Asymptotic Rate Analysis of Large-Scale Distributed Antenna System (DAS): From Cellular DAS to Virtual-Cell based DAS

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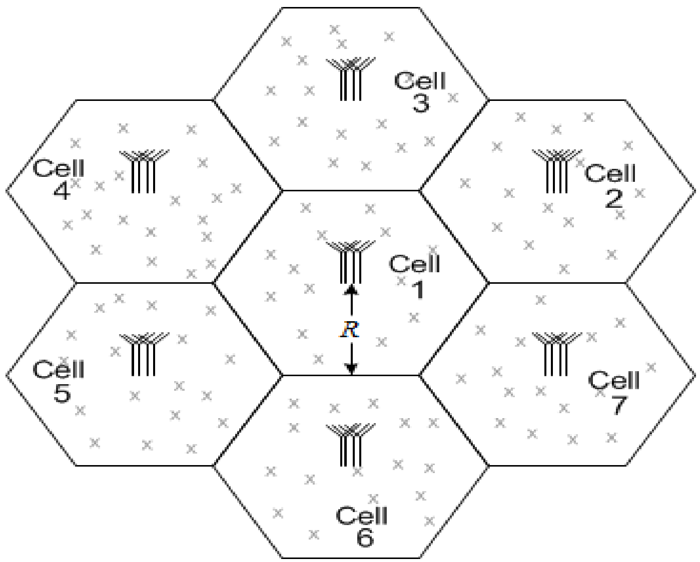
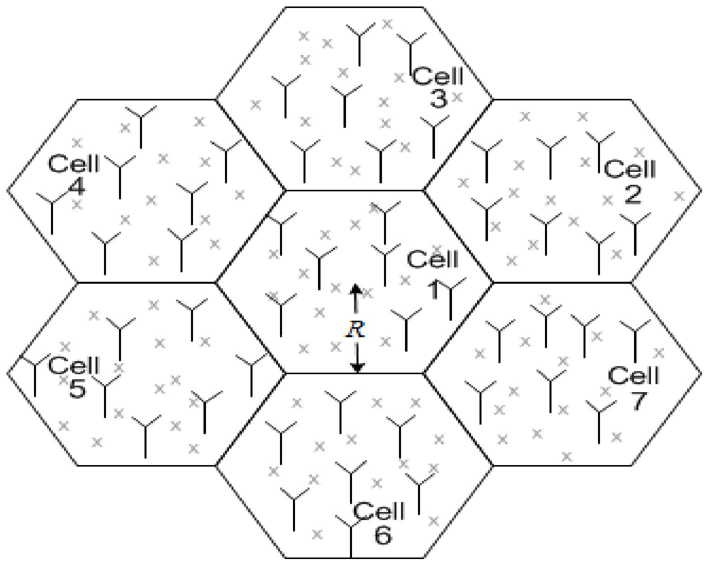
Distributed Antenna System (DAS)

- Originally proposed to cover the dead spots for indoor wireless communication systems.
- Implemented in cellular systems to improve cell coverage.
- Included into the 4G LTE standard.
- Key technology for C-RAN and 5G.

Base Station (BS) Antennas: Co-located or Distributed?





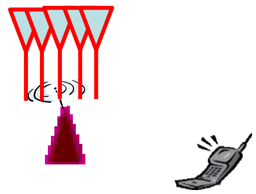
x: user

Y: BS antenna

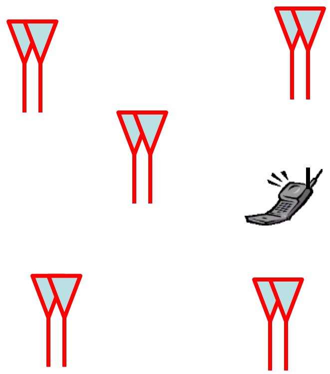
	Co-located Antennas (CA)	Distributed Antennas (DA)
Implementation cost	Lower	
Sum rate		How much higher?

Asymptotic Capacity Analysis for Large-Scale MIMO

- Consider a single user with N co-located antennas transmits to M BS antennas. No CSIT.
  - ✓ CA: As M and N go to infinity but with a fixed ratio of β, the ergodic capacity converges to a function of β and the mean received SNR.



  - ✓ DA:
    - Assume that M BS antennas are grouped into L distributed clusters. Each cluster has U co-located antennas.
    - As U and N go to infinity but with a fixed ratio of β, the asymptotic ergodic capacity is determined by β and L mean received SNRs (or equivalently, the large-scale fading gains from the user to L BS antenna clusters).
    - L+1 fixed-point equations need to be jointly solved to obtain the asymptotic ergodic capacity.



Asymptotic Capacity Analysis for Large-Scale MIMO

- In general, for a multiuser DAS with K users and L distributed BS antenna clusters, L+K fixed-point equations need to be jointly solved to calculate the asymptotic ergodic capacity.

- To reduce computational complexity, approximations have been developed to obtain the asymptotic ergodic capacity as an explicit function of LxK mean received SNRs (large-scale fading gains) by assuming
  - a doubly-regular large-scale fading gain matrix, or
  - LU>>KN (U and N co-located antennas at each cluster and user, respectively).

> ✓ Not accurate especially when LU>>KN is not satisfied
> ✓ Errors ↑ as L ↑

Questions to be Answered

- With a large number of distributed BS antenna clusters L:
  - How does the average ergodic capacity (i.e., averaged over the large-scale fading gains) scale with L?

    Bounds will be developed which share the same scaling behavior as the average ergodic capacity.
  - Does the capacity gain over CA increase with L?

    Yes, but with cautions.
  - Is the cellular structure still suitable?

Our Work

		Uplink	Downlink
Single-user		[Dai'11]	[Liu-Dai'14]
Multi-user	Single-cell	[Dai'11]	[Wang-Dai'15]
	Multi-cell	[Dai'14]	[Liu-Dai'14]
	Virtual-cell	[Dai'14]	[Wang-Dai'16]

- Lin Dai, "A Comparative Study on Uplink Sum Capacity with Co-located and Distributed Antennas," *IEEE J. Sel. Areas in Commun.*, vol. 29, no. 6, pp. 1200-1213, June 2011.
- Lin Dai, "An Uplink Capacity Analysis of the Distributed Antenna System (DAS): From Cellular DAS to DAS with Virtual Cells," *IEEE Trans. Wireless Commun.,* vol. 13, no. 5, pp. 2717-2731, May 2014.
- Zhiyang Liu and Lin Dai, "A Comparative Study of Downlink MIMO Cellular Networks with Co-Located and Distributed Base-Station Antennas," *IEEE Trans. Wireless Commun.*, vol. 13, no. 11, pp. 6259-6274, Nov. 2014.
- Junyuan Wang and Lin Dai, "Asymptotic Rate Analysis of Downlink Multi-user Systems with Co-located and Distributed Antennas," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3046-3058, June 2015.
- Junyuan Wang and Lin Dai, "Downlink Rate Analysis for Virtual-Cell based Large-Scale Distributed Antenna Systems," IEEE Trans. Wireless Commun., vol. 15, no. 3, pp. 1998-2011, Mar. 2016.

Cellular DAS

Part I: Single-Cell

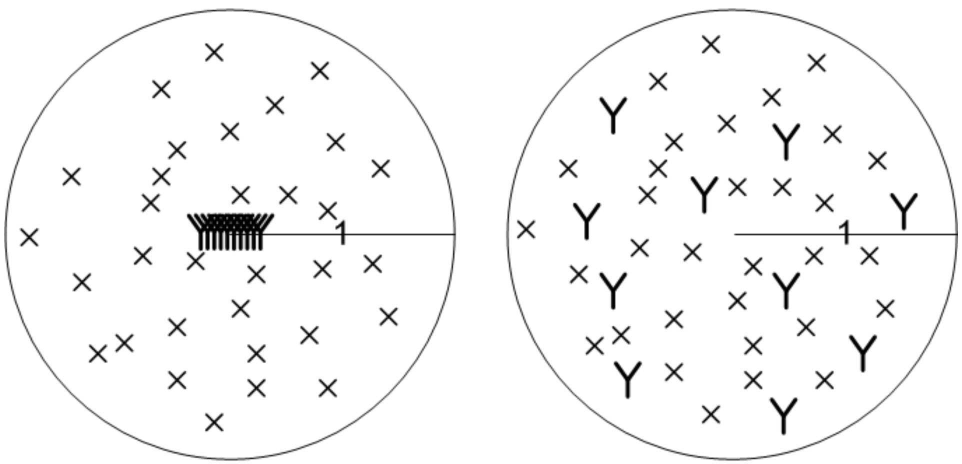
Junyuan Wang and Lin Dai, "Asymptotic Rate Analysis of Downlink Multi-user Systems with Co-located and Distributed Antennas," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3046-3058, June 2015.

Assumptions

- K single-antenna users are uniformly distributed within a circular cell.
- L BS antennas are either co-located at the center of the cell, or uniformly distributed over the cell.
- Downlink transmission with equal transmission power among users.
- Linear precoding
  - Nonorthogonal: Maximum Ratio Transmission (MRT)
  - Orthogonal: Zero-forcing Beamforming (ZFBF)

*: user

o: BS antenna



(a) Co-located Antennas (CA)

(b) Distributed Antennas (DA)

Downlink Asymptotic Average User Rate

- Achievable ergodic rate of user k:

$$\mathrm{R}_k = \mathbb{E}_{\mathbf{H}}\left[\log_2\left(1 + \frac{\bar{P}_k\|\gamma_k\|^2\tilde{\mathbf{g}}_k\mathbf{w}_k\mathbf{w}_k^\dagger\tilde{\mathbf{g}}_k^\dagger}{N_0 + I_k^{intra}}\right)\right]$$

- Average user rate:

$$\bar{R} = \mathbb{E}_{\{\mathbf{r}_k^U\}_{k\in\mathcal{K}},\{\mathbf{r}_l^B\}_{l\in\mathcal{B}}}\left[R_k\right]$$

- Asymptotic average user rate:

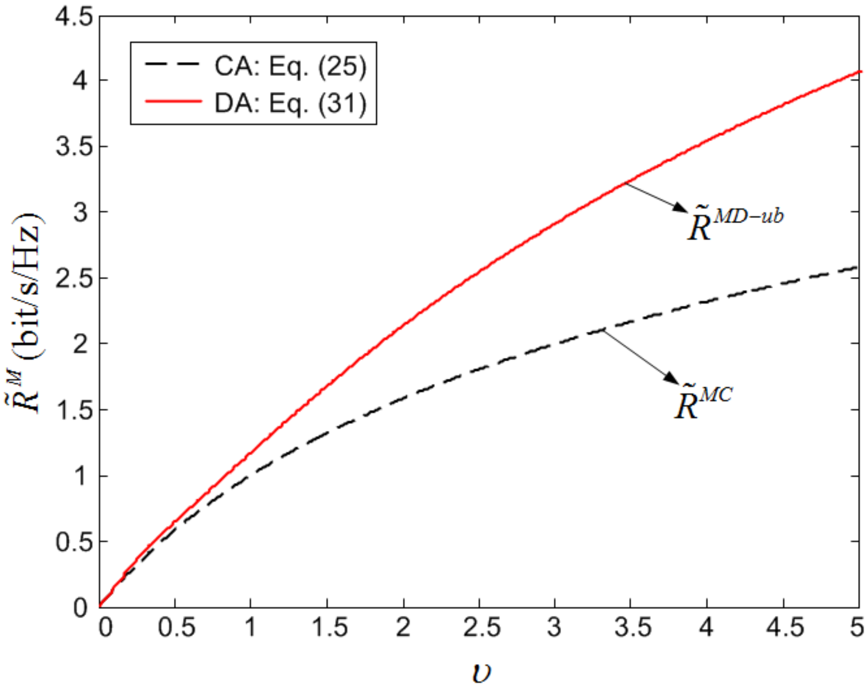
$$\tilde{R} = \lim_{\substack{L,K\to\infty,\\ L/K\to\upsilon}} \bar{R}$$

Downlink Asymptotic Average User Rate

Assume L, K go to infinity and L/K -> υ.

- MRT
  - CA: $\tilde{R}^{MC} = \log_2(1+\upsilon)$
  - DA: $\tilde{R}^{MD-ub} \sim \frac{\alpha}{2}\log_2 \upsilon$

    α>2 is the path-loss factor.
  - Rate gains of DA over CA increase with υ.

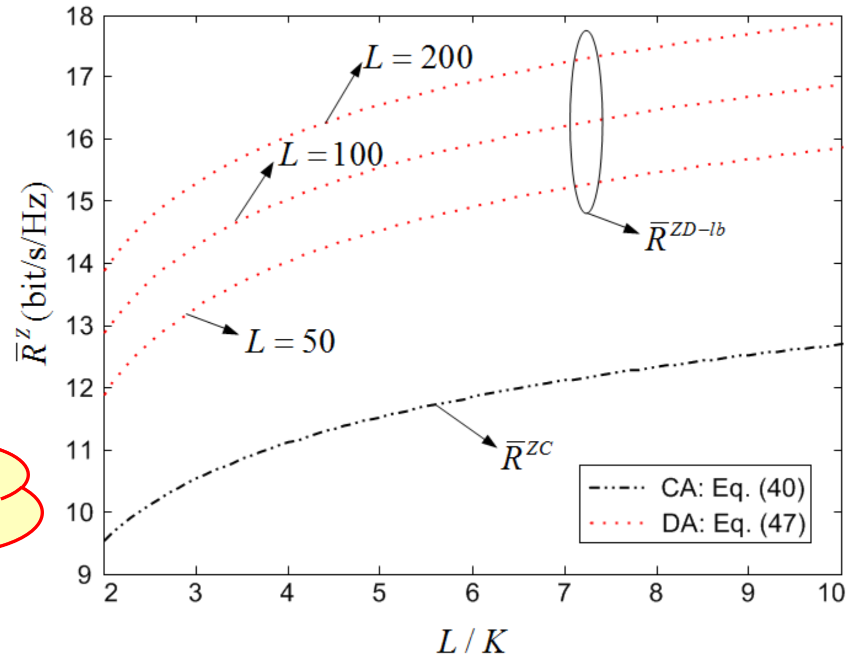


Downlink Asymptotic Average User Rate

Assume L, K go to infinity and L/K -> υ.

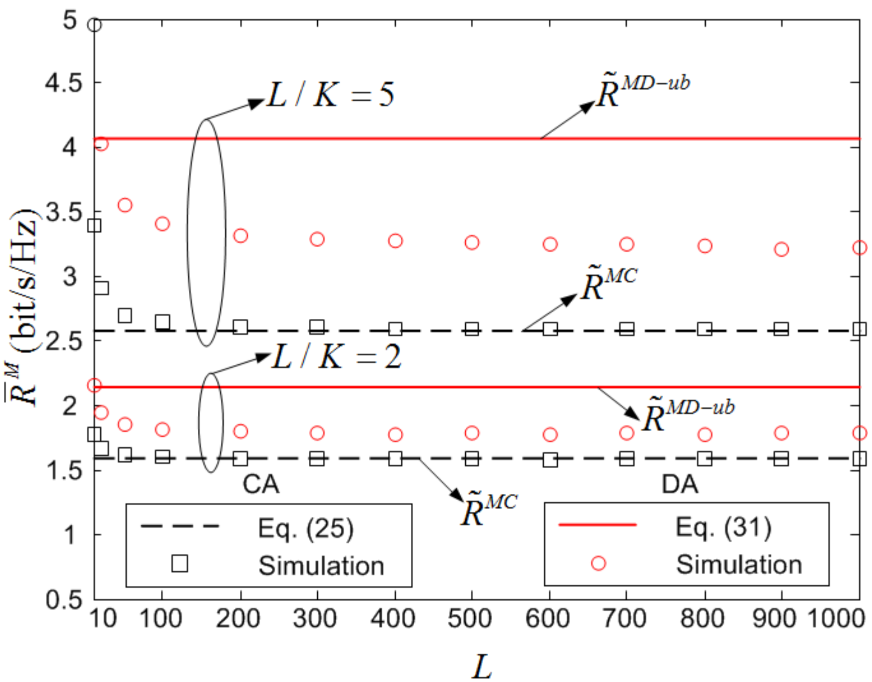
- ZFBF
  - CA: $\tilde{R}^{ZC} = \log_2\left(\frac{P_t}{N_0}(\upsilon - 1)\right) + \frac{\alpha}{2}\log_2 e$
  - DA: $\tilde{R}^{ZD-lb} = \infty$
  - For given ratio υ, rate gains of DA over CA increase with L.

$$\bar{R}^{ZD-lb} \sim \log_2 \frac{(L-K+1)^{\alpha/2}}{K}$$

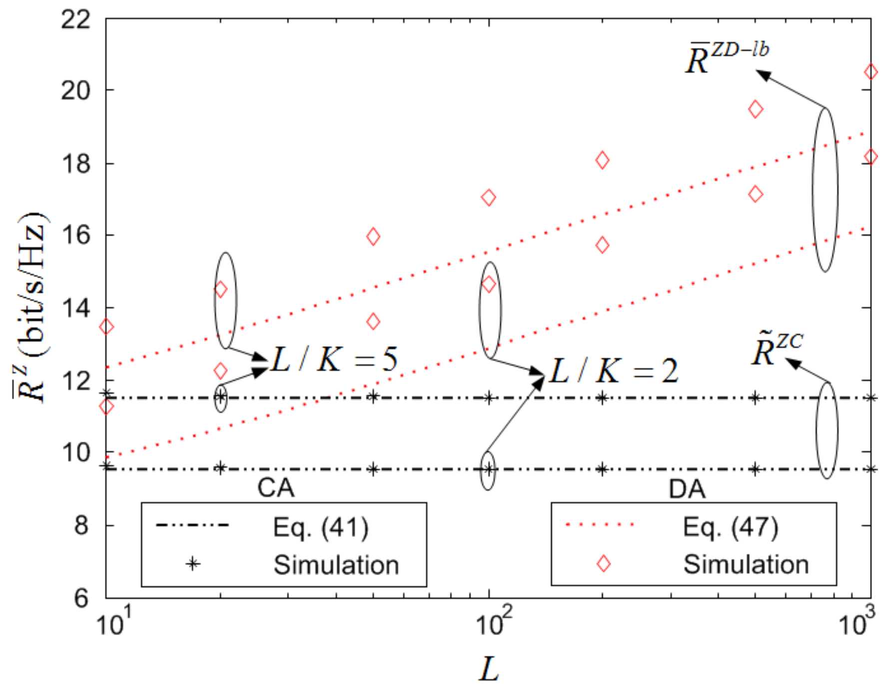


Simulation Results

- DA
  - ✓ Bounds well indicate the scaling behavior of average user rate.
  - ✓ Scaling behavior depends on the precoding schemes. Gains over CA are more significant with orthogonal precoding.



(a) MRT



(b) ZFBF

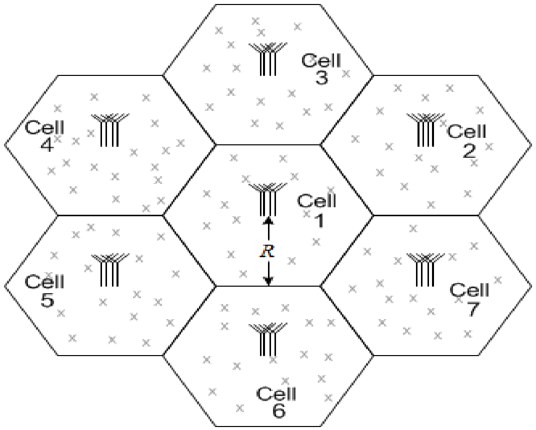
Cellular DAS

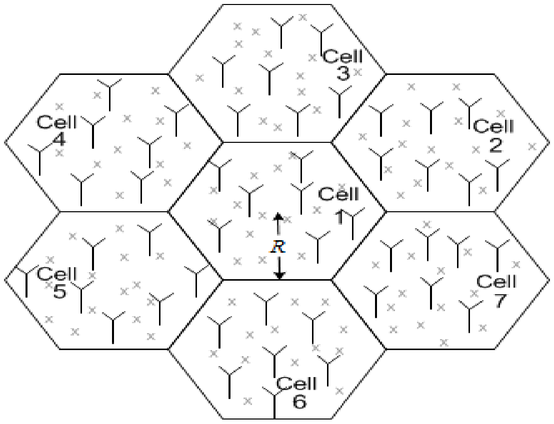
Part II: Multi-Cell

Zhiyang Liu and Lin Dai, "A Comparative Study of Downlink MIMO Cellular Networks with Co-Located and Distributed Base-Station Antennas," *IEEE Trans. Wireless Commun.*, vol. 13, no. 11, pp. 6259-6274, Nov. 2014.

System Model

- A total number of 7 cells share the same frequency band. No cooperation is adopted among BSs.
- K users are uniformly distributed within each cell, each with N co-located antennas.
- In each cell, M BS antennas are either co-located at the cell center, or divided into L uniformly distributed clusters each with a cluster size of N.
- Linear precoding: Block diagonalization (BD).





Downlink Asymptotic Average User Rate

- Achievable ergodic rate of user k:

$$\mathrm{R}_k = \frac{1}{N}\mathbb{E}_{\mathbf{H}_{k,\mathcal{B}_0}}\left[\log_2 \det\left(\mathbf{I}_N + \frac{\bar{P}_k \|\gamma_{k,\mathcal{B}_0}\|^2 \tilde{\mathbf{G}}_{k,\mathcal{B}_0}\mathbf{W}_k\mathbf{W}_k^\dagger\tilde{\mathbf{G}}_{k,\mathcal{B}_0}^\dagger}{N_0\mathbf{I}_N + \mathbf{Q}_k^{intra} + \mathbf{Q}_k^{inter}}\right)\right]$$

- Average user rate:

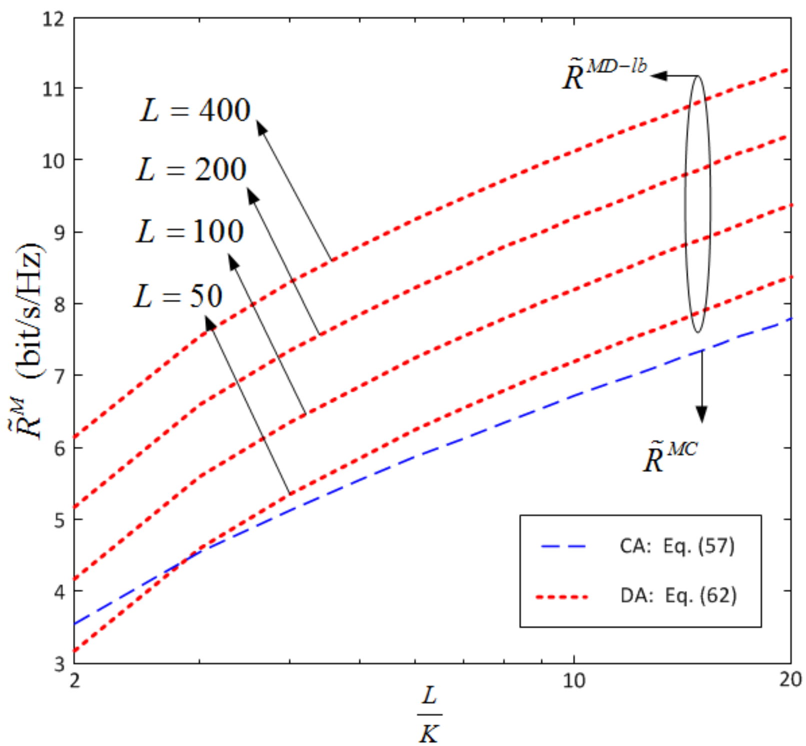
$$\bar{R} = \mathbb{E}_{\{\mathbf{r}_k^U\}_{k\in\mathcal{K}},\{\mathbf{r}_l^B\}_{l\in\mathcal{B}}}\left[R_k\right]$$

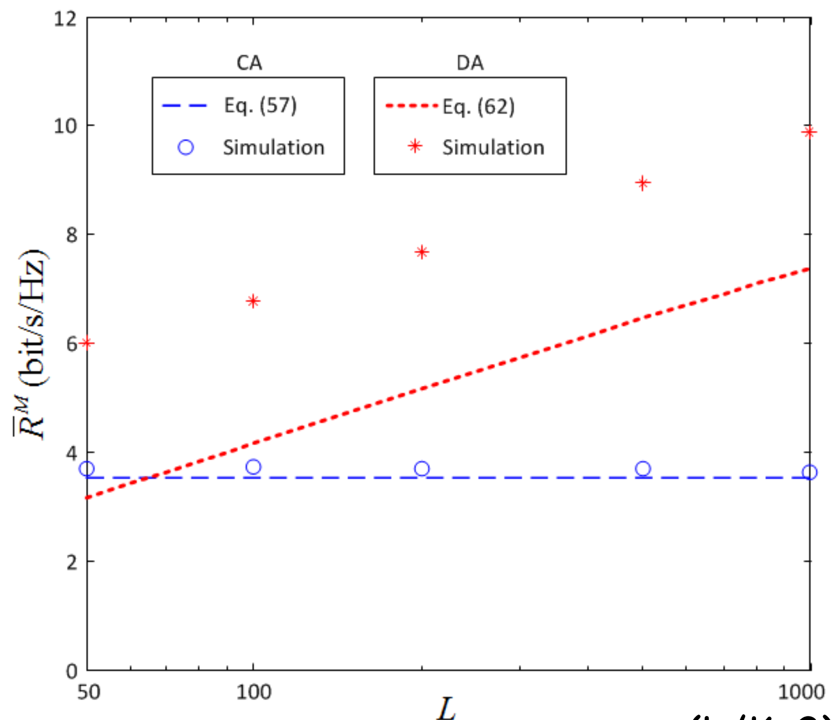
- Asymptotic average user rate:

$$\tilde{R} = \lim_{\substack{M,N\to\infty,\\ M/N\to L\geq K}} \bar{R}$$

Downlink Asymptotic Average User Rate

- Assume M, N go to infinity and M/N -> L≥K.
  - CA: $\tilde{R}^{MC} \sim \log_2 \frac{L}{K}$
  - DA: $\tilde{R}^{MD-lb} \sim \log_2 \frac{(L-K+1)^{\alpha/2}}{K}$



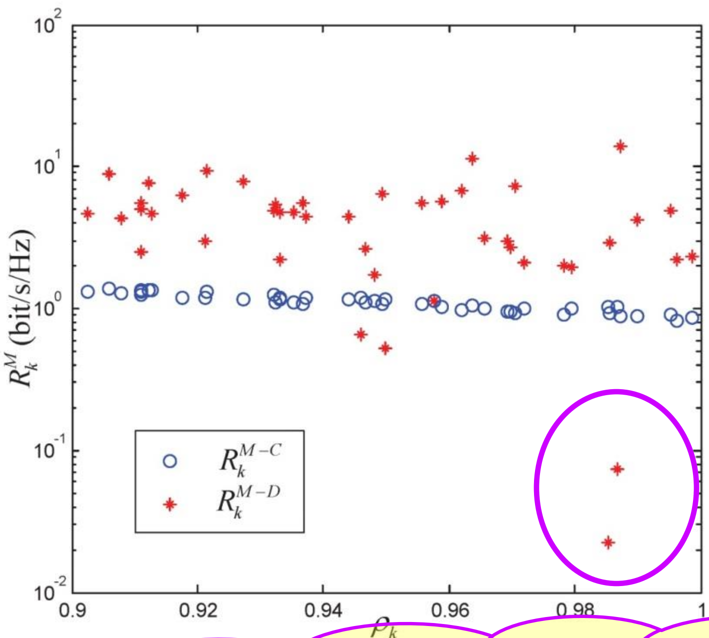


(L/K=2)

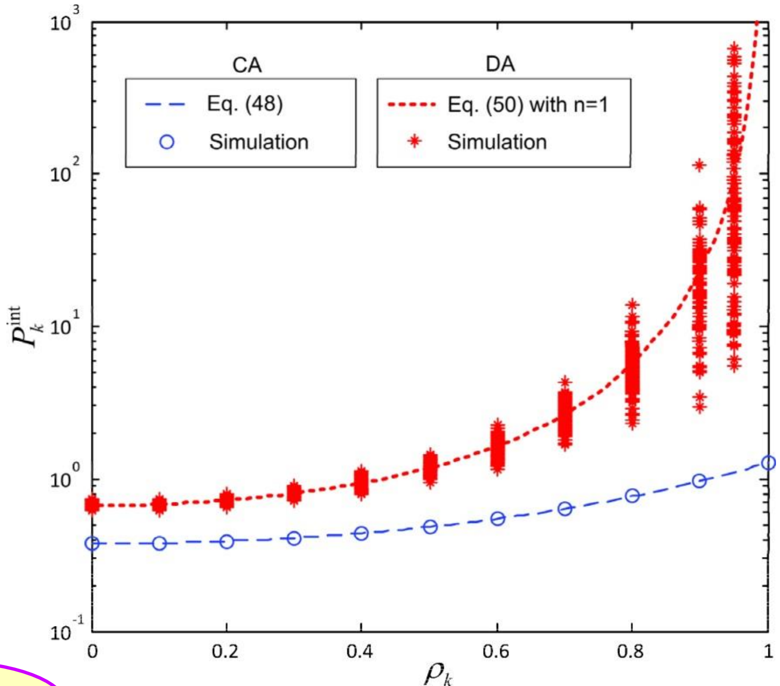
For given ratio L/K, rate gains of DA over CA increase with L.

Downlink User Rate versus User Location at Cell Edge

- CA: Insensitive to the user's location at the cell edge.
- DA: Significantly larger variance despite higher average rate.



A few "unlucky" users may suffer from strong inter-cell interference if they are close to some BS antennas in the neighboring cells!

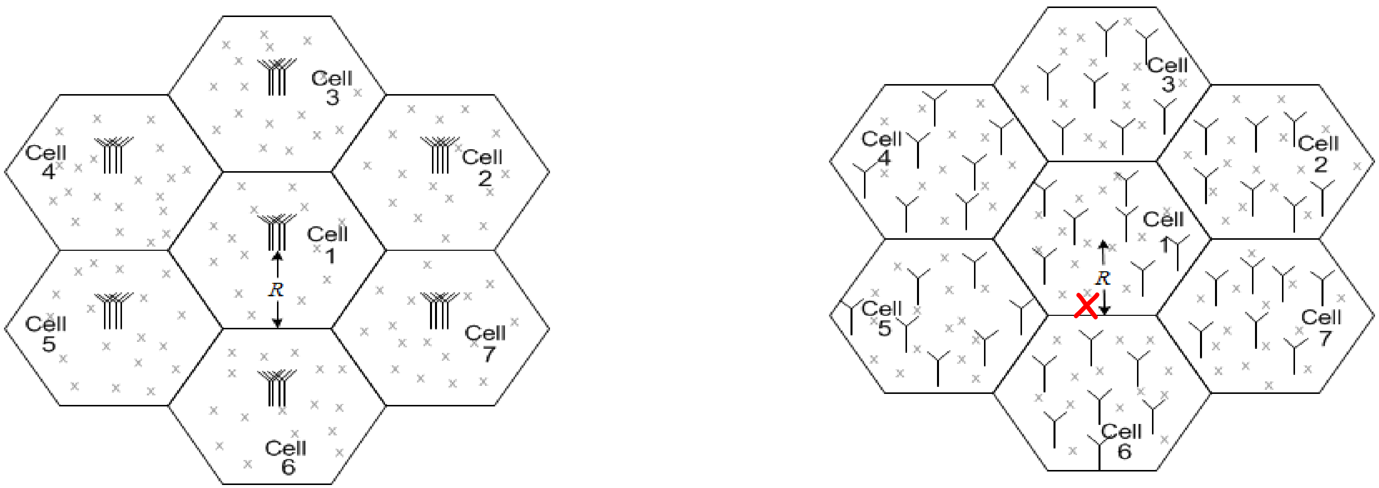


Despite gains in average user rate, the cell-edge problem is worsened in the DA case!

Virtual-Cell based DAS

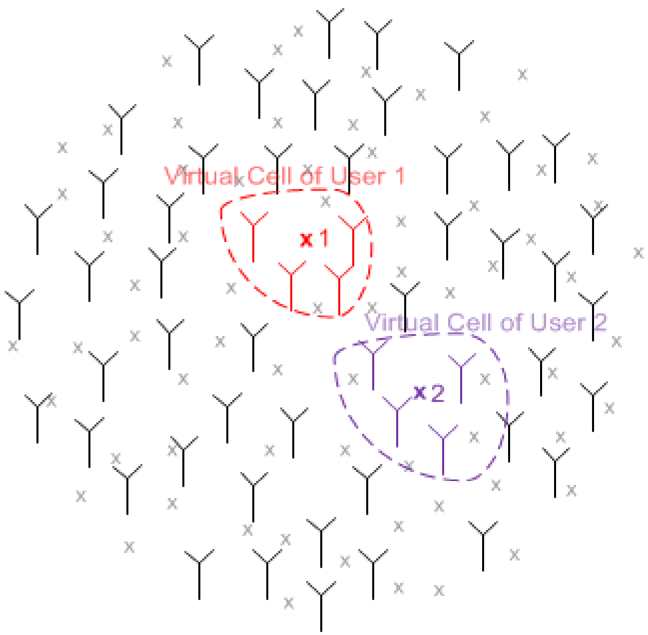
Junyuan Wang and Lin Dai, "Downlink Rate Analysis for Virtual-Cell based Large-Scale Distributed Antenna Systems," IEEE Trans. Wireless Commun., vol. 15, no. 3, pp. 1998-2011, Mar. 2016.

To Cellular or Not to Cellular?



- By splitting a large area into small ones, there are always a certain number of users/BS antennas located at the border and closer to the neighboring cells.
- With distributed BS antennas, the geographic division of cells becomes less justified.

Virtual Cell



- Each user chooses a few surrounding BS antennas as its virtual cell, i.e., its own serving BS antenna set.
- Different from the conventional cellular structure where cells are divided according to the coverage of each BS, here the virtual cell is formed in a user-centric manner.

With virtual-cell based DAS:

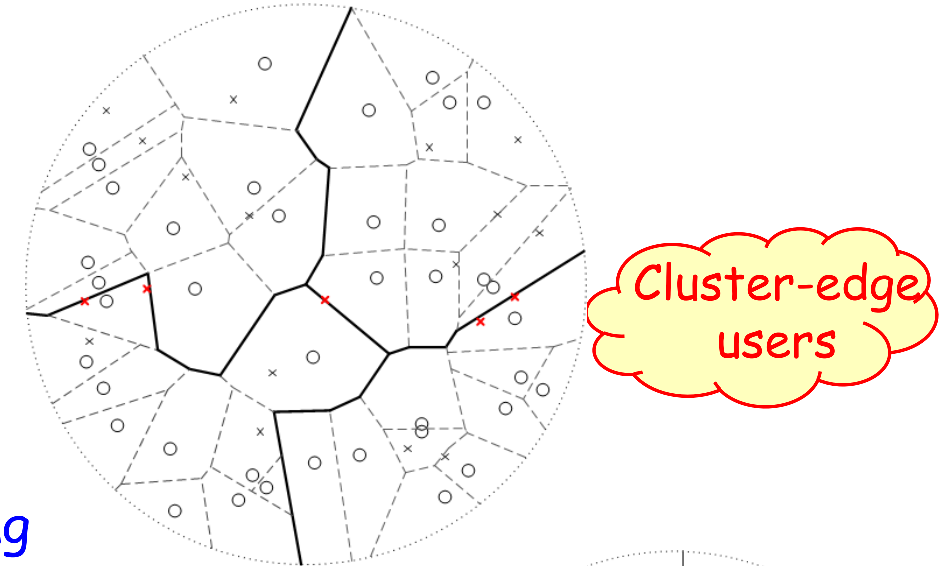
- ✓ Uniform rate performance among users
- ✓ Low CSI measurement overhead
- ✓ Scalable signal processing

Virtual-cell based DAS for 5G

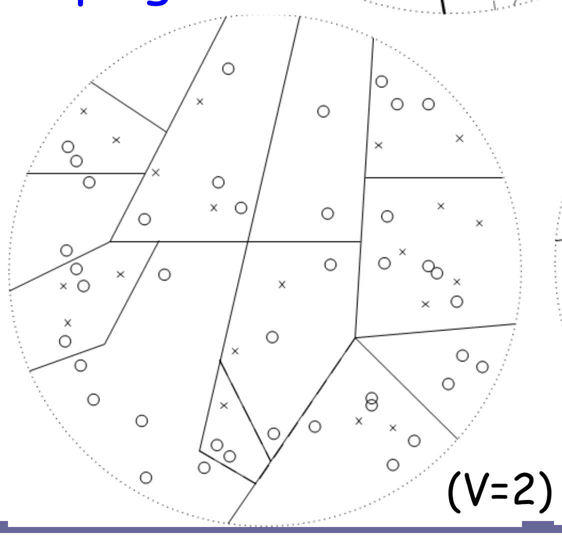
- C-RAN
  - ✓ Scalable signal processing
- Millimeter wave
  - ✓ Reduced cell coverage
- Small cells
  - ✓ Cooperation among BSs

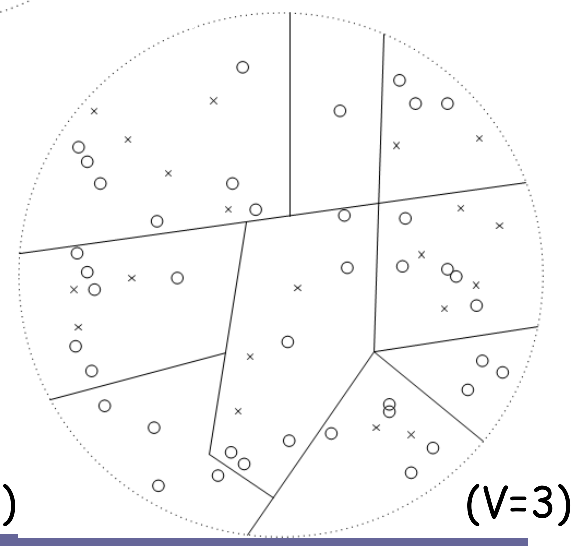
BS Clustering versus Virtual-Cell based User Grouping

- BS clustering
  - ✓ Based on the cellular structure where each user is associated with its closest BS.
  - ✓ Clusters are formed according to BSs' locations.



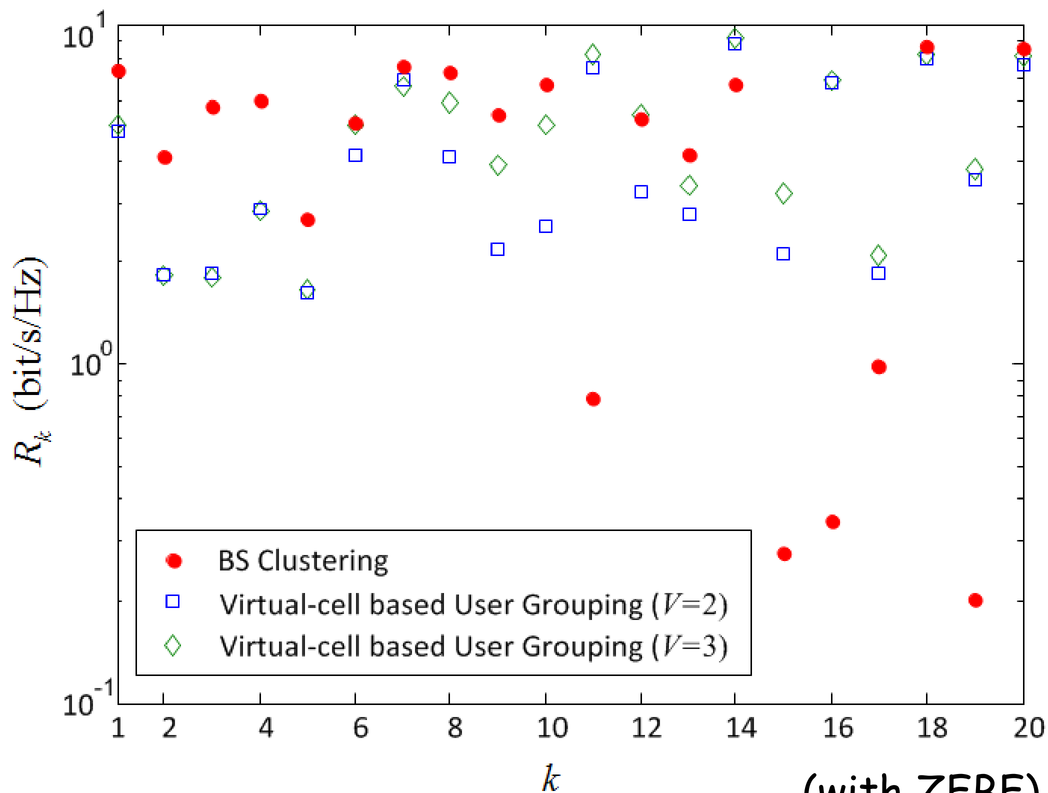
- Virtual-cell based user grouping
  - ✓ Each user chooses V closest BS antennas to form its virtual cell.
  - ✓ Users are grouped together if their virtual cells overlap with each other.





BS Clustering versus Virtual-Cell based User Grouping

- BS clustering: Cluster-edge users still suffer from significant rate degradation.
- Virtual-cell based user grouping:
  - ✓ Rate performance is less sensitive to the user's location.
  - ✓ Both the lowest user rate and the average user rate are improved.

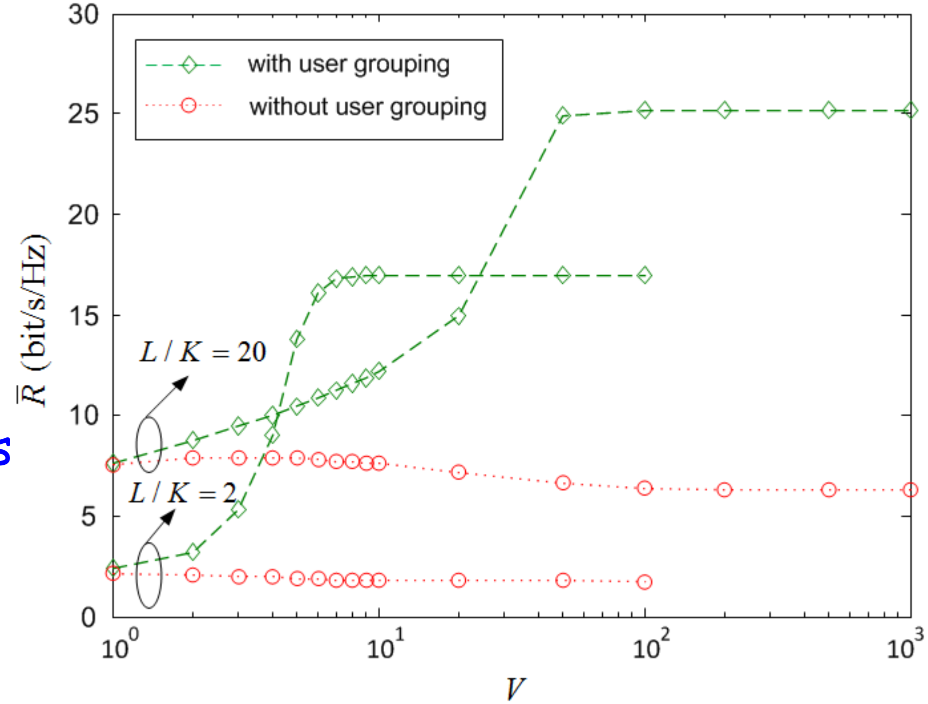


(with ZFBF)

Effect of Virtual-Cell Size V on Average User Rate

- Without user grouping (MRT is adopted in each user's virtual cell):
  - ✓ The optimal virtual cell size to maximize the average user rate: $V^* = \left\lceil 0.2 \frac{L}{K} \right\rceil$
  - ✓ A small virtual cell size should be chosen to avoid sharing BS antennas for different user which would otherwise cause strong interference.

- With user grouping (ZFBF is adopted in each group):
  - ✓ The larger virtual cell size, the more users grouped together, and the lower inter-group interference.
  - ✓ The virtual cell size V determines a rate-complexity tradeoff: with a larger V, the average user rate is improved at the cost of higher signal processing complexity.



Summary

- In a cellular system:
  - Substantial rate gains can be achieved by DA over CA, and the gains increase with the number of BS antennas due to distinct scaling orders.
  - Gains are more pronounced with orthogonal precoding.
  - Despite a higher downlink average user rate, the rate of each user with DA becomes more sensitive to its position.
- In a virtual-cell based DAS:
  - Uniform rate performance can be achieved among users.
  - The virtual cell size is an important design parameter which should be properly chosen based on the system setting.

Ongoing and Future Work

- Simple and accurate approximations for average rate/capacity
- Optimal network decomposition
- Innovative PHY-layer and MAC-layer designs for future mobile communication systems

The End

Thank you!