Precoding Designs in Multiuser Multicell Wireless Systems: Competition and Coordination

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Outline

1. Introduction and Motivation

2. Research Contributions
   - Downlink Beamforming for Power Minimization
   - Block-Diagonalization Precoding
   - Multicell MIMO Multiple-Access Channel (MIMO-MAC)
   - Multicell MIMO Broadcast Channel (MIMO-BC)

3. Conclusion

The Future of Wireless Communications

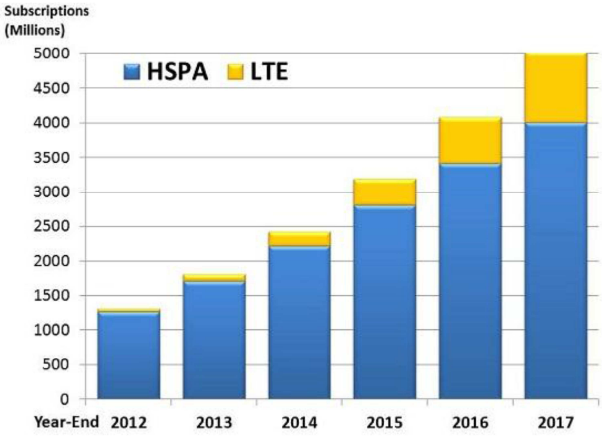


Figure courtesy of Informa Telecoms & Media.

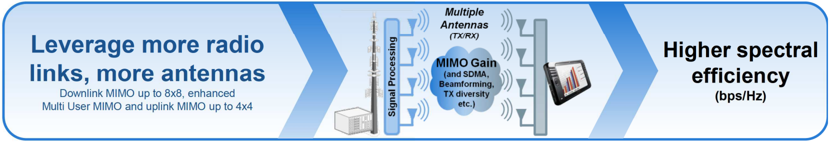
- Rapid increase in subscriptions to mobile broadband services
- Higher throughput, higher robustness, and better coverage

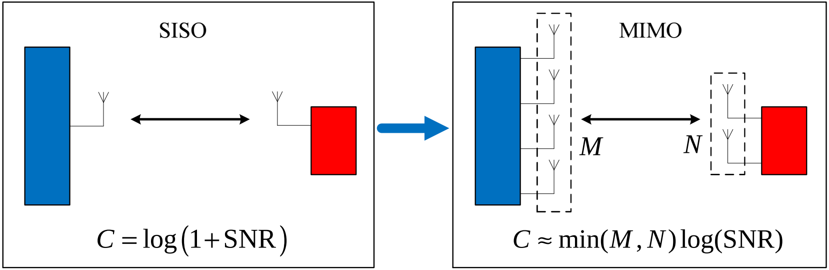
The Future of Wireless Communications

Figure courtesy of QUALCOMM Inc.

- Technical challenges: efficient utilization of the radio spectrum

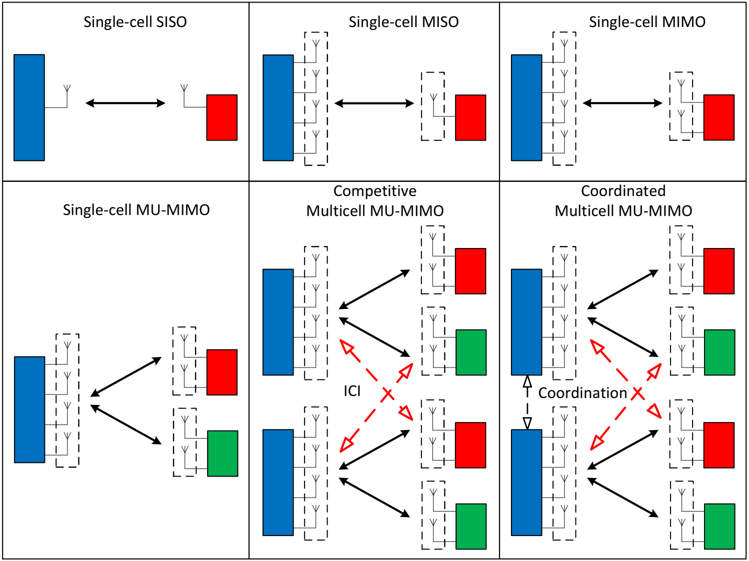
MIMO Communications





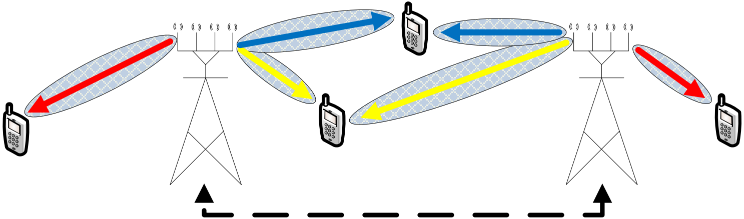
- Multiple-input Multiple-Output (MIMO): using multiple transmit/receive antennas
- MIMO precoding (beamforming) $\rightarrow$ Higher spectral efficiency

MIMO Configurations



ICI = Inter-cell Interference

- Cellular networks → inter-cell interference (ICI)
- Coordinated Multipoint Transmission/Reception (CoMP)
  - Coordinate simultaneous transmissions from multiple BSs to the MSs
  - Actively deal with the ICI by the means of MIMO precoding
- CoMP is a key technology for Long-Term Evolution (LTE)-Advanced



CoMP Modes

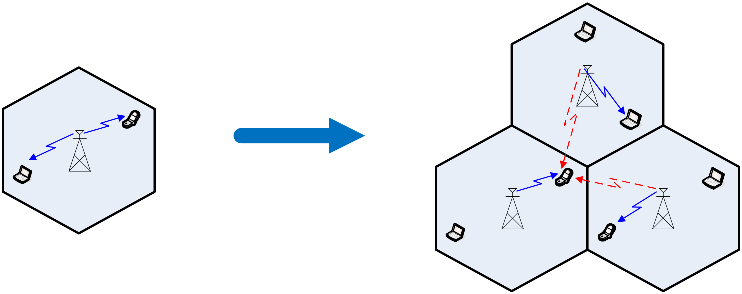
Competition *versus* Coordination

Interference Aware (IA) *versus* Interference Coordination (IC)

Challenges in CoMP Precoding Designs

A paradigm shift in precoding designs

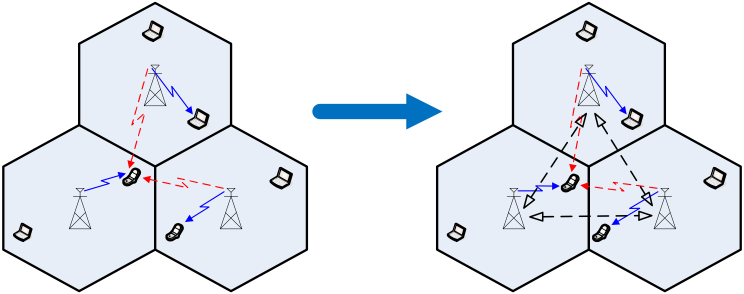
Independent per-cell approach to coordinated multicell approach



- Large-scale and distributed multicell network
- CSI: difficult to acquire
- Limited backhaul links for control/signaling
- Nonconvex precoding design problems

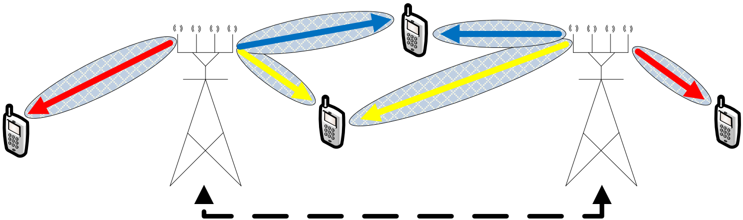
Competition and Coordination in Multicell Wireless Systems

Distributed strategies in precoding designs and ICI management



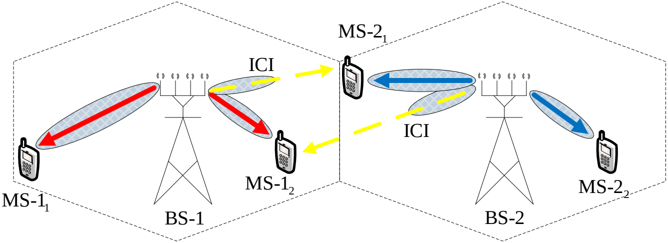
- Distributed algorithms for precoding designs and ICI management
- Local computation with local CSI
- Define and quantize the control/signaling messages
- Achievable optimality *versus* computational complexity

Research Contributions



- Develop low-complexity and distributed algorithms
- Devise the structure of the CoMP precoders
- Devise the message exchange mechanism
- Expose new perspectives and understanding the interactions between the coordinated BSs in a CoMP system
- Design criteria:
  - Power minimization *and* Sum-rate maximization
  - IA *and* IC
  - Uplink *and* Downlink

Downlink Beamforming for Power Minimization: A Game-Theoretical Approach



- Beamforming design to minimize the transmit power at each BS
- Guaranteed SINR requirement at each MS

$$\mathrm{SINR}_{q_i} \geq \gamma_{q_i}^{\min}, \forall q, \forall i \quad (1)$$

[J1] **D. H. N. Nguyen** and T. Le-Ngoc, "Multiuser downlink beamforming in multicell wireless systems: A game theoretical approach," *IEEE Trans. Signal Process.*, vol. 59, no. 7, pp. 3326–3338, Jul. 2011.

[J2] **D. H. N. Nguyen** and T. Le-Ngoc, "Efficient coordinated multicell beamforming with dynamic base-station assignment consideration," *to appear in IET Communications*, 2013.

[C1] **D. H. N. Nguyen** and T. Le-Ngoc, "Competitive downlink beamforming design in multiuser multicell wireless systems," in *Proc. IEEE Global Commun. Conf.*, Miami, FL, USA, Dec. 2010, pp. 1–6.

[C2] **D. H. N. Nguyen** and T. Le-Ngoc, "Efficient coordinated multicell beamforming with per-base-station power constraints," in *Proc. IEEE Global Commun. Conf.*, Houston, TX, USA, Dec. 2011, pp. 1–5.

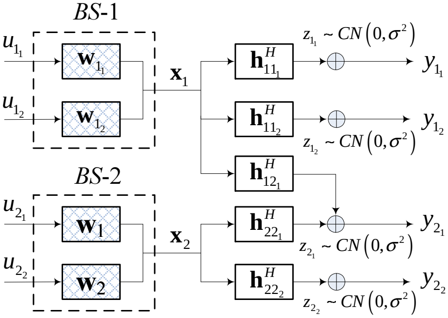
Downlink Beamforming Game (IA mode)

- SINR at a particular MS

$$\mathrm{SINR}_{q_i} = \frac{\left|\mathbf{w}_{q_i}^H \mathbf{h}_{qq_i}\right|^2}{\sum_{j\neq i}^{K}\left|\mathbf{w}_{q_j}^H \mathbf{h}_{qq_i}\right|^2 + r_{-q_i}},$$

  where r_{-q_i}: sum ICI + noise.

- Each BS is aware of the ICI at its connected MSs and *selfishly* adjusts its precoders accordingly



- Multicell game $\mathcal{G}_P = \left(\Omega,\ \{\mathcal{P}_q(\mathbf{W}_{-q})\}_{q\in\Omega},\ \{t_q(\mathbf{W}_q)\}_{q\in\Omega}\right)$
  - Players Ω: base-stations
  - Utility function: $t_q(\mathbf{W}_q) = \sum_{i=1}^{K} \|\mathbf{w}_{q_i}\|^2$
  - Set of admissible strategies: $\mathcal{P}_q(\mathbf{W}_{-q}) = \left\{\mathrm{SINR}_i(\mathbf{W}_q) \geq \gamma_i^{\min}, \forall i\right\}$
- $\mathbf{W}^\star = \{\mathbf{W}_q^\star\}_{q=1}^{Q}$ is a Nash Equilibrium (NE) if

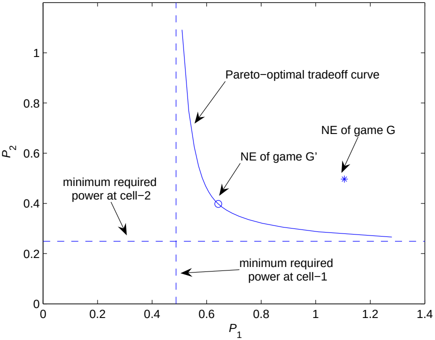
$$t_q(\mathbf{W}_q^\star) \leq t_q(\mathbf{W}_q),\ \forall \mathbf{W}_q \in \mathcal{P}_q(\mathbf{W}_{-q}^\star), \quad \forall q \in \Omega. \qquad (2)$$

Downlink Beamforming Game (cont.)

- Study the NE of game $\mathcal{G}_P$
- Unique NE if it exists

→ Best response strategies proved to converge (standard functions)

- Sufficient and necessary conditions: low ICI guarantees the NE's existence
- IC to obtain Pareto-optimality



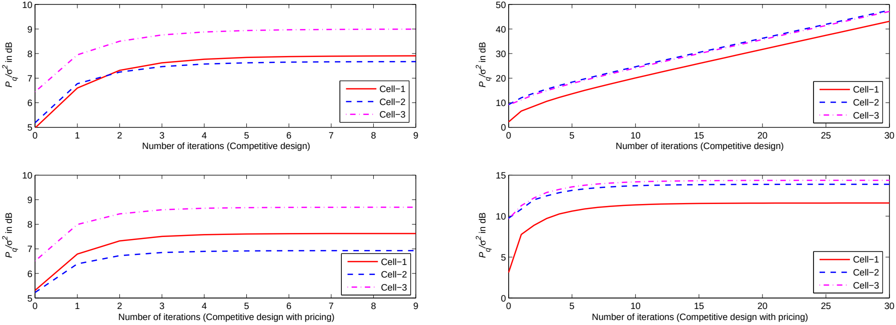
- To improve the NE's efficiency, modify the utility function

$$s_q(\mathbf{W}_q) = \sum_{i=1}^{K} \|\mathbf{w}_{q_i}\|^2 + \sum_{r \neq q}^{Q} \sum_{j=1}^{K} \pi_{qr_j} \left\|\mathbf{W}_q^H \mathbf{h}_{qr_j}\right\|^2,$$

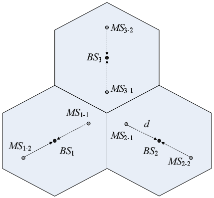
where π_{qr_j}: interference price charged on the ICI

- The new game $\mathcal{G}'_P$ is able to obtain a Pareto-optimal solution

Convergence

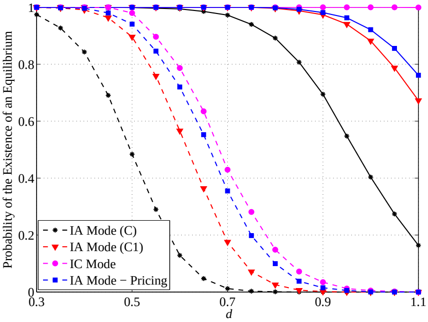


- IA mode
- IA mode with pricing with partial inter-cell CSI
- IC mode: IA mode with the right pricing scheme and full inter-cell CSI

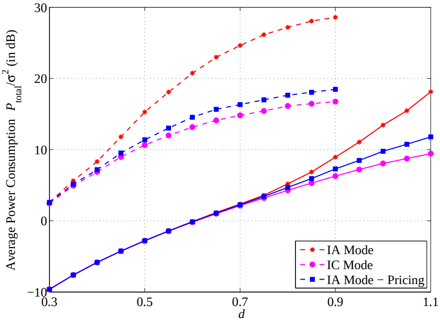


Competition *versus* Coordination

Prob. of Convergence

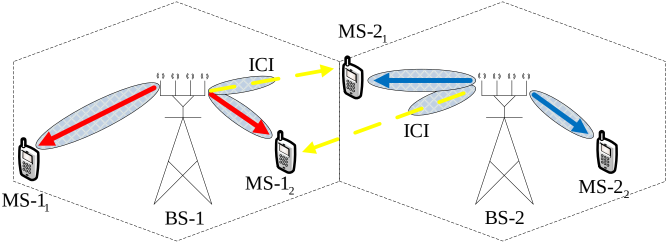


Transmit Power



- Target SINRs: $\gamma_{q_i} = 10$ dB (dashed lines) and $\gamma_{q_i} = 0$ dB (solid lines)
- Coordination $\longrightarrow$ power savings, better coverage
- Interference pricing $\longrightarrow$ limit ICI $\longrightarrow$ improve the efficiency of the game's NE

Block-Diagonalization Precoding: Competition and Coordination



- Precoding design to maximize the sum-rate at each cell
- Power constraint at each BS
- Block-Diagonalization (BD) precoding: suppress intra-cell interference
- BD-Dirty Paper Coding (BD-DPC): to further enhance the sum-rate performance

[J3] **D. H. N. Nguyen**, H. Nguyen-Le, and T. Le-Ngoc, "Block-diagonalization precoding in a multiuser multicell MIMO system: Competition and coordination," *submitted to IEEE Trans. Wireless Commun.*, Apr. 2013.
[C3] H. Nguyen-Le, **D. H. N. Nguyen**, and T. Le-Ngoc, "Game-based zero-forcing precoding for multicell multiuser transmissions," in *Proc. IEEE Veh. Technol. Conf.*, San Francisco, CA, USA, Sep. 2011.
[C4] **D. H. N. Nguyen** and T. Le-Ngoc, "Block diagonalization precoding game in a multiuser multicell system," in *Proc. IEEE Wireless Commun. and Networking. Conf.*, Shanghai, China, Apr. 2013.

BD Precoding - Competition

- Multicell game $\mathcal{G}_R = \left(\Omega,\ \{\mathcal{S}_q\}_{q\in\Omega},\ \{R_q(\mathbf{Q}_q)\}_{q\in\Omega}\right)$
  - Players Ω: base-stations
  - Utility function: $R_q(\mathbf{Q}_q) = \sum_{i=1}^{K} \log \left|\mathbf{I} + \mathbf{H}_{qq_i}^H \mathbf{R}_{-q_i}^{-1}(\mathbf{Q}_{-q})\mathbf{H}_{qq_i}\mathbf{Q}_{q_i}\right|$
  - Set of admissible strategies

$$\mathcal{S}_q = \left\{\mathbf{Q}_{q_i} : \sum_{i=1}^{K} \mathrm{Tr}\left\{\mathbf{Q}_{q_i}\right\} \le P_q,\ \mathbf{Q}_{q_i} \succeq \mathbf{0},\ \mathbf{H}_{qq_j}\mathbf{Q}_{q_i} = \mathbf{0}, \forall j \neq i\right\}$$

- $(\mathbf{Q}_q^\star, \mathbf{Q}_{-q}^\star)$ is a NE of game $\mathcal{G}_R$ if

$$R_q\left(\mathbf{Q}_q^\star, \mathbf{Q}_{-q}^\star\right) \ge R_q\left(\mathbf{Q}_q, \mathbf{Q}_{-q}^\star\right),\ \forall \mathbf{Q}_q \in \mathcal{S}_q, \quad \forall q \in \Omega. \qquad (3)$$

- Obtain closed-form best-response (water-filling) strategies by solving

$$\begin{aligned} \underset{\mathbf{Q}_{q_1},\ldots,\mathbf{Q}_{q_K}}{\text{maximize}} \quad & R_q(\mathbf{Q}_q, \mathbf{Q}_{-q}) \\ \text{subject to} \quad & \mathbf{Q}_{q_i} \in \mathcal{S}_q, \forall i. \end{aligned} \qquad (4)$$

- Convergence proved by the contraction mapping
- A NE is always existent and unique at low ICI

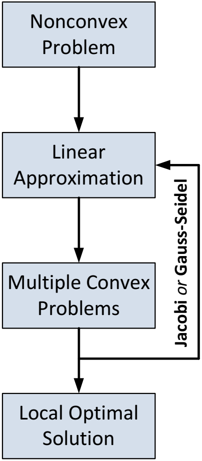
- Joint weighted sum-rate maximization

$$\begin{aligned} \underset{\mathbf{Q}_1,\ldots,\mathbf{Q}_Q}{\text{maximize}} \quad & \sum_{q=1}^{Q} \omega_q R_q(\mathbf{Q}_q, \mathbf{Q}_{-q}) \\ \text{subject to} \quad & \mathbf{Q}_{q_i} \in \mathcal{S}_q, \forall i, \forall q. \end{aligned} \tag{5}$$

- Nonconvex $\rightarrow$ iterative linear approximation (ILA) to Q per-cell convex problems

$$\begin{aligned} \underset{\mathbf{Q}_{q_1},\ldots,\mathbf{Q}_{q_K}}{\text{maximize}} \quad & \omega_q R_q(\mathbf{Q}_q, \mathbf{Q}_{-q}) - \sum_{i=1}^{K} \mathrm{Tr}\{\mathbf{A}_{q_i} \mathbf{Q}_{q_i}\} \\ \text{subject to} \quad & \mathbf{Q}_{q_i} \in \mathcal{S}_q, \forall i, \end{aligned} \tag{6}$$

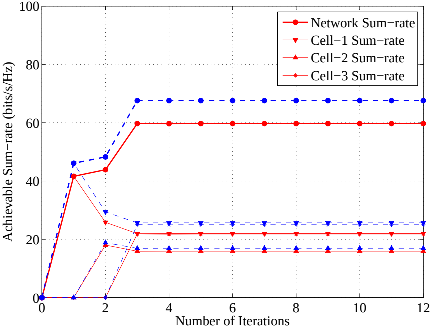
  where $\mathbf{A}_{q_i}$: interference price charged on the ICI



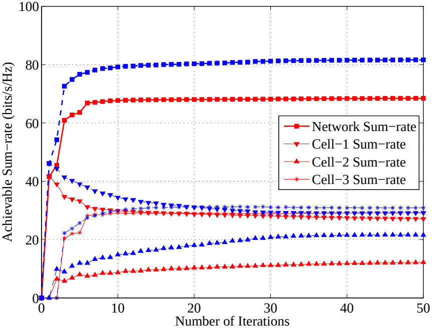
- Monotonic convergence to a local maximum (Gauss-Seidel update proved, Jacobi update observed)
- Distributed implementation with message exchange between BSs to compute the price $\mathbf{A}_{q_i}$'s

Convergence

Competition

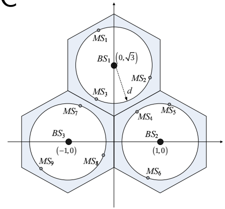


Coordination



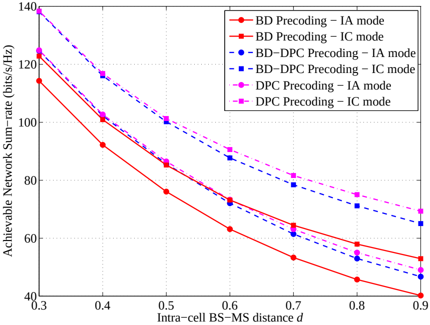
Solid lines: BD & Dashed lines: BD-DPC

- BD-DPC → higher sum-rate than BD
- Coordination → higher sum-rate than competition
- Coordination → slower to converge than competition

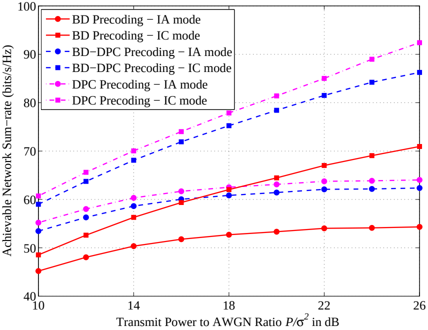


Network Sum-rate

versus **BS-MS Distance**



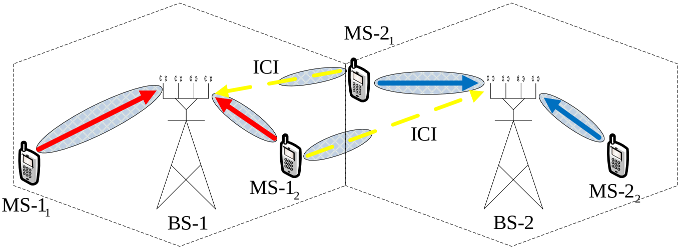
versus **Transmit Power**



- DPC $>$ BD-DPC $>$ BD
- Coordination $>>$ Competition, especially at high ICI region
- Performance saturated at high ICI region with competition

$\rightarrow$ Coordination

Multicell MIMO-MAC - Coordination



- Successive interference cancelation (SIC) on a per-cell basis
- Precoding design to maximize the weighted sum-rate in the uplink

$$\begin{aligned} \underset{\mathbf{X}_1,\ldots,\mathbf{X}_Q}{\text{maximize}} \quad & \sum_{q=1}^{Q} \omega_q \log \left| \mathbf{I} + \mathbf{R}_q^{-1} \left(\sum_{i=1}^{K} \mathbf{H}_{qq_i} \mathbf{X}_{q_i} \mathbf{H}_{qq_i}^H \right) \right| \\ \text{subject to} \quad & \mathrm{Tr}\{\mathbf{X}_{q_i}\} \leq P_{q_i},\ \forall i, \forall q \\ & \mathbf{X}_{q_i} \succeq 0,\ \forall i, \forall q. \end{aligned} \tag{7}$$

[J4] **D. H. N. Nguyen** and T. Le-Ngoc, "Sum-rate maximization in the multicell MIMO multiple-access channel with interference coordination," *to appear in IEEE Trans. on Wireless Commun.*, 2013.

[C5] **D. H. N. Nguyen** and T. Le-Ngoc, "Sum-rate maximization in the multicell MIMO multiple-access channel with interference coordination," in *Proc. IEEE Wireless Commun. and Networking. Conf.*, Paris, France, Apr. 2012.

ILA Solution Approach

- Approximation and decomposition into Q per-cell outer problems

$$\begin{aligned} \underset{\mathbf{X}_{q_1},\ldots,\mathbf{X}_{q_K}}{\text{maximize}} \;\; & \omega_q \log\left|\mathbf{R}_q + \sum_{i=1}^{K} \mathbf{H}_{qq_i}\mathbf{X}_{q_i}\mathbf{H}_{qq_i}^H\right| - \sum_{i=1}^{K} \mathrm{Tr}\{\mathbf{A}_{q_i}\mathbf{X}_{q_i}\} \\ \text{subject to} \;\; & \mathrm{Tr}\{\mathbf{X}_{q_i}\} \le P_{q_i},\ \forall i \\ & \mathbf{X}_{q_i} \succeq \mathbf{0}, \end{aligned} \tag{8}$$

  where $\mathbf{A}_{q_i}$: interference pricing charged on the ICI.
- Further decomposition into K per-user inner problems

$$\begin{aligned} \underset{\mathbf{X}_{q_i}}{\text{maximize}} \;\; & \omega_q \log\left|\mathbf{I} + \mathbf{R}_{q_i}^{-1}\mathbf{H}_{qq_i}\mathbf{X}_{q_i}\mathbf{H}_{qq_i}^H\right| - \mathrm{Tr}\{\mathbf{A}_{q_i}\mathbf{X}_{q_i}\} \\ \text{subject to} \;\; & \mathrm{Tr}\{\mathbf{X}_{q_i}\} \le P_{q_i}, \mathbf{X}_{q_i} \succeq \mathbf{0}, \end{aligned} \tag{9}$$

  where $\mathbf{R}_{q_i} = \mathbf{R}_q + \sum_{j\neq i}^{K} \mathbf{H}_{qq_j}\mathbf{X}_{q_j}\mathbf{H}_{qq_j}^H$.
- Monotonic convergence to a local maximum (Gauss-Seidel update proved, Jacobi update observed)
- Distributed implementation with message exchange between BSs to compute the price $\mathbf{A}_{q_i}$'s

WMMSE Solution Approach

- Transform the original nonconvex problem into a matrix weighted sum-MSE minimization problem (WMMSE)

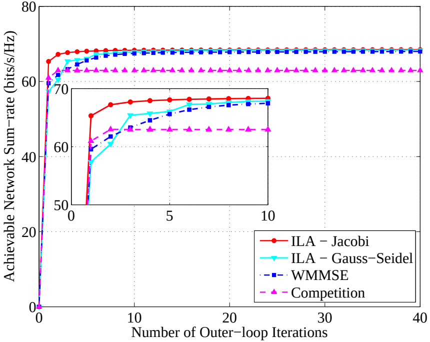
$$\begin{aligned} \underset{\mathbf{W}_{q_i},\mathbf{V}_{q_i},\mathbf{U}_{q_i}}{\text{minimize}} \quad & \sum_{q=1}^{Q} \omega_q \sum_{i=1}^{K} \left[\mathrm{Tr}\left\{ \mathbf{W}_{q_i} \mathbf{E}_{q_i} \right\} - \log \left| \mathbf{W}_{q_i} \right| \right] \\ \text{subject to} \quad & \mathrm{Tr}\left\{ \mathbf{V}_{q_i} \mathbf{V}_{q_i}^H \right\} \leq P_{q_i}, \forall q, \forall i, \end{aligned} \tag{10}$$

  where $\mathbf{V}_{q_i}$: transmit beamformer, $\mathbf{U}_{q_i}$: receive beamformer, $\mathbf{W}_{q_i}$: weight matrix, and $\mathbf{E}_{q_i}$: MSE matrix.

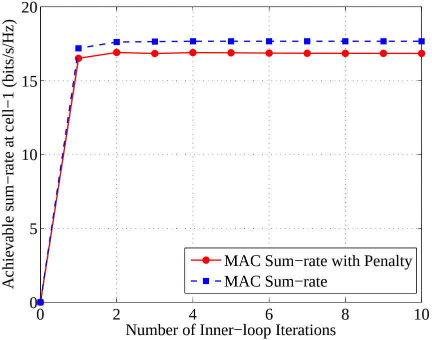
- Not jointly convex, but convex in each set of variables $\mathbf{V}_{q_i}$, $\mathbf{U}_{q_i}$, $\mathbf{W}_{q_i}$
- Iterative update across each set of variables in closed-form solutions
- Distributed implementation with monotonic convergence to a local optimum proved (also a local optimum of the original problem)

Convergence

Outer Loop



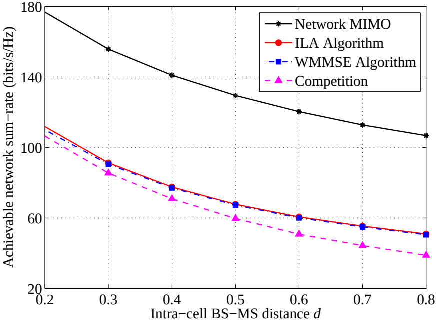
Inner Loop



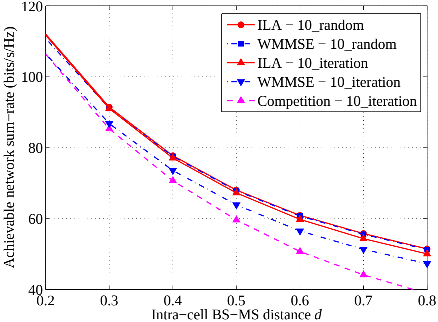
- Monotonic convergence for both ILA and WMMSE algorithms
- ILA: Jacobi (simultaneous) update converges faster than Gauss-Seidel (sequential) update
- ILA converges faster than WMMSE
- Coordination → higher network sum-rate than competition

Network Sum-rate

Full Convergence

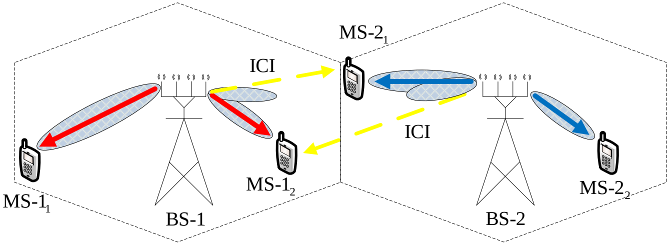


10 Iterations



- Full convergence: ILA $\approx$ WMMSE $>$ Competition
- Limited iteration: ILA $>$ WMMSE $>$ Competition
- Coordination: require $\mathrm{BS} \leftrightarrow \mathrm{BS}$ signaling

Multicell MIMO-BC - Coordination



- Dirty Paper Coding (DPC) on a per-cell basis
- Precoding design to maximize the weighted sum-rate in the downlink

$$\underset{\mathbf{Q}_1,\ldots,\mathbf{Q}_Q}{\text{maximize}} \quad \sum_{q=1}^{Q} \omega_q \sum_{i=1}^{K} \log \frac{\left|\mathbf{R}_{q_i} + \mathbf{H}_{qq_i}\left(\sum_{j=1}^{i} \mathbf{Q}_{q_j}\right)\mathbf{H}_{qq_i}^H\right|}{\left|\mathbf{R}_{q_i} + \mathbf{H}_{qq_i}\left(\sum_{j=1}^{i-1} \mathbf{Q}_{q_j}\right)\mathbf{H}_{qq_i}^H\right|} \tag{11}$$

$$\text{subject to} \quad \sum_{i=1}^{K} \mathrm{Tr}\{\mathbf{Q}_{q_i}\} \le P_q, \forall q; \; \mathbf{Q}_{q_i} \succeq 0, \forall i, \forall q.$$

[J5] **D. H. N. Nguyen** and T. Le-Ngoc, "Sum-rate maximization in the multicell MIMO broadcast channel with interference coordination," *submitted to IEEE Trans. Signal Process.*, Apr. 2013.

[C6] **D. H. N. Nguyen** and T. Le-Ngoc, "Sum-rate maximization in the multicell MIMO broadcast channel with interference coordination," in *Proc. IEEE Int. Conf. Commun.*, Budapest, Hungary, Jun. 2013.

- Approximation and decomposition into Q per-cell outer problems

$$\underset{\mathbf{Q}_{q_1},\ldots,\mathbf{Q}_{q_K}}{\text{maximize}} \ \ \omega_q \sum_{i=1}^{K} \log \frac{\left|\mathbf{R}_{q_i} + \mathbf{H}_{qq_i}\left(\sum_{j=1}^{i}\mathbf{Q}_{q_j}\right)\mathbf{H}_{qq_i}^H\right|}{\left|\mathbf{R}_{q_i} + \mathbf{H}_{qq_i}\left(\sum_{j=1}^{i-1}\mathbf{Q}_{q_j}\right)\mathbf{H}_{qq_i}^H\right|} - \sum_{i=1}^{K}\mathrm{Tr}\{\mathbf{A}_q\mathbf{Q}_{q_i}\} \quad (12)$$

$$\text{subject to} \ \sum_{i=1}^{K}\mathrm{Tr}\{\mathbf{Q}_{q_i}\} \leq P_q, \ \mathbf{Q}_{q_i} \succeq \mathbf{0}, \forall i,$$

where $\mathbf{A}_q$: interference pricing charged on the ICI.

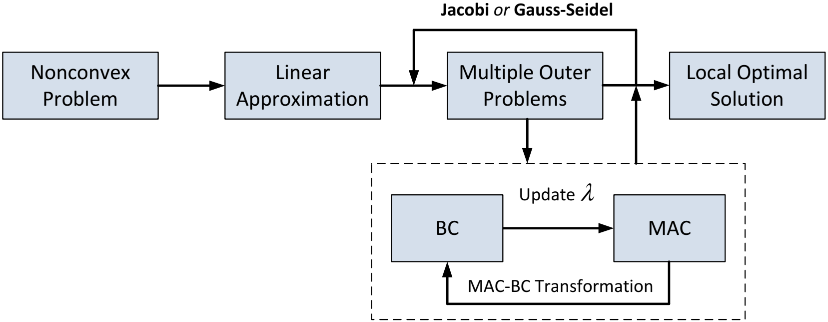
- Still a nonconvex problem
- Connection to the MAC problem via the uplink-downlink duality

$$\underset{\mathbf{X}_{q_1},\ldots,\mathbf{X}_{q_K}}{\text{maximize}} \ \ \omega_q \log\left|\mathbf{I} + \sum_{i=1}^{K}\tilde{\mathbf{H}}_{qq_i}^H\mathbf{X}_{q_i}\tilde{\mathbf{H}}_{qq_i}\right| - \sum_{i=1}^{K}\mathrm{Tr}\{\mathbf{X}_{q_i}\} \quad (13)$$

$$\text{subject to} \ \ \mathbf{X}_{q_i} \succeq \mathbf{0}, \ \forall i,$$

where $\tilde{\mathbf{H}}_{qq_i} = \mathbf{R}_{q_i}^{-1/2}\mathbf{H}_{qq_i}(\mathbf{A}_q + \lambda\mathbf{I})^{-1/2}$, λ: Lagrangian multiplier.

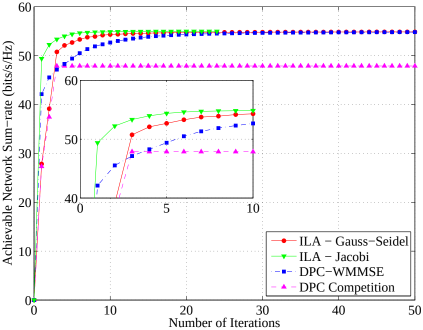
ILA Solution Approaches



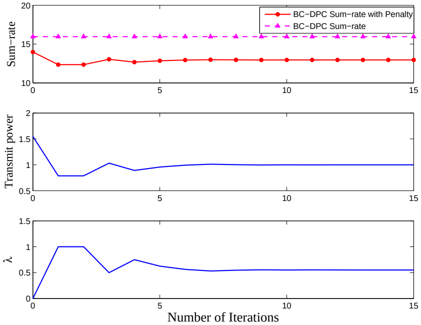
- Convergence and global optimality of the outer problem proved
- Distributed implementation with monotonic convergence to a local optimum proved (also a local optimum of the original problem)
- WMMSE algorithm
  - Similar to the multicell MIMO-MAC
  - Transform to an equivalent WMMSE problem
  - Iterative updates to each set of variables

Convergence

Outer Loop



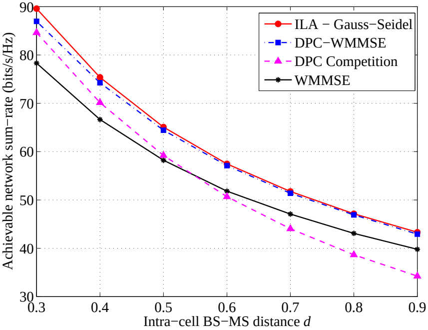
Inner Loop



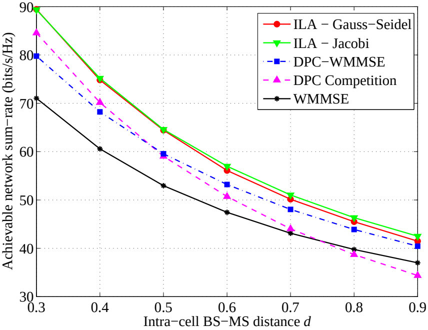
- Convergence to the globally optimal solution of the outer problem
- Monotonic convergence for both ILA and WMMSE algorithms
- ILA: Jacobi (simultaneous) update converges faster than Gauss-Seidel (sequential) update
- Coordination → higher network sum-rate than competition

Network Sum-rate

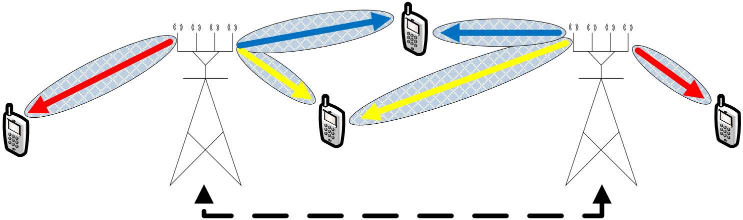
Full Convergence



10 Iterations



- Full convergence: ILA $\approx$ WMMSE $>$ Competition
- Limited iteration: ILA $>$ WMMSE $>$ Competition
- Nonlinear precoding (DPC) $>$ Linear precoding



- Multicell multiuser MIMO to improve spectral efficiency
- Multicell coordination → power savings, sum-rate enhancement over multicell competition
- Precoding with multicell coordination: more complex, more signaling
- Various precoding techniques: linear MMSE, BD and BD-DPC, MAC with SIC, BC with DPC

Q&A