Load Modulated Arrays using Channel Modulation with RF Mirrors

Sandeep Bhat and A. Chockalingam
Department of ECE, Indian Institute of Science, Bangalore 560012

***Abstract*—Multiantenna transmission using load modulated arrays (LMAs) is gaining recent research interest. LMAs use a single central power amplifier and tune the antenna loads according to the information signal. In this paper, we propose a novel multiantenna transmitter architecture that can enable high-rate transmissions using LMAs. The proposed architecture uses channel modulation with RF mirrors in conjunction with antenna load modulation to transmit information bits. The proposed architecture has two key advantages: 1) it facilitates simple construction of high-rate signal sets suited for LMAs, and 2) it requires significantly fewer channel coefficients to be estimated at the receiver compared to conventional channel modulation architectures. The proposed architecture is shown to achieve improved bit error performance compared to conventional load modulation as well as spatial modulation, which are also single power amplifier transmission schemes. We also investigate the use of the proposed transmission scheme in a multiuser setting on the uplink. The proposed scheme not only offers the advantage of RF hardware simplicity at the user equipment but also requires fewer receive antennas at the base station to achieve a target bit error performance.**

***Index Terms*—Load modulated arrays, LM signal set, multi-dimensional hypersphere, channel modulation, RF mirrors.**

I. INTRODUCTION

Multiple-input multiple-output (MIMO) techniques are increasingly getting adopted in modern wireless communication systems. The traditional approach in multiantenna transmission has been to employ a separate radio frequency (RF) chain for each antenna and use conventional modulation and precoding techniques such as QAM/PSK and OFDM for transmission. This approach leads to increased cost, complexity, and size with increasing number of antennas. In addition, owing to linearity requirements of the transmit signals, power amplifiers in each of the RF chains suffer from poor power efficiency. Load modulated arrays (LMA) is emerging as a promising MIMO array architecture that alleviates the aforementioned issues [1]-[3].

Conventional MIMO transmitters employ *voltage modulation* for transmission, i.e., the input voltage to the power amplifier (PA) in each transmit RF chain is modulated according to the transmit signal in that chain. On the other hand, *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 [2]. In a load modulated MIMO transmitter, a single central power amplifier (CPA) drives the entire transmit antenna array. The CPA is fed by a source with a fixed voltage level and frequency. Information bits directly modulate the antenna load impedances, which has the effect of implementing the signal set in the analog domain. This analog implementation of the signal set eliminates the need for DACs, mixers, and up converters that constitute the transmit RF chains [1]. However, varying the antenna load impedances results in the circuit impedance not being matched to the effective antenna load impedance, causing power to be reflected back to the CPA. This deteriorates the CPA power efficiency. For large antenna arrays, the law of large numbers ensures that the mismatch is negligible. For small arrays, however, this mismatch can be significant. This can be alleviated by constraining the signal set to be vectors on the surface of a multidimensional hypersphere [3]. Small sized LMAs with such signal sets have been shown to perform well in both point-to-point and multiuser systems [4],[5]. Construction of LM signal sets that satisfy this constraint is typically non-analytic. Constructing signal sets based on clustering has been shown to achieve good performance [3]. However, because of the non-analytic nature of clustering methods, construction and storage of signal sets suited for LMAs becomes an issue as the cardinality of the signal set increases. Thus, while RF advantages of LMAs make it a potential candidate for future wireless systems, they are limited by the difficulty in constructing well performing signal sets.

Media based modulation (MBM), also known as channel modulation (CM) [6]-[10], is gaining recent research attention as an excellent means to achieve increasing spectral efficiency at low RF costs. The basic version of MBM uses digitally controlled RF mirrors to alter (modulate) the propagation environment (channel) near a transmit antenna. Symbols from conventional modulation alphabets (e.g., QAM/PSK) when used over the basic channel modulation have been shown to offer significant performance gains over traditional single antenna and multiantenna transmission [8],[9].

A new modulation architecture for LMAs, termed as MBM-LM, was proposed in [4] wherein information bits are conveyed via the ON/OFF status of RF mirrors placed around the transmit antenna array. This helps reduce the LM signal set size and consequently its construction complexity. However, it suffers from a substantial increase in the number of channel coefficients to be estimated at the receiver as the number of mirrors increase. In this paper, first we extend the idea of using RF mirrors in LMAs to convey information bits while alleviating the need to estimate a large number of channel coefficients. In particular, we propose a novel architecture wherein channel modulation with RF mirrors is used in conjunction with antenna load modulation for transmission. We term this proposed scheme as 'LMAs with channel modulation (LMA-CM)'. The proposed scheme not only serves as an effective way to increase the spectral efficiency of LMAs but also does this with a lesser number of channel coefficients to be estimated compared to that in MBM and MBM-LM. Also, simulation results show that the proposed architecture achieves improved bit error rate (BER) performance compared to conventional load modulation and spatial modulation [11], both of which also use only a single power amplifier.

Next, motivated by the performance and RF cost advantages of LMA-CM, we employ this architecture in user terminals in multiuser communication on the uplink. Detection of multiuser LMA-CM signals is carried out using a message passing algorithm. Simulation results show that in a multiuser setting with 8 bits per channel use (bpcu) per user, LMA-CM achieves better performance up to about 2 dB and 10 dB compared to LM and SM, respectively. This better performance, in turn, allows the base station (BS) to use fewer receive antennas for a target BER performance, making LMA-CM as an attractive architecture for high-rate multiuser communications with low RF cost and complexity.

The rest of this paper is organized as follows. LMAs and channel modulation are introduced in Sec. II. The proposed LMA-CM architecture and its performance under maximum likelihood detection are presented in Sec. III. Section IV presents multiuser LMA-CM on the uplink and its performance using message passing detection. Conclusions are presented in Sec. V.

II. LMAs AND CHANNEL MODULATION

In this section, we introduce LMAs and channel modulation using RF mirrors.

A. Load modulated arrays

An LMA consists of multiple transmit antennas fed by a single CPA and a constant magnitude RF carrier source [1]-[3]. Let Z_l denote the tunable complex-valued load impedance of the lth antenna in the array. Let $Z = [Z_1 \ Z_2 \ \cdots \ Z_{n_t}]^T$ denote a $N \times 1$ load impedance vector. A collection of such load impedance vectors forms the vector signal set in LM arrays. In a given channel use, an impedance vector from this set is chosen based on information bits. The lth element in the impedance vector controls the antenna current in the lth antenna such that the antenna current is proportional to $1/Z_l$. LMAs therefore generate input currents to the antennas based on information bits, in effect implementing the signal constellation in the analog domain. A consequence of the load impedances varying in accordance with information bits is that the effective load impedance is not matched to the circuit impedance. This causes power to reflected back to the CPA and degrades the CPA efficiency. With large n_t, 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. With small n_t, variation in the average impedance is significant. This can be prevented by choosing the n_t-dimensional load impedance vectors to be on the surface of an n_t-dimensional hypersphere. Letting

$$\mathbb{S}_{\rm H}(n_t, P) = \{\mathbf{s} \in \mathbb{C}^{n_t} \mid \|\mathbf{s}\|^2 = P\} \tag{1}$$

to denote 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, called the LM alphabet, is given by

$$\mathbb{S}_{\rm lm} = \{\mathbf{s}_1, \mathbf{s}_2, \cdots, \mathbf{s}_{n_M}\} \subset \mathbb{S}_{\rm H}(n_t, P). \tag{2}$$

One way to obtain the signal vectors that constitute $\mathbb{S}_{\rm lm}$ is by generating uniformly distributed vectors on the hypersphere and clustering them [3]. An $n_t \times 1$ signal vector $\mathbf{s}$ from $\mathbb{S}_{\rm lm}$ chosen based on $\log_2 n_M$ information bits gets transmitted in a channel use by the n_t load modulators, where $n_M = |\mathbb{S}_{\rm lm}|$.

B. Channel modulation with RF mirrors

The transmitter in channel modulation (a.k.a media based modulation) consists of a transmit antenna with m_{rf} RF mirrors placed near the antenna [6]-[10]. The RF mirrors act as scatterers whose radiation characteristics can be digitally controlled by ON/OFF switches. Consequently, each RF mirror creates two different complex fades, one corresponding to the ON state of the switch and another corresponding to the OFF state. Each ON/OFF pattern of the m_{rf} RF mirrors is known as a mirror activation pattern (MAP), and $N_m = 2^{m_{rf}}$ MAPs are possible. When the antenna transmits a tone, the set of all possible fades at an n_r antenna receiver is given by $\mathbf{H} = \{\mathbf{h}_1, \cdots, \mathbf{h}_{N_m}\}$. This basic version of the system can convey m_{rf} bits. When the antenna transmits a symbol from a M-ary QAM/PSK alphabet, the system can achieve a rate of

$$\eta_{\rm mbm} = m_{rf} + \log_2 M \quad \text{bpcu}. \tag{3}$$

The $2^{m_{rf}}$ fade vectors have to be estimated at the receiver for MBM signal detection.

C. MBM with load modulation

The MBM-LM transmitter consists of n_t antennas and m_{rf} RF mirrors placed near the ensemble of the n_t-antenna array [4]. In a given channel use, an n_t-length LM signal vector gets transmitted by the n_t antennas, and m_{rf} information bits control the ON/OFF status of the m_{rf} mirrors. The achieved rate in MBM-LM scheme is therefore given by

$$\eta_{\rm mbm\text{-}lm} = m_{rf} + \log_2 n_M \quad \text{bpcu}. \tag{4}$$

Each MAP results in an $n_r \times n_t$ fade matrix. Let $\mathbf{H}_i$ denote the fade matrix corresponding to the ith MAP. The collection of all the fade matrices $\{\mathbf{H}_1, \mathbf{H}_2, \cdots, \mathbf{H}_M\}$ forms the channel alphabet. A total of $n_t 2^{m_{rf}}$ fade vectors which form the channel alphabet have to be estimated at the receiver for MBM-LM signal detection.

III. PROPOSED LMA-CM ARCHITECTURE

In this section, we present the proposed LMA-CM transmission architecture. Consider a multiantenna transmitter with n_t antennas. The n_t-antenna array is grouped into n_B blocks, each containing n_{tx} antennas so that $n_B n_{tx} = n_t$, and m_{tx} RF mirrors are placed near each block of n_{tx} antennas as shown in Fig. 1. In a given channel use, an n_{tx}-length signal vector from an n_M-ary LM signal set gets transmitted by each antenna block. Further, in each antenna block, m_{tx} information bits control the ON/OFF status of the m_{tx} RF mirrors near it. The achieved rate in this scheme is therefore given by

$$\eta_{\rm lma\text{-}cm} = n_B (m_{tx} + \log_2 n_M) \quad \text{bpcu}. \tag{5}$$

In each antenna block, $N_a \triangleq 2^{m_{tx}}$ MAPs are possible. Each MAP results in an $n_r \times n_{tx}$ fade matrix. Let $\mathbf{H}_i^{(n)}$ denote the fade matrix corresponding to the ith MAP of the nth antenna block. The collection of all the fade matrices $\{\mathbf{H}_i^{(n)}\}$, $i = 1, \cdots, N_a$, $n = 1, \cdots, n_B$ forms the channel alphabet.

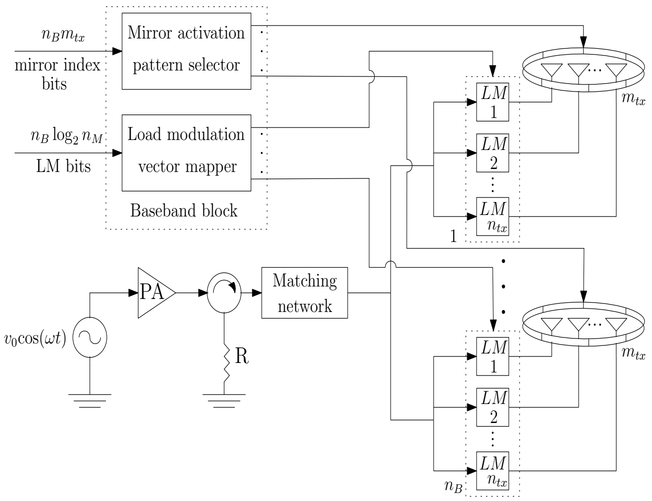

Fig. 1. LMA-CM transmitter.

LMA-CM signal set: The LMA-CM signal set, which is the set of all possible $n_B N_a n_{tx} \times 1$ vectors that can be transmitted, is given by

$$\mathbb{S}_{\text{lma-cm}} = \mathbb{S}^{n_B}, \text{ where } \mathbb{S} = \{\mathbf{s}_{j,l} : j = 1, \cdots, N_a,\ l = 1, \cdots, n_M\},$$
$$\text{s.t. } \mathbf{s}_{j,l} = [\mathbf{0}^T \cdots \mathbf{0}^T \ \underbrace{\mathbf{s}_l^T}_{[j]} \ \mathbf{0}^T \cdots \mathbf{0}^T]^T, \ \mathbf{s}_l \in \mathbb{S}_{\text{lm}}, \qquad (6)$$

where $\mathbf{0}$ denotes a $n_{tx} \times 1$ vector of zeros, $[j]$ denotes the set of indices $(j-1)n_{tx}+1 : jn_{tx}$, and $\mathbb{S}_{\text{lm}}$ denotes the LM signal set in n_{tx} dimensions.

Example: Let $n_t = 4$, $n_{tx} = 2$, $n_B = 2$, and $m_{tx} = 1$. Further, let $\mathbb{S}_{\text{lm}} = \{[+1 \ \ -j]^T, [-1 \ \ +j]^T\} \subset \mathbb{S}_{\text{H}}(2,2)$. For this system, we have

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

and the corresponding LMA-CM signal set is

$$\mathbb{S}_{\text{lma-cm}} = \left\{ \begin{bmatrix} +1 \\ -j \\ 0 \\ 0 \\ +1 \\ -j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} +1 \\ -j \\ 0 \\ 0 \\ -1 \\ +j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} +1 \\ -j \\ 0 \\ 0 \\ 0 \\ 0 \\ +1 \\ -j \end{bmatrix}, \begin{bmatrix} +1 \\ -j \\ 0 \\ 0 \\ 0 \\ 0 \\ -1 \\ +j \end{bmatrix}, \begin{bmatrix} -1 \\ +j \\ 0 \\ 0 \\ +1 \\ -j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ +j \\ 0 \\ 0 \\ -1 \\ +j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ +j \\ 0 \\ 0 \\ 0 \\ 0 \\ +1 \\ -j \end{bmatrix}, \begin{bmatrix} -1 \\ +j \\ 0 \\ 0 \\ 0 \\ 0 \\ -1 \\ +j \end{bmatrix}, \right.$$
$$\left. \begin{bmatrix} 0 \\ 0 \\ +1 \\ -j \\ +1 \\ -j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ +1 \\ -j \\ -1 \\ +j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ +1 \\ -j \\ 0 \\ 0 \\ +1 \\ -j \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ +1 \\ -j \\ 0 \\ 0 \\ -1 \\ +j \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ -1 \\ +j \\ +1 \\ -j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ -1 \\ +j \\ -1 \\ +j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ -1 \\ +j \\ 0 \\ 0 \\ +1 \\ -j \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ -1 \\ +j \\ 0 \\ 0 \\ -1 \\ +j \end{bmatrix} \right\}.$$

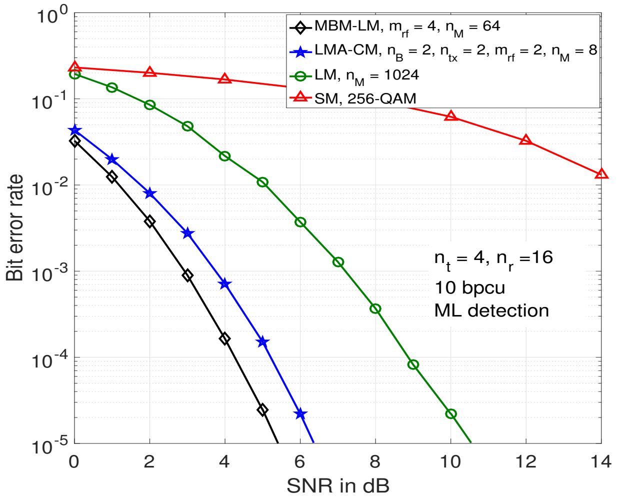

Fig. 2. BER performance of LMA-CM with $n_t = 4$, $m_{rf} = 4$, $n_B = 2$, $n_M = 8$, $n_r = 16$, and 10 bpcu with ML detection. Performance of MBM-LM, LM, and SM that achieve 10 bpcu are also shown.

Defining $\mathbf{H} \triangleq [\mathbf{H}_1^{(1)} \cdots \mathbf{H}_{N_a}^{(1)} \cdots \mathbf{H}_1^{(n_B)} \cdots \mathbf{H}_{N_a}^{(n_B)}]$ as the overall $n_r \times n_B N_a n_{tx}$ channel matrix, the received signal can be written as $\mathbf{y} = \mathbf{Hs} + \mathbf{n}$, where $\mathbf{s}$ belongs to the LMA-CM alphabet $\mathbb{S}_{\text{lma-cm}}$ and $\mathbf{n}$ is the $n_r \times 1$ noise vector. The entries of $\mathbf{H}$ are assumed to be i.i.d. $\mathcal{CN}(0,1)$ and the noise vector is distributed as $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2 \mathbf{I})$. The maximum likelihood (ML) detection rule is then given by

$$\hat{\mathbf{s}} = \underset{\mathbf{s} \in \mathbb{S}_{\text{lma-cm}}}{\text{argmin}} \ \|\mathbf{y} - \mathbf{Hs}\|^2. \qquad (7)$$

The total number of fade vectors to be estimated at the receiver is $n_B n_{tx} N_a$.

BER performance of LMA-CM: Here, we present the simulated BER performance of the proposed LMA-CM scheme with ML detection. We compare this performance with that of other multiantenna systems which also use only one PA for transmission. All the systems are configured for 10 bpcu. The systems considered for this comparison are: (i) spatial modulation (SM) with ($n_t = 4$, 256-QAM), (ii) LM with ($n_t = 4$, $n_M = 1024$), and (iii) MBM-LM with ($n_t = 4$, $m_{rf} = 4$, $n_M = 64$). The corresponding system parameters for the proposed LMA-CM are ($n_t = 4$, $n_B = 2$, $m_{tx} = 2$, $n_{tx} = 2$, $n_M = 8$). Signal vectors for LM in each of the LM based systems are obtained by spherical k-means clustering [3]. Figure 2 shows the BER performance comparison between the aforementioned systems. It can be observed that, at a BER of 10^{-4}, LMA-CM outperforms LM by about 4 dB, and SM by more than 10 dB. Smaller number of signal vectors on the surface of the hypersphere in LMA-CM give it this performance advantage over LM. It is also observed that MBM-LM outperforms LMA-CM by about 1 dB at 10^{-4} BER, for the same total number of RF mirrors ($m_{rf} = 4$) and total number of LM signal vectors ($n_M = 64$). This is because the LM signal vectors in MBM-LM are optimized jointly over $n_t = 4$ dimensions as opposed to the signal vectors being repeated over $n_{tx} = 2$ dimensions in LMA-CM. However, this

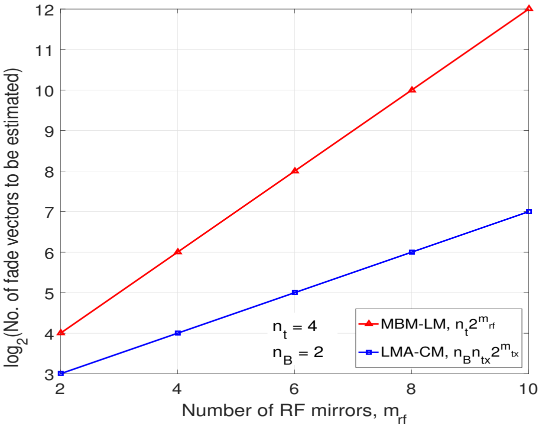

Fig. 3. Number of fade vectors to be estimated as a function of m_{rf}.

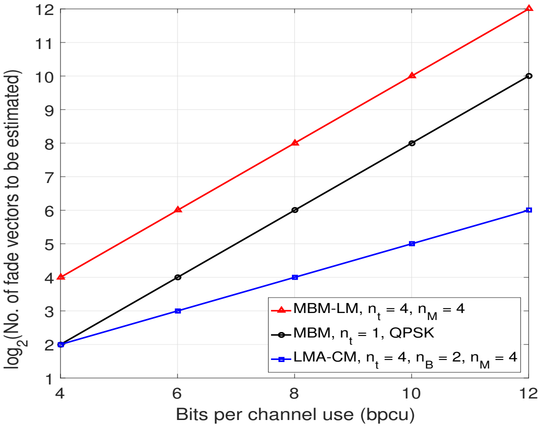

Fig. 4. Number of fade vectors to be estimated as a function of the system bpcu.

performance advantage comes at a cost of increased number of fade vectors to be estimated. This observation is illustrated in Figs. 3 and 4.

In Fig. 3, we show the number of fade vectors to be estimated as a function of the total number of RF mirrors m_{rf} for LMA-CM and MBM-LM. It can be observed that MBM-LM requires $2^{\frac{m_{rf}}{n_B}}$ times more fade vectors to be estimated compared to LMA-CM. For instance, at $m_{rf} = 4$, MBM-LM requires 4 times more fade vectors to be estimated compared to LMA-CM. This increases to 32 times at $m_{rf} = 10$. In Fig. 4, we show the number of fade vectors to be estimated as a function of the system bpcu for three systems, namely, MBM, MBM-LM, and LMA-CM. For the same number of information bits conveyed through conventional modulation/load modulation (i.e., QPSK in MBM and $n_M = 4$ in MBM-LM and LMA-CM), it is observed that LMA-CM requires significantly fewer fade vectors to be estimated at the receiver. For example, at 10 bpcu, MBM-LM requires 1024, MBM requires 256, and LMA-CM requires only 32 fade vectors to be estimated. The good performance of LMA-CM among single PA transmission schemes along with a lesser channel estimation overhead motivate us to consider the LMA-CM scheme for multiuser communication on the uplink. This forms the focus of the next section.

IV. LMA-CM ON THE MULTIUSER UPLINK

In this section, we employ the proposed LMA-CM scheme at the user terminals for uplink communication.

A. System model

Consider a multiuser system with K uplink users communicating with a BS having N receive antennas. Users employ LMA-CM for their transmission. Each user has n_t transmit antennas and their associated RF mirrors and load modulators. Let $\mathbf{s} \triangleq [\mathbf{s}_1^T \mathbf{s}_2^T \cdots \mathbf{s}_k^T \cdots \mathbf{s}_K^T]^T$ denote the vector comprising of transmit vectors from all the users, where $\mathbf{s}_k \in \mathbb{S}_{\text{lma-cm}}$ is the LMA-CM signal vector of the kth user, $(\cdot)^T$ denotes transpose operation. Note that $\mathbf{s} \in \mathbb{S}_{\text{lma-cm}}^K$.

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

$$y_i = \sum_{k=1}^{K} \mathbf{h}_{i,[k]} \mathbf{s}_k + n_i, \tag{8}$$

where $\mathbf{h}_{i,[k]}$ is a $1 \times n_t$ vector obtained from the ith row and $(k-1)n_t+1$ to kn_t columns of $\mathbf{H}$, and n_i is the noise modeled as a complex Gaussian random variable with zero mean and variance σ^2. The received signal at the BS antennas can be written in vector form as

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \tag{9}$$

where $\mathbf{y} = [y_1, y_2, \cdots, y_N]^T$ and $\mathbf{n} = [n_1, n_2, \cdots, n_N]^T$. For this system, the ML detection rule is

$$\hat{\mathbf{s}} \;=\; \underset{\mathbf{s} \in \mathbb{S}_{\text{lma-cm}}^K}{\operatorname{argmin}} \; \|\mathbf{y} - \mathbf{H}\mathbf{s}\|^2. \tag{10}$$

The exact computation of (10) requires exponential complexity in K. Based on the signal set defined in (6), the ML detection rule in (10) can be written as

$$\hat{\mathbf{s}} \;=\; \underset{\mathbf{x} \in \mathbb{S}^{Kn_B}}{\operatorname{argmin}} \; \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2. \tag{11}$$

For the above detection rule, a low-complexity detection algorithm based on message passing is developed in the following subsection.

B. Message passing based detection

The graphical model for the proposed message passing algorithm consists of Kn_B variable nodes each corresponding to a $\mathbf{v} \in \mathbb{S}$, and N observation nodes each corresponding to a y_i. This graphical model is illustrated in Fig. 5. The mean and variance of the multiuser interference term needed for message passing can be computed as

$$\mu_{i,k} \;=\; \mathbb{E}\Big[\sum_{j=1, j\neq k}^{Kn_B} \mathbf{h}_{i,[j]} \mathbf{x}_j + n_i\Big] = \sum_{j=1, j\neq k}^{Kn_B} \sum_{\mathbf{v} \in \mathbb{S}} p_{ji}(\mathbf{v}) \mathbf{h}_{i,[j]} \mathbf{v}, \tag{12}$$

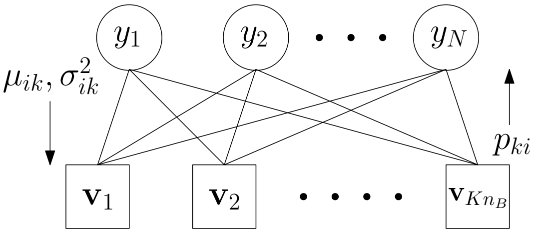

Fig. 5. Graphical model for message passing.

$$\sigma^2_{i,k} = \mathrm{Var}\Big(\sum_{j=1,j\neq k}^{Kn_B} \mathbf{h}_{i,[j]}\mathbf{x}_j + n_i\Big)$$

$$= \sum_{\substack{j=1,\\ j\neq k}}^{Kn_B} \Big(\sum_{\mathbf{v}\in\mathbb{S}} p_{ji}(\mathbf{v})\mathbf{h}_{i,[j]}\mathbf{v}\mathbf{v}^H\mathbf{h}^H_{i,[j]} - \Big|\sum_{\mathbf{v}\in\mathbb{S}} p_{ji}(\mathbf{v})\mathbf{h}_{i,[j]}\mathbf{v}\Big|^2\Big) + \sigma^2, \quad (13)$$

where $p_{ki}(\mathbf{v})$ denotes the a posteriori probability (APP) message computed at the variable nodes as

$$p_{ki}(\mathbf{v}) \propto \prod_{m=1,\ m\neq i}^{N} \exp\Big(\frac{-|y_m - \mu_{m,k} - \mathbf{h}_{m,[k]}\mathbf{v}|^2}{\sigma^2_{m,k}}\Big). \quad (14)$$

The message passing schedule is as follows.

1) Initialize $p_{ki}(\mathbf{v}) = \frac{1}{|\mathbb{S}|}$, $\forall k, i, \mathbf{v}$.
2) Compute μ_{ik} and $\sigma^2_{i,k}$, $\forall i, k$.
3) Compute p_{ki}, $\forall k, i$.

Damping of the messages is done in (14) with a damping factor $\delta \in (0, 1]$ to improve convergence. Steps 2 and 3 are repeated for a fixed number of iterations. At the end of these iterations, the vector probabilities are computed as

$$p_k(\mathbf{v}) \propto \prod_{i=1}^{N} \exp\Big(\frac{-|y_i - \mu_{i,k} - \mathbf{h}_{i,[k]}\mathbf{v}|^2}{\sigma^2_{i,k}}\Big),\ k = 1, \cdots, Kn_B. \quad (15)$$

The estimates $\hat{\mathbf{x}}_k$s are obtained by choosing the signal vector $\mathbf{v} \in \mathbb{S}$ that has the largest APP. That is,

$$\hat{\mathbf{x}}_k = \underset{\mathbf{v}\in\mathbb{S}}{\mathrm{argmax}}\ p_k(\mathbf{v}),\ k = 1, \cdots, Kn_B. \quad (16)$$

The decoded bits of all the users are obtained by demapping $\hat{\mathbf{s}}_k$ to information bits $\forall k$.

C. Simulation results

In Fig. 6, we present the BER performance of three large-scale multiuser MIMO systems with $K = 16$, $N = 128$, $n_t = 4$, and 8 bpcu per user. These systems include SM with 64-QAM, LM with $n_M = 256$, and the proposed LMA-CM with $m_{tx} = 2$, $n_{tx} = 2$, and $n_M = 4$. As was observed in a point-to-point setting in Fig. 2, here in the multiuser setting also, we observe that LMA-CM achieves significantly better performance compared to LM and SM. For example, at a BER of 10^{-4}, LMA-CM performs better by about 2 dB and 10 dB compared to LM and SM, respectively.

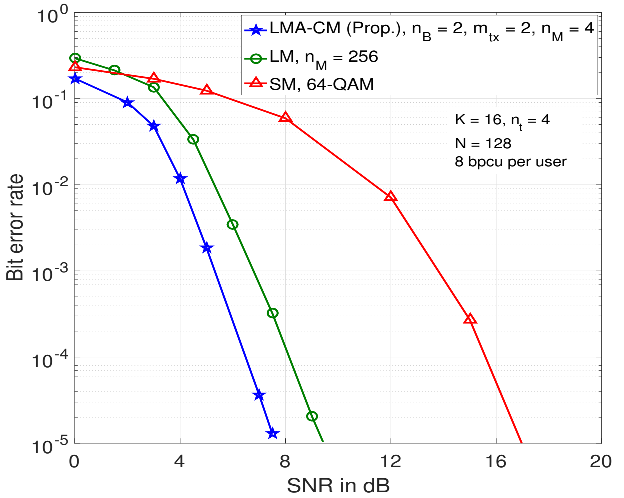

Fig. 6. Comparison between the BER performance of SM, LM and LMA-CM on the multiuser uplink with $K = 16$, $N = 128$, 8 bpcu per user, and message passing detection.

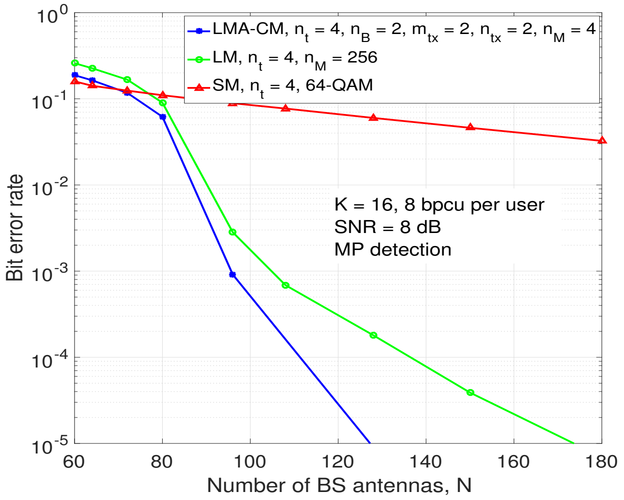

Fig. 7. Comparison between the BER performance of SM, LM, and LMA-CM on the multiuser uplink as a function of N for $K = 16$, 8 bpcu per user, SNR = 8 dB, and message passing detection.

Figure 7 shows the BER performance of the three systems as a function of number of BS receive antennas N at an SNR of 8 dB. At this SNR, LMA-CM is able to achieve 10^{-4} BER with about $N = 110$ receive antennas, whereas LM needs $N = 140$ antennas to achieve the same performance, and SM is unable to achieve this performance even with more than $N = 200$ antennas. This shows that not only can LMA-CM reduce RF cost and complexity at the user terminals, it also requires significantly lesser number of BS antennas to achieve a target BER, which translates to cost effective and power efficient base stations.

V. CONCLUSION

Load modulated arrays are efficient and promising for multiantenna communications. We presented a novel multiantenna transmitter architecture using LMAs and channel modulation as a means to realize high-rate LMAs. The proposed LMA-CM scheme was shown to achieve improved BER performance compared to other multiantenna transmission architectures such as LM and SM, which also use a single power amplifier. The LMA-CM scheme also required fewer channel fade vectors to be estimated compared to other multiantenna transmitters with channel modulation. Also, in a multiuser communication setting on the uplink, a message passing detector was proposed and it was observed that, in addition to RF cost and complexity benefits at the user terminals, fewer base station receive antennas were required to achieve a certain target BER performance. Design of pilot signals for LMA-CM systems is an interesting topic for future work.

REFERENCES

[1] M. A. Sedaghat, V. I. Barousis, R. R. Muller, and C. B. Papadias, "Load modulated arrays: a low-complexity antenna," *IEEE Commun. Mag.*, pp. 46-52, Mar. 2016.

[2] R. R. Muller, M. A. Sedaghat, and G. Fischer, "Load modulated massive MIMO," in *Proc. IEEE GlobalSIP*, pp. 622-626, Dec. 2014.

[3] M. A. Sedaghat, R. R. Muller, and C. Rachinger, "(Continuous) phase modulation on the hypersphere," *IEEE Trans. Wireless Commun.*, vol. 15, no. 8, pp. 5763-5774, Aug. 2016.

[4] B. Shamasundar, S. Bhat, S. Jacob, and A. Chockalingam, "Multidimensional index modulation in wireless communications," *IEEE Access, Special section on index modulation techniques for next-generation wireless networks*, vol. 6, pp. 589-604, 2018.

[5] S. Bhat and A. Chockalingam, "Detection of load-modulated multiuser MIMO signals," *IEEE Wireless Commun. Lett.*, vol. 7, no. 2, pp. 266-269, Apr. 2018.

[6] A. K. Khandani, "Media-based modulation: a new approach to wireless transmission," in *Proc. IEEE ISIT*, Jul. 2013, pp. 3050-3054.

[7] A. K. Khandani, "Media-based modulation: converting static Rayleigh fading to AWGN," in *Proc. IEEE ISIT*, Jun-Jul. 2014, pp. 1549-1553.

[8] E. Seifi, M. Atamanesh, and A. K. Khandani, "Media-based MIMO: outperforming known limits in wireless," in *Proc. IEEE ICC*, May 2016, pp. 1-7.

[9] Y. Naresh and A. Chockalingam, "On media-based modulation using RF mirrors," *IEEE Trans. Veh. Tech.*, vol. 66, no. 6, pp. 4967-4983, Jun. 2017.

[10] E. Basar and I. Altunbas, "Space-time channel modulation," *IEEE Trans. Veh. Tech.*, vol. 66, no. 8, pp. 7609-7614, Aug. 2017.

[11] R. Y. Mesleh, H. Haas, S. Sinanovic', C. W. Ahn, S. Yun, "Spatial modulation," *IEEE Trans. Veh. Tech.*, vol. 57, no. 4, pp. 2228-2241, Jul. 2008.