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Efficient Index Modulation Techniques for 5G and Beyond

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***Abstract*—Index modulation (IM) techniques are emerging as promising approaches to improve spectral efficiency and reliability for 5G/future wireless networks. This paper provides an overview of key IM schemes including spatial modulation, orthogonal frequency division multiplexing with index modulation (OFDM-IM), and enhanced variants like SIM-OFDM. The spectral efficiency gains of these techniques are quantified mathematically. Spatial modulation uses antenna indices to convey additional information bits, while OFDM-IM utilizes subcarrier indices. SIM-OFDM further activates subcarriers selectively based on incoming bits. Experiments demonstrate spectral efficiency improvements over classical OFDM.**

Keywords—Index modulation, Orthogonal frequency division multiplexing, spatial modulation, maximum likelihood detection

I. Introduction

Wireless communication systems require constant improvements to meet the growing demand for higher data rates and reliability. The 3rd Generation Partnership Project (3GPP) has identified three fundamental generic services that must be supported by the next-generation wireless network, one of which is the provision of massive machine-type communication (mMTC). Through mMTC, the Internet of things devices efficiently send small amounts of traffic to communicate. The provision of ultra-high reliable low latency communication, commonly referred to as ultra-low latency communication (uRLLC), is of utmost importance for mission-critical applications that depend on ultra-low latency service to guarantee seamless operations.

The third category is known as Enhanced Mobile Broadband (eMBB), which provides users with an improved experience through high data transfer rates [1, 2].

The increasing requirement for high-speed wireless communication necessitates the developing of more efficient modulation techniques. Extensive research has been conducted on the spectrum and energy-efficient modulation techniques to tackle the present and future obstacles. The implementation of advanced physical layer modulation techniques in wireless communication is imperative to facilitate the operational requirements of upcoming networking technologies. Index Modulation (IM) is a novel technique utilized in wireless communication systems, which endeavors to increase the spectral efficiency (SE) and dependability of the system by capitalizing on the index domain of communication channels. The modulation of physical resources is not limited to traditional methods, but also involves mapping onto predetermined index sets to communicate supplementary information. IM can potentially enhance spectral efficiency (SE) and reliability in wireless communication systems.

The field of IM techniques encompasses a range of modalities, including spatial modulation (SM), frequency modulation, and space-time modulation. Each of these techniques uses a different domain to convey additional information.

II. Spatial Modulation

Spatial Modulation (SM) was first introduced by [3] in 2006. Since then, several researchers have investigated its potential benefits. SM employs a single antenna for transmission, where only one antenna is active at a time for transmission, and the active antenna is selected to modulate the information bits. Implementation of this particular technique results in a decrease in the intricacy of both the transmitter and receiver, as well as a reduction in power consumption, compared to alternative multiple input multiple output (MIMO) techniques. SM has the potential to enhance performance concerning bit error rate (BER) and outage probability, especially under conditions of low signal-to-noise ratio (SNR) [4].

The primary benefit of SM lies in its elevated spectral efficiency, which enables the conveyance of numerous bits per symbol. This phenomenon can be attributed to the abundance of antennas that are usually available in comparison to the number of bits that require transmission. The utilization of the sparsity of the channel matrix [5] is a means by which SM attains energy efficiency, thereby constituting another benefit of this technology. Moreover, the implementation of SM has the potential to enhance the security of the communication infrastructure by augmenting the complexity of intercepting the transmitted signals, thereby impeding eavesdropping activities [6].

Notwithstanding the advantages, SM encounters certain obstacles. A significant obstacle pertains to the receiver's elevated intricacy, necessitating precise channel estimation and antenna selection. An additional obstacle that arises is the requirement for precise synchronization between the transmitter and receiver, particularly in scenarios involving multiple antennas. In addition, it has been observed that the efficacy of SM is subject to diverse influences, including antenna correlations, non-line-of-sight (NLOS) paths, and multipath fading [7].

Contemporary studies in SM have prioritized the resolution of aforementioned obstacles and the augmentation of its efficacy. [8] Presented a combined antenna selection and precoding approach for SM in their study, which enhances the system's performance concerning capacity and BER. The authors of [9] conducted a study on the utilization of SM in communication systems operating in the millimeter wave (mmWave) frequency range. They suggested a hybrid approach that combines SM and beam-forming techniques to address the challenges posed by the high path loss and narrow beam width of mmWave channels. [10] Conducted a study to examine the effects of antenna correlations on the performance of SM. They also introduced a simplified antenna selection algorithm that considers these correlations. Fig. 1 shows a SM Transmitter block diagram. When one antenna is chosen from among N_t available antennas on a transmitter, the total number of antenna activation patterns is equal to $\left(\frac{N_t}{1}\right)$. As a result $\left[log_2 \frac{Nt}{1}\right]$, is the total amount of bits that may be utilized to choose one of these patterns. By utilizing $\log_2|A|$ bits a symbol is carefully chosen from what is known as the modulation alphabet to transmit through the active antenna after choosing the active antenna. The SE of SM expressed in bits per channel is given by [11];

$$SE_{SM} = log_2 \frac{N_t}{1} + log_2|A| \text{ bpcu} \quad (1)$$

where, $\left[log_2 \frac{Nt}{1}\right]$ represents the index mapping and $\log_2|A|$ represents the symbol mapping. Mathematically, the maximum likelihood (ML) solution at the receiver to achieve the optimal detection can be written as

$$\widehat{X_{ml}} = argmin_{x\epsilon s_{sm}} \| y - H_x \|_2^2 \quad (2)$$

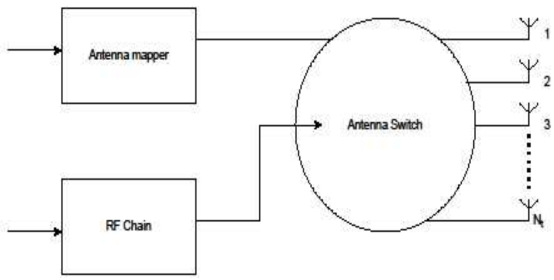

Fig.1. SM Transmitter Block Diagram [11]

Generalised SM

SM faces constraints in spectral efficiency since it permits the utilization of only one active antenna at a time. In response to this limitation, GSM was conceived as a spectrally efficient extension of SM with the objective of enhancing spectral efficiency through the simultaneous transmission of multiple data streams using multiple antennas. The GSM technology exhibits a distinction from spatial multiplexing-based MIMO transmission due to the non-activation of certain antennas. The attainment of a higher SE in GSM necessitates an increase in architecture complexity, as a result of the need for dedicated RF chains for each active antenna. Given that N_a antennas out of N_t are active in GSM, the total number of antenna activation patterns in GSM would be $\left(\frac{N_t}{Na}\right)$ .The total number of bits that can be used to select one of these activation patterns is given by $log_2\left(\frac{N_t}{N_a}\right)$. In addition, each of the N_a active antennas transmits a symbol chosen from the alphabet of modulation A , resulting in the transmission of $N_a \log_2|A|$ information bits. Therefore, the total number of information bits that a single GSM subscriber can transmit is ;

$$\left(\left[log_2 \frac{N_t}{N_a} + N_a\, log_2|A|\right]\right). \quad (3)$$

This is much higher than that of SM.

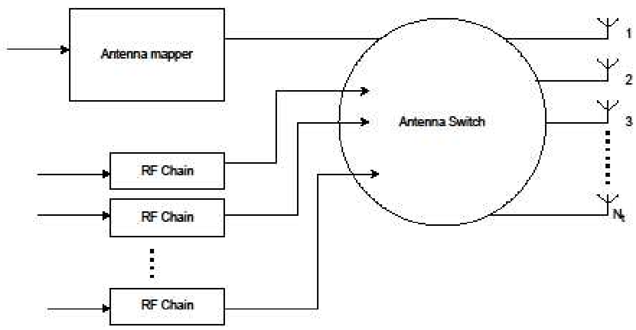

Fig. 2. GSM Transmitter Block Diagram [11]

Space-Time IM

Multiple resources are utilized in space-time IM for indexing, such as time-slots and antennas at the transmitter. This is in addition to the transmission of the symbol selected from the modulation alphabet. In this context, we shall examine the availability of T time slots and N_t antennas for indexing. There exist $\frac{T}{I}$ time-slot activity patterns, and for each of these patterns, there are $\frac{N_t}{I}$ possible antenna activity patterns. Consequently, the aggregate quantity of bits that can be transmitted through the process of indexing across time slots is equivalent to the floor of the $\left\langle log_2\left(\frac{T}{1}\right)\right\rangle$, while the total number of bits that can be conveyed through the process of indexing across the antenna is equivalent to the floor of the $\left[log_2 \frac{Nt}{1}\right]$. The data that is being received is partitioned into three distinct segments. The selection process involves three distinct parts: the first part pertains to the selection of a time slot, the second part pertains to the selection of an antenna, and the third part pertains to the selection of a symbol from the set A for transmission.

In terms of bpcu, the SE in space-time IM is given by.

$$SE_{ST-IM} = \left[\log_2 \frac{T}{1} + \log_2 \frac{N_t}{1} \right] + \log_2 |\mathrm{A}| \tag{4}$$

III. Frequency Domain IM

Orthogonal Frequency Division Multiplexing (OFDM) is a waveform that utilizes multiple carriers to address the challenges of multipath reception, including inter-symbol interference. The method employs a rapid Fourier transformation and exhibits commendable efficiency. The utilization of a cyclic prefix (CP) in OFDM can effectively mitigate the delay spread of wireless channels while employing straightforward detection techniques, rendering it a favored approach for data transmission. OFDM is insufficient to fulfill the diverse demands of 5G and next-generation wireless networks [12]. The primary drawbacks are the elevated out-of-band emission (OOBE) and peak-to-average power ratio (PAPR). The limitations associated with conventional OFDM systems have prompted a transition towards alternative approaches. The OFDM-IM technique is a recent innovation that merges the benefits of OFDM and spatial modulation (SM) to enhance spectral and energy efficiencies. OFDM-IM was first introduced by authors of [13] in 2013. In OFDM-IM, the modulation of information bits occurs not only through the subcarriers but also via the subcarrier indices. The active subcarriers are selected based on the information bits, and the indices of these active subcarriers convey additional information. This technique can provide additional degrees of freedom for spatial multiplexing, as well as better energy efficiency by reducing the number of active subcarriers.

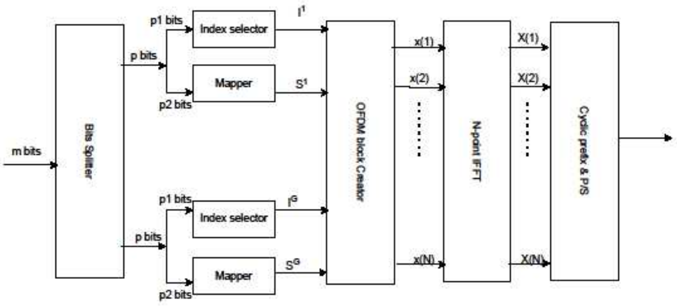

Fig. 3. OFDM-IM Transmitter Block Diagram

Fig. 3 depicts the OFDM-IM baseband transmitter structure. The system transmits m bits per OFDM frame over a frequency Raleigh fading channel. The source bits are equally split into G blocks, each consisting of two parts. $m = pG$. These groups of p bits are then assigned to one.

of the G OFDM sub-blocks. If we assign each sub-block length n, then the total number of OFDM subcarriers $N = nG$. In classical OFDM, all subcarriers in an OFDM sub-block are active and may carry in total n M-ary signal constellation symbols, while in OFDM-IM, not all subcarriers are active.

One of the key advantages of OFDM-IM is its high spectral efficiency, as it allows for the transmission of multiple bits per subcarrier. This can be attributed to the abundance of subcarriers in comparison to the number of bits that require transmission. Furthermore, it has been demonstrated that OFDM-IM can enhance energy efficiency by reducing active subcarriers, thereby leading to decreased power consumption and interference. Moreover, it has been observed that OFDM-IM has the potential to improve the system's performance concerning BER and outage probability, especially in scenarios characterized by low SNR values [14].

Notwithstanding the advantages, OFDM-IM encounters certain obstacles. A significant obstacle pertains to the intricate nature of both the transmitter and receiver, necessitating precise execution of channel estimation, subcarrier selection, and index modulation. A further obstacle pertains to the requirement for precise synchronization between the transmitting and receiving devices, particularly in scenarios involving multiple antennas. Moreover, the efficacy of OFDM-IM can be influenced by diverse factors, including channel fading, subcarrier correlation, and index modulation complexity, as stated in [15].

Contemporary research in OFDM-IM has prioritized the resolution of certain obstacles and the augmentation of its efficacy. [16] Introduced a novel approach for enhancing the performance of OFDM-IM systems through a combined subcarrier and index selection mechanism. This scheme has been shown to yield improvements in both capacity and BER. The authors of [17] conducted a study on the application of OFDM-IM in massive MIMO systems. They put forth a receiver architecture that is low in complexity and accounts for the spatial correlation of the channels. [18] Conducted a study to examine the influence of subcarrier correlation on the efficacy of OFDM-IM. They also introduced a subcarrier selection algorithm that is low in complexity and accounts for the correlation.

Apart from the aforementioned research, recent studies have delved into the implementation of OFDM-IM in emerging wireless communication scenarios. [19] Introduced a combined OFDM-IM and NOMA approach for visible light communication systems, which enhances the system's spectral and energy efficiencies.[20] Conducted a study on the application of OFDM-IM in non-orthogonal multiple access (NOMA) systems. They also introduced a detection algorithm that is designed to be low in complexity and considers index modulation. [21] Provides a comprehensive overview of index modulation multiple access (IMMA) for 6G communications. IMMA merges index modulation with NOMA to improve spectral efficiency, energy efficiency, performance, and massive connectivity compared to classical NOMA. Potential applications of IMMA in vehicular, RIS-aided, cooperative, and secure networks are discussed, demonstrating the flexibility of IMMA. [22] proposes a novel reconfigurable intelligent surface (RIS) grouping based IM (RGB-IM) technique to enhance spectral efficiency and improve bit error rate (BER) in wireless communications. RIS are divided into group-surfaces (GR) and the index of the active GR is used to convey additional information bits. The scheme was shown to provide better BER performance compared to relay-assisted spatial modulation, especially with intelligent RIS and higher number of elements per GR.

SIM-OFDM

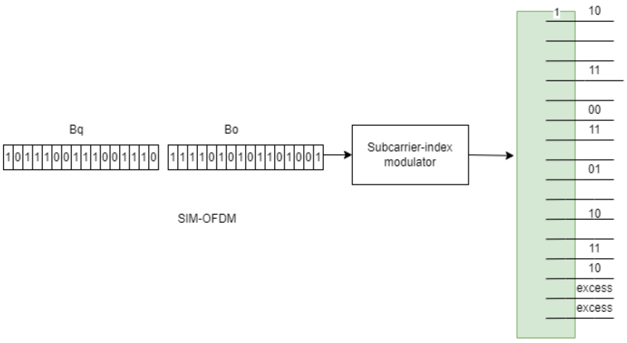

Fig. 4. SIM-OFDM carrier modulation scheme [23].

The SIM-OFDM system, which consists of two functions, is depicted in Fig. 4, which comprises two distinct functions. Initially, two subsets are formed B_{ook} based on the value of each bit, namely the subset of ones and the subset of zeroes. The proposed method involves tallying the occurrences of zeros and ones within the range of $\frac{N}{2}$, where N represents the total number of points in the Inverse Discrete Fourier Transform. The bit with the highest count is then identified as the majority bit. The subcarrier index is directly linked to the position of each B_{ook}bit. The formulation for determining the number of bits in the majority bit-value N_{maj} can be expressed as:

$$N_{maj} = \max\left[NB_{ook}ones, \left(N_{FFT} - NB_{ook}ones\right)\right] \tag{5}$$

The classical M-QAM constellation diagram can be mathematically expressed as $K_{M-QAM} = \frac{N}{2} log_2 M$, where K represents the number of symbols modulated. Furthermore, it is possible to express the indices bits as $K_{OOK} = N$. N represents the aggregate quantity of subcarriers. Consequently, the aggregate number of bits per SIM-OFDM symbol, denoted as K_b, is determined by:

$$K_b = K_{M-QAM} + K_{ook} = \frac{N}{2}\log_2 M + N \tag{6}$$

Maximum PAPR value for SIM-OFDM is:

$$PAPR_{MAX} = 10\log_{10} N_{SIM} dB \tag{7}$$

The variable N_{sim} denotes the number of operational subcarriers. Typically, the maximum peak-to-average power ratio (PAPR) of the SIM_OFDM system is lower than that of a conventional OFDM system since is generally less than N. Thus, using SIM_OFDM can effectively mitigate the peak-to-average power ratio (PAPR) and enhance its performance. The Power Relocation Policy (PRP) involves the reallocation of excess power from deactivated subcarriers to active subcarriers. Consequently, the signal-to-noise ratio experiences an increase, leading to a notable enhancement in the bit error rate.

Enhanced SIM-OFDM

The ESIM_OFDM system is configured such that the state of two adjacent subcarriers is determined by a single B_{ook} bit. The activation status of the subcarriers in a B_{ook} is determined by the value assigned to the corresponding bit. Specifically, a 1-bit indicates that the first subcarrier is active and the second subcarrier is inactive, whereas a 0-bit indicates that the first subcarrier is inactive and the second subcarrier is active. The scheme achieves a reduction in the required size of B_{ook} bits $\frac{N}{2}$, as compared to the original SIM OFDM scheme that necessitates N bits. This modification offers the benefit of activating only one subcarrier out of every two consecutive subcarriers, rendering the other subcarrier inactive. This approach eliminates the need for threshold detection, thereby preventing the erroneous detection of subsequent subcarriers due to a single subcarrier being incorrectly detected. Consequently, any errors that may occur are confined to a specific location. Furthermore, the necessity for performing majority-bit calculations will be eliminated.

One disadvantage of this scheme is the slightly reduced spectral efficiency compared to SIM_OFDM. The spectral efficiency of SIM_OFDM, measured in bits/carrier, is given by:

$$SE_{SIM-OFDM} = \frac{\log_2 M}{2} + 1 \tag{8}$$

The spectral efficiency of the enhanced SIM_OFDM is

$$SE_{enhanced-sim-ofdm} = \frac{\log_2 M}{2} + \frac{1}{2} \tag{9}$$

Consider a hypothetical scenario wherein there exist N=32 sub-carriers. These sub-carriers can be segregated into four distinct blocks or groups, each comprising eight sub-carriers. Within each block, seven sub-carriers are active while one remains inactive. The determination of the number of states for each block involves the computation of all possible combinations through the utilization of the combination formula.

Specifically, the number of states for each block can be obtained by computing 8!/7!(8-7)!=8 states. Subsequently, the control of the state of subcarriers in each block necessitates the utilization of 3 bits OOK. The utilization of 4QAM results in the transmission of two bits on each active subcarrier, leading to a spectral efficiency of (2*7+3)/8= 2.125 bits/subcarrier [23].

$$SE_{general-sim-ofdm} = \frac{7\log_2 4}{8} + \frac{\left(\log_2 \frac{8!}{7!(8-7)!}\right)}{8} bit \tag{10}$$

Upon comparing this value with the spectral efficiency of OFDM, which is equivalent to $log_2 4$ = 2, it can be observed that the spectral efficiency of ESIM surpasses that of traditional OFDM when active subcarriers are utilized near the total available subcarriers. Moreover, a certain quantity of power will be conserved as a result of the utilization of partially active subcarriers. On the contrary, there exists a potential risk of elevated BER in comparison to OFDM. This is because in the event of a block failure, all bits conveyed on that subcarrier are lost, whereas in OFDM, only $\log_2 M$ bits are lost.

IV. Experiments and Results

Simulations carried out demonstrate the performance and comparison of different IM modulation schemes. In the simulation, a flat Rayleigh fading channel is assumed with additive white Gaussian noise (AWGN). It is assumed the channel fading information is fully available at the receiver and the transmit power is allocated equally among all the active antennas.

TABLE I. Parameters used in the evaluation.

Item	values
SM	$N_t = 1$, $N_a = 2$
GSM	$N_t = 3$, $N_a = 2$
Number of transmit antennae	2

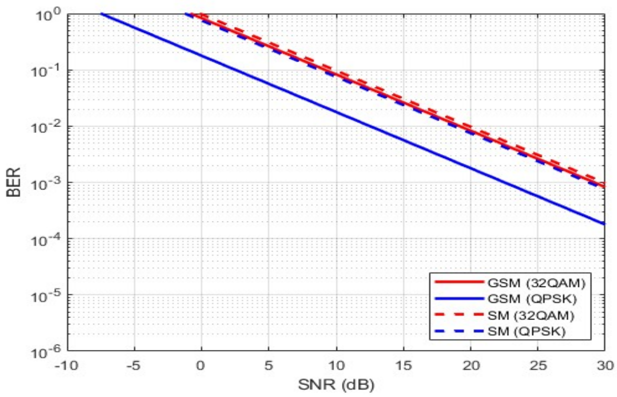

Fig. 5. BER comparisons for SM and GSM

BER performance is being evaluated for the two different spatial modulation schemes: SM, and GSM. As demonstrated by the plots of Fig.3, 32QAM can achieve higher data rates but requires higher SNR levels for reliable communication, while QPSK is more robust in noisy environments. SM is more suitable for scenarios where maximizing data rate is crucial, such as high-capacity wireless links. GSM is preferred in environments with high noise and interference, where maintaining reliable communication is paramount. OFDM achieves lower BER at higher SNR levels.

By referring to Fig.4, we note that as the SNR increases, ESIM-OFDM achieves lower BER but may require a higher SNR than OFDM to achieve the same level of reliability. OFDM-IM with 16QAM achieves a balance between spectral efficiency and reliability compared to the other two schemes. It performs better than ESIM-OFDM at lower SNR and exhibits similar or slightly worse performance than OFDM with 8QAM.

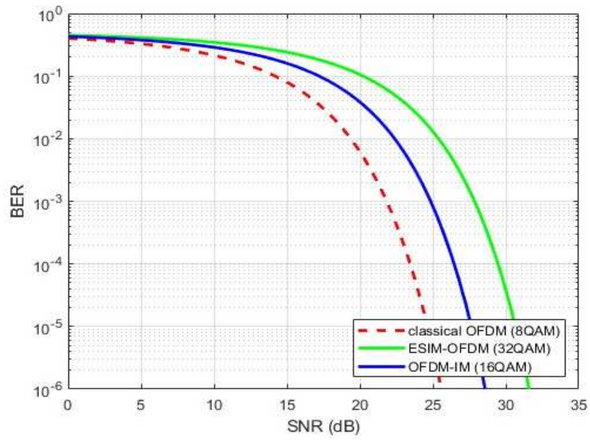

Fig.6. BER comparisons of classical OFDM, OFDM-IM and ESIM-OFDM

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V. Conclusion

This paper has provided an overview of emerging index modulation techniques and their potential to enhance spectral and energy efficiency in 5G and beyond wireless networks. Key schemes such as spatial modulation, OFDM with index modulation, and SIM-OFDM were explored. The spectral efficiency gains of these techniques were quantified mathematically, showing the additional bits conveyed through index domains. Experiments demonstrated that OFDM-IM and SIM-OFDM can outperform classical OFDM in terms of error performance and spectral efficiency. While IM shows great promise, there are practical challenges that need to be addressed, encompassing synchronization, channel estimation, and computational complexity. These challenges can be effectively mitigated in future research making use of machine learning. Machine learning-assisted estimation methods can be employed to predict channel characteristics based on historical data, thereby enabling adaptive adjustments to channel estimation algorithms. This approach holds the potential to enhance the precision of channel state information. Furthermore, machine learning techniques can be harnessed for error detection within index modulation symbols, affording an additional layer of error correction. Addressing these challenges will be crucial in realizing the full potential of IM. Nonetheless, the ability of IM to boost spectral efficiency and reliability without requiring additional time/frequency resources makes it an attractive approach as the demands on wireless networks continue to grow.

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