Channel Modulation in Wireless Communications

A. Chockalingam

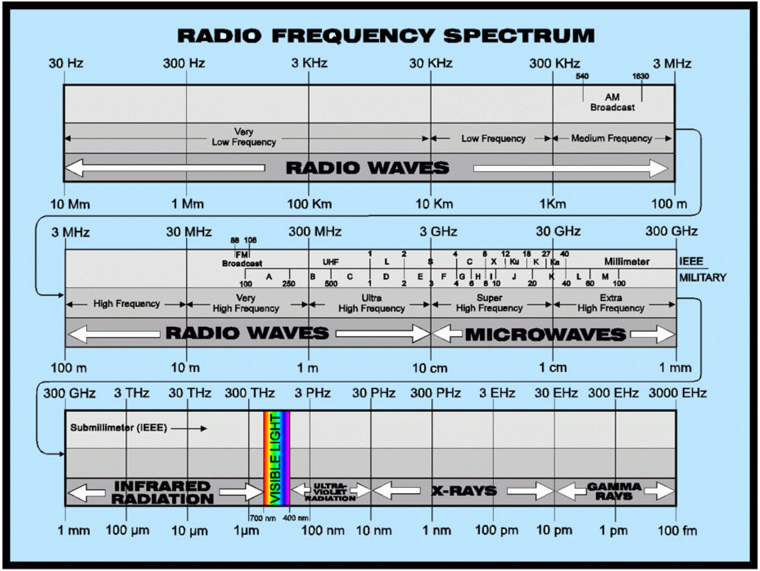
Department of ECE
Indian Institute of Science, Bangalore

BITS 2018
12 January 2018

(Joint work with Y. Naresh, Bharath Shamasundar, Swaroop Jacob, Prof. K. J. Vinoy, Aritra)

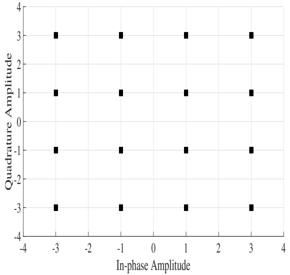
Outline

Wireless spectrum



Source: Internet

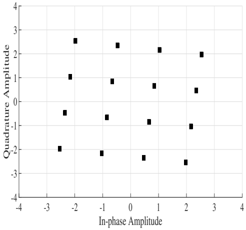
- Conventional view
  - Symbols from complex modulation alphabet (e.g., QAM/PSK) convey information bits



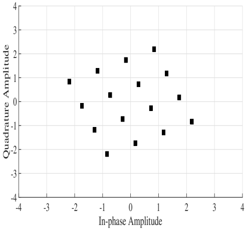
Modulation alphabet $\mathbb{A}$

Modulation approaches

- Conventional view
  - Channel fades viewed as causing amplitude/phase distortion to transmitted symbols



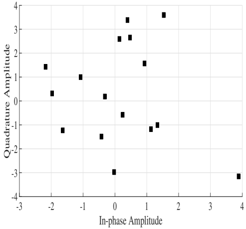
$h_1 x, \; x \in \mathbb{A}$



$h_2 x, \; x \in \mathbb{A}$

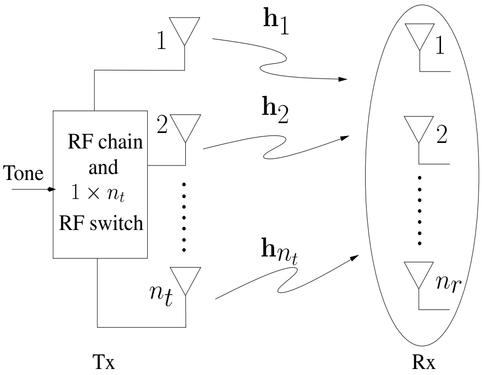
  - $h_1, h_2 \in \mathcal{CN}(0,1)$: Complex channel fades
  - Detrimental to performance

- Alternate view
  - View complex channel fade coefficients themselves to constitute a modulation alphabet
  - $\mathbb{H} = \{h_i, i = 1, \cdots, M\}$ as the modulation alphabet



Channel alphabet $\mathbb{H}$

  - How to create this alphabet?
    - transmit antennas, RF mirrors (parasitic elements)



- # tx. antennas, $n_t > 1$; # tx. RF chains, $n_{rf} = 1$
- Constellation: $\mathbb{H}_{\text{ssk}} = \{\mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_{n_t}\}$

Y. A. Chau and S.-H. Yu, "Space modulation on wireless fading channels," in *Proc. IEEE 54th VTC'2001 (Fall)*, vol. 3, Oct. 2001, pp. 1668-1671.

J. Jeganathan, A. Ghrayeb, L. Szczecinski, and A. Ceron, "Space shift keying modulation for MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3692-3703, Jul. 2009.

Parasitic elements

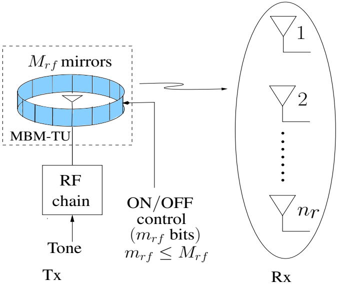
- Parasitic elements
  - capacitors, varactors or switched capacitors that can adjust the resonance frequency
- Use of parasitic elements external to antennas
  - Applications
    - beamforming, DoA estimation
    - selection/switched diversity
    - reconfigurable antennas
- Indexing using parasitic elements
  - *aerial modulation:* index orthogonal antenna patterns realized using parasitic elements
  - *media-based modulation:* index channel fades realized using RF mirrors

---

O. N. Alrabadi, A. Kalis, C. B. Papadias, R. Prasad, "Aerial modulation for high order PSK transmission schemes," in *Wireless VITAE 2009*, May 2009, pp. 823-826.

R. Bains, "On the usage of parasitic antenna elements in wireless communication systems," Ph.D. dissertation, Dept. Electron. Telecommun., Norwegian Univ. Sci. Technol., Trondheim, Norway, May 2008.

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



- \# tx. antennas, $n_t = 1$; \# tx. RF chains, $n_{rf} = 1$
- \# RF mirrors available, M_{rf}; \# RF mirrors used, m_{rf}
- Mirrors act as digitally controlled scatterers
- ON/OFF status of mirrors (a.k.a 'Mirror Activation Pattern') create independent fade realizations
- Constellation: $\mathbb{H}_{\text{mbm}} = \{\mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_{2^{m_{rf}}}\}$

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

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

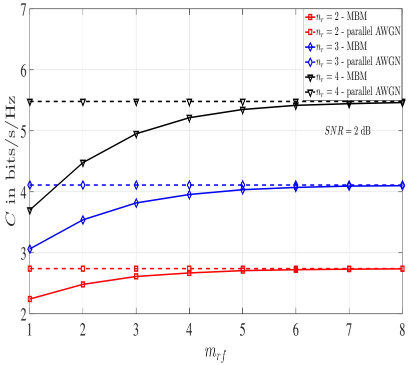
[C] E. Seifi, M. Atamanesh, and A. K. Khandani, "Media-based modulation: A new frontier in wireless communications," online: arXiv:1507.07516v3 [cs.IT] 7 Oct 2015.

SSK, MBM

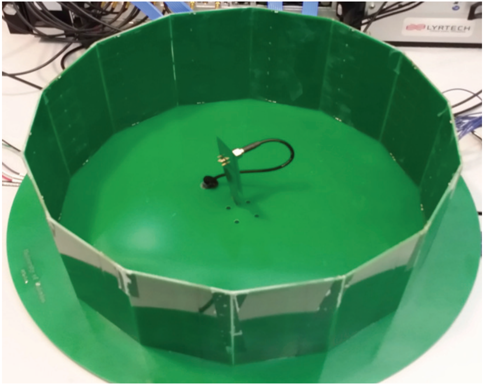
- SSK
  - Multiple tx. antennas create channel fade alphabet $\mathbb{H}_{\text{ssk}}$
  - Advantage
    - simple, need only 1 tx. RF chain, no interference
  - Issue
    - $|\mathbb{H}_{\text{ssk}}| = n_t$, $\eta_{\text{ssk}} = \lfloor \log_2 n_t \rfloor$ bpcu
    - need exponential increase in n_t to increase bpcu

- SSK
  - Multiple tx. antennas create channel fade alphabet $\mathbb{H}_{\text{ssk}}$
  - Advantage
    - simple, need only 1 tx. RF chain, no interference
  - Issue
    - $|\mathbb{H}_{\text{ssk}}| = n_t, \quad \eta_{\text{ssk}} = \lfloor \log_2 n_t \rfloor$ bpcu
    - need exponential increase in n_t to increase bpcu
- MBM
  - Multiple RF mirrors create channel fade alphabet $\mathbb{H}_{\text{mbm}}$
  - Advantage
    - $|\mathbb{H}_{\text{mbm}}| = 2^{m_{rf}}; \quad \eta_{\text{mbm}} = m_{rf}$ bpcu
    - bpcu increases linearly with m_{rf}
  - Issue
    - need to estimate $|\mathbb{H}_{\text{mbm}}| = 2^{m_{rf}}$ constellation points at the rx. through pilot transmission

- MBM with 1 tx. antenna and n_r rx. antennas achieves the capacity of n_r parallel AWGN channels as $m_{rf} \to \infty$.

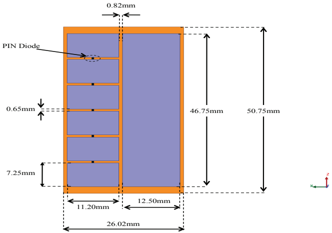


MBM implementation

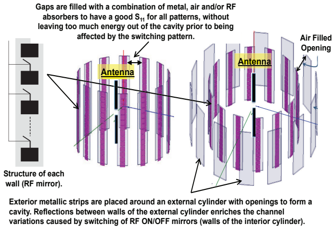


Source: E. Seifi, M. Atamanesh, and A. K. Khandani, “Media-based Modulation: Improving Spectral Efficiency Beyond Conventional MIMO,” E&CE Department, University of Waterloo. http://www.cst.uwaterloo.ca/content/Media-based-ISIT2014.pdf

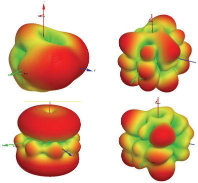
MBM implementation



(c) RF mirror



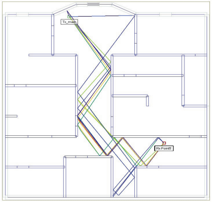
(d) Cylindrical structure with RF mirrors



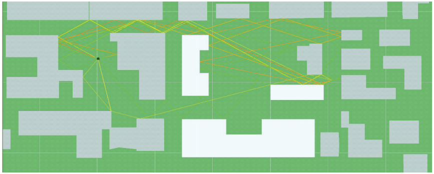
(e) Antenna patterns

Source: http://www.cst.uwaterloo.ca/content/Media-based-ISIT2014.pdf
http://www.cst.uwaterloo.ca/reports/media-report.pdf

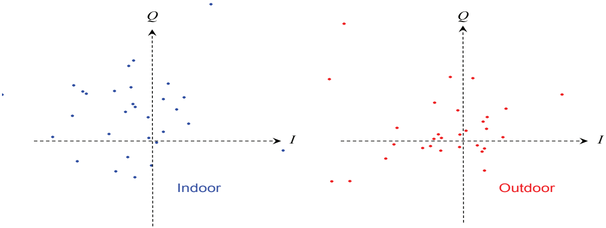
MBM in indoor/outdoor environments



Indoor (residential building with dry-walls)



Outdoor Model (down-town Ottawa)



MBM constellation points

Source: http://www.cst.uwaterloo.ca/content/Media-based-ISIT2014.pdf
http://www.cst.uwaterloo.ca/reports/media-report.pdf

MBM: An instance of index modulation

- Index modulation
  - bits are conveyed through indices of transmit entities
- Examples
  - Indexing in spatial domain in multiantenna systems
    - SSK, SM, GSM
  - Indexing in frequency domain in multicarrier systems
    - subcarrier index modulation in OFDM
  - Indexing in space and frequency
    - GSFIM (generalized space-frequency index modulation)
  - Indexing in space and time
    - STIM (space-time index modulation)
  - Indexing precoders
    - PIM (precoder index modulation)
  - Indexing RF mirrors
    - MBM (media-based modulation)

- MBM + conventional modulation
- $\mathbb{A}$: a conventional modulation alphabet (e.g., QAM)
- Define $\mathbb{A}_0 \triangleq \mathbb{A} \cup 0$ and $N_m \triangleq 2^{m_{rf}}$
- MBM signal set: set of $N_m \times 1$-sized vectors given by

$$\mathbb{S}_{\text{mbm}} = \Big\{ \mathbf{s} \in \mathbb{A}_0^{N_m} : \mathbf{s} = [0 \cdots 0 \underbrace{s}_{k\text{th coordinate}} 0 \cdots 0]^T, \; s \in \mathbb{A}, k = 1, \cdots, N_m \Big\}$$

where k is the index of the MAP. $|\mathbb{S}_{\text{mbm}}| = N_m |\mathbb{A}|$

- Example: for $m_{rf} = 2$ and $|\mathbb{A}| = 2$ (i.e., BPSK),

$$\mathbb{S}_{\text{mbm}} = \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ -1 \end{bmatrix} \right\}$$

- MBM signal vectors are sparse vectors
- $n_r \times 1$ rx. signal vector: $\mathbf{y} = s\mathbf{h}_k + \mathbf{n}$; k: MAP index

MBM performance

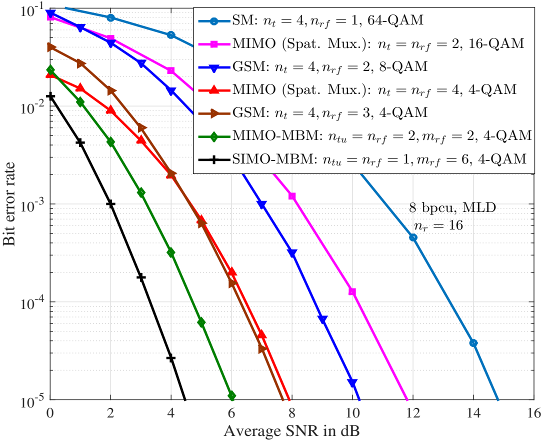
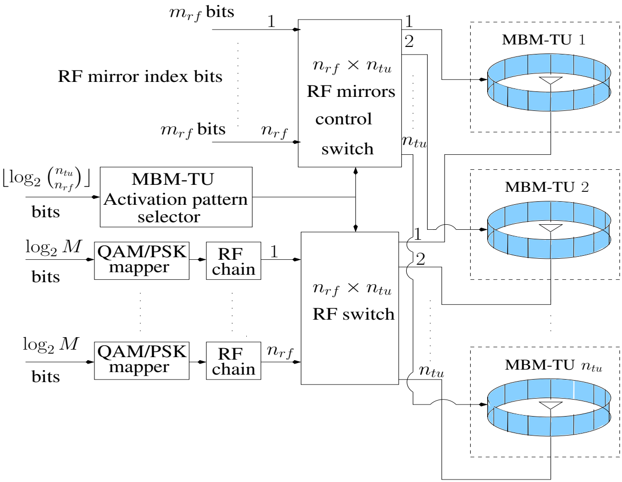


Figure : Comparison between SIMO-MBM with RF mirrors and other multi-antenna schemes without RF mirrors (MIMO, SM, GSM).

- MBM achieves very good performance

Point-to-point GSM-MBM

GSM-MBM transmitter



Y. Naresh and A. Chockalingam, "On media-based modulation using RF mirrors," in Proc. ITA'2016, San Diego, Feb. 2016. Also in IEEE Trans. Veh. Tech., vol. 66, no. 6, pp. 4967-4983, Jun. 2017.

- Information bits are conveyed through
  - MBM-TU indexing
    - n_{rf} out of n_{tu} MBM-TUs selected using $\lfloor \log_2 \binom{n_{tu}}{n_{rf}} \rfloor$ bits
  - M-ary modulation (QAM/PSK) symbols
    - n_{rf} M-ary symbols (formed using $n_{rf} \log_2 M$ bits) are sent on the selected MBM-TUs
  - RF mirror indexing
    - ON/OFF status of m_{rf} mirrors (mirror activation pattern) conveys m_{rf} bits per MBM-TU
- Achieved rate in GSM-MBM

$$\eta = \underbrace{\left\lfloor \log_2 \binom{n_{tu}}{n_{rf}} \right\rfloor}_{\text{MBM-TU index bits}} + \underbrace{n_{rf}\, m_{rf}}_{\text{mirror index bits}} + \underbrace{n_{rf} \log_2 M}_{\text{QAM/PSK symbol bits}} \quad \text{bpcu}$$

GSM-MBM system model

- # MAPs per MBM-TU: $N_m = 2^{m_{rf}}$
- $\mathbb{S}_m$: Set of all N_m MAPs per MBM-TU
- $\mathbb{H}^j = \{\mathbf{h}_1^j, \mathbf{h}_2^j, \cdots, \mathbf{h}_{N_m}^j\}$: MBM alphabet of jth MBM-TU
- $\mathbf{h}_k^j = [h_{1,k}^j \ h_{2,k}^j \ \cdots \ h_{n_r,k}^j]^T$
- $h_{i,k}^j \sim \mathcal{CN}(0,1)$: channel fade corresponding to the kth MAP of jth MBM-TU to the ith receive antenna
- Received signal vector

$$\mathbf{y} = \sum_{j=1}^{n_{tu}} s_j \mathbf{h}_{l_j}^j + \mathbf{n}, \quad s_j \in \mathbb{A}_0$$

$l_j \in \{1, \cdots, N_m\}$: index of MAP chosen on jth MBM-TU

$$\mathbf{y} = \sum_{j=1}^{n_{tu}} s_j \mathbf{H}^j \mathbf{e}_{l_j} + \mathbf{n}, \quad \mathbf{H}^j = [\mathbf{h}_1^j \ \mathbf{h}_2^j \ \cdots \ \mathbf{h}_{N_m}^j]$$

GSM-MBM system model

- Received signal vector can be written in the form

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad \mathbf{H} = [\mathbf{H}^1 \ \mathbf{H}^2 \ \cdots \ \mathbf{H}^{n_{tu}}]$$

- $\mathbf{x}$ belongs to the GSM-MBM signal set given by

$$\mathbb{S}_{\text{gsm-mbm}} = \Big\{ \mathbf{x} = [\mathbf{x}_1^T \ \mathbf{x}_2^T \ \cdots \ \mathbf{x}_{n_{tu}}^T]^T : \mathbf{x}_j = s_j \mathbf{e}_{l_j}, \\ l_j \in \{1, \cdots, N_m\}; \ \ \mathbf{s} = [s_1 \ s_2 \ \cdots \ s_{n_{tu}}]^T \in \mathbb{S}_{\text{gsm}} \Big\}$$

- ML decision rule is

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathbb{S}_{\text{gsm-mbm}}}{\text{argmin}} \ \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2$$

GSM-MBM performance

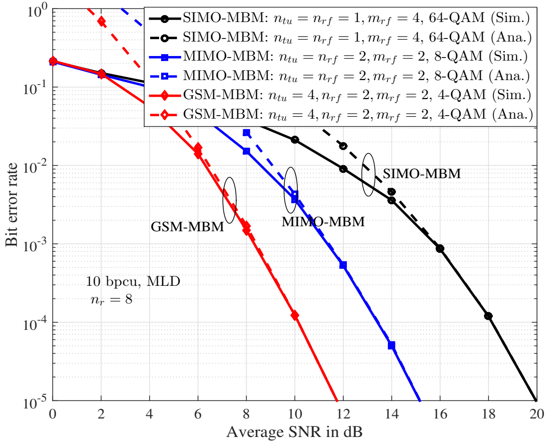


Figure : Performance of SIMO-MBM, MIMO-MBM, and GSM-MBM with $n_r = 8$, and 10 bpcu.

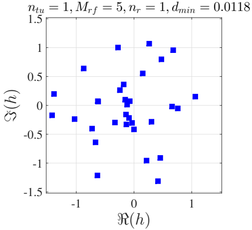
MAP selection

- An MBM-TU may be designed to have more RF mirrors than actually used ($M_{rf} \geq m_{rf}$)
- $2^{m_{rf}}$ best MAPs among $2^{M_{rf}}$ MAPs can be selected (similar to tx. antenna selection in multiantenna systems)
- Consider MAP selection in MIMO-MBM
- $\mathbb{S}_{\text{all}}$: set of all possible MAPs per MBM-TU. $|\mathbb{S}_{\text{all}}| = 2^{M_{rf}}$
- $\mathbb{S}_{\text{sub}}$: possible subset of $\mathbb{S}_{\text{all}}$. $|\mathbb{S}_{\text{sub}}| = 2^{m_{rf}}$
- Rx. estimates all $|\mathbb{S}_{\text{all}}|$ constellation points, selects the best $|\mathbb{S}_{\text{sub}}|$ among them, and sends the indices of the corresponding MAPs to the Tx.
- Tx. uses these selected MAPs to index the mirrors

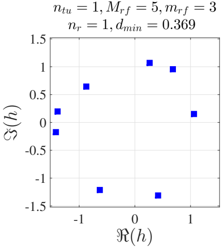
Energy-based MAP selection

- Choose the MBM constellation points with the highest energies
- $\mathbb{L}^{j}_{\mathrm{MI}} = \{l_{j1}, l_{j2}, \cdots, l_{j|\mathbb{S}_{\mathrm{sub}}|}\}$: set of MAP indices corresponding to the $|\mathbb{S}_{\mathrm{sub}}|$ largest energies for the jth MBM-TU

$$\|\mathbf{h}^{j}_{l_{j1}}\|^2 \geq \|\mathbf{h}^{j}_{l_{j2}}\|^2 \geq \cdots \geq \|\mathbf{h}^{j}_{l_{j|\mathbb{S}_{\mathrm{sub}}|}}\|^2 \geq \cdots \geq \|\mathbf{h}^{j}_{l_{j|\mathbb{S}_{\mathrm{all}}|}}\|^2$$



(a) All constellation points

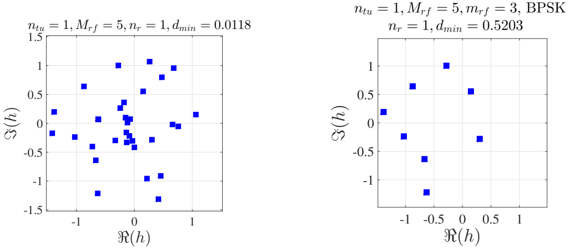


(b) Energy-based selection

ED-based MAP selection

- $\mathcal{I}^j$: collection of sets of MAP indices corresponding to the enumerations of the $\binom{|\mathbb{S}_{\mathsf{all}}|}{|\mathbb{S}_{\mathsf{sub}}|}$ combinations of selecting $|\mathbb{S}_{\mathsf{sub}}|$ out of $|\mathbb{S}_{\mathsf{all}}|$ MAPs of the jth MBM-TU
- $\mathcal{L} = \left\{\mathbb{L} = \{\mathbb{L}^1, \mathbb{L}^2, \cdots, \mathbb{L}^{n_{tu}}\} : \mathbb{L}^j \in \mathcal{I}^j, j = \{1, \cdots, n_{tu}\}\right\}$
- Choose the set from $\mathcal{L}$ such that

$$\mathbb{L}_{\mathsf{ED}} = \underset{\mathbb{L}\in\mathcal{L}}{\operatorname{argmax}} \left\{ \min_{\substack{\mathbf{x}_1,\mathbf{x}_2\in\mathcal{X} \\ \mathbf{x}_1\neq\mathbf{x}_2}} \left|\left|\mathbf{H}_{\mathbb{L}}\left(\mathbf{x}_1 - \mathbf{x}_2\right)\right|\right|^2 \right\}$$



(c) All constellation points

(d) ED-based selection

MAP selection performance

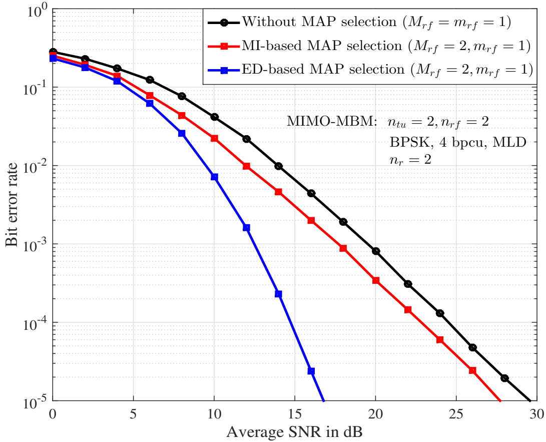
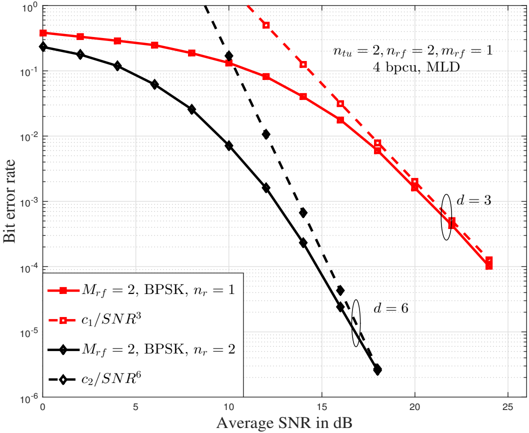


Figure : Performance of MIMO-MBM schemes without and with MAP selection. $n_{tu} = n_{rf} = 2$, BPSK, 4 bpcu, $n_r = 2$.

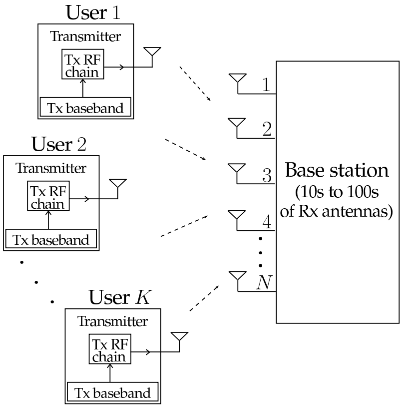
MAP selection performance

- Diversity order of ED-based MAP selection:
  $d = n_r \left(|\mathbb{S}_{\text{all}}| - |\mathbb{S}_{\text{sub}}| + 1 \right)$



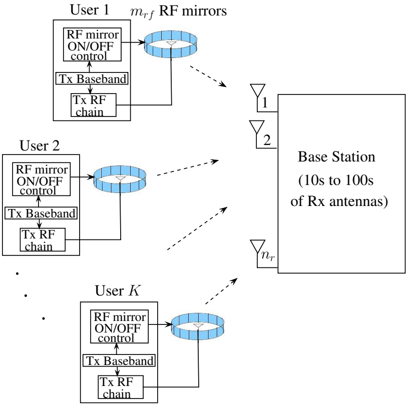
Multiuser MBM in massive MIMO systems

Conventional massive MIMO system



- K : # uplink users (in 10's)
- Each user has $n_t = 1$ tx. antenna
  - uses conventional modulation
- n_r : # rx. antennas at BS (in 100's)

MU-MBM system

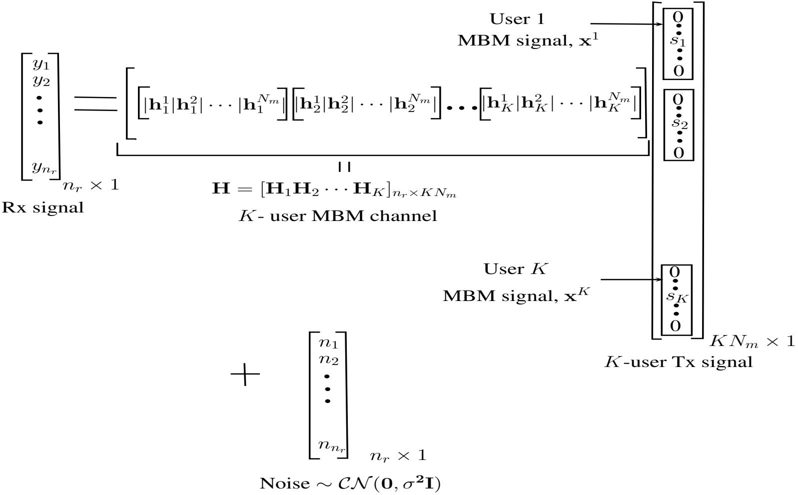


- Each user has $n_t = 1$ tx. antenna and m_{rf} RF mirrors
  - uses MBM for signal transmission
- Multiuser MBM signal set: $\mathbb{S}_{\text{mu-mbm}} = \mathbb{S}_{\text{mbm}}^K$

B. Shamasundar, A. Chockalingam, "Multiuser Media-based Modulation for Massive MIMO Systems," in Proc. IEEE SPAWC'2017, Sapporo, Japan, Jul. 2017.

MU-MBM rx. signal

- MU-MBM rx. signal: $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$



Sparsity-exploiting detection

- MBM signal vectors are inherently sparse
- An MBM signal vector has only one non-zero element out of N_m elements, leading to a sparsity factor of $1/N_m$
- Example: Let $K = 16$, $m_{rf} = 4$, $N_m = 2^{m_{rf}} = 16$. Out of $KN_m = 256$ elements, only 16 are non-zeros, resulting in a sparsity factor of $\frac{16}{256} = \frac{1}{16}$
- This inherent sparsity can be exploited for low complexity detection
- Sparse recovery algorithms like OMP, CoSaMP, and subspace pursuit (with necessary modifications) can be used

Algorithm : Sparsity-exploiting detection of MU-MBM signals

Inputs: $\mathbf{y}, \mathbf{H}, K$
Initialize: $j = 0$
repeat
  $\hat{\mathbf{x}}_r = \text{SR}(\mathbf{y}, \mathbf{H}, K + j)$ ▷ Sparse Recovery algorithm
  $\mathbf{u}^j = \text{UAP}(\hat{\mathbf{x}}_r)$ ▷ Extract User Activity Pattern
  if $\|\mathbf{u}^j\|_0 = K$
    for $q = 1$ to K
      $\hat{\mathbf{x}}^q = \underset{\mathbf{s}\in\mathbb{S}_{\text{mbm}}}{\text{argmin}} \|\hat{\mathbf{x}}_r^q - \mathbf{s}\|^2$ ▷ Nearest MBM signal mapping
    end for
    break;
  else $j = j + 1$
  end if
until $j < K(N_m - 1)$
Output: The estimated MU-MBM signal vector

$$\hat{\mathbf{x}} = [\hat{\mathbf{x}}^{1^T}, \hat{\mathbf{x}}^{2^T}, \cdots, \hat{\mathbf{x}}^{K^T}]^T$$

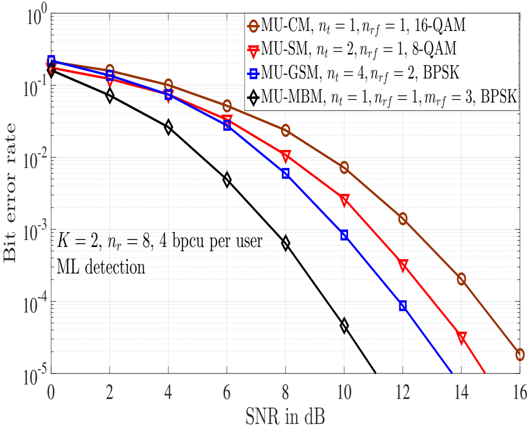


Figure : BER performance of MU-MBM, MU-CM, MU-SM, and MU-GSM with $K = 2$, $n_r = 8$, 4 bpcu per user, and ML detection

MU-MBM performance

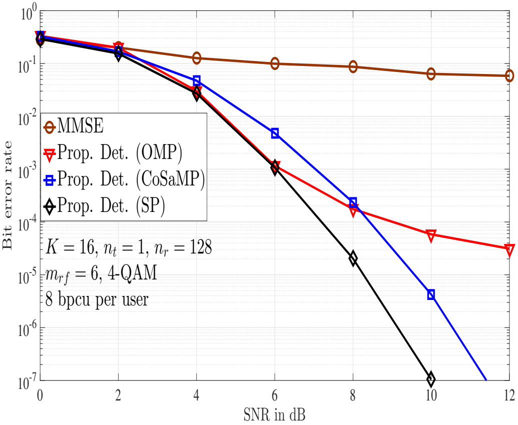


Figure : BER performance of MU-MBM in a massive MIMO system with $K = 16$, $n_r = 128$, $n_t = 1$, $n_{rf} = 1$, $m_{rf} = 6$, 4-QAM, 8bpcu per user, using the proposed detection algorithm

MU-MBM performance

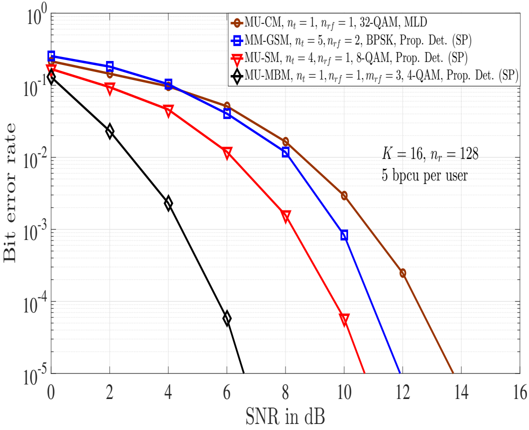


Figure : BER performance MU-MBM, MU-CM, MU-SM, and MU-GSM in a massive MIMO setting with $K = 16$, $n_r = 128$, and 5 bpcu per user

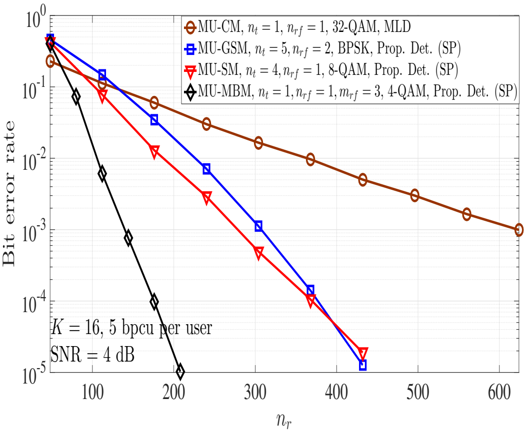
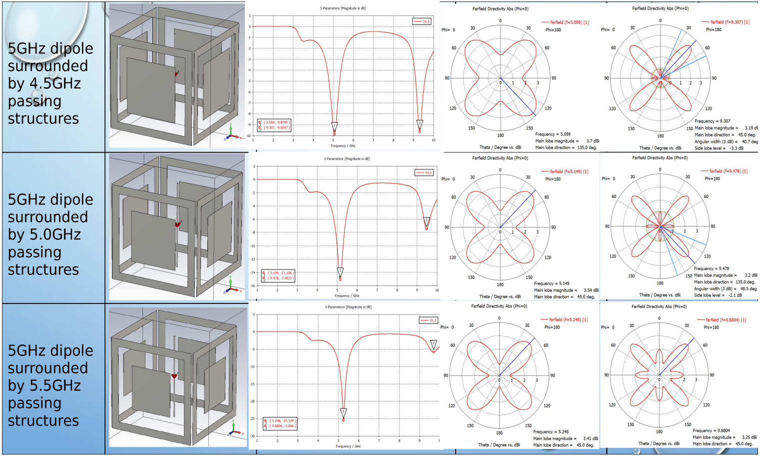


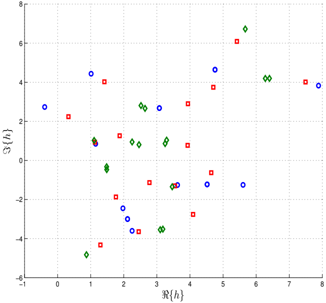
Figure : BER performance MU-MBM, MU-CM, MU-SM, and MU-GSM as a function of n_r in a massive MIMO setting with $K = 16$, 5 bpcu per user, and SNR $= 4$ dB

Modulation screens @ IISc

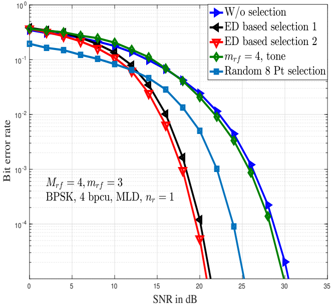


* Collaborative work Prof. K. J. Vinoy, Aritra, Naresh.

Modulation screens @ IISc



(a) MBM constellations



(b) BER performance

* Collaborative work Prof. K. J. Vinoy, Aritra, Naresh.

Concluding remarks

- Media-based modulation
  - uses digitally controlled parasitic elements (RF mirrors) for modulation purposes
  - conveys information by indexing RF mirrors
  - offers rate, performance, hardware, and cost advantages
  - suited for point-to-point and multiuser communications
  - a promising modulation approach for next generation wireless (5G)

Thank you