THE UNIVERSITY OF TEXAS AT AUSTIN

Cockrell School of Engineering

What is the Role of MIMO in Future Cellular Networks: Massive? Coordinated? mmWave?

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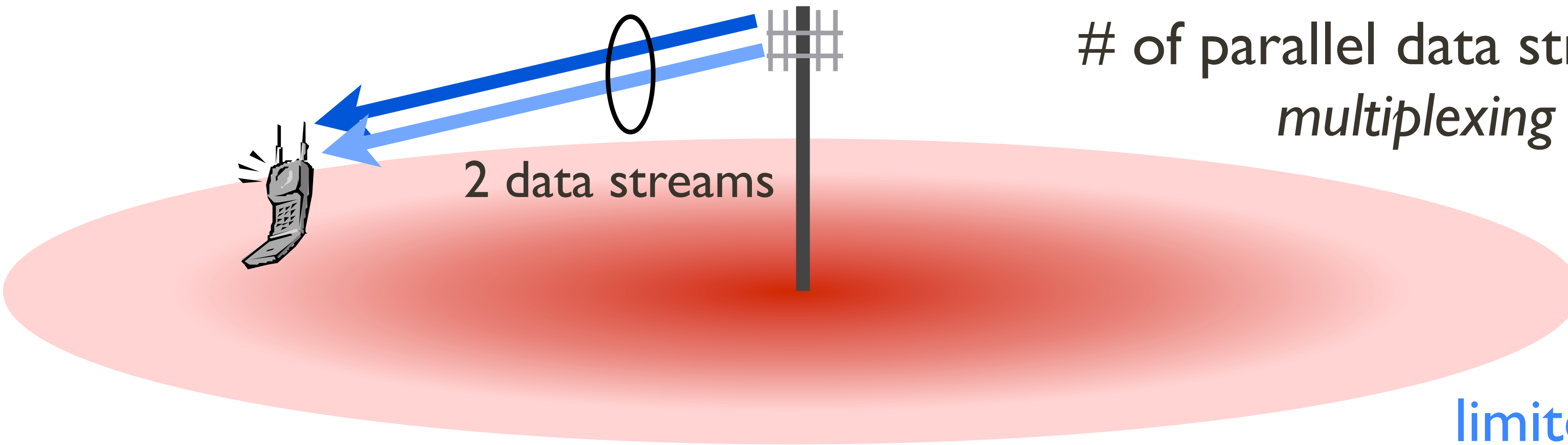
Outline

- **MIMO in cellular networks**
- Coordinated Multipoint a.k.a. network MIMO
- Massive MIMO
- Millimeter wave MIMO
- Comparison between technologies
- Parting thoughts

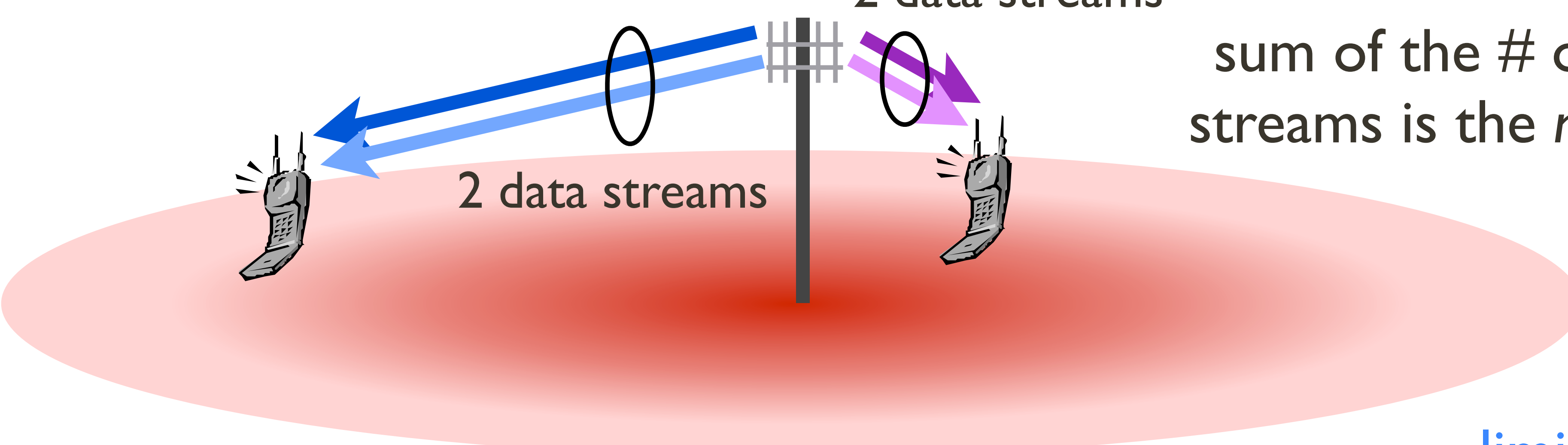
MIMO in Cellular Systems



\# of parallel data streams is the *multiplexing gain*

limited by **# user** antennas

Point-to-point MIMO

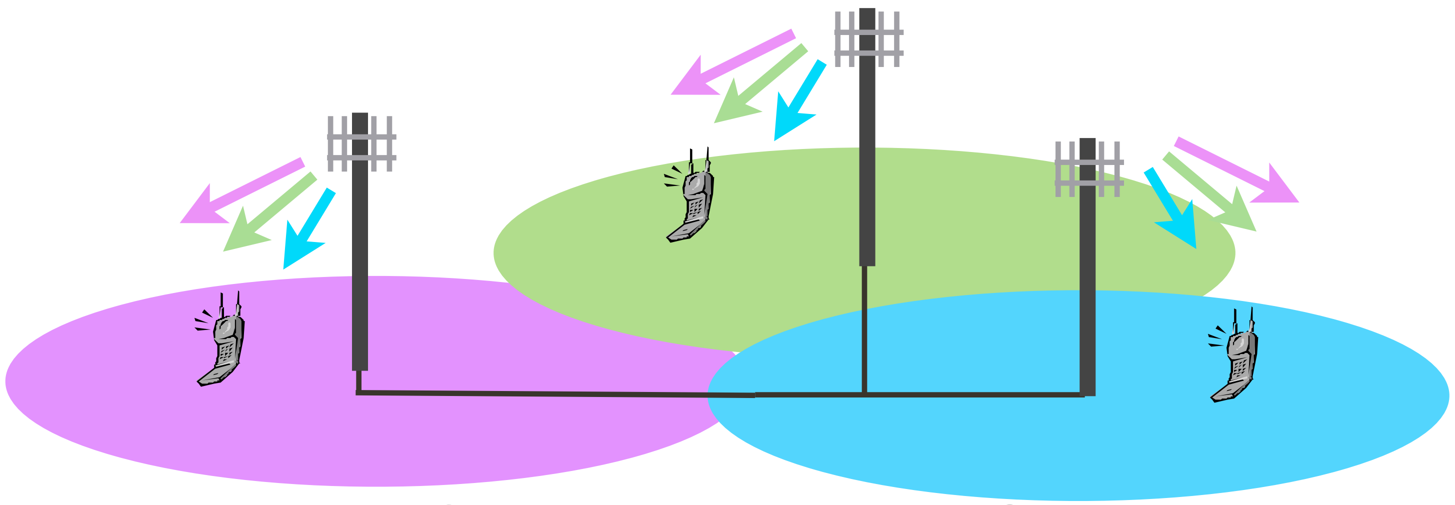


sum of the # of parallel data streams is the *multiplexing gain*

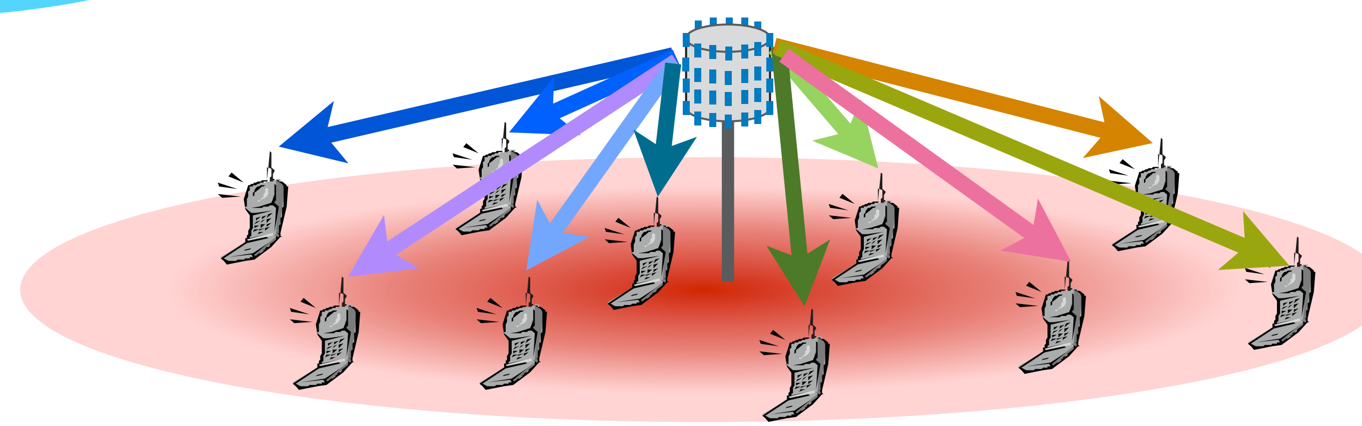
limited by **# BS** antennas

Multiuser MIMO

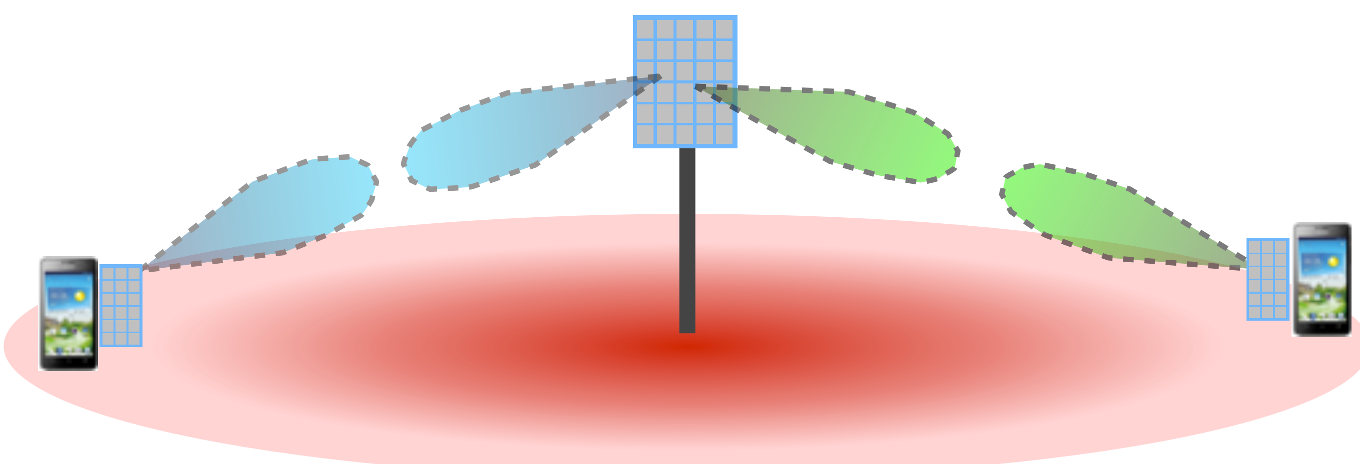
Where is MIMO Headed?



Coordinated MIMO



Massive MIMO



mmWave MIMO

Candidate architectures for 5G cellular

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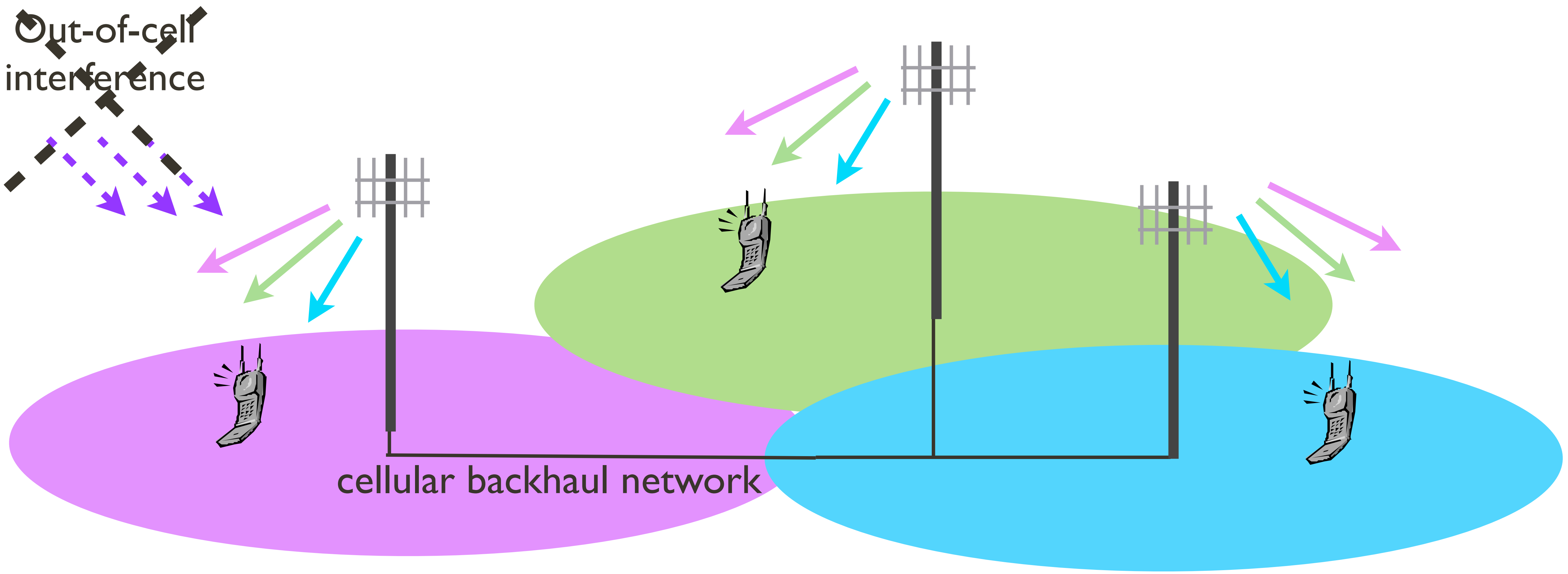
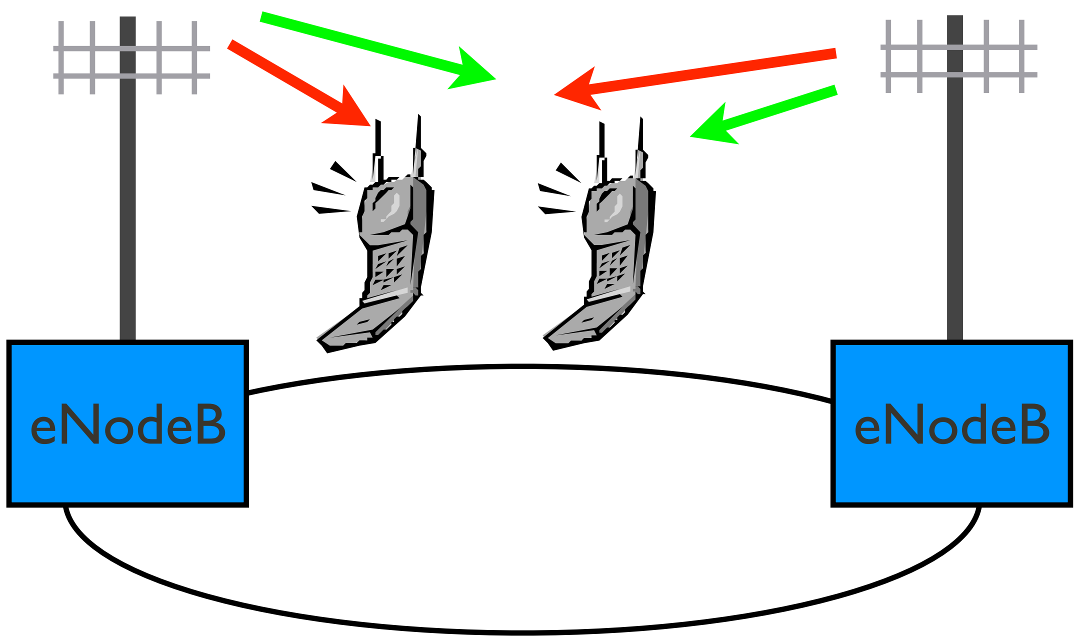
What is Network MIMO?

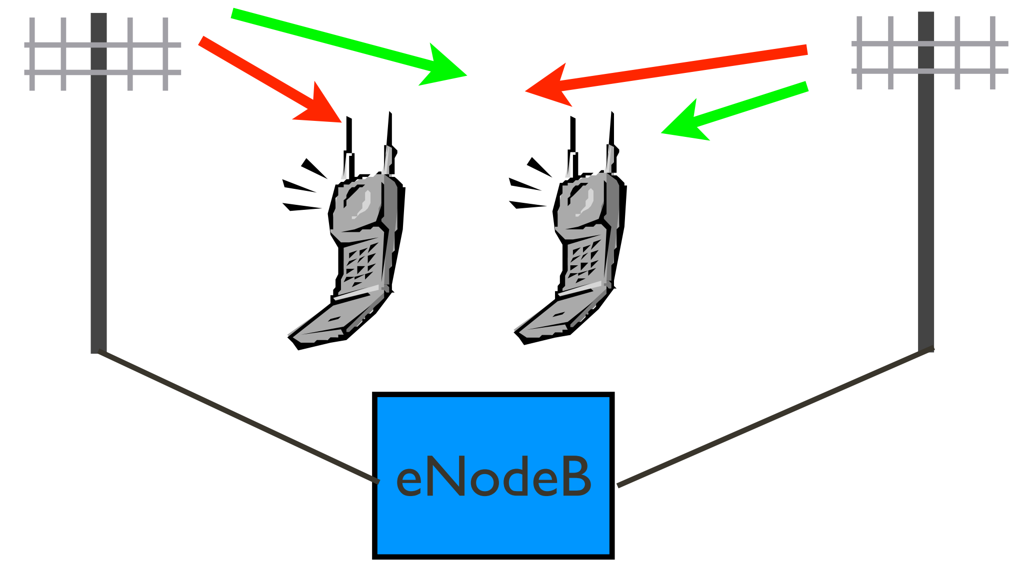


- Coordinated transmission from multiple base stations
  - Known as CoMP or Cooperative MIMO or base station coordination
  - Interference turned from *foe* to *friend*
  - Exploits presence of a good backhaul connection
- Used to improve area spectral efficiency, system capacity

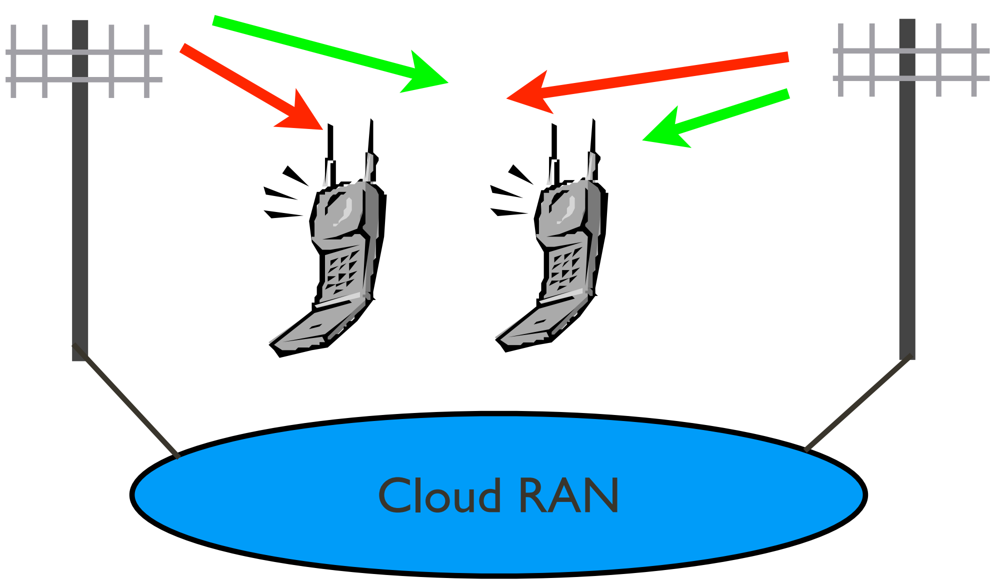
Network MIMO Architectures



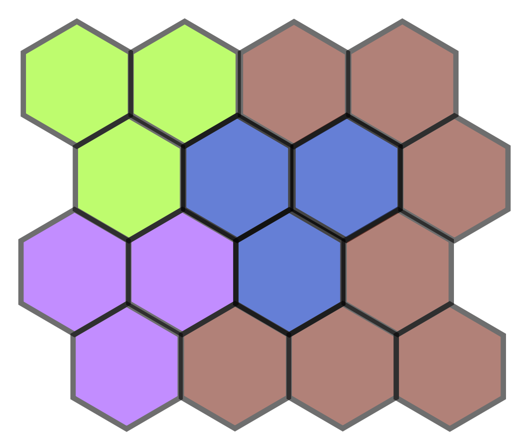
Coordinate over backhaul



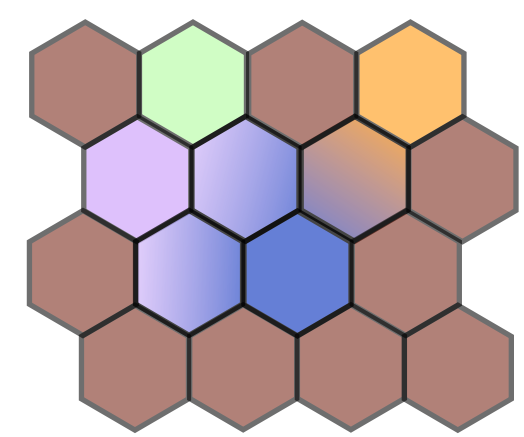
Like DAS uses local coordination



Processing for many base stations using cloud

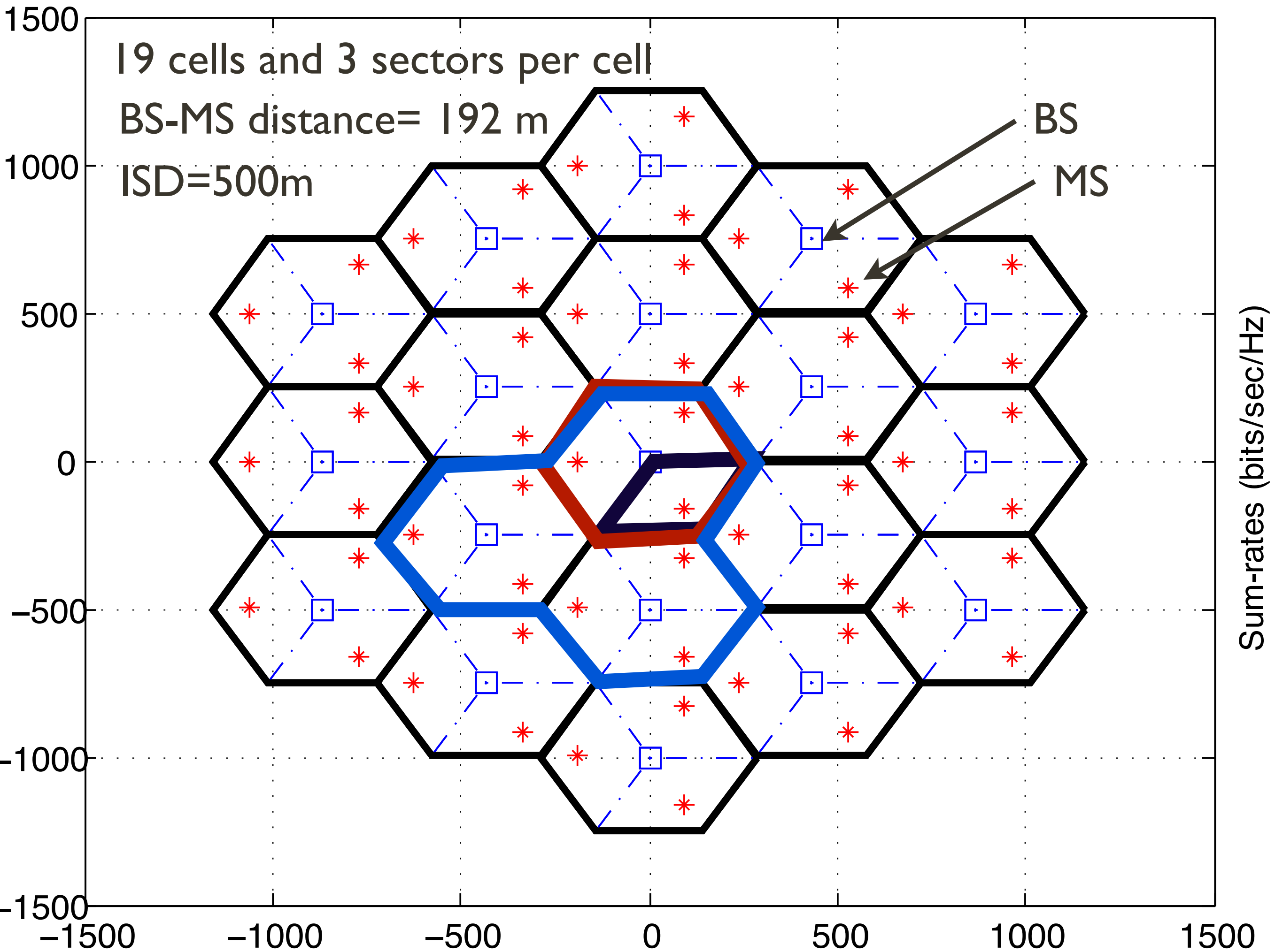


Coordination clusters

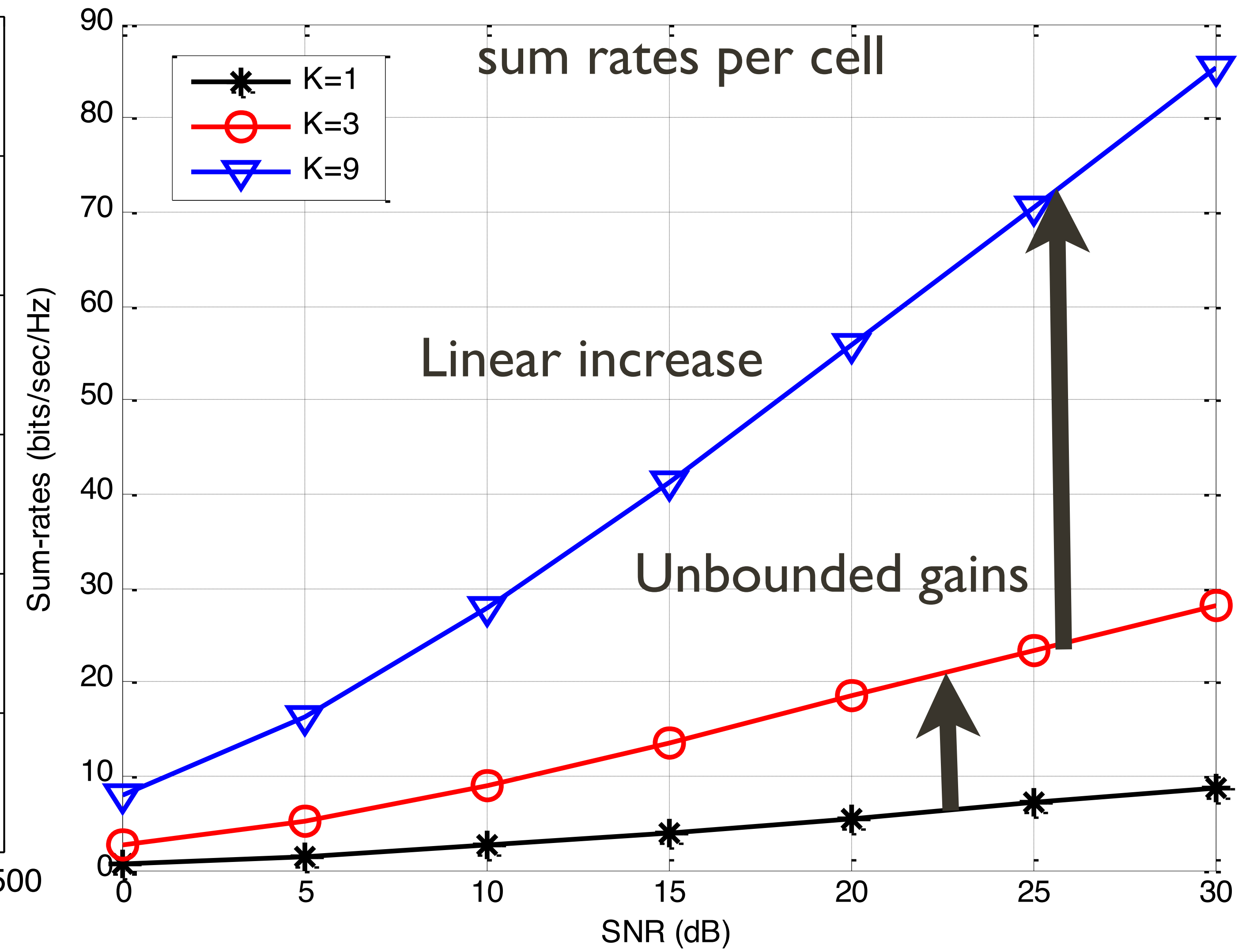


Dynamic coordination

Potential Gains from Coordination

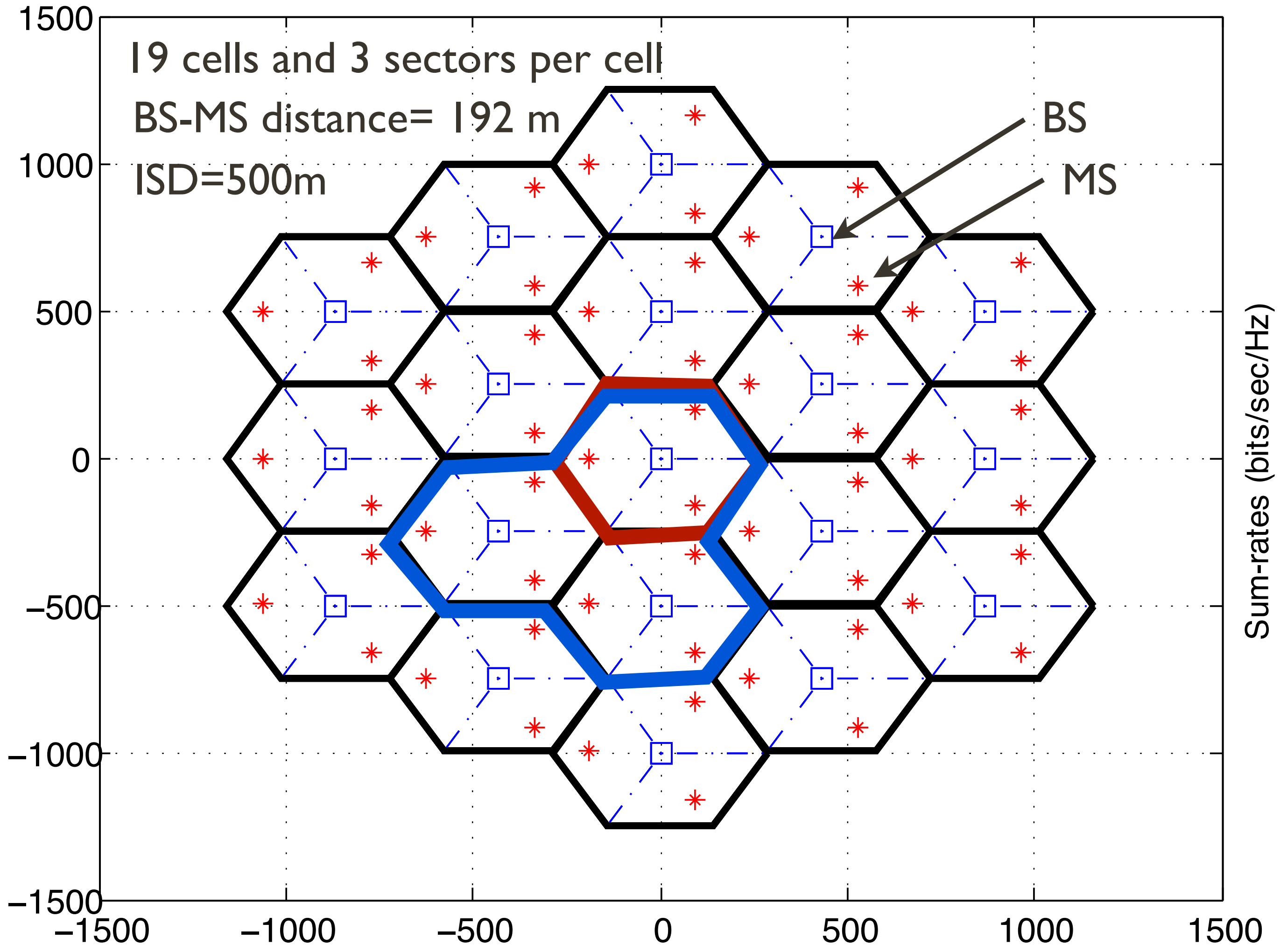


Grid model for a cellular network



- Throughput gains when out-of-cluster interference is ignored
  - More cooperation leads to higher gains
  - Cell edge pushed further out, no uncoordinated interference in the cell

Addressing Out-of-Cell Interference



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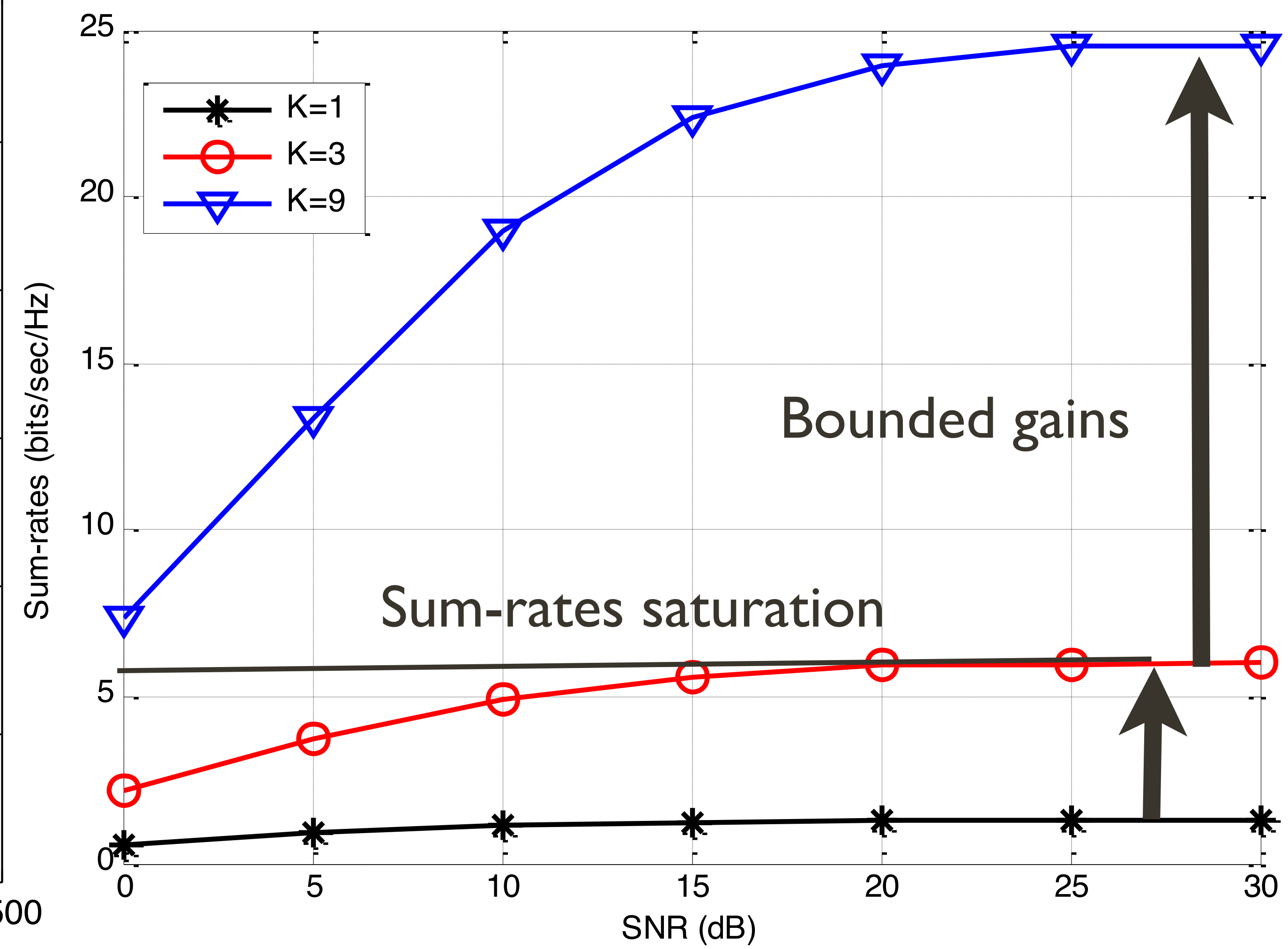


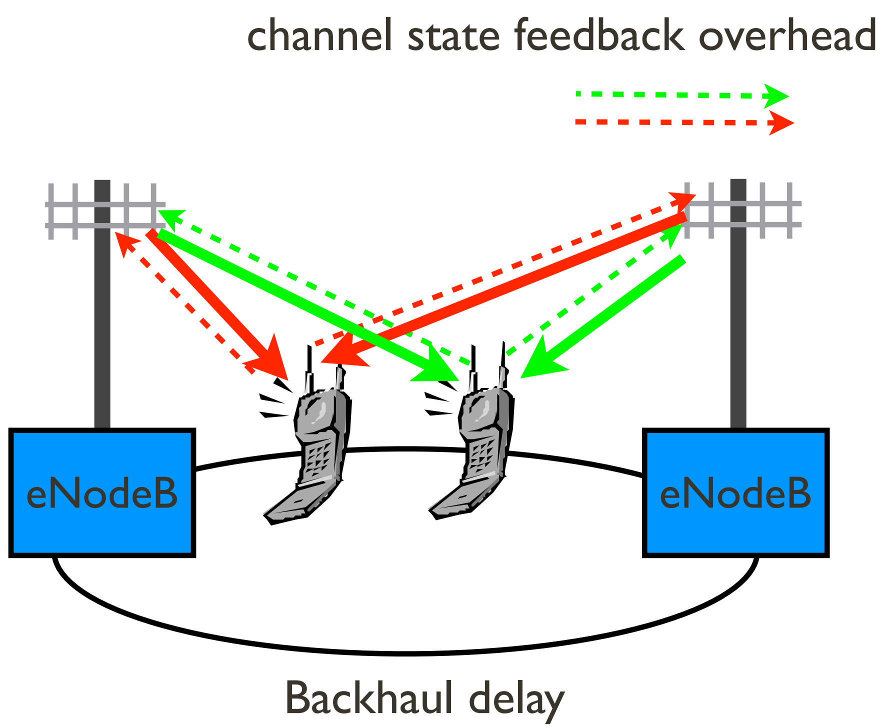
- Performance saturates with out-of-cluster interference
- 30% performance gains observed in industrial settings

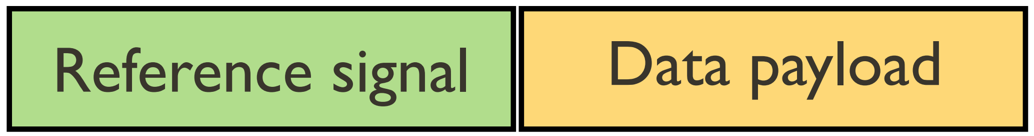
Be mindful of the saturation point

A. Lozano, R. W. Heath, Jr., and J. G. Andrews, ``Fundamental Limits of Cooperation'' to appear in the IEEE Trans. on Info. Theory. Available on ArXiv.

Critical Issues with Network MIMO

- Out-of-cell interference
  - When included, results are not as good
- Feedback overhead
  - Need channel state information
  - Performance seriously degrades
- Control channel overhead
  - Increased reference signal overhead
- Backhaul link constraints
  - Backhaul link latency (delayed CSI and data sharing)
- Cluster edge effects
  - Coordination still has a cell edge with fixed clusters
  - Dynamic clustering solves the problem, but more more implementation overhead





Network MIMO Conclusions

- Observations
  - Network MIMO promises a way to get rid of interference
  - ...Yet uncoordinated interference still limits high SNR performance
  - Backhaul constraints and system overheads further reduce performance gains
  - General disconnect between academia and industry on the potential
- Forecast
  - Already incorporated into 4G, coordination will be part of 5G as well
  - Architectures will evolve to support network MIMO-like coordination
    - Distributed antenna systems are a good starting point
    - Distributed radio access networks are a likely evolution point
    - Cloud radio access networks are a possible end objective

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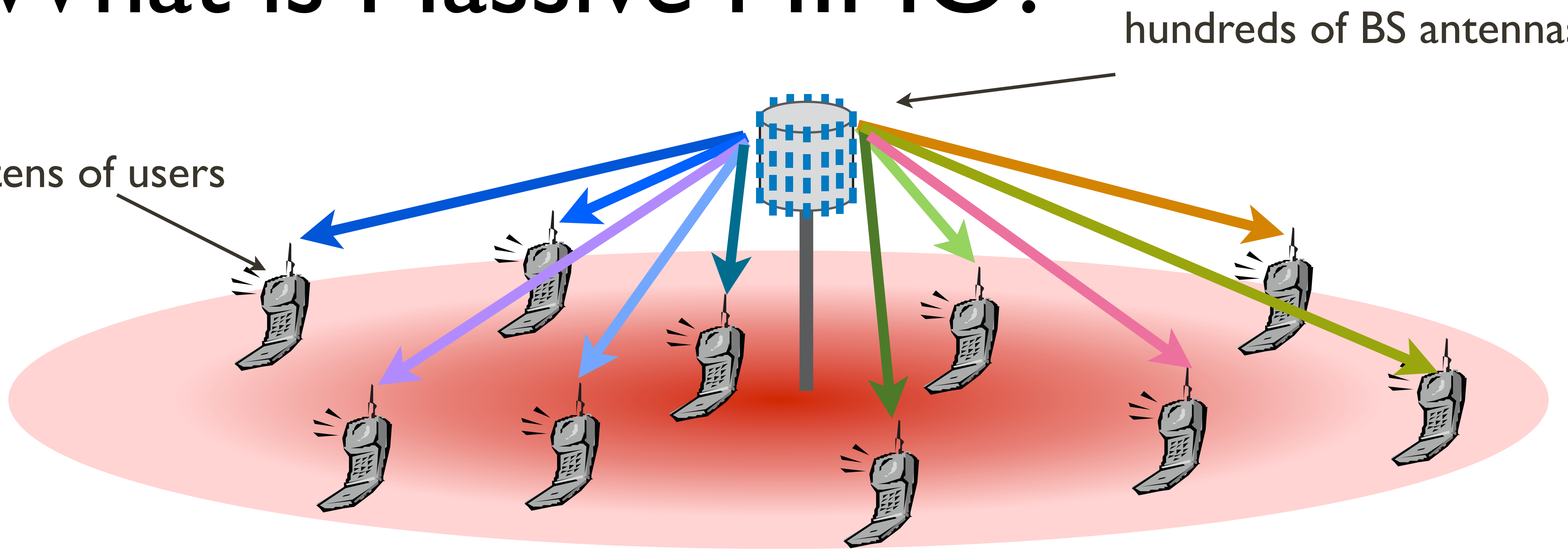
What is Massive MIMO?

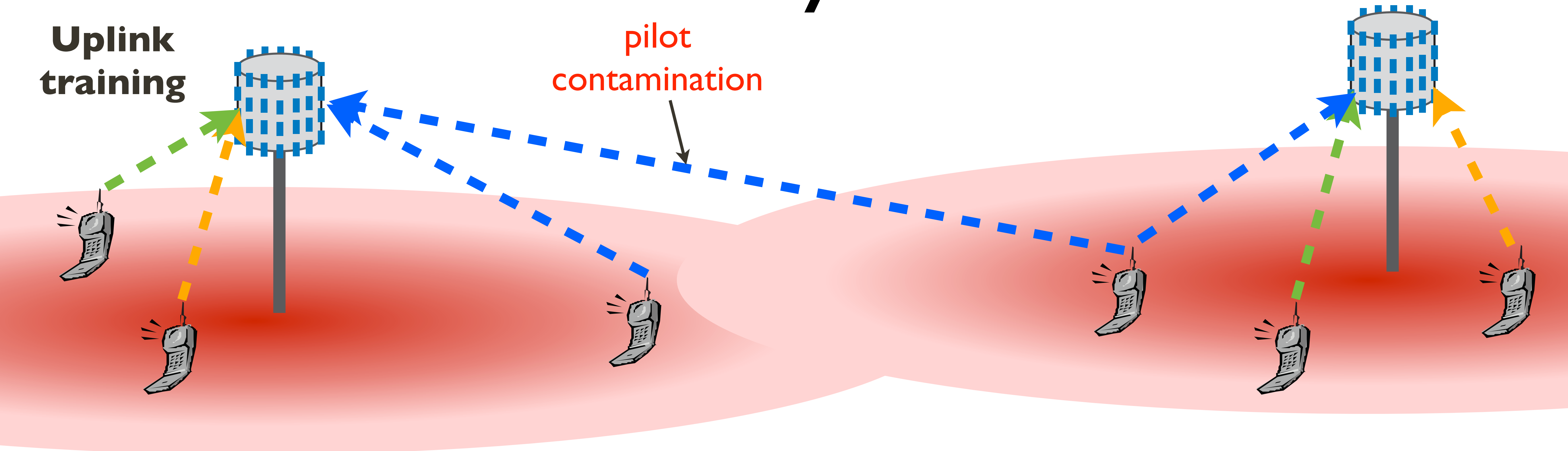


- A very large antenna array at each base station
  - An order of magnitude more antenna elements in conventional systems
- A large number of users are served simultaneously
- An **excess** of base station (BS) antennas

Essentially multiuser MIMO with lots of base station antennas

T. L. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” IEEE Trans. Wireless Commun., vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

Massive MIMO Key Features



- Benefits from the (many) excess antennas
  - Simplified multiuser processing
  - Reduced transmit power
  - Thermal noise and fast fading vanish
- Differences with MU MIMO in conventional cellular systems
  - Time division duplexing used to enable channel estimation
  - Pilot contamination limits performance

F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: Opportunities and challenges with very large arrays," IEEE Signal Processing Mag., vol. 30, no. 1, pp. 40–60, Jan. 2013.

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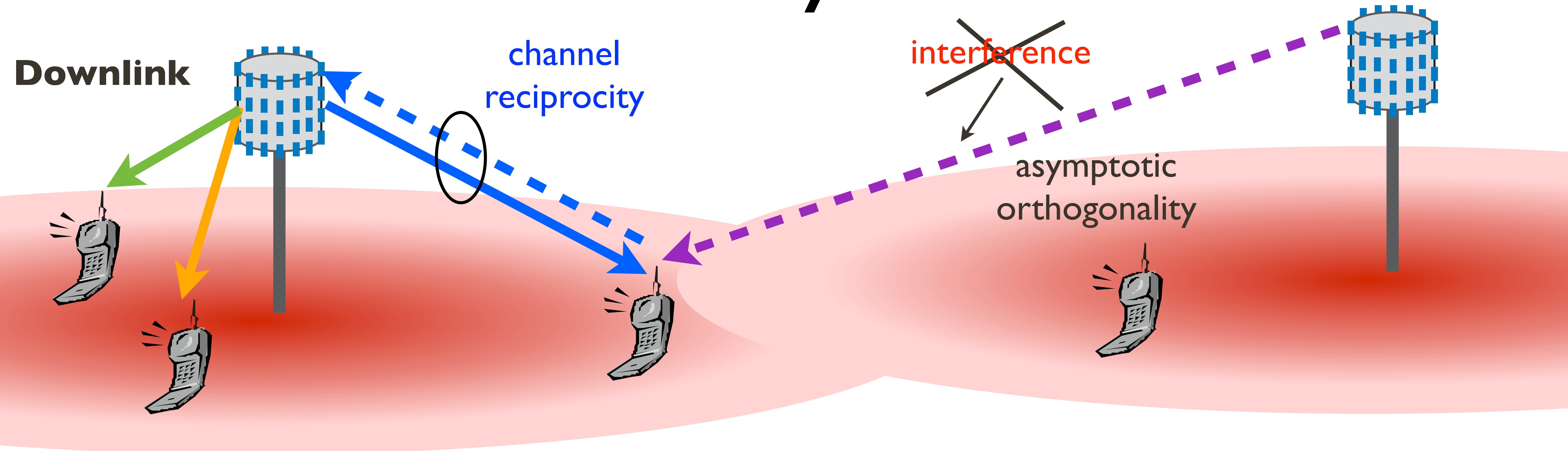

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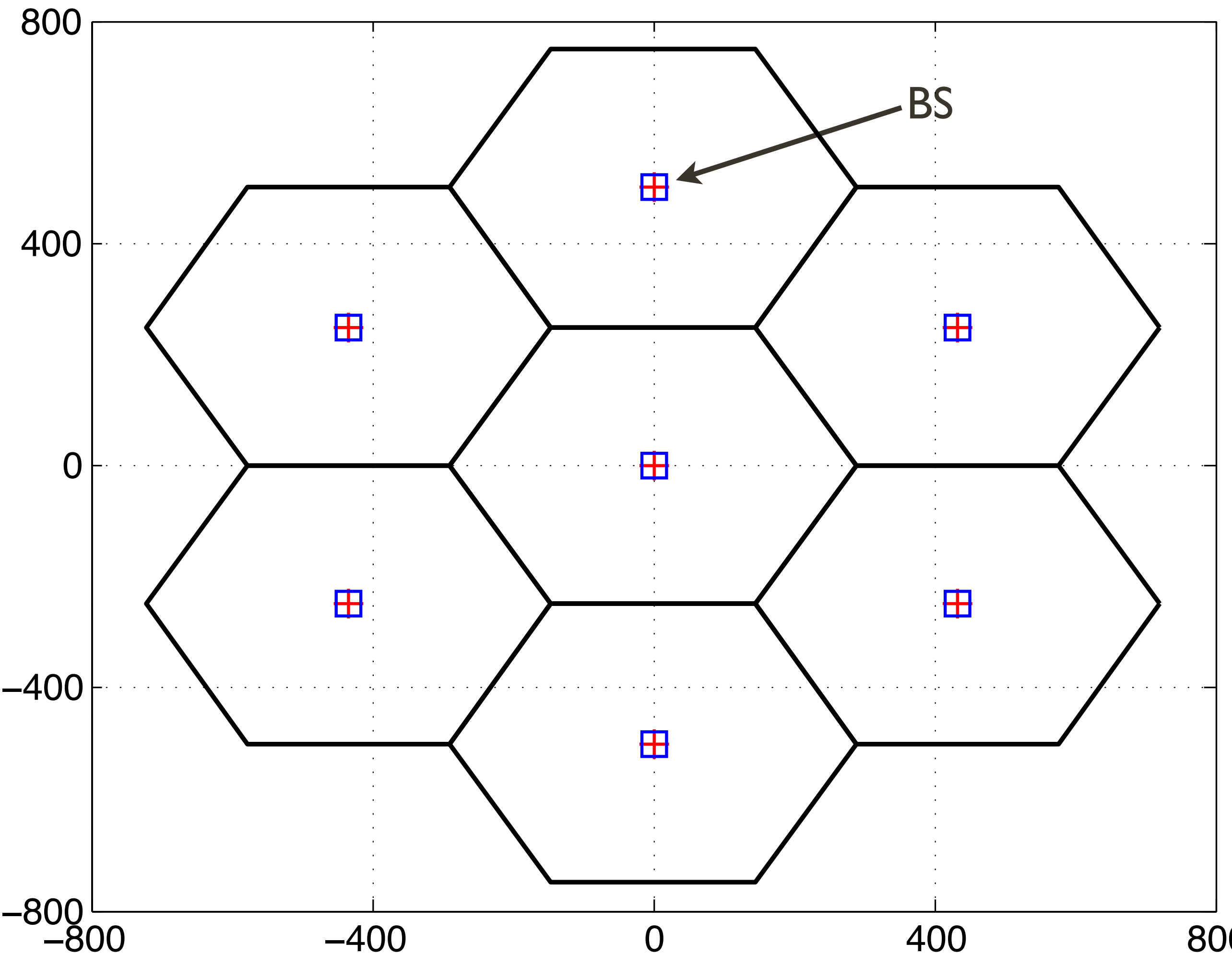
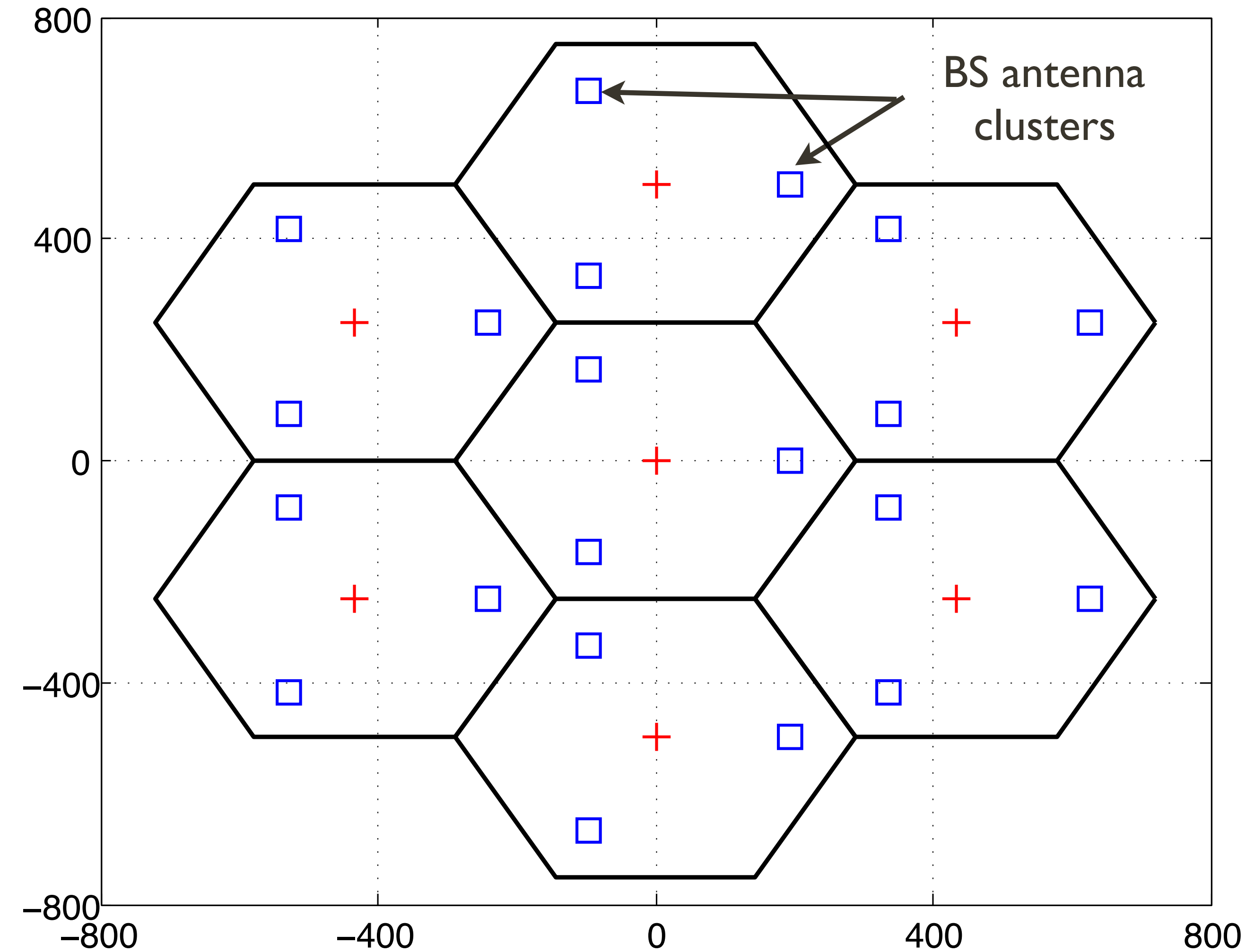
Centralized vs. Distributed

7 cells without sectorization
12 users uniformly distributed in each cell
ISD = 500m

Centralized



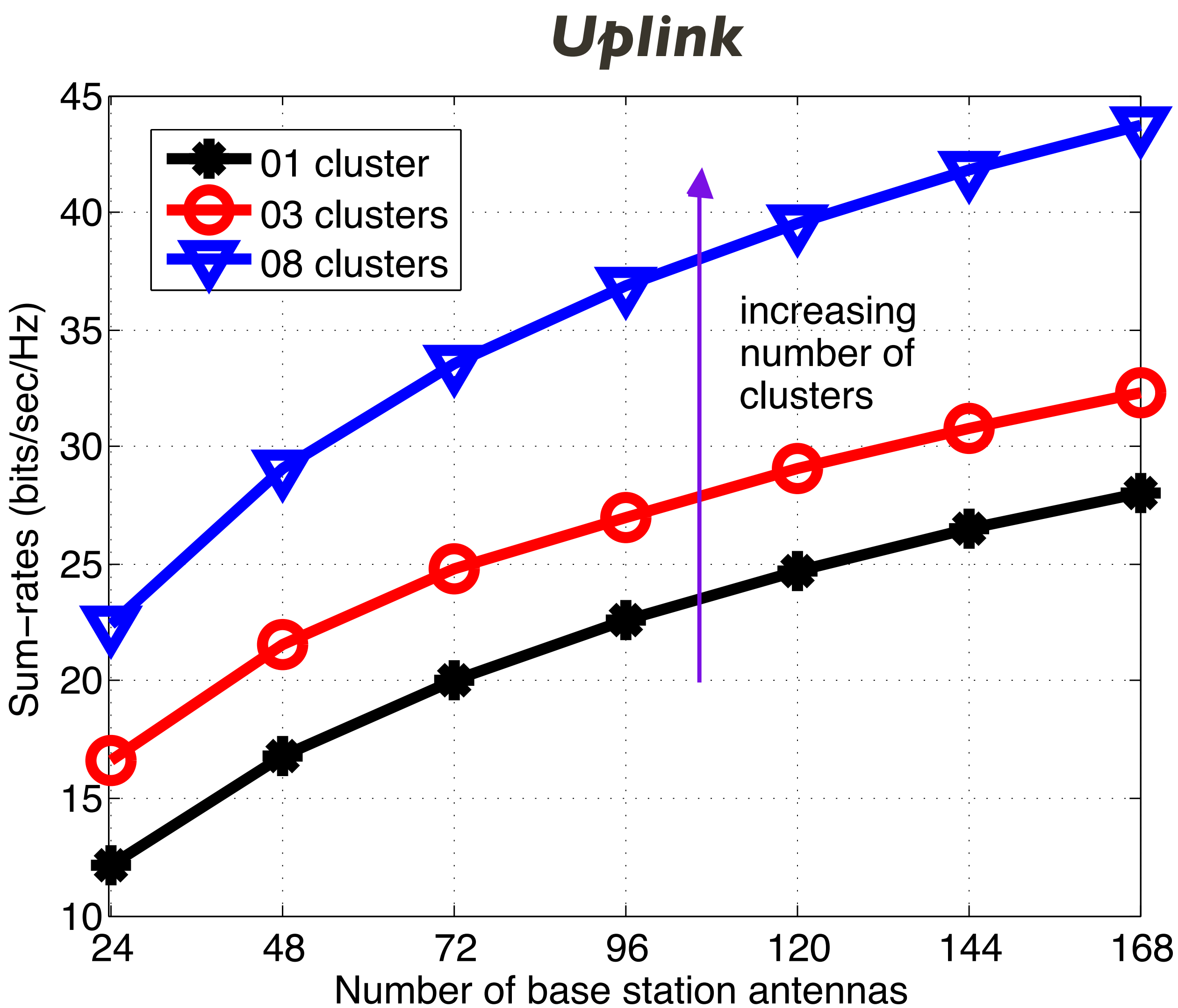
Distributed

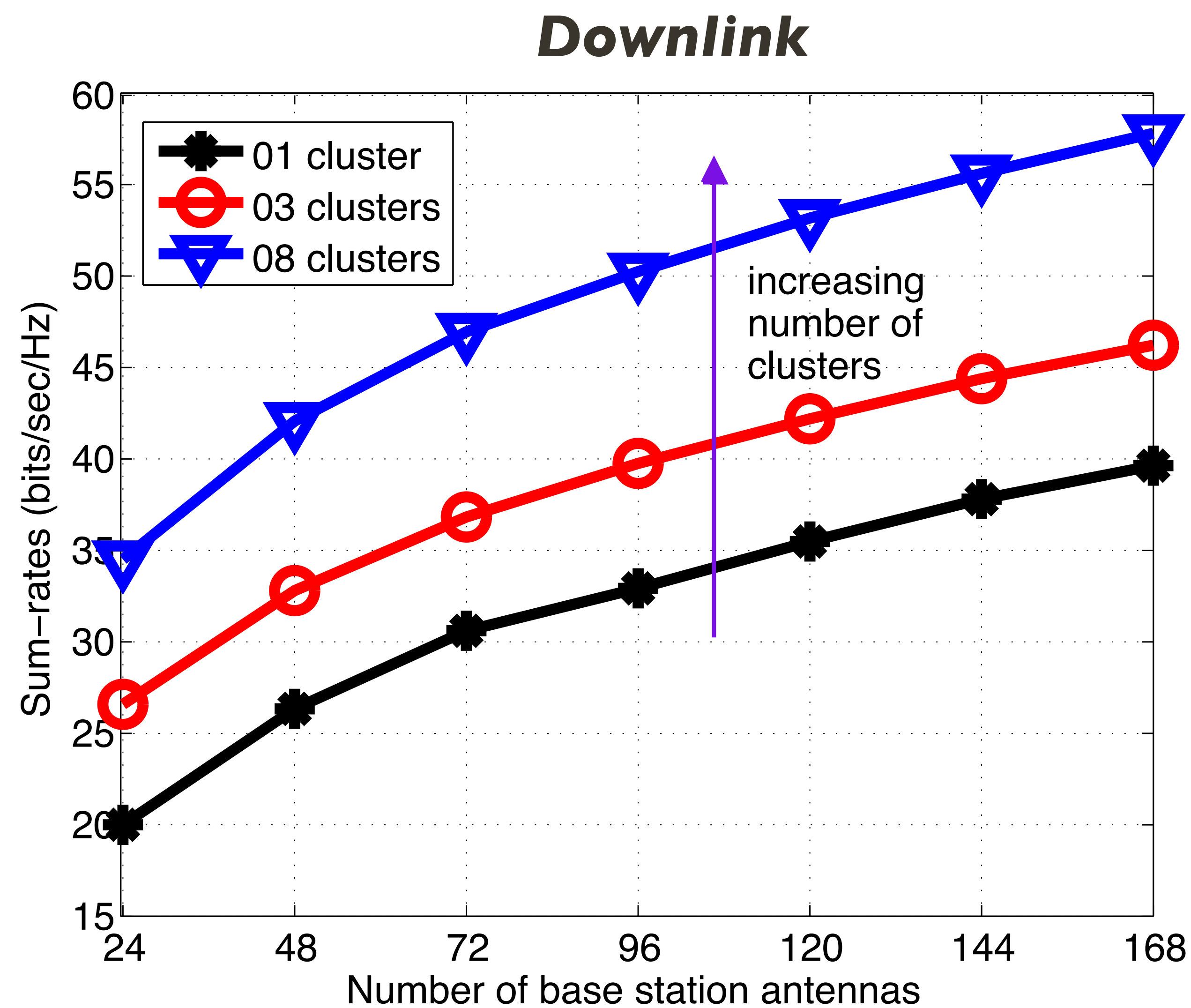


- Fixed number of base station antennas per cell

* K. T. Truong and R. W. Heath, Jr., “Impact of Spatial Correlation and Distributed Antennas for Massive MIMO systems,” to appear in the Proceedings of the Asilomar Conference on Signals, Systems, and Computers, Nov. 3-6, 2013.

Potential Gains from Massive MIMO





7 cells without sectorization, 12 users uniformly distributed in each cell, ISD = 500m

- Distributing antennas achieves higher gains
- Saturation is not observed without huge # of antennas

Critical Issues in Massive MIMO

- Gains are not that big with not-so-many antennas
  - Require many antennas to remove interference
  - Need more coordination to remove effects of pilot contamination
- Massive MIMO seems to be more “uplink driven”
  - Certain important roles are reserved between base stations and users
  - A different layout of control and data channels may be required
- Practical effects are not well investigated
  - Channel aging affects energy-focusing ability of narrow beams
  - Spatial correlation reduces effective DoFs as increasing number of antennas
  - Role of asynchronism in pilot contamination and resulting performance

Massive MIMO Conclusions

- Observations
  - Pilot contamination is a big deal, but possibly overcome by coordination
  - Performance is sensitive to channel aging effects *
  - Good performance can be achieved with distributed antennas *
  - Not clear how to pack so many microwave antennas on a base station
  - Needs more extensive simulation study with realistic system parameters
- Forecast
  - Massive MIMO will probably not be used in isolation
  - Will be combined with distributed antennas or base station coordination
    - Reduces the effects of pilot contamination
    - Work with smaller numbers of antennas

* K. T. Truong and R. W. Heath, Jr., "Effects of Channel Aging in Massive MIMO Systems," to appear in the Journal of Communications and Networks, Special Issue on Massive MIMO, February 2013.

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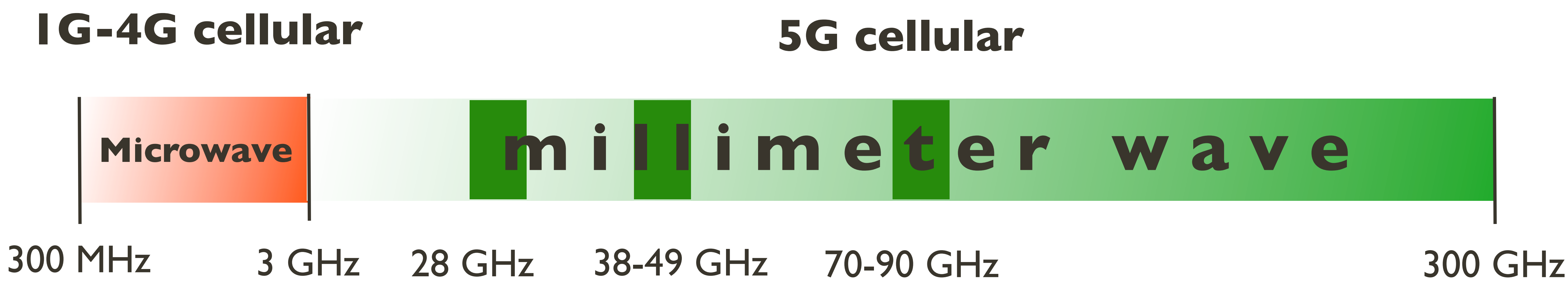
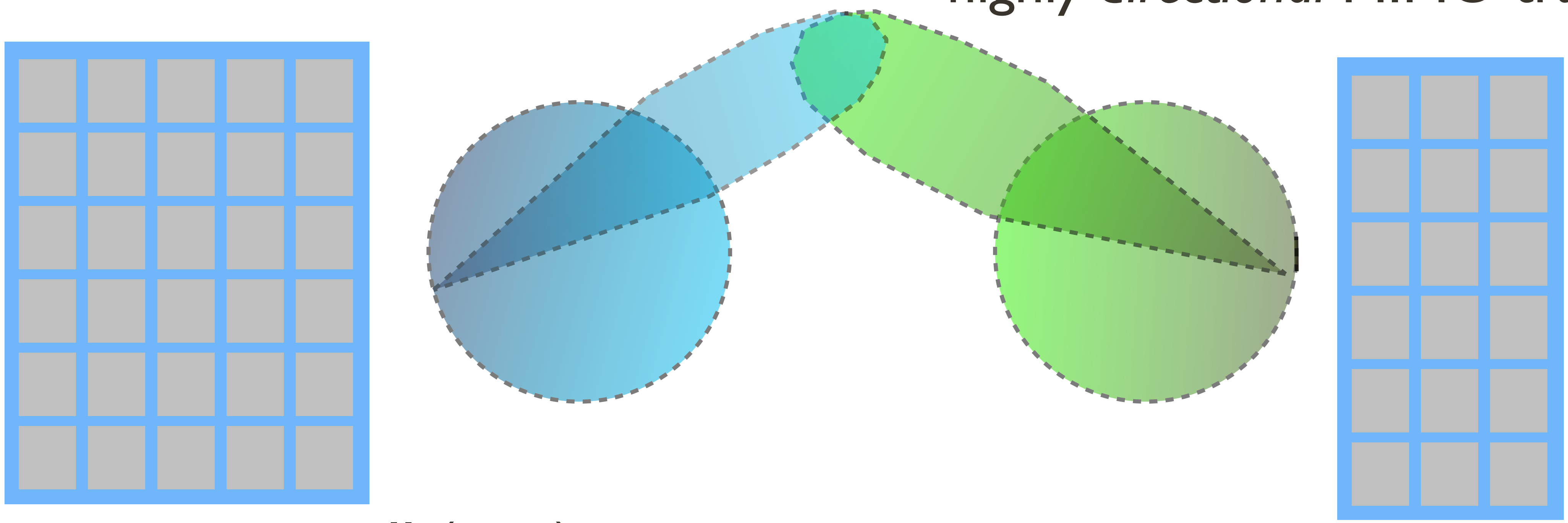
Why mmWave for Cellular?



- Cellular systems live with a little microwave spectrum
  - 600MHz total (best case) in the US
  - Spectrum efficiency is king (MIMO, MU MIMO, HetNets)
- Huge amount of spectrum available in mmWave bands [KhanPi]
  - 29GHz **possibly** available in 23GHz, LMDS, 38, 40, 46, 47, 49, and E-band
  - mmWave already used in LAN, PAN, and VANET
  - mmWave links are used for backhaul in cellular networks

Antenna Arrays are Important

highly *directional* MIMO transmission



antennas are small (mm)
~100 antennas

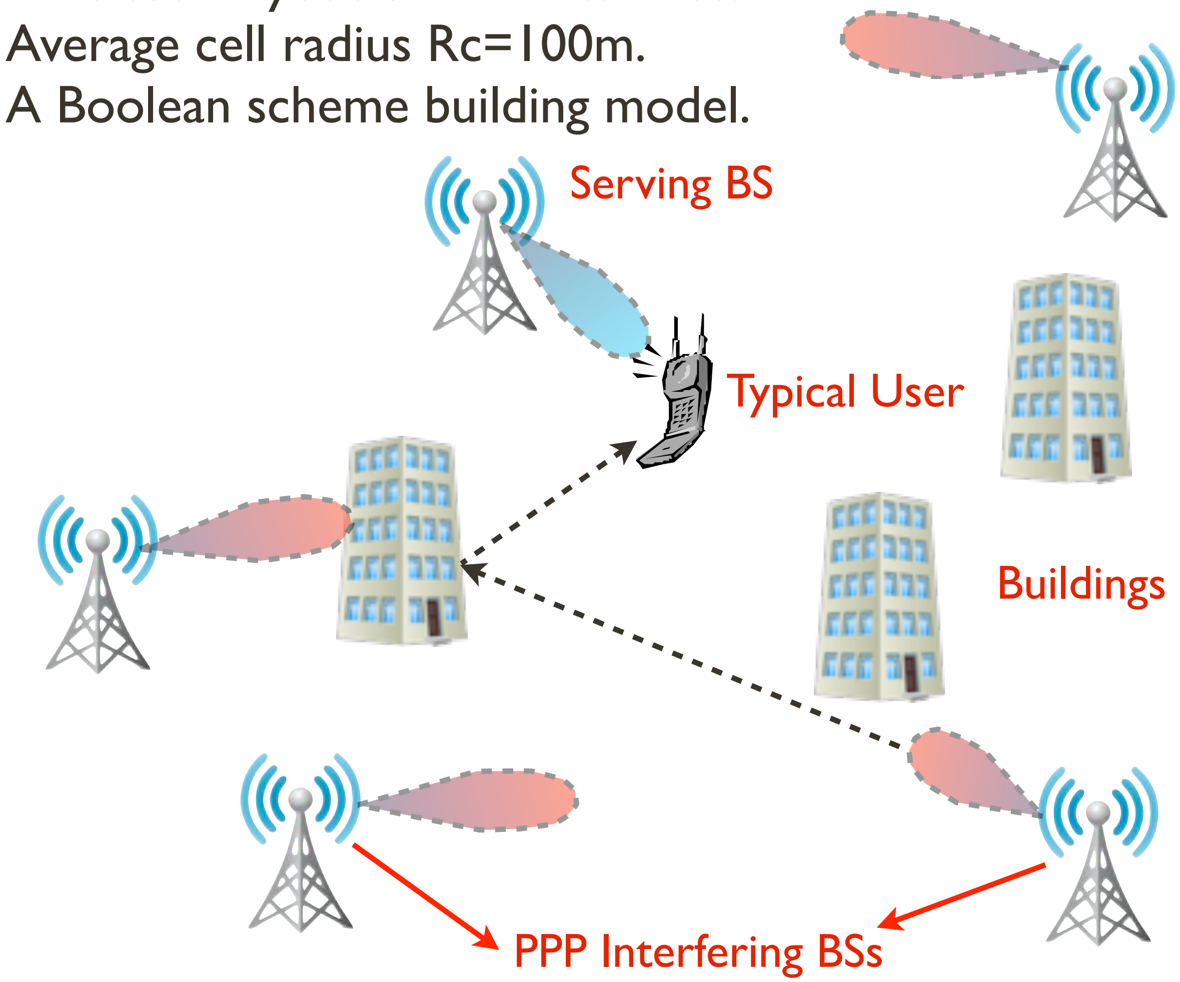
used at TX and RX

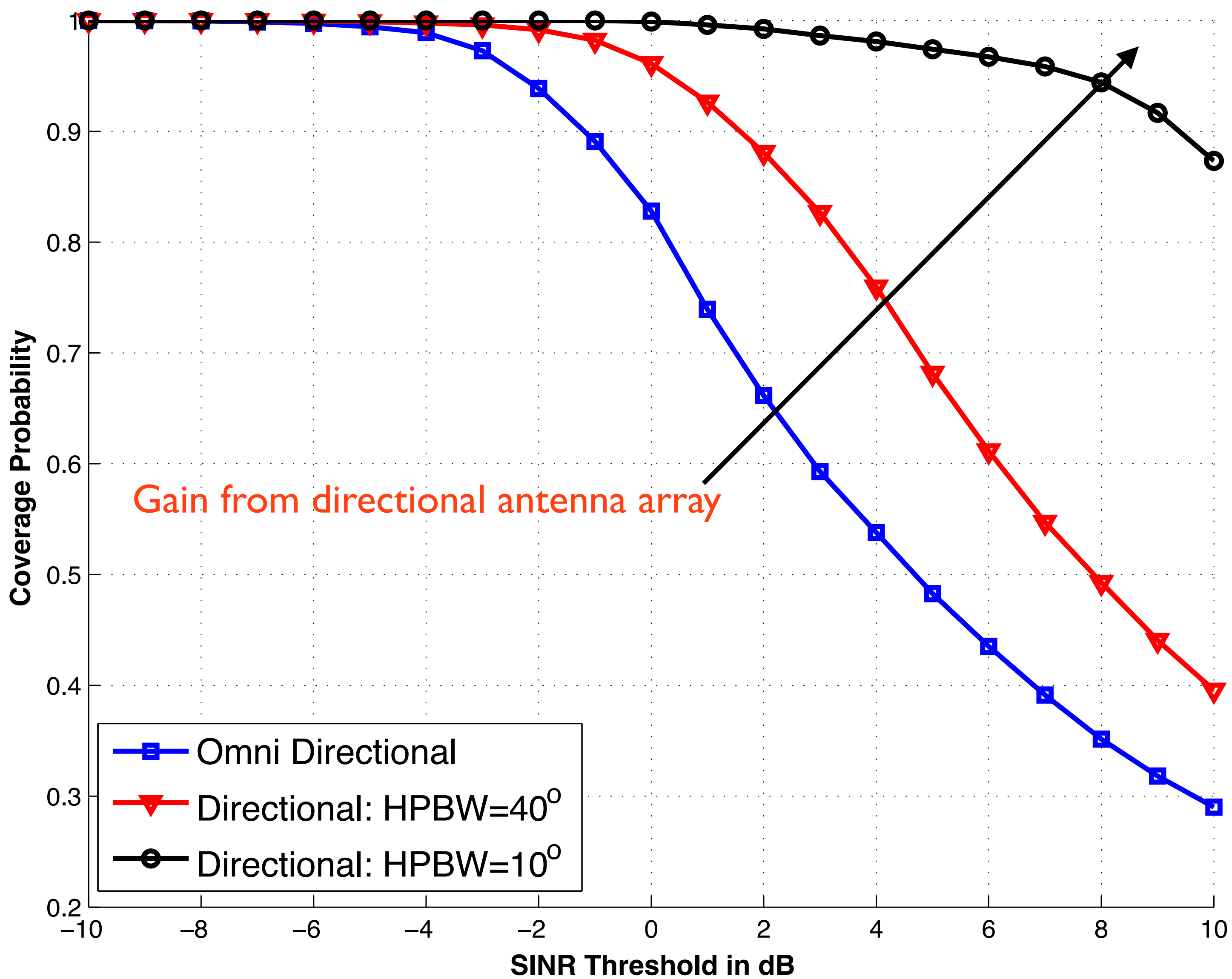
- New challenges faced by mmWave cellular
  - Larger bandwidth means higher noise power and lower SNR
  - Smaller wavelength means smaller captured energy in an antenna

Solution: Exploit array gain from large arrays

Coverage Gains from Large Arrays

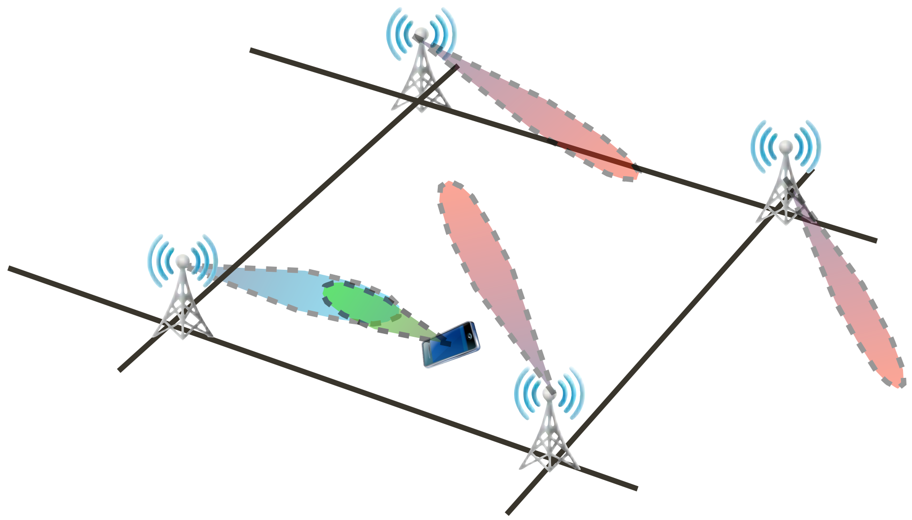
LOS & blocked path loss model from measurements.
A Poisson layout of mmWave BSs.
Average cell radius Rc=100m.
A Boolean scheme building model.

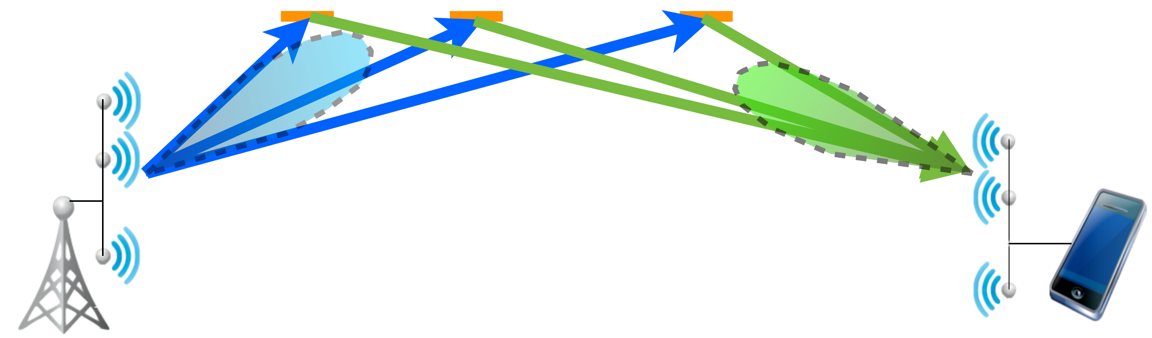




- mmWave networks can provide acceptable coverage
  - Directional array gain compensates severe path loss
  - Smaller beamwidth reduces the effect of interference

Critical Issues in mmWave MIMO





- Dealing with hardware constraints
  - Need a combination of analog and digital beamforming
  - Array geometry may be unknown, may change
- Performance in complex propagation environments
  - Evaluate performance with line-of-sight and blocked signal paths
- Must adapt to frequent blockages and support mobility
- Entire system must support directionality
- Need approval to employ the spectrum

mmWave Conclusions

- Observations
  - Coverage may be acceptable with the right system configuration
  - Strong candidate for higher per-link data rates
  - Hardware can leverage insights from 60GHz LAN and PAN
  - Highly directional antennas may radically change system design
  - Supporting mobility may be a challenge
- Forecast
  - Will be part of 5G if access to new spectrum becomes viable
  - Most likely will co-exist with microwave cellular systems
  - Will remain useful for niche applications like backhaul

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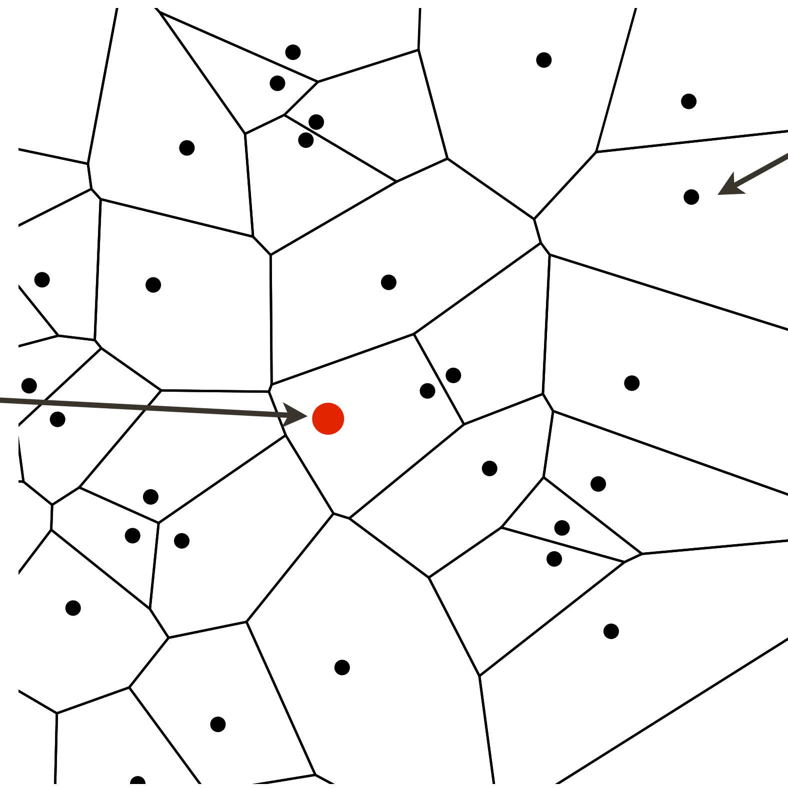
Stochastic Geometry for Cellular



- Stochastic geometry is a useful tool for analyzing cellular nets
  - Reasonable fit with real deployments
  - Closed form solutions for coverage probability available
  - Provides a system-wide performance characterization

J. G. Andrews, F. Baccelli, and R. K. Ganti, "A Tractable Approach to Coverage and Rate in Cellular Networks", IEEE Transactions on Communications, November 2011.
T. X. Brown, "Cellular performance bounds via shotgun cellular systems," IEEE JSAC, vol.18, no.11, pp.2443,2455, Nov. 2000.

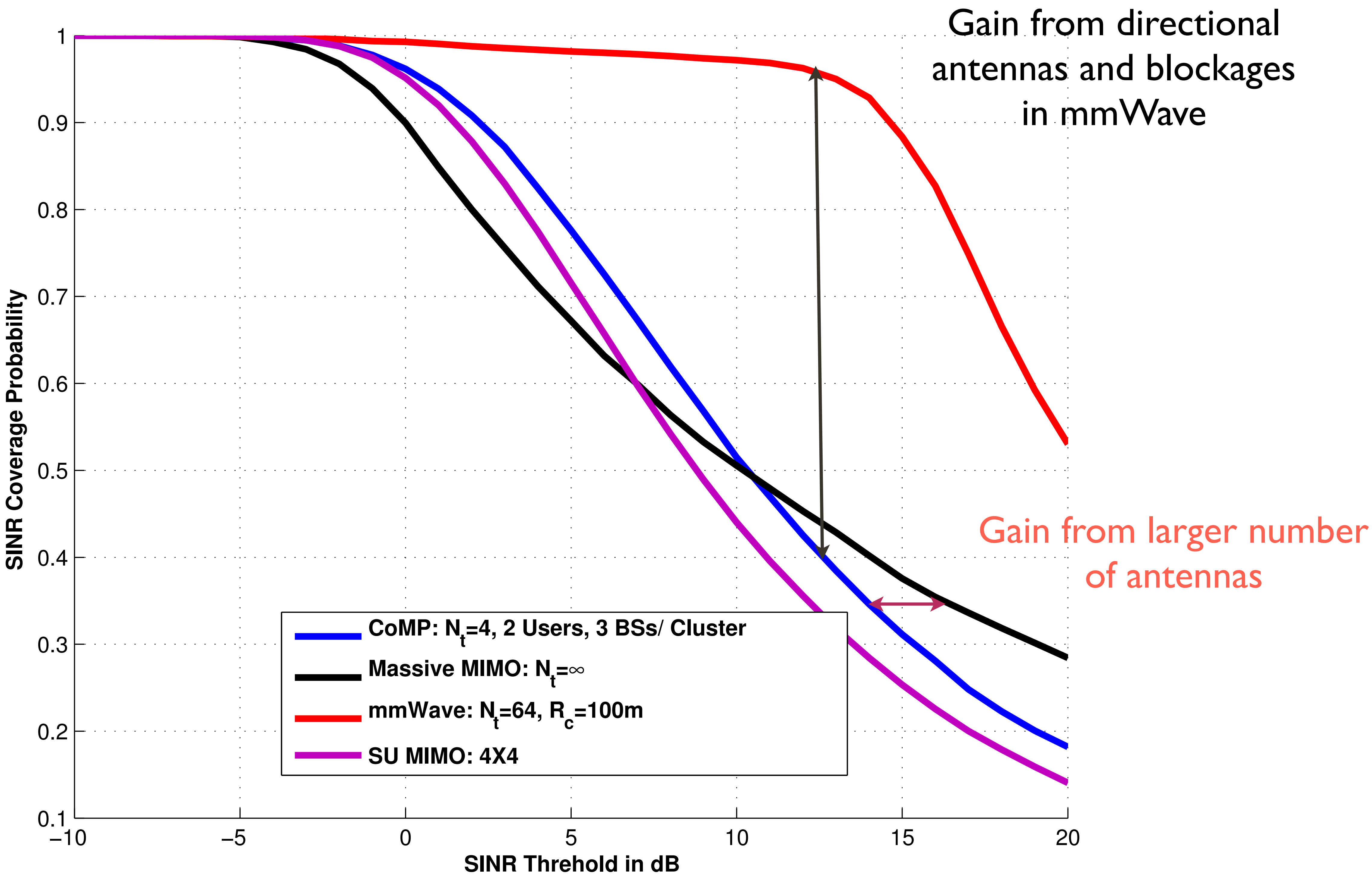
Comparing Different Approaches

- CoMP model
  - Sectored cooperation model
  - Typical user can be edge or center user of the cluster
  - Several assumptions made to permit calculation
- mmWave model
  - Directional antennas are incorporated as marks of the base station PPP
  - Blockages due to buildings incorporated via random shape theory
- Massive MIMO model
  - Analyze asymptotic case with infinite number of antennas at the base station
  - No spatial correlation, includes estimation error, pilot contamination

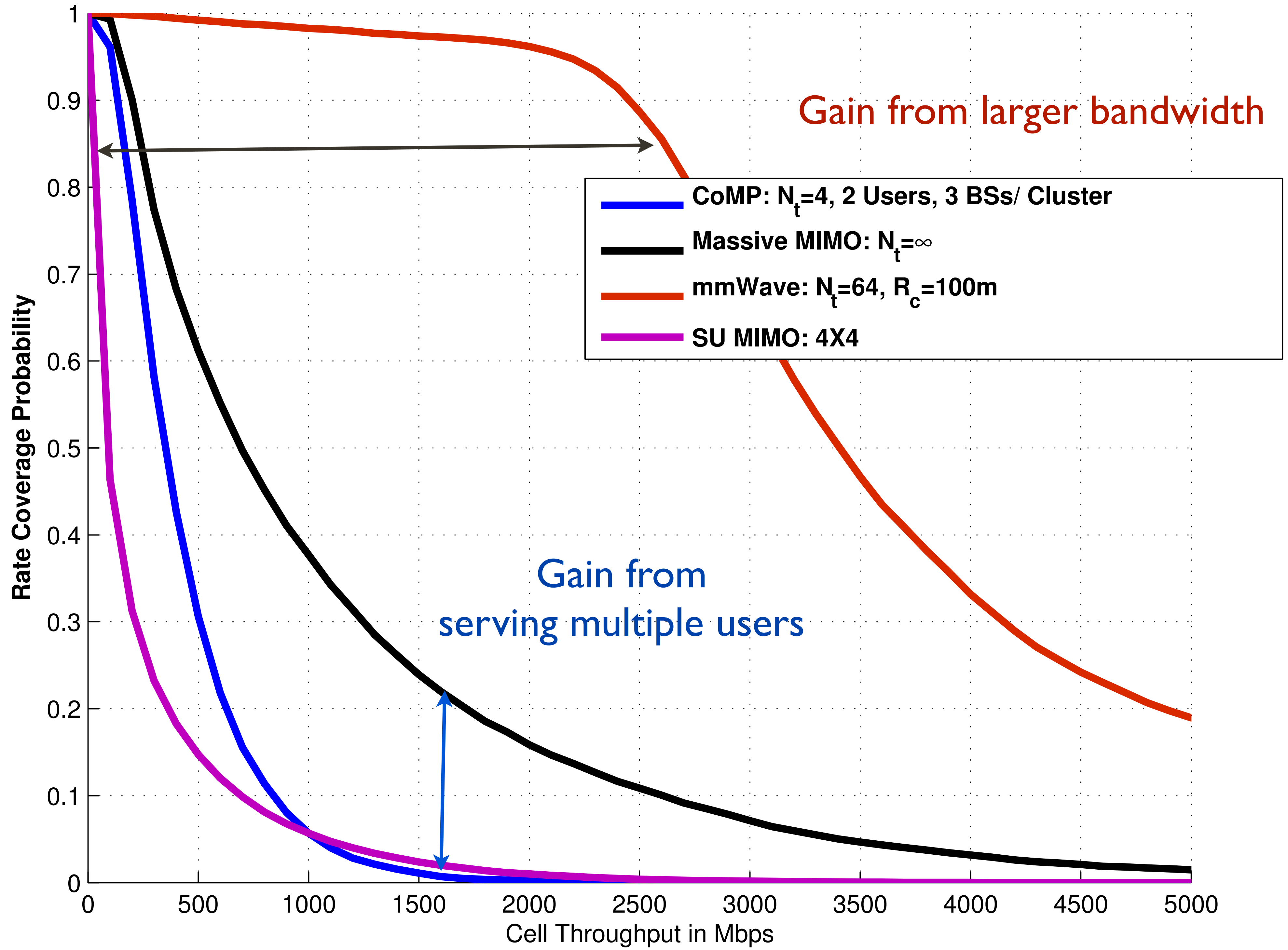
New expressions derived for each case

Tianyang Bai and R. W. Heath, Jr., `` Asymptotic Coverage Probability and Rate in Massive MIMO Networks ,'' submitted to IEEE Wireless Communications Letters, May 2013. Available on ArXiv.

SINR Coverage Comparison



Rate Comparison



Rate Comparison

	Massive MIMO	MMwave	CoMP	SU MIMO
Signal BW	50 MHz	500 MHz	50 MHz	50 MHz
User/ Cell	8	1	2	1
bps/Hz per user	5.47 bps/Hz	8.00 bps/Hz	4.34 bps/Hz	4.95 bps/Hz
Rate/Cell	21.88 bps/Hz	8.00 bps/Hz	8.68 bps/Hz	4.95 bps/Hz
Capacity/ Cell	1.10 Gbps	4.00 Gbps	434 Mbps	248 Mbps

mmWave outperforms due to more available BW

* of course various parameters can be further optimized
** SU MIMO is 4x4 w/ zero-forcing receiver

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Parting Thoughts

	Conclusions
cooperative MIMO	cooperation will be used in some form, more powerful with better infrastructure, need to be mindful of overheads in system design
massive MIMO	some potential for system rates, need large base station arrays, can be used with cooperation
mmWave MIMO	large potential for peak rates, more hardware challenges, requires more spectrum, more radical system design potential

Questions?

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