CHEMP RECEIVER FOR LARGE-SCALE MULTIUSER MIMO SYSTEMS USING SPATIAL MODULATION

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ABSTRACT

In spatial modulation (SM), information bits are conveyed through the index of the active transmit antenna in addition to the information bits conveyed through conventional modulation symbols. In this paper, we propose a receiver for large-scale multiuser spatial modulation MIMO (SM-MIMO) systems. The proposed receiver exploits the channel hardening phenomenon observed in large-dimensional MIMO channels. It works with a matched filtered system model. On this system model, it obtains an estimate of the matched filtered channel matrix (rather than the channel matrix itself) and uses this estimate for detecting the data. The data detection is done using an approximate message passing algorithm. The proposed receiver, referred to as the channel hardening-exploiting message passing receiver for SM (CHEMP-SM), is shown to achieve very good performance at low complexity.

Keywords – *Large-scale MIMO systems, spatial modulation, SM-MIMO, message passing, channel hardening.*

1. INTRODUCTION

Large-scale MIMO systems with tens to hundreds of antennas are becoming viable in practice [1]- [4]. More and more research and development efforts are being directed towards this promising area with a motivation to harness the theoretically predicted rate, reliability, and power efficiency benefits of large-scale MIMO systems in practice. One of the key issues in MIMO systems with a large number of antennas is the need to have a large number of radio frequency (RF) chains. This increases the hardware complexity, size, and cost. Spatial modulation (SM) [5] is an interesting multi-antenna modulation scheme which can address this issue. In SM, the transmitter will have multiple transmit antennas but only one transmit RF chain. In a given channel use, only one antenna will be active and the remaining antennas remain silent. The index of the active transmit antenna conveys information bits in addition to the information bits conveyed through the modulation symbol transmitted through the active antenna. In this paper, we are interested in multiuser systems where tens of users employing SM communicate with a base station having tens to hundreds of antennas. We refer to this system as large-scale multiuser SM-MIMO system.

One of the key issues in large-scale multiuser SM-MIMO systems is the large-dimensional signal processing at the base station receiver. Maximum-likelihood (ML) detection performance of multiuser SM-MIMO for small number of users and base station antennas is reported in [6]. Because of its exponential complexity in the number of dimensions, ML detection is not possible in large-scale SM-MIMO systems. In [7], low complexity algorithms based on local search and message passing have been reported for large-scale SM-MIMO systems. The works in [6], [7] have demonstrated that, for the same spectral efficiency, multiuser SM-MIMO performs better than conventional multiuser MIMO[1] under typical system configurations.

In the context of low complexity receiver signal processing in large dimensions, [8] has reported an efficient receiver scheme for conventional multiuser MIMO systems. Since this receiver exploited the channel hardening effect that occurs in large-dimension MIMO channels, it is referred to as 'channel-hardening-exploiting message passing (CHEMP)' receiver. Two key aspects in the CHEMP receiver are: 1) it works with a matched filtered system model instead of the original system model, and 2) it estimated the matched filtered channel matrix instead of the channel matrix itself. The detection was based on approximate message passing. The CHEMP receiver architecture is a promising architecture in terms of both performance and complexity. So the CHEMP receiver architecture is worth investigating in the context of large-scale multiuser SM-MIMO. Our new contribution in this paper is in this direction. We propose CHEMP receiver for multiuser SM-MIMO and and study its performance and complexity We refer to the proposed receiver as CHEMP-SM receiver. Our simulation results show that 1) the CHEMP-SM receiver achieves significantly better performance than MMSE receiver at a lesser complexity than the MMSE receiver, and 2) multiuser SM-MIMO achieves better performance than conventional multiuser MIMO under typical system configurations.

2. SYSTEM MODEL

Consider the multiuser SM-MIMO system on the uplink shown in Fig. 1. The system consists of K uplink user terminals transmitting to a base station (BS) having N receive

[1]Large-scale conventional multiuser MIMO systems with tens of users and hundreds of base station antennas are referred to as 'massive MIMO systems' in the recent literature.

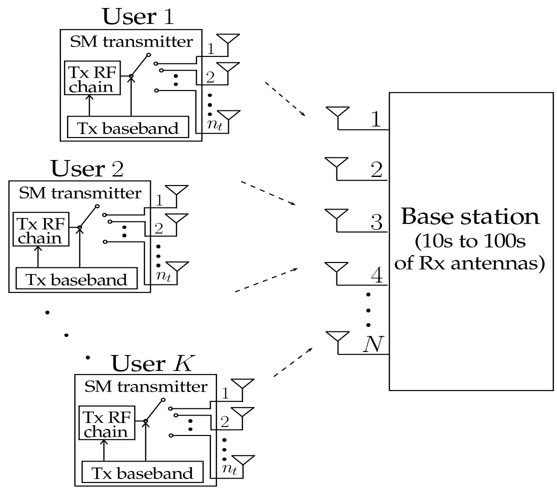


Fig. 1: Large-scale multiuser SM-MIMO system.

antennas. N is in the order of tens to hundreds, and K is in tens. The ratio $\alpha = K/N$ is defined as the system loading factor. Each one of the K user terminals has n_t transmit antennas but only one transmit RF chain, and the information transmitted by these K user terminals are spatially modulated. That is, each user's information bits are conveyed to the BS in two parts: $i)$ through the index of the transmitting antenna, and $ii)$ through a symbol from a modulation alphabet $\mathbb{A}$. Specifically, in each channel use, each user terminal transmits a symbol from $\mathbb{A}$ through one of its n_t transmit antennas, and this transmit antenna is chosen based on antenna index bits. The number of bits conveyed per channel use per user through the modulation symbol is $\lfloor \log_2 |\mathbb{A}| \rfloor$ and that through the antenna index is $\lfloor \log_2 n_t \rfloor$. Hence, a total of $\lfloor \log_2 |\mathbb{A}| \rfloor + \lfloor \log_2 n_t \rfloor$ bits per channel use (bpcu) per user is conveyed. For e.g., in a system with $K = 10$, $n_t = 2$, 4-QAM, the system throughput is 30 bpcu.

The SM signal set, denoted by $\mathbb{S}_{n_t,\mathbb{A}}$, is parameterized by n_t and $\mathbb{A}$, and is given by

$$\begin{aligned} &\mathbb{S}_{n_t,\mathbb{A}} = \big\{ \mathbf{s}_{j,l} : j = 1, \cdots, n_t, \;\; l = 1, \cdots, |\mathbb{A}| \big\}, \\ &\text{s.t. } \mathbf{s}_{j,l} = [0, \cdots, 0, \underbrace{s_l}_{j\text{th coordinate}}, 0, \cdots, 0]^T, \;\; s_l \in \mathbb{A}. \end{aligned} \quad (1)$$

For e.g., for $n_t = 2$ and 4-QAM, $\mathbb{S}_{n_t,\mathbb{A}}$ is given by

$$\mathbb{S}_{2,\text{4-QAM}} = \left\{ \begin{bmatrix} +1+j \\ 0 \end{bmatrix}, \begin{bmatrix} +1-j \\ 0 \end{bmatrix}, \begin{bmatrix} -1+j \\ 0 \end{bmatrix}, \begin{bmatrix} -1-j \\ 0 \end{bmatrix}, \right.$$
$$\left. \begin{bmatrix} 0 \\ +1+j \end{bmatrix}, \begin{bmatrix} 0 \\ +1-j \end{bmatrix}, \begin{bmatrix} 0 \\ -1+j \end{bmatrix}, \begin{bmatrix} 0 \\ -1-j \end{bmatrix} \right\}. \quad (2)$$

Let $\mathbf{x}_k \in \mathbb{S}_{n_t,\mathbb{A}}$ denote the spatially modulated signal vector of the kth user. Let

$$\mathbf{x} \triangleq [\mathbf{x}_1^T \;\; \mathbf{x}_2^T \; \cdots \; \mathbf{x}_i^T \; \cdots \; \mathbf{x}_K^T]^T \quad (3)$$

denote the vector obtained by stacking the SM signal vectors from all the K users. Note that $\mathbf{x} \in \mathbb{S}_{n_t,\mathbb{A}}^K$.

Let $\mathbf{H} \in \mathbb{C}^{N \times K n_t}$ denote the channel gain matrix, where the entry $H_{i,(k-1)n_t+j}$ denotes the channel gain from the jth transmit antenna of the kth user to the ith receive antenna at the BS. The entries of $\mathbf{H}$ are assumed to be i.i.d. Gaussian with zero mean and variance σ_k^2, such that $\sum_k \sigma_k^2 = K$. The σ_k^2 models the imbalance in the received power from user k due to path loss etc., and $\sigma_k^2 = 1$ corresponds to the case of perfect power control. Assuming perfect synchronization, the signal received at the ith BS antenna is

$$y_i = \sum_{k=1}^{K} x_{l_k} H_{i,(k-1)n_t+j_k} + n_i, \quad (4)$$

where x_{l_k} is the l_kth symbol in $\mathbb{A}$, transmitted by the j_kth antenna of the kth user, and n_i is the noise modeled as $\mathcal{CN}(0, \sigma^2)$. The received signal at the BS antennas can be written in vector form as

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

where $\mathbf{y} = [y_1, \; y_2, \cdots, \; y_N]^T$ and $\mathbf{n} = [n_1, \; n_2, \cdots, \; n_N]^T$. For the system model in (5), the maximum-likelihood (ML) detection rule is given by

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

and the maximum a posteriori probability (MAP) decision rule is given by

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathbb{S}_{n_t,\mathbb{A}}^K}{\text{argmax}} \; \Pr(\mathbf{x} \mid \mathbf{y}, \mathbf{H}). \quad (7)$$

Note that, $|\mathbb{S}_{n_t,\mathbb{A}}^K| = (|\mathbb{A}| n_t)^K$. So the exact computation of (6) and (7) requires exponential complexity in K. We propose a low complexity message passing based SM signal detection algorithm that exploits channel hardening.

Channel hardening in large-scale MIMO channels: Channel hardening refers to the phenomenon where, as n_r and n_t in a $n_r \times n_t$ MIMO channel are increased keeping their ratio fixed, the distribution of the singular values of the MIMO channel matrix $\mathbf{H}$ becomes less sensitive to the actual distribution of the entries of the channel matrix (as long as the entries are i.i.d.) [9]- [11]. An effect of channel hardening is that very tall or very wide channel matrices[2] are very well conditioned. Another interesting result of channel hardening is that as the dimensions of $\mathbf{H}$ increases, the off-diagonal terms of the $\mathbf{H}^H\mathbf{H}$ matrix become increasingly weaker compared to the diagonal terms, i.e., $\frac{\mathbf{H}^H\mathbf{H}}{n_r} \rightarrow \mathbf{I}_{n_t}$ for $n_r, n_t \rightarrow \infty$ with $n_t/n_r = \alpha$. The receiver scheme we propose in the next section, referred to as the CHEMP-SM receiver, exploits the channel hardening phenomenon for efficient signal detection and channel estimation in large-scale SM-MIMO systems.

3. CHEMP-SM RECEIVER

We refer to the detection algorithm proposed in this section as 'CHEMP-SM detector'. We refer to the CHEMP-SM detector along with the channel estimator proposed in this section as the 'CHEMP-SM receiver'. We present the CHEMP-SM detector and the channel estimator below.

[2]In practice, the channel matrix in a multiuser system with tens of single-antenna users and hundreds of BS antennas will become a very tall matrix on the uplink, and a very wide matrix on the downlink.

3.1. Proposed CHEMP-SM detector

First, perform a matched filter operation on the received signal vector $\mathbf{y}$ in (5) as $\mathbf{H}^H\mathbf{y}$, which can be written as

$$\mathbf{H}^H\mathbf{y} = \mathbf{H}^H(\mathbf{H}\mathbf{x} + \mathbf{w}). \tag{8}$$

An equivalent system model corresponding to (8) can be written as

$$\mathbf{z} = \mathbf{J}\mathbf{x} + \mathbf{v}, \tag{9}$$

where

$$\mathbf{z} \triangleq \frac{\mathbf{H}^H\mathbf{y}}{N}, \quad \mathbf{J} \triangleq \frac{\mathbf{H}^H\mathbf{H}}{N}, \quad \mathbf{v} \triangleq \frac{\mathbf{H}^H\mathbf{w}}{N}. \tag{10}$$

Similar to (3) in the original system model, the vector $\mathbf{z}$ in (9) can be viewed as a concatenation of K sub-vectors each of dimension $n_t \times 1$, i.e., $\mathbf{z} = [\mathbf{z}_1^T \ \mathbf{z}_2^T \cdots \mathbf{z}_i^T \cdots \mathbf{z}_K^T]^T$. Likewise, $\mathbf{v} = [\mathbf{v}_1^T \ \mathbf{v}_2^T \cdots \mathbf{v}_i^T \cdots \mathbf{v}_K^T]^T$, where $v_j = \sum_{l=1}^{N} \frac{H_{lj}^* w_l}{N}$ is the jth element of $\mathbf{v}$ and H_{ji} is the (j,i)th element of $\mathbf{H}$. For large N, the v_j can be approximated to be Gaussian with zero mean and variance $\sigma_v^2 = \frac{\sigma^2}{N}$. Each sub-vector $\mathbf{z}_i$ can be expressed as

$$\mathbf{z}_i = \mathbf{J}_{ii}\mathbf{x}_i + \underbrace{\sum_{j=1, j\neq i}^{K} \mathbf{J}_{ij}\mathbf{x}_j + \mathbf{v}_i}_{\triangleq\, \mathbf{g}_i}, \tag{11}$$

where $\mathbf{J}_{ij}$ is a $n_t \times n_t$ sub-matrix of $\mathbf{J}$ formed from the elements in rows $(i-1)n_t + 1$ to in_t and columns $(j-1)n_t + 1$ to jn_t, i.e., $\mathbf{J}$ can be written in terms of the sub-matrices as

$$\mathbf{J} = \begin{bmatrix} \mathbf{J}_{11} & \mathbf{J}_{12} & \cdots & \mathbf{J}_{1K} \\ \mathbf{J}_{21} & \mathbf{J}_{22} & \cdots & \mathbf{J}_{2K} \\ \vdots & & \ddots & \vdots \\ \mathbf{J}_{K1} & \mathbf{J}_{K2} & \cdots & \mathbf{J}_{KK} \end{bmatrix}.$$

The vector $\mathbf{g}_i$ defined in (11) denotes the interference-plus-noise to the ith user's signal, which involves the off-diagonal elements of $\frac{\mathbf{H}^H\mathbf{H}}{N}$ (i.e., J_{ij}, $i \neq j$). By virtue of channel hardening, the matrix $\mathbf{J}$ has strong diagonal elements for large N, K, and so does $\mathbf{J}_{ii}$ for all i. We approximate $\mathbf{g}_i$ to have a joint Gaussian distribution with mean $\boldsymbol{\mu}_i$ and variance $\boldsymbol{\Sigma}_i$, which can be written as

$$\boldsymbol{\mu}_i \ = \ \mathbb{E}(\mathbf{g}_i) = \sum_{j=1, j\neq i}^{K} \mathbf{J}_{ij}\mathbb{E}(\mathbf{x}_j) \tag{12}$$

$$\boldsymbol{\Sigma}_i \ = \ \mathrm{Var}(\mathbf{g}_i) = \sum_{j=1, j\neq i}^{K} \mathbf{J}_{ij}\mathrm{Var}(\mathbf{x}_j)\mathbf{J}_{ij}^H + \sigma_v^2\mathbf{I}_{n_t}. \tag{13}$$

Let $\mathbf{p}_i$ denote the $|\mathbb{A}|n_t$-sized vector of probability masses corresponding to SM signal vector $\mathbf{x}_i$. The entries of $\mathbf{p}_i$ are

$$p_i(\mathbf{s}) = \Pr\big(\mathbf{x}_i = \mathbf{s}\big), \ \mathbf{s} \in \mathbb{S}_{n_t,\mathbb{A}}.$$

Now, we have

$$\mathbb{E}(\mathbf{x}_j) \ = \sum_{\forall \mathbf{s}, \ \mathbf{s}\in\mathbb{S}_{n_t,\mathbb{A}}} \mathbf{s}p_j(\mathbf{s}) \tag{14}$$

$$\mathrm{Var}(\mathbf{x}_j) \ = \sum_{\forall \mathbf{s}, \ \mathbf{s}\in\mathbb{S}_{n_t,\mathbb{A}}} \mathbf{s}\mathbf{s}^H p_j(\mathbf{s}) - \mathbb{E}(\mathbf{x}_j)\mathbb{E}(\mathbf{x}_j)^H. \tag{15}$$

The $\mathbf{p}_i$s are approximated with the corresponding a posteriori probabilities (APP), i.e.,

$$p_i(\mathbf{s}) \leftarrow \Pr(\mathbf{x}_i = \mathbf{s}|\mathbf{z}_i, \mathbf{J}), \tag{16}$$

where

$$\Pr(\mathbf{x}_i = \mathbf{s}|\mathbf{z}_i, \mathbf{J}) \ \propto \ \exp\Big(\frac{-1}{2}(\mathbf{z}_i - \mathbf{J}_{ii}\mathbf{s} - \boldsymbol{\mu}_i)^H \boldsymbol{\Sigma}_i^{-1}(\mathbf{z}_i - \mathbf{J}_{ii}\mathbf{s} - \boldsymbol{\mu}_i)\Big).$$

Message passing: The multiuser SM-MIMO system is modeled as a fully-connected graph with K nodes, where the ith node is an approximate APP processor corresponding to $\mathbf{x}_i$. The probability vectors $\mathbf{p}_i$s are initialized with equiprobable masses. The ith node uses the knowledge of $\mathbf{J}$, $\mathbf{z}_i$ and the incoming vector messages $\{\mathbf{p}_1, \mathbf{p}_2, \cdots, \mathbf{p}_{i-1}, \mathbf{p}_{i+1}, \cdots, \mathbf{p}_K\}$, to compute $\mathbf{p}_i$ as per (16), which also requires the computation of (12) and (13). We employ damping of messages to improve the rate of convergence. At the end of the tth iteration, the message is damped with a damping factor $\Delta \in [0, 1)$. Thus, if $\tilde{\mathbf{p}}_i^t$ is the computed probability vector at the tth iteration, the message at the end of tth iteration is given by

$$\mathbf{p}_i^t = (1 - \Delta)\tilde{\mathbf{p}}_i^t + \Delta\mathbf{p}_i^{t-1}. \tag{17}$$

The message passing is carried out for a certain number of iterations, after which the algorithm stops. Now, an estimate of the modulation symbol transmitted by the ith user is obtained as

$$\hat{s}_i = \underset{s\in\mathbb{A}}{\mathrm{argmax}} \sum_{\forall \mathbf{s}, \ \mathbf{s}\in\mathbb{S}_{n_t,\mathbb{A}} : \mathcal{X}(\mathbf{s}) = s} p_i(\mathbf{s}), \tag{18}$$

where $\mathcal{X}(\mathbf{s})$ is the non-zero element in $\mathbf{s}$. An estimate of the antenna index chosen for transmission by the ith user is obtained as

$$\hat{q}_i = \underset{q\in\{1,\cdots,n_t\}}{\mathrm{argmax}} \sum_{\forall \mathbf{s}, \ \mathbf{s}\in\mathbb{S}_{n_t,\mathbb{A}} : \mathcal{I}(\mathbf{s}) = q} p_i(\mathbf{s}). \tag{19}$$

where $\mathcal{I}(\mathbf{s})$ is the index of the non-zero element in $\mathbf{s}$. The values of $\hat{s}_i$ and $\hat{q}_i$ are then demapped to obtain the information bits of the ith user.

Complexity: The orders of complexity for the computation of $\mathbf{z}$ and $\mathbf{J}$ are $O(NKn_t)$ and $O(NK^2n_t^2)$, respectively. The complexities for the computation of (12), (13) and (16) are of orders $O(n_t^2K^2)$, $O(n_t^3K^2)$ and $O(n_t^3K|\mathbb{S}_{n_t,\mathbb{A}}|)$, respectively. Therefore, the overall complexity of the algorithm is $O(NK^2n_t^2)$. For large N and K, this complexity is less than the complexity of MMSE detection. This is because MMSE detection requires $O(K^3n_t^3)$ for the inversion of a Kn_t-sized matrix and $O(NK^2n_t^2)$ for matrix multiplication. This complexity advantage of the proposed message passing based detection over MMSE detection is captured in Table 1.

K	Complexity in number of operations $\times 10^6$			
	$N=128$		$N=256$	
	MMSE	CHEMP-SM (prop)	MMSE	CHEMP-SM (prop)
16	3.593	2.802	5.789	4.375
24	9.584	5.796	14.450	9.335
32	19.770	9.907	28.355	16.198

Table 1: Comparison between the complexities (in number of real operations) of CHEMP-SM and MMSE detectors for $n_t = 4$, 4-QAM, and different values of K, N. Number of iterations in CHEMP-SM is 15.

3.2. Proposed channel estimator

As per (12),(13),(16), we see that knowledge of the channel matrix $\mathbf{H}$ is needed to perform the detection operation. A conventional approach is to directly estimate the channel matrix $\mathbf{H}$ as $\widehat{\mathbf{H}}$ through channel estimation techniques (MMSE channel estimation, for example) using pilot transmissions, and use $\widehat{\mathbf{H}}^H\widehat{\mathbf{H}}$ in place of $\mathbf{J}$ in (12),(13),(16). We take a different approach, where we directly obtain an estimate of the matrix $\mathbf{J}$, instead of $\mathbf{H}$. The motivation for this approach is that $\mathbf{H}$ influences the proposed detection operation through $\mathbf{J} = \mathbf{H}^H\mathbf{H}$ (see the transformed system model (9), (10)). Interestingly, this approach performs better compared to the conventional approach. The proposed approach is described below.

Assume that the channel is slowly fading, where the channel remains constant over one frame duration (which is taken to be equal to the coherence time of the channel). The duration of a frame is L_f channel uses. Each frame has a pilot part and a data part. The pilot part consists of Kn_t channel uses, and the data part consists of $L_f - Kn_t$ channel uses.

Let $\mathbf{X}_{\text{p}} = A\mathbf{I}_{Kn_t}$ denote the pilot matrix, where in the ith channel use, $1 \leq i \leq Kn_t$, $\lceil \frac{i}{n_t} \rceil$th user terminal transmits a pilot through its antenna whose index is given by $\big((i-1) \bmod n_t\big) + 1$, with amplitude A and the other user terminals are scheduled to remain silent. The signal received at the BS during pilot phase is given by

$$\mathbf{Y}_{\text{p}} \;=\; \mathbf{H}\mathbf{X}_{\text{p}} + \mathbf{W}_{\text{p}} \;=\; A\mathbf{H} + \mathbf{W}_{\text{p}}, \tag{20}$$

where $A = \sqrt{KE_s}$, E_s is the average symbol energy, and $\mathbf{W}_{\text{p}}$ is the noise matrix. An estimate of the matrix $\mathbf{J}$ is obtained as

$$\widehat{\mathbf{J}} \;=\; \frac{\mathbf{Y}_{\text{p}}^T\mathbf{Y}_{\text{p}}}{NA^2} - \frac{\sigma_v^2}{A^2}\mathbf{I}_{Kn_t}. \tag{21}$$

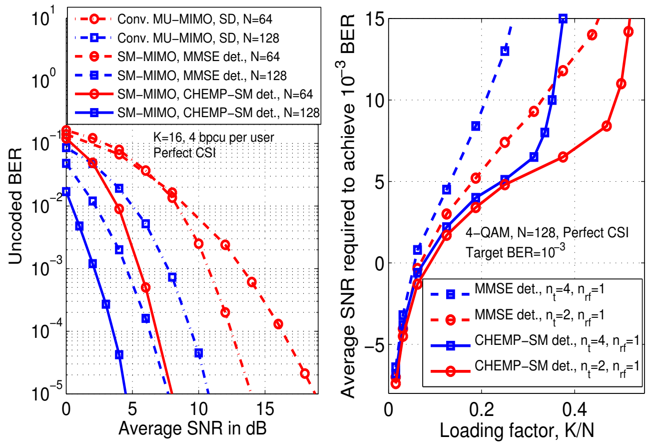
An estimate of the vector $\mathbf{z}$ is obtained as

$$\widehat{\mathbf{z}} \;=\; \frac{\mathbf{Y}_{\text{p}}^T\mathbf{y}}{NA}. \tag{22}$$

These estimates $\widehat{\mathbf{J}}$ and $\widehat{\mathbf{z}}$ in (21) and 22) are used in the proposed detection algorithm in place of $\mathbf{J}$ and $\mathbf{z}$.

4. SIMULATION RESULTS

In this section, we present the BER performance of large-scale multiuser SM-MIMO systems using the proposed CHEMP-SM receiver.

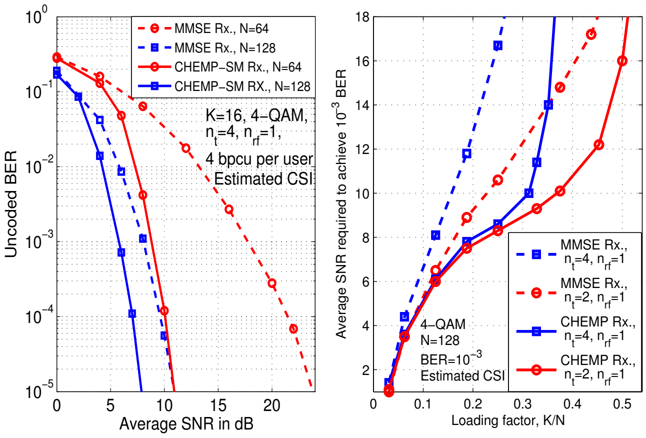


(a) BER vs SNR (b) SNR reqd. vs loading factor

Fig. 2: (a) BER performance of multiuser SM-MIMO and conventional MU-MIMO for $K = 16$, $N = 64, 128$, 4 bpcu per user, and perfect CSI. (b) Average SNR required in CHEMP-SM and MMSE detectors to achieve 10^{-3} BER as a function of loading factor (K/N) in multiuser SM-MIMO with $N = 128$, $n_t = 2, 4$, $n_{rf} = 1$, 4-QAM, 3 and 4 bpcu per user, and perfect CSI.

CHEMP-SM detector performance: In Fig. 2(a), we present the performance of the proposed CHEMP-SM detector at a spectral efficiency of 4 bpcu per user, $K = 16$, $N = 64, 128$, assuming perfect CSI. Figure 2(a) compares the performance of multiuser SM-MIMO with $n_t = 4$, $n_{rf} = 1$, 4-QAM and CHEMP-SM detector, with that of conventional MU-MIMO with $n_t = 1$, $n_{rf} = 1$, 16-QAM and sphere (ML) decoding. Note that, under this setting, both multiuser SM-MIMO and conventional MU-MIMO have a spectral efficiency of 4 bpcu per user. From Fig. 2(a), it can be seen that multiuser SM-MIMO outperforms conventional MU-MIMO by about 5 to 6 dB at 10^{-3} BER. This is because, for achieving the same spectral efficiency, multiuser SM-MIMO can use a smaller-sized QAM (4-QAM in this setting) compared to that used in conventional MU-MIMO (16-QAM in this setting), and a small-sized QAM is more power efficient than a larger-sized one. Figure 2(a) also shows comparisons between the performance of CHEMP-SM detector and MMSE detector in multiuser SM-MIMO. It can be seen that CHEMP-SM detector outperforms MMSE detector by about 2 to 7 dB at 10^{-3} BER. This performance advantage of CHEMP-SM detector over MMSE detector is very attractive given that CHEMP-SM detector has a lesser complexity than MMSE detector as shown in Table 1.

Figure 2(b) shows the performance of CHEMP-SM detector and MMSE detector as a function of the loading factor $\alpha = K/N$, for $N = 128$, $n_t = 2, 4$, $n_{rf} = 1$, 4-QAM, 3 and 4 bpcu per user, assuming perfect CSI. It plots the average SNR required to achieve a target BER of 10^{-3} as a function of α. In this figure also, we can see that CHEMP-SM detector performs better than MMSE detector. For example, at a loading factor of $\alpha = 0.25$, the CHEMP-SM detector requires about 8 dB less SNR compared to MMSE detector at a spectral efficiency of 4 bpcu per user.



(a) BER vs SNR (b) SNR reqd. vs loading factor

Fig. 3: Performance comparison between CHEMP-SM receiver and MMSE receiver in multiuser SM-MIMO with $N = 128$, $n_t = 4$, $n_{rf} = 1$, 4-QAM, 4 bpcu per user, and estimated CSI.

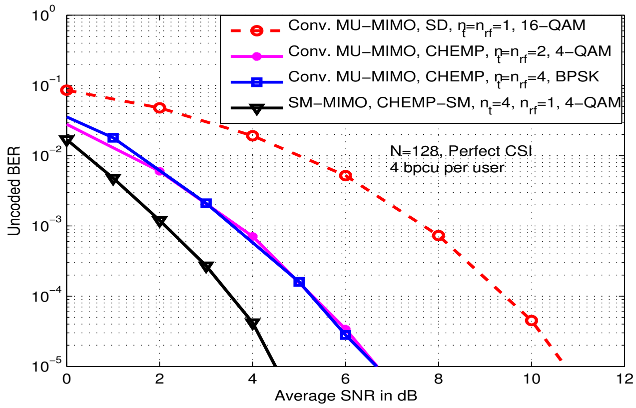


Fig. 4: BER performance of multiuser SM-MIMO (with $n_t = 4, n_{rf} = 1$) and conventional MU-MIMO (with $n_t = n_r = 1, 2, 4$) for $K = 16$, $N = 128$, 4 bpcu per user, and perfect CSI.

The effect of increase in number of spatial streams per user in conventional MU MIMO for the same spectral efficiency on the performance is illustrated in Fig. 4 for $K = 16$ and $N = 128$. In Fig. 4, we compare the performance of the following four systems with the same spectral efficiency of 4 bpcu per user: SM-MIMO with ($n_t = 4$, $n_{rf} = 1$, 4-QAM), and conventional MU MIMO with ($n_t = 1$, $n_{rf} = 1$, 16-QAM), ($n_t = 2$, $n_{rf} = 2$, 4-QAM), ($n_t = 4$, $n_{rf} = 4$, BPSK). It can be seen that among the four systems considered in Fig. 4, SM-MIMO performs the best. This is because conventional MU MIMO loses performance because of higher-order QAM or increased spatial interference from increased number of spatial streams per user.

CHEMP-SM receiver performance: In Figs. 3(a) and 3(b), we present the performance of the proposed CHEMP-SM receiver (i.e., CHEMP-SM detector using the proposed channel estimator). These figures also show comparisons between CHEMP-SM receiver performance and MMSE receiver performance. Here, MMSE receiver refers to MMSE detector using MMSE channel estimate. Figure 3(a) shows the BER vs SNR plots for CHEMP-SM receiver and MMSE receiver for $N = 64, 128$, $K = 16$, $n_t = 4$, $n_{rf} = 1$, 4-QAM, 4 bpcu per user. It can be seen that the CHEMP-SM receiver performs better than the MMSE receiver. For example, to achieve 10^{-3} BER, CHEMP-SM receiver requires 2 dB and 8 dB less SNR compared to MMSE receiver for $N = 128$ and $N = 64$, respectively. Figure 3(b) shows the performance comparison (average SNR required to achieve 10^{-3} BER vs α) between CHEMP-SM receiver and MMSE receiver as a function of loading factor α. It is seen that CHEMP-SM receiver's performance gets increasingly better compared to that of MMSE receiver for increasing α.

5. CONCLUSIONS

We proposed a novel receiver scheme suited for signal detection and channel estimation in large-scale multiuser MIMO systems, where tens of user terminals transmit using spatial modulation and the base station receives them through tens to hundreds of receive antennas. The detection is based on approximate message passing. Both detection and channel estimation operated on a matched filtered system model, and they exploited the channel hardening effect that occurs in large MIMO channels. The performance and complexity of the proposed receiver was shown to be attractive compared to the MMSE receiver.

REFERENCES

[1] A. Chockalingam and B. Sundar Rajan, *Large MIMO Systems*, Cambridge Univ. Press, Feb. 2014.

[2] K. V. Vardhan, S. K. Mohammed, A. Chockalingam, and B. S. Rajan, "A low-complexity detector for large MIMO systems and multicarrier CDMA systems," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 3, pp. 473-485, Apr. 2008.

[3] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: opportunities and challenges with very large arrays," *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40-60, Jan. 2013.

[4] R. C. de Lamare, "Massive MIMO systems: signal processing challenges and research trends," available online: arXiv:1310.7282 [cs.IT] 28 Oct 2013.

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

[6] N. Serafimovski1, S. Sinanovic, M. Di Renzo, and H. Haas, "Multiple access spatial modulation," *EURASIP J. Wireless Commun. and Networking 2012*, 2012:299.

[7] T Lakshmi Narasimhan, P. Raviteja, and A. Chockalingam, "Large-scale multiuser SM-MIMO versus massive MIMO," *ITA'2014*, San Diego, Feb. 2014, doi 10.1109/ITA.2014.6804246.

[8] T. Lakshmi Narasimhan and A. Chockalingam, "Channel hardening-exploiting message passing (CHEMP) receiver in large-scale MIMO systems," *IEEE J. Sel. Topics in Signal Processing*, doi 10.1109/JSTSP.2014.2314213,

[9] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*, Cambridge University Press, 2005.

[10] V. A. Marčenko and L. A. Pastur, "Distribution of eigenvalues for some sets of random matrices," *Math. USSR Sbornik*, vol. 1, pp. 457-483, 1967.

[11] A. Tulino and S. Verdu, *Random Matrix Theory and Wireless Communications*, Foundations and Trends in Communications and Information Theory, Now Publishers, Inc., 2004.