Transceiver Design for Large-Scale Systems

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Introduction

- Research and engineering interest on large-scale systems
- Our focus: large-scale **multi-antenna** systems
  - Very large aperture arrays
  - Massive multiple-input multiple-output (MIMO)
- Why the interest?
  - High spatial resolution
  - Large beamforming gain
  - Better interference rejection

Introduction

- Challenges
  - Energy and computational efficiencies
  - Channel state information (CSI) acquisiton
- Proposed solutions
  - Multi-linear (tensor) filtering
  - Layered filtering

Introduction

Multi-linear filtering

MmWave massive MIMO transceiver design

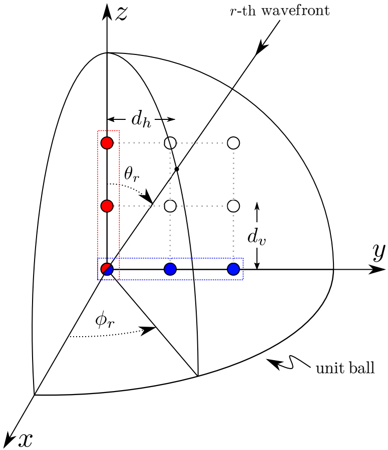
Multi-linear filtering

- Linear and time-invariant filter: $\boldsymbol{w} = [w_1, \ldots, w_N]^\mathsf{T}$
- Multi-linear and time-invariant filter:

$$\boldsymbol{w} = \boldsymbol{w}_1 \otimes \ldots \otimes \boldsymbol{w}_M \in \mathbb{C}^N$$

  where $\boldsymbol{w}_m \in \mathbb{C}^{N_m}$ with $\prod_{m=1}^{M} N_m = N$
- Basic idea: design **each** factor instead of the **whole** vector
- Questions
  - Fewer computations?
  - How much performance loss, if any?
- Application: beamforming

Uniform planar array



- Far-field propagation and narrow-band signal assumptions
- No coupling
- Uniform planar array (UPA) response vector

$$\boldsymbol{a}(\phi_r, \theta_r) = [a_n(\phi_r, \theta_r)]$$

$$a_n(\phi_r, \theta_r) = \underbrace{g_n(\phi_r, \theta_r)}_{\text{element response}} \cdot \underbrace{e^{j\pi[(n_h-1)\sin\phi_r \sin\theta_r + (n_v-1)\cos\theta_r]}}_{\text{relative phase shift}}$$

- Let's ignore the element responses g_n for the moment
- Array response vector rewritten as

$$\boldsymbol{a}(\phi_r, \theta_r) = \begin{bmatrix} 1 \\ e^{j\pi \cos\theta_r} \\ \vdots \\ e^{j\pi (N_v - 1)\cos\theta_r} \end{bmatrix} \otimes \begin{bmatrix} 1 \\ e^{j\pi \sin\phi_r \sin\theta_r} \\ \vdots \\ e^{j\pi (N_h - 1)\sin\phi_r \sin\theta_r} \end{bmatrix}$$
$$= \boldsymbol{a}_v(q_r) \otimes \boldsymbol{a}_h(p_r)$$

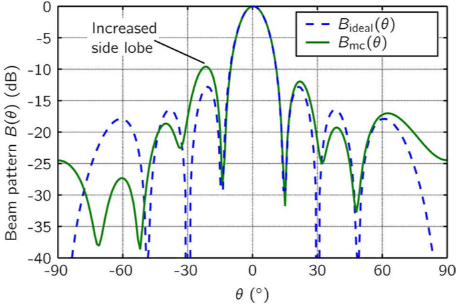
with $N = N_h \cdot N_v$, $p_r = \sin\phi_r \sin\theta_r$ and $q_r = \cos\theta_r$.

- Response vector is **separable** in horizontal and vertical domains
- Separable filter $\boldsymbol{w} = \boldsymbol{w}_v \otimes \boldsymbol{w}_h$
- Array factor:

$$AF = \boldsymbol{w}^{\mathsf{H}} \boldsymbol{a}(p_r, q_r) = [\boldsymbol{w}_v^{\mathsf{H}} \boldsymbol{a}_v(q_r)] \cdot [\boldsymbol{w}_h^{\mathsf{H}} \boldsymbol{a}_h(p_r)]$$
$$= AF_v \cdot AF_h$$

- Optimize each **sub-array** individually!

Is this model valid?



8-elements uniform linear array. Ideal BP (separable) and BP with mutual coupling[1].

- Beampattern (BP) is not separable in general
- Antenna response and mutual coupling not important in some scenarios
- **Approximate** separable model

[1] C. M. Schmid, et al., “On the effects of calibration errors and mutual coupling on the beam pattern of an antenna array,” IEEE Transactions on Antennas and Propagation 61.8 (2013): 4063-4072.

Tensor filters

Separable beamformers

- Tensor MMSE and Tensor LMS [Ribeiro et al., 2019b]
- Tensor LCMV and Tensor Frost [Ribeiro et al., 2019a]

What if the system is not separable?

- **Low-rank** Tensor MMSE

Tensor MMSE – Signal model

- Received signal model – R incoming signals

$$\boldsymbol{x}[k] = \sum_{r=1}^{R} \boldsymbol{a}(p_r, q_r) s_r[k] + \boldsymbol{b}[k] = \boldsymbol{A}\boldsymbol{s}[k] + \boldsymbol{b}[k] \in \mathbb{C}^N$$

- Assumptions
    - Separability: $\boldsymbol{A} = \boldsymbol{A}_v \diamond \boldsymbol{A}_h \in \mathbb{C}^{N \times R}$
    - Separable filter: $\boldsymbol{w} = \boldsymbol{w}_v \otimes \boldsymbol{w}_h$
- Filtered signal

$$y[k] = \sum_{n=1}^{N} [\boldsymbol{w}]_n^* x_n[k] = \sum_{n_h=1}^{N_h} \sum_{n_v=1}^{N_v} [\boldsymbol{w}_h]_{n_h}^* [\boldsymbol{w}_v]_{n_v}^* x_{n_h, n_v}[k]$$

$$= \boldsymbol{w}_h^{\mathsf{H}} \boldsymbol{X}[k] \boldsymbol{w}_v^* = \boldsymbol{w}_v^{\mathsf{H}} \boldsymbol{X}[k]^{\mathsf{T}} \boldsymbol{w}_h^*$$

with $n = n_h + (n_v - 1)N_h$

- Let

$$\boldsymbol{u}_h[k] = \boldsymbol{X}[k]\boldsymbol{w}_v^* \in \mathbb{C}^{N_h}, \quad \boldsymbol{u}_v[k] = \boldsymbol{X}[k]^{\mathsf{T}}\boldsymbol{w}_h^* \in \mathbb{C}^{N_v}$$

- Training sequences $s_d[k]$
- We formulate – mean square error (MSE) criterion

$$\min_{\boldsymbol{w}_v, \boldsymbol{w}_h} J_{\mathrm{MSE}}(\boldsymbol{w}_h, \boldsymbol{w}_v)$$

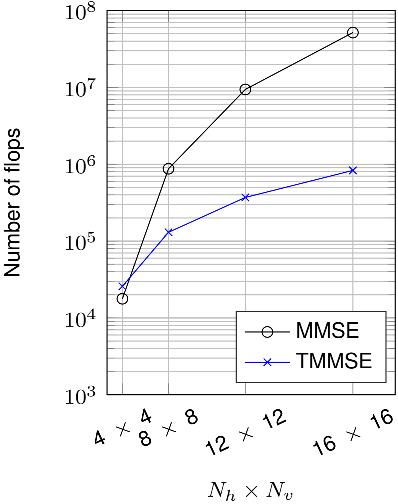
where

$$J_{\mathrm{MSE}}(\boldsymbol{w}_h, \boldsymbol{w}_v) = \mathbb{E}\left[\left|s_d[k] - \boldsymbol{w}_h^{\mathsf{H}}\boldsymbol{u}_h[k]\right|^2\right] \quad (1)$$

$$= \mathbb{E}\left[\left|s_d[k] - \boldsymbol{w}_v^{\mathsf{H}}\boldsymbol{u}_v[k]\right|^2\right] \quad (2)$$

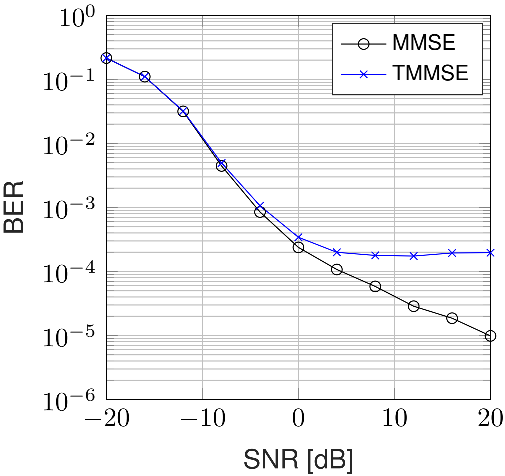
- Block coordinate descent: solve (1) and (2) in alternate fashion (TMMSE filter)

Computational complexity



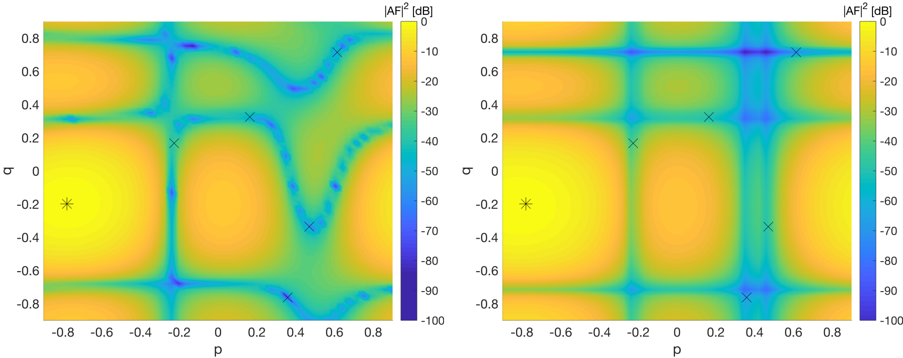
- MMSE: $O(N^3)$ flops
- TMMSE: $O(I(N_h^3 + N_v^3))$ flops
- I: number of iterations
- $N_h,\ N_v \leq N$

Bit error rate



$N_h \times N_v = 8 \times 8$, $R = 4$ wavefronts.

Array factor



MMSE TMMSE

Desired signal (asterisk), interfering signals (cross)

- TMMSE reduces calculations
- Needs fewer samples to estimate statistics (compared to MMSE)
- Performance cost (high SNR)
- Strong degradation when $R > \min(N_h, N_v)$

Questions

- Perforance with more elaborate channel model?
- Higher filter order? E.g., $\boldsymbol{w} = \boldsymbol{w}_1 \otimes \boldsymbol{w}_2 \otimes \boldsymbol{w}_3$?

Non-separable system

- MIMO system, U users, uplink scenario

$$\boldsymbol{x}[k] = \sum_{u=1}^{U} \boldsymbol{H}_u \boldsymbol{s}_u[k] + \boldsymbol{b}[k]$$

- Channel model

$$\boldsymbol{H}_u = \sum_{\ell=1}^{L} \alpha_{u,\ell} \boldsymbol{a}(\theta_{u,\ell}) \boldsymbol{g}(\tau_{u,\ell})^{\mathsf{T}} \in \mathbb{C}^{N \times Q}$$

$$\boldsymbol{a}(\theta_{u,\ell}) = \left[1, \ldots, e^{-\jmath\pi(N-1)\cos\theta_{u,\ell}}\right]^{\mathsf{T}} \in \mathbb{C}^{N}$$

$$\boldsymbol{g}(\tau_{u,\ell}) = [g(-\tau_{u,\ell}), \ldots, g((Q-1)T - \tau_{u,\ell})]^{\mathsf{T}} \in \mathbb{C}^{Q}$$

- $\boldsymbol{H}_u$ is not separable; but admits a **low-rank** structure

Low-rank equalizer

- Rank-1 order M filter

$$\boldsymbol{w} = \boldsymbol{w}_1 \otimes \ldots \otimes \boldsymbol{w}_M$$

- Rank-R order M filter

$$\boldsymbol{w} = \sum_{r=1}^{R} \boldsymbol{w}_{1,r} \otimes \ldots \otimes \boldsymbol{w}_{M,r}$$

- Number of parameters
  - Linear filter: N
  - Low-rank multi-linear filter: $R(N_1 + \ldots + N_M)$

Low-rank Tensor MMSE[2]

- We formulate for each filter mode

$$\min_{\boldsymbol{w}_d} \mathbb{E}\left[\left|s_u[k-\delta] - \boldsymbol{w}_d^{\mathsf{H}} \boldsymbol{u}_d[k]\right|^2\right], \quad d \in \{1, \ldots, D\}.$$

where

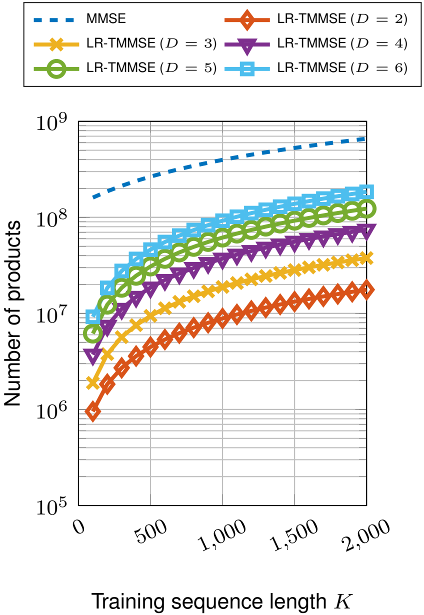
$$\boldsymbol{u}_d[k] = \left[\boldsymbol{u}_{d,1}^{\mathsf{T}}[k], \ldots, \boldsymbol{u}_{d,R}^{\mathsf{T}}[k]\right]^{\mathsf{T}} \in \mathbb{C}^{RN_d}$$

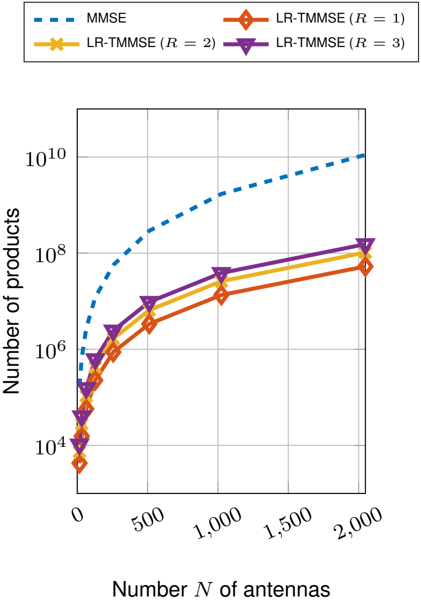
$$\boldsymbol{u}_{d,r}[k] = \boldsymbol{X}_{(d)}[k] \bigotimes_{q \neq d}^{D} \boldsymbol{w}_{q,r}^* \in \mathbb{C}^{N_d}$$

$$\boldsymbol{w}_d = \left[\boldsymbol{w}_{d,1}^{\mathsf{T}}, \ldots, \boldsymbol{w}_{d,R}^{\mathsf{T}}\right]^{\mathsf{T}} \in \mathbb{C}^{RN_d}$$

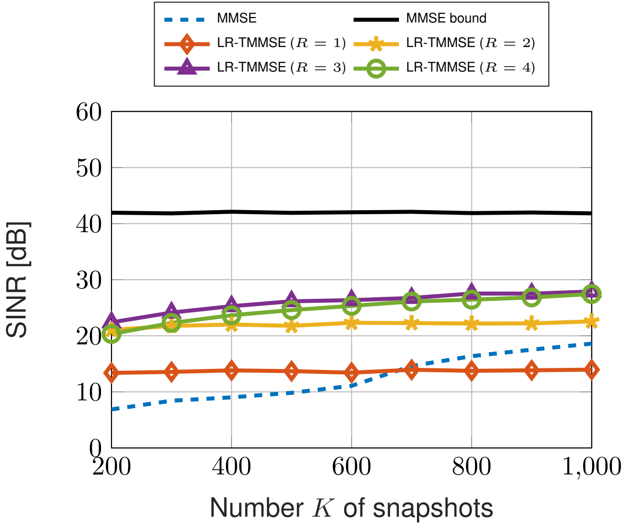
- Block coordinate descent sweeping between modes

[2] To be presented at IEEE ISWCS 2019, Oulu, Finland


MMSE
LR-TMMSE ($D = 2$)
LR-TMMSE ($D = 3$)
LR-TMMSE ($D = 4$)
LR-TMMSE ($D = 5$)
LR-TMMSE ($D = 6$)
10^9
10^8
10^7
10^6
10^5
Number of products
0
500
1,000
1,500
2,000
Training sequence length K


MMSE
LR-TMMSE ($R = 1$)
LR-TMMSE ($R = 2$)
LR-TMMSE ($R = 3$)
10^{10}
10^8
10^6
10^4
Number of products
0
500
1,000
1,500
2,000
Number N of antennas

Symbol recovery performance



$N = 512$ antennas, SNR = 20 dB, filter order $D = 3$, $U = 4$ users, $L = 4$ paths.

Conclusion

- $\uparrow$ filter order $\uparrow$ calculations: **tensor overhead**
  - number of tensor products, unfoldings, etc, increase with tensor order!
- $\uparrow$ rank $\uparrow$ equalization performance (up to a point)
- Fewer samples to estimate covariance matrices
- **Attractive complexity/performance trade-off**

Research perspectives

- Incorporate non-idealities
- Simulations with realistic arrays (HFSS)
- **Low-rank beamforming**

Introduction

Multi-linear filtering

MmWave massive MIMO transceiver design

Introduction

- Efficient hardware architectures for mmWave massive MIMO
  - Analog? Digital? Hybrid analog/digital?
  - Fully- or partially-connected hybrid?
- We found[3]
  - full digital and partially-connected hybrid
  - + coarse quantization (~ 3 bits)
  - are most energy-efficient structures
  - single-user MIMO scenario and perfect CSI
- **Transceiver schemes with practical CSI requirements?**

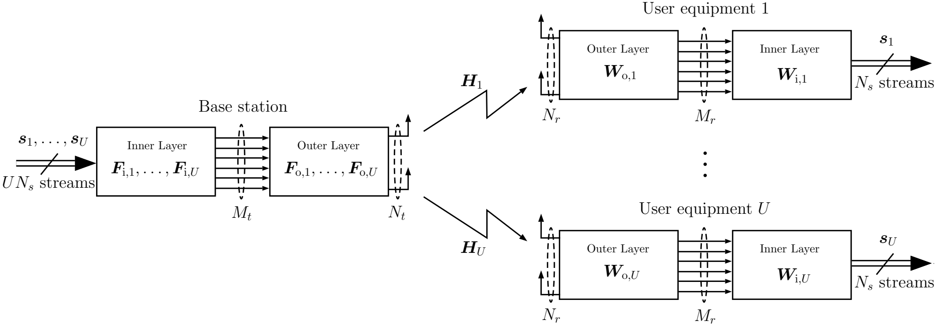
[3] L. N. Ribeiro, S. Schwarz, M. Rupp, A. L. F. de Almeida, "Energy efficiency of mmWave massive MIMO precoding with low-resolution DACs," IEEE Journal of Selected Topics in Signal Processing 12.2 (2018): 298-312.

Double-sided massive MIMO

- Massive MIMO at both base station (BS) and user equipment (UE)[4]
- Why?
  - Potentially better performance than canonical massive MIMO
  - Wireless backhauling, terahertz communications, unmanned aerial vehicle communcations, etc
- Contributions
  - Low-complexity transceiver scheme with practical CSI requirements
  - Performance evaluation under different propagation conditions

[4] L. N. Ribeiro, S. Schwarz, A. L. F. de Almeida, "Double-Sided Massive MIMO Transceivers for MmWave Communications," arXiv preprint arXiv:1907.08750 (2019).

Multi-layer precoding – System model



$$\boldsymbol{H}_{\mathsf{eff},u,j} = \boldsymbol{W}_{\mathsf{o},u}^{\mathsf{H}} \boldsymbol{H}_u \boldsymbol{F}_{\mathsf{o},j} \in \mathbb{C}^{M_r \times M_t}, \quad \gamma_u = \frac{\sqrt{P_t/U}}{\|\boldsymbol{F}_{\mathsf{o},u}\boldsymbol{F}_{\mathsf{i},u}\|_{\mathrm{F}}}$$

$$\boldsymbol{y}_u = \gamma_u \boldsymbol{W}_{\mathsf{i},u}^{\mathsf{H}} \boldsymbol{H}_{\mathsf{eff},u} \boldsymbol{F}_{\mathsf{i},u} \boldsymbol{s}_u + \sum_{\substack{j=1 \\ j \neq u}}^{U} \gamma_j \boldsymbol{W}_{\mathsf{i},u}^{\mathsf{H}} \boldsymbol{H}_{\mathsf{eff},u,j} \boldsymbol{F}_{\mathsf{i},j} \boldsymbol{s}_j + \boldsymbol{W}_{\mathsf{i},u}^{\mathsf{H}} \boldsymbol{b}_{\mathsf{eff},u}$$

Multi-layer precoding – Schemes

- Both full-digital and hybrid A/D architectures
- Outer layer – *increase SNR*
  - Covariance matrix eigenfilter (CME)
  - Power-dominant path selection (PPS)
  - Semi-orthogonal path selection (SPS)
- Inner layer – *cancel multi-user interference out*
  - Max. Eig. Tx. (MET) - Max. Eig. Rx. (MER)
  - MET-Block diagonalization (BD)
  - MET-MMSE
  - BD-MER
- When BD conditions for zero multi-user interference are not met, apply "minimal interference precoding" of [Schwarz and Rupp, 2014]

Multi-layer precoding – CSI assumptions

CSI assumptions

- Statistical CSI – of uplink and downlink cov. matrices
- Partial CSI – paths power, departure and arrival angles

Design stages

1. Calculate outer filters w/ available CSI
2. Efficiently estimate low-dimension effective channels
3. Calculate inner filters w/ effective CSI

Outer layer – CME and PPS

Covariance matrix eigenfilter

- Outer filters as uplink and downlink cov. matrices eigenvectors
- Statistical CSI
- Relatively simple

Power-dominant path selection

- Points to the strongest path directions
- Partial CSI
- Very simple, but naive (correlation issues)

Outer layer – SPS

- Sophistication of the power-dominant path selection
- Among the L paths, select the $M < L$ "most semi-orthogonal"
- Inspired on semi-orthogonal user selection scheduling scheme [Yoo and Goldsmith, 2006]

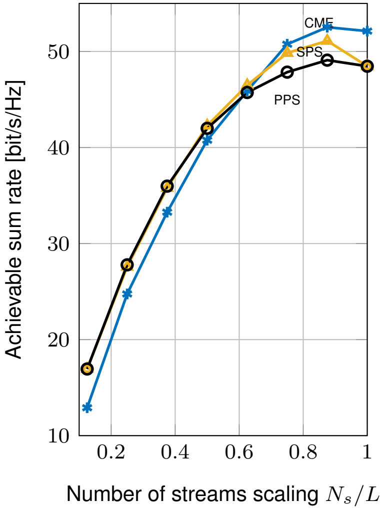
<u>Pseudo-code</u>

- Initialize index sets S (selected) and Λ (non-selected)
- While $\#(S) < M$
  1. Form orthogonal projections for paths in Λ
  2. Select new path
  3. Update S and Λ
- Return S

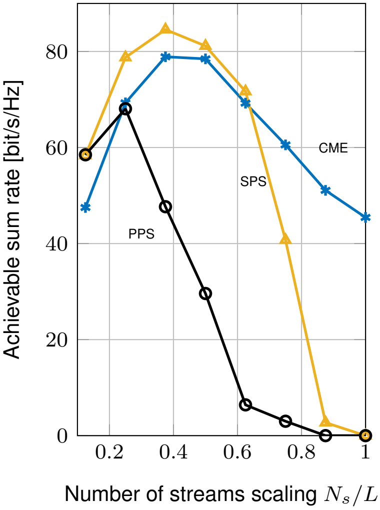
Simulation results

- Investigate spatial multiplexing capabilities
- **Needs enough degrees of freedom**
- Evaluation under different channel scattering conditions
  - Poor scattering – $L = 8$ rays – pessimistic and realistic for mmWave
  - Rich scattering – $L = 64$ rays – optimistic and plausible for sub-6 GHz (Rayleigh regime)
- Outer layer simulations: effect of N_s/L on sum rate (number of data streams scaling) and $U = 1$ UE
- Inner layer simulations: influence of number U of UEs on performance ($N_s = 1$)

Simulation results – Outer layer

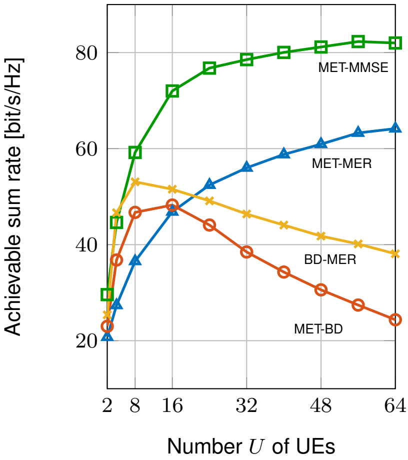


Poor scattering, $N_t = N_r = 64$ antennas

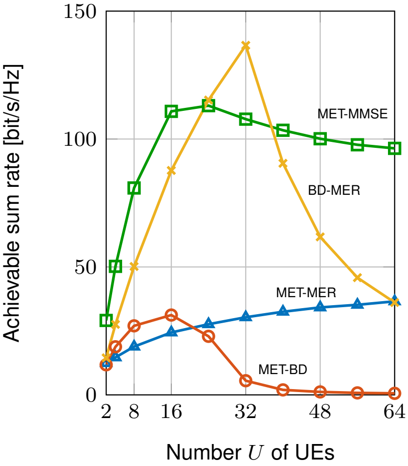


Rich scattering, $N_t = N_r = 64$ antennas

Simulation results – Inner layer



Poor scattering ($L = 8$ paths), $M_t = M_r = 4$, $N_s = 1$ stream per user and SNR $= 20$ dB, $N_t = N_r = 64$ antennas



Rich scattering ($L = 64$ paths) and $M_t = M_r = 32$, $N_s = 1$ stream per user and SNR $= 20$ dB, $N_t = N_r = 64$ antennas

Conclusion

- Semi-orthogonal path selection best performance (when N_s/L not close to 1)
- Covariance matrix eigenfilter robust and less complex
- BD-MER and MET-MMSE best throughput
- Latter is more robust to UE congestion and poor scattering

Research perspectives

- Evaluation in more practical scenarios
- Imperfect CSI **robust** transceivers
- Exploit channel structure to simplify precoding, feedback, channel estimation, etc

Thank you!
Questions?

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Slides will be available at http://lnribeiro.github.io

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