International Workshop on Emerging Technologies for LTE-Advanced and Beyond-4G

Emerging Technologies Beyond 4G: Massive MIMO, Dense Small Cells, Virtual MIMO, D2D and Distributed Caching

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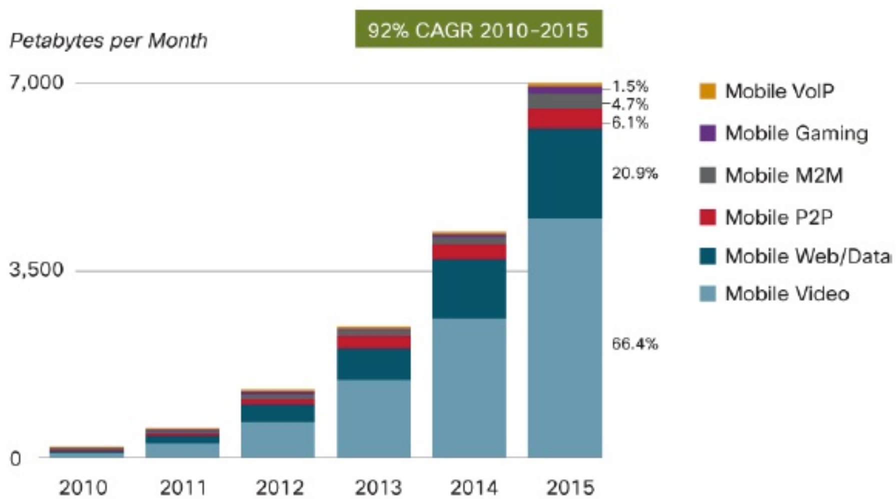
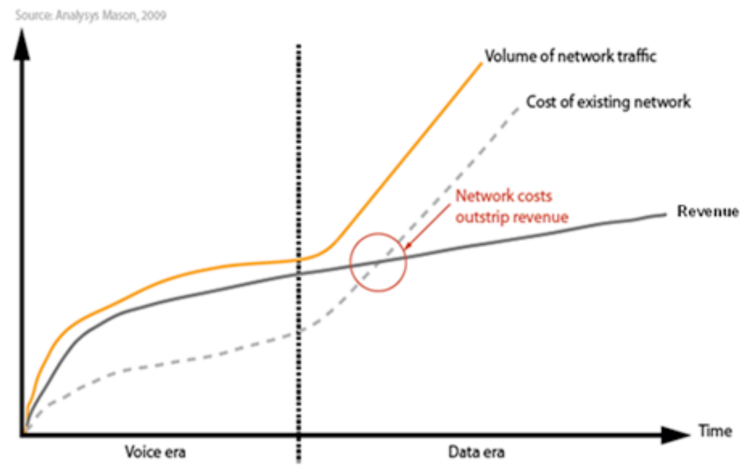
Wireless operators' nightmare





Mobile Broadband's Profitability Gap

- 100x Data traffic increase, due to the introduction of powerful multimedia capable user devices.
- Operating costs trends not matched by revenue trends.

Possible answers

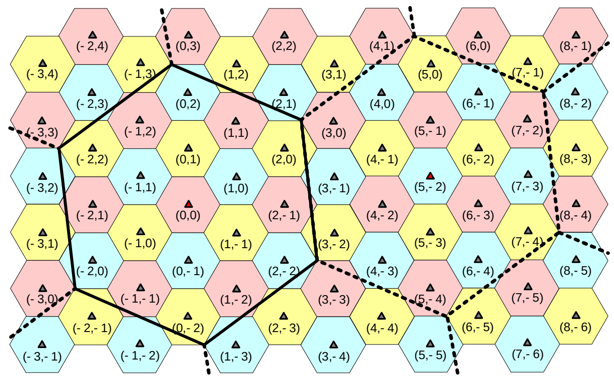
- Release of new wireless spectrum: today, cellular $+$ Wifi accounts for ≈ 500 MHz of bandwidth. Releasing new spectrum will at most double the available overall spectrum (at most x2 increase with same technology).

- Following current technology trend: LTE ... painstakingly slow, incremental gain due to backward compatibility.

- Disruptive technology approach: Massive MIMO, Dense Small Cells, Virtual MU-MIMO, D2D, Wireless Caching.

What Can We Expect?

MU-MIMO Cellular Networks



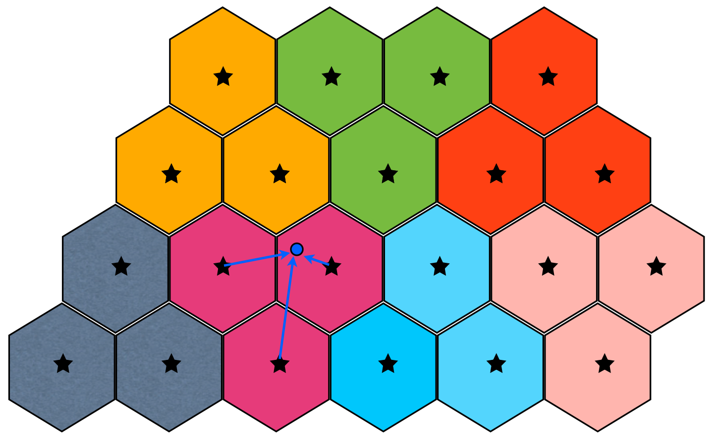
- Multiuser MIMO cooperative upper bound:

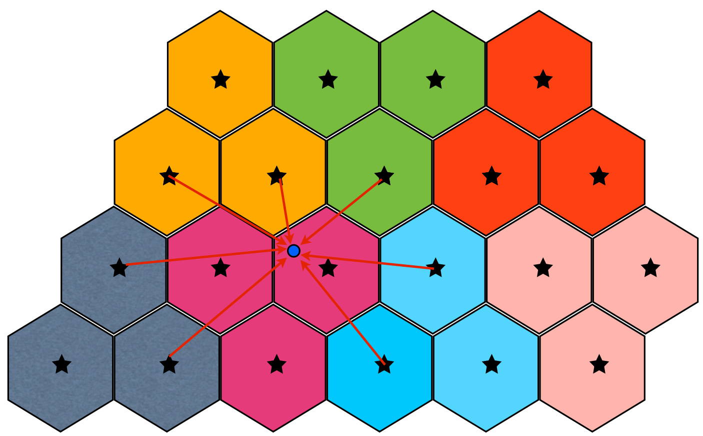
$$C = W \times M^* \left(1 - \frac{M^*}{T}\right) \times \log \text{SINR} + O(1),$$

  were $M^* = \min\{M, KN, T/2\}$.

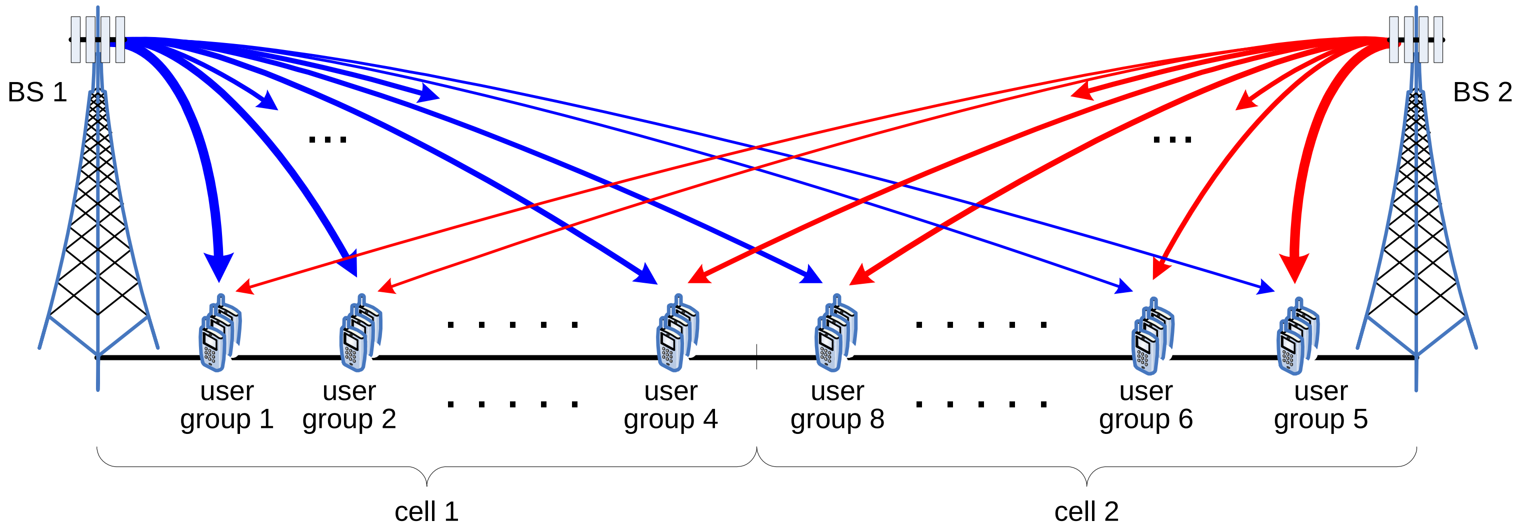
- Fundamental dimensionality bottleneck: channel state estimation overhead (information theoretic upper bound).
- See also high-SNR saturation effect in "Fundamental Limits of Cooperation," [Lozano, Heath, Andrews, arXiv:1204.0011].
- Per-user throughput vanishes as $O(\frac{1}{K})$.

Network MIMO: A Large-System Analysis





Discretization of the Users Distribution



- We assume that the users are partitioned in co-located groups with N single-antenna terminals each.

- We have A user groups per cluster, and clusters of B cells.

- We have $M = \gamma N$ base station antennas per cell.

Cluster of Cooperating Base Stations

- Modified path coefficients $\beta_{m,k} = \frac{\alpha_{m,k}}{\sigma_k}$ taking into account the ICI power.
- Cluster channel matrix

$$\mathbf{H} = \begin{bmatrix} \beta_{1,1}\mathbf{H}_{1,1} & \cdots & \beta_{1,A}\mathbf{H}_{1,A} \\ \vdots & \ddots & \vdots \\ \beta_{B,1}\mathbf{H}_{B,1} & \cdots & \beta_{B,A}\mathbf{H}_{B,A} \end{bmatrix}.$$

- Reference cluster channel model

$$\mathbf{y} = \mathbf{H}^{\mathsf{H}}\mathbf{x} + \mathbf{z}$$

where $\mathbf{y} = \mathbb{C}^{AN}$, $\mathbf{x} = \mathbb{C}^{\gamma BN}$, and $\mathbf{z} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$.

Linear ZF Downlink Beamforming

- We consider the weighted rate sum maximization for given channel matrix:

$$\begin{aligned} \text{maximize} \quad & \sum_{k=1}^{A} \sum_{i=1}^{N} W_k^{(i)} R_k^{(i)} \\ \text{subject to} \quad & \mathbf{R} \in \mathcal{R}_{\mathrm{lzfb}}(\mathbf{H}) \end{aligned}$$

where $W_k^{(i)}$ denotes the rate weight for user i in group k, and $\mathcal{R}_{\mathrm{lzfb}}(\mathbf{H})$ is the achievable *instantaneous* rate region of LZFB for given channel matrix $\mathbf{H}$.

Some Simplifying Assumptions

- The scheduler picks a fraction μ_k of users in group k by random selection inside the group.

- LZFB precoder obtained by normalizing the columns of the Moore-Penrose pseudo-inverse of the channel matrix.

- Let $\boldsymbol{\mu} = (\mu_1, \ldots, \mu_A)$ denote the fractions of active users in groups $1, \ldots, A$, respectively. For given $\boldsymbol{\mu}$, the corresponding effective channel matrix is given by

$$\mathbf{H}_{\boldsymbol{\mu}} = \left[\begin{array}{ccc} \beta_{1,1}\mathbf{H}_{1,1}(\mu_1) & \cdots & \beta_{1,A}\mathbf{H}_{1,A}(\mu_A) \\ \vdots & & \vdots \\ \beta_{B,1}\mathbf{H}_{B,1}(\mu_1) & \cdots & \beta_{B,A}\mathbf{H}_{B,A}(\mu_A) \end{array} \right],$$

LZFB "parallel channels"

- Letting $\mathbf{V}_{\boldsymbol{\mu}} = \mathbf{H}_{\boldsymbol{\mu}}^{+} \boldsymbol{\Lambda}_{\boldsymbol{\mu}}^{1/2}$, we obtain the "parallel" channel model

$$\mathbf{y}_{\boldsymbol{\mu}} = \mathbf{H}_{\boldsymbol{\mu}}^{\mathsf{H}} \mathbf{V}_{\boldsymbol{\mu}} \mathbf{Q}^{1/2} \mathbf{u} + \mathbf{z}_{\boldsymbol{\mu}} = \boldsymbol{\Lambda}_{\boldsymbol{\mu}}^{1/2} \mathbf{Q}^{1/2} \mathbf{u} + \mathbf{z}_{\boldsymbol{\mu}}.$$

Theorem 1. *For all $i = 1, \ldots, \mu_k N$, the following limit holds almost surely:*

$$\lim_{N \to \infty} \Lambda_k^{(i)}(\boldsymbol{\mu}) = \Lambda_k(\boldsymbol{\mu}) = \gamma \sum_{m=1}^{B} \beta_{m,k}^2 \eta_m(\boldsymbol{\mu})$$

where $(\eta_1(\boldsymbol{\mu}), \ldots, \eta_B(\boldsymbol{\mu}))$ is the unique solution in $[0,1]^B$ of the fixed point equations

$$\eta_m = 1 - \sum_{q=1}^{A} \mu_q \frac{\eta_m \beta_{m,q}^2}{\gamma \sum_{\ell=1}^{B} \eta_\ell \beta_{\ell,q}^2}, \quad m = 1, \ldots, B$$

with respect to the variables $\boldsymbol{\eta} = \{\eta_m\}$. ■

Channel Estimation and Non-Perfect CSIT

- We assume that the channels are constant over time-frequency blocks of size WT complex dimensions.
- For each such block, $\gamma_p BN$ dimensions are dedicated to downlink training.
- Since the channel vectors are Gaussian, linear MMSE estimation is optimal with respect to the MSE criterion.
- The MMSE can be made arbitrarily small as $\sigma_k^2 \to 0$ (vanishing noise plus ICI) if and only if $\gamma_p \geq \gamma$.
- The ratio γ_p/γ denotes the "pilot dimensionality overhead".

- From the well-known MMSE decomposition, the channel matrix $\mathbf{H}$ can be written as $\mathbf{H} = \widehat{\mathbf{H}} + \mathbf{E}$, where

$$\widehat{\mathbf{H}} = \begin{bmatrix} \widehat{\beta}_{1,1}\mathbf{H}_{1,1} & \cdots & \widehat{\beta}_{1,A}\mathbf{H}_{1,A} \\ \vdots & & \vdots \\ \widehat{\beta}_{B,1}\mathbf{H}_{B,1} & \cdots & \widehat{\beta}_{B,A}\mathbf{H}_{B,A} \end{bmatrix},$$

with

$$\widehat{\beta}_{m,k} = \frac{\beta_{m,k}^2}{\sqrt{1/p + \beta_{m,k}^2}},$$

and where

$$\mathbf{E} = \begin{bmatrix} \bar{\beta}_{1,1}\mathbf{E}_{1,1} & \cdots & \bar{\beta}_{1,A}\mathbf{E}_{1,A} \\ \vdots & & \vdots \\ \bar{\beta}_{B,1}\mathbf{E}_{B,1} & \cdots & \bar{\beta}_{B,A}\mathbf{E}_{B,A} \end{bmatrix},$$

with

$$\bar{\beta}_{m,k} = \sqrt{\beta_{m,k}^2 - \widehat{\beta}_{m,k}^2} = \frac{\beta_{m,k}}{\sqrt{1 + p\beta_{m,k}^2}},$$

and the blocks $\mathbf{E}_{m,k}$ and independent with i.i.d. $\mathcal{CN}(0,1)$ elements.

Achievable rate lower bound

Theorem 2. *Under the downlink training scheme described above and assuming genie-aided CSIT feedback, the achievable rate of users in group* k *is lower bounded by*

$$R_k \geq \log \left(1 + \frac{\widehat{\Lambda}_k(\boldsymbol{\mu}) q_k}{1 + \sum_{m=1}^{B} \bar{\beta}_{m,k}^2 P_m} \right)$$

where

$$\widehat{\Lambda}_k(\boldsymbol{\mu}) = \gamma \sum_{m=1}^{B} \widehat{\beta}_{m,k}^2 \eta_m(\boldsymbol{\mu})$$

where $(\eta_1(\boldsymbol{\mu}), \ldots, \eta_B(\boldsymbol{\mu}))$ *is the unique solution with components in* $[0, 1]$ *of the fixed point equation*

$$\eta_m = 1 - \sum_{q=1}^{A} \mu_q \frac{\eta_m \widehat{\beta}_{m,q}^2}{\gamma \sum_{\ell=1}^{B} \eta_\ell \widehat{\beta}_{\ell,q}^2}, \quad m = 1, \ldots, B$$

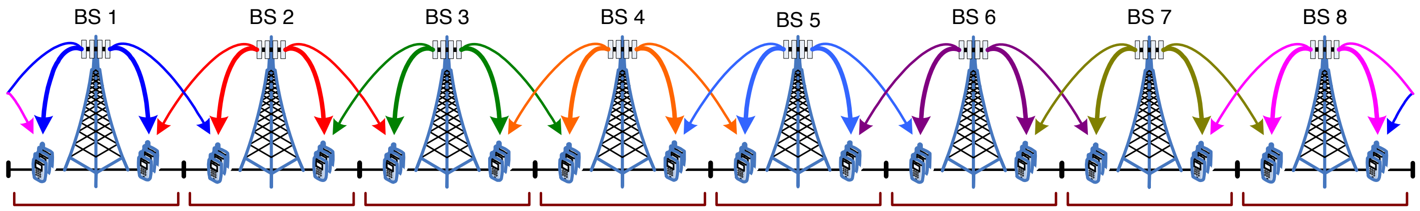
with respect to the variables $\boldsymbol{\eta} = \{\eta_m\}$*.* ■

Degrees of freedom and cost of training

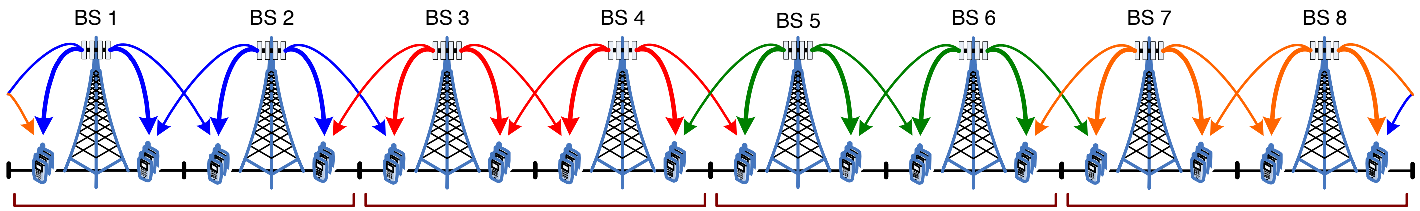
- The system spectral efficiency must be scaled by the factor $\left[1 - \frac{\gamma_p N B}{WT}\right]_+$, that takes into account the downlink training overhead, i.e., fraction of dimensions per block dedicated to (downlink) training.
- In particular, letting $\tau = \frac{N}{WT}$ denote the ratio between the number of users per group, N, and the dimensions in a time-frequency slot, we can investigate the system spectral efficiency for fixed τ, in the limit of $N \to \infty$.
- The ratio τ captures the "dimensional crowding" of the system.

Linear cellular layout

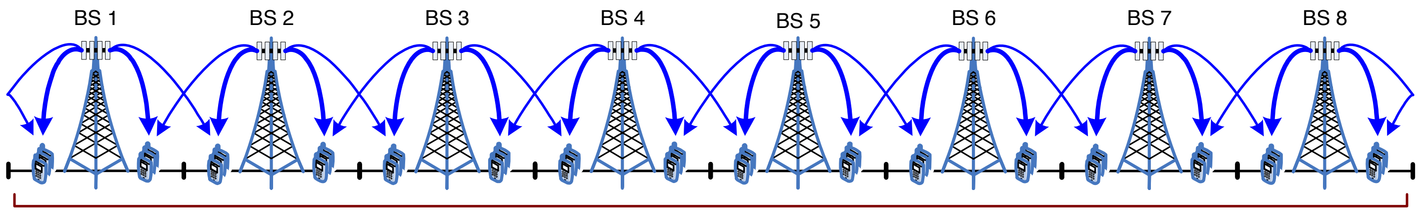
Example: linear cellular layout with $M = 8$ cells



$|\mathcal{M}_\ell| = B = 1$ cell cooperation

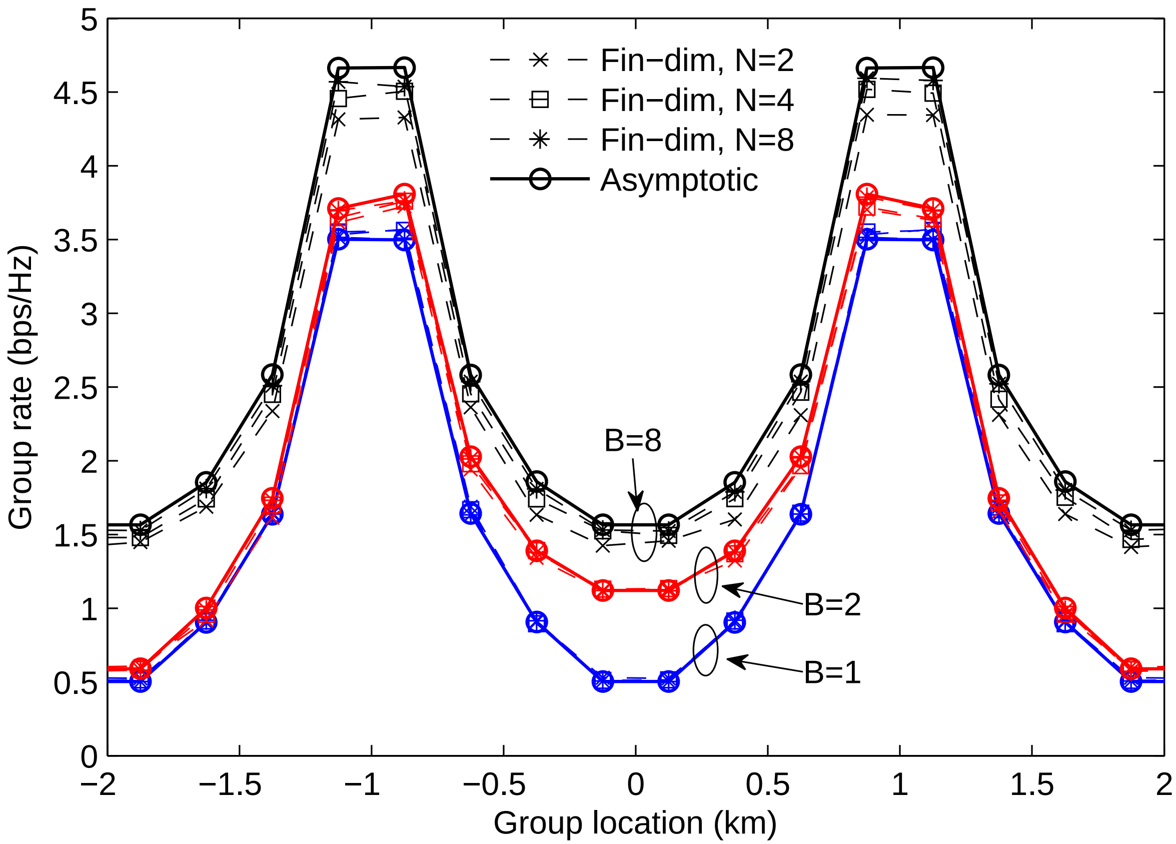


$|\mathcal{M}_\ell| = B = 2$ cell cooperation



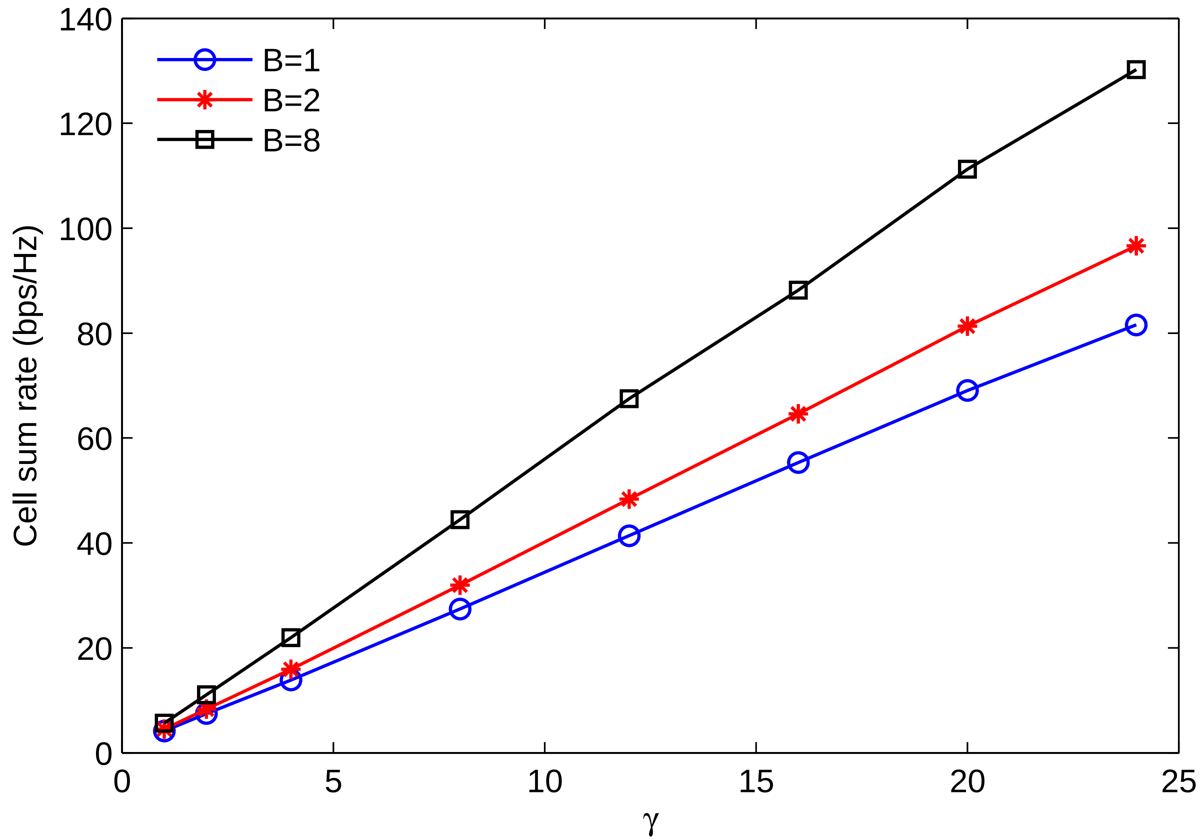
$|\mathcal{M}_\ell| = B = 8$ cell cooperation

Comparison with finite dimensional systems



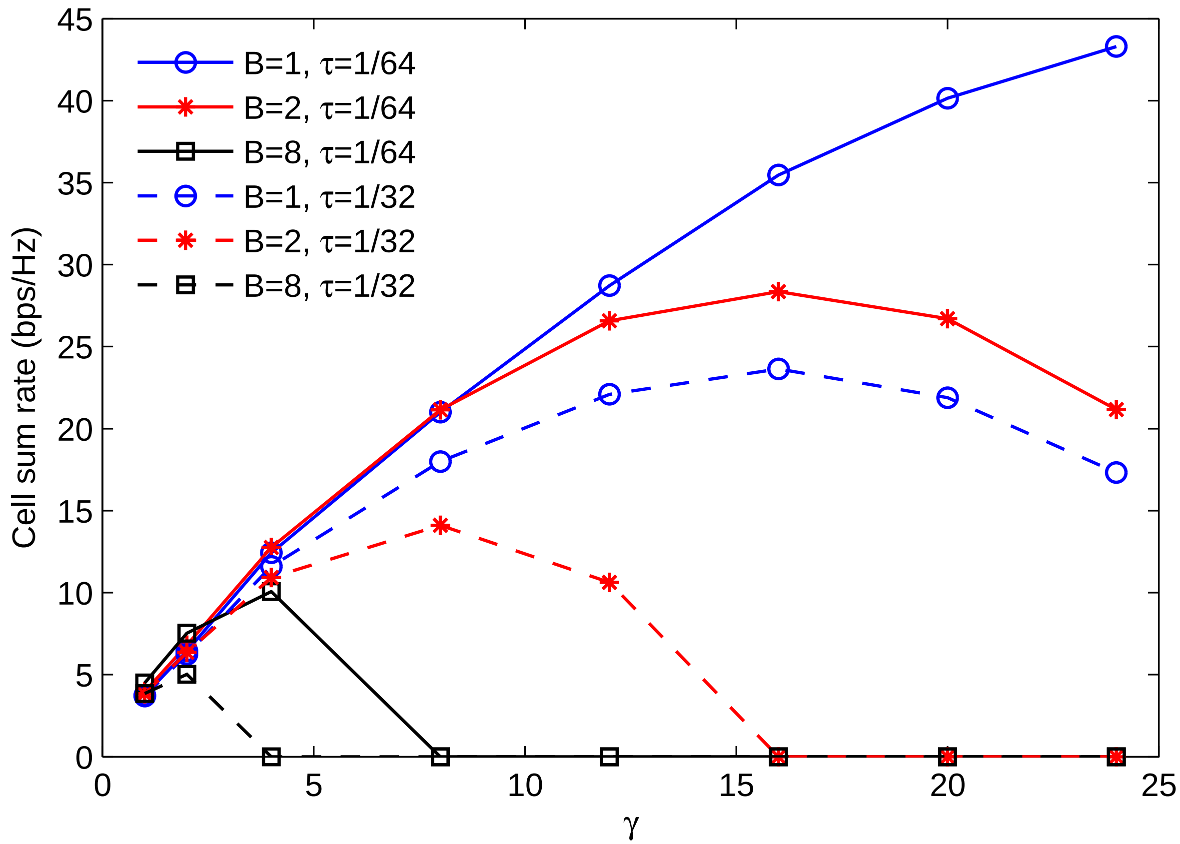
User group rate in finite dimension (N = 2, 4, and 8) for cooperation clusters of size B=1, 2, and 8, with perfect CSIT. $M = 8$ cells and $K = 64$ user groups.

Cost of CSIT and choice of network MIMO architecture (1)



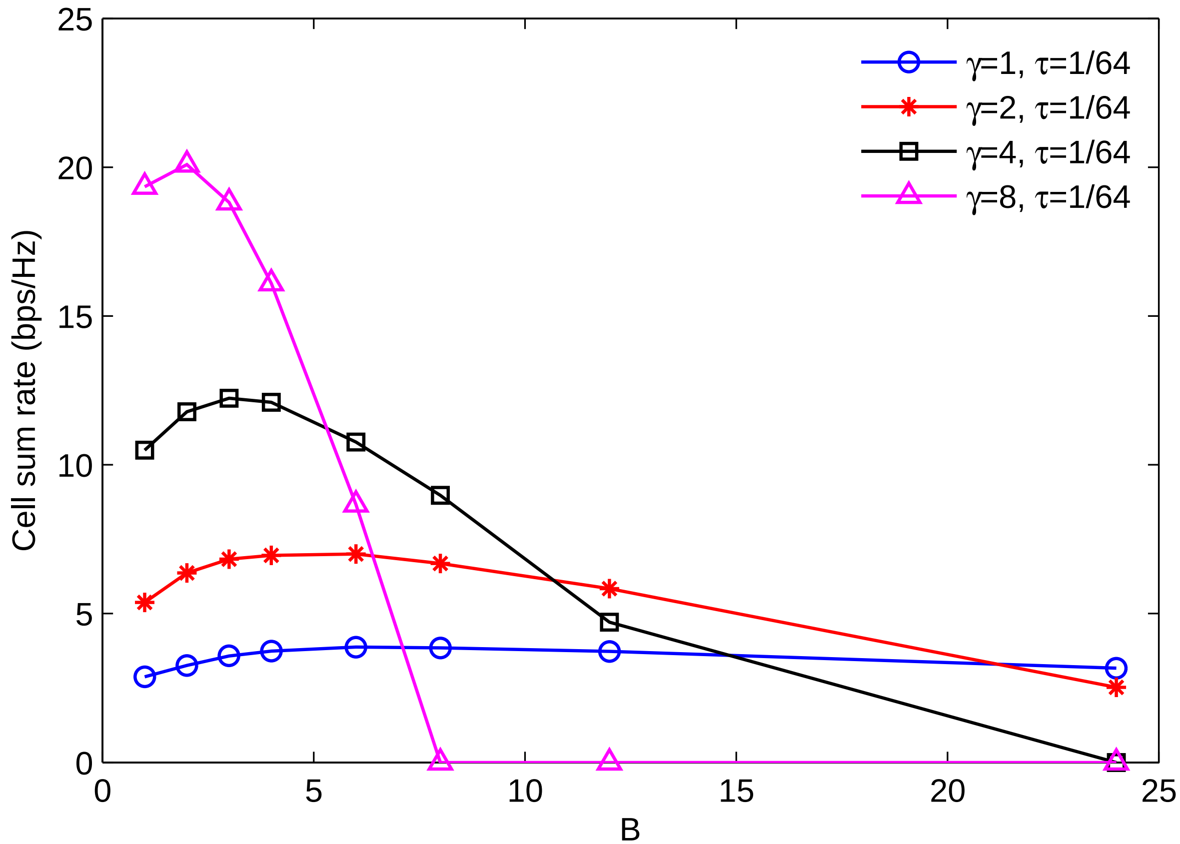
Cell sum rate versus the antenna ratio γ for cooperation clusters of size B=1, 2, and 8. $M = 8$ cells and $K = 192$ user groups.

Cost of CSIT and choice of network MIMO architecture (2)



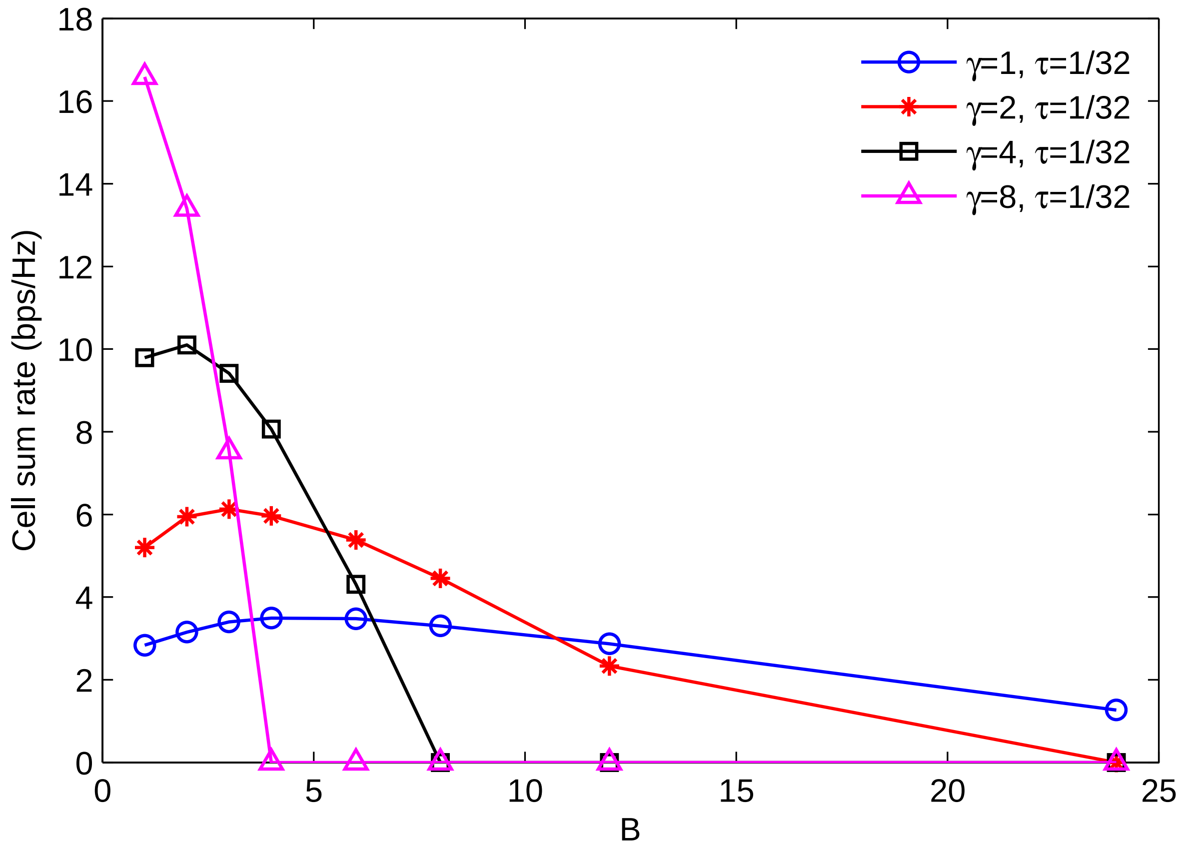
Cell sum rate versus the antenna ratio γ for cooperation clusters of size B=1, 2, and 8. $M = 8$ cells and $K = 192$ user groups.

Large cooperating clusters?



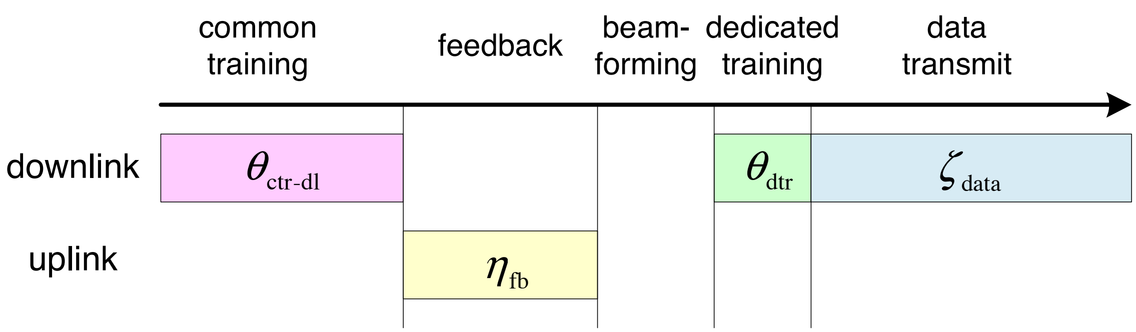
Cell sum rate versus the cluster size B for the antenna ratio γ=1, 2, 4, and 8 $\gamma_p = \gamma$, $M = 24$ cells and $K = 192$ user groups and $\tau = 1/64$.

Large cooperating clusters?



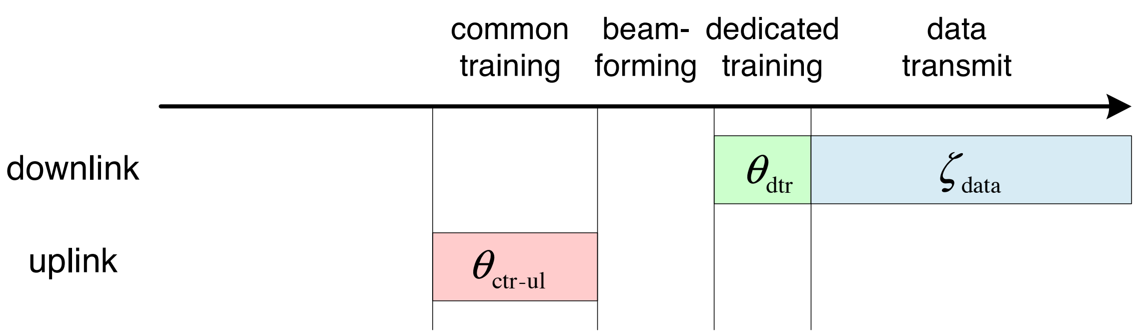
Cell sum rate versus the cluster size B for the antenna ratio γ=1, 2, 4, and 8 $\gamma_p = \gamma$, $M = 24$ cells and $K = 192$ user groups and $\tau = 1/32$.

FDD versus TDD



Frequency-division duplex (FDD)

- Estimation error
- Training overhead proportional to the number of transmit antennas



Time-division duplex (TDD)

- Estimation error
- Training overhead proportional to the number of served users

Marzetta's Massive MIMO Scheme

- No BS cooperation, each cell on its own.

- On each slot, a fraction T_{tr}/T is dedicated to uplink training, and $(1 - T_{\mathrm{tr}}/T)$ is dedicated to downlink data transmission.

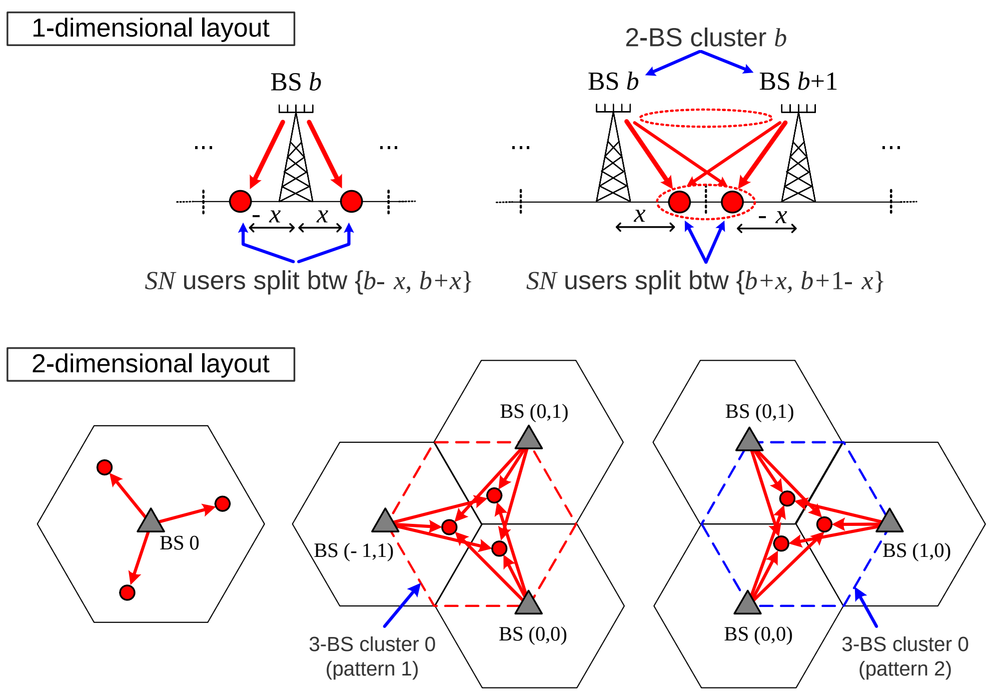
- Single-user downlink beamforming: transmit with the Hermitian transpose of the estimated channel matrix.

- Marzetta considers the limit for a finite number K of users per cell, and the number of BS antennas $M \to \infty$.

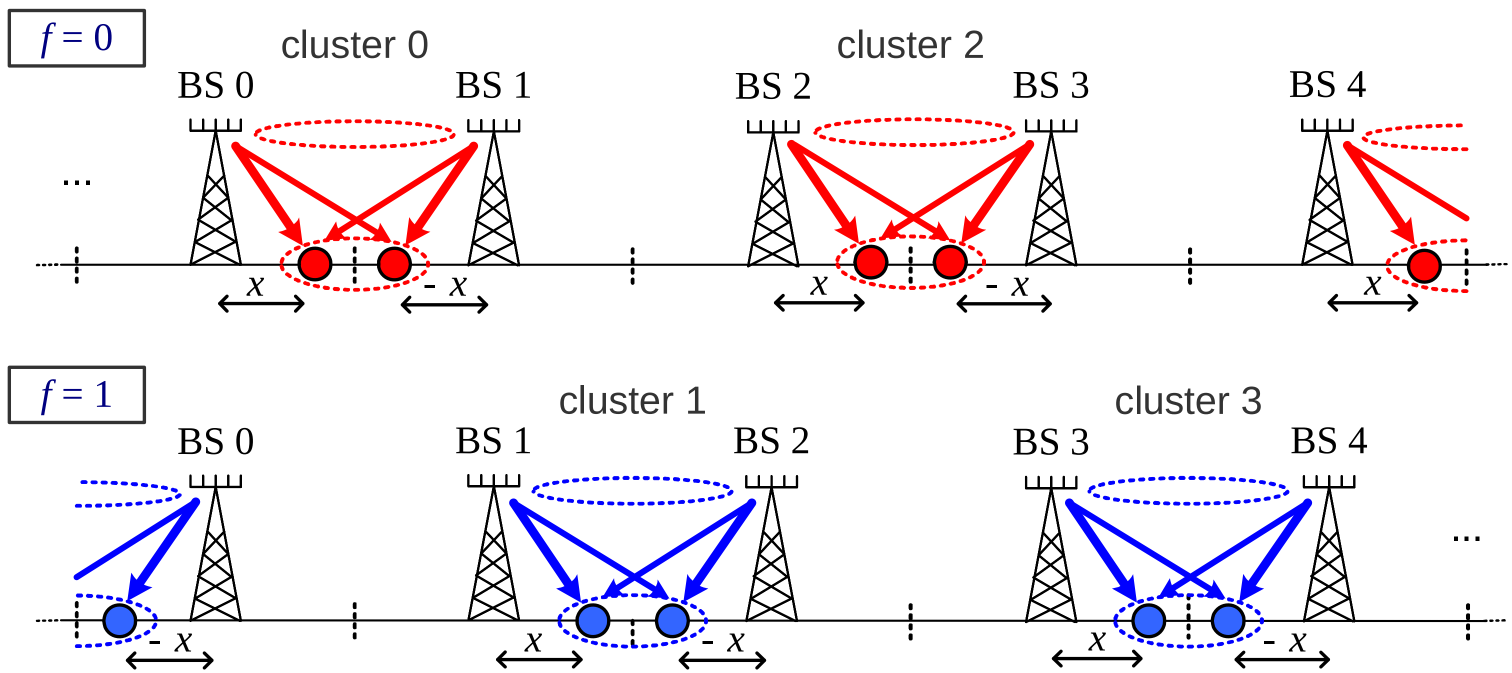
- In this regime, intra and inter cell interference and noise disappear, except for the inter-cell interference due to PILOT CONTAMINATION.

What happens for finite M/N?

- We partition the user population in "bins" of co-located users. Users in the same bin are (roughly) statistically equivalent.
- For each "bin" we consider an optimized MU-MIMO scheme.
- Scheduling over the user bins to maximize a desired Network Utility Function.

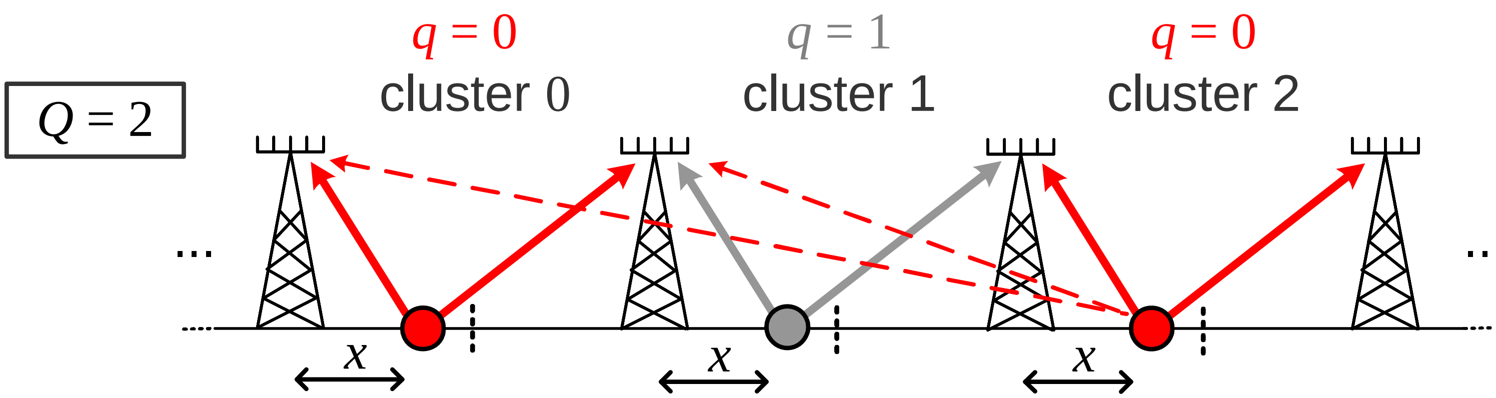


Frequecy reuse



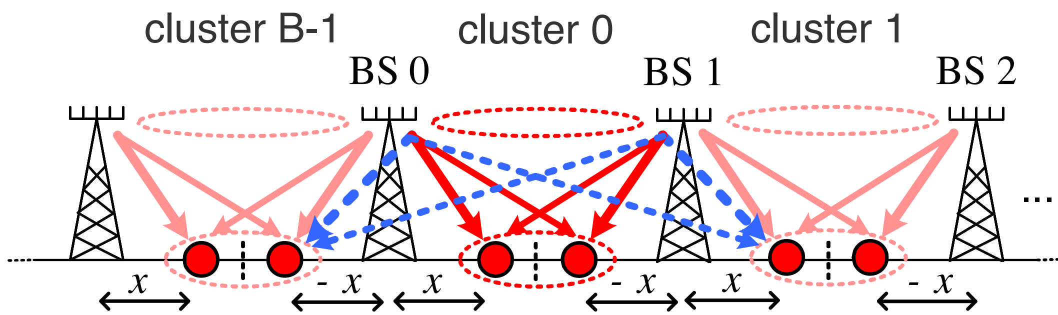
- 1-dimensional layout with $C = 2$ and $F = 2$.

Pilot reuse

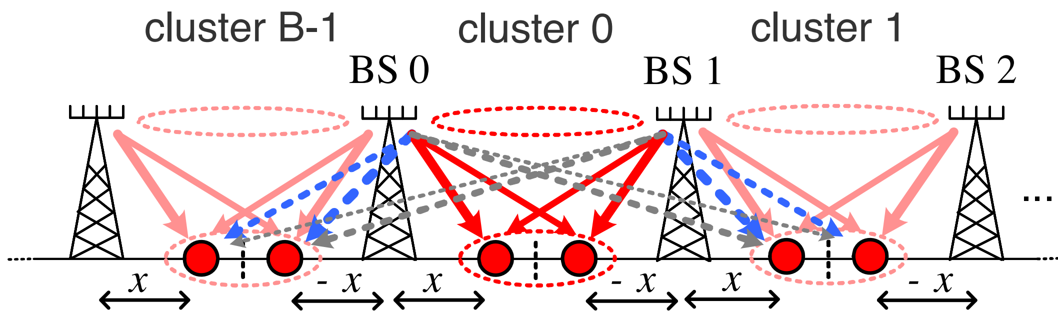


- Pilot reuse and contamination for $C = 2$, $F = 1$, and $Q = 2$. The dashed lines show the pilot contamination at cluster 0 from a user in cluster 2, sharing the same pilot signal.

Zero-Forcing and interference mitigation



(a) $J = Q$



(b) $J = C(Q-1)+1$

Multi-Mode MU-MIMO downlink scheduling

- Consider a system with K bins, $\{v(\mathcal{X}_0), \ldots, v(\mathcal{X}_{K-1})\}$, chosen to sample uniformly the coverage area $\mathcal{V}$.

- The net bin spectral efficiency (in bit/s/Hz)

$$\max\{1 - QS/T, 0\} \times R_{\mathcal{X}_k,\mathcal{C}}(F, C, J),$$

- Let $R^\star(\mathcal{X}_k)$ denote the maximum of the above for given $\mathcal{X}_k$, optimized over the the parameters S, C, J, Q, F.

- A scheduler gives fraction ρ_k of the total time-frequency transmission resource to bin $v(\mathcal{X}_k)$ in order to maximize a desired Network Utility Function.

- The scheduler determines the transmission resource allocation $\{\rho_k\}$ by solving the following convex problem:

$$\begin{array}{ll} \text{maximize} & \mathcal{G}(R_0, \ldots, R_{K-1}) \\ \text{subject to} & R_k \leq \rho_k R^\star(\mathcal{X}_k), \quad \sum_{k=0}^{K-1} \rho_k \leq 1, \quad \rho_k \geq 0. \end{array}$$

- We obtain a multi-modal network MIMO architecture.

- Optimization can be done easily based on large-system limit closed form results.

- Example: *Proportional Fairness* (PF) criterion corresponds to the choice

$$\mathcal{G}(R_0, \ldots, R_{K-1}) = \sum_{k=0}^{K-1} \log R_k,$$

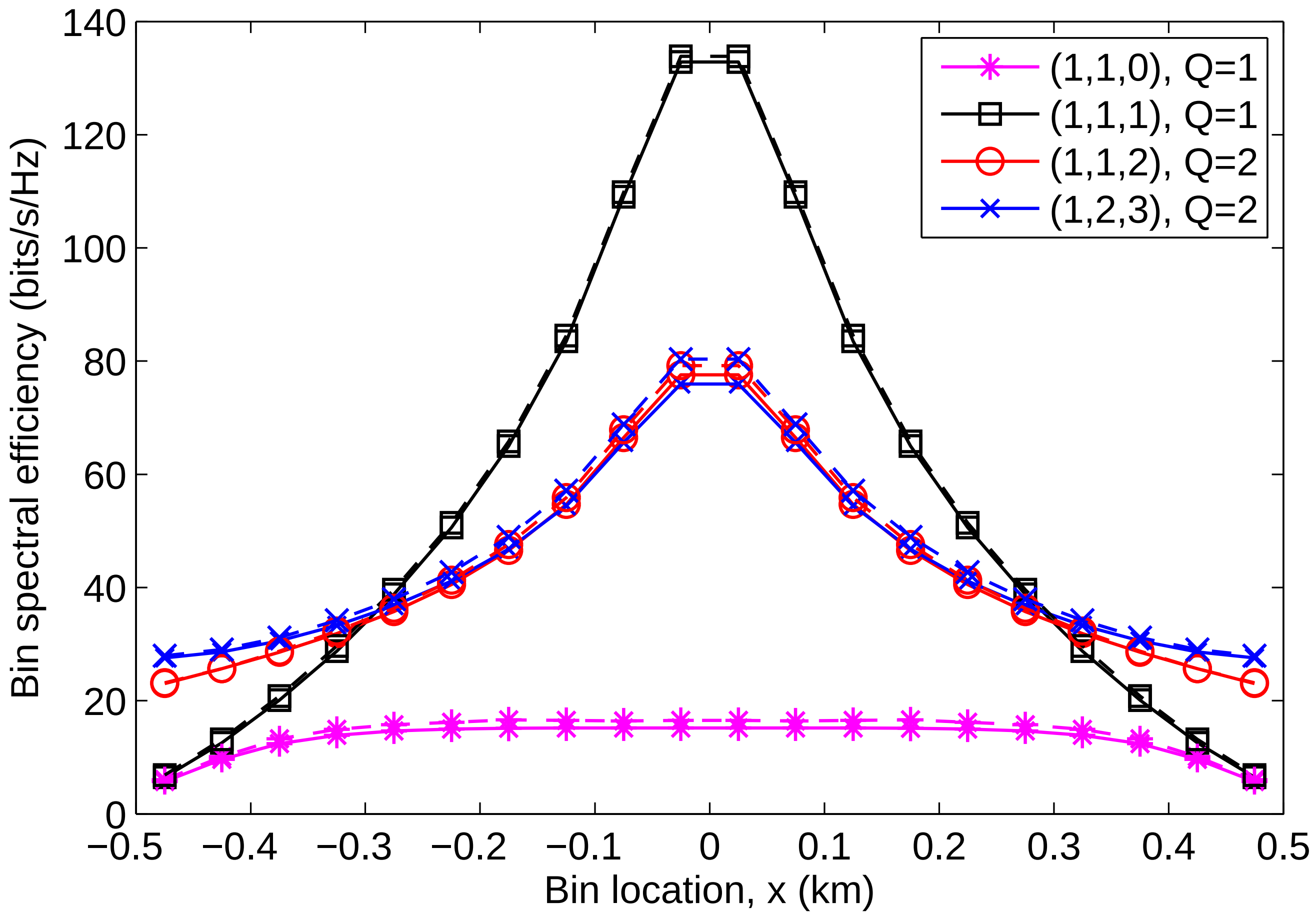
and yields $\rho_k = 1/K$ (each bin is given an equal amount of slots).

- Example: *Max-Min fairness* criterion corresponds to the choice

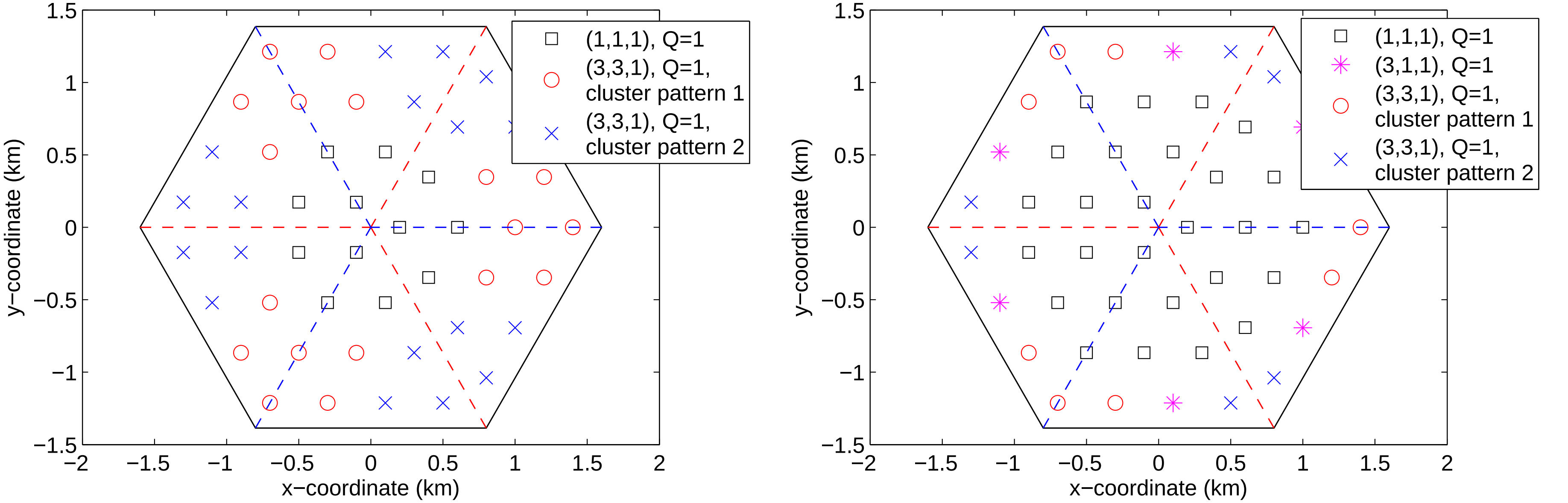
$$\mathcal{G}(R_0, \ldots, R_{K-1}) = \min_{k=0,\ldots,K-1} R_k,$$

and yields $\rho_k = \frac{\frac{1}{R^\star(\mathcal{X}_k)}}{\sum_{j=0}^{K-1} \frac{1}{R^\star(\mathcal{X}_j)}}$.

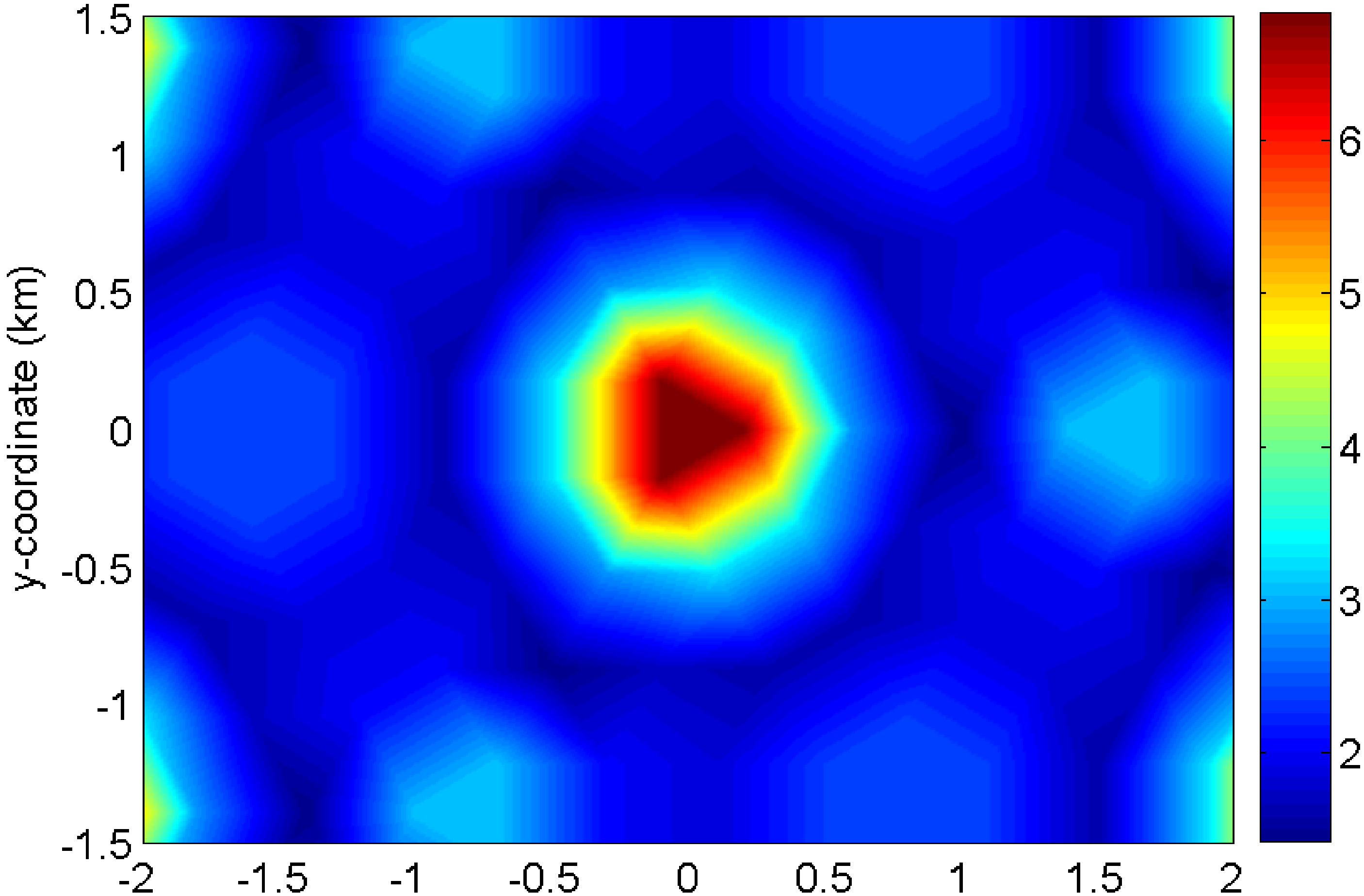
Results



Bin spectral efficiency vs. location within a cell obtained from the large system analysis (solid) and the finite dimension ($N = 1$) simulation (dotted) for various (F, C, J). $M = 30$ and $L = 40$.

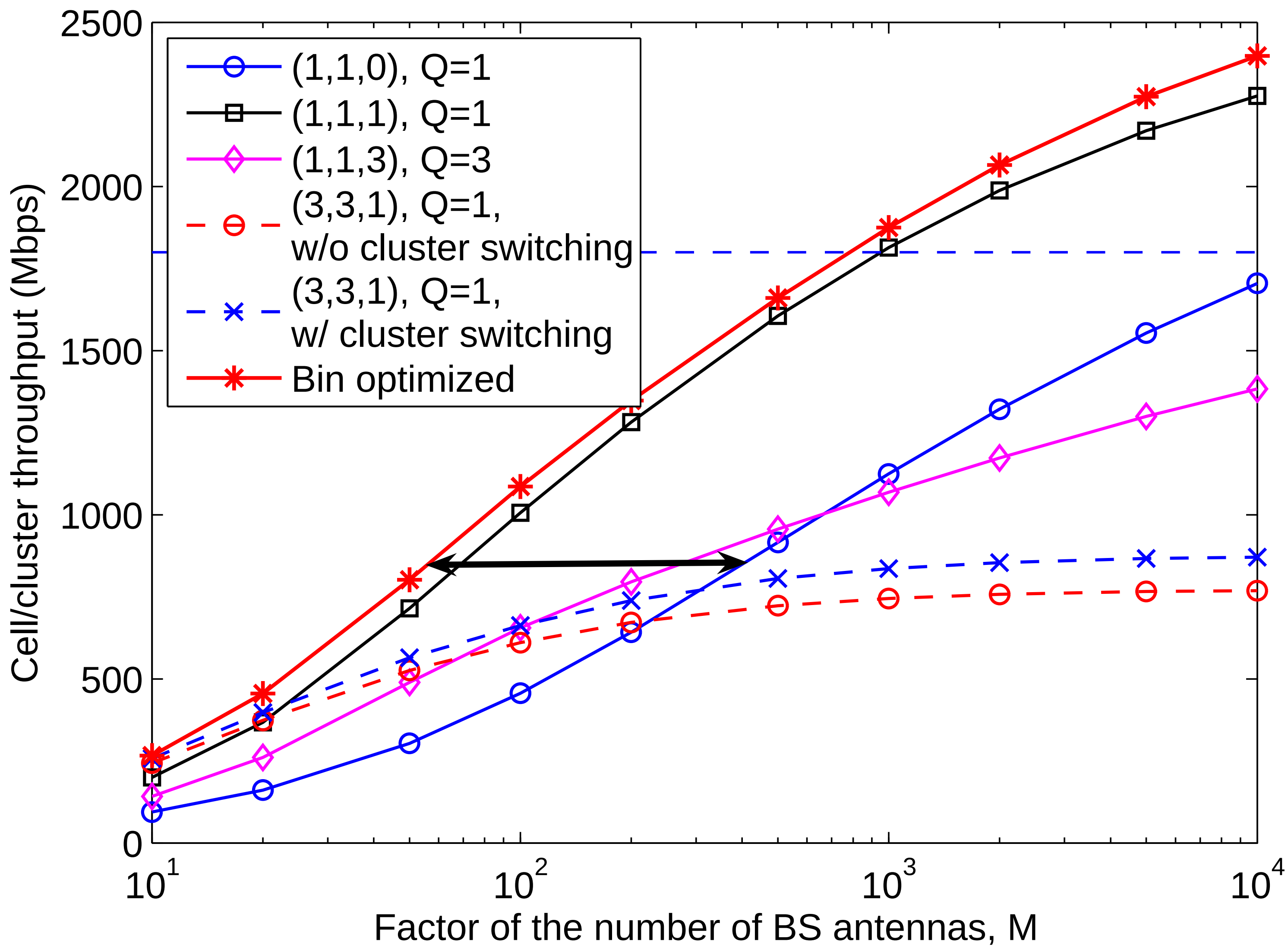


Optimal scheme at each user locations. $M = 20$ and 100, $K = 16$, and $L = 84$.

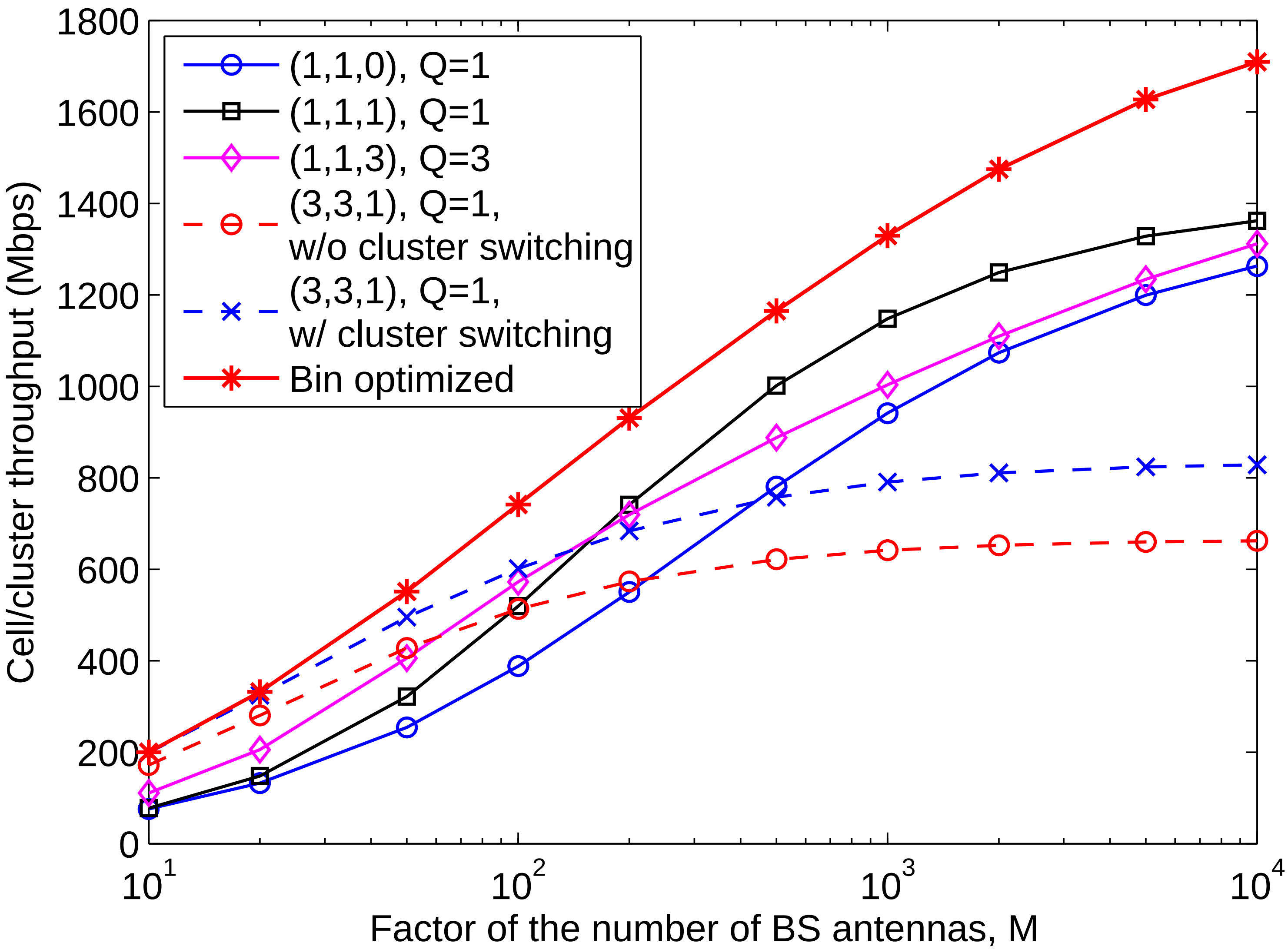


Bin-optimized spectral efficiencies normalized by the (1,1,0) (Marzetta) spectral efficiencies, for $M = 50$, $K = 48$,and $L = 84$.

Performance under PFS

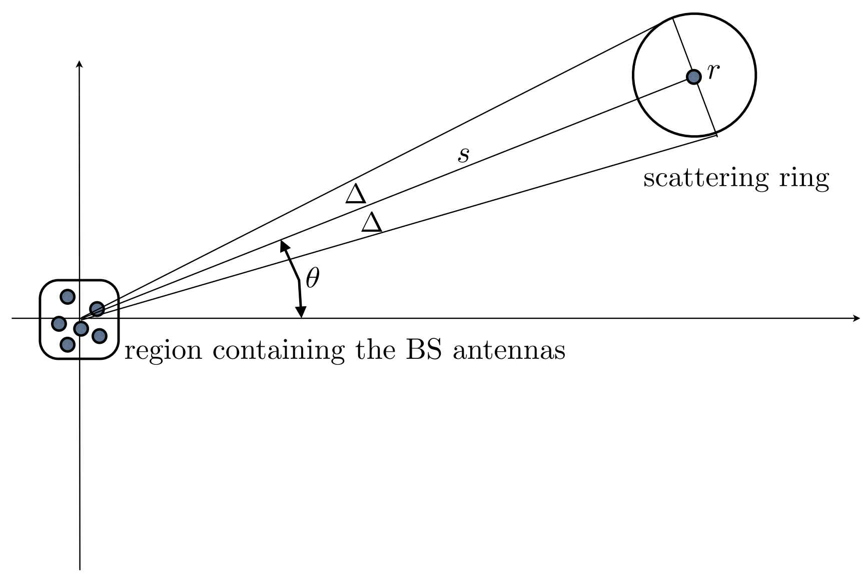


Performance under Max-Min Fairness



What about FDD systems? Exploiting Tx antenna correlation

- Users separated by a few meters (say 10 λ) are practically uncorrelated.
- In contrast, the base station sees user groups at different AoAs under narrow Angular Spread $\Delta \approx \arctan(\mathsf{r}/\mathsf{s})$.



- Tx antenna correlation:

$$\mathbf{h} = \mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{w}, \quad \mathbf{R} = \mathbf{U}\boldsymbol{\Lambda}\mathbf{U}^{\mathsf{H}}$$

with

$$[\mathbf{R}]_{m,p} = \frac{1}{2\Delta}\int_{-\Delta}^{\Delta} e^{j\mathbf{k}^{\mathsf{T}}(\alpha+\theta)(\mathbf{u}_m - \mathbf{u}_p)} d\alpha.$$

- The downlink channel model is given by

$$\mathbf{y} = \underline{\mathbf{H}}^{\mathsf{H}}\mathbf{x} + \mathbf{z} = \underline{\mathbf{H}}^{\mathsf{H}}\mathbf{V}\mathbf{d} + \mathbf{z}$$

where $\underline{\mathbf{H}}$ is the $M \times K$ system channel matrix (channel vectors by columns).

Joint Space Division and Multiplexing (JSDM)

- K users selected to form G groups, with $\approx$ same channel correlation.

$$\underline{\mathbf{H}} = [\mathbf{H}_1, \ldots, \mathbf{H}_G], \text{ with } \mathbf{H}_g = \mathbf{U}_g \mathbf{\Lambda}_g^{1/2} \mathbf{W}_g.$$

- Two-stage precoding: $\mathbf{V} = \mathbf{B}\mathbf{P}$.
- $\mathbf{B} \in \mathbb{C}^{M \times b}$ is a pre-beamforming matrix function of $\{\mathbf{U}_g, \mathbf{\Lambda}_g\}$ only.
- $\mathbf{P} \in \mathbb{C}^{b \times s}$ is a precoding matrix that depends on the effective channel.
- The effective channel matrix is given by

$$\underline{\mathbf{H}}^{\mathsf{H}} = \begin{bmatrix} \mathbf{H}_1^{\mathsf{H}}\mathbf{B}_1 & \mathbf{H}_1^{\mathsf{H}}\mathbf{B}_2 & \cdots & \mathbf{H}_1^{\mathsf{H}}\mathbf{B}_G \\ \mathbf{H}_2^{\mathsf{H}}\mathbf{B}_1 & \mathbf{H}_2^{\mathsf{H}}\mathbf{B}_2 & \cdots & \mathbf{H}_2^{\mathsf{H}}\mathbf{B}_G \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{H}_G^{\mathsf{H}}\mathbf{B}_1 & \mathbf{H}_G^{\mathsf{H}}\mathbf{B}_2 & \cdots & \mathbf{H}_G^{\mathsf{H}}\mathbf{B}_G \end{bmatrix}.$$

- Joint Group Processing: If the estimation and feedback of the transformed channel $\underline{\mathbf{H}}$ can be afforded, the precoding matrix $\mathbf{P}$ is determined as a function of $\underline{\mathbf{H}}$.

- Per-Group Processing: If estimation and feedback of the whole $\underline{\mathbf{H}}$ is still too costly, then each group estimates its own diagonal block $\underline{\mathbf{H}}_g = \mathbf{B}_g^{\mathsf{H}}\mathbf{H}_g$, and $\mathbf{P} = \mathrm{diag}(\mathbf{P}_1, \cdots, \mathbf{P}_G)$.

- This results in

$$\mathbf{y}_g = \mathbf{H}_g^{\mathsf{H}}\mathbf{B}_g\mathbf{P}_g\mathbf{d}_g + \sum_{g' \neq g} \mathbf{H}_g^{\mathsf{H}}\mathbf{B}_{g'}\mathbf{P}_{g'}\mathbf{d}_{g'} + \mathbf{z}_g$$

Achieving capacity with reduced CSI

- Assume that the G groups are such that $\underline{\mathbf{U}} = [\mathbf{U}_1, \cdots, \mathbf{U}_G]$ is $M \times rG$ *tall unitary* (i.e., $rG \leq M$ and $\underline{\mathbf{U}}^{\mathsf{H}}\underline{\mathbf{U}} = \mathbf{I}$).

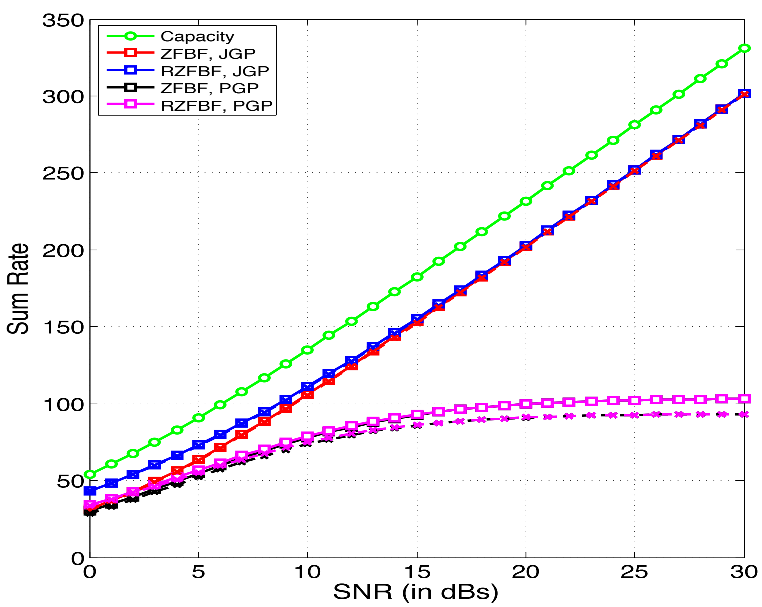
- We choose $b' = r$ and $\mathbf{B}_g = \mathbf{U}_g$ and obtain exact Block Diagonalization (BD):

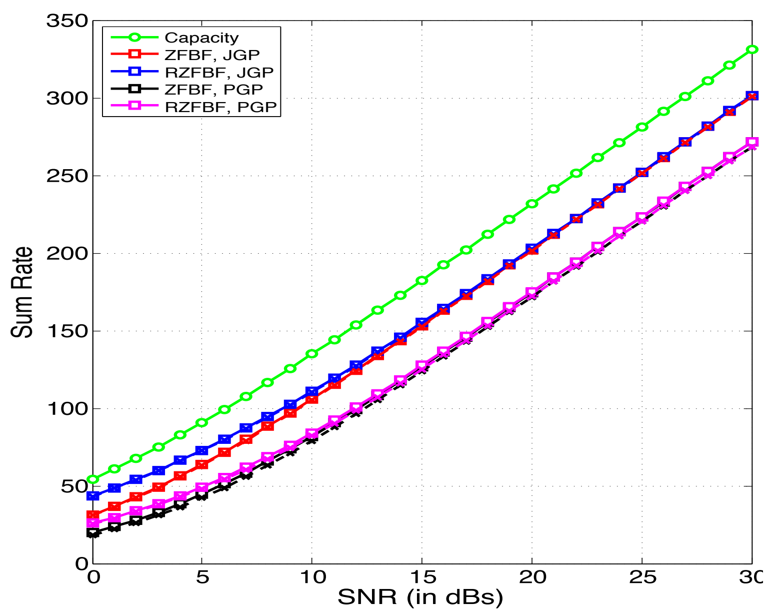
$$\mathbf{y}_g = \mathbf{H}_g^{\mathsf{H}}\mathbf{B}_g\mathbf{P}_g\mathbf{d}_g + \mathbf{z}_g = \mathbf{W}_g^{\mathsf{H}}\mathbf{\Lambda}_g^{1/2}\mathbf{P}_g\mathbf{d}_g + \mathbf{z}_g \tag{1}$$

Theorem 3. For $\underline{\mathbf{U}}$ tall unitary, the sum capacity of the original Gaussian vector broadcast channel with full CSI is equal to the sum capacity of the set of decoupled channels (1). ■

Analysis and results

- Analysis possible using the "deterministic equivalent method" (see [Couillet, Debbah, CUP 2011]).
- Example: $M = 100$, $G = 6$ user groups, Rank$(\mathbf{R}_g) = 21$, we serve 5 users per group with $b' = 10$.
- Sum throughput (bit/s/Hz) vs. SNR (dB) , approximated BD and regularized ZF, $r^\star = 6$ and $r^\star = 12$.





Remarks

- Full CSI: 100×30 channel matrix $\Rightarrow$ 3000 complex channel coefficients per coherence block (CSI feedback), with 100×100 unitary "common" pilot matrix for downlink channel estimation.

- JSDM with PGP: $6 \times 10 \times 5$ diagonal blocks $\Rightarrow$ 300 complex channel coefficients per coherence block (CSI feedback), with 10×10 unitary "dedicated" pilot matrices for downlink channel estimation, sent in parallel to each group through the pre-beamforming matrix.

- One order of magnitude saving in both downlink training and CSI feedback.

- 150 bit/s/Hz at SNR $= 18$ dB: 5 bit/s/Hz per user, for 30 users served simultaneously on the same time-frequency slot.

Is the tall unitary realistic?

- For a Uniform Linear Array (ULA), $\mathbf{R}$ is Toeplitz, with elements

$$[\mathbf{R}]_{m,p} = \frac{1}{2\Delta}\int_{-\Delta}^{\Delta} e^{-j2\pi D(m-p)\sin(\alpha+\theta)}d\alpha, \quad m,p \in \{0,1,\ldots,M-1\}$$

- We use Szego's asymptotic theory of Toeplitz matrices.

Theorem 4. *The empirical eigenvalue distribution of* $\mathbf{R}$ *can be approximated by*

$$\lim_{M\to\infty} F_{\mathbf{R}}(\lambda) = \mu\{S(\xi) \leq \lambda\}$$

where

$$S(\xi) = \sum_{m=-\infty}^{\infty} [\mathbf{R}]_{m,0} = \frac{1}{2\Delta} \sum_{m\in[D\sin(-\Delta+\theta)+\xi, D\sin(\Delta+\theta)+\xi]} \frac{1}{\sqrt{D^2-(m-\xi)^2}}.$$

■

Theorem 5. *The asymptotic normalized rank of the channel covariance matrix* $\mathbf{R}$ *with antenna separation* λD*, AoA* θ *and AS* Δ*, is given by*

$$\rho = \lim_{M\to\infty} \frac{1}{M}\mathrm{Rank}(\mathbf{R}) = \min\{1, B(D,\theta,\Delta)\},$$

where

$$B(D,\theta,\Delta) = \left|D\sin(-\Delta+\theta) - D\sin(\Delta+\theta)\right|.$$

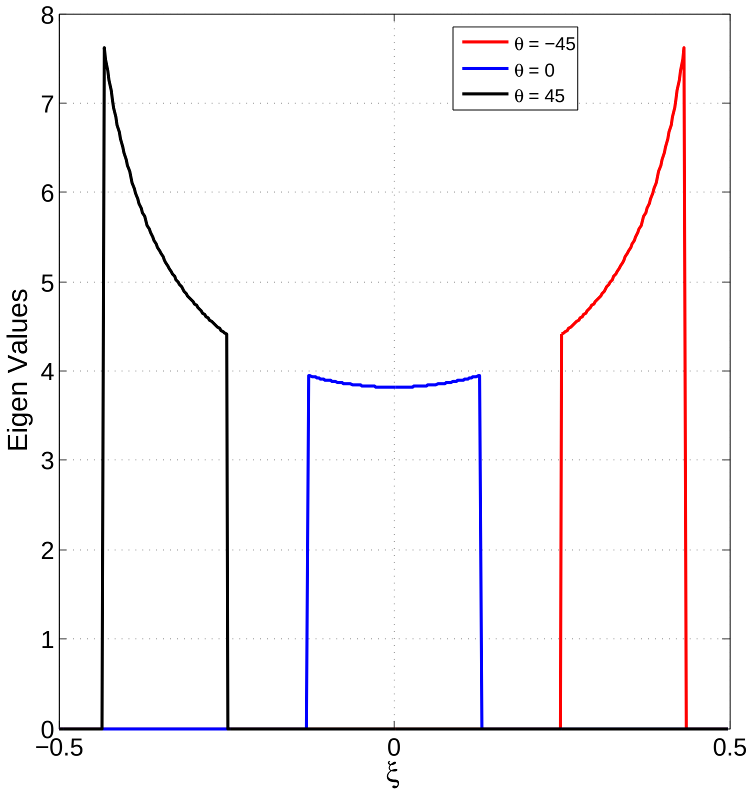
■

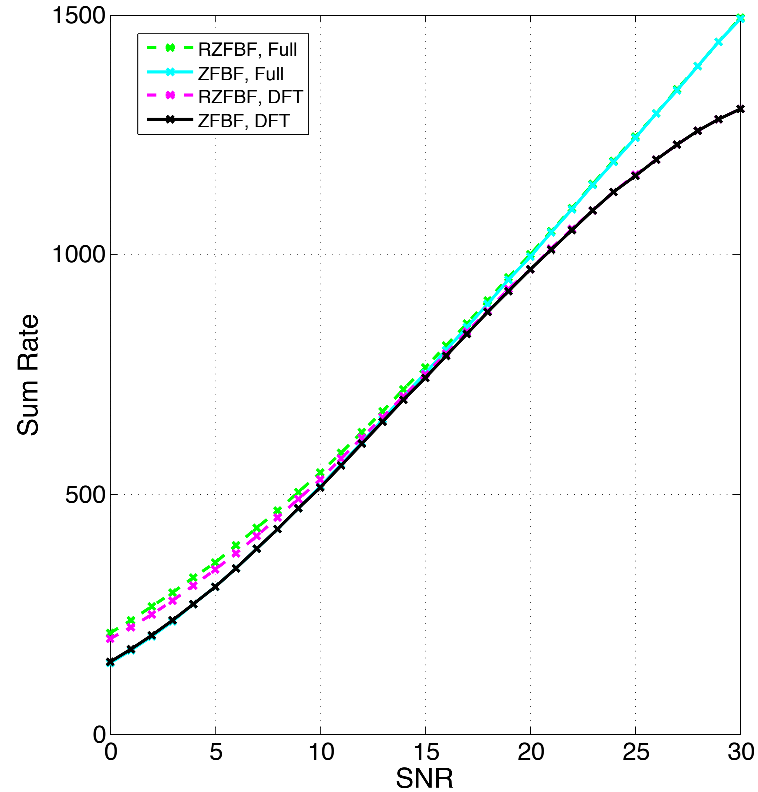
Theorem 6. *Let $\mathcal{S}$ denote the support of $S(\xi)$, let $\mathcal{J}_{\mathcal{S}} = \{m : [m/M] \in \mathcal{S}, m = 0, \ldots, M-1\}$ be the set of indices for which the corresponding "angular frequency" $\xi_m = [m/M]$ belongs to $\mathcal{S}$, let $\mathbf{f}_m$ denote the m-th column of the unitary DFT matrix $\mathbf{F}$, and let $\mathbf{F}_{\mathcal{S}} = (\mathbf{f}_m : m \in \mathcal{J}_{\mathcal{S}})$ be the DFT submatrix containing the columns with indices in $\mathcal{J}_{\mathcal{S}}$. Then,*

$$\lim_{M \to \infty} \frac{1}{M} \left\| \mathbf{U}\mathbf{U}^{\mathsf{H}} - \mathbf{F}_{\mathcal{S}}\mathbf{F}_{\mathcal{S}}^{\mathsf{H}} \right\|_F^2 = 0,$$

where $\mathbf{U}$ is the $M \times r$ "tall unitary" matrix of the non-zero eigenvectors of $\mathbf{R}$. ■

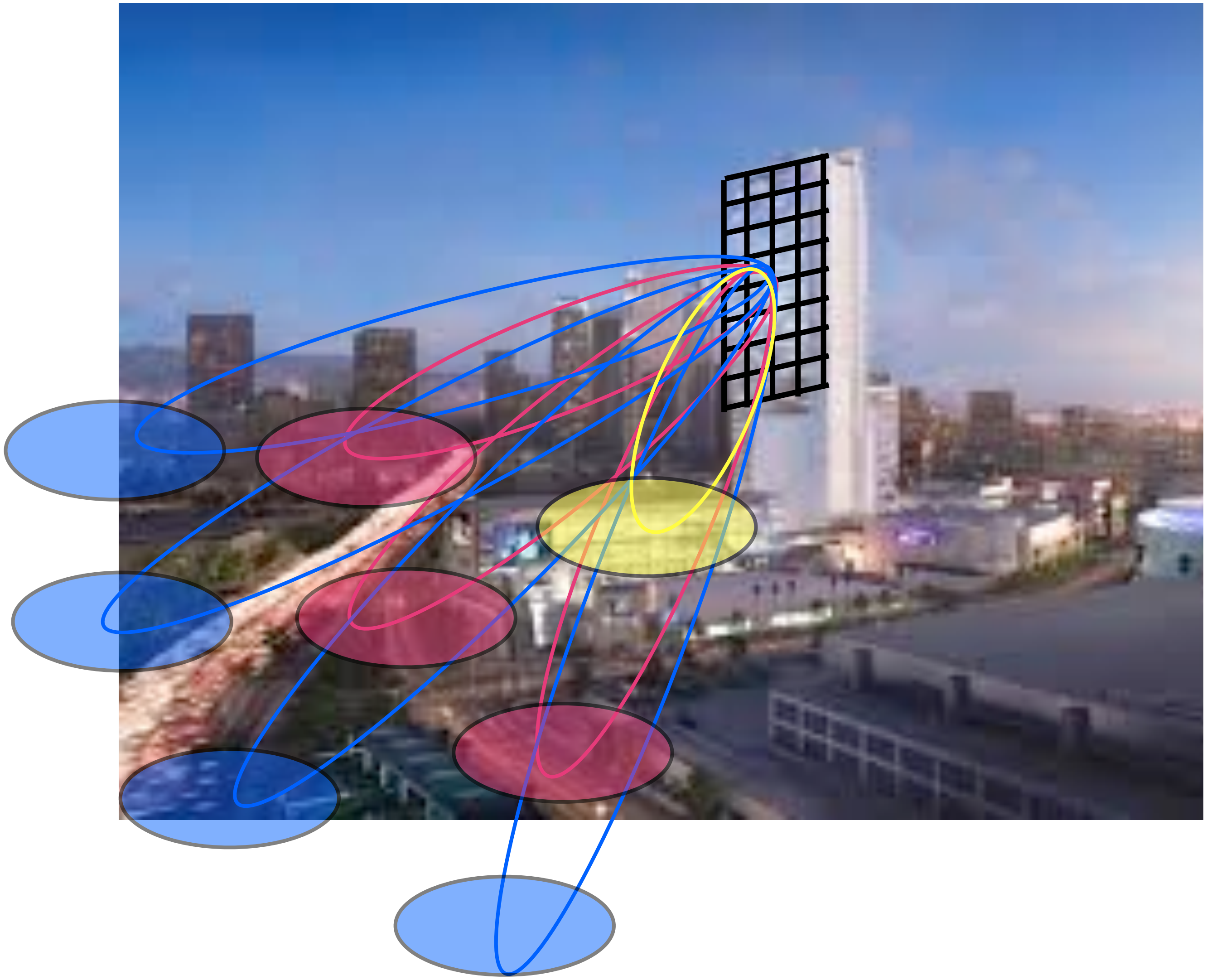
Corollary 1. *Groups g and g' with angle of arrival θ_g and $\theta_{g'}$ and common angular spread Δ have spectra with disjoint support if their AoA intervals $[\theta_g - \Delta, \theta_g + \Delta]$ and $[\theta_{g'} - \Delta, \theta_{g'} + \Delta]$ are disjoint.* ■





- ULA with $M = 400$, $G = 3$, $\theta_1 = \frac{-\pi}{4}, \theta_2 = 0, \theta_3 = \frac{\pi}{4}$, $D = 1/2$ and $\Delta = 15$ deg.

Super-Massive MIMO



- Idea: produce a 3D pre-beamforming by Kronecker product of a "vertical" beamforming, separating the sector into L concentric regions, and a "horizontal" beamforming, separating each ℓ-th region into G_ℓ groups.

- Horizontal beam forming is as before.

- For vertical beam forming we just need to find one dominating eigenmode per region, and use the BD approach.

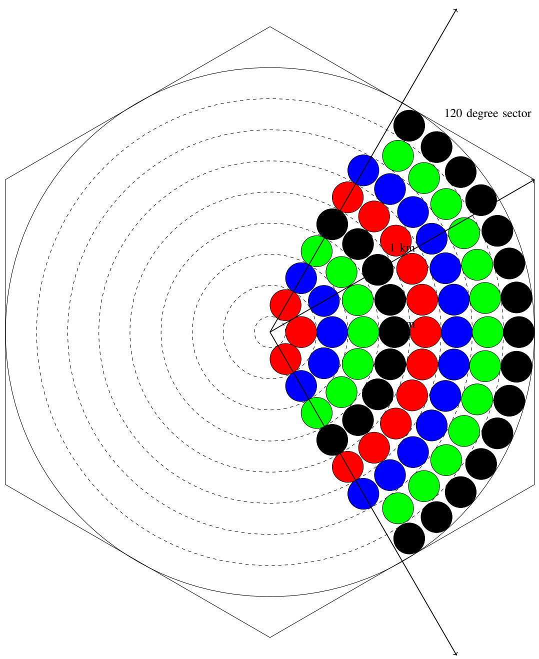
- A set of simultaneously served groups forms a "pattern".

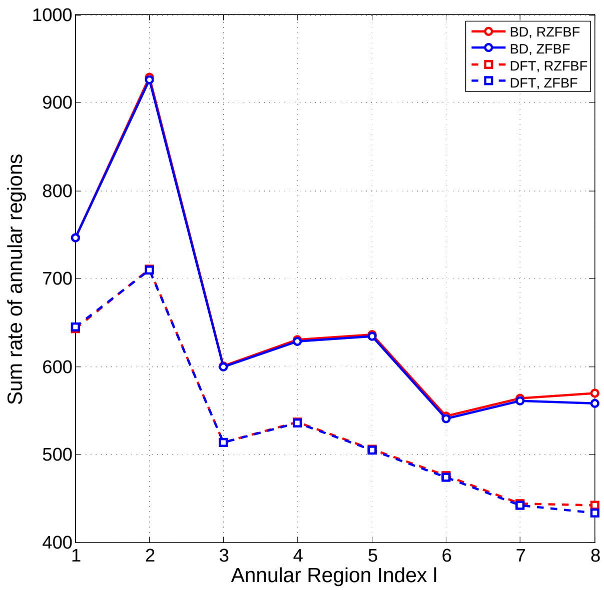
- Patterns need not cover the whole sector.

- Different intertwined patterns can be multiplexed in the time-frequency domain in order to guarantee a fair coverage.

An example

- Cell radius 600m, group ring radius 30m, array height 50m, $M = 200$ columns, $N = 300$ rows.
- Pathloss $g(x) = \frac{1}{1+(\frac{x}{d_0})^\delta}$ with $\delta = 3.8$ and $d_0 = 30$m.
- Same color regions are served simultaneously. Each ring is given equal power.



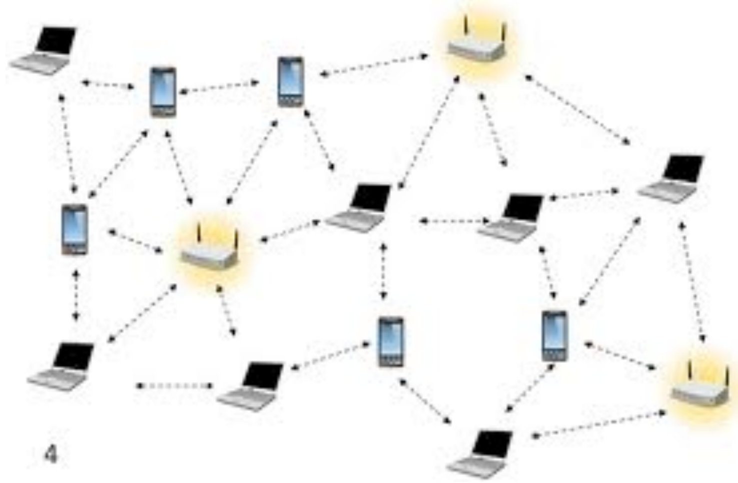


Sum throughput (bit/s/Hz) under PFS and Max-min Fairness

Scheme	Approximate BD	DFT based
PFS, RZFBF	1304.4611	1067.9604
PFS, ZFBF	1298.7944	1064.2678
MAXMIN, RZFBF	1273.7203	1042.1833
MAXMIN, ZFBF	1267.2368	1037.2915

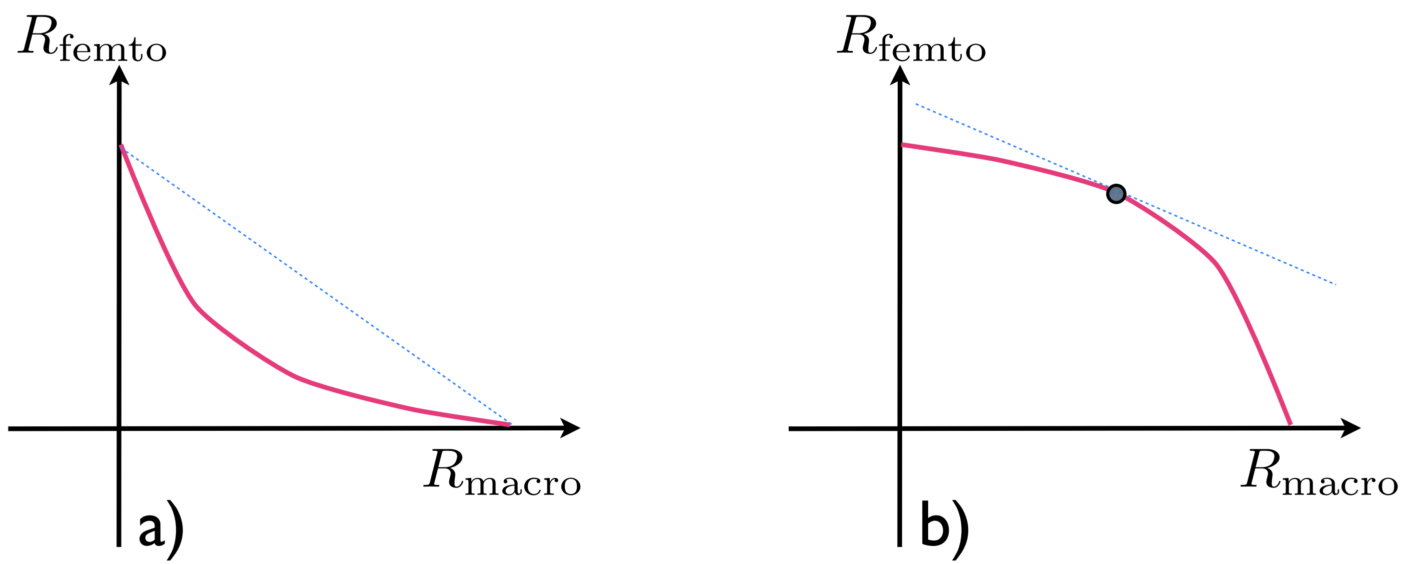
1000 bit/s/Hz $\times$ 40 MHz of bandwidth $= 40$ Gb/s per sector.

Heterogeneous/D2D Wireless Networks



- Scaling laws of D2D wireless networks: $C = O(\sqrt{K})$ bit$\times$meter/second.
- If source-destination are at distance $O(1)$, then the per-connection throughput vanishes as $O(\frac{1}{\sqrt{K}})$.
- If source-destination are at distance $O(1/\sqrt{K})$, then the per-connection throughput is constant $O(1)$.
- Source-destination pairs at 1 hop $\Longrightarrow$ Small Cells or D2D with Caching.

User-deployed small cells tier: In-Band or Out-of-Band?



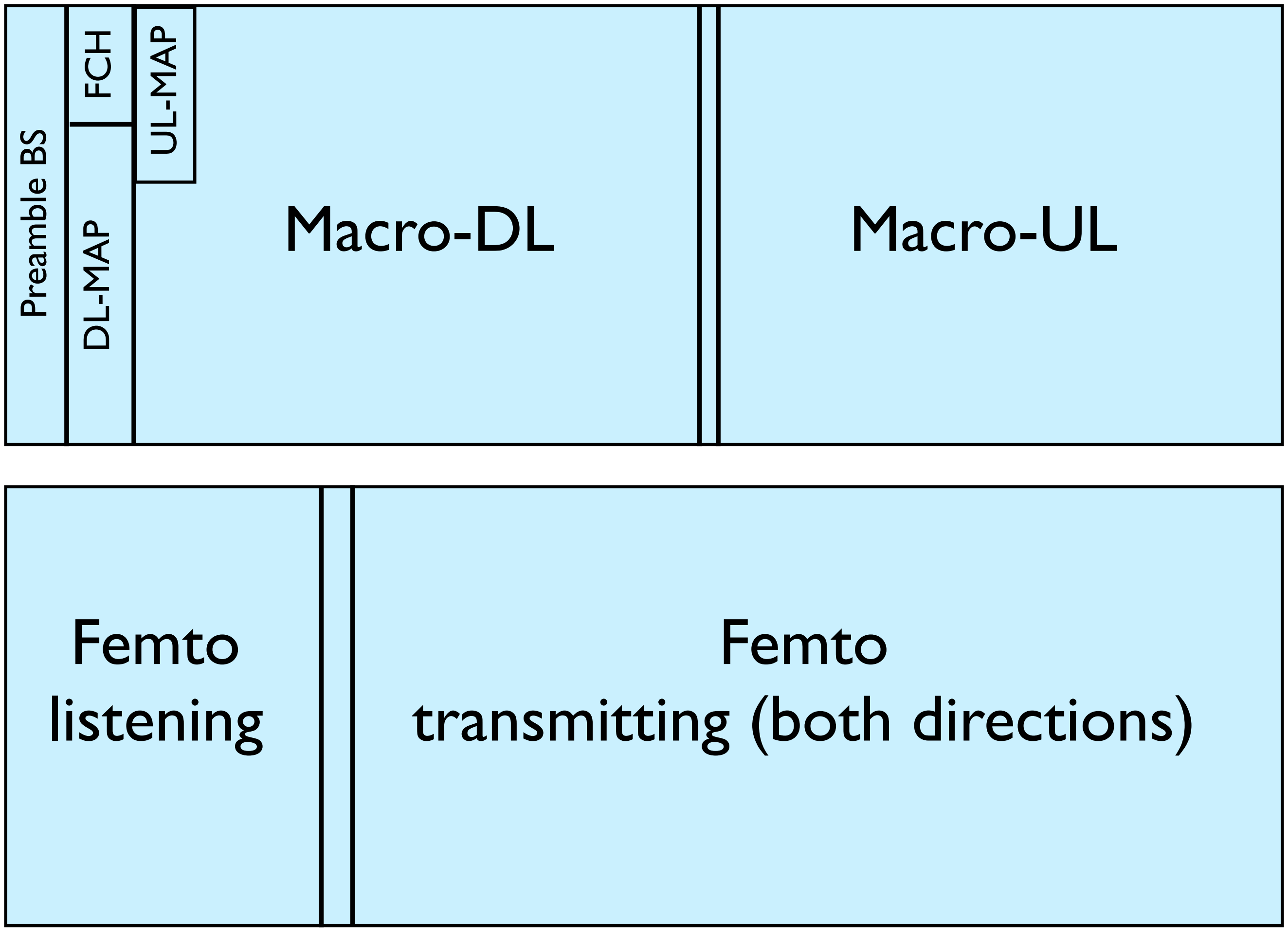
- In case a), time-sharing or bandwidth splitting is optimal (tier 1 and tier 2 on orthogonal dimensions).

- In case b), orthogonalization is not optimal, and tier 1 and tier2 should *interfere*.

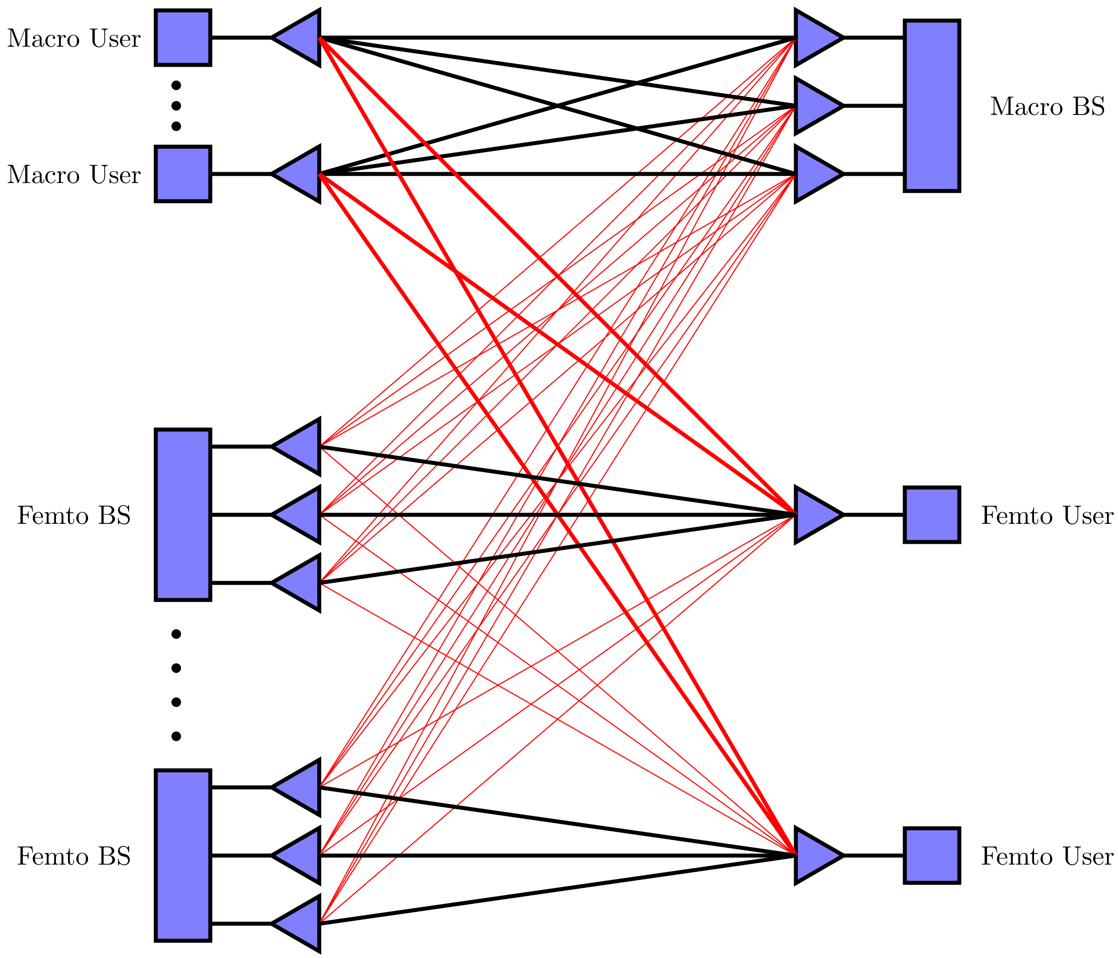
Smart Spectrum Reuse via “Cognition”

- Small Cells operate in TDD, macrocell operates either in TDD or in FDD (in this talk we focus on TDD macrocell).
- Small Cells overhear the macrocell control channel (similar to relays in WiMax 802.16j).
- Small Cells are aware of their location, and of the location of the macrocell users being scheduled.
- Open-access: any macrocell user inside the range of a small cell is absorbed.
- Closed-access: macrocell users can be anywhere, even inside a small cell.

Frame Structure for Cognition



Reverse TDD



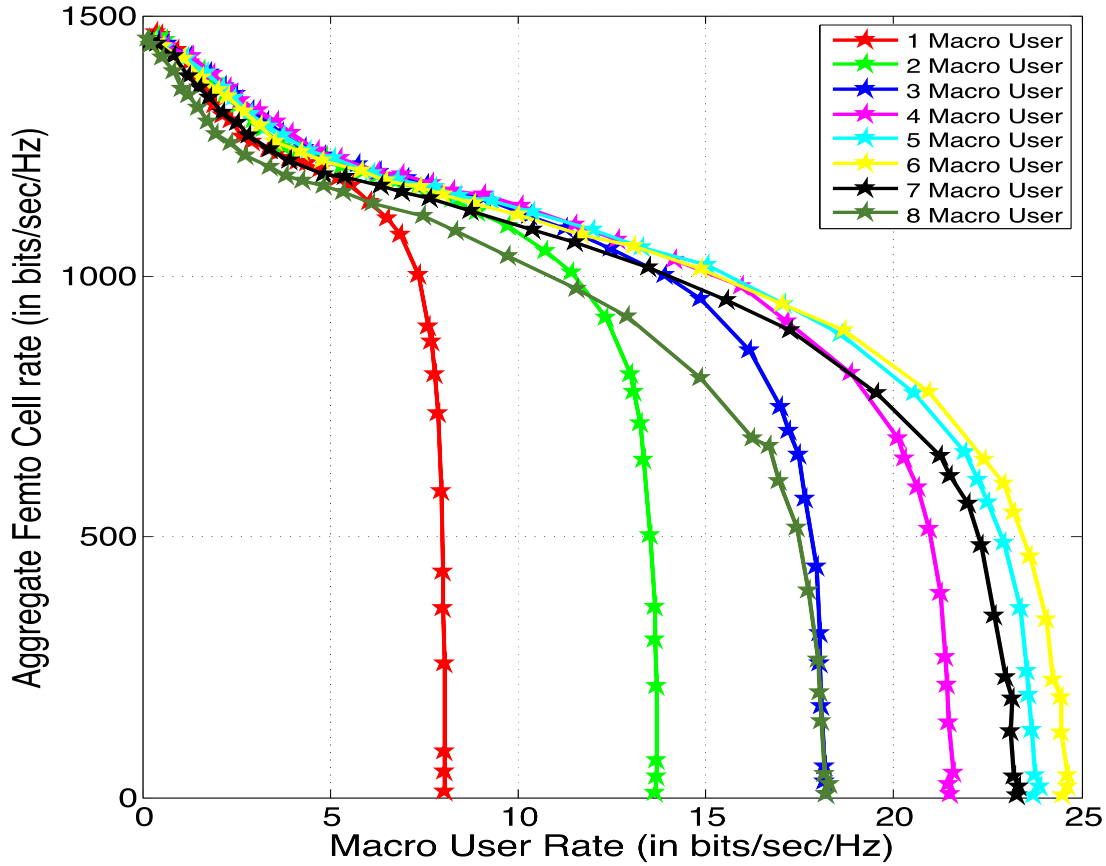
- We align the Macro DL with the Femto UL, and Vice-Versa.

MISO/SIMO Interference Channel and UL/DL Duality

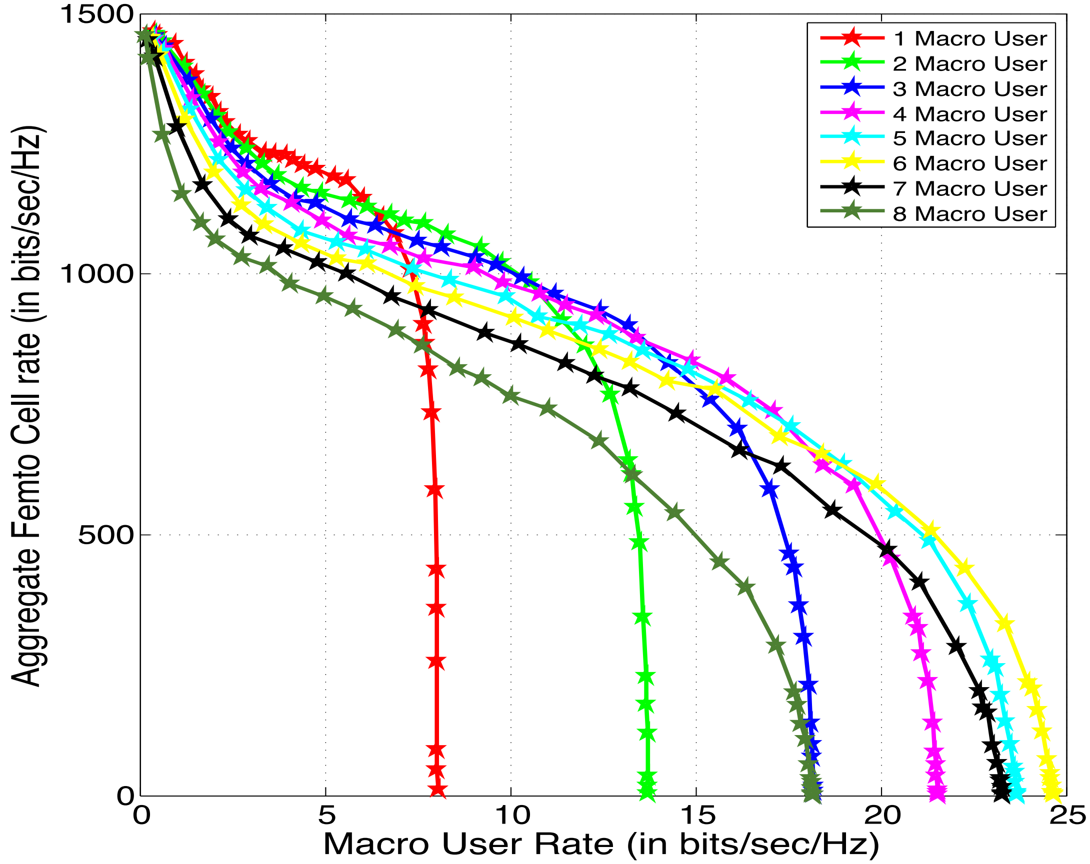
- In the macro-DL/femto-UL, we use interference temperature PC as in the baseline scheme.
- Femto APs use linear MMSE (optimal linear receivers).
- In the macro-UL/femto-DL, we use the MMSE receiving vectors as transmit beamforming vectors.
- By UL/DL duality, there exist a power assignment of the Femto APs and of the Macro user powers such that:

1. The sum-power is the same.
2. The SINR are the same.

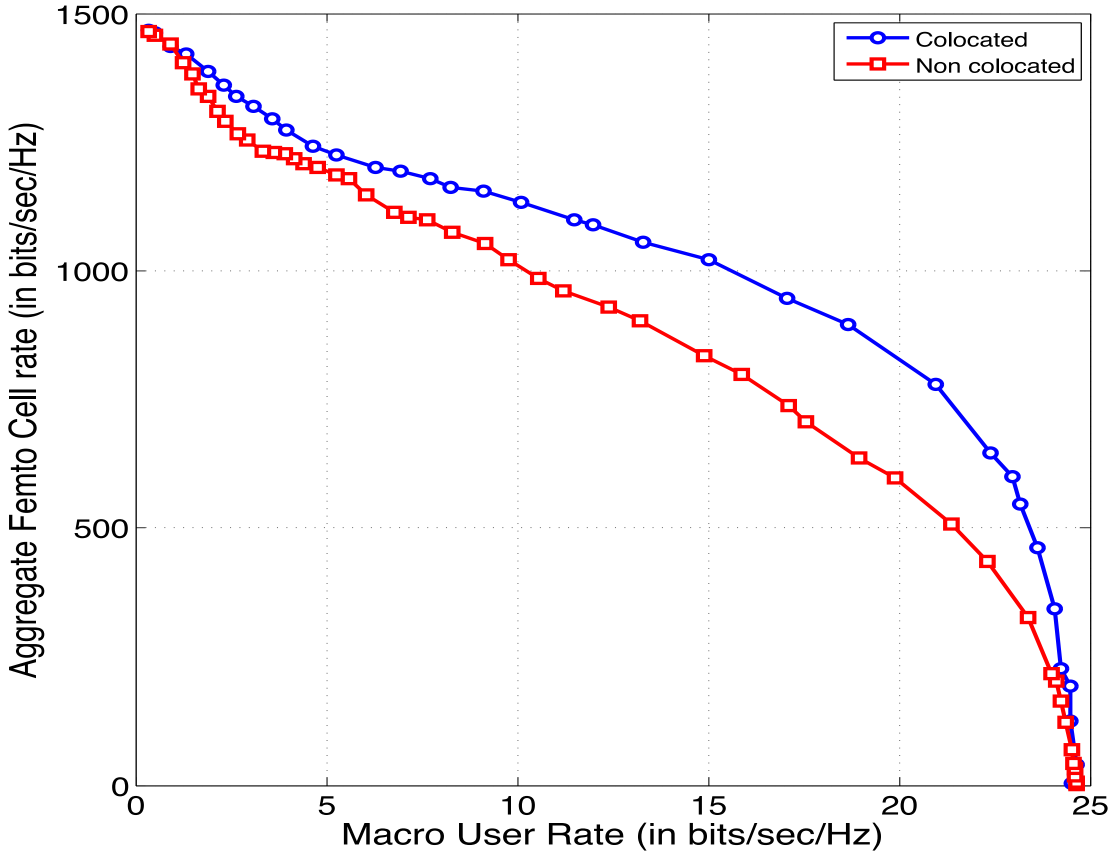
Femto-UL/Macro-DL with co-located macro UTs



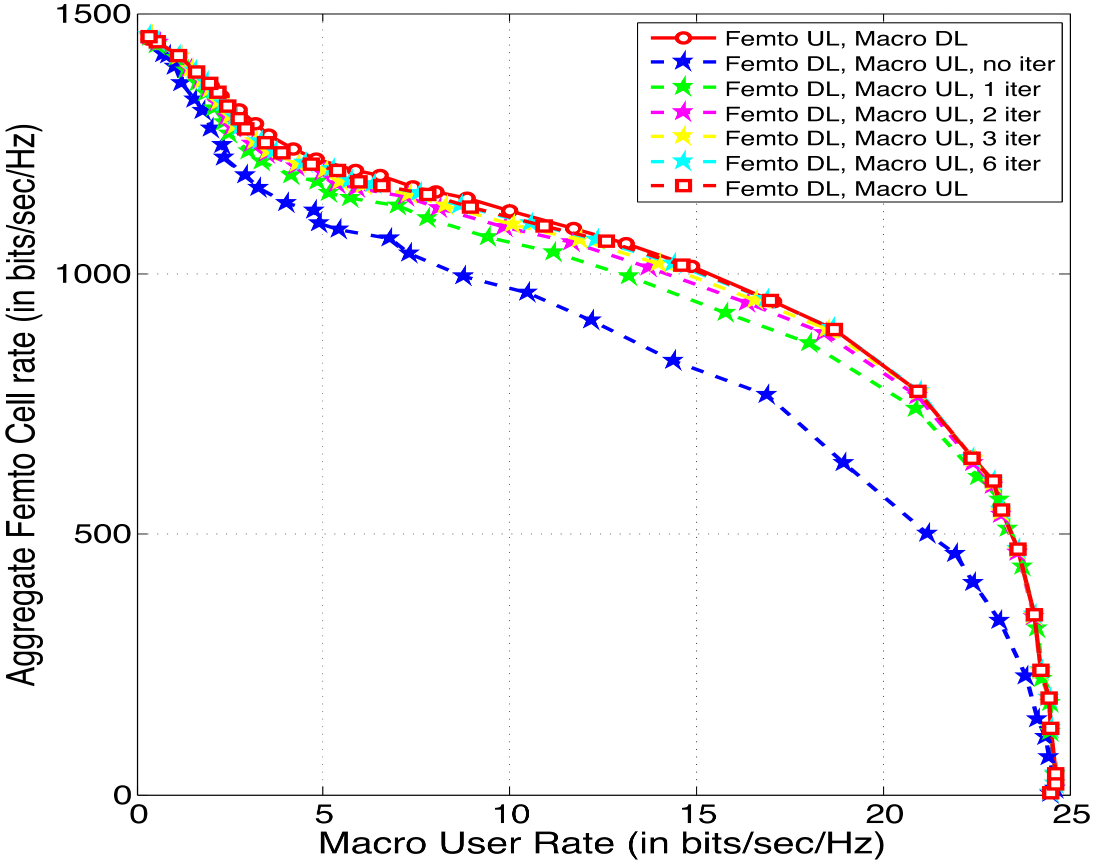
Femto-UL/Macro-DL with non co-located macro UTs



Co-located vs. non co-located: comparison



Femto-DL/Macro-UL: iterative power allocation

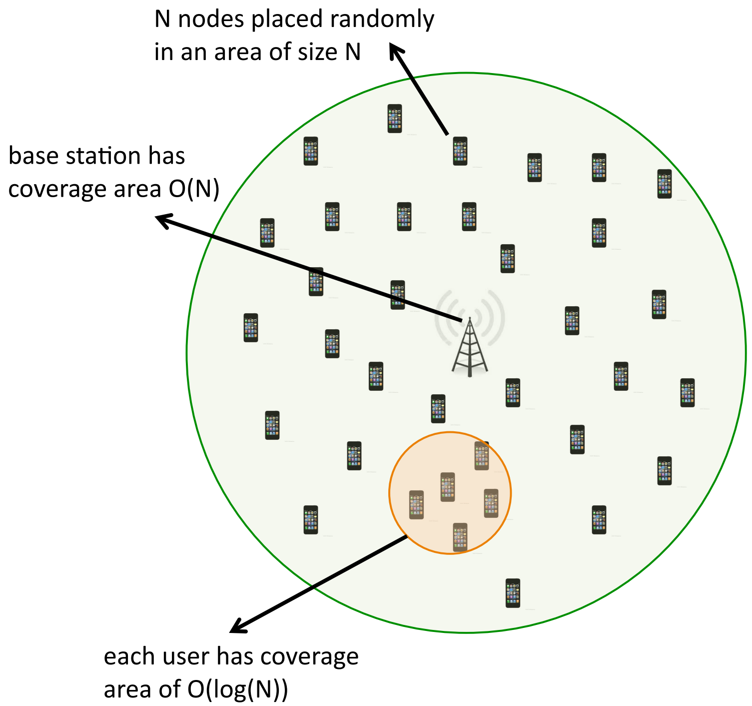


Performance

- Let's focus on the point $(15, 1000)$ and assume 40 MHz of system bandwidth.
- Macro users: 6 users per cell at 2.5 bit/s/Hz yields 100 Mb/s per user.
- Femto users: 625 femtocells per cell at 1.6 bit/s/Hz yields 64 Mb/s per femtocell.
- These rates are in line with today's target peak rates for LTE and WLANs (Wifi).
- The two systems can co-exist in the same system bandwidth.
- In terms of system special efficiency, we go well above the desired x100 increase, with relatively conventional technology.
- **Key point to take home: multiuser MIMO and inter-tier interference management must be at the core of the system design, not added later as "afterthoughts".**

Even Denser Spatial Reuse: Distributed Caching in Wireless Devices

- Cache predictable Internet content (web-pages, coded video) into the user devices and auxiliary wireless "helpers".



- N nodes in an area of size N.
- The base station has total downlink capacity $C_{\rm base}$ bit/s/Hz.
- Short-range D2D links between the user terminals can support capacity $C_{\rm d2d}$.
- Following the current LTE-Advanced eICIC the base station leaves a fraction β of the time-frequency slots free for D2D communication.
- Random placement of content in the caches. Probability that a given cache satisfies a random demand: $0 < p_{\rm cache} \leq 1$.
- Range of D2D communication such that the number of nodes reachable from any given node in one hop is $c \log N$, for some $c > 0$.
- Probability of not finding the requested file in the neighboring caches is $\bar{p} = (1 - p_{\rm cache})^{c \log N}$.
- Let the fraction of users originating demands (active users) be α, and let the individual rate per user be r bit/s/Hz.

- The demands not found in the local caches are handled directly by the base station. Hence, we have the constraint

$$r\alpha N\bar{p} \leq (1-\beta)C_{\text{base}}. \tag{2}$$

- The demands found in the neighboring caches are handled by D2D communication.

- Using simple *interference avoidance*, we can schedule $\frac{N}{c \log N}$ non-interfering links simultaneously on each time-frequency slot freed by the base station.

- The source rate constraint for the traffic handled by the caches is

$$r\alpha N(1-\bar{p}) \leq \beta \frac{N}{c \log N} C_{\text{d2d}}. \tag{3}$$

- By solving for the optimum β and replacing it in (3), we find

$$r \leq \frac{1}{1 - \bar{p} + \frac{\bar{p}N}{c \log N} \frac{C_{\rm d2d}}{C_{\rm base}}} \frac{C_{\rm d2d}}{\alpha c \log N}. \tag{4}$$

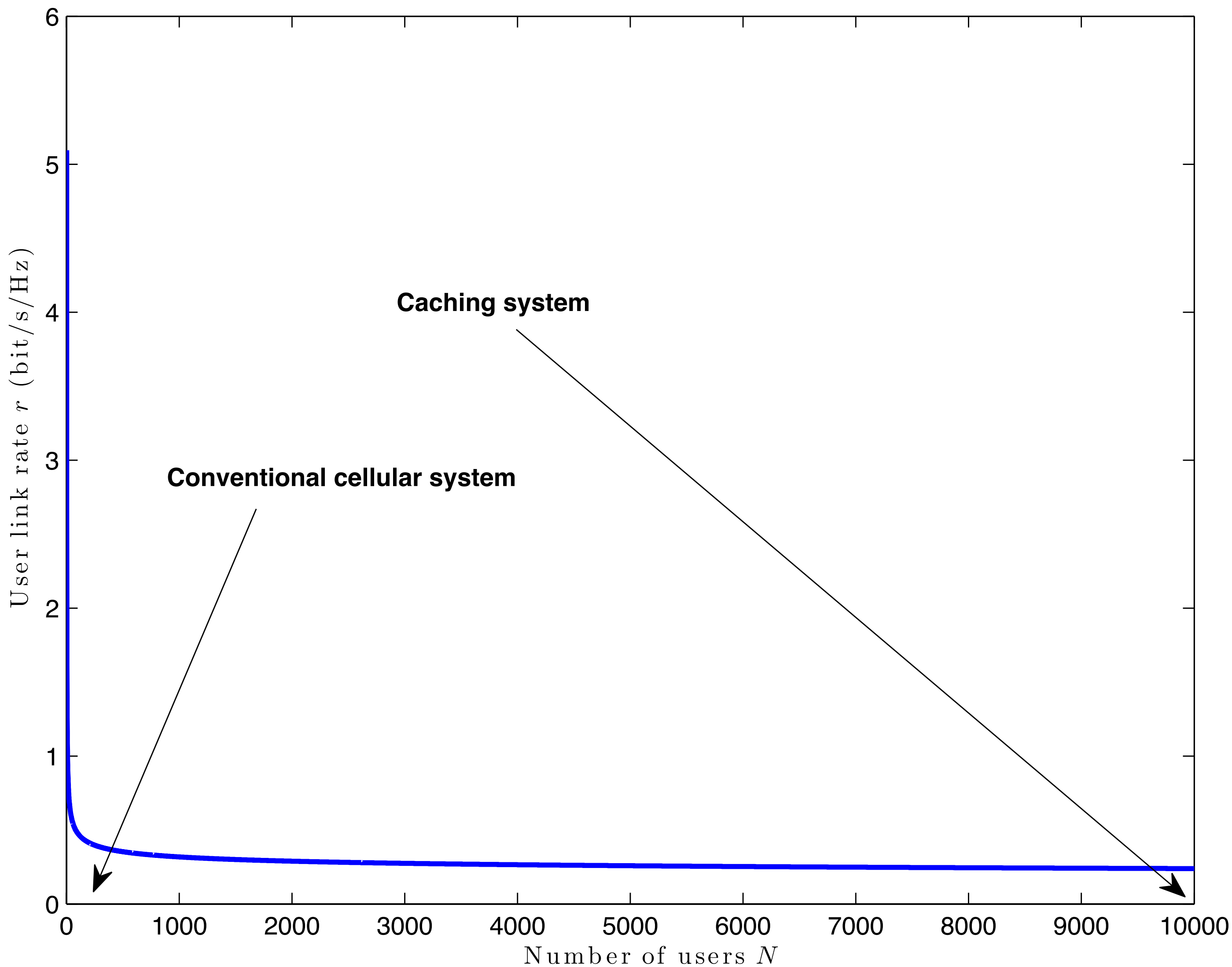
- Since $\bar{p} = N^{-c \log \frac{1}{1-p_{\rm cache}}}$, for $c \log \frac{1}{1-p_{\rm cache}} > 1$, we have that $N\bar{p} \to 0$ polynomially with N.

- As a consequence, $r \approx \frac{C_{\rm d2d}}{\alpha c \log N}$ vanishes only logarithmically with N.

- The gain over a conventional cellular system, achieving system: $r_{\rm conv} = \frac{C_{\rm base}}{\alpha N}$, is unbounded !!!

Example

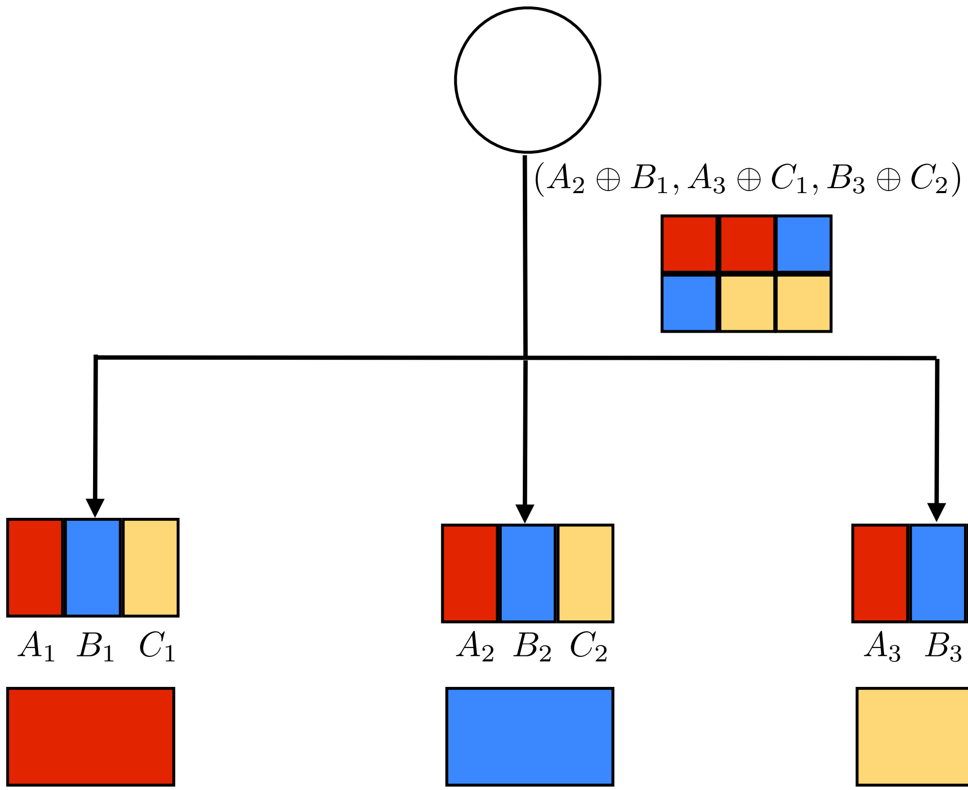
- Realistic LTE downlink capacity and a D2D link capacity inspired by Qualcomm FlashLinQ.
- $C_{\text{base}} = 5$ bit/s/Hz and $C_{\text{d2d}} = 2$ bit/s/Hz.
- Assume a cell bandwidth of 40 MHz and a target per-user rate of 10 Mb/s resulting in $r = 0.25$ bit/s/Hz.
- Assuming a user activity factor $\alpha = 0.2$, a conventional system would serve $N = 100$ users.
- With a modest cache hit probability $p_{\text{cache}} = 0.2$, requiring $c > \frac{1}{\log(1.25)} = 4.4814$, and letting $c = 4.5$, the proposed system serves $N = 10000$ users (we meet the target 100x capacity boost).



6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
User link rate r (bit/s/Hz)
Number of users N
Caching system
Conventional cellular system

Global Caching Gain

- Recent result [Maddah-Ali, Neesen, arXiv:1209.5807] .... caching turns broadcast into multicast.



Conclusions

- Network MIMO (CoMP): appears to be fundamentally limited in conventional cellular systems.
- Large number of antennas at each BS: essentially no need for BS cooperation, beyond simple coordination of scheduling/frequency/pilots/beams.
- Large number of antennas naturally suited to TDD: but also possible with FDD, if Tx antenna correlation is properly exploited (JSDM).
- Further improvements: reduce the distance between source and destination.
- HetNets: cognitive multi-antenna small cells can share the same macro bandwidth.
- D2D: for throughput is meaningful if coupled with caching.
- Further caching gains from (index) coding.

Thank You