Towards Energy Efficient Massive MIMO System with Reconfigurable Index Modulation

The increasing requirements for higher data rate, larger system capacity, better energy efficiency, lower latency, and better link reliability lead to new technology requirements for the next generation wireless communication systems. The massive multiple input multiple output (MIMO) beamforming has become one of the promising strategies to meet the tremendous demands. On the other hands, in order to satisfy the varieties of application features, it is unnecessary and is usually infeasible to achieve all the requirements simultaneously. More agile in flexibility or so called “soft” communication systems are needed. However, the transmission strategy of classical MIMO technology is fixed and stiff that cannot provide the flexibility between the above application features. In order to response the issues, new technology that aims higher spectral and energy efficiency and can flexibly adjust the system parameters for combination of spectral and energy efficiency is needed.

The concept of index modulation (IM) has been studied to provide flexibility in adjusting the system parameters to achieve higher spectral efficiency or energy efficiency. The IM technique uses the indices of the resources in the considered communication systems to deliver additional information bits, which brings the features with high spectral and energy efficiency. Recent developments on index modulation have also been proposed based on antenna indexing or subcarrier indexing. Furthermore, the IM concept can combine with the traditional digital modulation scheme to achieve more flexibility and spectral efficiency. The antenna indexing based IM is usually called Spatial modulation (SM) and the subcarrier indexing IM is usually called Orthogonal Frequency Division Multiplexing-Index Modulation (OFDM-IM).

For the Spatial modulation, the IM technique is realized in the transmit antennas of MIMO systems. The SM manipulates the on-off behavior between antennas and uses the indices of antennas to convey extra bits in spatial domain. Different forms of antenna index modulation technologies have been studied. Spatial modulation and generalized spatial modulation (G-SM) are new technologies that combine IM with digital modulations as shown in Fig. 1.
The system can provide better flexibility in adjusting the system parameters to achieve spectral efficiency or energy efficiency. The input data stream is split into two portions, spatial bits and signal bits. The modulator of G-SM in transmitter is also divided into two parts, the antenna index mapper and conventional amplitude-phase modulator (M-QAM). Each type of modules modulates its corresponding bits in the input stream, spatial bits select the antenna pattern through index mapping switch and signal bits are transferred into QAM symbols by amplitude-phase modulator. Then, the receiver estimates both spatial bits and signal bits by G-SM MIMO detector.

Table 1 shows an example for the G-SM scheme with total antennas \( N_t = 4 \), active antennas \( n_r = 3 \), and transmitted data streams equal to 3. Though the SM provides extra spatial index bits by switching the antenna, and increases the energy efficiency of transmission. But, SM still has issues to be overcome. First, the data rate of SM is limited due to the slow antenna switching speed in hardware. Secondly, the SM is incompatible with MIMO-OFDM systems. Since the on-off pattern of antennas is based on the transmitted information bits, we must enhance the rate of the antenna switching if the data rate becomes higher. However, the hardware components nowadays cannot support for switching antennas in the short time, which limits the speed of the SM scheme. Moreover, for the second issue, since it may appear different antenna switching patterns between subcarriers at the same time and only one of the antenna patterns can be configured in the MIMO system, SM technique is incompatible to the communication system based on OFDM architecture. The above drawbacks make SM technique cannot apply to current mainstream MIMO-OFDM systems.

Table 1: G-SM with \( N_t = 4 \), \( n_r = 3 \), and 3 data streams where \( x_i \) is the QAM symbol and \( i = 1, 2, \ldots, n_r \).

<table>
<thead>
<tr>
<th>Active antenna index</th>
<th>Spatial bits</th>
<th>SM codeword</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3</td>
<td>00</td>
<td>([x_1, x_2, x_3, 0]^T)</td>
</tr>
<tr>
<td>1, 2, 4</td>
<td>01</td>
<td>([x_1, x_2, 0, x_3]^T)</td>
</tr>
<tr>
<td>1, 3, 4</td>
<td>10</td>
<td>([x_1, 0, x_2, x_3]^T)</td>
</tr>
<tr>
<td>2, 3, 4</td>
<td>11</td>
<td>([0, x_1, x_2, x_3]^T)</td>
</tr>
</tbody>
</table>

On the other hand, the OFDM-IM, for which the IM technique is realized in the subcarriers of an OFDM system, uses combinations of subcarriers to carry out index bits from indices selection. In the literatures, it has been studied that index modulation has great potential to effectively enhance the energy efficiency of the multi-antenna or multicarrier communication systems with the adoption of both index domain (the indices of the resources, such as antenna indices or subcarrier indices) and signal domain (amplitude-phase modulation, i.e. QAM modulation) as shown in Fig. 2.
In this work, we exploit the index modulation in the MIMO beamforming, which indexes the MIMO beams as shown in Fig. 3. Assuming the number of affordable beams is \( N_B \), we choose \( n_p \) transmit beams from \( N_B \) affordable beams. Thus, there are \( \binom{N_B}{n_p} \) possible beam combinations, and \( \log_2 \left( \binom{N_B}{n_p} \right) \) spatial bits can be represented. We use the singular value decomposition (SVD) to generate the precoder used at transmitter and the combiner used at receiver, and then the effective channel composed of the precoder, channel, and combiner is equivalent to the parallel channel, which means that we can select the -beams by using the different codewords.

The proposed index modulation applies the index selection in the dimension of beams instead of antennas for G-SM, which relief the data rate limitation due to the hardware constraint in G-SM system. The antenna switching speed is limited to the RF switches ability which is around milli-seconds or KHz. The beam indexing retains the merits of G-SM that carries extra spatial bits by switching the transmitted beams in the baseband precoder. Consequently, the proposed scheme could operate at the speed of symbol rate of tens to hundreds of MHz, which is at least 3 orders of magnitudes faster than the current SM approach. The comparison of expected speed gap with G-SM is depicted in Fig. 4-(a).

The IM provides higher energy efficiency (EE) of transmission than conventional MIMO beamforming scheme at all times. By selecting off the beams and fix the transmit power on each active beam, the transmit power and QAM modulated symbol streams decreases linearly. However, the increased index bits help to improve the overall energy efficiency. Therefore, the energy efficiency of an IM system would be always better than that of the classical MIMO system. The IM on the beam also finds better spectral efficiency (SE) than the classical MIMO system is cases. With increasing the available beams \( N_B \) or decreasing the modulation order \( M \), the system may find opportunities which have better SE performance than the classical MIMO system. In general, the EE and SE trade off in a system. The trade-off relation in the IM based MIMO system is shown in Fig. 4-(b) when different type of QAM modulation is used. The classical MIMO system is represented at the left end of each curve that the number of data streams \( (N_s) \) equals the number of selected beams \( (N_B) \). The IM shows more flexibility in selecting suitable configuration based on user requirements and channel environment.
At receiver, the ML detection provides the optimal BER performance, but has high computational complexity that increases exponentially in the number of data streams. Therefore, the sphere decoding (SD) detection, also known as the lattice decoding detection, is considered. The IM SD detection corresponds to a pruned integer least-squares problem, since the search space is restricted to the finite lattice for all the possible combinations composed of \( nb \cdot M \)-QAM symbols and \((Na - nb)\) zeros. The SD detection visits all nodes in the \( M \)-ary tree of depth \( Na \) and discards the nodes which lie outside a distance \( R \) to the receive symbol vector \( z \), where \( R \) denotes the sphere radius. After the search, it finds the solution which has the minimum distance. According to the searching direction, the SD detection can be further divided into two types, the depth-first type with variable computational complexity and the breadth-first type with fixed computational complexity.

The breadth-first search based sphere decoding (BFS-SD), also known as \( K \)-best sphere decoding, searches for the minimum distance \( d_m \) in forward direction only. The best \( K \) candidates are chosen at each level of the tree. The children of these nodes will be the new candidates and the new best \( K \) candidates will be chosen. Hence, when the value of \( K \) is fixed, the computational complexity is fixed. However, the BFS-SD detection does not guarantee the optimal BER performance. If we set the value of \( K \) larger, the BER performance will be closer to the optimal BER performance. But if we set the value of \( K \) smaller, the computational complexity will be lower.

The tree structure of the SD needs to be modified for the IM scheme. Unlike the conventional spatial multiplexing schemes, the beam combinations of the IM limits the allowable code words to \( nb \cdot M \)-QAM symbols and \((Na - nb)\) zeros. For example, assume that \( Na = 4 \), \( nb = 3 \), and the SD detection has already visited three QAM symbol nodes. Then the leaf node that will be visited next must be the zero node. Figure 4 depicts the pruned tree 16 structure where the white node represents the zero node and the black node represents the QAM symbol. The error performances of the BFS-SD or the DFS-SD are very close to that of the maximum likelihood (ML) detector.

Fig. 4. (a) Speed gap with conventional SM, (b) SE-EE comparison with conventional MIMO
In this article, we have presented the index modulation schemes on different resources, such as antennas, subcarriers, or spatial beams. The IM schemes carry the extra index bits by selecting resource indices. At receiver, we have shown that the search tree in sphere decoder detection for the IM scheme can be pruned, which helps in avoiding fault traps as well as reducing the complexity of receiver. The energy efficiency (bits/J) of IM is always better than the classical MIMO OFDM system. The spectral efficiency (bits/Hz) of IM can also be better than the classical MIMO system in cases. The degree of freedom on selecting the combinations of resources indexing provides flexibility than the classical MIMO OFDM system. As “softness” being one of the key features for the next generation wireless communications, the flexibility provided by the IM technology offers attractive opportunities.

![Example of modified tree structure for the proposed BISM SD](image)

**Fig. 5.** Example of modified tree structure for the proposed BISM SD: \( N_b = 4; n_b = 3; M = 4 \). The white circle represents the zero, the black circle represents the QAM symbol, and the cross represents the invalid combination.

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