OFDM with Double Spatial Modulation for Improving the Reliability of Wireless Communication

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Abstract. Orthogonal frequency division multiplexing with index modulation (OFDM-IM) has recently attracted numerous research interests, which enhances the spectral efficiency and the reliability of wireless communication by well transplanting the core idea of spatial modulation (SM) into the OFDM system such as the index of subcarrier. Due to that double spatial modulation (DSM) improves the spectral efficiency and the uncoded bit error rate (BER) as compared with SM, in this paper, a new design of OFDM with DSM (OFDM-DSM) is further investigated. Specifically, the design of the OFDM-DSM system is elaborately introduced. Based on the maximum-likelihood (ML) detector, the average bit error probability is presented. Finally, compared to conventional schemes such as OFDM, OFDM-IM, simulation results show that the OFDM-DSM system has better BER performance than other schemes over Rayleigh distribution and additive white Gaussian noise (AWGN) in wireless communication network.

Keywords: Double spatial modulation; Orthogonal frequency division multiplexing; maximum-likelihood detector.

1. Introduction
Orthogonal frequency division multiplexing with index modulation [1] (OFDM-IM), which conveys the additional information bits via the active subcarriers, satisfies the quickly increasing demand for higher data rate wireless communications systems and achieves the better performance as compared with the classical OFDM. Existing works on OFDM-IM can be divided into two categories [2-6]: reliability enhancement and spectral efficiency (SE) enhancement. In [2], by allowing the equiprobable activation of all subcarriers, OFDM-IM achieves the better BER performance. OFDM-IM with transmit diversity (OFDM-IM-TD) [3] is proposed to achieve transmit diversity through employing silent subcarriers and multiple signal constellations. In [4], OFDM-IM with the conducting of rotating and coordinate interleaving is proposed to increase the Hamming distance for the improvement of the BER performance. Further, in order to simultaneously achieve the improvement of both the spectral efficiency and the BER performance, OFDM with in-phase/quadrature index modulation (OFDM-I/Q-IM) [5], which extends the index domain to the in-phase and quadrature dimensions, is proposed to exploit the spatial domain to achieve transmit diversity.

Motivated by the work in [5], in order to achieve a higher spectral efficiency and improve the BER performance with the IM technology, we proposed a new scheme of applying the recently developed
DSM [6] technology to the OFDM system, termed as OFDM-OFDM-DSM. In OFDM-DSM, which further exploits the spatial domain for carrying more extra information bits in each subblock, the spatial gain for the frequency domain vector signal is achieved. Then, to evaluate its BER performance, based on the ML detector, the average bit error probability is derived using the union bound with assumption of the known channel estimation. Finally, simulation results using Monte Carlo show that OFDM-DSM outperforms the conventional OFDM systems and OFDM-IM system in term of BER performance.

2. System Model
Considering that the OFDM-DSM system equipped with \( N \) subcarriers employs the DSM and OFDM technologies for the transmission of information bits. The block diagram of the transmitter of OFDM-DSM is illustrated in left-hand side of Fig.1. For each OFDM block, its \( N \) subcarriers are divided into \( G = N / g \) subblocks, each of which has \( g \) subcarriers.

Through the S/P splitter, the input \( B \) information bits are divided into \( G \) groups of data streams (e.g. \( B_1, \cdots, B_G \)). With the aid of DSM technology, \( G \) groups of data streams \( B_1, \cdots, B_G \) are respectively transformed into \( G \) groups of complex spatial vector symbols \( S_1, \cdots, S_G \). Then, using \( G \) groups of \( g \) subcarriers to modulate the complex spatial vectors \( S_1, \cdots, S_G \), respectively. Especially speaking, each group of data stream \( B_i \) are further partitioned into four parts (e.g. \( I^s_i, I^s_i, I^x_i, I^x_i \)): The two parts of \( I^s_i = \log_2(M) \) , \( I^x_i = \log_2(M) \) information bits are mapped into two symbols \( s^x, \bar{s}^x \) from \( M \) -ary QAM/PSK constellation, respectively. The part of \( I^s\lambda = \log_2(g) \) information bits are used to select the \( \tau \) -th column vector \( v^\tau, \tau \in \{1, \cdots, G\} \) of the identify index matrix \( A = [v^1, v^2, \cdots, v^G] \) with \( g \times g \) dimension for the activation of one subcarrier. Similarly, The remaining part of \( I^x\lambda = \log_2(g) \) information bits are used to select the \( \lambda \) -th column vector \( \bar{v}^\lambda, \lambda \in \{1, \cdots, G\} \) of the identify index matrix \( \bar{A} = [\bar{v}^1, \bar{v}^2, \cdots, \bar{v}^G] \) with \( g \times g \) dimension for the activation of one subcarrier.

![Fig 1. System model of OFDM-DSM.](image)

With the aid of the DSM technology, a complex spatial vector \( S_x \) is obtained by the following steps.

a). A spatial vector symbol \( S_x^s \) is obtained by multiplying the resulting \( v^\tau \) by the resulting QAM/PSK symbol \( s^x \), namely \( S_x^s = s^x \cdot v^\tau \).
b). After the rotation of the resulting QAM/PSK symbol \( \tilde{s}^x \) with the angle of \( \theta \), a spatial vector symbol \( S^3_x \) is obtained by multiplying the resulting \( \mathbf{v}^x_\alpha \) by the resulting \( \tilde{s}^x \cdot e^{j\theta} \), namely \( S^3_x = \tilde{s}^x \cdot e^{j\theta} \cdot \mathbf{v}^x_\alpha \).

c). Finally, by adding the spatial vector symbol \( S^3_x \) to the spatial vector symbol \( \mathbf{v}^x_\alpha \), the complex spatial vector symbol is given by \( S_x = S^3_x + S^3_x = \tilde{s}^x \cdot \mathbf{v}^x_\alpha + \tilde{s}^x \cdot e^{j\theta} \cdot \mathbf{v}^x_\alpha \).

Thus, the complex symbol vector \( S_x \) is formed for an OFDM group having \( g \) subcarriers. Furthermore, in order to be clear the component value corresponding to each subcarrier, the \( \alpha \)-th component \( S_x(\alpha) \), \( \alpha \in \{1, \cdots, g\} \) value of the resulting \( S_x \) corresponding to the \( \alpha \)-th subcarrier has \( S_x(\gamma) \in \{0, \tilde{s}^x, \tilde{s}^x + e^{j\theta} \cdot \tilde{s}^x\} \).

After mapping \( G \) groups of information bits and then transforming into \( G \) groups of spatial vector symbols \( S_1, \cdots, S_G \) with DSM technology, concatenating these \( G \) vector symbols, it has

\[
\tilde{S}_F = [S_1, \cdots, S_G]^T = [S_1(1), S_1(2), \cdots, S_g(1), S_g(2), \cdots, S_g]^T \tag{1}
\]

which is modulated by an OFDM block with \( N \) carriers. Further, through the N-point IFFT transformation, an OFDM symbol \( \tilde{S}_T \) for \( N \) carriers for the time domain is created as

\[
\tilde{S}_T = \left[ \tilde{S}_T(1), \tilde{S}_T(2), \cdots, \tilde{S}_T(N-1), \tilde{S}_T(N) \right]^T, \tilde{S}_T = \frac{N}{\sqrt{G}} \text{IFFT} \{ \tilde{S}_F \} \tag{2}
\]

where \( \tilde{S}_F \) and \( \tilde{S}_T \) are respectively the frequency domain OFDM block and the time domain OFDM block. Note that, In order for each OFDM symbol to satisfy \( E \{ \tilde{S}_F^H \tilde{S}_F \} = N \), a normalization factor \( N/\sqrt{G} \) is considered before transmission when the IFFT algorithm is implemented. Similarly, a normalization factor \( \frac{\sqrt{G}}{N} \) is employed in the FFT algorithm at the receiver.

Then, the beginning of the OFDM symbol is appended with a cyclic prefix (CP) with these components about \( \left[ \tilde{S}_T(N-\ell+1), \cdots, \tilde{S}_T(N-1), \tilde{S}_T(N) \right]^T \), where \( \ell \) is the length of CP, length \( \ell \) of which is longer than the maximum delay spread of the multi-path transmit channel. Thus, a whole OFDM symbol can be obtained as

\[
S_{\text{OFDM-DSM}} = \left[ \tilde{S}_T(N-\ell+1), \cdots, \tilde{S}_T(N-1), \tilde{S}_T(N), \tilde{S}_T \right]^T \tag{3}
\]

Subsequently, the symbol \( S_{\text{OFDM-DSM}} \) is transmitted over a frequency-selective Rayleigh fading channel \( \mathbf{H} \), which is expressed as

\[
\mathbf{H} = [h_T(1), h_T(2), \cdots, h_T(\nu)]^T, \nu \leq \ell \tag{4}
\]
where \( h_f(v) \) obeys the channel frequency response with covariance of \( \text{CN}(1, \frac{1}{v}) \), \( v \) is the number of paths.

At the receiver, the receiver spatial symbol \( y_r \) for the time domain is given by

\[
y_r = S_{\text{OFDM-DSM}} \ast H + N.
\]  

(5)

where the symbol “ \( \ast \) ” denotes the convolution of both \( S_{\text{OFDM-DSM}} \) and \( H \).

After the removal of the CP and the \( N \)-point FFT algorithm, the symbol \( y_f \) for the frequency domain is given by

\[
y_f = \tilde{S}_{f,\text{diag}} \times \tilde{H}_f + \tilde{N}_f
\]

(6)

where \( \tilde{S}_{f,\text{diag}} = \text{diag} \left\{ S_f(1), \cdots, S_f(N) \right\} \) = \text{diag} \left\{ \left[ S_1, \cdots, S_S, \cdots, S_S \right] \right\} \), \( \tilde{H}_f = \text{FFT} \{H\} \), \( \tilde{N}_f = \text{FFT} \{N\} \), \( \tilde{N}_f \in C^{N \times 1} \), \( y_f \in C^{N \times 1} \). The channel frequency response \( \tilde{H}_f = [h_f(1), \cdots, h_f(N)]^T \in C^{N \times 1} \), each term of which follows the distribution \( \text{CN}(0, 1) \), and the zero-mean complex additive white Gaussian noise (AWGN) \( \tilde{N}_f = [\tilde{N}_f(1), \cdots, \tilde{N}_f(N)]^T \in C^{N \times 1} \), each distribution of which are \( \text{CN}(0, \sigma_f^2) \).

At the receiver, the optimum maximum-likelihood (ML) decoder is employed. Moreover, due to that an OFDM block consist of \( G \) groups of spatial vectors \( S_x \), the detective rule for the \( x \)-th group of information bits is given by

\[
[I_x^s, I_x^s, \hat{I}_x^s, \hat{I}_x^s] = \arg \min_{I_x^s, I_x^s, \hat{I}_x^s, \hat{I}_x^s} \sum_{l_x^s, l_x^s, l_x^s, l_x^s} \left[ y_{f,x} \left[ (x-1) \cdot g + \kappa \right] - \bar{S}_{f,x} \left[ (x-1) \cdot g + \kappa \right] \right] \times \left[ (x-1) \cdot g + \kappa \right] \]  

(7)

where \( I_x^s, I_x^s, \hat{I}_x^s, \hat{I}_x^s \) denote the detected spatial index bits and the constellation point index bits in the \( x \)-th group, respectively. \( y_{f,x}, \bar{S}_{f,x}, \tilde{H}_{f,x} \) denote the receiver symbol, the OFDM symbol, the response coefficient at the \( x \)-th group for the frequency domain.

3. Performance Analysis

In this section, the total number of information bits in one OFDM block and the average pairwise error probability (PEP) events within a single OFDM group are investigated.

According to the schematic of transmitter of OFDM-DSM with the DSM and OFDM technology and the entering of \( B \) bits, the total number of information bits transmitted in one OFDM-DSM symbol can be calculated as

\[
B = G \cdot \left[ 2 \cdot \log_2(L) + 2 \cdot \log_2(g) \right] \text{bits}
\]

(8)
Before the $N$-IFFT transformation, the $G$ groups of complex symbol vector $\mathbf{S}_1, \cdots, \mathbf{S}_G$ are obtained by the DSM technology. Then, after the $N$-FFT transformation, with the ML detector, the information bits $B_x$ for the $x$-th group are retrieved out in group by group of complex symbol vector $\mathbf{S}_x$.

Hence, According to the derivation of (6), the $x$-th group of the receive signal $\mathbf{y}_F$ for the frequency domain is given by

$$\mathbf{y}_{F,x} = \tilde{\mathbf{S}}_{F,x} \cdot \tilde{\mathbf{H}}_{F,x} + \tilde{\mathbf{N}}_{F,x}$$

(9)

where $\tilde{\mathbf{S}}_{F,x} = \text{diag}\left\{ [\mathbf{S}_x(1), \cdots, \mathbf{S}_x(g)]^T \right\}$, $\mathbf{y}_{F,x} \in \mathbb{C}^{g \times 1}$.

Based on the channel frequency response, the conditional PEP [6] can be given by

$$P\left( \tilde{\mathbf{S}}_{F,x} \rightarrow \hat{\mathbf{S}}_{F,x} \bigg| \tilde{\mathbf{H}}_{x} \right) = Q\left( \frac{\| \tilde{\mathbf{S}}_{F,x} - \hat{\mathbf{S}}_{F,x} \|_F^2}{2\sigma_x^2} \right)$$

(10)

where $\tilde{\mathbf{S}}_{F,x}$ is erroneously detected as $\hat{\mathbf{S}}_{F,x}$.

Then, at high SNR, the unconditional PEP [7] based (10) can be calculated as

$$P\left( \tilde{\mathbf{S}}_{F,x} \rightarrow \hat{\mathbf{S}}_{F,x} \right) = \left( \frac{\sigma_x^2}{\sigma_y^2} \right)^r \left( \prod_\xi \eta_\xi(\mathbf{B}_{F,x}) \right)^{-1} \left( \frac{4r}{12} + \frac{3r}{4} \right)$$

(11)

where $\mathbf{B}_{F,x} = \mathbf{K}_{F,x} \mathbf{A}_{F,x}$, $\mathbf{K}_{F,x} = E\left\{ \mathbf{h}_{F,x} (\mathbf{h}_{F,x})^H \right\}$, $\mathbf{A}_{F,x} = \left( \tilde{\mathbf{S}}_{F,x} - \hat{\mathbf{S}}_{F,x} \right)^H \left( \tilde{\mathbf{S}}_{F,x} - \hat{\mathbf{S}}_{F,x} \right)$, $\eta_\xi(\cdot)$ denotes the $\xi$-th non-zero eigenvalue of the matrix $\mathbf{B}_{F,x}$, $r = \text{rank}(\mathbf{B}_{F,x})$.

Therefore, the average BEP of the $x$-th OFDM group at high SNR can be given by

$$P_x \approx \eta \sum_{\tilde{\mathbf{S}}_{F,x}, \hat{\mathbf{S}}_{F,x}} \left( \frac{\sigma_x^2}{2} \right)^r \left( \prod_\xi \eta_\xi(\mathbf{B}_{F,x}) \right)^{-1} \left( \frac{4r}{12} + \frac{3r}{4} \right) e\left( \tilde{\mathbf{S}}_{F,x}, \hat{\mathbf{S}}_{F,x} \right)$$

(12)

where $\mu = \frac{1}{B_x 2^{R_x}}$, $e\left( \tilde{\mathbf{S}}_{F,x}, \hat{\mathbf{S}}_{F,x} \right)$ is the number of bit errors associated with the corresponding PEP event $B_x$.

4. Simulation Results

In this section, with the assumption of perfect channel information state and using ML detector at the receiver, the bit error ratio (BER) performances of the OFDM-DSM scheme, which is evaluated via Monte Carlo method, are presented and compared with the classical OFDM, OFDM-IM schemes. Our simulation parameters are given as: $N = 128$ subcarriers, the length of CP is $\ell = 16$, the transmit multi-path channels has $\nu = 10$. 
In Fig. 2, we compared the BER performance of different schemes at 256 bits per OFDM symbol, such as classical OFDM with 4QAM modulation, OFDM-IM using 8QAM and k=2, OFDM-DSM using 4QAM. It can be observed that the OFDM-DSM scheme achieves better BER performance with increasing SNR values. For instance, at the transmission of 256 bits, the proposed OFDM-DSM system can achieve 3 dB over OFDM, 2.5 dB over OFDM-IM, at the SNR value of 10^{-4}. Also, at the transmission of 192 bits, it can be observed that OFDM-DSM with 4QAM achieves better BER performance than OFDM-IM with 4QAM and k=2 at the region of the higher SNR, achieving gain is more significant with increasing of SNR value.

5. Conclusion
In this paper, a new design called OFDM-DSM, which combines OFDM with the DSM technology, is investigated for the improvement of the BER performance of communication. Then, the number of transmit information bits per OFDM symbol and the PEP are further analyzed and calculated. Finally, our simulation results demonstrates that the proposed OFDM-DSM improves the BER performance in comparison with the classical OFDM, OFDM-IM in the high SNR region.

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