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BER Performance Evaluation of OFDM-IM exploiting all Possible SAPs with Subcarriers Interleaving under Rayleigh Fading Channel

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Abstract-Orthogonal Frequency Division Multiplexing with Index Modulation (OFDM-IM) has been recently developed based on OFDM to reduce the amount of required transmitted power. In addition to the robustness against multipath fading, OFDM-IM has better energy efficiency and BER performance than OFDM. A source of error in OFDM-IM is that it uses a subset of the all possible subcarrier activation patterns (SAPs). A latest modification is the OFDM-IMA, which used a modified data loading scheme and overcomes this problem by employing all of the possible SAPs in data transmission. In this paper, it is proposed to use OFDM-IMA with subcarrier-level interleaving to improve the system performance under multipath Rayleigh fading channel. The results of computer simulation show that the proposed scheme achieves significant BER improvement with respect to OFDM-IM.

Keywords: **OFDM, OFDM-IM, BER, Interleaving, Multipath Rayleigh fading.**

I. INTRODUCTION

Green communication systems are one of the outcomes of the rapid development in the field of wireless communication systems. Green communications improve the reliability and reduce power consumption. However, due to its many advantages, the well-known multicarrier communication technique known as Orthogonal Frequency Division Multiplexing (OFDM) has been widely used and adopted in many standard communication systems such as WiFi, WiMax, DVB, …etc. Then, the adaptation of multicarrier transmission to meet the requirements of green communications became an attractive research field. OFDM with index modulation (OFDM-IM) is a recent modification to the traditional OFDM, originally developed to reduce the amount of transmitted power. The OFDM-IM is robust against multipath fading due to the division of a singlewide bandwidth into several sub bands that undergo flat fading. Most importantly, it is efficient in power consumption with respect to OFDM since it uses a limited number of subcarriers to transmit data. The OFDM-IM scheme provides an interesting trade-off among system complexity, spectral efficiency, energy efficiency and BER performance by the change the number of active subcarriers [1].

The idea of subcarrier index modulation (SIM) was proposed for the first time in [2]. The proposed system is referred to as SIM-OFDM. It activates a subset of the available subcarriers to transmit constellation M-ary symbols while the rest of the subcarriers are turned off. It makes use of the on-off keying (OOK) nature of the subcarrier indices to send information. The SIM-OFDM achieves a BER performance enhancement conventional OFDM by exploiting suitable power allocation policies. However, the SIM-OFDM suffers from the problem of bit error propagation which could lead to significant error bursts [2].

The Enhanced Subcarrier Index Modulation (ESIM-OFDM) is then proposed in [3] involving a modification to the way of subcarrier activation to avoid bit error propagation. The subcarriers are dealt with as pairs of opposite states, and the activation is controlled by a data stream called B_{OOK}. That is, whenever a "1" is encountered in B_{OOK}, then the first carrier of the pair is set as active and the second as passive, and vice versa for a "0".

Next in [1] a generalization to the ESIM-OFDM is proposed that allows the activation of k subcarriers out of a sub block of n subcarriers. The proposed technique is called OFDM-IM. It is shown that the error performance of the OFDM-IM scheme is significantly better than that of classical OFDM due to the bits transmitted in the spatial domain. By controlling the number of active carriers, the OFDM-IM provides an interesting trade-off among complexity, spectral efficiency and BER performance. The BER improvement of OFDM-IM is at the expense of a reduction in the spectral efficiency. Therefore, many works have been done to improve the spectral efficiency of OFDM-IM. In [4], sub block interleaving is proposed to be used with OFDM-IM in vehicular communications. It is shown that interleaved subcarrier grouping can improve the spectral efficiency and provide high reliability communication. Then, a generalized form for the OFDM-IM is proposed in [5] to improve the spectral efficiency. In this technique, the number of active subcarriers in a sub block is variable such that depending on the input binary data string, different numbers of active subcarriers are assigned to carry constellation symbols in each sub block. As a result, the spectral efficiency of this approach is higher than that of OFDM-IM.

However, a common feature in all versions of OFDM-IM, is that the number of subcarrier activation patterns (SAPs) used to transmit data is less than the total number of all possible SAPs. Then, due to channel impairments and detection errors at the receiver, there is a possibility to receive unused SAPs which can cause errors in the received data. In [6],a new scheme is proposed to exploit all of the

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possible SAPs to transmit data and then to avoid detecting unused SAPs at the receiver. It is shown that the system employing all possible SAPs, OFDM-IMA, achieves an improvement in BER performance with respect to classical OFDM-IM when tested over an additive white Gaussian noise (AWGN) channel.

In this paper, the BER performance of the OFDM-IMA under Rayleigh multipath fading channel is investigated. It is proposed to use OFDM-IMA with subcarrier-level interleaving rather than sub block-level interleaving presented in the literature. The BER performance of the proposed system is evaluated by computer simulation under different realistic outdoor Rayleigh multipath fading scenarios.

The rest of paper is organized as follows. In Section II, a detailed description to the dominant parameters of the Rayleigh multipath fading channel is given. Then, the mathematical model of the OFDM-IM system is described in Section III. In Section IV, the proposed system is presented. Computer simulation and the BER performance of the tested systems are presented in Section V. Finally, concluding remarks are given in section VI.

II. RAYLEIGH FADING CHANNEL

Signal fading refers to the variation of signal levels due to the constructive and destructive interference from multiple signal paths. Multipath is a propagation phenomenon where radio signals reach the receiving antenna through two or more paths. Signals arriving to the receiver along different paths will encounter different attenuation values and delays. Multipath propagation occurs due to many reasons including atmospheric ducting, ionospheric reflection and refraction, and reflection from water bodies and terrestrial objects such as mountains and buildings. In digital radio communications multipath can cause errors and then affects the quality of communication. Multipath fading in wireless communication systems is commonly modeled by Rayleigh and Rician distributions [7] [8].

When there are multiple propagation paths, each path has a propagation delay and an attenuation factor. The received signal may be expressed as follows

$$x(t) = \sum_n \alpha_n(t)\delta[t - \tau_n(t)] \qquad (1)$$

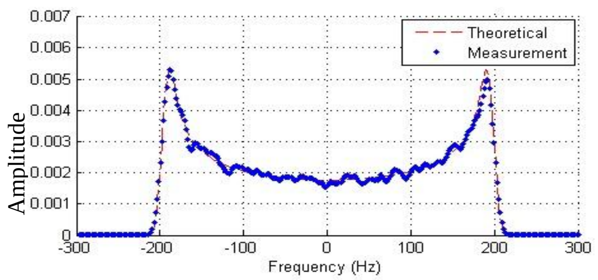
Where, $\alpha_n(t)$and $\tau_n(t)$ are the attenuation factor and the propagation delay of the nth path [9].
Rayleigh fading channel is a useful model of the real-world phenomena when there is no line of site component present but only have indirect paths in wireless communications. These phenomena include multipath scattering effects, time dispersion, and Doppler shifts that arise from relative motion between the transmitter and receiver. There are several shapes related to power spectral distribution of the Doppler spreading applied to the signal such as Jakes, Flat and Gaussian Doppler spectra. Each Doppler spectrum is suitable to model a specific environment. That is, the Jakes Doppler spectrum is used for outdoor vehicular environment and Flat Doppler spectrum for both pedestrian outdoor and indoor environments. Figure 1shows the theoretical and measured (for realistic channel parameters) shapes of these Doppler spectra. The envelope of the received signal is statistically described by a Rayleigh probability density function given by

$$P(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} & 0 \le r \le \infty \\ 0 & r < 0 \end{cases} \qquad (2)$$

Where r is the envelope amplitude of the received signal and σ is the rms value of the received signal before envelope detection and σ^2 is the time-average power of the received signal [10][11]. Doppler shift is the change in frequency of the received signal due to the motion of the transmitter or receiver or both. The amount of Doppler shift depends on the relative velocity of the transmitter or receiver in case of one station moving, angle of arrival and the carrier frequency. Doppler shift (f_d) is defined as

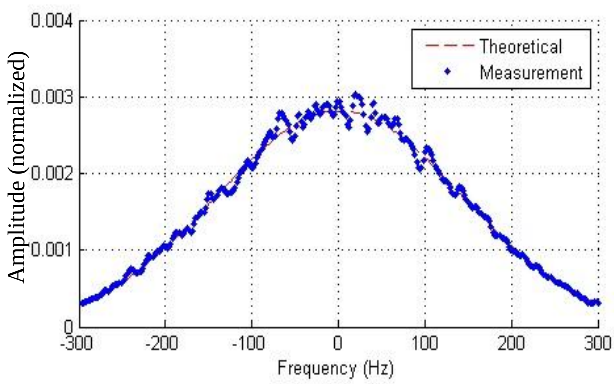
$$f_d = \frac{v * f_c}{c} * \cos(\theta) \qquad (3)$$

Where v is the velocity,f_c is the carrier frequency, and$\theta$is angle of arrival and C is speed of light. The value of Doppler shift is directly proportional to velocity and $\cos(\theta)$.The maximum Doppler shift happens when $\theta = 0°$ or $180°$. The Doppler shift translates the frequency of the received signal carrier by($f_c + f_d$) when the angle is less than 90° or ($f_c - f_d$) when the angle is more than 90°, where θranges from 0° to 180° [7][12].



(a) Jakes Doppler spectrum

(b) C



(b) Gaussian Doppler spectrum

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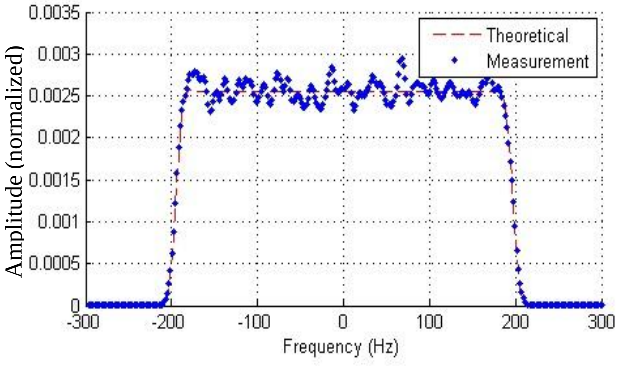

(c) Flat Doppler spectrum

Fig. (1) Doppler Spectra

III. OFDM-IM SYSTEM

The block diagram of an OFDM-IM system is presented in Fig. (2).Basically, OFDM-IM divides an OFDM block of N subcarriers into g sub blocks. For each sub block, only k out of n subcarriers are employed to carry M-QAM constellation symbols. There are a total of $C(n,k)$ $(= n!/((n-k)!\,k!))$ possible SAPs. The data stream is segmented into groups of bits, each group is mapped to a sub block by splitting a group of bits into two parts, one part is used to select the activation pattern of the subcarriers and the other part of information is modulated on the active subcarriers. The sub blocks are then combined into one block and forwarded to the inverse fast Fourier transform (IFFT) and then transmitted [1].

However, for a block of information of m bits entering the OFDM-IM transmitter, it is split into g groups of p bits, where$p = p_1 + p_2$. Each group of $p$bits is mapped to an OFDM sub block of length n subcarriers, the segment of p_1 bits used to select the SAP, where $p_1 = \lfloor log_2(C(n,k)) \rfloor$ and the $\lfloor . \rfloor$ is the greatest lower integer operator. Then, each active subcarrier within a sub block is modulated by an M-QAM symbol leading to the modulation of p_2 bits to the k active subcarriers of a sub block, where $p_2 = k\ log_2 M$. Referring to Fig. 2, in this case the data segment assigned to a sub block is $m = 12$bits. The total number of subcarriers is$N = 8$, with $n = 4$ and $k = 2$ which produce two sub blocks (g=2)with two active subcarriers per sub block. The number of used subcarrier activation patterns is 4 out of 6 available SAPs. Therefore, $p_1 = 2$ bits are mapped to a SAP, and $p_2 = 4$ bits are modulated to a subblock when $M = 4$.

It worth mentioning that the OFDM-IM uses only2^{p1} out of the total number of possible available SAPs,$C(n,k)$. There are$C(n,k) - 2^{p1}$ wasted SAPs. This causes unused SAPs to be detected at the receiver and leads to incorrect subblock information demapping. However, this error possibility is cancelled by the latest yet development of OFDM-IM called OFDM-IMA where all of the possible SAPs are used to transmit data.

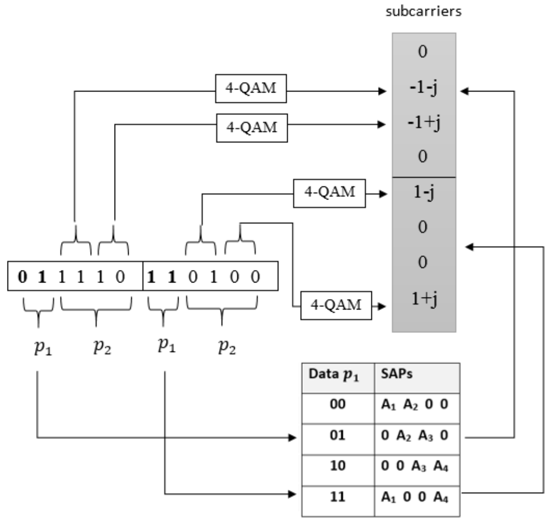

Fig. (2) OFDM-IM transmitter diagram with $N = 8,\ g = 2, n = 4$ and $k = 2$

IV. PROPOSED SYSTEM

In this paper, it is proposed to use OFDM-IMA together with subcarrier-level interleaving for communications under multipath Rayleigh fading environment. The aim is to get rid of the probability of receiving unused SAPs and improve the BER performance of the system.

Generally, the use of all SAPs is achieved by relaxing the number of data bits that are used to select the SAPs from being fixed to p_1, as in OFDM-IM. In OFDM-IMA, data segments of p_1 or $p_1 + 1$ are used, refer to [6] for more details. However, for the two systems to be equivalent in terms of spectral efficiency, then the total number of bits assigned to a subblock must be kept p bits. Then in OFDM-IMA, the bits used to modulate the active subcarriers may be p_2 or $p_2 - 1$. The latter is implemented by using a lower order modulation in one of the active subcarriers within the specific subblock. For example, when $N = 8,\ g = 2,\ n = 4, k = 2$ and $M = 16$, the table of data-to-SAP mapping is presented in Table 1,which uses all possible SAPs.

Table 1 SAPs of proposed scheme

Data p_1	SAPs
00	$A_1 A_2$ 0 0
01	0 $A_2 A_3$ 0
010	0 0 A_3 A_4
011	A_1 0 0 A_4
110	A_1 0 A_3 0
111	0 A_2 0 A_4

When $p_1 = 2$ bits, each one of the two active subcarriers is modulated by a 16-QAM symbol, which means that$p_2 = 8$ bits and $p = 10$ bits. Whereas in the case of$p_1 = 3$ bits, the first active subcarrier is modulated by a

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16-QAM symbol and the second active subcarrier is modulated by an 8-QAM symbol, making $p_2 = 7$ bits and again $p = 10$ bits.

Moreover, the proposed system operates in an outdoor wireless environment which is simulated by Matlab Rayleigh fading channel with Jakes Doppler spectrum. Then, in addition to OFDM-IMA, the proposed scheme involves using a subcarrier-level interleaving, rather than subblock-level interleaving, to better reduce the correlation between fading coefficients of the channel at adjacent sub bands.

V. SIMULATION AND RESULTS

The proposed system is simulated using Matlab. For performance comparison, the OFDM-IM system is also simulated. The general simulation parameters are shown in Table 2.

The BER performance of the simulated systems is evaluated under the outdoor environment, which is simulated as Rayleigh channel with Jakes Doppler spectrum and $60°$ average angle of arrival with five signal propagation paths having a path gain vector of[0 -9.3 -14 -18 -19.4] dB and $400\ ns$ maximum delay spread. The results are shown in Figs (3) and (4).

Table 2 General simulation parameters

Parameters	Value
Number of total subcarriers	64
Number of data subcarriers	48
Number of pilots subcarriers	4
Carrier frequency	2.4 GHz
Subcarrier frequency spacing	312.5 kHz
FFT Points	64
Guard interval (GI)	0.8 μsec
Symbol interval including GI	4 μsec
Size of subblock n	4
Order of QAM modulation (M)	4 and 8

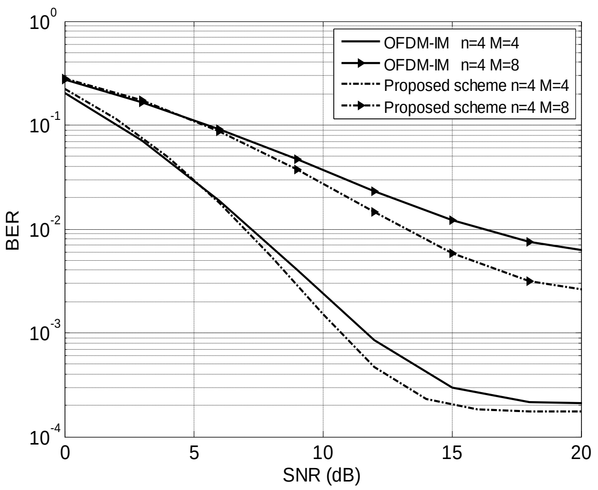

Fig. (3) BER Performance of proposed scheme and OFDM-IM at 50 km/h speed

Generally in all of the tested cases, the proposed scheme shows a clear improvement with respect to OFDM-IM. The performance of the proposed system and OFDM-IM degrades under the severe channel condition (150 km/h) with respect to the moderate channel condition (50 km/h), but the relative behavior is preserved. That is for $M = 4$ at a BER of $5 \times 10^{-4}$the proposed scheme achieves an advantage in SNR of about 1.5dB with respect to OFDM-IM in the case of 50 km/h speed. Whereas, at a BER of 10^{-2},it achieves2.7 dB in the case of 50 km/h speed and $M = 8$. In the case of 150 km/h speed, the proposed scheme for $M = 4$ achieves 1.3 dB advantage over OFDM-IM at BER of 3×10^{-3} and it achieves 2.2 dB at BER of $2 \times 10^{-2}$for$M = 8$.

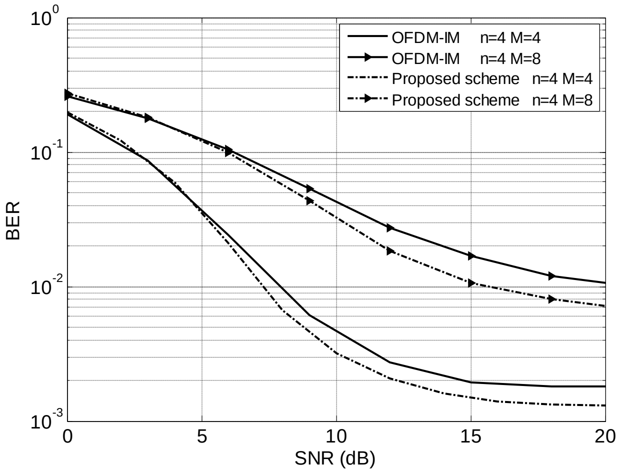

Fig. (4) BER Performance of proposed scheme and OFDM-IM at 150 km/h speed

VI. CONCLUSION

In this work, the application of the yet latest modification of OFDM-IM, referred to as OFDM-IMA, is extended to wireless outdoor environments. It is proposed to use OFDM-IMA with subcarrier-level interleaving to improve the BER performance of OFDM-IM. The BER performance of the proposed scheme and the OFDM-IM is evaluated by computer simulation under simulated outdoor communication scenarios with realistic channel parameters. The results show the significant superiority of the proposed scheme with respect to the tested traditional OFDM-IM system in terms of BER performance.

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