Performance analysis of OFDM-IM scheme under STO and CFO

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Article Info

Article history:

Received Aug 26, 2020
Revised Dec 11, 2020
Accepted Jan 13, 2021

Keywords:

CFO
Frequency-selective channel
ICI
OFDM-IM
STO

ABSTRACT

In this letter, performance analysis of orthogonal frequency division multiplexing with index modulation (OFDM-IM) is presented in term of bit error rate (BERs). The analysis considers its performance under two impairments, symbol time offset (STO) and carrier frequency offset (CFO) in frequency-selective fading channel. As orthogonal multicarrier system, OFDM-IM is subject to both inter-symbol interference (ISI) and inter-carrier interference (ICI) in a frequency-selective fading channel. OFDM-IM is a new multicarrier communication system, where the active subcarriers indices are used to carry additional bits of information. In general, in the previous existing works, OFDM-IM are evaluated only for near-ideal communication scenarios by only incorporating the CFO factor. In this work, the OFDM-IM performance is investigated and compared with conventional OFDM in the presence of two impairments, STO and CFO. Simulation results show that OFDM-IM outperforms the conventional OFDM with the presence of STO and CFO, especially at high SNR areas.

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1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is a multicarrier transmission that excels in handling inter-symbol interference (ISI) caused by multipath fading. This allows high speed transmission so that this technique has been adopted in many wireless communication standards [1-8]. The next OFDM development is OFDM with index modulation (OFDM-IM). OFDM-IM is a new OFDM scheme where information transmission is carried out by the M-ary signal constellation and also using a subcarrier index. The subcarrier index is activated according to the relevant information bits [9-11]. By adjusting the number of active subcarriers in the OFDM-IM scheme, this technique provides an interesting trade-off between performance and spectral efficiency [9].

The use of index modulation techniques has also been expanded to direct-sequence spread spectrum (DSSS) modulation techniques to thrift spectrums efficiency and to achieve higher data rates with lower complexity [12, 13]. Even so, as a multicarrier systems, which is alike to conventional OFDM; where performance is affected by a symbol time offset (STO) [2, 14, 15] and carrier frequency offset (CFO) [2, 16-21]. In particular, OFDM-IM is even very susceptible to CFO as indicated by [22-24].

Wide-ranging of analysis and simulation studies were discussed in [2, 14, 15, 20, 21] to describing the effects of STO and CFO in conventional OFDM systems. In [20], studied the impact of STO and CFO on OFDM performance under the AWGN channel. In [21], the authors reproduce the approximation method [20] into a frequency-selective fading channel for some errors due to CFO that improves work assessment (BERs). In [2, 14, 15], STO causes ISI and inter-carrier interference (ICI) for the frequency-selective fading channel. Moreover, ICI can significantly degrade the channel estimation performance [25-29].

Since OFDM-IM adopts block-based modulation, while existing contributions assume freedom from the OFDM subcarriers, it may not be directly applicable to the OFDM-IM scheme. The authors [22] examined the OFDM-IM signal-to-interference ratio (SIR) under Doppler spread that caused CFO to deploy scenarios under a simplified AWGN channel rather than a more practical frequency-selective fading channel. The authors [23] derived analysis and simulation of the OFDM-IM scheme's performance under ICI conditions in the frequency-selective fading channel. The authors [24] analyzed and compared the OFDM-IM scheme's performance in conditions under ICI and in-phase/quadrature (IQ) imbalance.

In this letter, we simulate the OFDM-IM scheme's performance under STO and CFO, where STO can also cause ISI and ICI in a frequency-selective fading channel. Apart from STO, ICI can also be caused by CFO. Even though the current OFDM-IM scheme is evaluated and compared from the perspective of spectrums efficiency, CFO, and IQ; error performances of the OFDM-IM scheme under STO is yet unknown. Hence, this letter aims to analyze and compare the OFDM-IM scheme with conventional OFDM under the influence of STO and CFO in a frequency-selective Rayleigh fading channel.

The rest of this letter is arranged as follows: Section 2 provides a signal model for OFDM-IM scheme. Furthermore, mathematical models of STO and CFO are concisely discussed. Section 3 provides related work and section 4 provides simulation results and discussions. Finally, section 5 concludes the letter.

2. OFDM-IM SIGNAL MODEL

In this section, the OFDM-IM scheme is described first. After that, a mathematical model of the signal received under STO and CFO will be given.

2.1. OFDM-IM scheme

In the conventional OFDM scheme, several N subcarriers are used to transmit information from transmitter to receiver, which operates in the frequency-selective Rayleigh fading channel. The number of bits of information carried is $t = N \times log_2(M)$, where M denotes the modulation order. X frequency domain signals are obtained after the information bits are mapped to the subcarrier through a serial to parallel converter process. After that, inverse fast fourier transform (IFFT) is used on X to get OFDM signal in the time domain as (1).

$$x(n) = \sum_{k=0}^{N-1} X(k) e^{\frac{j2\pi nk}{N}},\ 0 \leq n \leq N-1. \quad (1)$$

The transmitted signal is sent via the frequency-selective Rayleigh fading channel as (2).

$$y(n) = \sum_{l=0}^{L-1} x(n-l)h(l) + w(n), \quad (2)$$

with $h(l)$ represents the channel response, L denotes the number of channel paths, and $w(n)$ represents complex Gaussian noise with zero mean and variance σ_0^2. At the receiver, the relationship between input-output in the frequency domain for the k-th subcarrier can be described as (3).

$$Y(k) = X(k)H(k) + W(k), \quad (3)$$

with $H(k)$ and $W(k)$ denote the frequency response of channel $h(n)$ and noise $w(n)$, respectively. To prevent ISI in the OFDM scheme, a cycle prefix (CP) with length of C_p is added on $x(n)$.

In contrast to the conventional OFDM, OFDM-IM carries data information on the modulated subcarrier and the active subcarrier indices. In OFDM-IM, the OFDM block of size N is divided into G subblocks with $m = N/G$ subcarriers per subblock. The number of subcarriers is assigned some q from m per subblock. The active subcarriers' indices carry $p1 = \lfloor log_2 C(m, q) \rfloor$ bits, where $C(m, q)$ and $\lfloor . \rfloor$ denote the binomial coefficient and floor function, respectively. Some $p2 = q \times log_2(M)$ bits are converted to M-ary symbols s_i and are carried by active subcarriers, where $s_i \in [s_1, s_2, .., s_M]$. Therefore, the total number of data bits sent in one OFDM-IM block is as (4).

$$t = Gp = G(p1 + p2), \quad (4)$$

where $p = p1 + p2$ is the number of bits per OFDM-IM subblock. Figure 1 shows the block diagram of OFDM-IM transmitter.

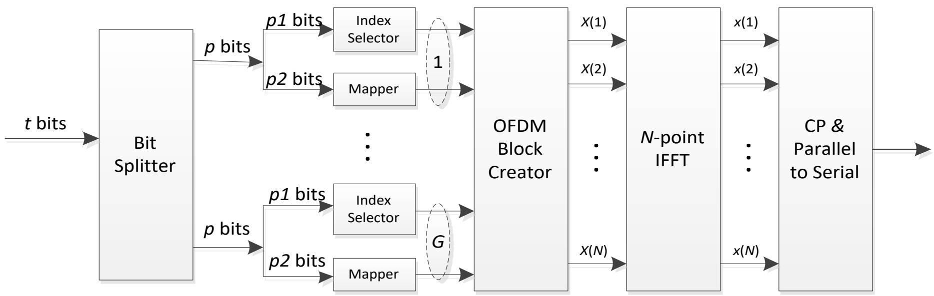

Figure 1. Block diagram of the OFDM-IM transmitter [9]

2.2. STO model

In the OFDM-IM, just like the conventional OFDM, IFFT and FFT functions are needed for modulation and demodulation in each transmitter and receiver, respectively. To obtain one block of OFDM-IM symbol with several N samples in the receiver, it is necessary to have a proper samples of the transmitted signal for the duration of the OFDM-IM symbol. Therefore, time synchronization is required to obtain a proper samples of each OFDM-IM symbol, where in this process has also discarded the CP. Hence, the signal received in the time domain under STO can be written (5).

$$\hat{y}(n) = y(n - \delta), \quad (5)$$

where δ denotes the STO. The frequency response of $\hat{y}(n)$ equals [2].

$$\hat{Y}(k) = \frac{N-\delta}{N} X(i) e^{\frac{j2\pi i\delta}{N}} + \sum_{i=0, i\neq k}^{N-1} X(i)\, e^{\frac{j2\pi i\delta}{N}} \sum_{n=0}^{N-1-\delta} e^{\frac{j2\pi(i-k)n}{N}} + \frac{1}{N} \sum_{i=0}^{N-1} X_l(i)\, e^{\frac{j2\pi i(2\delta - C_p)/N}{N}} \sum_{n=N-\delta}^{N-1} e^{j2\pi(i-k)n/N}, \quad (6)$$

where:

$$\sum_{n=0}^{N-1-\delta} e^{\frac{j2\pi(i-k)n}{N}} = e^{j\pi(i-k)\frac{N-1-\delta}{N}} . \frac{\sin(\frac{(N-\delta)\pi(k-i)}{N})}{\sin(\frac{\pi(k-i)}{N})} = \begin{cases} N - \delta & \text{for } i = k \\ Nonzero & \text{for } i \neq k \end{cases},$$

with $i, k \in \{0, 1, \dots, N - 1\}$. The second term in (6) correlate with ICI, which states that the orthogonality has been ruined. In the third term in (6), it is also clear that the received signal exist ISI (of the OFDM symbol in front of it (X_l)).

2.3. CFO model

CFO is generally caused by two types of interference [17], the first is the phase noise caused by instability of the carrier signal generators used at the transmitter and receiver. This phase noise can be modeled by a zero-mean Wiener random process as shown in [18, 19]. The second is CFO, which is caused by the Doppler frequency. Hence, the signal received in the time domain under CFO can be written as (7).

$$\hat{y}(n) = y(n) e^{\frac{j2\pi n\varepsilon}{N}}, \quad (7)$$

where ε denotes normalized CFO (NCFO) to subcarrier spacing. The frequency response of $\hat{y}(n)$ equals [2].

$$\hat{Y}(k) = \frac{\sin(\pi\varepsilon)}{N sin\left(\frac{\pi\varepsilon}{N}\right)} e^{\frac{j\pi\varepsilon(N-1)}{N}} H(k)X(k) + I(k) + W(k), \quad (8)$$

where:

$$I(k) = e^{\frac{j\pi\varepsilon(N-1)}{N}} \sum_{i=0, i\neq k}^{N-1} \frac{\sin(\pi(i-k)+\varepsilon))}{N sin(\pi(i-k+\varepsilon)/N)} H(i)X(i)\, e^{j\pi(i-k)(N-1)/N},$$

The first term in (8) denotes the amplitude and phase distortion of the k-th subcarrier frequency component due to CFO. The second term ($I(k)$) in (8) denotes the ICI from other subcarriers into the k-th subcarrier frequency component. In this situation, the orthogonality among subcarrier frequency components is not preserve any more due to the CFO.

3. RELATED WORK

The authors in [22] examined the OFDM-IM signal-to-interference ratio (SIR) under Doppler spread that caused CFO to deploy scenarios under AWGN channel. It was found that the theoretical values and simulation results are almost the same, and the SIR performance for OFDM-IM modulation is around 3 dB better than OFDM modulation. In [23], the authors derived analysis and simulation of the OFDM-IM scheme's performance in conditions under ICI in the frequency-selective fading channel. The authors in [23] proposed a different approach on the influence of ICI on OFDM-IM based on subblocks (the intra-subblock and the inter-subblocks) and found that OFDM-IM outperformed conventional OFDM with CFO. In [24], the authors analyzed and compared the OFDM-IM scheme's performance with other multicarrier scheme in conditions under ICI and IQ imbalance. They found that OFDM with generalized IM (OFDM-GIM) offers the highest spectrums efficiency, being the most susceptible to IQ effects. OFDM with subcarrier number modulation (OFDM-SNM) offers worse BERs performance than OFDM-IM under the imbalance of CFO and IQ due to sequential subcarrier activation.

4. SIMULATION RESULTS AND DISCUSSION

The performance of the OFDM-IM and conventional OFDM systems was investigated under the influence of STO and CFO. The simulation parameters are given in Table 1. For OFDM-IM, the number subcarriers per subblock (m) is set to 4, so that $G = N/4$, active subcarriers used per subblock (q) is set to 2, and maximum likelihood detector [9] is used for active subcarriers detection. The parameter of STO $=$ 0 indicates the correct arrival time of the OFDM/OFDM-IM symbol.

Table 1. The simulation parameters

No.	Parameter	Values
1.	Channel model	Vehicular B [30]
2.	Number of FFT (N)	2048
3.	C_p	220
4.	Data modulation	4-quadrature amplitude modulation (4-QAM)
5.	Number of bit per Symbol (t)	3072
6.	Sampling rate	0.1 μs
7.	STO (δ)	$0, -100, 10$
8.	NCFO (ε)	$0.04, 0.08, 0.12$
9.	Number of symbol per simulation	5000

We set the STO distance for the STO parameters before the correct arrival time to be much greater than the STO after the correct arrival time. This is done to ensure the STO before the OFDM/OFDM-IM symbol's correct arrival time contains ISI from the previous OFDM symbol; since the STO before the correct arrival time of the OFDM/OFDM-IM symbol is in the CP areas. We use the same training symbol for channel estimation for multicarrier systems generated from real pseudo-noise sequence placed in even subcarriers and give zero values for odd subcarriers. The Least Squared algorithm [2] is used for the channel estimation.

In Figure 2 shows the results of the conventional OFDM and the OFDM-IM simulations with the value of $NCFO = 0.04$. The OFDM-IM has better performance than the conventional OFDM at $STO = 10$, while at STO $= 0$ and $STO = -100$, the conventional OFDM performance is slightly better than the OFDM-IM. This shows that the OFDM-IM is more resistant to STO interference, especially the STOs greater than 0. The STOs in this area are more significant, causing ISI and ICI than STOs smaller than 0 (protected by CP).

In Figure 3, the results of the conventional OFDM and the OFDM-IM simulations with the value of $NCFO = 0.08$. OFDM-IM has better performance than conventional OFDM on all tested STOs, namely $STO = 10$, $STO = -100$, and $STO = 0$, especially at high signal-to-noise ratio (SNR) (SNR ≥ 20 dB).

Figure 4 shows the results of the conventional OFDM and OFDM-IM simulations with the value of $NCFO = 0.12$. OFDM-IM also performs better than conventional OFDM on all tested STOs, namely $STO = 10$, $STO = -100$, and $STO = 0$, especially at high SNR (SNR ≥ 15 dB). This shows that OFDM-IM is more resistant against ICI interference caused by CFO, where the more significant the CFO, the performance of OFDM-IM is better than conventional OFDM. This is because the number of subcarriers used (modulated subcarriers) on OFDM-IM is smaller than conventional OFDM with the same number of bits transmitted. Note that the BERs results are obtained without STO and CFO compensation in the receiver.

From the test results on the Vehicular B [30] channel, where this channel is commonly used for modeling mobile communications, it can be concluded that STO can cause ISI and ICI, especially at STO > 0. Likewise, with the CFO, which worsens the ICI. The presence of ISI and ICI can reduce the performance in both conventional OFDM and OFDM-IM systems. From the performance evaluation results, it was found that OFDM-IM had better performance than conventional OFDM with the presence of STO and CFO, especially at high SNR areas (SNR ≥ 15 dB). However, at low SNR, the detection of active subcarriers on OFDM-IM experiences an error so that the bit error rate increases at low SNR. Therefore, more accurate detection of active subcarriers is needed to improve OFDM-IM performance, especially at low SNR. This study does not yet involve IQ imbalance effects, so future studies may involve the effects of IQ imbalance together with the effects of STO and CFO on the OFDM-IM scheme.

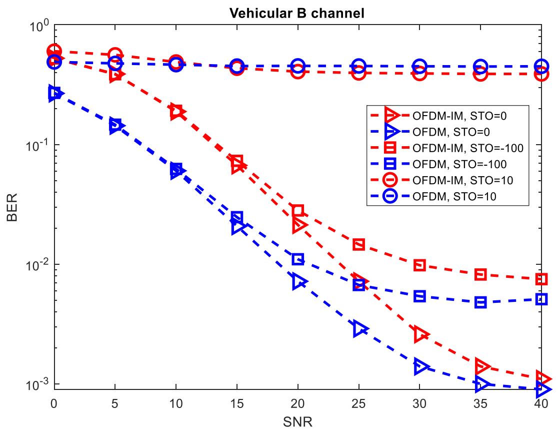

Figure 2. Comparison of BERs of OFDM-IM and conventional OFDM with NCFO=0.04

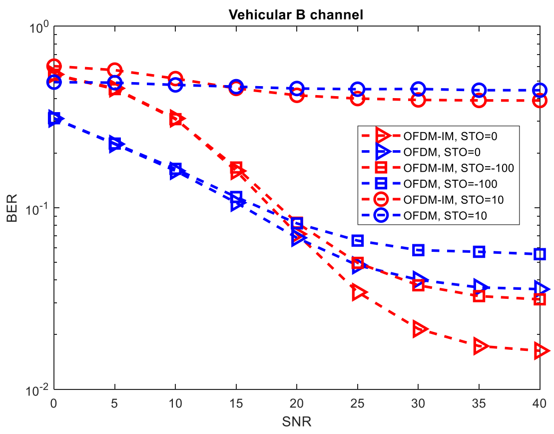

Figure 3. Comparison of BERs of OFDM-IM and conventional OFDM with NCFO=0.08

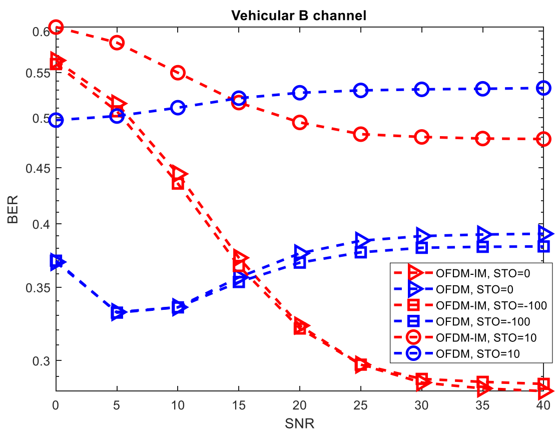

Figure 4. Comparison of BERs of OFDM-IM and conventional OFDM with NCFO=0.12

5. CONCLUSION

In this letter, we have provided an analysis and computer simulations of the OFDM-IM disturbances caused by STO and CFO compared with the conventional OFDM, where STO causes ISI and ICI, and CFO also causes ICI. The simulation results show that the OFDM-IM performance is better than the conventional

OFDM in high STO and CFO conditions and in the high frequency-selective Rayleigh fading channel, especially in high SNR areas (SNR ≥15 dB). Therefore, OFDM-IM is suitable for high data rates communications and high mobility and spectrum allocation, which is more flexible than conventional OFDM.

ACKNOWLEDGEMENTS

The authors thank the editors and anonymous reviewers for their comments and suggestions which have been very helpful in improving the grade of this letter, and we also thank to the Indonesia Endowment Fund for Education (LPDP) for their endorsement to our works in this research.

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