Comparing Massive MIMO and mmWave MIMO

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Joint work with Tianyang Bai

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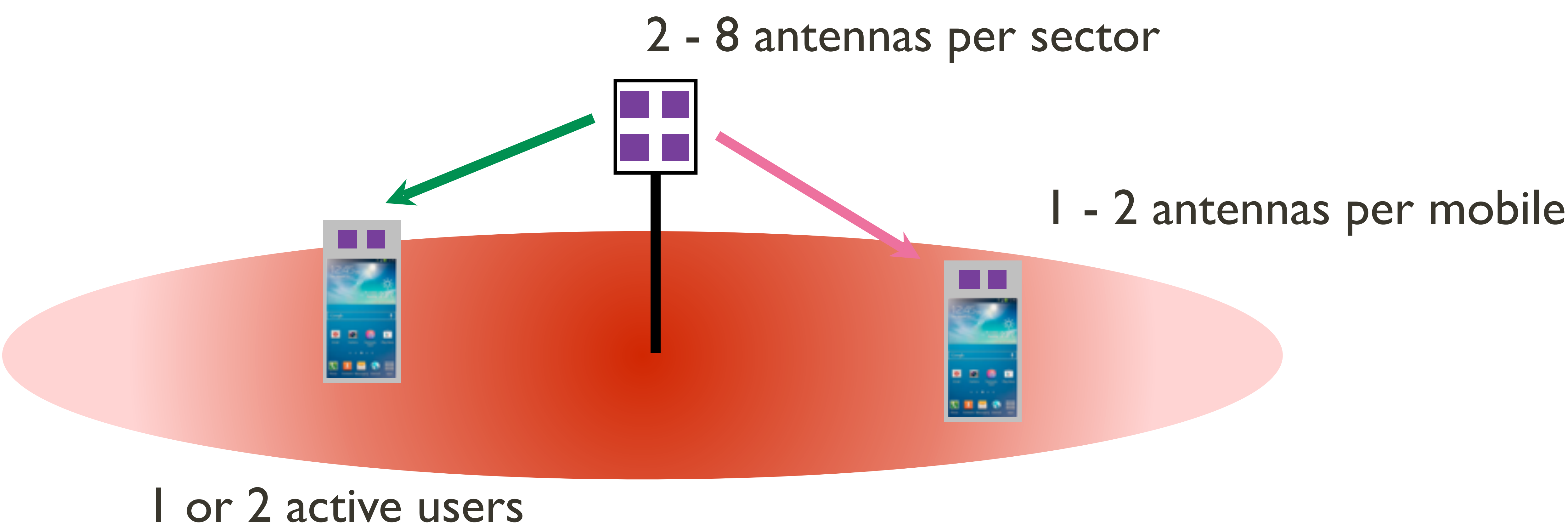
Going Towards 5G with MIMO

status quo

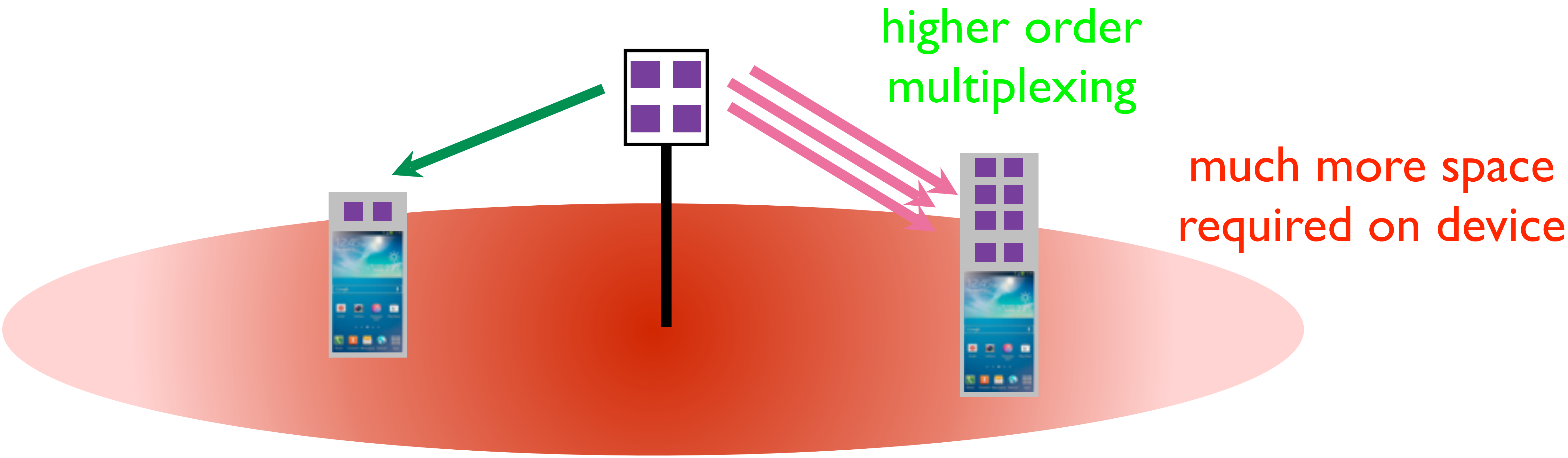


MIMO is a marketing success but …
has not met its real world promise in cellular

F. Boccardi, R.W. Heath, Jr., A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," IEEE *Commun. Mag.*, Feb. 2014

Going Towards 5G with MIMO

~~more antennas at the mobile?~~



significant engineering challenges due to multi-band considerations

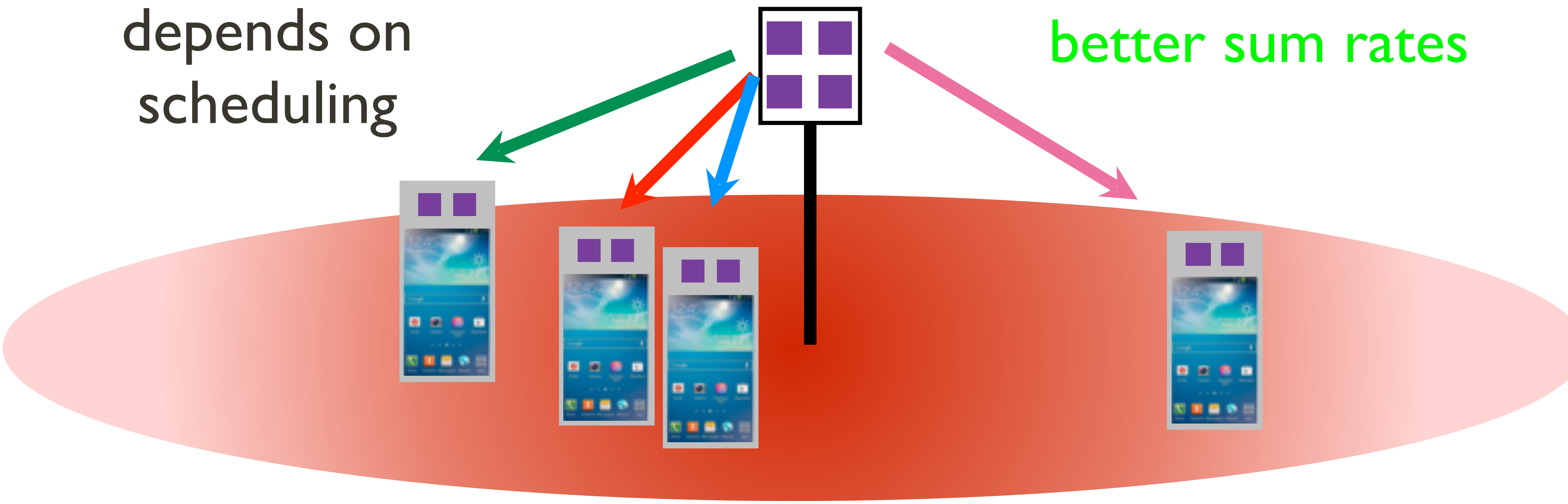
[Bac06] A. Baschirotto, R. Castello, F. Campi et all, "Baseband analog front-end and digital back-end for reconfigurable multi-standard terminals," *IEEE Circuits and Systems Magazine*, 2006

Going Towards 5G with MIMO

~~more multiuser MIMO?~~

performance depends on scheduling

better sum rates



feedback becomes a huge bottleneck

performance with heavy quantization (favored by industry) is dismal

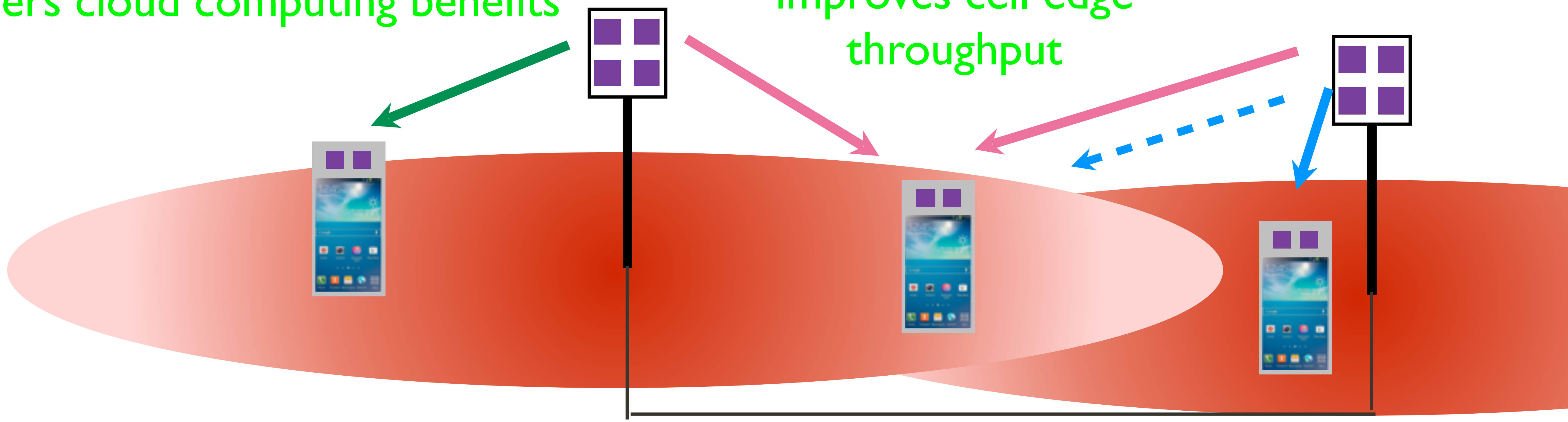
[Wang12] M. Wang, F. Li, J. S. Evans, and S. Dey, "Dynamic Multi-User MIMO scheduling with limited feedback in LTE-Advanced," In proc. of *PIMRC,* 2012
[Yoo07] T. Yoo, N. Jindal., and A. Goldsmith "Multi-Antenna Downlink Channels with Limited Feedback and User Selection," *JSAC,* 2007

Going Towards 5G with MIMO

- - - - - more cooperation? - - - -

when implemented via C-RAN offers cloud computing benefits

improves cell edge throughput



backhaul for C-RAN

feedback, coordination, and scheduling lead to practical losses

gains in 4G systems have not been stellar

[Loz13] A. Lozano, R.W. Heath Jr., J. G. Andrews, "Fundamental Limits of Cooperation", IEEE Trans. Inf. Theory, vol. 59, no. 9, Sept.2013, pp. 5213-5226.
[C-RAN] C-RAN: the road toward green RAN, white paper by China Mobile, Oct, 2011

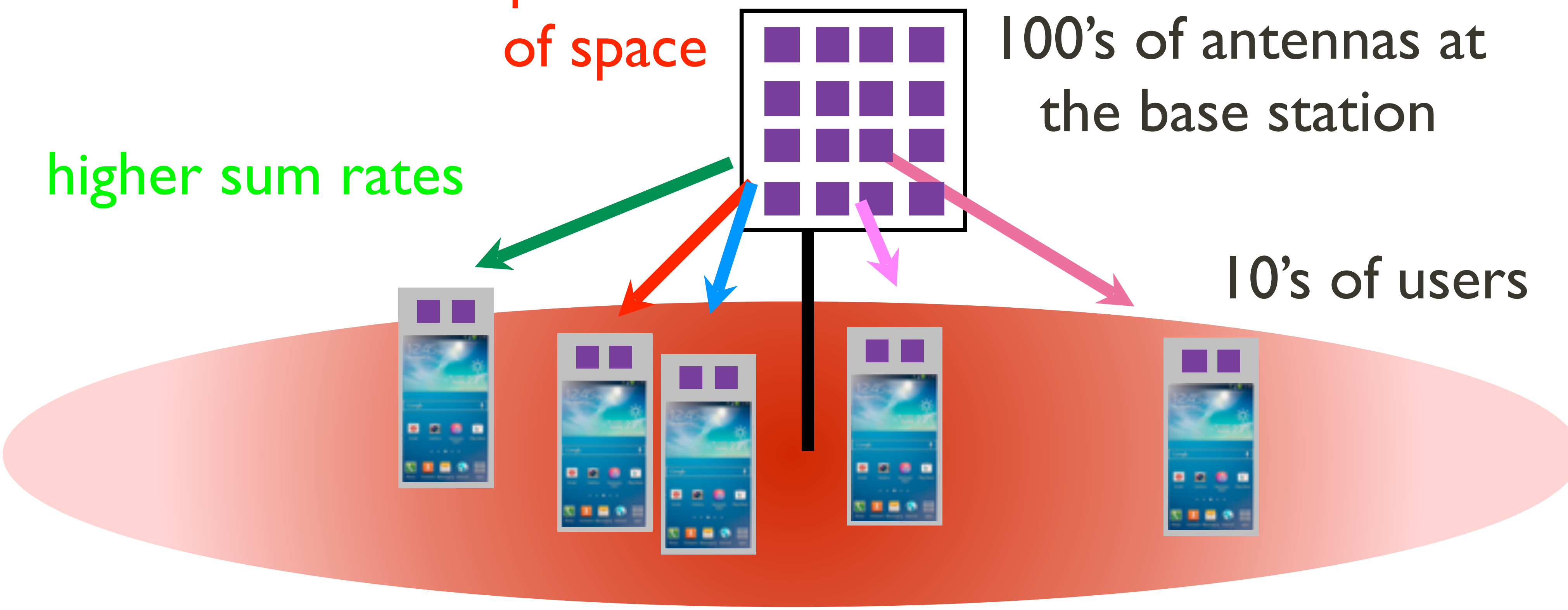
Going Towards 5G with MIMO

massive MIMO?

requires a lot of space

100's of antennas at the base station

higher sum rates



10's of users

use of TDD avoids significant feedback overhead

accounts for out-of-cell interference

[Mar10] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," IEEE Trans. Wireless Commun., Nov., 2010.

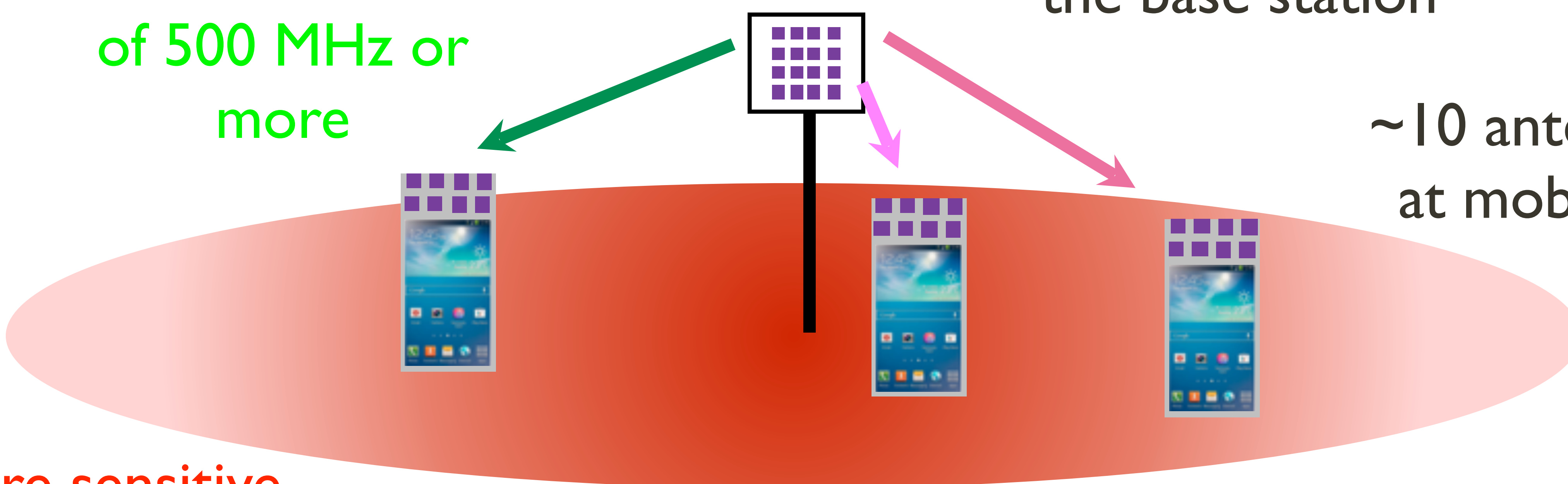
[Rus13] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: Opportunities and Challenges with Very Large Arrays", IEEE Signal Proces. Mag., vol. 30, no. 1, pp. 40-46, Jan. 2013.

Going Towards 5G with MIMO

mmWave MIMO?

channel bandwidths of 500 MHz or more

100's of antennas at the base station



~10 antennas at mobile *

more sensitive to blockage

requires spectrum

more circuit challenges

directional antennas at transmitter and receiver reduce interference

** Note: Wilocity has 802.11ad smartphone chips with 32 antennas already available, Large arrays are perfectly reasonable and practical at consumer prices*

[RapHea14] T. S. Rappaport, R. W. Heath Jr., R. C. Daniels, and J. N. Murdock, Millimeter Wave Wireless Communication. Prentice Hall, 2014.
[RanRap14] S. Rangan, T.S. Rappaport, and E. Erkip, "Millimeter Wave Cellular Wireless Networks: Potentials and Challenges", Proceedings of IEEE, 2014
[BaiAlk14] T. Bai, A. Alkhateeb, and R. W. Heath, Jr., "Coverage and Capacity of Millimeter Wave Cellular Networks", To appear in IEEE Comm, Mag., 2014

Some differentiating features in going massive

	microwave	mmWave
bandwidth	20-50 MHz	> 500 MHz
# antennas @ BS	32 - 64	64 - 256
# antennas @ MS	1 - 4	4 - 12
beamforming	digital	analog
# of users	~ 10	~ 4
cell size	micro / macro	pico
small-scale fading	more AS & clusters	fewer AS & clusters
large-scale fading	distant dependent + shadowing	distant dependent + blockage
penetration loss	some	possibly high
channel sparsity	less	more
spatial correlation	less	more
orientation	less	more

Approach for Comparison

1. Consider large network with randomly deployed BSs
   - Use stochastic geometry to analyze SINR and rate distribution
   - Usual (boring) PPP model (no clustering, GPP, etc)
   - Uplink and downlink are different network, but w/ same density

2. Consider a large number of antennas at the base station
   - TDD based massive MIMO w/ matched filtering
   - Incorporate differentiating features into the spatial correlation model

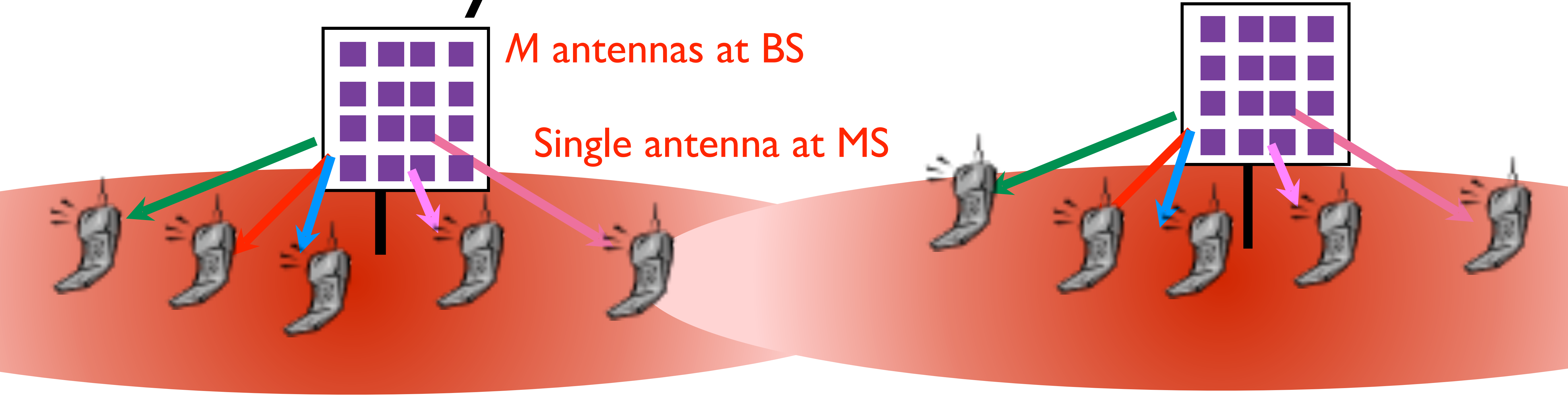
infinity of base stations and antennas creates challenges

[And11] 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.
[Hae13] M. Haenggi, *Stochastic Geometry for Wireless Networks,* Cambridge Press 2013.
[Mar10] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," IEEE Trans. Wireless Commun., Nov., 2010.

Incorporating the Differences

	microwave	mmWave
small-scale fading	correlated with high rank	correlated with low rank esp. in LOS
large-scale fading	distant dependent pathloss	distant dependent with random blockage model
network deployment	low BS density	high BS density

SINR Analysis of Massive Microwave



Channel estimate of ℓ-th BS to its k-th user

$$g_{\ell\ell}^{(k)} = h_{\ell\ell}^{(k)} + \sum_{\ell' \neq \ell} h_{\ell\ell'}^{(k)}$$

pilot contamination

interference

infinite # interferers

$$\mathrm{SIR}_{\mathrm{UL}} = \frac{\|h_{00}^{(1)}\|^4}{\sum_{\ell\neq 0}\|h_{0\ell}^{(1)}\|^4 + \sum_{\ell\neq\ell'}|h_{0\ell}^{(1)'} h_{0\ell'}^{(1)}|^2 + \sum_{k\neq 1}\sum_{\ell',\ell}|h_{0\ell}^{(1)'} h_{0\ell'}^{(k)}|^2}$$

inside-of-cell out-of-cell

$$\mathrm{SIR}_{\mathrm{DL}} = \frac{\|h_{00}^{(1)}\|^4}{\sum_{\ell\neq 0}\|h_{0\ell}^{(1)}\|^4 + \sum_{\ell\neq\ell'}|h_{0\ell}^{(1)'} h_{0\ell'}^{(1)}|^2 + \sum_{k\neq 1}\sum_{\ell',\ell}|h_{0\ell}^{(1)'} h_{0\ell'}^{(k)}|^2}$$

inside-of-cell out-of-cell

Channel Model Assumptions

- M antennas at BS & single antenna at MS
  - Channel vector modeled as

Covariance matrix for small-scale fading

$$\mathbf{h}_{\ell n}^{(k)} = \left(\beta_{\ell n}^{(k)}\right)^{1/2} \mathbf{\Phi}_{\ell n}^{(k)1/2} \mathbf{w}_{\ell n}^{(k)}$$

Path loss in power — i.i.d. random vector

- Use log-distance model for path loss gain $\beta_{\ell n}^{(k)}$
  - A link of length *d* has path loss $\min(1, d^{-\alpha})$
- Mean square of eigenvalues of $\mathbf{\Phi}_{\ell n}^{(k)}$ is finite, i.e., $\sum_{m=1}^{M} \lambda_{\ell n}^{(k)2}[m]/M < \infty$
  - More general than the finite max. eigenvalue assumption [Hoy13]
  - Ensure the rank of $\mathbf{\Phi}_{\ell n}^{(k)}$ grows with the size of antennas *M*
  - Intuitively assumes larger array sees more indepen. multi-paths
  - Reasonable assumption in rich-scattered microwave

[Hoy13] J. Hoydis et al, "Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?" IEEE JSAC, Feb, 2013

SINR Convergence Results

Lemma 1 (even with correlation asymptotic orthogonality holds)
When $M \to \infty$, $\mathbf{h}_{\ell\ell'}^{(k)*}\mathbf{h}_{\ell\ell'}^{(k)}/M \xrightarrow{p} \beta_{\ell\ell'}^{(k)}$, and $\mathbf{h}_{\ell\ell'}^{(k)*}\mathbf{h}_{ss'}^{(n)}/M \xrightarrow{p} 0$.

Theorem 1 [Downlink Asymptotic SIR]
When $M \to \infty$, the downlink SIR converges as

$$\mathrm{SIR_{DL}} \xrightarrow{p} \beta_{00}^{(1)2} / \left(\sum_{\ell>0} \beta_{\ell 0}^{(1)2} \right).$$

SIR limited by pilot contamination

The CCDF of the asymptotic SIR approximately equals

$$\mathbb{P}(\mathrm{SIR} > T) = \min\left(\frac{\alpha \sin(\pi/\alpha)}{\pi T^{1/\alpha}}, 1 \right).$$

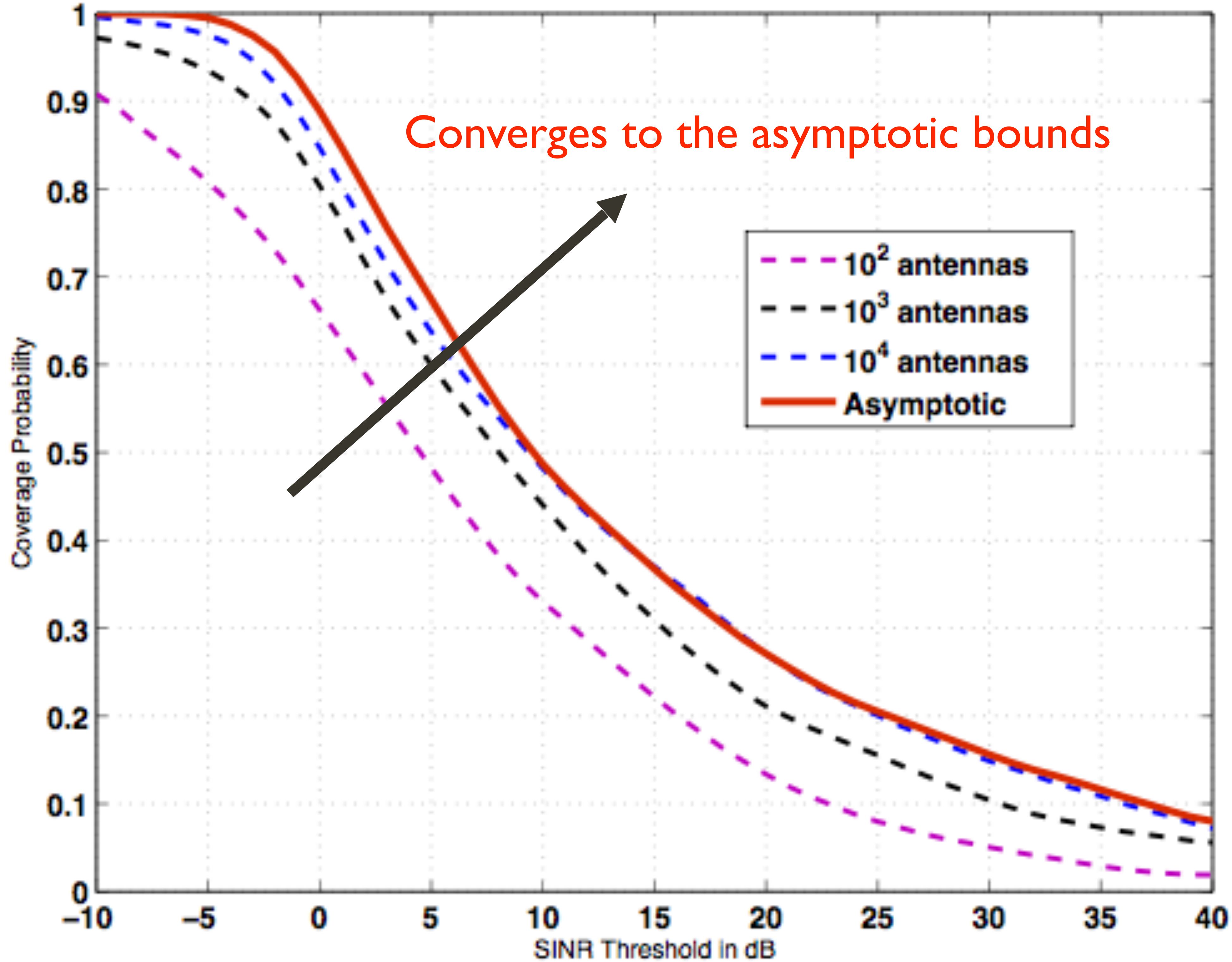
An increasing function of path loss exponent

- Convergence with an infinite number of nodes is non-trivial
  - Use Campbell's them and factorial moment to prove convergence
- Uplink SINR has the same asymptotic distribution
  - Asymptotic rate are the same in downlink and uplink

T. Bai, R.W. Heath, Jr.," Asymptotic coverage and rate analysis in massive MIMO cellular networks", under preparation for submission, May 2014, prior version available on Arxiv

SINR Simulations(1/2)

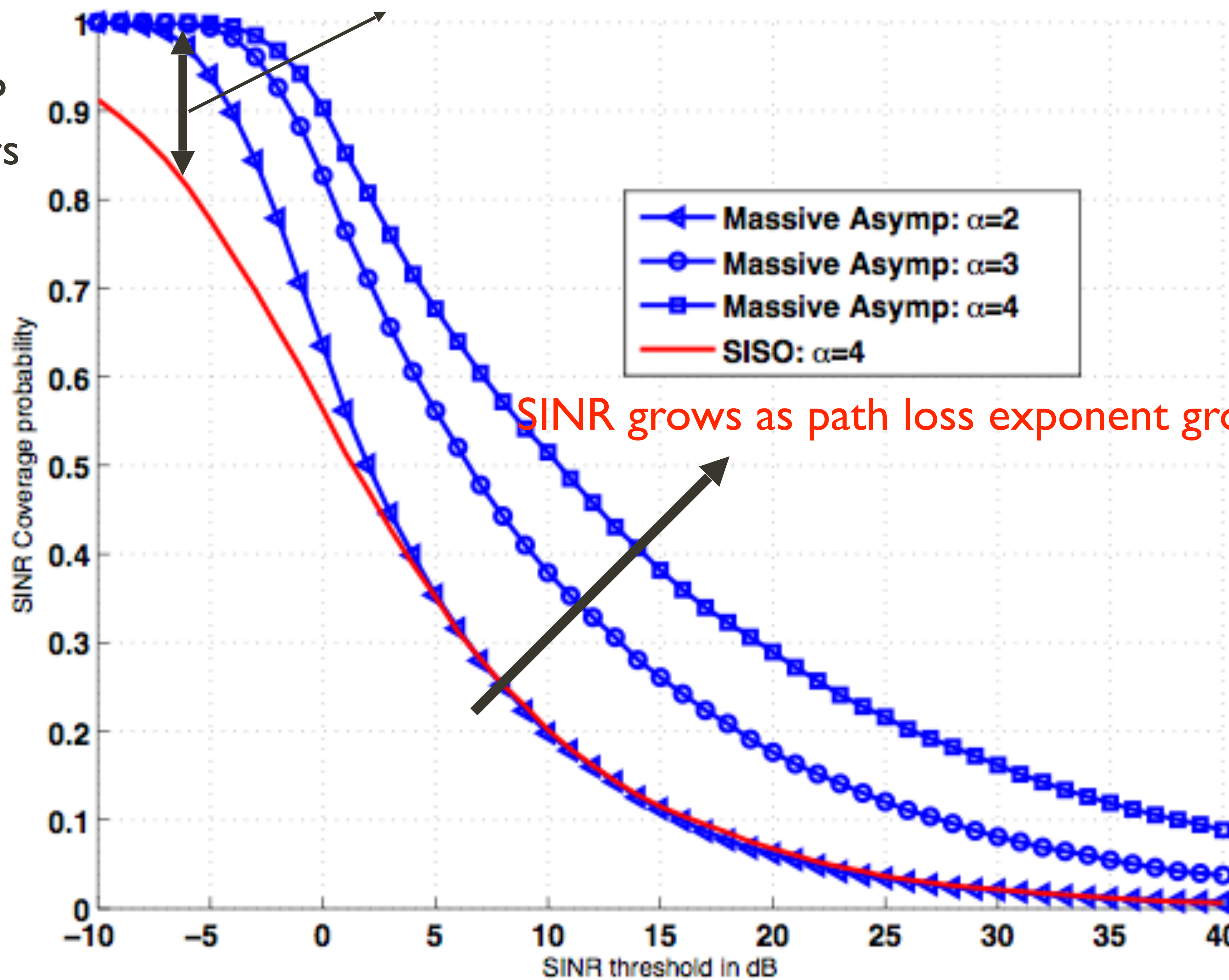
BS distributed as PPP
Assume i.i.d fading
Avg. ISD: 1000 meters



SINR Simulations(2/2)

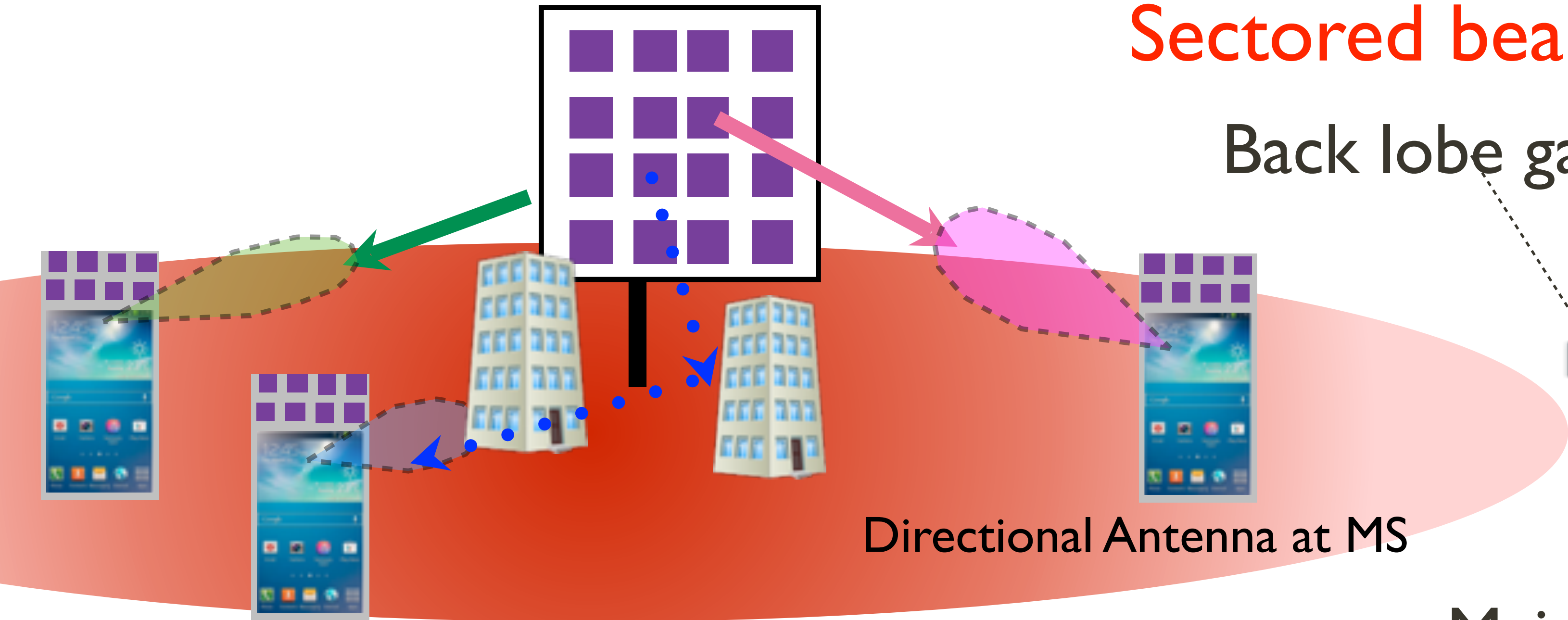
Gain from large # of antennas

BS distributed as PPP
Avg. ISD: 1000 meters

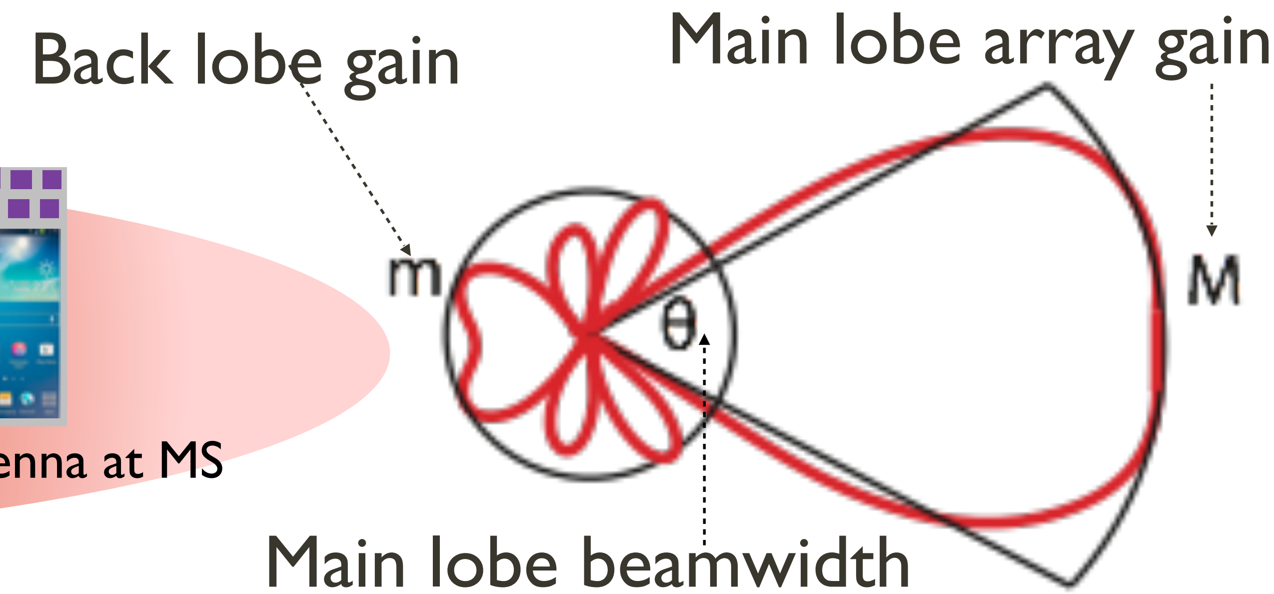


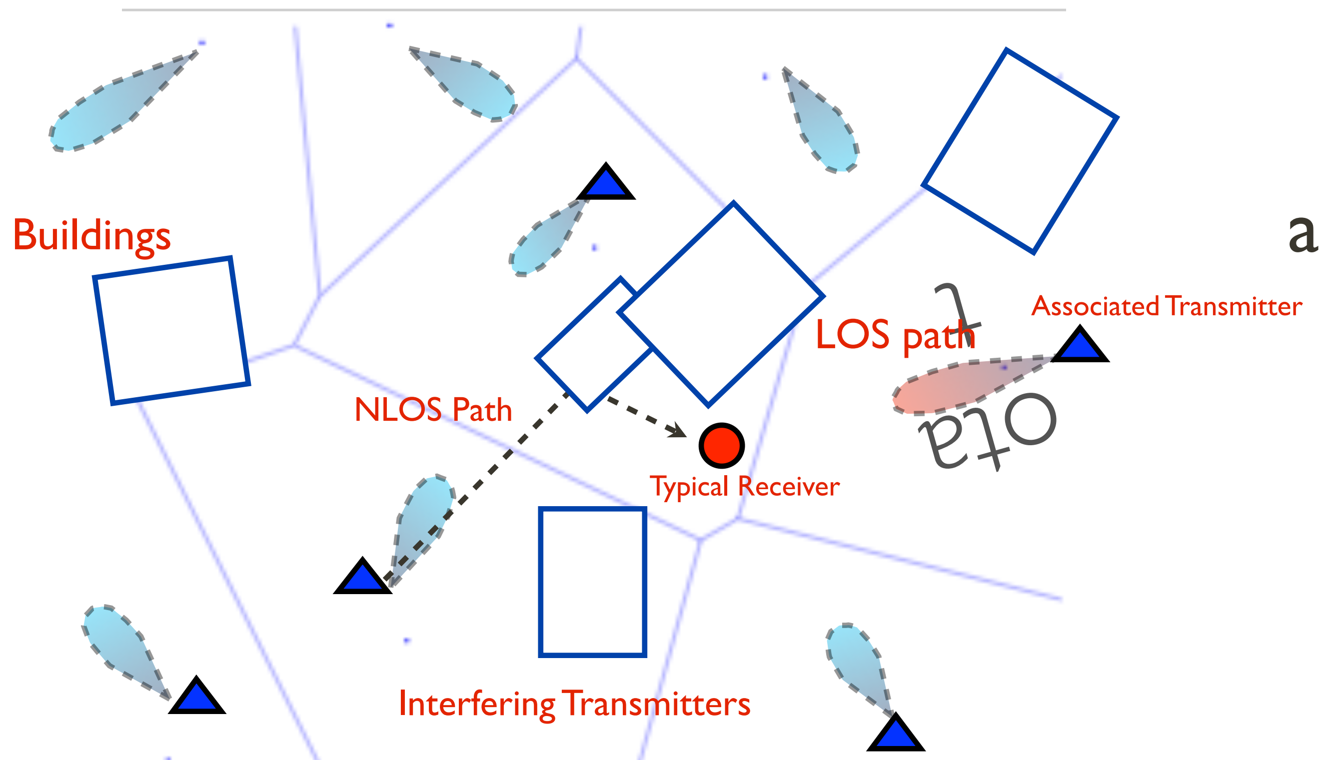
SINR grows as path loss exponent grows

SINR Analysis of Massive mmWave



Sectored beamforming pattern model @ RX





Different path loss exponents in the LOS and NLOS links

The LOS prob. for a link with length d is

$$e^{-\beta d}$$

proportional to building density

T. Bai, R. Vaze, and R. W. Heath, Jr., ``Analysis of Blockage Effects in Urban Cellular Networks", Submitted to IEEE Trans. Wireless Commun., Aug. 2013. On arXiv.
T. Bai and R. W. Heath Jr., "Coverage and rate analysis for millimeter wave cellular networks", submitted to IEEE Trans. Wireless Commun., March 2014. On arXiv.
M. R. Akdeniz, Y. Liu, M. K. Samimi, S. Sun, S. Rangan, T. S. Rappaport, E. Erkip, " Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," available on arXiv.

Channel Model Assumptions

- MmWave channel vector as

Covariance matrix for small-scale fading

$$\mathbf{h}_{\ell n}^{(k)} = \left(\beta_{\ell n}^{(k)} A_{\ell n}^{(k)}\right)^{1/2} \mathbf{\Phi}_{\ell n}^{(k)1/2} \mathbf{w}_{\ell n}^{(k)}$$

Path loss in power — Directivity gain at MS — i.i.d. **Gaussian** vector

- Use blockage model to determine LOS/ NLOS status
  - Path loss exponent 2 in LOS and around 4 in NLOS for $\beta_{\ell n}^{(k)}$
- Assume $\mathbf{\Phi}_{\ell n}^{(k)}$ has rank one for all *M* in all LOS links
  - LOS mmWave channels have few multi-paths
  - Eigenvalue decomposition as $\mathbf{\Phi}_{\ell n}^{(k)} = M \mathbf{u}_{\ell n}^{(k)} \mathbf{u}_{\ell n}^{(k)*}$
- Assume eigenvectors for all LOS links asymptotically orthogonal
  - Requires all angles of arrival non-overlap if using ULA at BSs
- $\mathbf{\Phi}_{\ell n}^{(k)}$ in NLOS paths the same as in microwave case
  - NLOS links potentially have more multi-path

SINR Convergence Results

Lemma 2
For a LOS link, $\mathbf{h}_{\ell n}^{(k)*}\mathbf{h}_{\ell n}^{(k)}/M \xrightarrow{d} \beta_{\ell n}^{(k)} A_{\ell n}^{(k)} |g_{\ell n}^{(k)}|^2$, where $g_{\ell n}^{(k)}$ is i.i.d Gaussian RV.

Lemma 3
For any two mmWave links, $\mathbf{h}_{\ell n}^{(k)*}\mathbf{h}_{\ell' n'}^{(k')}/M \xrightarrow{p} 0.$

Theorem 2 [Asymptotic mmWave DL SINR]
The mmWave downlink SINR converges in distribution as

$$\mathrm{SINR}_{\mathrm{DL}} \xrightarrow{d} \left(t_{00}^{(1)}\right)^2 / \sum_{\ell \neq 0} \left(t_{\ell 0}^{(1)}\right)^2,$$

where for LOS channel $t_{\ell 0}^{(1)} = |g_{\ell 0}^{(1)}|^2 \beta_{\ell 0}^{(1)} A_{\ell 0}^{(1)}$, $g_{\ell 0}^{(1)}$ is i.i.d. Gaussian random variable, and for NLOS channel $t_{\ell 0}^{(1)} = \beta_{\ell 0}^{(1)} A_{\ell 0}^{(1)}$.

- Asymptotic SINR different from microwave due to channel structure
  - Effects of small-scale fading do not totally vanish in low-rank LOS channels
  - Analytical expressions for asymptotic SINR distribution available*

* T. Bai, R. W. Heath, Jr., " Asymptotic coverage and rate analysis in massive MIMO cellular networks", to be submitted soon, prior version available on Arxiv

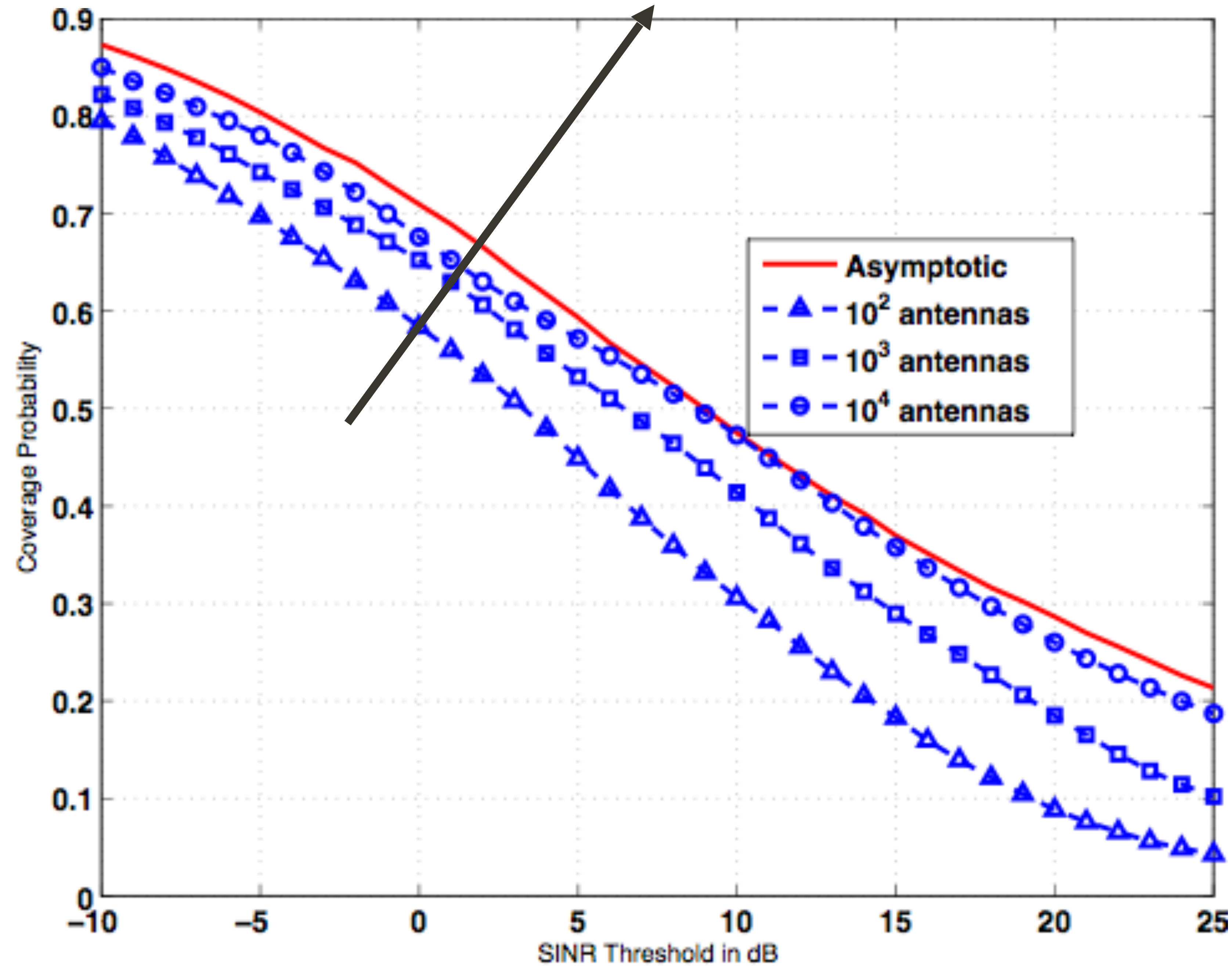
Simulations (1/2)

Blockage model $p(r) = \mathrm{e}^{-\beta r}$

1. LOS prob.
2. Avg. LOS range 200 meters
3. LOS path loss exponent: 2
4. NLOS exponent: 4

No MS beamforming

Convergence to the asymptotic SINR in distribution



Simulations (2/2)

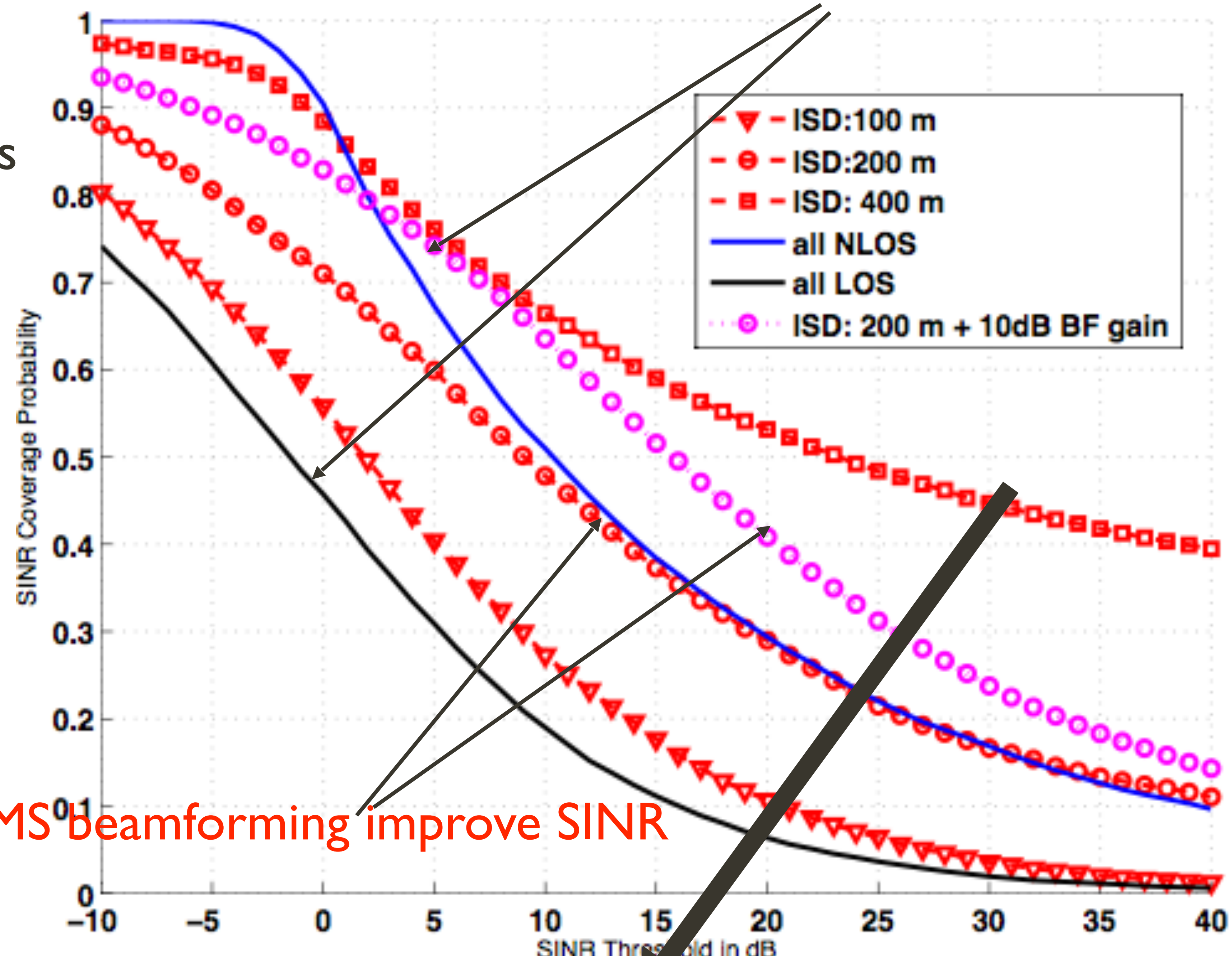
NLOS has better asymptotic SINR than LOS, due to large path loss exponent

Blockage model

1. LOS prob. $p(r) = e^{-\beta r}$
2. Avg. LOS range 200 meters
3. LOS path loss exponent: 2
4. NLOS exponent: 4

mmWave MS beamforming:

1. 10 dB gain
2. 90 degree beam width



MS beamforming improve SINR

Increasing BS density worsen SINR as having more LOS pilot contaminators

Asymptotic Coverage Comparison

Blockage model

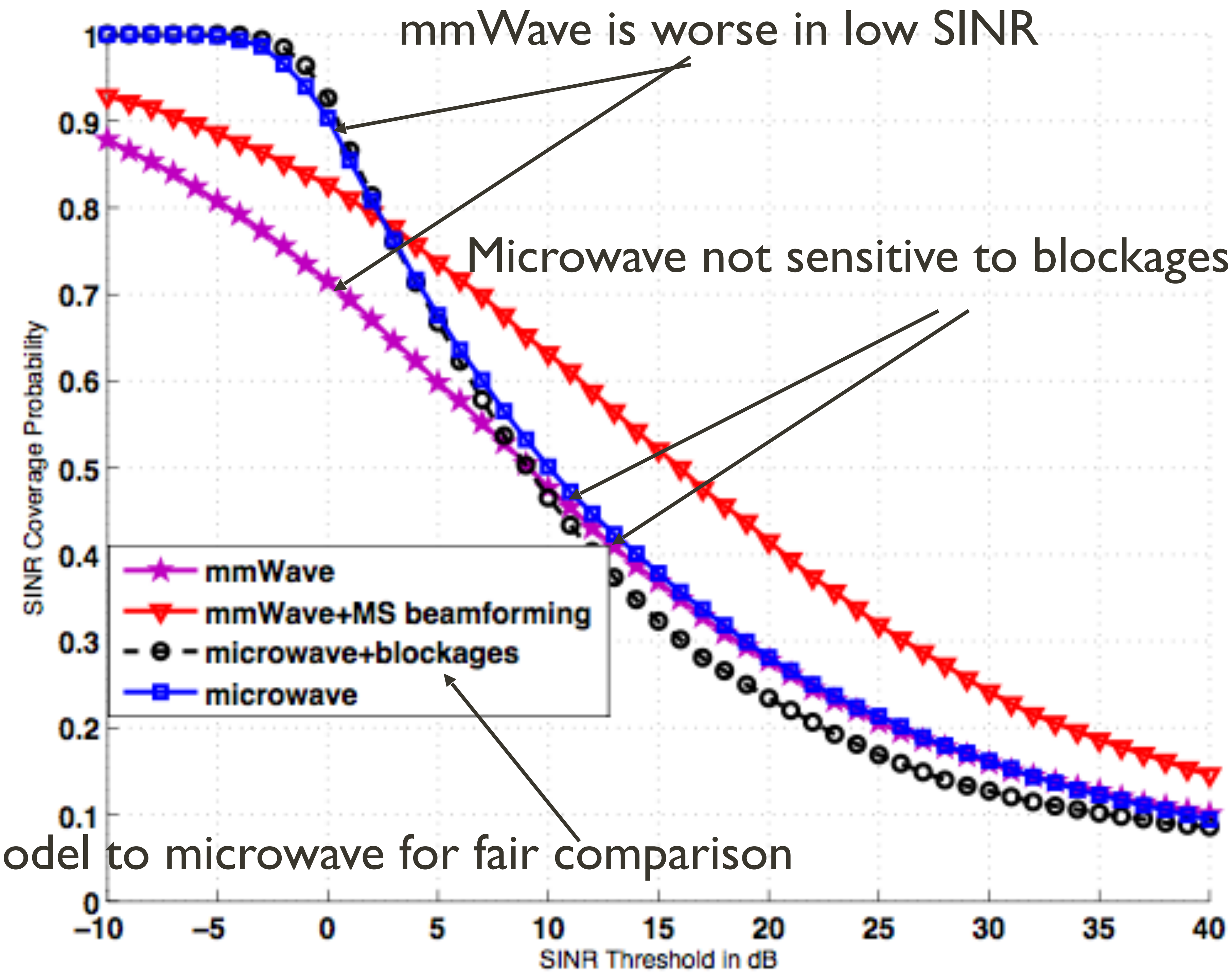
1. LOS prob. $p(r) = \mathrm{e}^{-\beta r}$
2. Avg. LOS range 200 meters
3. LOS path loss exponent: 2
4. NLOS exponent: 4

Avg. ISD: 200 meters

Microwave path loss exponent: 4

mmWave MS beamforming:

1. 10 dB gain
2. 90 degree beam width



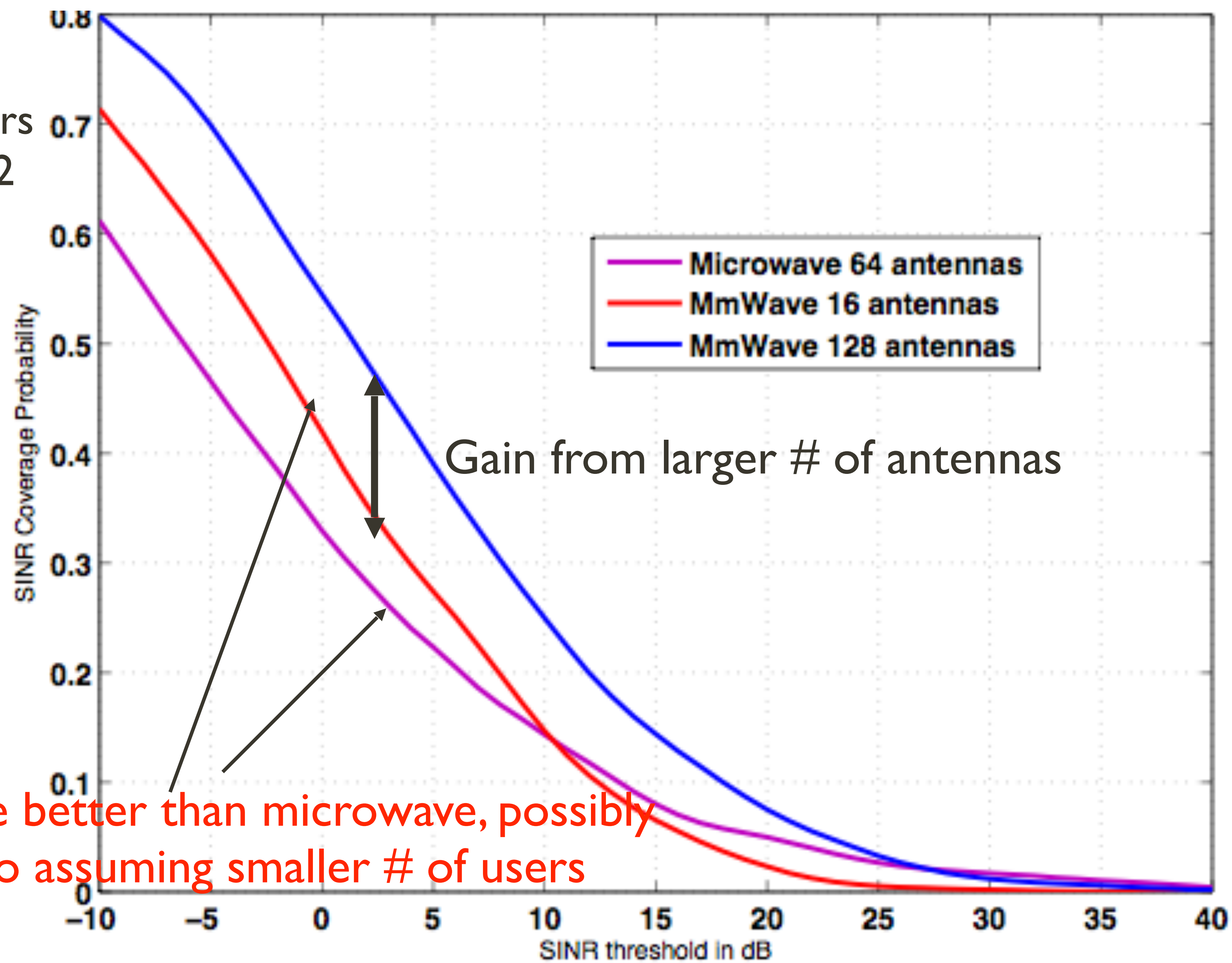
Apply blockage model to microwave for fair comparison

Coverage with Finite Antennas

mmWave blockage model
1. LOS prob. $p(r) = e^{\beta r}$
2. Avg. LOS range 200 meters
3. LOS path loss exponent: 2
4. NLOS exponent: 4

Mmwave
1. Avg. ISD: 200 meters
2. 4 users per cell
3. No MS beamforming

Microwave
1. Avg. ISD 400 meters
2. 10 users per cell
3. path loss exponent: 4



mmWave better than microwave, possibly due to assuming smaller # of users

Training Overhead

	BW (MHz)	T_{OFDM} OFDM symbol time (μs)	T_g CP length (μs)	T_c Coherent time (μs)	OFDM symbol# in a slot	# of users per training symbol
Microwave (2 GHz)	30	71.5	4.76	500	7	14
MmWave* (28 GHz)	500	4.16	0.46	35	8	7

- Using τ OFDM symbol as training, max. # of simultaneous users**

$$K_{\max} = \frac{\tau(T_{\text{OFDM}} - T_g)}{T_g}$$

- Given per user rate R_u, cell throughput can be computed as

$$R_{\text{cell}} = R_u K_{\max} \left(1 - \frac{\tau T_{\text{OFDM}}}{T_c}\right)\left(1 - \frac{T_g}{T_{\text{OFDM}}}\right)$$

Training overhead   Overhead from CP

* Z. Pi. F. Khan, "A millimeter-wave massive MIMO system for next generation mobile broadband," In proc. of *Asilomar*, Nov. 2012
** T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," IEEE Trans. Wireless Commun., Nov., 2010.

Asymptotic Rate Comparison

	Spectrum efficiency (bps/Hz)	# of users/ cell	% useful BW	Cell throughput (Mbps)	ISD (m)	Rate per area (Mbps/km2)
Micro SISO	2.0	1	30*93.4%	56.0	400	446
Micro Massive MIMO	3.6	14	30*80.0%	1209.6	400	9626
Micro Massive MIMO	3.6	14	30*80.0%	1209.6	200	38522
MmWave Massive MIMO	4.0	4	500*77.8%	6224.0	200	198216

20x

4x

5x

MmWave MS beamforming: 10 dB gain with 90 degree beam width

Asymptotic rate gain is substantial

Rate with Finite Antennas

	Spectrum efficiency (bps/Hz)	# of users/ cell	BW* Overhead(MHz)	Cell throughput (Mbps)	ISD (m)	Rate per area (Mbps/km2)
Micro SISO	2.0	1	30*93.4%	56.0	400	446
						20x
Micro 64 antennas	1.2	10	30*80.0%	288.0	400	2292
						4x
Micro 64 antennas	1.2	10	30*80.0%	288.0	200	9172
				7x		7x
MmWave 16 antennas	1.4	4	500*77.8%	2178.4	200	69376
				1.6x		
MmWave 128 antennas	2.2	4	500*77.8%	3423.2	200	109019

MmWave MS beamforming: 10 dB gain with 90 degree beam width

Still notably large gain with finite antennas

Conclusion

Go Massive