Dual-Mode Index Modulation Schemes for CPSC-MIMO Systems

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***Abstract*—Dual-mode index modulation schemes are those where a subset of the transmitted modulation symbols are from a different constellation than the rest of the transmitted modulation symbols. The indices of the symbols from two different constellations convey information bits in addition to those conveyed by the modulation symbols. In this paper, we employ this constellation-indexing technique to develop two new modulation schemes for frequency selective fading channels using cyclic-prefixed single-carrier (CPSC). We refer to these schemes as the *dual-mode time index modulation (DM-TIM)* and *dual-mode space-time index modulation (DM-STIM)*. The DM-TIM is a single transmit antenna modulation scheme and DM-STIM is a multi-antenna multiple-input multiple-output (MIMO) modulation scheme. In DM-TIM, information bits are conveyed through constellation indexing in the time domain as well as M-ary modulation symbols. In DM-STIM, in addition to the above two modes, information bits are also conveyed through antenna indexing in the spatial domain. Hence, the proposed index modulation schemes provide high data rate. We compare the proposed dual-mode index modulation schemes with state-of-art index modulation schemes and show that the proposed schemes can achieve better bit-error performance. Further, we present low-complexity message passing based algorithm for the detection of large-dimensional DM-TIM and DM-STIM signals.**

Keywords *– Dual-mode index modulation, multi-antenna systems, single-carrier systems, OFDM, CPSC, low-complexity detection.*

I. Introduction

Recently, index modulation schemes have been developed for reaping the spectral and energy advantages of the multi-antenna multiple-input multiple-output (MIMO) wireless systems [1]. Spatial modulation (SM) is an index modulation scheme in the spatial domain [2]. In SM, only one among many transmit antennas is activated in any channel use. The index of the active antenna used for transmission conveys information bits. Thus, SM reduces hardware complexity by using only one transmit radio frequency (RF) chain while improving spectral efficiency. It has been shown that SM and its generalization, known as the generalized spatial modulation (GSM) [3],[4] can provide better bit error performance for a given spectral efficiency [5].

For frequency selective fading channels, the index modulation technique has been applied using orthogonal frequency division multiplexing (OFDM). The index of the OFDM subcarriers are used to convey information bits in subcarrier index modulation (SIM) [6]. Generalized space-frequency index modulation (GSFIM) which performs indexing both in space and frequency domains was reported in [7]. In OFDM based index modulation schemes such as SIM and GSFIM, modulation symbols are transmitted only in the active subcarriers. The inactive subcarriers do not carry any modulation symbols. This can lead to a loss in throughput. To address this issue, a dual-mode subcarrier index modulation aided OFDM (DM-SIM) scheme was proposed in [8], [9]. In DM-SIM, subcarriers are split into two disjoint subsets. Subcarriers from one subset are modulated using a constellation that is different from that used to modulate the subcarriers from the complementary subset. The choice of the indices of the subcarriers in a subset conveys information bits. This scheme suffered from two disadvantages, namely, low diversity order (as OFDM does not provide channel diversity), and exponential complexity of detection. In order to obtain diversity advantages using single carrier schemes such as cyclic-prefixed single-carrier (CPSC), space-time index modulation (STIM) was proposed in [10]. In STIM, apart from the transmit antennas, time slots were indexed to convey information bits. Though STIM provides improved detection performance, the existence of inactive time slots may result in loss of system throughput.

In this paper, we propose the use of dual-mode constellation indexing for MIMO wireless systems with CPSC. Such a scheme would provide both high spectral efficiency and better bit-error-rate performance. The proposed dual-mode index modulation schemes are referred to as dual-mode time index modulation (DM-TIM) and dual-mode space-time index modulation (DM-STIM). In DM-TIM, only a single transmit antenna is used and the time slots in a CPSC frame are indexed using dual-mode constellations. Thus, information bits are conveyed through constellation indexing and modulation symbols. DM-STIM is the generalization of DM-TIM to multi-antenna transmitters, where only one of the multiple transmit antennas are activated in any channel use. In DM-STIM, in addition to constellation-indexing and modulation symbols, information bits are conveyed by the index of the active antenna as well. We also propose a low complexity algorithm based on multi-stage message passing for the detection of DM-STIM signals. Finally, using the low complexity detector, we show that the proposed dual-mode index modulation schemes perform better than other state-of-art index modulation schemes while providing high data rate.

In the next section, we shall mathematically describe the system model for the proposed index modulation schemes.

II. System model

Consider a wireless transmitter with n_t transmit antennas, n_{rf} transmit RF chains ($1 \leq n_{rf} \leq n_t$). Let n_r denote the number of receive antennas at the receiver. The transmitter communicates with the receiver through a frame of symbols using the cyclic-prefixed single-carrier (CPSC) scheme. The channel between all pairs of transmit and receive antennas is assumed to be frequency-selective with L multipaths. Each of the n_t transmit antennas transmit a frame, and each frame consists of $N + L - 1$ channel uses (time slots). The first N time slots convey information bits and the remaining $L - 1$ time slots are meant for appending cyclic prefix (CP). The

This work was supported in part by the J. C. Bose National Fellowship, Department of Science and Technology, Government of India.

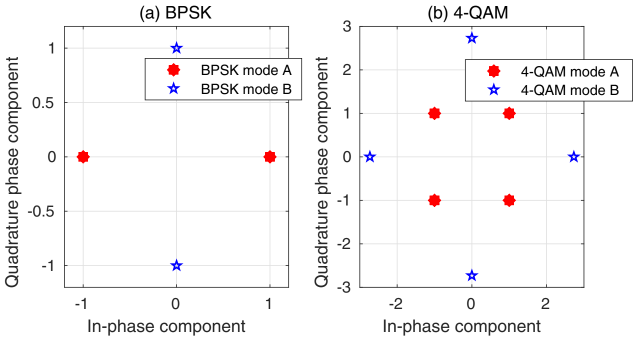

Fig. 1: Dual mode constellations.

information bits are conveyed using modulation symbols that are chosen from one of the two constellation alphabets $\mathcal{C}_A$ and $\mathcal{C}_B$, such that $\mathcal{C}_A \cap \mathcal{C}_B = \emptyset$.

Examples of $\mathcal{C}_A$ and $\mathcal{C}_B$: (1) $\mathcal{C}_A$ = binary phase shift keying (BPSK) symbols and $\mathcal{C}_B$ = BPSK rotated by $90°$. That is, $\mathcal{C}_A = \{1, -1\}$ and $\mathcal{C}_B = \{j, -j\}$. The constellations in the two modes A and B are illustrated in Fig. 1(a).
(2) An example using 4-QAM (quadrature amplitude modulation) is illustrated in Fig. 1(b). Here, $\mathcal{C}_A = \big\{1+j, 1-j, -1+j, -1-j\big\}$ is the 4-QAM constellation, and $\mathcal{C}_B = \big\{1+\sqrt{3}, -1-\sqrt{3}, j(1+\sqrt{3}), -j(1+\sqrt{3})\big\}$. In the next section, we shall describe the system models of our proposed dual-mode time index modulation (DM-TIM) and dual-mode space-time index modulation (DM-STIM) schemes.

III. Dual-Mode Index Modulation Schemes

Here, we shall describe the proposed index modulation schemes that achieve better rates compared to conventional index modulation schemes. Using maximum likelihood (ML) detector, we also show that the proposed schemes achieve better performance in terms of bit-error-rate (BER) compared to other index modulation and dual-mode schemes known in the literature.

A. Dual-Mode Time Index Modulation

In DM-TIM, we have $n_t = n_{rf} = 1$. The N time slots in a frame, corresponding to the information bits, are divided into two sets $\mathcal{I}_A$ and $\mathcal{I}_B$. The set $\mathcal{I}_A$ consists of the indices of k time slots, and the set $\mathcal{I}_B$ consists of the indices of $N-k$ slots. The symbols transmitted in the index of the time slots given by the sets $\mathcal{I}_A$ and $\mathcal{I}_B$ are chosen from the constellations $\mathcal{C}_A$ and $\mathcal{C}_B$, respectively. For an $N-$length frame and a fixed k, there are $\binom{N}{k}$ possible ways of constructing the sets $\mathcal{I}_A$ and $\mathcal{I}_B$. The choice of the two sets from the $\binom{N}{k}$ possible pairs conveys information bits. That is, the choice of $\mathcal{I}_A$ and $\mathcal{I}_B$ out of the $2^{\lfloor \log_2 \binom{N}{k} \rfloor}$ possible pairs, convey $\left\lfloor \log_2 \binom{N}{k} \right\rfloor$ information bits in addition to the information bits conveyed by the N modulation symbols. Thus, the rate achieved by the proposed DM-TIM is given by

$$R_{\text{DM-TIM}} = \frac{1}{N+L-1}\Bigg[\underbrace{\left\lfloor \log_2 \binom{N}{k} \right\rfloor}_{\text{constellation index bits}} + \underbrace{k \log_2 |\mathcal{C}_A| + (N-k)\log_2 |\mathcal{C}_B|}_{\text{modulation symbol bits}} \Bigg] \quad \text{bpcu}, \qquad (1)$$

where 'bpcu' stands for bits per channel use.

Let $\mathbf{x} = \begin{bmatrix} x_1 & x_2 & \ldots & x_N \end{bmatrix}^T$ denote the transmitted DM-TIM symbol vector of size $N \times 1$, where x_i is the symbol transmitted in the ith time slot. At the receiver, after removing the cyclic prefix, the received vector $\mathbf{y}$ can be represented as

$$\mathbf{y} \; = \; \mathbf{H}\mathbf{x} + \mathbf{n}, \qquad (2)$$

where $\mathbf{n}$ is the noise vector of size $Nn_r \times 1$ with $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}_{Nn_r})$, and $\mathbf{H}$ is the $Nn_r \times N$ equivalent block circulant channel matrix given by

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}_0 & 0 & 0 & 0 & \cdots & 0 & \mathbf{H}_{L-1} & \cdots & \mathbf{H}_1 \\ \mathbf{H}_1 & \mathbf{H}_0 & 0 & 0 & \cdots & 0 & 0 & \cdots & \mathbf{H}_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \mathbf{H}_{L-2} & \mathbf{H}_{L-3} & \mathbf{H}_{L-4} & \cdot & \mathbf{H}_0 & 0 & & \cdots & \mathbf{H}_{L-1} \\ \mathbf{H}_{L-1} & \mathbf{H}_{L-2} & \mathbf{H}_{L-3} & \cdot & \mathbf{H}_1 & \mathbf{H}_0 & 0 & \cdots & 0 \\ 0 & \mathbf{H}_{L-1} & \mathbf{H}_{L-2} & \cdot & \mathbf{H}_2 & \mathbf{H}_1 & \mathbf{H}_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \\ 0 & 0 & 0 & \cdot & \cdot & \cdot & \cdot & \cdots & \mathbf{H}_0, \end{bmatrix},$$

where $\mathbf{H}_l$ is the $n_r \times n_t$ channel matrix corresponding to the lth multipath. The channel is assumed to remain invariant over each frame of transmission. Assuming perfect knowledge of $\mathbf{H}$ at the receiver, the ML detection rule for DM-TIM is

$$\hat{\mathbf{x}} = \underset{\forall \mathbf{x}}{\text{argmin}} \; \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2. \qquad (3)$$

Example: Let $N = 4, L = 2$, $k = 2$. Here, $\binom{N}{k} = 6$ and $\left\lfloor \log_2 \binom{4}{2} \right\rfloor = 2$. Out of the 6 possible pairs of the index sets $\mathcal{I}_A$ and $\mathcal{I}_B$, we allow $2^{\lfloor \log_2 \binom{N}{k} \rfloor} = 4$ pairs for modulation, let the allowed pairs be

$$\mathcal{I}_A \in \left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix}, \begin{bmatrix} 2 \\ 3 \end{bmatrix}, \begin{bmatrix} 3 \\ 4 \end{bmatrix}, \begin{bmatrix} 1 \\ 4 \end{bmatrix} \right\} \text{ and } \mathcal{I}_B = \mathcal{I}_A^c,$$

where $(.)^c$ denotes set complement. Now, $\left\lfloor \log_2 \binom{N}{k} \right\rfloor = 2$ information bits select one of the 4 pairs of the index sets. In those time slots whose indices are given by the set $\mathcal{I}_A$, modulation symbols from the constellation $\mathcal{C}_A$ are transmitted. These symbols are chosen using $k \log_2 |\mathcal{C}_A|$ information bits. Similarly, $(N-k)\log_2 |\mathcal{C}_A|$ information bits are conveyed by modulation symbols, from the constellation $\mathcal{C}_B$, transmitted in the time slots given by the set $\mathcal{I}_B$. If $\mathcal{C}_A$ = BPSK and $\mathcal{C}_B$ = BPSK rotated by $90°$, then 4 bits are conveyed through modulation symbols and 2 bits are conveyed through indexing. Thus, the achievable rate by DM-TIM in this example is $\frac{6}{5} = 1.2$ bpcu. In a frame, if the chosen index sets are $\mathcal{I}_A = \begin{bmatrix} 1 & 2 \end{bmatrix}^T$ and $\mathcal{I}_B = \begin{bmatrix} 3 & 4 \end{bmatrix}^T$, then the transmit vector can be $\mathbf{x} = \begin{bmatrix} 1 & -1 & -j & j \end{bmatrix}^T$.

Note that, under the same system configurations, DM-OFDM achieves the same rate; however, the CPSC scheme gives higher diversity order compared to OFDM [11]. Thus, the proposed DM-TIM can achieve better detection performance than DM-OFDM. This will be further illustrated in Section III-C.

The proposed DM-TIM scheme works with a single transmit antenna. In order to harness the advantages of multiple transmit antennas with a single transmit RF chain and dual-mode constellations, we propose DM-STIM in the next subsection.

B. Dual-Mode Space-Time Index Modulation

Here, we shall construct the dual-mode space-time index modulation (DM-STIM) scheme by extending the DM-TIM scheme to include multiple transmit antennas. In DM-STIM, the transmitter consists of multiple transmit antennas (i.e., $n_t > 1$) and a single RF chain ($n_{rf} = 1$). In any given channel use (i.e., time slot), only one of the n_t transmit antennas are active, and the rest of the $n_t - 1$ transmit antennas remain silent. In a given time slot, the active transmit antenna sends a modulation symbol as discussed in the previous subsection. The choice of the active transmit antenna in every channel use is given by $\lfloor \log_2 n_t \rfloor$ information bits. Thus, in addition to the modulation symbols and the indices of the time slots, the index of the active antenna also conveys information bits. Thus, the total achievable rate in DM-STIM is given by

$$R_{\text{DM-TI-SM}} = \frac{1}{N+L-1}\Bigg[\underbrace{N\lfloor \log_2 n_t \rfloor}_{\text{antenna index bits}} + \underbrace{\left\lfloor \log_2 \binom{N}{k} \right\rfloor}_{\text{constellation index bits}} + \underbrace{k \log_2 |\mathcal{C}_A| + (N-k)\log_2 |\mathcal{C}_B|}_{\text{modulation symbol bits}}\Bigg] \text{bpcu.} \quad (4)$$

Let $\mathbf{x}_i$ denote the transmitted symbol vector of size $n_t \times 1$ in the ith channel use. Here, $\mathbf{x}_i$ is a spatially modulated vector with a non-zero symbol at the index given by the index of the active antenna in the ith time slot. After removing the cyclic prefix, the received vector $\mathbf{y}$ can be represented as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (5)$$

where $\mathbf{n}$ is the noise vector, $\mathbf{x}$ is the transmit vector of size $Nn_t \times 1$ given by $\mathbf{x} = \left[\mathbf{x}_L^T \;\; \mathbf{x}_{L+1}^T \;\; \dots \;\; \mathbf{x}_{N+L-1}^T\right]^T$, and $\mathbf{H}$ is the $Nn_r \times Nn_t$ equivalent block circulant channel matrix. With perfect channel knowledge at the receiver, the ML detection rule for DM-STIM is given by

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathbb{S}}{\text{argmin}} \; \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2, \quad (6)$$

where $\mathbb{S}$ denotes the set of all possible DM-STIM transmit vectors.

C. ML Performance Results

In this subsection, we shall compare the ML detection performance of the proposed DM-TIM and DM-STIM systems with that of the state-of-art index modulation schemes such as DM-SIM [8] and STIM [10] systems. We consider a frequency selective fading channel with $L = 2$ multipaths. The power delay profile of the channel is assumed to follow the exponential model.

In Fig. 2, we present the ML performance comparisons between (i) DM-STIM system with $n_t = 2$, $n_{rf} = 1$, $k = 3$, dual-mode BPSK and 2.3 bpcu, (ii) STIM system with $n_t = 2$, $n_{rf} = 1$, $k = 3$, 8-QAM and 2.3 bpcu, (iii) DM-TIM and DM-SIM systems with $n_t = 1$, $n_{rf} = 1$, $k = 3$, dual-mode 4-QAM and 2.3 bpcu, and (iv) OFDM with $n_t = n_{rf} = 1$, 8-QAM and 2.57 bpcu. For all the systems, we assume $N = 6, L = 2$, and $n_r = 4$. From Fig. 2, we can observe that the proposed DM-TIM scheme

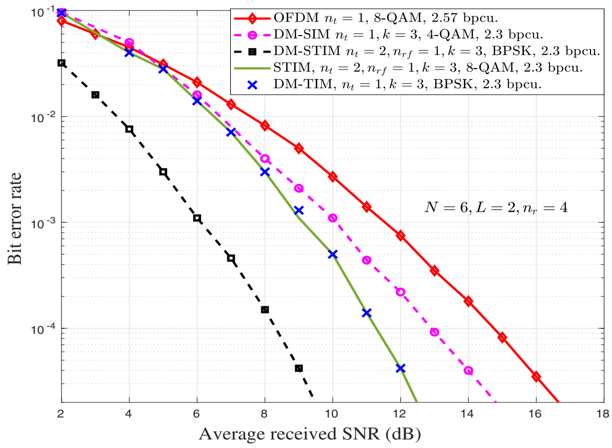

Fig. 2: ML performance comparison of DM-STIM, DM-TIM, STIM, DM-SIM and OFDM for $N = 6, L = 2, n_r = 4$. DM-STIM system parameters are: $n_t = 2$, $n_{rf} = 1$, $k = 3$, BPSK, and 2.3 bpcu. STIM system parameters are: $n_t = 2$, $n_{rf} = 1$, $k = 3$, 8-QAM, and 2.3 bpcu. DM-TIM and DM-SIM system parameters are: $n_t = n_{rf} = 1$, $k = 3$, 4-QAM, and 2.3 bpcu. OFDM system parameters are: $n_t = n_{rf} = 1$, 8-QAM, and 2.57 bpcu

outperforms the DM-SIM scheme by about 1.8 dB at a BER of 10^{-4}. Further, the proposed DM-STIM scheme outperforms both DM-TIM and STIM by about 3 dB at 10^{-4} BER. The proposed DM-TIM and DM-STIM schemes achieve this performance advantage due to the additional time diversity provide by the CPSC technique. Thus, we can see that the proposed DM-TIM and DM-STIM schemes can achieve better performance and high data rate compared to the state-of-art index modulation schemes.

The ML detection complexity is given by $O(N^2 n_r n_t 2^{R(N+L-1)})$, where R is the rate of DM-TIM or DM-STIM scheme. Note that the complexity of ML detection of the proposed DM-TIM and DM-STIM schemes increase exponentially with the increase in the frame length N. the ML. This motivates us to design low complexity detectors for the proposed dual-mode index modulation schemes to reap its benefits of high data rate and improved performance.

IV. Low Complexity DM-STIM Signal Detection

In this section, we design message passing based low complexity detector for the proposed DM-STIM signaling scheme. Note that the DM-STIM scheme reduces to the DM-TIM scheme when $n_t = 1$; hence, the following low complexity detection technique is also applicable for DM-TIM.

The proposed low complexity DM-STIM detection (DSD) is carried out in two stages, both the stages are based on message passing algorithm. The first stage performs message passing over a factor graph [12] to provide an estimate of the index of the active antenna in each of the N time slots of the DM-STIM frame. This is followed by a layered message passing detector [13] to obtain an estimate of the index sets $\mathcal{I}_A$, $\mathcal{I}_B$, and the modulation symbols. These estimates are demapped to get the transmitted bit sequence. The two stages of the detection algorithm can be described as follows.

Stage-1 : The first stage of the detection algorithm is a vector message passing [14] based technique to detect the N

indices of the active antennas in a DM-STIM frame. Let $\mathbb{M}$ denote the set of all possible $n_t \times 1$ vectors that could be transmitted by the DM-STIM transmitter in any channel use. For example, consider a system with $n_t = 2$ and dual-mode BPSK constellation. The set $\mathbb{M}$ for this system is given by

$$\mathbb{M} = \left\{ \begin{bmatrix}1\\0\end{bmatrix}, \begin{bmatrix}0\\1\end{bmatrix}, \begin{bmatrix}-1\\0\end{bmatrix}, \begin{bmatrix}0\\-1\end{bmatrix}, \begin{bmatrix}j\\0\end{bmatrix}, \begin{bmatrix}0\\j\end{bmatrix}, \begin{bmatrix}-j\\0\end{bmatrix}, \begin{bmatrix}0\\-j\end{bmatrix}. \right\}.$$

The first stage of the message passing algorithm works on the system model given by (5). Here, $\mathbf{x} = \begin{bmatrix}\mathbf{x}_1^T & \mathbf{x}_2^T & \cdots & \mathbf{x}_j^T & \cdots & \mathbf{x}_N^T\end{bmatrix}^T$, where $\mathbf{x}_j \in \mathbb{M}$ is the n_t-length vector transmitted in the jth time slot. The factor graph representing this system model consists of N variable nodes each corresponding to a transmit vector $\mathbf{x}_j$, and Nn_r observation nodes each corresponding to a received symbol y_i. From (5), the received signal y_i can be written as

$$y_i \;=\; \mathbf{h}_{i,[j]}\mathbf{x}_j + \underbrace{\sum_{l=1,l\neq j}^{N} \mathbf{h}_{i,[l]}\mathbf{x}_l + n_i}_{\triangleq q_{i,j}}, \tag{7}$$

where $\mathbf{h}_{i,[l]}$ is a row vector of length n_t given by $\begin{bmatrix}H_{i,(l-1)n_t+1} & H_{i,(l-1)n_t+2} & \cdots & H_{i,ln_t}\end{bmatrix}$. For large values of N, using central limit theorem, we approximate the term $q_{i,j}$ to be Gaussian with mean $\mu_{i,j}$ and variance $\sigma^2_{i,j}$, where

$$\mu_{i,j} = \mathbb{E}\left[\sum_{\substack{l=1,\\ l\neq j}}^{N} \mathbf{h}_{i,[l]}\mathbf{x}_l + n_i\right] = \sum_{\substack{l=1,\\ l\neq j}}^{N}\sum_{\mathbf{s}\in\mathbb{M}} \hat{p}_{li}(\mathbf{s})\mathbf{h}_{i,[l]}\mathbf{s}, \tag{8}$$

$$\begin{aligned}\sigma^2_{i,j} &= \mathrm{Var}\left(\sum_{\substack{l=1,\\ l\neq j}}^{N} \mathbf{h}_{i,[l]}\mathbf{x}_l + n_i\right)\\ &= \sum_{\substack{l=1,\\ l\neq j}}^{N}\left(\sum_{\mathbf{s}\in\mathbb{M}}\hat{p}_{li}(\mathbf{s})\mathbf{h}_{i,[l]}\mathbf{s}\mathbf{s}^H\mathbf{h}^H_{i,[l]} - \left|\sum_{\mathbf{s}\in\mathbb{M}}\hat{p}_{li}(\mathbf{s})\mathbf{h}_{i,[l]}\mathbf{s}\right|^2\right) + \sigma^2, \end{aligned} \tag{9}$$

where $\hat{p}_{ji}(\mathbf{s})$ denotes the a posteriori probability message computed at the variable nodes using the following expression:

$$\hat{p}_{ji}(\mathbf{s}) \propto \prod_{m=1,\ m\neq i}^{Nn_r} \exp\left(\frac{-\left|y_m - \mu_{m,j} - \mathbf{h}_{m,[j]}\mathbf{s}\right|^2}{\sigma^2_{m,j}}\right). \tag{10}$$

The final APPs in stage-1 are computed as

$$\hat{p}_j(\mathbf{s}) \propto \prod_{i=1}^{Nn_r} \exp\left(\frac{-\left|y_i - \mu_{i,j} - \mathbf{h}_{i,[j]}\mathbf{s}\right|^2}{\sigma^2_{i,j}}\right),\ j = 1,2,\ldots,N. \tag{11}$$

The stage-1 of the detection algorithm is concluded by computing the estimates $\hat{\mathbf{x}}_j = \underset{\mathbf{s}\in\mathbb{M}}{\mathrm{argmax}}\ \hat{p}_j(\mathbf{s})$. The estimate of the active antenna index in the jth time slot is obtained from the position of the non-zero element in $\hat{\mathbf{x}}_j$. Having obtained the estimates of the index of the active antenna in the N time slots of the DM-STIM frame, we can reduce (5) to the form

$$\mathbf{y} \;=\; \bar{\mathbf{H}}\mathbf{z} + \mathbf{n}, \tag{12}$$

where $\mathbf{z}$ is an $N \times 1$ vector such that z_j is the non-zero element in $\mathbf{x}_j$, and $\bar{\mathbf{H}}$ is the $Nn_r \times N$ channel matrix obtained by retaining only those columns of $\mathbf{H}$ that correspond to the non-zero entries of $\hat{\mathbf{x}}_j$. The reliability of the estimate of the non-zero entries of $\hat{\mathbf{x}}_j$ can be further improved using a second stage of message passing.

Stage-2: The second stage of the detection algorithm is a layered message passing based detector [13] that works on a graph representing the system model given by (12). This stage gives the estimates of the index sets $\mathcal{I}_A$ and $\mathcal{I}_B$ and the modulation symbols. Let s_j be an indicator variable for the jth time slot defined as $s_j = \mathbb{I}_{\mathcal{I}_A}(j)$, where $\mathbb{I}(.)$ is the indicator function. That is, $s_j = 1$ for $j \in \mathcal{I}_A$ and $s_j = 0$ for $j \in \mathcal{I}_B$. Since $\mathcal{I}_A$ and $\mathcal{I}_B$ consist of k and $N-k$ indices, respectively, we have $\sum_{j=1}^{N} s_j = k$. This is referred to as the DM-STIM index set constraint $\mathbf{S}$. Let $\mathbf{s} \triangleq [s_1, s_2, \cdots, s_N]$. The layered graph consists of two layers, with each layer consisting of two sets of nodes [13]. Messages are exchanged between these layers: one corresponding to the probabilities of the modulation symbols and the other corresponding to the probabilities of the indicator variables. The following are the four sets of nodes: (i) Nn_r observation nodes corresponding to the elements of $\mathbf{y}$, (ii) N variable nodes corresponding to the elements of $\mathbf{z}$, (iii) N indicator nodes corresponding to the elements of $\mathbf{s}$, and (iv) a constraint node corresponding to the index set constraint $\mathbf{S}$. In the first layer, the approximate APPs of the individual elements of $\mathbf{z}$ are produced by exchanging messages between the observation and the variable nodes. In the second layer, messages are exchanged between the indicator nodes and the DM-STIM index set constraint node to produce the APPs of the elements of $\mathbf{s}$. To generate these messages, we utilize Gaussian approximation of interference. We write the ith element of $\mathbf{y}$ in (12) as

$$y_i \;=\; \bar{H}_{i,l}z_l + \underbrace{\sum_{j=1,j\neq l}^{N} \bar{H}_{i,j}z_j + n_i}_{\triangleq f_{i,l}}, \tag{13}$$

where $i = 1,2,\cdots,n_rN$ and $l = 1,2,\cdots,N$. We approximate $f_{i,l}$ to be Gaussian with mean $\hat{\mu}_{i,l}$ and variance $\hat{\sigma}^2_{i,l}$, which are calculated as

$$\hat{\mu}_{i,l} = \mathbb{E}\left[\sum_{\substack{j=1,\\ j\neq l}}^{N} \bar{H}_{i,j}z_j + n_i\right],\quad \hat{\sigma}^2_{i,l} = \mathrm{Var}\left(\sum_{\substack{j=1,\\ j\neq l}}^{N} \bar{H}_{i,j}z_j\right) + \sigma^2. \tag{14}$$

The messages passed between the nodes in stage-2 can be computed as follows.

Layer 1: The message v_{il} at the observation node is

$$v_{il}(z) \triangleq \Pr(z_l = z|y_i) \approx \frac{1}{\hat{\sigma}_{i,l}\sqrt{2\pi}}\exp\left(\frac{-(y_i - \hat{\mu}_{i,l} - z\bar{H}_{i,l})^2}{2\hat{\sigma}^2_{i,l}}\right), \tag{15}$$

where $z \in \mathcal{C}_A \cup \mathcal{C}_B$. The APP of the individual elements of $\mathbf{z}$ is obtained at the variable nodes as

$$p_{li}(z) \triangleq \Pr(z_l = z|\mathbf{y}_{/i}) \approx \prod_{j=1,j\neq i}^{n_rN} \Pr(z_l = z|y_j) \propto u_l(z^0)\prod_{j=1,j\neq i}^{n_rN} v_{jl}(z), \tag{16}$$

where $\mathbf{y}_{/i}$ denotes the set of all elements of $\mathbf{y}$ except y_i.

Layer 2: The APPs of s_l are computed from the variable nodes as

$$q_l(b) \triangleq \Pr(s_l = b|\mathbf{z}) \propto \begin{cases} \sum_{z \in C_A} \prod_{j=1}^{n_r N} v_{jl}(z), & \text{if } b = 1 \\ \sum_{z \in C_B} \prod_{j=1}^{n_r N} v_{jl}(z), & \text{if } b = 0. \end{cases} \tag{17}$$

The APP estimate of s_l computed at the indicator nodes after processing the DM-STIM index set constraint $\mathbf{S}$ is

$$\begin{aligned} u_l(b) &= \Pr(s_l = b|\mathbf{z}_{/l}) \\ &\propto \begin{cases} \Pr(\sum_{j=1, j\neq l}^{N} s_j = k-1|\mathbf{s}_{/l}), & \text{if } b = 1 \\ \Pr(\sum_{j=1, j\neq l}^{N} s_j = k|\mathbf{s}_{/l}), & \text{if } b = 0 \end{cases} \end{aligned} \tag{18}$$

where $\Pr(\sum_{j=1, j\neq l}^{N} s_j = k-1|\mathbf{s}_{/l})$ denotes the probability that the estimated index sets satisfy the DM-STIM index set constraint $\mathbf{S}$ given that the lth time slot belongs to $\mathcal{I}_A$, and $\Pr(\sum_{j=1, j\neq l}^{s} s_j = k|\mathbf{s}_{/l})$ denotes the probability that the estimated index sets satisfy $\mathbf{S}$ given that the lth time slot belongs to $\mathcal{I}_B$.

The schedule of the messaging passing algorithm can be summarized as follows.

1) Stage-1
   a) Initialize $\hat{p}_{ji}(\mathbf{s}) = \frac{1}{|\mathbb{M}|}$, $\forall j, i, \mathbf{s}$.
   b) Compute μ_{ij}, and $\sigma^2_{i,j}$ $\forall i, j$.
   c) Compute $\hat{p}_{ji}$, $\forall j, i$.
   d) After Q_1 iterations, compute $\hat{\mathbf{x}}_j$.
2) Stage-2
   a) Initialize $p_{li}(z) = \frac{1}{|C_A \cup C_B|}$, $q_l(1) = \frac{k}{N}$, $q_l(0) = 1 - \frac{k}{N}$, $\forall z, i, l$.
   b) Compute $v_{il}(z)$ and $p_{li}(z)$, $\forall z, l, i$.
   c) Compute $u_l(b)$ and $q_l(b)$, $\forall l, b$.
   d) Compute , $\forall l, b$.
   e) Terminate after Q_2 iteration

At the end of message passing algorithm, an estimate of the index sets are obtained from the APPs of the time slots. These estimates are demapped to get the time slot index bits. From p_{li}'s, an estimate of the information bits corresponding to the N modulation symbols are also obtained.

Performance results: Here, we compare the performance of the proposed DM-STIM scheme using the low complexity DM-STIM detector (DSD) with that of the stat-of-art index modulation schemes. In Fig. 3, we present the performance comparisons between (i) DM-STIM system with $n_t = 2$, $n_{rf} = 1$, $k = 8$, dual-mode BPSK, 2.65 bpcu, and the proposed DSD algorithm, (ii) STIM system with $n_t = 2$, $n_{rf} = 1$, $k = 15$, 4-QAM, 2.88 bpcu, and DSD algorithm with $\mathcal{C}_B = \{0\}$, (iii) DM-SIM system with $n_t = n_{rf} = 1$, $k = 8$, dual-mode 4-QAM, 2.65 bpcu, and the LLR based optimal detector presented in [8], and (iv) OFDM with $n_t = n_{rf} = 1$, 8-QAM, 2.82 bpcu, and ML detector.

In all the considered systems, we have $N = 16$, $L = 2$, and $n_r = 4$. From Fig. 3, we can see that the proposed DM-STIM scheme outperforms all other index modulation schemes using the proposed DSD algorithm. Specifically, the proposed DM-STIM is better than STIM and DM-SIM by about 2 dB and 4 dB, respectively, at a BER of 10^{-4}. Further, the proposed DSD algorithm achieves the benefits of high data rate and better BER performance offered by DM-STIM at low computational complexity. Thus, we conclude that the proposed DM-STIM scheme is a promising index modulation scheme with high data rate and low complexity of detection.

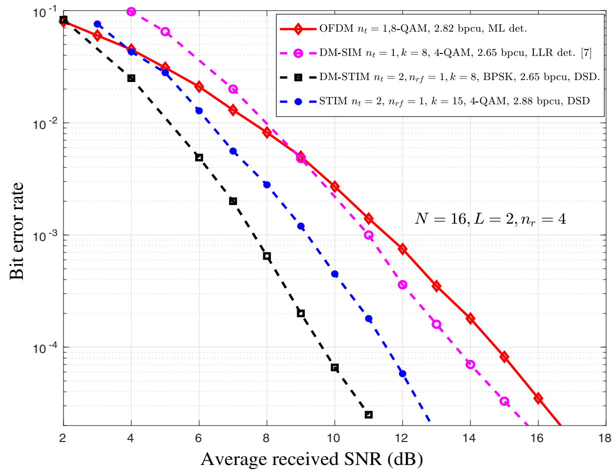

Fig. 3: Performance comparison of DM-STIM, STIM, DM-SIM and OFDM for $N = 16, L = 2, n_r = 4$. DM-STIM system parameters are: $n_t = 2$, $n_{rf} = 1$, $k = 8$, BPSK, and 2.65 bpcu. STIM system parameters are: $n_t = 2$, $n_{rf} = 1$, $k = 15$, 4-QAM, and 2.88 bpcu. DM-SIM system parameters are: $n_t = n_{rf} = 1$, $k = 8$, 4-QAM, and 2.65 bpcu. OFDM system parameters are: $n_t = n_{rf} = 1$, 8-QAM, and 2.82 bpcu

References

[1] E. Basar, "Index modulation techniques for 5G wireless networks," *IEEE Commun. Mag.*, vol. 54, no. 7, pp. 168-175, Apr. 2016.

[2] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized MIMO: challenges, opportunities and implementation," *Proc. of the IEEE*, vol. 102, no. 1, pp. 56-103, Jan. 2014.

[3] J. Wang, S. Jia, and J. Song, "Generalised spatial modulation system with multiple active transmit antennas and low complexity detection scheme," *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1605-1615, Apr. 2012.

[4] T. Datta and A. Chockalingam, "On generalized spatial modulation," *Proc. IEEE WCNC'2013*, pp. 2716-2721, Apr. 2013.

[5] T. L. Narasimhan, P. Raviteja, and A. Chockalingam, "Generalized spatial modulation in large-scale multiuser MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3764-3779, Jul. 2015.

[6] E. Basar, U. Aygolu, E. Panayirci, and H. V. Poor, "Orthogonal frequency division multiplexing with index modulation," *Proc. IEEE GLOBECOM'2012*, pp. 4741-4746, Dec. 2012.

[7] T. Datta, H. Eshwaraiah, and A. Chockalingam, "Generalized space and frequency index modulation," *IEEE Trans. Veh. Tech.*, vol. 65, no. 7, pp.4911-4924, Jul. 2016.

[8] T. Mao, Z. Wang, Q. Wang, S. Chen, and L. Hanzo, "Dual-mode index modulation aided OFDM," *IEEE Access*, vol. 5, pp. 50-60, Feb. 2017.

[9] T. Mao, Q. Wang, and Z. Wang, "Generalized dual-mode index modulation aided OFDM," *IEEE Commun. Letters*, vol. 21, no. 4, pp. 761-764, Apr. 2017.

[10] S. Jacob, T. L. Narasimhan, and A. Chockalingam, "Space-time index modulation," *Proc. IEEE WCNC*, San Francisco, Mar. 2017.

[11] Z. Wang, X. Ma, and G. B. Giannakis, "OFDM or single-carrier block transmissions?," *IEEE Trans. Commun.*, vol. 52, no. 3, pp. 380-394, Mar. 2004.

[12] P. Som, T. Datta, N. Srinidhi, A. Chockalingam, and B. S. Rajan, "Low-complexity detection in large-dimension MIMO-ISI channels using graphical models," *IEEE Jl. Sel. Topics in Signal Processing (JSTSP)*, vol. 5, no. 8, pp. 1497-1511, Dec. 2011.

[13] T. L. Narasimhan and A. Chockalingam, "On the capacity and performance of generalized spatial modulation," *IEEE Commun. Letters*, vol. 20, no. 2, pp. 252-255, Feb. 2016.

[14] T. L. Narasimhan and A. Chockalingam, "Detection and decoding in large-scale MIMO systems: A non-binary belief propagation approach," *Proc. IEEE VTC*, Korea, May 2014.