t$ antennas. In the proposed system model, firstly, the synthetically generated binary input data are mapped onto the digital modulators, which especially perform quadrature amplitude modulation (QAM). The synthetically generated binary input data are transformed into the sequence of complex-valued multilevel modulated symbols, $x_m (m = 0, 1, 2, \ldots, M - 1)$. At the
transmitter side, an additional signal processor stage performs $M$-point DFT operations $[X_k(k = 0, 1, 2, \ldots, M - 1)]$ to each blocked symbol $x_m$ and subsequently mapped onto each subcarrier via IFFT. This DFT precoding is used to limit the PAPR of the transmitted signal. Figure 2 illustrates the variation of subbands (group of subcarriers) due to different DFT sizes. For example, if $N = 16$ and $M = 4$, the number of subbands would be $16/4 = 4$. And if we consider DFT size $M = 8$, the number of subbands would be $16/8 = 2$. This change of subbands causes variation of PAPR for different DFT sizes. $Y_l(l = 0, 1, 2, \ldots, N - 1)$ represents the frequency-domain samples after localized subcarrier mapping. The mapping process is also called scheduling. With the localized subcarrier mapping, the modulation symbols are allocated to $N$ adjacent symbols. Time-domain

Figure 1. Block diagram of the proposed MIMO-OFDM system based on DFT precoding and the windowing technique with $N_r \times N_t$ antennas.

Figure 2. Illustration of subband variations due to different DFT sizes: (a) $N = 16$ and $M = 4$ and (b) $N = 16$ and $M = 8$. 
samples $y_n(n = 0, 1, 2, \ldots, N - 1)$ can be obtained from the IFFT. After the IFFT operation, the time-domain signals change into a serial stream from the parallel stream by the parallel-to-serial (P/S) block. Then, the cyclic prefix (CP) is added. A windowing technique is used after the CP addition stage to greatly reduce OOB power emission. After that, the signals are transmitted sequentially through the radio frequency (RF) module with $N_t$ transmit antennas. On the receiver side, reverse operations are performed after the noisy signals are received by the $N_r$ receive antennas. Then, it removes the CP, and the restructuring procedure takes place to recover the damaged portion of the OFDM symbols due to the windowing technique. After the restructuring process, the signals are transformed into frequency-domain signals via FFT operations. Then, the frequency-domain equalization (FDE)-MMSE technique is used to cope with inter-symbol interference (ISI). Finally, it de-maps the subcarriers and transforms them back into the time-domain signal via $M$-point IDFT block, and signal is detected in the time-domain.

### 3.1. MIMO channel capacity

Figure 3 shows a conventional MIMO system architecture with $N_t$ transmit and $N_r$ receive antennas. We consider the Shannon capacity formula; for any MIMO configurations, the channel throughput is defined as

$$C = \log_2 \left( \det \left[ I_{N_r} + \left( \frac{\rho}{N_r} \right) H H^T \right] \right)$$  \hspace{1cm} (4)

where ‘det’ represents the determinant, $I_{N_r}$ is the $N_r \times N_r$ identity matrix, $\rho$ is the signal to noise ratio and $H$ represents the channel matrix.

When CSI is not available at the transmitter, and thus, the total power is equally allocated to all transmit antennas. When channel state information (CSI) is known at the transmitter, modal decomposition can be executed, as shown in Figure 4, where a transmitted signal is pre-processed with $V$ in the transmitter and then post-processed with $U^H$ in the receiver, where $V$ and $U$ are the unitary matrices and $z$ is a noise vector (Cho et al., 2010).

![Figure 3. Typical MIMO system with $N_t$ transmit and $N_r$ receive antennas.](image-url)
3.2. Windowing technique

The time-domain windowing technique is a popular method for reducing out-of-band emissions (OOBE) in the OFDM system. It reduces OOBE by multiplying the left and right end segments of the OFDM symbol to improve spectral characteristics. Conventional OOBE reducing techniques, such as f-OFDM, FBMC, UFMC, require plenty of multiplication, increasing the complexity of the transmitter. In contrast, the time-domain windowing technique needs single multiplication only which is effective in reducing complexity than the conventional techniques. In this paper, the Tukey window function is performed that can be defined as follows (Hossain & Ryu, 2021):

\[
\begin{align*}
    w_{tx}(\ell) &= \begin{cases} 
    \frac{1}{2} \left(1 + \cos\left(\frac{2\pi}{\alpha} \left[\ell - \frac{\alpha}{2}\right]\right)\right), & 0 \leq \ell < \frac{\alpha}{2} \\
    1, & \frac{\alpha}{2} \leq \ell < 1 - \frac{\alpha}{2} \\
    \frac{1}{2} \left(1 + \cos\left(\frac{2\pi}{\alpha} \left[\ell - \frac{\alpha}{2}\right]\right)\right), & 1 - \frac{\alpha}{2} \leq \ell < 1
\end{cases}
\end{align*}
\]  

(5)

where \(w_{tx}(\ell)\) denotes Tukey window coefficients, and \(r\) is the cosine fraction. This window function is utilized for left and right segments of the OFDM symbol by multiplication operations. Figure 5 shows the symbol formation and the windowing technique of the proposed method. The proposed scheme time-domain symbol length is \(N + CP\), precisely the same as the conventional OFDM system.

3.3. Restructuring technique

Figure 6 shows the restructuring technique of the proposed method. On the transmitter side, some portions of the OFDM symbol have been affected due to the windowing technique. A restructuring procedure must be needed on the receiver side to recover the affected portion of the OFDM symbol. By replacing the CP right end segment, the affected OFDM symbol is recovered. We call this procedure the restructuring technique of the proposed method.

4. Simulation results and discussions

In this section, we present the simulation results to evaluate the performances of our proposed MIMO DFT-Spread WR-OFDM scheme compared with the conventional OFDM and WR-OFDM schemes. In every part of the simulations, we assume \(N = 2048\) subcarriers and \(M = 512\) DFT size using 4-QAM modulation. The oversampling factor \(L = 4\) is considered for

![Figure 4. Modal decomposition when CSI is available at the transmitter side (Cho et al., 2010).](image-url)
the true PAPR estimation, and PAPR reduction performance is evaluated by the CCDF. Additionally, uncoded BER performance and channel capacity performance comparisons have been investigated among different schemes. Table 1 presents the setting parameters we have considered.

To evaluate the PAPR reduction performance for different schemes, the complementary cumulative distribution function (CCDF) is used. Usually, to get the PAPR reduction, we kept \( M \) to be less than \( N \) (\( N \geq M \)), which is actually the fundamental of the DFT-Spreading technique. The \( N \)-point IFFT effect is mainly cancelled out by the \( M \)-point DFT. If \( M = N \) (no zero), they are completely cancelled out, and the symbols would be just a time-domain symbol. Even though \( N \) is much larger than \( M \), the resulting symbol has more like time-domain symbols, the PAPR is lower. CCDF performance varies with the DFT sizes. In (Cho et al., 2010) and our previous paper (Hossain & Ryu, 2021) revealed this property.

Figure 7 shows the CCDF performance of PAPR for different schemes. Our proposed scheme can reduce PAPR substantially, due to its single (quasi) carrier property, in comparison with the other multi-carrier systems. For \( WL = 4 \), at the level of \( 10^{-3} \), the suggested method reduced PAPR by 1.8 and 2.3 dB compared to OFDM and WR-OFDM systems, respectively. PAPR reduction performance of the proposed scheme is slightly degraded when the window length is increased; nevertheless, the degradation is almost negligible. Figure 8 illustrates the CCDF of PAPR performance comparison of
the proposed DFT-Spread WR-OFDM scheme for different DFT sizes. From this figure, we can see that the PAPR of the proposed scheme increases with DFT sizes. High power amplifier (HPA) efficiencies for different modulation systems are depicted in Figure 9. In a practical wireless communication transmitter, HPA facilitates signal transmission over long distances. Since the PAPR of the suggested system is lower than the OFDM counterparts, the HPA efficiency is higher than conventional systems. From this figure, we can see that the maximum efficiencies of the OFDM system are 12.85% and 20.18% for Class A and B amplifiers, respectively. When $WL = 4$, the maximum efficiencies of the WR-OFDM system are 12.42% and 19.49% for Class A and B amplifiers, respectively. For the case of $WL = 62$, the maximum efficiencies of the WR-OFDM system are 12.13% and 19.05% for Class A and B amplifiers, respectively. The maximum efficiencies of the proposed system for $WL = 4$ are 15.81% and 24.82% for Class A and B amplifiers, respectively. And finally, for the case of $WL = 62$, the maximum efficiencies of the suggested system are 15.45% and 24.26% for Class A and B amplifiers, respectively.

To study the out-of-band (OOB) power emission performance, we plotted the power spectral density (PSD) for OFDM, WR-OFDM, and the proposed scheme. Figure 10 shows the power spectrums of different modulation schemes. OOB power emission of

\[
\begin{array}{|l|c|}
\hline
\text{Parameters} & \text{Values} \\
\hline
\text{Modulation alphabet} & 4\text{-QAM} \\
\text{FFT size} & 2048 \\
\text{DFT size}, M & 512 \\
\text{No. of subcarriers}, N & 2048 \\
\text{No. of active carriers} & 512 \\
\text{Subcarrier spacing} & 15 \text{kHz} \\
\text{CP overhead} & 128 \\
\text{Window function} & \text{Tukey (tapered cosine)} \\
\text{Window length} & \text{Several} \\
\text{Channel} & \text{MIMO Rayleigh fading channel} \\
\hline
\end{array}
\]

Figure 7. PAPR reduction performance comparison of different modulation schemes.
OFDM scheme is $-44$ dB. Also, we can observe that the OOB power emissions of the WR-OFDM scheme are the same as the proposed scheme for different window lengths since both systems have similar subcarrier mapping stages. The effect of the windowing technique is prominent in this figure. The higher the window length, the lower the OOB power emission. In this research, however, we considered maximum window length, which is less than half of the CP length to avoid inter-carrier interference (ICI). For example, when $WL = 4$, the OOB power emission for WR-OFDM and the proposed scheme is $-83$ dB. The amount of OOB emission is lowered by 39 dB. The OOB power emission is achieved $-125$ dB when $WL = 62$, i.e. OOB power emission is reduced by 81 dB.

![Figure 8](image.png)

**Figure 8.** CCDF of PAPR performance of the proposed DFT-Spread WR-OFDM scheme for different DFT sizes.

![Figure 9](image.png)

**Figure 9.** Comparative high power amplifier efficiency for different modulation schemes.
The comparison of OOB power emissions for different modulation schemes is shown in Table 2. The OFDM system has the highest level of OOB power emission. In contrast, the WR-OFDM and our suggested method have low-level OOB power emissions due to the windowing technique. And low-level OOB power emission is essential to avoid adjacent channel interference (ACI).

In Figures 11–13, the BER performance is depicted among different schemes for various MIMO orders using 4-QAM modulation. Throughout the simulations, MIMO Rayleigh fading channel is considered. The proposed scheme shows better performance than the conventional OFDM and WR-OFDM systems in every scenario. Degradation of BER performance can be seen as the MIMO order grows. However, our proposed scheme outperforms than OFDM and WR-OFDM systems. For the 8 × 8 MIMO case and WL = 4, we note that BER of 4 × 10⁻³ can be obtained by the WR-OFDM system at 9.9 dB (9.77 Watt), the same BER can be obtained by the proposed scheme at 8 dB (6.31 Watt).

In Figures 14–16, the BER performance is evaluated among different schemes for various MIMO orders for 16-QAM modulation. The proposed scheme is similar to the conventional OFDM and WR-OFDM systems for 2 × 2 MIMO order and WL = 4. However, the robustness of the DFT-Spread WR-OFDM scheme is observed compared to other schemes for 4 × 4 and for 8 × 8 MIMO orders using 16-QAM. For example, an SNR gain of 1.4 dB is achieved at BER 1 × 10⁻³ by the proposed scheme compared to the WR-OFDM scheme for 4 × 4 the MIMO case and WL = 62. However, the BER performance could be degraded if the window length is increased. Because increased window length can create partial

\[\text{Table 2. OOB power emission comparison.}\]

| OFDM [dB] | WR-OFDM [dB] | Proposed [dB] |
|-----------|--------------|---------------|
|           | WL = 4      | WL = 62       | WL = 4      | WL = 62       |
| −44       | −83          | −125          | −83          | −125          |

Figure 10. Out-of-band power rejection of different modulation schemes.
interference between OFDM symbols. Since the noted BER is obtained at lower SNR, the additional SNR can be used to increase the channel capacity.

The channel capacity improvements in throughput versus SNR are obtained due to the PAPR reduction by the proposed scheme, as shown in Figure 17. We evaluate the channel capacity performance for $2 \times 2$, $4 \times 4$, and $8 \times 8$ MIMO orders. In terms of throughput, the WR-OFDM scheme shows the worst performance due to its high PAPR, and our proposed scheme outperforms the conventional OFDM scheme because additional SNR gain is achieved due to its low PAPR. The better performance of every scheme is achieved as

![Figure 11](image1.png)

**Figure 11.** BER performance comparison of the OFDM scheme using 4-QAM modulation for different MIMO orders over the Rayleigh fading channel.

![Figure 12](image2.png)

**Figure 12.** BER performance comparison of the WR-OFDM scheme using 4-QAM modulation for different MIMO orders over the Rayleigh fading channel.
the MIMO order grows. The bit rates of 15.45, 8.84 and 5.15 bps/Hz are observed for the DFT-Spread WR-OFDM scheme at the SNR level of 10 dB for $8 \times 8$, $4 \times 4$ and $2 \times 2$ MIMO configurations, respectively. These results demonstrate superior performance to the other systems. Moreover, the higher the SNR higher the throughput can be achieved for each system. Figure 18 shows the channel capacity of different MIMO orders when channel state information (CSI) is known at the transmitter side. This figure reveals that in the low SNR case, channel capacities are slightly improved in each system. However, in high SNR cases, the availability of CSI is not working to improve the channel capacity.

![Figure 13. BER performance comparison of the proposed DFT-Spread WR-OFDM scheme using 4-QAM modulation for different MIMO orders over the Rayleigh fading channel.](image13.png)

![Figure 14. BER performance comparison of the OFDM scheme using 16-QAM modulation for different MIMO orders over the Rayleigh fading channel.](image14.png)
In this paper, we present a new waveform candidate DFT-Spread WR-OFDM to meet the increasing demand of high spectrum efficiency in the future generation beyond 5G and 6G cellular and wireless communication systems. The proposed scheme yields an effective reduction of OOB power emission compared to the conventional OFDM system. Low-level OOB power emission is very crucial to save frequency resources. Simulation results also demonstrated that the proposed scheme significantly reduced PAPR by 2.2 and 2.8 dB.

5. Conclusion

In this paper, we present a new waveform candidate DFT-Spread WR-OFDM to meet the increasing demand of high spectrum efficiency in the future generation beyond 5G and 6G cellular and wireless communication systems. The proposed scheme yields an effective reduction of OOB power emission compared to the conventional OFDM system. Low-level OOB power emission is very crucial to save frequency resources. Simulation results also demonstrated that the proposed scheme significantly reduced PAPR by 2.2 and 2.8 dB.
compared to the conventional OFDM and WR-OFDM systems, respectively. Moreover, BER performance is also investigated for $2 \times 2$, $4 \times 4$ and $8 \times 8$ MIMO configurations. The uncoded BER performance is improved by the proposed scheme. SNR gain of 1.9 dB is achieved by the proposed scheme compared to the WR-OFDM system for the case of $W=4$ and $8 \times 8$ MIMO configuration using 4-QAM signalling. The synergistic effect of utilizing the DFT precoding and the windowing technique guarantees the low-level out-of-band power radiation and PAPR reduction, thereby improving the communication

Figure 17. Channel capacity performance comparison of different modulation schemes when CSI is not known.

Figure 18. Channel capacity performance comparison of different modulation schemes when CSI is known.
quality of the proposed scheme. Additionally, the DFT-Spread WR-OFDM scheme improves channel capacity for different MIMO configurations. At the SNR level of 10 dB and for $8 \times 8$ MIMO configuration, the DFT-Spread WR-OFDM scheme improves the channel capacity by 4.25 and 5.45 bps/Hz compared to the OFDM and WR-OFDM schemes, respectively.

Acknowledgements

The author would like to thank Prof. Tetsuya Shimamura, Saitama University, Japan and Prof. Heung-Gyoon Ryu, Chungbuk National University, South Korea for supporting this research academically. Also, the author thanks the reviewers for their valuable comments, suggestions, and questions that significantly improved the article.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributor

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