EFFICIENT TECHNIQUES FOR IN-BAND SYSTEM INFORMATION BROADCAST IN MULTI-CELL MASSIVE MIMO

SPCOM-P3: MIMO and Multi-antenna Systems

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IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)
4 – 8 May, 2020

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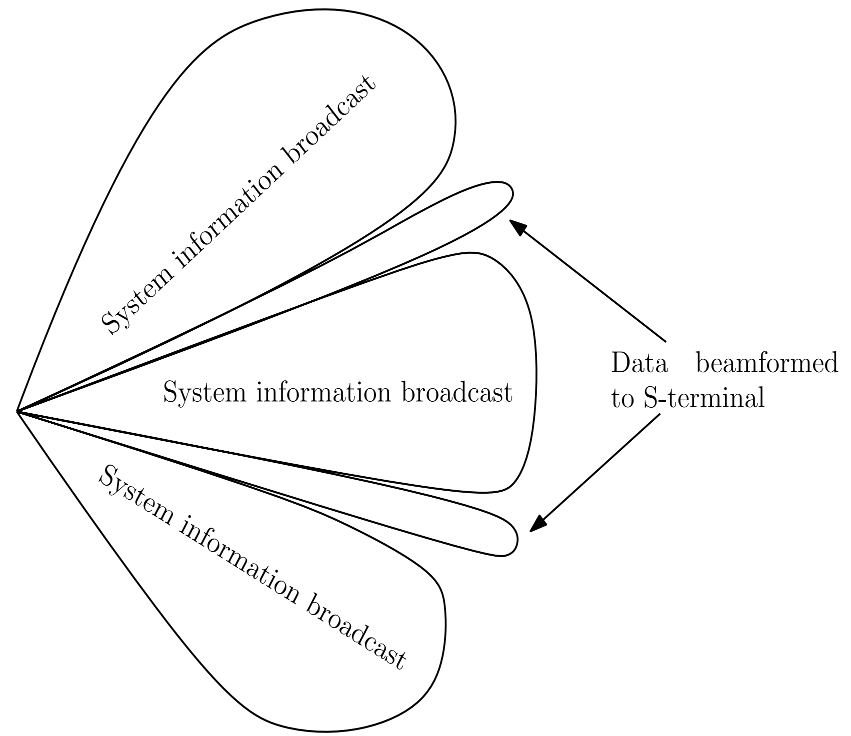
Joint Beamforming and Broadcasting

- Traditional Broadcast of System Information (SI): Fraction of resource reserved i.e. orthogonal access (OA)
- Joint Beamforming and Broadcasting in Massive MIMO:
  - Beamforming of information to scheduled terminals (STs)
  - Simultaneous broadcast of SI to idle terminals (ITs) in the null-space of STs on the same physical resource
  - No SI overhead
  - I.I.D. Rayleigh fading: JBB is more power efficient than OA
  - [1] E. G. Larsson and H. V. Poor, "Joint Beamforming and Broadcasting in Massive MIMO," *IEEE Transactions on Wirelsss Communications*, vol 15, no. 4, pp. 3058–3070, April 2016



Source of figure: K. Biswas, S. K. Mohammed and E. G. Larsson, "Efficient Techniques for Broadcast of System Information in mmWave Communications Systems," *in Proc. IEEE SPAWC' 2018.*

Multi-cell JBB

- Only single-cell scenario considered in [1]
- JBB vs. OA in multi-cell scenario
  - Interference due to broadcast of SI from other cells
  - SI pilot contamination
- In this paper, we propose
  - JBB-DIFF-SI
    - For cell-specific SI
    - Independent SI is broadcast from each cell
  - JBB-SAME-SI
    - For cell-common SI
    - Same SI symbols/pilot is broadcast from each cell
  - Derive analytical expressions for sum rate to STs and the rate of SI broadcast
- Conclusion: Even in multi-cell systems, JBB is more power efficient than OA.

Multi-cell JBB (System Model)

- L cells, each cell has K single-antenna STs served by a BS having M antennas
- $\mathbf{g}_{jkl} \sim \mathcal{CN}(0, \beta_{jkl}\mathbf{I})$: Channel gain vector between k-th ST of the j-th cell and the l-th BS
- TDD system: Uplink pilots used to estimate channel at BS
- Multi-cell pilot-reuse
  - Cells are partitioned into groups
  - Same set of K orthogonal pilots are used in each cell of a group
  - Cells in the same group are spaced far apart to reduce pilot contamination
- $\widehat{\mathbf{g}}_{lkl}$: MMSE channel estimate of the k-th UT in the l-th cell
- ρ_p , τ_p : Avg. uplink pilot transmission power and duration

Multi-cell JBB (Transmit Signal)

- Signal vector transmitted from the BS in l-th cell

$$\mathbf{x}_l = \sqrt{\rho_s}\sum_{k'=1}^{K}\mathbf{v}_{lk'}\, s_{lk'} + \sqrt{\rho_I}\,\Pi^{\perp}_{\hat{\mathbf{G}}_l}\,\mathbf{z}_l$$

  - ρ_s : Total downlink power beamformed to K STs in a cell
  - Maximum Ratio Transmission precoding for k-th ST in l-th cell

$$\mathbf{v}_{lk} = \left(\sqrt{\eta_{lk}/(M\gamma_{lkl})}\right)\hat{\mathbf{g}}^{*}_{lkl}$$

  - $s_{lk} \sim \mathcal{CN}(0,1)$: Information symbol for k-th ST in l-th cell
  - η_{lk} : Power control coefficient for k-th ST in l-th cell, $\sum_{k=1}^{K}\eta_{lk} = 1$

Multi-cell JBB (Transmit Signal cont'd..)

- Signal vector transmitted from the BS in l-th cell

$$\mathbf{x}_l = \sqrt{\rho_s} \sum_{k'=1}^{K} \mathbf{v}_{lk'} s_{lk'} + \sqrt{\rho_I} \Pi_{\widehat{\mathbf{G}}_l}^{\perp} \mathbf{z}_l$$

  - $\widehat{\mathbf{G}}_l \in \mathbb{C}^{M \times K}$: Matrix whose k-th column is $\widehat{\mathbf{g}}_{lkl}$
  - Projection matrix for space orthogonal to space spanned by $\widehat{\mathbf{G}}_l$

$$\Pi_{\widehat{\mathbf{G}}_l}^{\perp} \triangleq \mathbf{I} - \widehat{\mathbf{G}}_l^{*} (\widehat{\mathbf{G}}_l^{T} \widehat{\mathbf{G}}_l^{*})^{-1} \widehat{\mathbf{G}}_l^{T}$$

  - ρ_I : Total SI broadcast power
  - $\mathbf{q}_l \in \mathbb{C}^{M' \times 1}$: Vector of SI symbols in l-th cell ($M' \leq M$)

    $\mathbf{q}_l \sim \mathcal{CN}(0, \mathbf{I}/M')$
  - $\mathbf{z}_l = \mathbf{U}_l \mathbf{q}_l$: $\mathbf{U}_l \in \mathbb{C}^{M \times M'}$, Span($\mathbf{U}_l$) = Span($\Pi_{\widehat{\mathbf{G}}_l}^{\perp}$),

    $\mathbf{U}_l^{H} \mathbf{U}_l = \mathbf{I}$

Multi-cell JBB (Signal Rx. at STs)

- Signal vector transmitted from the BS in l-th cell

$$\mathbf{x}_l = \sqrt{\rho_s}\sum_{k'=1}^{K}\mathbf{v}_{lk'}\,s_{lk'} + \sqrt{\rho_I}\,\Pi_{\widehat{\mathbf{G}}_l}^{\perp}\,\mathbf{z}_l$$

- Signal received at k-th ST in l-th cell

$$y_{lk}=\sqrt{\rho_s}\sum_{j=1}^{L}\mathbf{g}_{lkj}^{T}\left(\sum_{k'=1}^{K}\mathbf{v}_{jk'}\,s_{jk'}\right)+\sqrt{\rho_I}\sum_{j=1}^{L}\mathbf{g}_{lkj}^{T}\Pi_{\widehat{\mathbf{G}}_j}^{\perp}\mathbf{z}_j + n_{lk}$$

$$= \sqrt{\rho_s\eta_{lk}/(M\gamma_{lkl})}\,\mathbb{E}\left[\|\widehat{\mathbf{g}}_{lkl}\|^2\right]s_{lk} + w_{lk}$$

- Little interference at STs due to SI

$$\mathbf{g}_{lkl}^{T}\Pi_{\widehat{\mathbf{G}}_l}^{\perp} \approx \mathbf{g}_{lkl}^{T}\Pi_{\mathbf{G}_l}^{\perp} = 0$$

Multi-cell JBB (JBB-SAME-SI)

- Same common SI symbol vector $\mathbf{q}$ broadcast in each cell

- $\mathbf{h}_{jl} \sim \mathcal{CN}(\mathbf{0}, \beta_{I_{jl}}\mathbf{I})$: Channel gain vector from BS in j-th cell to a Idle terminal (IT) in l-th cell

- Signal received at a IT in l-th cell

$$y_{Il} = \sqrt{\rho_I}\,\mathbf{h}_l^T\mathbf{q} + \sqrt{\rho_s}\sum_{j=1}^{L}\mathbf{h}_{jl}^T\Big(\sum_{k'=1}^{K}\mathbf{v}_{jk'}s_{jk'}\Big) + w_{Il}$$

$$\mathbf{h}_l \triangleq \sum_{j=1}^{L}\mathbf{U}_j^T\mathbf{h}_{jl} \qquad w_{Il} \sim \mathcal{CN}(0,1) \text{ is AWGN}$$

- No Interference due to SI broadcast in other cells

Multi-cell JBB (JBB-SAME-SI cont'd ...)

- Same SI pilot vectors broadcast from each cell

$$\mathbf{q}_p(t) \in \mathbb{C}^{M' \times 1}, \; t = 1, 2, \cdots, \tau_p^I$$

- No ST beamforming during SI pilot transmission
- SI pilot received at the IT

$$y_{Il}^p(t) = \sqrt{\rho_I}\, \mathbf{h}_l^T \mathbf{q}_p(t) + w_{Il}(t), \; t = 1, 2, \cdots, \tau_p^I$$

- The IT computes

$$\mathbf{y}_{Il}^p \triangleq \sum_{t=1}^{\tau_p^I} y_{Il}^p(t) \mathbf{q}_p^H(t) = \frac{\sqrt{\rho_I} \tau_p^I}{M'} \mathbf{h}_l^T + \sum_{t=1}^{\tau_p^I} w_{Il}(t) \mathbf{q}_p^H(t)$$

- $\widehat{\mathbf{h}}_l$: MMSE estimate of $\mathbf{h}_l$ from $\mathbf{y}_{Il}^p$
- No SI pilot contamination
- SI rate : $R_I^{\text{same}} \triangleq I(y_{Il}; \mathbf{q} \,|\, \widehat{\mathbf{h}}_l) = \mathbb{E}_{\widehat{\mathbf{h}}_l}\left[\log_2\left(1 + \frac{\rho_I \|\widehat{\mathbf{h}}_l\|^2 / M'}{\mathbb{E}[|w'_{Il}|^2 | \widehat{\mathbf{h}}_l]}\right)\right]$

Multi-cell JBB (JBB-DIFF-SI)

- Independent SI symbol vectors broadcast from each cell
- Signal received at a IT in l-th cell

$$y_{Il} = \sqrt{\rho_I}\mathbf{h}_{ell}^T\mathbf{q}_l + \sqrt{\rho_I}\sum_{j=1,j\neq l}^{L} \mathbf{h}_{ejl}^T\mathbf{q}_j + w_{Il}$$
$$+\sqrt{\rho_s}\sum_{j=1}^{L}\mathbf{h}_{jl}^T\left(\sum_{k'=1}^{K}\mathbf{v}_{jk'}s_{jk'}\right), \quad \mathbf{h}_{ejl} \triangleq \mathbf{U}_j^T\mathbf{h}_{jl}$$

- SI pilot reuse similar to pilot reuse for STs
- $\widehat{\mathbf{h}}_{ell}$: MMSE estimate of $\mathbf{h}_{ell}$
- Rate of SI broadcast : $R_I^{\text{diff}} \triangleq I(y_{Il};\mathbf{q}_l \mid \widehat{\mathbf{h}}_{ell})$

Multi-cell Orthogonal Access (OA)

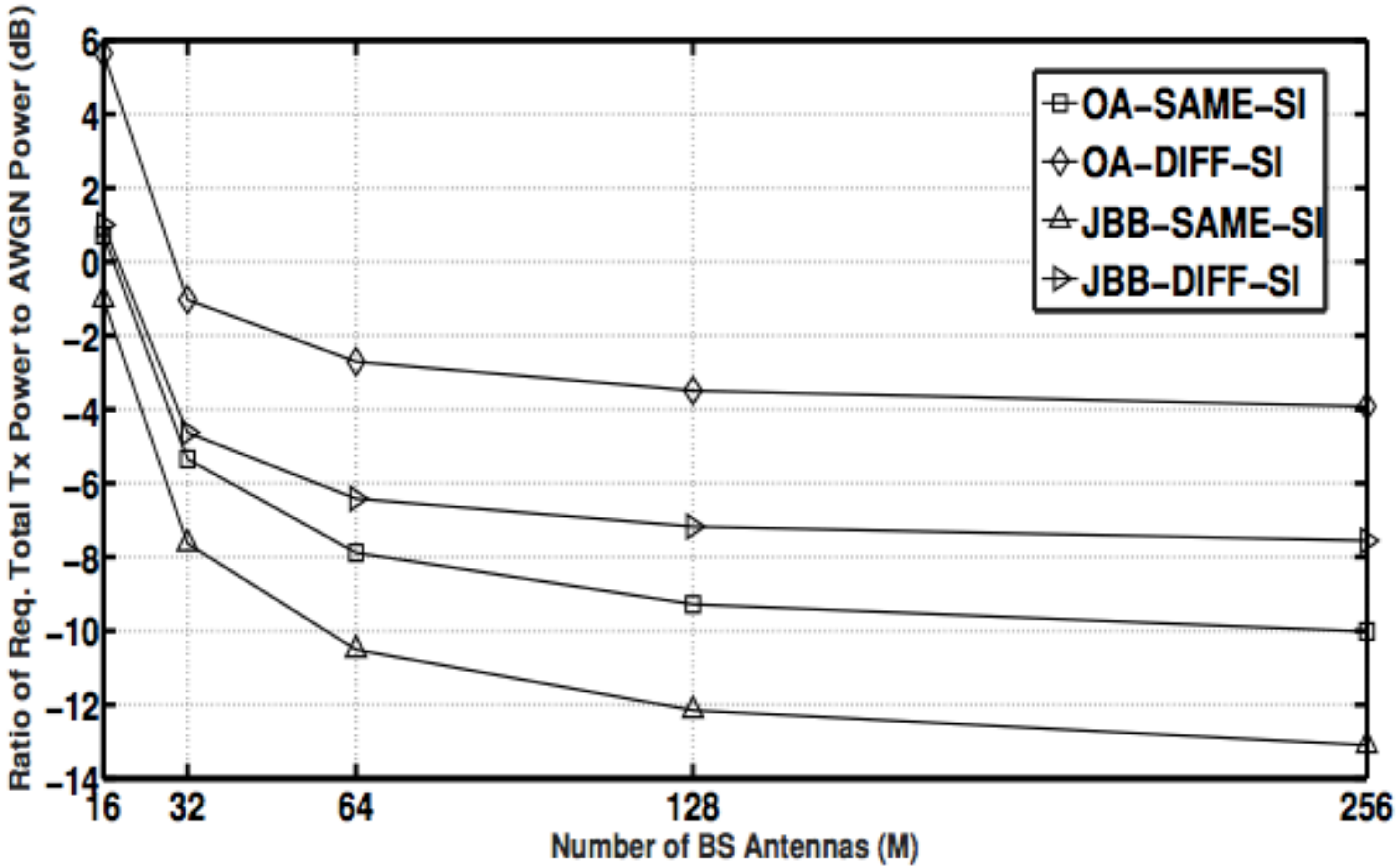
- Fraction of resource reserved for SI broadcast: ϵ
- OA-SAME-SI : Same SI broadcast from each cell
- OA-DIFF-SI : Independent SI broadcast from each cell
- ST rate same as for JBB with $\rho_{I} = 0$ and a pre-log factor $(1-\epsilon)$
- SI rate same as for JBB with $\rho_s = 0$ and a pre-log factor ϵ
- Total power tx. from each BS : $P_T^{\mathrm{OA}} \triangleq (1-\epsilon)\rho_s^{\mathrm{OA}} + \epsilon\rho_{I}^{\mathrm{OA}}$

Numerical Simulation

- L = 49 hexagonal cells, Radius 1 Km, a BS at centre
- K = 10 STs distributed uniformly in cell, except 100 m around BS. Idle terminals distributed uniformly in cell
- Pilot reuse factor: 7 (both ST and SI pilots)
- Coherence interval: 500 (half uplink, half downlink)
- Other parameters: $\tau_p = 70$, $\tau_p^I = 10$, $M' = 7$

  path-loss exponent: 3.8
- Orthogonal Access: Total Tx. power is minimized w.r.t. ϵ
- Uplink pilot power fixed to $\rho_p = -11$ dB

Total Req. Tx. Power vs. M



- Desired sum rate to STs: 4 bps/Hz/cell, Avg. SI rate: 0.01 bps/Hz
- JBB is more power efficient than OA even in multi-cell massive MIMO systems. JBB-SAME-SI is better than JBB-DIFF-SI.

Conclusions

- Proposed new JBB methods for SI broadcast in multi-cell massive MIMO systems
- JBB-SAME-SI
  - For cell common SI
  - Same SI information and pilots broadcast in each cell
- JBB-DIFF-SI
  - Cell specific SI broadcast in each cell
  - SI pilot reuse
- JBB methods more power efficient than OA even in multi-cell systems
- JBB-SAME-SI is more power efficient than JBB-DIFF-SI

Thank You