LSE Precoder for Load Modulated Arrays with Channel Modulation

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***Abstract*—In this letter, we consider novel multiuser precoding techniques suited for load modulated arrays (LMAs) on the downlink, wherein a base station employs an LMA to transmit data to multiple users. For implementation simplicity, it is desired that the antenna load impedance values in the LMA are drawn from a discrete set. For such LMAs with discrete-valued load impedances, we propose an iterative precoding algorithm using the least square error (LSE) framework. For the same setting, we also propose a precoding scheme that employs channel modulation (CM) using radio frequency (RF) mirrors in each element of the LMA. This LMA-CM precoding scheme tunes the RF mirrors as well as antenna load modulators such that the instantaneous constraint of constant hypersphere signaling from a discrete set required for LMAs is satisfied. Improved distortion and bit error performance of the proposed schemes are reported.**

***Index Terms*—Load modulation, LM array, channel modulation, RF mirrors, multiuser downlink, precoding.**

I. Introduction

Current approach in multiantenna transmission is to employ a separate radio frequency (RF) chain for each antenna. For massive multiple-input multiple-output (MIMO) systems, this results in high complexity and equipment cost. Further, higher order QAM and precoding techniques are widely used in these systems to improve spectral efficiency. The power amplifier (PA) backoff needed in each RF chain to accommodate these techniques leads to power inefficiency. Load modulated arrays (LMA) [1]-[3] is emerging as a promising multiantenna architecture that alleviates the aforementioned issues.

Load modulation (LM) creates an antenna current by varying the antenna load impedance in accordance with the transmit information signal, while the PA input is maintained at a constant level [3]. This enables the entire antenna array in a load modulated MIMO transmitter to be driven by a single central power amplifier (CPA) [4]. This is in contrast to traditional voltage modulation, wherein antenna current proportional to the transmit signal in each RF chain is achieved by modulating the input voltage to the PA in that chain. The CPA in an LM array is fed by a source with a fixed voltage level and frequency. Varying the antenna load impedances can result in the circuit impedance not being matched to the effective antenna load impedance, causing power to be reflected back to the CPA and deteriorating it's power efficiency. This mismatch can be made negligible by ensuring that all possible transmit signals have the same sum power. Further, when antenna load impedance values are drawn from a discrete set, the load modulators admit a cheap, digital implementation using pin-diodes [3]. This implementation eliminates the need for digital-to-analog converters (DACs), mixers, and upconverters that constitute traditional transmit RF chains. Requirement a single CPA for the entire antenna array and complete elimination of RF chains are appealing factors to consider LMAs for next generation wireless systems.

In multiuser MIMO downlink, the base station (BS) transmitter typically employs a precoding method to facilitate individual users to obtain their data. Conventional precoders such as zero forcing precoder do not consider instantaneous transmit signal constraints such as constant sum power and discrete signaling required for efficient implementation of LMAs. A new framework for multiuser precoding, termed generalized least square error (GLSE) framework, was introduced in [5]-[7] to address general constraints on transmit signals. Using an average distortion measure, this framework can be used to analyze performance of precoders for a variety of transmit signal constraints. This distortion measure is related to the multiuser interference (MUI) at the user terminals. Precoders that minimize MUI at the user terminals while satisfying particular constraints on transmit signals have been studied in the literature, e.g., precoder with constant envelope signaling in each antenna [8], precoder with low resolution DACs [9], precoder for reduced number of RF chains and analog-only transmitter architecture [10]. GLSE is a framework that incorporates such transmit signal constraints in the precoder design. In LMAs, signaling over a discrete set presents the following two issues: 1) computing the precoded signal vector according to the GLSE criterion is a constrained optimization problem whose complexity grows exponentially as the number of BS antennas increases, and 2) the precoder shows a poor distortion performance owing to limited signal states available to eliminate multiuser interference. Towards addressing these issues, our new contributions in this letter are summarized as follows.

Taking the requirement of discrete-valued antenna load impedances and constant sum power as transmit signal constraints, we propose an iterative algorithm to compute precoded vectors according to the LSE criterion for LMAs. Precoding with discrete transmit signal constraint is typically achieved by algorithms based on semi-definite relaxation or sphere decoding [9], while that with constant envelope constraint is accomplished by coordinate descent based algorithms [10]. The proposed algorithm is based on stochastic local search, wherein coordinate updates are dictated by a probability mass function that depends on the least square error (LSE) cost function. The coordinates of the solution (i.e., the precoded vector) obtained from the algorithm are the discrete impedance values used to tune the antenna load modulators for transmission. Further, to improve the distortion performance, we propose the use of channel modulation (CM) in addition to antenna load modulation for the purpose of precoding. This proposed scheme is termed LMA-CM precoding scheme.

LM and CM are emerging as promising techniques for

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next generation wireless systems that would use smart radio environments with reconfigurable meta surfaces [11]. Radio frequency (RF) mirrors have been employed in single and multiple antenna CM systems as a means to increase spectral efficiency and achieve good bit error performance [12],[13]. RF mirrors are parasitic elements placed external to the antenna, whose radiation characteristics, and consequently the channel fades, can be changed by ON/OFF signals applied to them. In [14], CM has been proposed to be used in LMAs for the purpose of increasing data rate in point-to-point and multiuser uplink scenarios. In this letter, however, we propose CM to be used in LMAs for the purpose of efficient multiuser precoding on the downlink. The proposed LMA-CM precoding scheme, in addition to tuning antenna load modulators, chooses the ON/OFF status of the RF mirrors in each antenna element such that interference at the user terminals is minimized while meeting the LMA transmit signal constraints. This hybrid precoding scheme, which has not been reported before, is shown to achieve significantly improved distortion and bit error performance in multiuser downlink LMA systems.

II. Iterative LSE Precoder Algorithm for LMA

A. Load modulated arrays

An LMA consists of multiple transmit antennas fed by a single CPA and a constant amplitude RF carrier source. Each antenna has a tunable complex-valued load impedance associated with it. Let Z_l denote the tunable load impedance of the lth antenna in the array. Let $Z = [Z_1 \ Z_2 \ \cdots \ Z_N]^T$ denote a $N \times 1$ load impedance vector. A collection of such load impedance vectors forms the vector signal set. In a given channel use, an impedance vector from this set is chosen to tune the load modulators. A consequence of the load impedances varying in each transmission is that the effective load impedance is not matched to the circuit impedance. This causes power to be reflected back to the CPA which degrades the CPA efficiency. For large N, the variation in the average impedance reduces due to the law of large numbers. The impedance of the matching network is set corresponding to this average impedance. This ensures that there is little power reflection into the CPA. For small N, variation in the average impedance can be significant. This can be prevented by choosing the N-dimensional load impedance vectors to be on the surface of an N-dimensional hypersphere. Denote $\mathbb{S}_{\rm H}(N,P) = \{\mathbf{s} \in \mathbb{C}^N \mid \|\mathbf{s}\|^2 = P\}$ as the set of points on the surface of a complex-valued hypersphere of radius $\sqrt{P}$. The set of all load impedance vectors used for signaling in LMA, which constitutes an n_M-ary LM alphabet, is given by

$$\mathbb{S}_{\rm lm} = \{\mathbf{s}_1, \mathbf{s}_2, \cdots, \mathbf{s}_{n_M}\} \subset \mathbb{S}_{\rm H}(N,P), \tag{1}$$

where $n_M = |\mathbb{S}_{\rm lm}|$.

B. GLSE criterion for precoding

Traditional precoding techniques such as zero forcing (ZF), regularized zero forcing (RZF) do not assume any restriction on the instantaneous transmit signal. With the exception of an average power constraint, it is assumed that the antennas can transmit any signal. GLSE framework was introduced to deal with precoders having general constraints on the transmit signal. For a generic transmit alphabet, GLSE precoders minimize the interference at user terminals while ensuring that the constraints on the transmit signal are satisfied. Specifically, consider a BS consisting of N antennas serving K user terminals on the downlink. Each user is equipped with a single receive antenna. Let $\mathbf{H} \in \mathbb{C}^{K\times N}$ denote the channel matrix, whose (k,j)th element h_{kj} denotes the channel gain from the jth BS antenna to the kth user terminal. Let u_k denote the data symbol intended for the kth user. The overall user symbol vector $\mathbf{u} = [u_1 \ u_2 \ \cdots \ u_K]^T \in \mathbb{C}^{K\times 1}$ is precoded to get the transmit signal vector $\mathbf{x} \in \mathbb{C}^{N\times 1}$. The GLSE precoder is defined as follows:

$$\mathbf{x} = \operatorname*{argmin}_{\mathbf{v}\in\mathbb{X}} \|\mathbf{H}\mathbf{v} - \sqrt{\gamma}\mathbf{u}\|^2 + \lambda\|\mathbf{v}\|^2, \tag{2}$$

where γ is a positive constant denoting power gain of users' signals at the receive side, λ is a tuning parameter controlling the total transmit power, and $\mathbb{X}$ is the precoding support. The GLSE precoder[1] specializes to a variety of precoders depending on the nature of the precoding support. For example,

- when $\mathbb{X} = \mathbb{C}^N$, the conventional RZF precoder is obtained with
$$\mathbf{x} = \sqrt{\gamma}\mathbf{H}^H(\mathbf{H}\mathbf{H}^H + \lambda\mathbf{I})^{-1}\mathbf{u}. \tag{3}$$
- when $\mathbb{X} = \mathbb{S}_{\rm lm}$ in (1), precoder for LMAs using signaling on the hypersphere is obtained.
- when $\mathbb{X} = \mathbb{A}^N$, where $\mathbb{A} = \left\{\sqrt{r}e^{j\frac{2\pi}{M}m}, m = 0, \cdots, M-1\right\}$ is the discrete set of points each having power r, precoder for LMA with a single CPA and no RF chain is obtained. Here, $\mathbb{A}$ represents the set of M tunable impedance values of the load modulators in each antenna.

For the last two cases, note that $\lambda = 0$ as the sum power of the transmitted signal is constant in every transmission.

The performance of GLSE precoders is measured by the *distortion* at the user terminals. For user data vector $\mathbf{u}$, channel

Algorithm 1: Iterative algorithm for LSE precoding

Input: $\mathbf{H}$, $\mathbf{u}$, γ, β, $\mathbf{x}^{(0)}$, *max-iter*
$t = 0$; $\mathbf{x} = \mathbf{x}^{(0)}$;
$D = f(\mathbf{x}^{(0)})$; $f(\mathbf{x}) = \|\mathbf{H}\mathbf{x} - \sqrt{\gamma}\mathbf{u}\|^2$
while $t <$ *max-iter* **do**
  for $n = 1$ *to* N **do**
    Form the set $\mathcal{S}_n^{(t+1)}$ according to (6)
    Generate pmf $\Pr(\mathbf{s}) \propto f(\mathbf{s})^{-\beta}$ on $\mathcal{S}_n^{(t+1)}$
    Sample $\mathbf{x}^{(t+1)}$ from this pmf
  end
  $D' = f(\mathbf{x}^{(t+1)})$
  if $(D' \leq D)$ **then**
    $\mathbf{x} = \mathbf{x}^{(t+1)}$
    $D = D'$
  end
  $t = t + 1$;
end
Output $\mathbf{x}$

[1]Since the GLSE precoding framework takes into account the constant envelope transmit signal constraint to design the precoding algorithm, the PAPR of the transmitter is unity which enables the transmitter to operate at full power amplifier (PA) efficiency. In practice, other transmit signal processing functions like analog pulse shaping can cause the PAPR to be more than unity, degrading PA efficiency. An investigation of this aspect can be an interesting topic for further study.

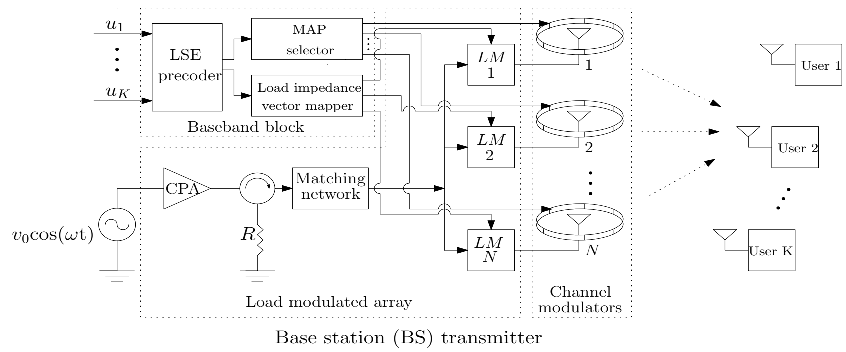

Fig. 1. Proposed LMA-CM precoding on the multiuser downlink.

$\mathbf{H}$, and the precoded vector $\mathbf{x}$ found in (2), the per-user distortion measure is given by

$$D = \frac{1}{K}\mathbb{E}\|\mathbf{H}\mathbf{x} - \sqrt{\gamma}\mathbf{u}\|^2. \tag{4}$$

The per-user distortion measure is useful as it can be used to find a lower bound on the average ergodic rate of the users on the downlink channel [6], i.e.,

$$R = \frac{1}{K}\sum_{k=1}^{K} R_k \geqslant \log\left(\frac{\gamma\sigma_u^2}{\sigma_n^2 + D}\right), \tag{5}$$

where R is the average ergodic rate per user, R_k is the ergodic achievable rate of user k, σ_u^2 is the variance of the users' data, and σ_n^2 is the noise variance at the user terminals. For small systems (small N) with $\mathbb{X} = \mathbb{A}^N$, the precoded vector $\mathbf{x}$ can be computed by brute force according to (2). However, the complexity of computing the precoded vector by brute force increases exponentially with N. This complexity becomes prohibitive for large arrays. We therefore propose an iterative algorithm to compute the precoded vector.

C. Proposed iterative algorithm for precoding

In the proposed algorithm, we start with an initial value of $\mathbf{x}^{(0)} \in \mathbb{A}^N$, wherein the coordinates x_1 through x_N are each randomly initialized to elements in $\mathbb{A}$. Each iteration updates the coordinates of $\mathbf{x}$ in a sequential manner as follows. Towards updating the nth coordinate in the $(t+1)$th iteration, we form the set

$$\mathcal{S}_n^{(t+1)} = \left\{\mathbf{s}\,|\,\mathbf{s} = \left[x_1^{(t+1)} \cdots\ x_{n-1}^{(t+1)}\ v\ x_{n+1}^{(t)} \cdots\ x_N^{(t)}\right]^T, \forall v \in \mathbb{A}\right\}. \tag{6}$$

On this set, define a probability mass function (pmf) $\Pr(\mathbf{s}) \propto \|\mathbf{H}\mathbf{s} - \sqrt{\gamma}\mathbf{u}\|^{-2\beta}$, where β is a positive constant. To update the nth coordinate of $\mathbf{x}$, we sample a vector from the set $\mathcal{S}_n^{(t+1)}$ according to the pmf $\left\{\Pr(\mathbf{s}),\ \mathbf{s} \in \mathcal{S}_n^{(t+1)}\right\}$, which results in the vector with the largest probability mass being sampled more often than the other vectors. This has the effect that a reasonably large value of β favors the minimizer of the LSE cost function $\|\mathbf{H}\mathbf{s} - \sqrt{\gamma}\mathbf{u}\|^2$, while also exploring other solutions in the search space. This ensures that the solution does not get stuck in a local solution corresponding to the minimizer $\hat{\mathbf{s}} \in \mathcal{S}_n^{(t+1)}$ of $\|\mathbf{H}\mathbf{s} - \sqrt{\gamma}\mathbf{u}\|^2$. The $(t+1)$th iteration of the algorithm is complete when all the coordinates of $\mathbf{x}^{(t+1)}$ are updated. Finally, the updated solution is accepted for the next iteration only when the distortion measure of the updated solution is less than the solution found in the previous iteration. **Algorithm 1** provides a listing of the proposed algorithm. The computational complexity of the proposed algorithm is $O(N^2KM)$ per iteration. From simulations, we observe that the algorithm needs $O(N)$ iterations for convergence. Hence the total computational complexity of the algorithm is $O(N^3KM)$.

III. LSE Precoder for LMA with CM

A. Channel modulation using RF mirrors

A channel modulation transmitter with a single antenna consists of m_{rf} RF mirrors placed near the antenna. Each of these RF mirrors acts as a near-field scatterer whose radiation characteristics can be digitally controlled by an ON/OFF switch. Two complex channel fades are consequently created corresponding to the state of the switch. This process of varying the channel fades by the application of an external signal is termed channel modulation. Each ON/OFF pattern of the m_{rf} RF mirrors is known as a mirror activation pattern (MAP). There are $N_m = 2^{m_{rf}}$ MAPs possible, each corresponding to a complex channel fade coefficient. When the antenna transmits a tone, the set of all possible channel fades with a single receive antenna is given by $\mathbb{H} = \{h_1, \cdots, h_{N_m}\}$. In each transmission, the ON/OFF state of the RF mirrors can be tuned such that the fade coefficient is h_j. This is equivalent to choosing the vector $\mathbf{e}_j, j = 1, \cdots, N_m$ for transmission, where $\mathbf{e}_j$ is an $N_m \times 1$ vector whose jth coordinate is 1 and all other coordinates are zeros. This ensures that the received signal corresponding to the jth MAP is

$$y = [h_1 \cdots h_j \cdots h_{N_m}]\ \mathbf{e}_j + w, \tag{7}$$

where w is the additive noise at the receiver.

B. Proposed LMA-CM precoding scheme

The BS transmitter consists of N antennas with m_{rf} RF mirrors placed near each antenna as shown in Fig. 1. The support of the LMA-CM precoding scheme is as follows.

LMA-CM precoding support: The set of all possible signal vectors that can be transmitted by the LMA-CM precoder in Fig. 1 is given by $\mathbb{S}_{\text{lma-cm}} = \mathbb{X}^N$, where

$$\mathbb{X} = \{\mathbf{s}_{j,l} = s_l\mathbf{e}_j, j = 1, \cdots, N_m,\ l = 1, \cdots, M\},$$
$$\text{i.e., } \mathbf{s}_{j,l} = [0 \cdots 0\ \underbrace{s_l}_{j}\ 0 \cdots 0]^T,\ s_l \in \mathbb{A}. \tag{8}$$

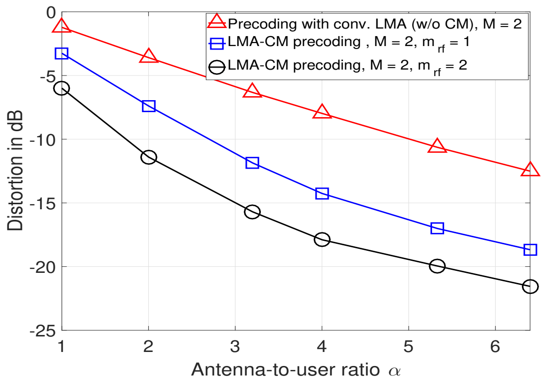

Fig. 2. Distortion versus antenna-to-user ratio for the proposed LMA-CM precoding scheme with $N = 64$, $m_{rf} = 1, 2$, $M = 2$, and proposed iterative algorithm. Performance of precoding with conventional LMA with $M = 2$ is also shown.

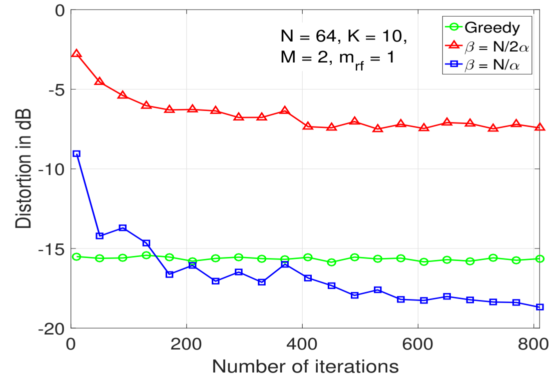

Fig. 3. Convergence behavior of the proposed iterative algorithm in LMA-CM precoding. $N = 64$, $K = 10$, $m_{rf} = 1$, and $M = 2$.

Example: Let $m_{rf} = 2$ and $\mathbb{A} = \{-1, +1\}$ represent the two impedances each antenna load modulator can be tuned to. For this system, we have

$$\mathbb{X} = \left\{ \begin{bmatrix} +1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ +1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ +1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ +1 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ -1 \end{bmatrix} \right\}. \quad (9)$$

Let $\mathbf{h}^{(n)} = [h_1^{(n)} \cdots h_j^{(n)} \cdots h_{N_m}^{(n)}]$ denote the row of N_m channel coefficients corresponding to the nth BS antenna, $n = 1, \cdots, N$. Then the $1 \times NN_m$ channel matrix at the kth user is $\mathbf{h}_k = [\mathbf{h}_k^{(1)} \cdots \mathbf{h}_k^{(n)} \cdots \mathbf{h}_k^{(N)}]$, $k = 1, \cdots, K$. The overall multiuser channel $\mathbf{H} \in \mathbb{C}^{K \times NN_m}$ is then given by $\mathbf{H} = [\mathbf{h}_1^T \cdots \mathbf{h}_k^T \cdots \mathbf{h}_K^T]^T$. The $K \times 1$ user data vector $\mathbf{u} = [u_1 \cdots u_k \cdots u_K]^T$ is precoded into the transmit vector $\mathbf{x} \in \mathbb{X}^N$ based on the channel knowledge $\mathbf{H}$. The received vector at the user terminals is then given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}, \quad (10)$$

where $\mathbf{w} = [w_1 \ w_2 \ \cdots \ w_K]^T$ is the noise vector with $\mathbf{w} \sim \mathcal{CN}(0, \sigma_n^2 \mathbf{I})$.

The precoded vector $\mathbf{x}$ is obtained from (2) with $\mathbb{X} = \mathbb{S}_{\text{lma-cm}}$. Based on the precoded vector $\mathbf{x} \in \mathbb{S}_{\text{lma-cm}}$ obtained above, one of the $N_m = 2^{m_{rf}}$ MAPs corresponding to each antenna is selected by a MAP selector, and the load impedance in each antenna is tuned from the discrete set $\mathbb{A}$. Both of these are performed directly from baseband without the requirement of RF chains. The precoded vector is computed using the proposed iterative algorithm in the previous section, wherein the set $\mathcal{S}_n^{(t+1)}$ is now formed as

$$\mathcal{S}_n^{(t+1)} = \Big\{ \mathbf{s} \,|\, \mathbf{s} = \big[\mathbf{x}_1^{(t+1)T} \cdots \ \mathbf{x}_{n-1}^{(t+1)T} \ \mathbf{v}^T \ \mathbf{x}_{n+1}^{(t)T} \ \cdots \ \mathbf{x}_N^{(t)T}\big]^T, \forall \mathbf{v} \in \mathbb{X} \Big\}. \quad (11)$$

IV. Results and Discussions

In Fig. 2, we show the distortion performance of the proposed LMA-CM precoding scheme against the antenna-to-user ratio $\alpha = N/K$ with $N = 64$ and varying K. The following three systems are considered: (i) LMA-CM with $m_{rf} = 2$, (ii) LMA-CM with $m_{rf} = 1$, and (iii) conventional LMA with no CM. Further, the antenna load modulators in each system

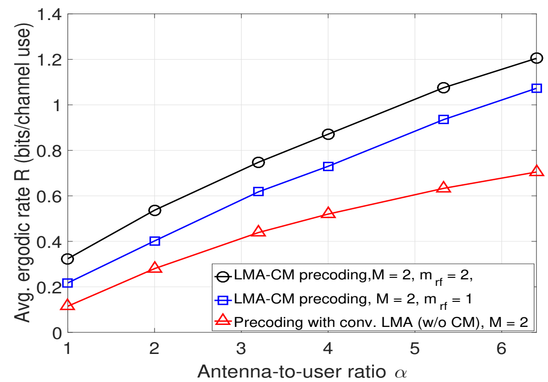

Fig. 4. Lower bound on the average ergodic rate of the proposed LMA-CM precoder with $M = 2$, $m_{rf} = 1, 2$, and the proposed iterative algorithm.

are tuned from $M = 2$ impedance values. User data vector $\mathbf{u} \sim \mathcal{CN}(0, \sigma_u^2 \mathbf{I})$ with $\sigma_u^2 = 1$ and entries of channel matrix $\mathbf{H}$ are distributed as $\mathcal{CN}(0, \frac{1}{N})$. The proposed algorithm is used to compute the precoded vector in all the cases. The parameters for this algorithm are $\gamma = 1$, $\beta = \frac{N}{\alpha}$, and maximum number of iterations $max - iter = 4NN_m$. The distortion measure of the system is obtained using Monte Carlo simulation with 5000 trials. In each trial, channel matrix $\mathbf{H}$ and user data vector $\mathbf{u}$ are generated according to the distributions above. The precoded vector $\mathbf{x}$ is obtained using the proposed algorithm and the distortion is obtained using (4). It is observed that LMA-CM precoding scheme gives an improvement of about 7 dB in distortion performance with $m_{rf} = 1$ and up to 10 dB with $m_{rf} = 2$ compared to precoding with conventional LMA (without CM). This is because the channel modulators in each antenna provide additional states for interference cancellation while maintaining the same impedance values for the load modulators. The convergence behavior of the proposed iterative algorithm for two choices of β is shown in Fig. 3. We see that a higher value of β causes the algorithm to converge to a poor solution owing to significant probability masses on signal vectors other than the minimizer of the distortion measure. Also shown is the behavior of the algorithm in which the signal coordinate which minimizes the distortion is chosen in each iteration (labeled 'greedy'). It is seen that this method gets stuck in a local solution having a poor performance. For the same setting, we show the lower bound on the average (per user) ergodic rate in bits per channel use according to

(5) in Fig. 4 for noise variance $\sigma_n^2 = 1$. The power gain parameter γ is tuned such that the rate is maximized. It is observed that the rate bound with $m_{rf} = 2$ and $\alpha = 6.4$ is about 80% more compared to that in the precoding system with conventional LMA (without CM), viz., 0.7 bpcu vs 1.2 bpcu. Next, in Fig. 5 we show the BER performance of the proposed precoding scheme. User data $u_1, \cdots, u_K$ each come from the QPSK set, and noise variance $\sigma_n^2 = 1$. It is seen that, at a BER of 10^{-3}, LMA-CM precoding scheme with $m_{rf} = 2$ outperforms precoding with conventional LMA (without CM) by about 10 dB. This is in agreement with the distortion performance in Fig. 2, wherein a higher amount of residual MUI in the precoding system with conventional LMA (without CM) causes an error floor. With $m_{rf} = 1$, the gain is about 8-9 dB. These performance advantages, along with the inherent RF hardware complexity reduction, make load modulation, channel modulation, and suitable combinations of the two interesting areas for further research and deployment in future generation wireless systems.

Impact of spatial correlation: Two kinds of spatial correlation effects can arise in an LMA-CM BS transmitter [13]: 1) the channel fades corresponding to the MAPs in a single antenna can be correlated, and 2) the fades corresponding to MAPs in different antennas can be correlated. The correlated channel matrix according to the Kronecker model is given by

$$\mathbf{H} = \tilde{\mathbf{H}}\mathbf{R}_{\text{tx}}^{1/2}, \tag{12}$$

where $\tilde{\mathbf{H}}$ is a $K \times NN_m$ channel matrix whose elements are i.i.d and $\mathbf{R}_{\text{tx}}$ is the $NN_m \times NN_m$ transmit correlation matrix. We express the transmit correlation matrix to incorporate the two types of correlation effects as

$$\mathbf{R}_{\text{tx}} = \begin{bmatrix} \mathbf{R}_{1,1} & \mathbf{R}_{1,2} & \cdots & \mathbf{R}_{1,N} \\ \mathbf{R}_{2,1} & \mathbf{R}_{2,2} & \cdots & \mathbf{R}_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{R}_{N,1} & \mathbf{R}_{N,2} & \cdots & \mathbf{R}_{N,N} \end{bmatrix},$$

where $\mathbf{R}_{i,i}$ is the matrix of correlation coefficients corresponding to MAPs in the ith antenna, and $\mathbf{R}_{i,j}, i \neq j$ is the matrix of correlation coefficients corresponding to the MAPs in the ith and jth antennas. By the equicorrelation and the exponential decaying correlation models, $\mathbf{R}_{i,i} = \rho_m \mathbf{I}$ and $\mathbf{R}_{i,j} = \rho_a^{|i-j|}\mathbf{1}$, respectively. Here, $\mathbf{I}$ and $\mathbf{1}$ denote the identity matrix and the matrix of ones, respectively, each of size $N_m \times N_m$. Figure 6 shows the effect of spatial correlation on the BER performance of the proposed LMA-CM precoder with $N = 64$, $K = 10$, $M = 2$, $m_{rf} = 1$, and QPSK. We observe that, compared to the system with no correlation, the system with $\rho_a = \rho_m = 0.1$ experiences a degradation of about 2 dB at 10^{-3} BER.

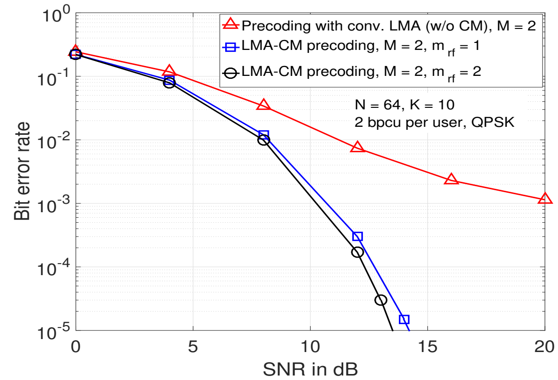

Fig. 5. BER performance of the proposed LMA-CM precoding scheme with $N = 64$, $K = 10$, $M = 2$, $m_{rf} = 1, 2$, QPSK, and the proposed iterative algorithm. Performance of precoding with conventional LMA with $M = 2$ is also shown.

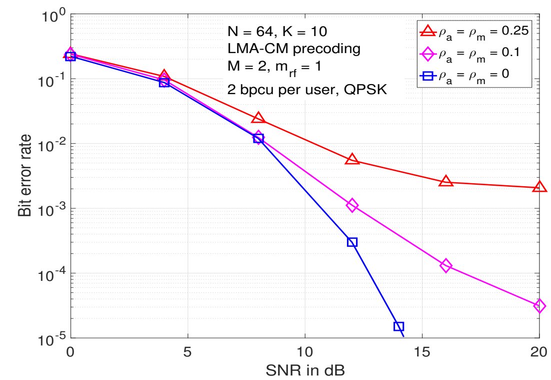

Fig. 6. BER performance of the proposed LMA-CM precoding scheme with $N = 64$, $K = 10$, $M = 2$, $m_{rf} = 1$, QPSK, and the proposed iterative algorithm in the presence of spatial correlation.

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