WTS 2023

An Efficient Fast Walsh-Hadamard Transform Based OFDM-IM Scheme with Lower PAPR

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April 13, 2023

Outline

1. Background and Motivation
2. System Model
3. Principle of WHT
4. The Transceiver & Optimal Parameter
5. Numerical Results
6. Conclusion

Background and Motivation

- The next generation of B5G/6G wireless networks requires **higher spectrum efficiency and superior performance.** To meet these demands, the concept of Index Modulation (IM) has gained attention in recent year.
- Among all these Index Modulation Scheme, IM can be mainly divided into frequency domain and spatial index modulation. **And OFDM-IM[1] provides lower BER, faster transmission rates, and higher spectrum efficiency.**
- OFDM-IM still inherits the problem of high power amplifier (HPA) cost caused by the distortion from its enormous Peak-to-Average Power Ratio (PAPR) when passing through non-linear devices. However, Walsh-Hadamard Transform (WHT) can significantly enhance communication efficiency and effectively decrease HPA costs in OFDM[2].

[1] ("Orthogonal frequency division multiplexing with index modulation")

[2] ("WHT/OFDM - an improved OFDM transmission method for selective fading channels"; "On some properties of Walsh-Hadamard transformed OFDM")

Contributions

The major contributions are summarized as follows:

- Introduce the transceiver structure of WHT-OFDM-IM, which incorporates WHT into the OFDM-IM system.
- Evaluate the PAPR of the WHT-OFDM-IM under different activated subcarriers by comparing the (CCDF) curve between OFDM-IM and WHT-OFDM-IM.
- Evaluate the BER performance of WHT-OFDM-IM by comparing it with OFDM-IM and evaluate the impact on WHT-OFDM-IM under different number of subcarriers and activated subcarriers.

Abbreviations

OFDM-IM: Orthogonal Frequency Division Multiplexing With Index Modulation;
WHT: Walsh-Hadamard Transform; PAPR: Peak-to-Average Power Ratio;
CCDF: Complementary Cumulative Distribution Function.

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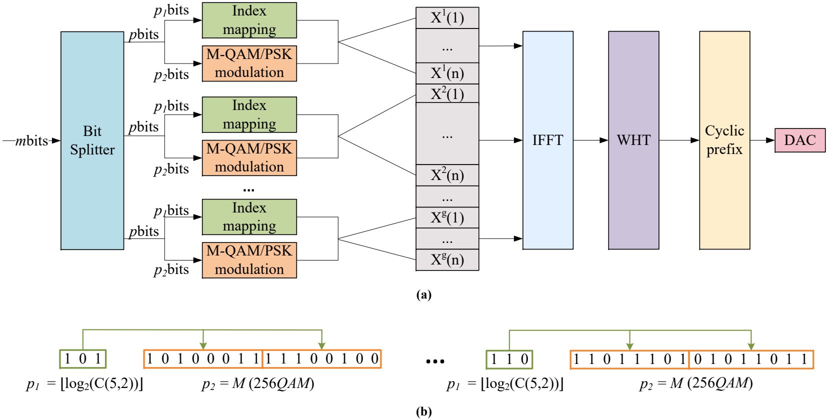
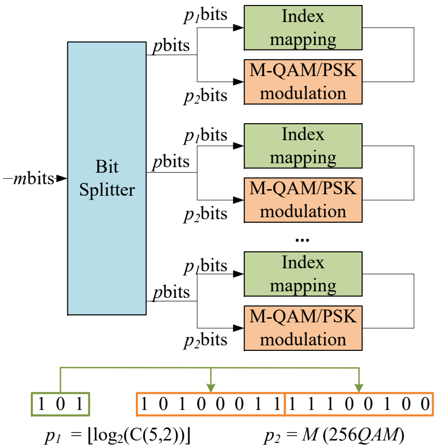
Here is a transmitter of WHT-OFDM-IM



- ❑ (a) is the transmitter of WHT-OFDM-IM;
- ❑ (b) is the example of the division between the index bit and information bit in OFDM-IM.

System Model



Index mapping - Index bit p_1

$$p_1 = \frac{m_1}{g} = \lfloor \log_2 C(n,\ k) \rfloor$$

M-QAM/PSK modulation - Modulation bit p_2

$$p_2 = \frac{m_2}{g} = k(\log_2 M)$$

WHT-OFDM-IM m bit

$$m = pg = [k(\log_2 M) + \lfloor \log_2 C(n,\ k) \rfloor]g$$

System Model (Index Mapping Method)

Table: Index Mapping Table

p_1 bits	Subcarrier index combination	Subblock
0 0 0	2, 1, 0	$[0\ \ 0\ \ s(1)\ \ s(2)\ \ s(3)]$
0 0 1	3, 1, 0	$[0\ \ s(1)\ \ 0\ \ s(2)\ \ s(3)]$
0 1 0	3, 2, 0	$[0\ \ s(1)\ \ s(2)\ \ 0\ \ s(3)]$
0 1 1	3, 2, 1	$[0\ \ s(1)\ \ s(2)\ \ s(3)\ \ 0]$
1 0 0	4, 1, 0	$[s(1)\ \ 0\ \ 0\ \ s(2)\ \ s(3)]$
1 0 1	4, 2, 0	$[s(1)\ \ 0\ \ s(2)\ \ 0\ \ s(3)]$
1 1 0	4, 2, 1	$[s(1)\ \ 0\ \ s(2)\ \ s(3)\ \ 0]$
1 1 1	4, 3, 0	$[s(1)\ \ s(2)\ \ 0\ \ 0\ \ s(3)]$

- Given the number of subcarriers, $n = 5$ and the number of activated subcarriers, $k = 3$
- $C\,(5,\ 3) = 10$ possible permutations of active subcarriers, the proposed WHT-OFDM-IM scheme eliminates 2 of these permutations;

Combinatorial method

$$
\begin{aligned}
34 &= C(6,3) + C(5,2) + C(4,1) \rightarrow J = \{6,5,4\} \\
33 &= C(6,3) + C(5,2) + C(3,1) \rightarrow J = \{6,5,3\} \\
&\cdots \\
1 &= C(3,3) + C(1,2) + C(0,1) \rightarrow J = \{3,1,0\} \\
0 &= C(2,3) + C(1,2) + C(0,1) \rightarrow J = \{2,1,0\}
\end{aligned}
$$

- p_1 bit of index is converted directly to a positive decimal integer Z in each WHT-OFDM-IM subblock
- Look for the largest c_k such that $C\left(c_k, k\right) \leq Z$ for the determined Z;
- Select the largest c_{k-1} such that $C\left(c_{k-1}, k-1\right) \leq \ z - c \ \left(c_k, k\right)$

System Model (Demodulaton)

- The **Maximum Likelihood (ML)**[1] hard decision algorithm and the **Log-Likelihood Ratio (LLR)**[1] soft decision detection algorithm can be applied in WHT-OFDM-IM systems.

$$\left(\hat{I}^i, \hat{s}^i\right) = \arg\min_{I^i, s^i} \sum_{a=1}^{n} \left|y_a^i - x_a^i\right|^2$$

- In order to maximize the performance improvement of WHT-OFDM-IM compared to OFDM-IM, this paper adopts the **ML detection algorithm**.

[1] ("Orthogonal frequency division multiplexing with index modulation")

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The WHT matrix

$$\begin{pmatrix} H & H \\ H & -H \end{pmatrix}$$

$$H_1 = (1)\,, H_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}, \ldots,$$

$$H_{i=2^l} = \frac{1}{\sqrt{i}}\begin{pmatrix} H_{k=2^{l-1}} & H_{k=2^{l-1}} \\ H_{k=2^{l-1}} & -H_{k=2^{l-1}} \end{pmatrix}$$

- A precoding matrix, whose code length $i = 2^l (l \in \mathbf{Z}^+)$;
- Assuming that H is a matrix orthogonal composed of 1 and -1;
- $1/\sqrt{i}$ is expressed as a normalization factor, as the order of the Hadamard matrix, k is used to derive the WHT matrix;
- Utilize **Fast Walsh-Hadamard-Fourier Transform (FWHFT) algorithm**[1] to significantly reduce the computational and implementation costs of the WHT-OFDM-IM systems

[1] ("Fast Walsh-Hadamard-Fourier transform algorithm")

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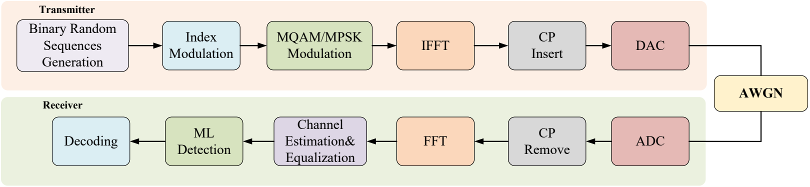
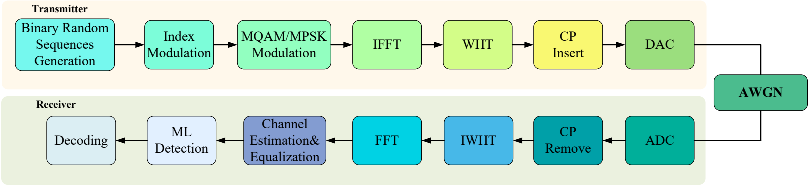
The Transceiver Structure



(a)



(b)

- (a) is the OFDM-IM transceiver architecture;
- (b) is the WHT-OFDM-IM transceiver architecture.

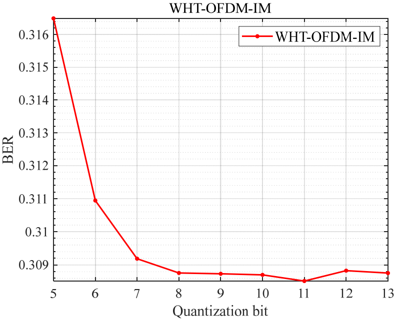
Zero-Forcing (ZF) Equalization

- Based on the above power transceiver structure, the channel estimation and equalization operation is **Zero-Forcing (ZF) equalization**:

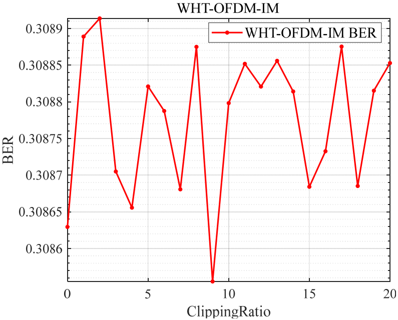
$$Y_E = \frac{P_p}{P_p \cdot P} Y$$

- Y is received signal by FFT, P is the estimated channel impulse response, P_p is the complex conjugate transpose of P.

The Optimal Parameter Setting



(a)



(b)

- (a) is the optimal quantization bit in the WHT-OFDM-IM: the optimal quantization bit is 11 bits;
- (b) is the optimal clippingratio in the WHT-OFDM-IM: the optimal clipping ratio is 9 dB, which has a minimal impact on the BER in the WHT-OFDM-IM system.

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Simulations

Parameter Settings

- Length of sequence: 140000
- Modulation formats: 64QAM
- Cyclic Prefix (CP): 0.125
- DAC & ADC quantization bit: 11 bits
- clippingratio: 9dB
- Detection: ML & Equalization: Zero-Forcing (ZF)
- SNR: 0∼25dB & PAPR 0∼12dB

Application Scenario Comparisons

- PAPR under $n = 16$, $k = 8, 10, 12, 14$
- CCDF under $n = 64$, $k = 62, 60, 58, 56$
- Comunication efficiency between WHT-OFDM-IM and OFDM-IM

The PARP Comparison

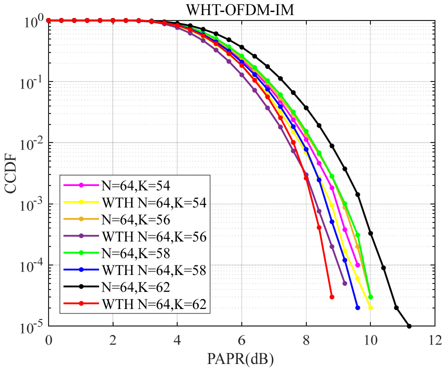
Table: The PARP Comparison

k	$PAPR_0$	$PAPR_1$
8	**5.0081**	5.6142
10	**5.1007**	5.2787
12	5.1616	**5.0162**
14	5.2042	**4.8051**

- ✓ PAPR in WHT-OFDM-IM is **2.82% lower** than OFDM-IM when $n = 16$, $k = 12$;
- ✓ PAPR in WHT-OFDM-IM is **7.67% lower** than OFDM-IM when $n = 16$, $k = 14$;

- Also, the simulation demonstrates that **the WHT-OFDM-IM can effectively reduce the high PAPR in scenarios with multiple activated subcarriers.**

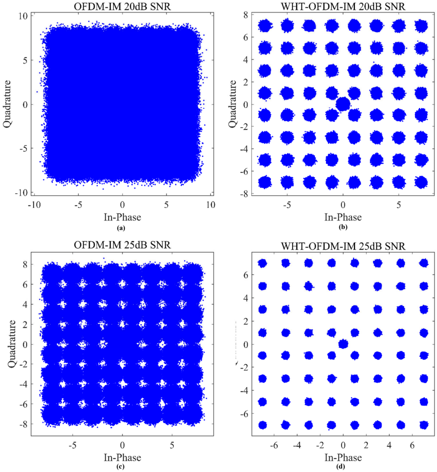
The PARP Comparison(CCDF curve)



- ✓ The PAPR of the WHT-OFDM-IM system is **lower** than that of the OFDM-IM system in this scenario;
- ✓ WHT-OFDM-IM can combat the issue of PAPR in multiple subcarrier and multiple activated subcarrier scenarios;

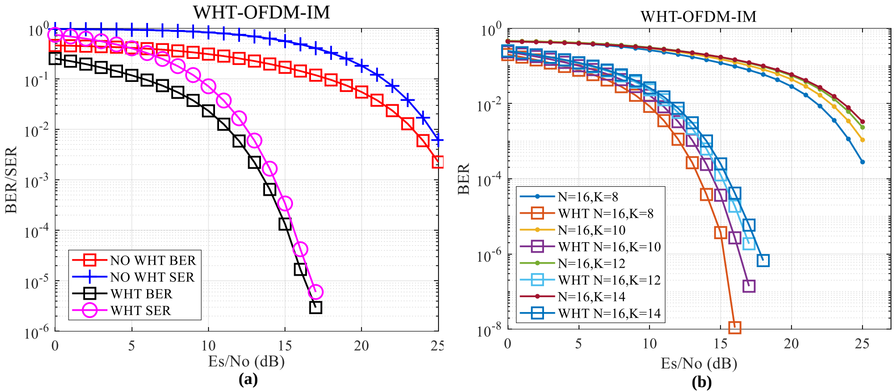
- Also, as the number of activated subcarriers increases, the signal bit rate R_b decreases, thus future research should focus on **finding an optimal balance between PAPR and signal bit rate R_b in WHT-OFDM-IM.**

Constellation of Recived Signals



- ✓ Reducing noise→WHT-OFDM-IM;
- ✓ Transmission Performance: WHT-OFDM-IM >OFDM-IM;
- ✓ With 50% of SNR, WHT-OFDM-IM reaches nearly 95% of BER.

BER & SER Simulation



- Compared to traditional OFDM-IM, WHT-OFDM-IM incurs approximately 11 dB SNR penalty when the BER is 1.0×10^{-3}.
- As the number of activated subcarriers increases, both the SER and BER will increase, which is in line with the inherent properties of OFDM-IM.

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Conclusion

- Introduce the WHT-OFDM-IM system, which integrates the WHT and OFDM-IM techniques;
- Demonstrate the high efficiency and PAPR friendliness of the proposed system for a large number of activated subcarriers.
- WHT-OFDM-IM system is capable of mitigating the cost of HPA associated with the high PAPR of OFDM-IM signals when passing through non-linear devices.
- Exhibit significantly reduced BER and SER compared to traditional OFDM-IM.

Outlook

- The results provided intriguing insights into finding an adaptive balance between PAPR and signal bit rate R_b in WHT-OFDM-IM and the next generation of wireless communication systems.

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Thank You
Q & A