Index Modulation-Aided Orthogonal Frequency Division Multiplexing and Its Applications

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Abstract   The novel technique of using the indices of the active subcarriers of orthogonal frequency division multiplexing (OFDM) to transmit data, called index modulation-aided OFDM or OFDM-IM is a recently proposed multicarrier transmission technique for achieving high spectral and energy efficiency in the forthcoming fifth generation (5G) networks. In this paper, the principle of operation of OFDM-IM, its dual mode counterpart DM-OFDM and the OFDM with multiple constellation (OFDM-MC) schemes were firstly investigated. We review a number of the recent promising advances in these technologies. Their implementations in various applications such as visible light communication (VLC) and Asynchronous mMTC Networks etc are then introduced. Finally, their various performances are compared with each other to authenticate their ability for enhancing the energy efficiency of various physical (PHY) layer technologies. We see that, at the BER of 10^{-5}, the SNR of precoded OFDM-MC is 33 dB while that of precoded DM-OFDM is 37 dB and that of precoded OFDM-IM is 38 dB, a clear 4 dB to 5 dB advantage. This advantage is due to precoded OFDM-MC diversity order of 4 compared to the two other schemes with diversity order of 2.

Keywords   OFDM-IM, DM-OFDM, OFDM-MC, 5G, MIMO, Index Modulation

1. Introduction

A lot of efforts has been put into ensuring the proposed fifth generation 5G wireless networks offers a 1000 times network capacity increase compared to the current fourth generation 4G LTE-A via the use of new emerging physical (PHY) layer technologies such as massive multiple input multiple output (massive MIMO) [1,2], massive machine type communication (mMTC) and the visible light communication (VLC) etc. However, one of the challenges still facing the research community is the required energy efficiency of the 5G networks that seems to decrease as the base station (BS) antenna and carrier frequency increases leading to increase in BS static power [3]. Index modulation (IM) is a newly up-and-coming concept, which is a type of modulation techniques that uses the index(es) of several medium to modulate information bits. Such medium are either actual, such as antennas and frequency carriers, or virtual, such as space-time matrix, antenna activation order, or virtual parallel channels. The information bits carried by the index(es) usually uses minute or no power, thereby

making IM techniques a competitive energy efficient (EE) candidate for the 5G wireless networks [4]. The application of IM to the spatial domain in MIMO called spatial modulation (SM) is an IM technique where the incoming data bit to be transmitted is divided into two parts. One part is use to modulate the phase and amplitude of the carrier signal and the other data part is used to select the index (I) of the activated antenna that transmit the matching modulated signal [5].

In classical orthogonal frequency division multiplexing (OFDM), all the N_F subcarriers are used to transmit $N_F \log_2(M)$ bits at a channel use where M is the selected modulation order such as M-PSK, M-QAM etc. However, in OFDM using index modulation, called index-modulation orthogonal frequency division multiplexing (OFDM-IM), the subcarriers of an OFDM are grouped such that the indices of the activated subcarriers of the groups are utilized to carry additional information. This has an attractive advantage over legacy OFDM which is used in many current state-of-the-art cellular systems [5]. Many researchers has worked on index modulation assisted OFDM such as the authors of [5] where the potentials and implementation of the OFDM-IM was considered. The authors in [6] worked on the application of OFDM-IM for visible light communication while in [7] the performance of OFDM-IM in uplink and downlink was treated in a multi-user network by the authors, where they show that OFDM-IM outperform classical OFDM. The authors of [8] employed OFDM-IM in dual-hop relay system while the authors of [9] suggested using OFDM-IM as a

solution to alleviate inter-channel interference (ICI) caused by asynchronous transmission in uncoordinated massive machine type communication (mMTC) networks.

The initial work on OFDM-IM was on single input single output (SISO) systems but lately, MIMO and OFDM-IM are integrated to promote and enhance the spectral efficiency and energy efficiency of the OFDM-IM system [5] where the SISO-OFDM-IM transmitters were concatenated to achieve the MIMO-OFDM-IM which operate over $N_T \, X \, N_R$ MIMO frequency selective fading channels. This technology which provides adaptable trade-off between spectral efficiency and error performance has been suggested as a hopeful communication method for energy efficient 5G communication systems. In recent times, the authors of [10] proposed the dual-mode index modulation-aided OFDM (DM-OFDM). Here every subcarrier is employed to transmit data contrary to OFDM-IM. The subcarriers in every sub-block are partitioned into 2 sets, and using different constellation mode, each of them is modulated. Extra data bits are then conveyed with the indices of either subcarrier set. Since the signal constellation is also referred to as mode, this technique uses two modes and thus derived its name as the dual mode OFDM. Thus, DM-OFDM realizes superior spectral efficiency over traditional OFDM and the OFDM-IM.

In this work, we present the principles of operation of OFDM-IM, its enhanced version DM-OFDM. Compare their spectral efficiencies and performances as well as their application in various emerging physical (PHY) layer technologies for 5G network. The rest of this paper is arranged as follows. Section II is about the principle of operation of OFDM-IM and DM-OFDM, while Section III is a review of its application in various PHY layer technologies. We conclude in section IV.

2. How OFDM-IM, DM-OFDM and OFDM-MC Works

OFDM-IM

There have been efforts to increase the efficiency of OFDM including the replacement of discrete Fourier transform (DFT) with discrete wavelet transform (DWT) in OFDM to solve the problem of spectral wastage resulting from the insertion of cyclic prefix (CP) [11]. Another method of improving the performance of OFDM is the OFDM index modulation technique. Like in SM, the inward bound bit stream into the OFDM-IM is divided into index selection bits and M-ary constellation bits where the first set of bits are used for a selected subset of presented subcarriers as active, and the remaining not used are set to zero. The activated subcarriers are then modulated based on the M-ary constellation bits [5,6]. In an OFDM with N_F subcarriers, the large OFDM frames can provide a bottleneck in computational complexity as 512, 1024 or 2048 subcarriers (as in LTE-A standard) can create billions of likely combinations if active subcarriers index selection is applied directly. The total N_F subcarriers are therefore split into G

smaller OFDM-IM sub-blocks each with sub-block having N subcarriers to implement index modulation where N_F = G x N. See figure 1.
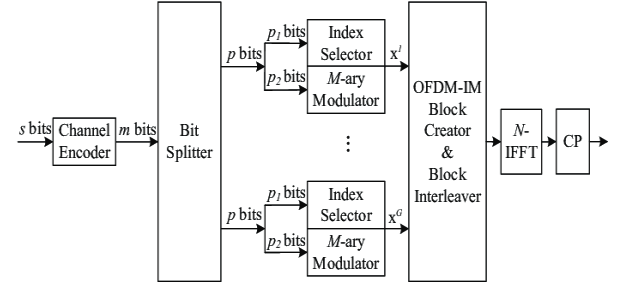

Figure 1.   Block diagram of OFDM-IM transmitter

The modulating M bits are also split into G groups with each group having P bits where M = G x P. The modulated active subcarriers in each sub-block of the OFDM-IM subcarriers is K out of N while the rest are inactive. Typical values of N = 2, 4, 8, 16 or 32 with 1 < K < N. Thus, the activated subcarrier indices can carry P_1 bits index data as seen in equation (1)

$$P_1 = \left\lfloor \log_2 \binom{N}{K} \right\rfloor \tag{1}$$

Where $\lfloor . \rfloor$ is the integer floor operator. If M of an M-ary constellation is employed for the K- activate subcarriers, P_2 bits are then transmitted by the subcarriers of each OFDM as given by equation (2).

$$P_2 = K \log_2(M) \tag{2}$$

In an OFDM-IM frame, the entire amount of bits transmitted is thus given by equation (3) [6]

$$m = G \left(\left\lfloor \log_2 \binom{N}{K} \right\rfloor + K \log_2(M) \right) \tag{3}$$

In the above scheme, the OFDM-IM sub-block maker generates all required N x 1 OFDM-IM sub-block $x^g, g = 1, 2, \ldots G$ taking into account the indices and the vector of the modulated symbols at the output of the M-ary modulator for all sub-blocks. Next the $N_F \, X \, 1$ main OFDM-IM block is formed by the OFDM-IM block creator [5].

$$X_F = [x^1 + x^2 + \ldots . x^G]^T$$

Where $x^g \in \{0, S\}, g = 1, 2, \ldots G$ by concatenating these G OFDM-IM sub-blocks.

Once the above is done, for improved error performance of the detector at the receiver, G x N block interleaving is carried out. This way, the subcarriers of each sub-block can go through uncorrelated fading channels. Finally, inverse fast Fourier transform (IFFT) is performed followed by cyclic prefix (CP) inclusion and then conversion of the signal from the digital domain to analog (DAC) is carried out before broadcasting the signals as in conventional OFDM systems. The IFFT is performed as in equation (4) in [12]

$$X_T = \frac{N}{\sqrt{K}} \, IFFT\{X_F\} = \frac{1}{\sqrt{K}} \, \boldsymbol{W}_N^H \, X_F \tag{4}$$

Where X_T is the OFDM block in the time domain, $\boldsymbol{W}_N$ is the DFT matrix where $\boldsymbol{W}_N^H \boldsymbol{W}_N = N I_N$ and the expression $N/\sqrt{K}$ is employed to normalise $E\{X_T^H X_T\} = N$ such that the receiver FFT demodulator uses a normalization factor of

$\sqrt{K}/N$. At the output of the IFFT, cyclic prefix (CP) is attached. After parallel to serial (P/S) and digital-to-analog conversion (ADC), the signal is transmitted via a frequency selective Rayleigh fading channel [12].

The spectral efficiency of OFDM-IM is thus given by equation (5) in [6]

$$\gamma_{IM} = \frac{m}{N} = \frac{\lfloor \log_2 \binom{N}{K} \rfloor + K \log_2(M)}{N} \text{ bps/Hz} \quad (5)$$

If we assume N is 4, K is 2 and M is 2 (BPSK modulation), the spectral efficiency or throughput of this OFDM-IM as above is approximately 1.15 bps/Hz which is identical with that of classical OFDM using BPSK. However, because OFDM-IM uses only half of its subcarriers, its energy efficiency is obviously higher than that of OFDM.

According to [6] OFDM-IM not only offers good advantages over classical OFDM but that it also provide an attractive compromise amid spectral efficiency and error performance as a result of its flexible system design. The modifiable active subcarriers of OFDM-IM is the key distinction between it and classical OFDM, where the desired error performance or spectra efficiency can be attained by adjusting the number of active subcarriers. Also, in low to middle range spectral efficiency values, OFDM-IM is better than classical OFDM in terms of superior bit error rate (BER) performance using a decoder of similar complexity and the near-optimal log likelihood ration (LLR) detector [13,14]. This BER enhancement is ascribed to the lower error probability of the IM information bits in contrast to regular *M*-ary constellation bits of classical OFDM. Finally [15] shows in term of ergodic realizable rate that OFDM-IM offers an improved performance to conventional OFDM. Therefore owing to its advantages over OFDM, OFDM-IM is a likely contender for forthcoming 5G wireless communications systems as well as been suited for low power consumption communication system such as machine-to-machine (M2M) communication.

DM-OFDM-IM

A major limitation of OFDM-IM system is its restricted spectral efficiency as a result of some of its subcarriers been inactive since they do not carry information for IM functions. This result in the BER gain of OFDM-IM above conventional OFDM diminishing with rising spectral efficiency rate. We understand this by looking at equation (3) where the percentage of IM bits decreases as we increase the modulation orders. In recent times, the dual-mode index modulation-aided OFDM (DM-OFDM-IM) is suggested in [10] as an intelligent way to mitigate the spectral efficiency constraint of OFDM-IM . In DM-OFDM, all the subcarriers in the OFDM carries information. In this technique, the subcarriers in each sub-block are separated into two sets and each set or group is modulated by two dissimilar constellation process. The indices of each set are then used to broadcast information bits. This way, DM-OFDM-IM attains superior spectral efficiency over OFDM-IM and classical OFDM.

In DM-OFDM, the incoming *m* bits are divided into *p* groups using the bit splitters with each group made up of *g* bits such that $p = m/g$. The group of *g* bits are further divided into g_1 and g_2 see figure (2). While the former is inputted into an index selector, the latter is fed into two distinct constellation mappers to generate an OFDM sub-block of length $q = N/p$ where *N* is the fast Fourier transform (FFT) size employed. The index bits g_1 are used by the selector to partition the indices of each corresponding sub-block into I_A and I_B index subsets. The two distinct mappers fed by g_2 are termed *A* and *B* with constellation sets of M_A and M_B having M_A and M_B sizes respectively with $M_A \cap M_B = \emptyset$. This is required in order to help the receiver achieve distinct detection of A and B. With the help of the index selector, each subcarrier related to I_A and I_B are modulated by the mappers A and B in that order. If *k* subcarriers out of a sub-block are modulated with M_A, the rest (*l-k*) subcarriers will be modulated by M_B and the total DM-OFDM transmitted symbol bits will be given as in equation (6) [14]
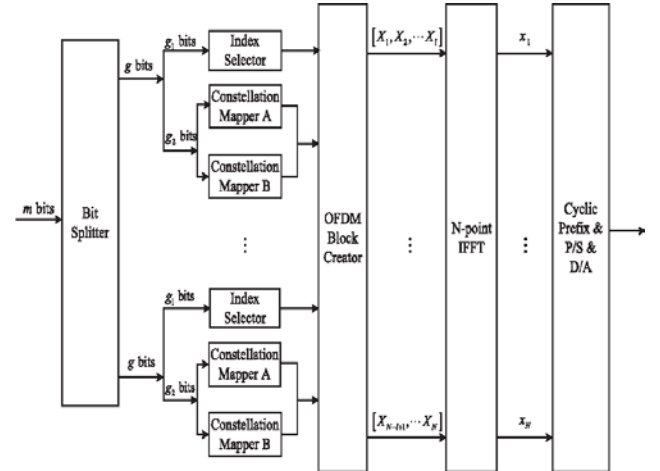

Figure 2. Block diagram of Dual Mode OFDM-IM transmitter

$$m = p(g_1 + g_2) = p\left(\begin{array}{c} \lfloor log_2 \binom{l}{k} \rfloor + k log_2(M_A) \\ + (l-k) log_2(M_B) \end{array} \right) \quad (6)$$

While the spectral efficiency of DM-OFDM is derived as shown in equation (7) [6]

$$\gamma_{DM} = \frac{m}{N} = \frac{\lfloor \log_2 \binom{l}{k} \rfloor + k \log_2(M_A) + (l-k) log_2(M_B)}{n} \text{ bps/Hz} \quad (7)$$

OFDM-MC

OFDM subcarriers employ same constellation transmission scheme and each subcarrier going through the frequency selective and fast fading channel experience different attenuation. Thus the channel performance will vary across the subcarriers and also based on the subcarrier symbol used. Another problem with this transmission scheme is that the error probability of the transmission is governed by the OFDM subcarriers with greatest attenuation leading to a poor performance [16]. OFDM having multiple constellations where each subcarrier is assigned a dissimilar modulation scheme according to the calculated channel

conditions which we call OFDM with multiple constellation or multiple-constellation OFDM (OFDM-MC) solves the above challenge. This enables subcarriers to be adaptively allocated modulation schemes according to the SNR of each subcarrier [16,17].

3. Application of OFDM-IM

(A) Massive Machine Type Communication

The demand for massive Machine type Communication (mMTC) otherwise known as machine-to-machine (M2M) communication such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), Internet of Things (IoT), control of autonomous vehicles communication etc is one of the major requirement of the forthcoming 5G wireless communication system [18]. Unfortunately, mMTC systems experience sporadic transmission with the base station leading to lack of synchronization between the BS and the MTC devices which destroys the orthogonality between the subcarriers of the OFDM scheme causing inter-carrier interference (ICI). Therefore OFDM has the major challenge of providing services to non-synchronous mMTC users/devices. One way of solving this problem is the use of OFDM with index modulation to alleviate ICI [9]. According to [12], OFDM-IM is used as a transmission candidate for vehicle to X (V2X) communication systems as a result of its toughness against mobility when going through frequency selective fading channels turbulence unlike classical OFDM.

(B) Underwater Acoustic Communication

The underwater acoustic propagation channel is non homogeneous as a result of density and temperature gradients. It is vastly frequency selective with limited bandwidth, constrained communication capacity and signal dispersion in time and frequency. Therefore, time-varying multipath propagation combined with narrow bandwidth put considerable limitations on the attainable throughput of Under Water Acoustic (UWA) communication systems [19,20]. To resolve the challenges of time-varying multipath dispersion, several modulation techniques were suggested for UWA communications among which OFDM is generally accepted as a major contender since it offers ability to overcome the intersymbol interference (ISI) caused by the multipath propagation. In doing so, the subcarrier spacing of OFDM signals are positioned smaller compared to the narrow coherence bandwidth thereby rendering the system vulnerable to Doppler effect occurring from terminal mobility and ocean waves. This Doppler effect obliterate the subcarrier orthogonality of OFDM and additionally encourage inter-carrier interference (ICI) that severely weaken system performance [21]. While OFDM-IM will eliminate ICI, the spectral efficiency of OFDM-IM was improved upon in [21] where the authors proposed a hybrid OFDM-IM system, which integrates an ICI self-cancellation mechanism where different OFDM-IM subcarrier groups can autonomously choose the OFDM-IM mode for transmission. This mode can readily be detected by the receiver, thereby producing an extra channel of information transfer which can be used in UWA communication system and other communication systems with severe Doppler effect such as vehicular wireless communications.

(C) Visible Light Communication (VLC)

The interference in cellular network due to frequency reuse as a result of crowded RF spectrum makes the need for a substitute to RF communications unavoidable. Visible light communications (VLC) provides this alternative as a talented technology for the 5G networks [22]. VCL offers better performance over RF based systems in many areas since it operates in unregulated band with very wide spectrum. It requires no license with low operating cost and less interference to RF susceptible equipment. VLC systems merges lighting with communications and its existing lightning infrastructure are been used in VLC systems without health risk as long as eye safety related to visible light is ensured [23]. VLC system uses high speed light emitting diodes (LEDs) as transmitters, while using photodiodes (PDs) as receivers.

VLC uses positive real-valued signals for its data modulation unlike RF systems which uses complex valued and bi-polar signals. This is because of the incoherent output of the lights coming from the LEDs. In order to thus modulate the VLC signals, such cost effective modulation scheme as pulse width modulation(PAM), pulse amplitude modulation (PWM) in combination with intensity modulation (IM) and direct detection (DD) systems are used [24]. The above modulation techniques offers low transmission rate and increasing the rate leads to intersymbol interference leading to the need for a better scheme such as the OFDM [23]. Though not without first applying Hermitian symmetry to the frequency domain in order to achieve real OFDM signals after the inverse fast Fourier transform (IFFT) operation. The next thing is to ensure the resultant signal is positive, thus either we insert a direct current (DC) bias to it to form the DC biased optical OFDM (DCO-OFDM) or we clip the signal at zero level to ensure transmitted signals are positive-valued only thereby giving us the asymmetrically clipped optical OFDM (ACO-OFDM). According to [23], a unipolar OFDM design (U-OFDM) should be used so as to resolve the DC biasing setback of DCO-OFDM. This will also help us attain superior spectral efficiency than ACO-OFDM. OFDM-IM and DM-OFDM can also be used in visible light communication OFDM (VLC-OFDM) systems with some modifications such as the unipolar OFDM-IM (U-OFDM-IM) where the OFDM frame is divided into two of the same length similar to U-OFDM, we also have unipolar DM-OFDM (U-DM-OFDM) with better spectral efficiency than other schemes [6].

4. Performance Comparison

Every subcarrier of DM-OFDM were used to carry information bits contrary to OFDM-IM. Its dual grouping of subcarriers which are modulated by two dissimilar constellation modes are employed to broadcast extra information bits thereby making DM-OFDM attain superior spectral efficiency than both OFDM-IM and classical OFDM [6]. On the other hand OFDM-IM systems outperform the conventional OFDM system as a result of its superior diversity gain attained by its subcarrier index bits transmission [17]. Figure 3 shows a performance comparison chart of the three OFDM scheme under AWGN and Frequency-selective fading channels with precoding and without precoding. The simulation result reveals that for frequency selective Rayleigh fading channel without precoding, DM-OFDM outperforms OFDM-IM. The performance of OFDM-MC is worse than that of both OFDM-IM and DM-OFDM since both of them have a higher diversity gain for the subcarrier indexing bits than OFDM-MC.
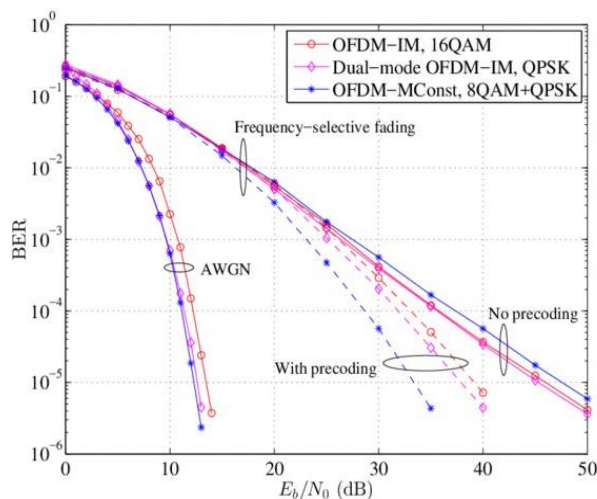

Figure 3. BER performance comparison chart [17]

However, we see that precoded OFDM-MC outperforms precoded OFDM-IM and precoded DM-OFDM. At BER of 10^{-5}, the SNR of precoded OFDM-MC is 33 dB while that of precoded DM-OFDM is 37 dB and that of precoded OFDM-IM is 38 dB, a clear 4 dB to 5 dB advantages. This advantage is due to precoded OFDM-MC diversity order of 4 compared to the two other schemes with diversity order of 2.

5. Conclusions

We have been able to show the novel technique of OFDM-IM and its variants in their application for spectral and energy efficient 5G enabling technologies such as VLC and mMTC as well as under water acoustic communication. Performance analysis shows that, at the BER of 10^{-5}, the SNR of precoded OFDM-MC is 33 dB while that of precoded DM-OFDM is 37 dB and that of precoded

OFDM-IM is 38 dB, a clear 4 dB to 5 dB advantage. This advantage is due to precoded OFDM-MC diversity order of 4 compared to the two other schemes with diversity order of 2. The application of modulation index in the spatial domain can also be used for solving the high cost of radio frequency (RF) chain and its prohibitive power consumption in mmWave massive MIMO transceiver implementation.

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