# Comparing Massive MIMO
# and
# mmWave MIMO

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Joint work with Tianyang Bai

WNCG

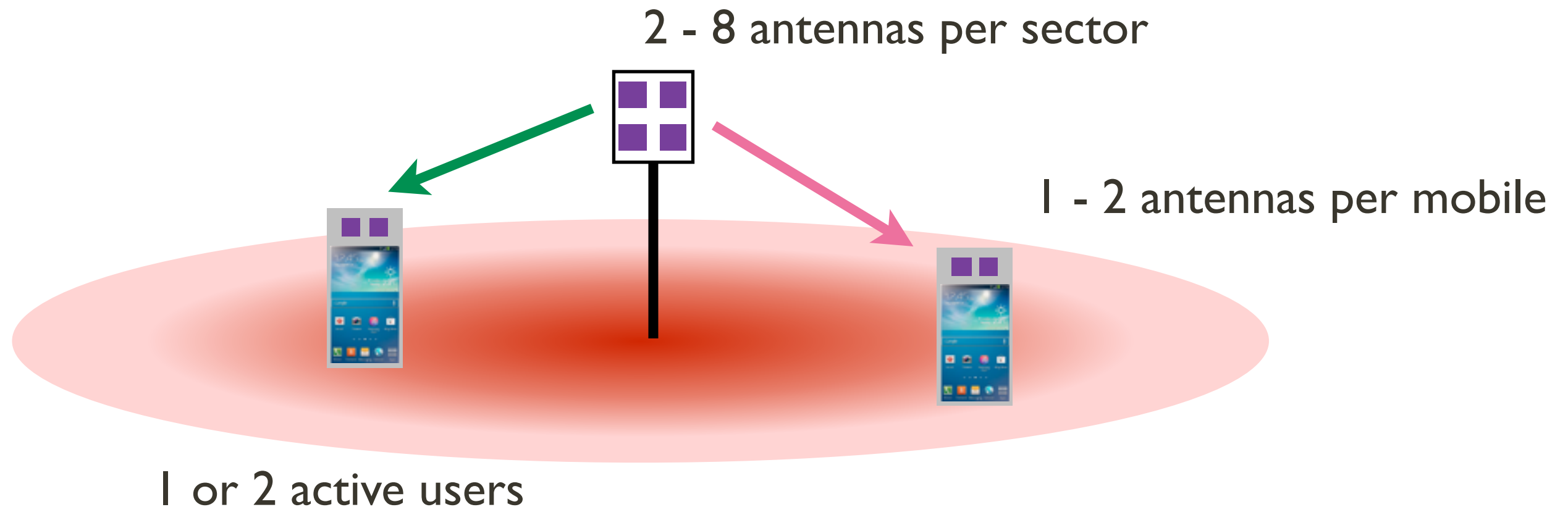www.profheath.org

# Going Towards 5G with MIMO

2 - 8 antennas per sector



1 - 2 antennas per mobile

1 or 2 active users

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?



higher order multiplexing

much more space required on device
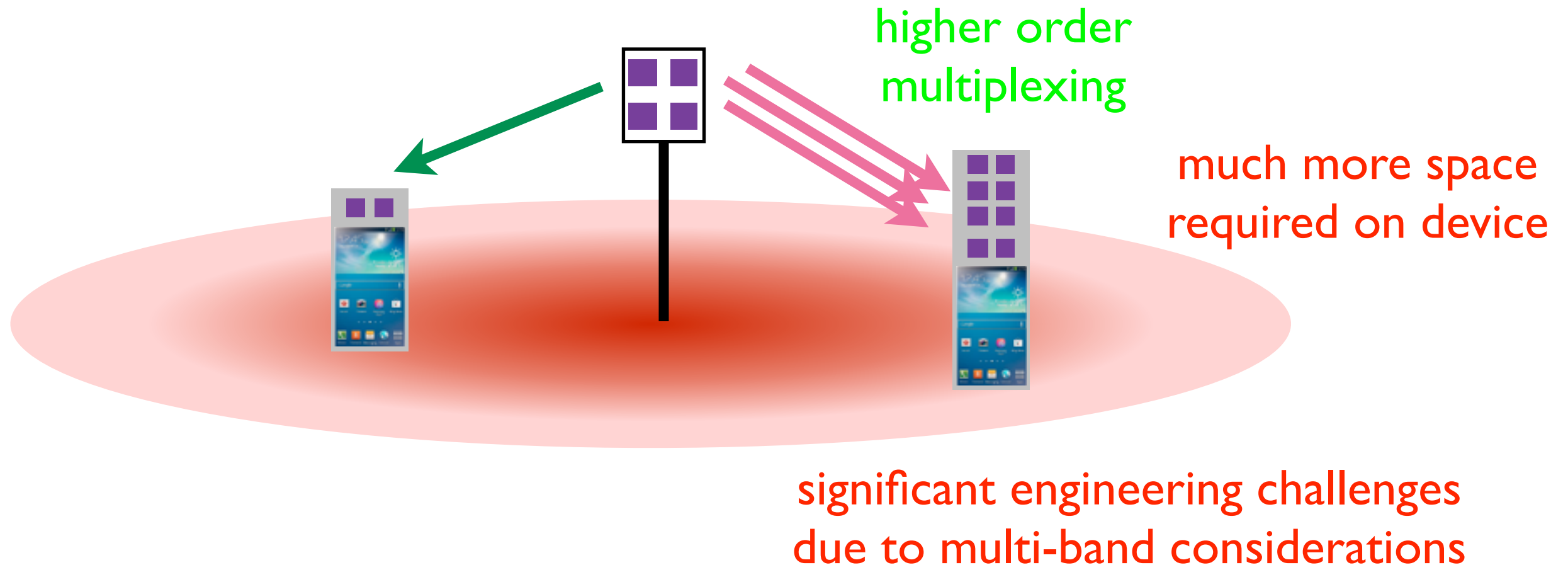
significant engineering challenges due to multi-band considerations

[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*

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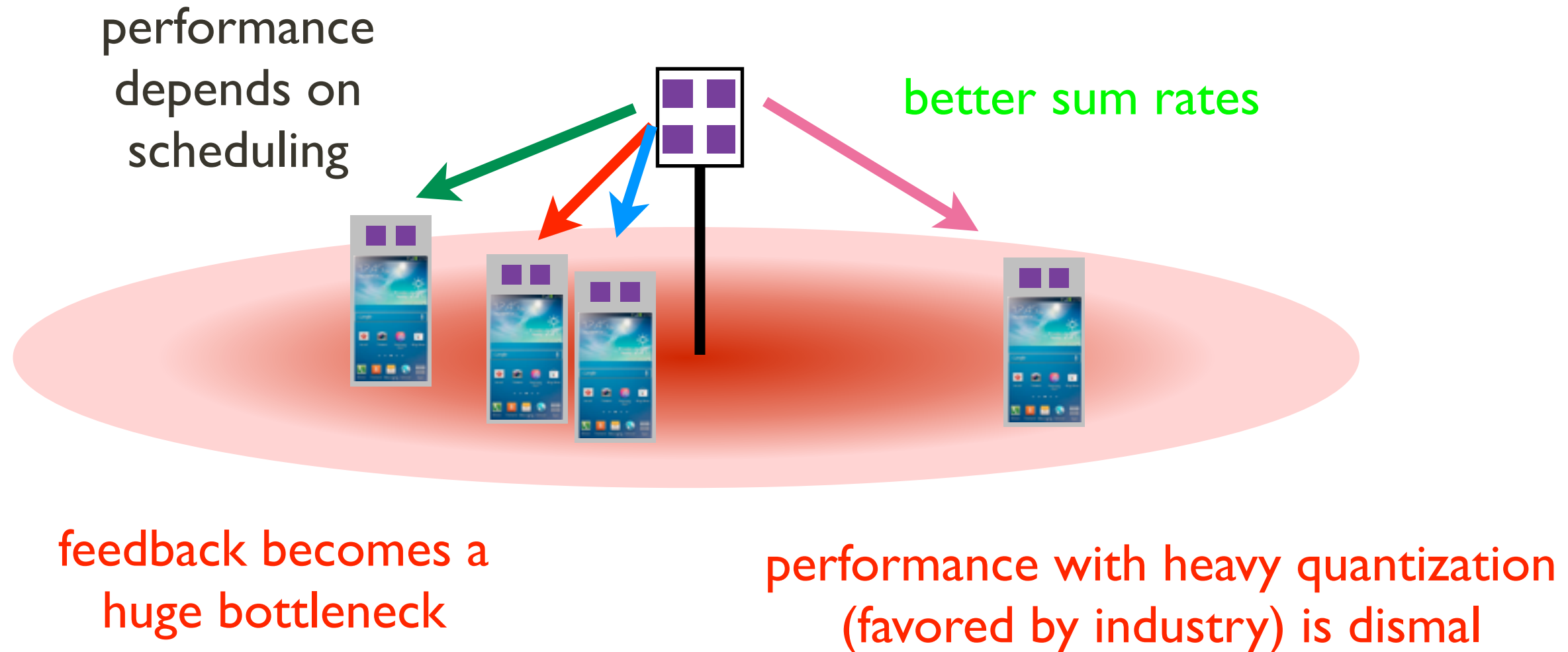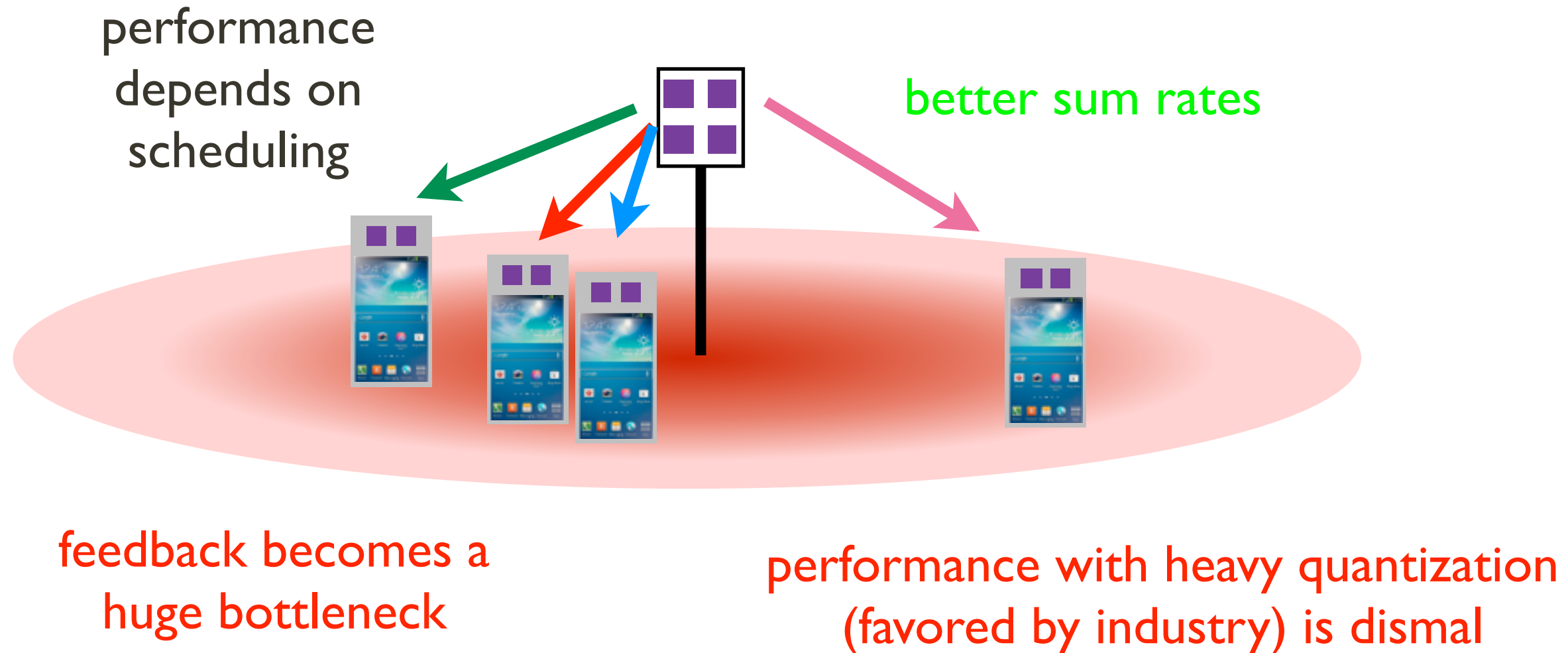
# Going Towards 5G with MIMO

## 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

THE UNIVERSITY OF
TEXAS
AT AUSTIN

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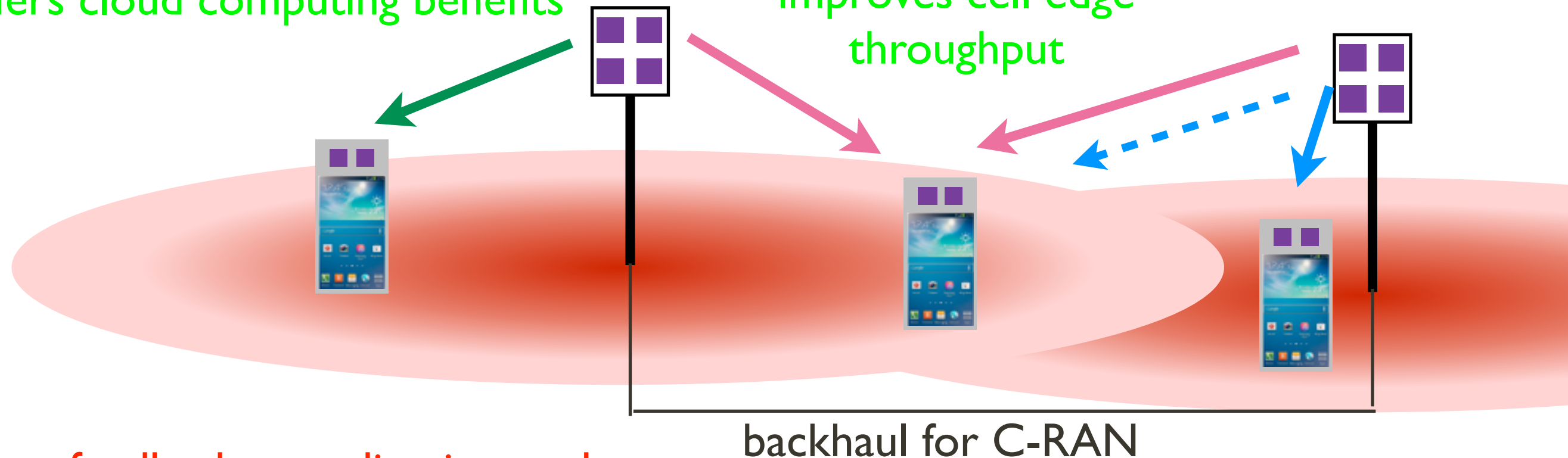performance with heavy quantization (favored by industry) is dismal

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# 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.
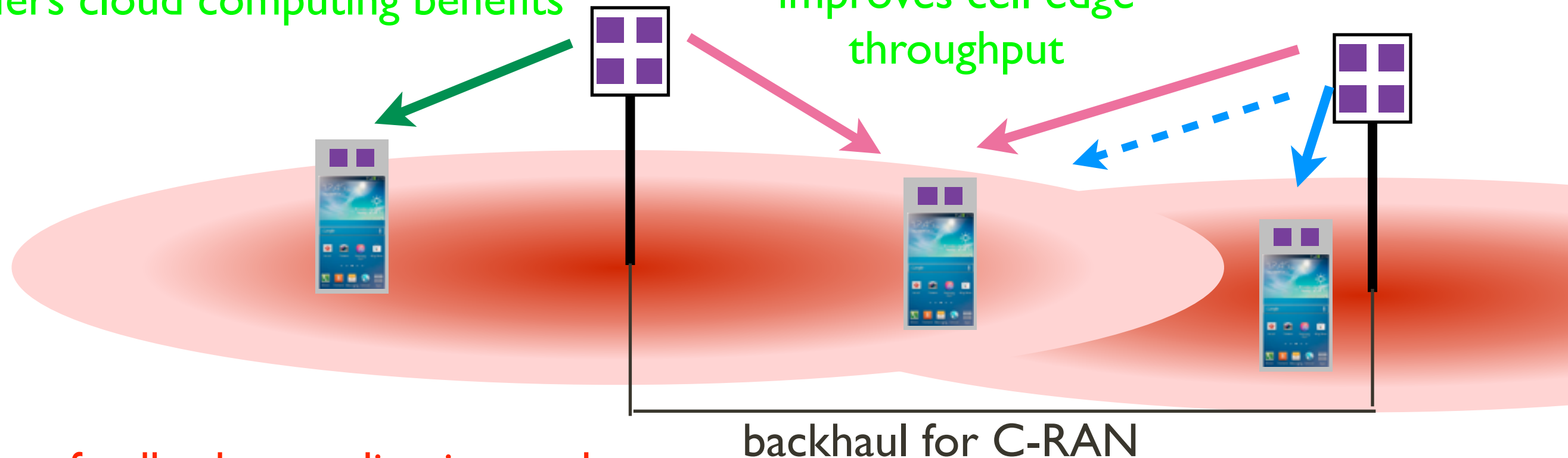[C-RAN] C-RAN: the road toward green RAN, white paper by China Mobile, Oct, 2011

# Going Towards 5G with MIMO

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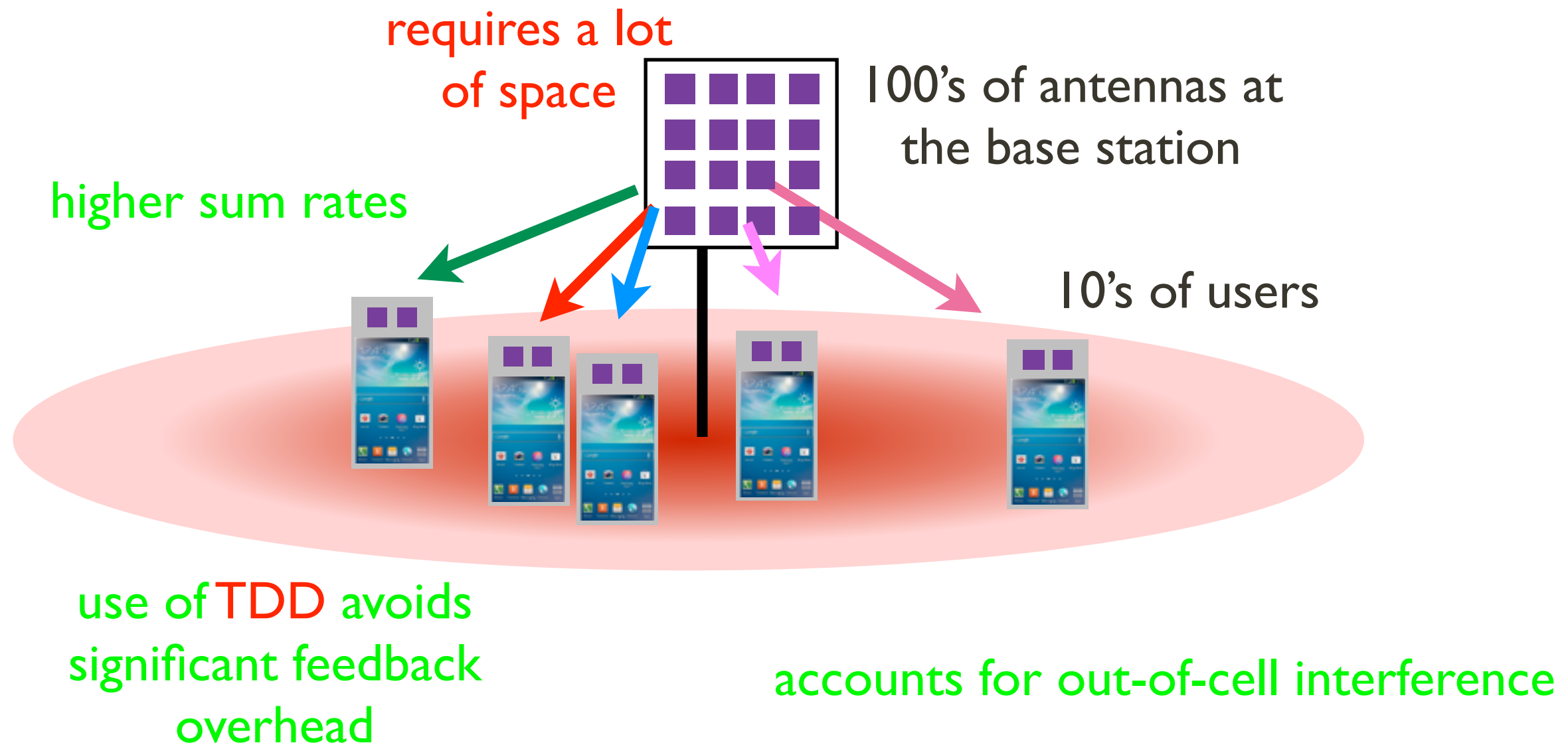scheduling lead to practical losses

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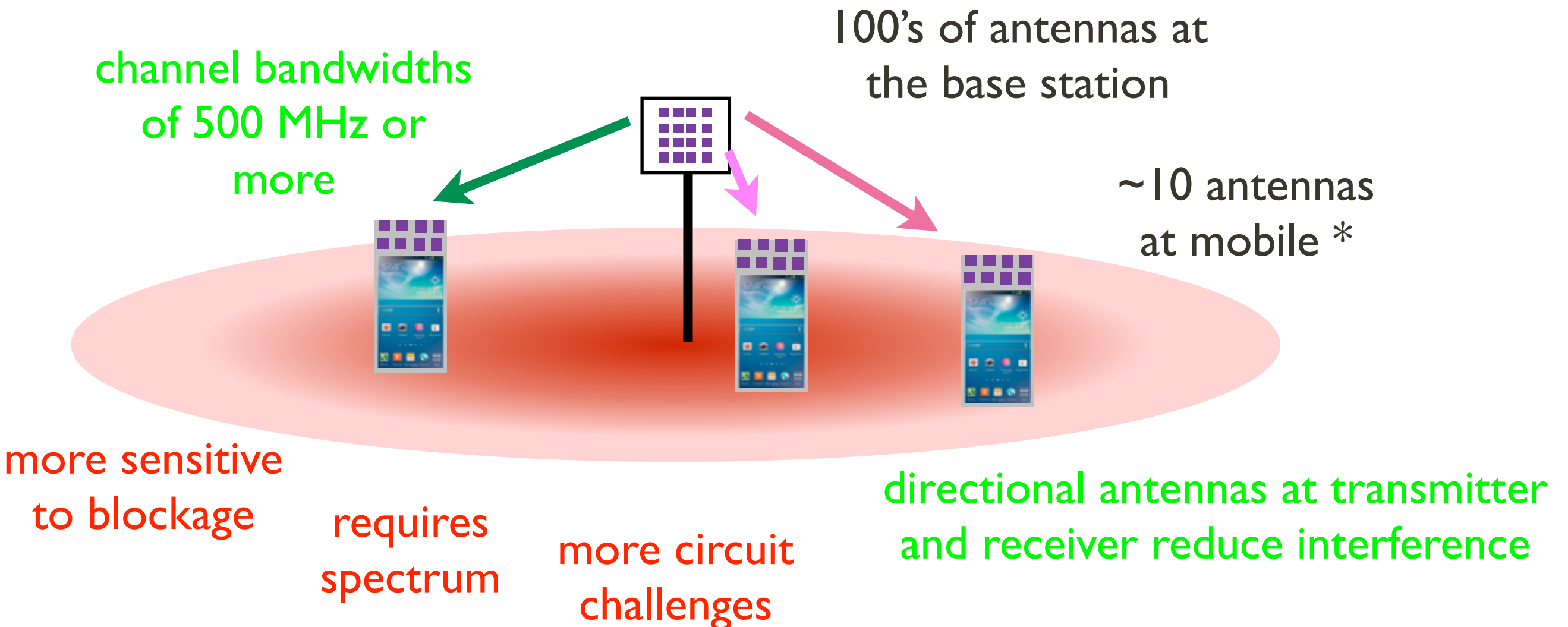
# Going Towards 5G with MIMO

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?

100's of antennas at the base station

channel bandwidths of 500 MHz or more

~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



M antennas at BS

Single antenna at MS
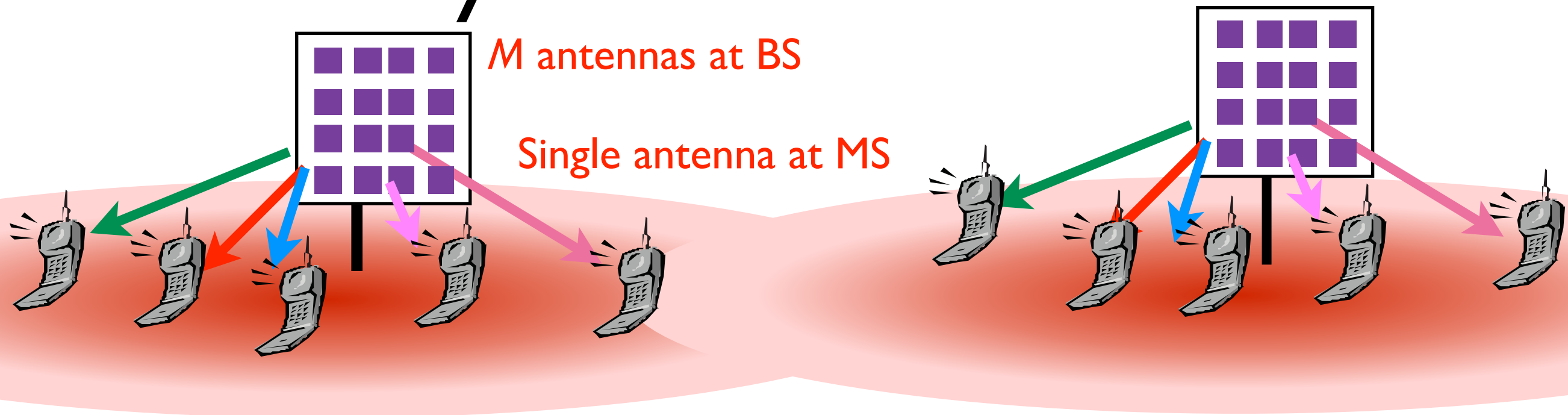
Channel estimate of $\ell$-th BS to its k-th user

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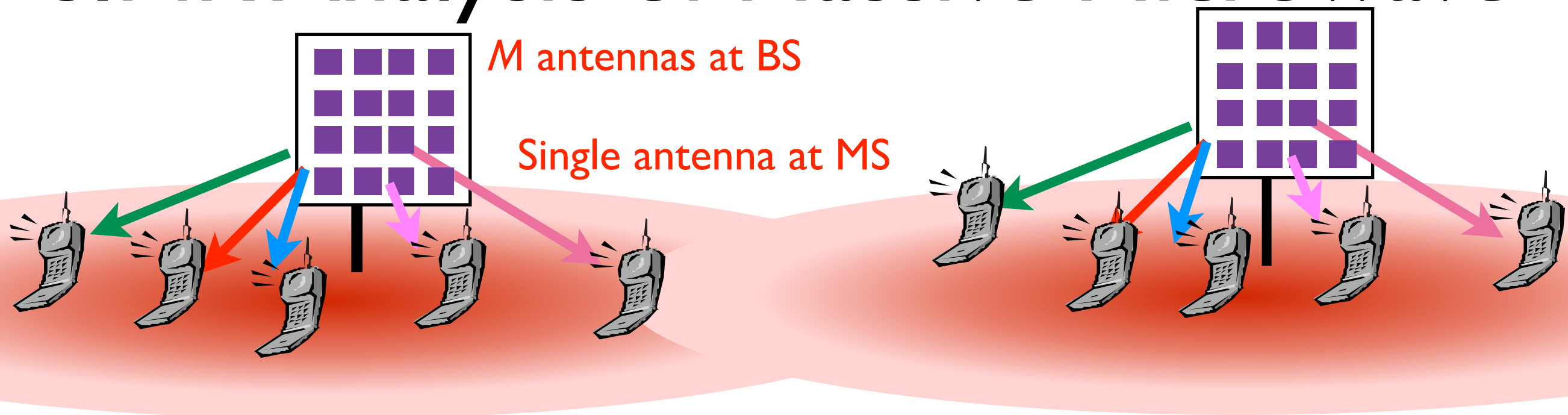
pilot contamination

interference

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

inside-of-cell          out-of-cell

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

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# SINR Analysis of Massive Microwave



**M antennas at BS**

**Single antenna at MS**

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interference

infinite # interferers

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inside-of-cell    out-of-cell

# Channel Model Assumptions

* $M$ antennas at BS & single antenna at MS
  * 🔴 Channel vector modeled as <span style="color:red">Covariance matrix for small-scale fading</span>

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

<span style="color:red">Path loss in power</span>  <span style="color:red">i.i.d. random vector</span>

* 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 $\boldsymbol{\Phi}_{\ell n}^{(k)}$ 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 $\boldsymbol{\Phi}_{\ell n}^{(k)}$ 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

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 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 $\mathbf{h}_{\ell\ell'}^{(k)*} \mathbf{h}_{ss'}^{(n)}/M \xrightarrow{p.} 0$.

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

SIR limited by pilot contamination

$$\text{SIR}_{\text{DL}} \xrightarrow{p} \beta_{00}^{(1)2} / \left( \sum_{\ell > 0} \beta_{\ell 0}^{(1)2} \right).$$
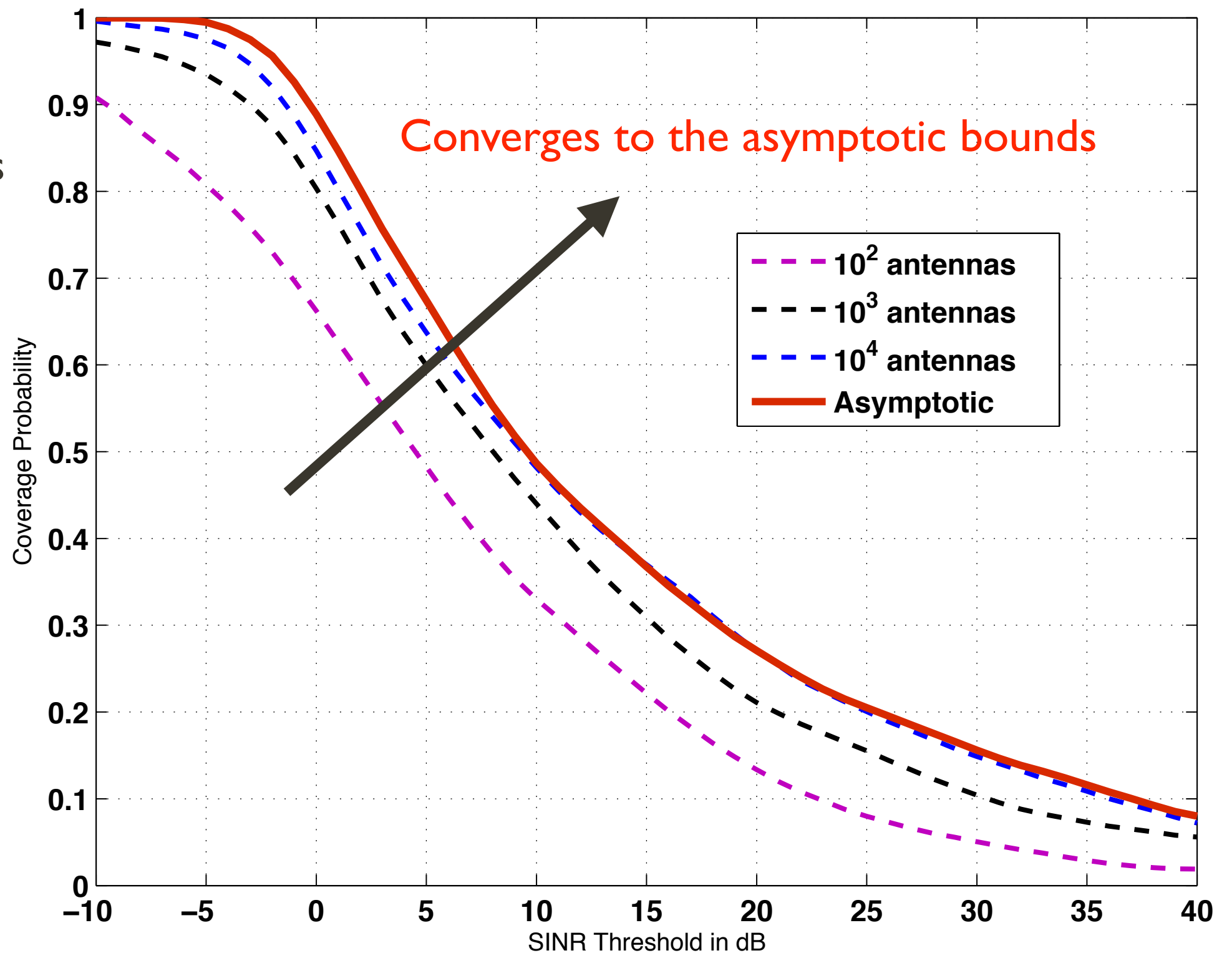
The CCDF of the asymptotic SIR approximately equals

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

An increasing function of path loss exponent

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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
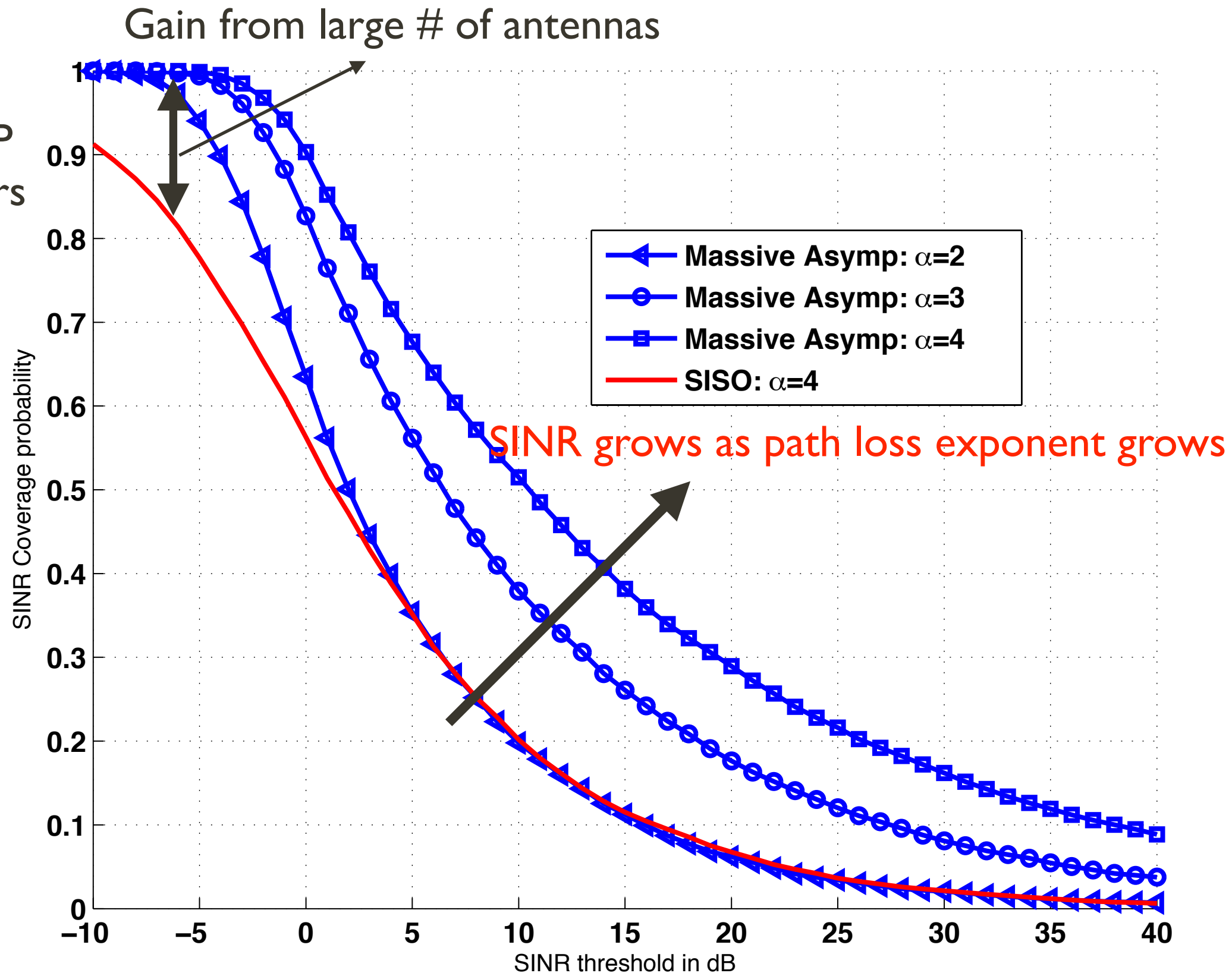
🔴 Asymptotic rate are the same in downlink and uplink

 **13**

# SINR Simulations(1/2)
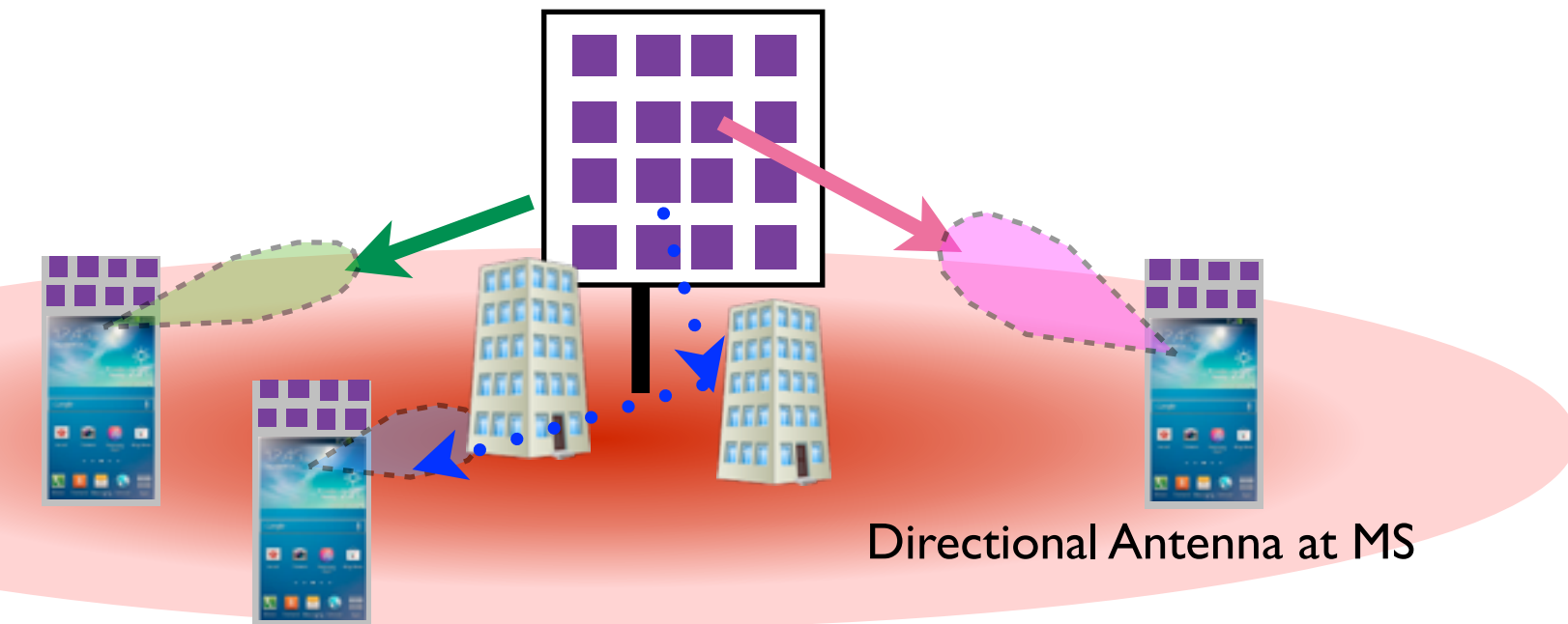


BS distributed as PPP
Assume i.i.d fading
Avg. ISD: 1000 meters

Converges to the asymptotic bounds

Coverage Probability

SINR Threshold in dB

- – – $10^2$ antennas
- – – $10^3$ antennas
- – – $10^4$ antennas
- —— Asymptotic

# SINR Simulations(2/2)



Gain from large # of antennas

BS distributed as PPP
Avg. ISD: 1000 meters

SINR Coverage probability

SINR threshold in dB

Massive Asymp: $\alpha=2$
Massive Asymp: $\alpha=3$
Massive Asymp: $\alpha=4$
SISO: $\alpha=4$

SINR grows as path loss exponent grows

# SINR Analysis of Massive mmWave



Directional Antenna at MS

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.

# SINR Analysis of Massive mmWave



Sectored beamforming pattern model @ RX

Back lobe gain

Main lobe array gain

NLOS link by reflections

Indoor BS

Typical user

NLOS BS

Directional beamforming

$m$

$M$

LOS BS

Directional Antenna

$\theta$

Random blockage process

Main lobe beamwidth

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Back lobe gain

Main lobe array gain

Typical user

Indoor BS

NLOS BS

m

M

Directional beamforming

θ

LOS BS

Directional Antenna

Main lobe beamwidth

Random blockage process

Buildings

Different path loss exponents in the LOS and NLOS links

LOS path

Associated Transmitter

NLOS Path

Typical Receiver

The LOS prob. for a link with length d is

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

proportional to building density

Interfering Transmitters

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.
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# Channel Model Assumptions

✳ MmWave channel vector as

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

Covariance matrix for small-scale fading

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*

# Simulations (1/2)

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



Legend:
- Asymptotic
- $10^2$ antennas
- $10^3$ antennas
- $10^4$ antennas

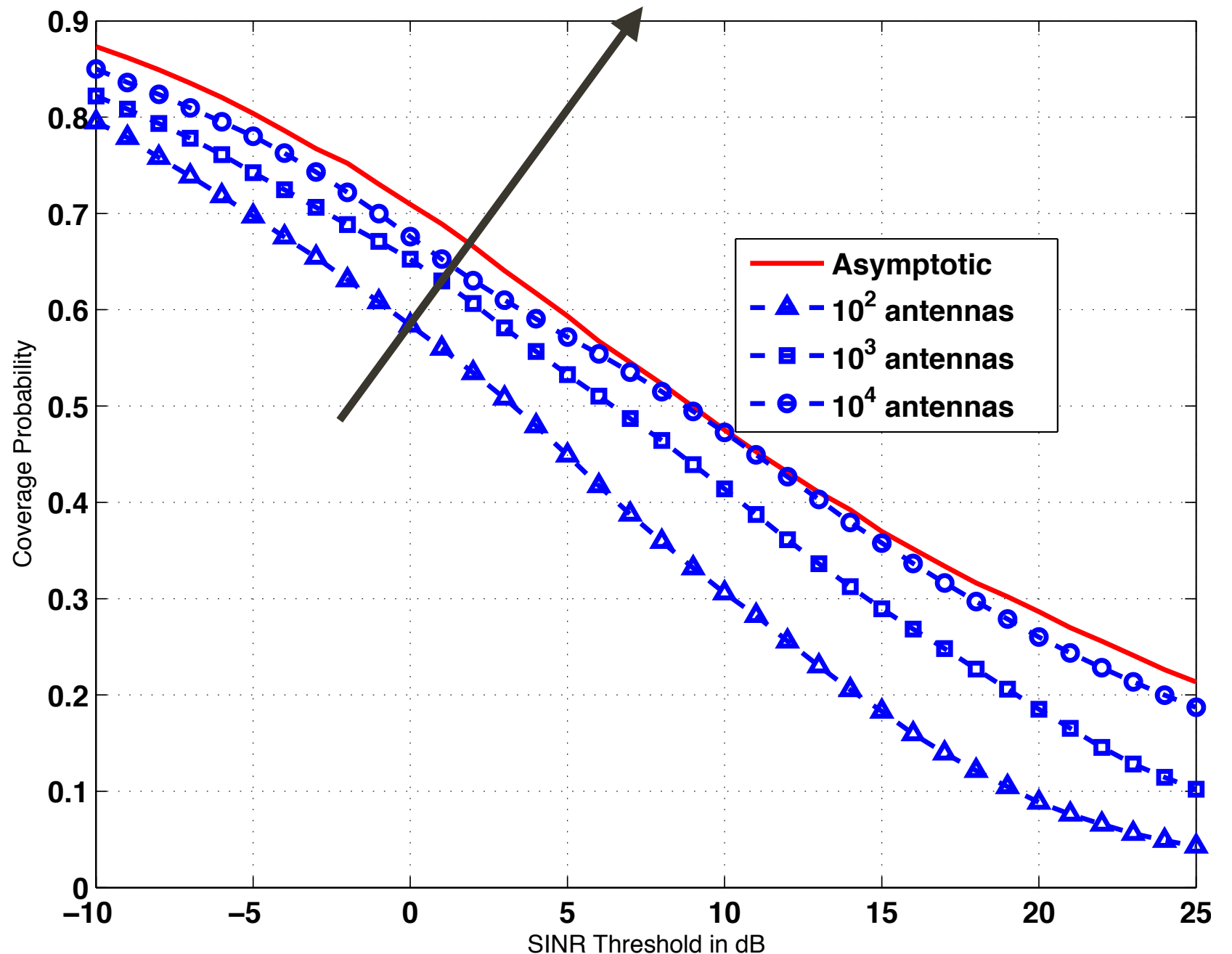X-axis: SINR Threshold in dB
Y-axis: Coverage Probability

# Simulations (2/2)

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

# Simulations (2/2)

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

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Legend:
- ISD:100 m
- ISD:200 m
- ISD: 400 m
- all NLOS
- all LOS
- ISD: 200 m + 10dB BF gain

X-axis: SINR Threshold in dB
Y-axis: SINR Coverage Probability

# Simulations (2/2)

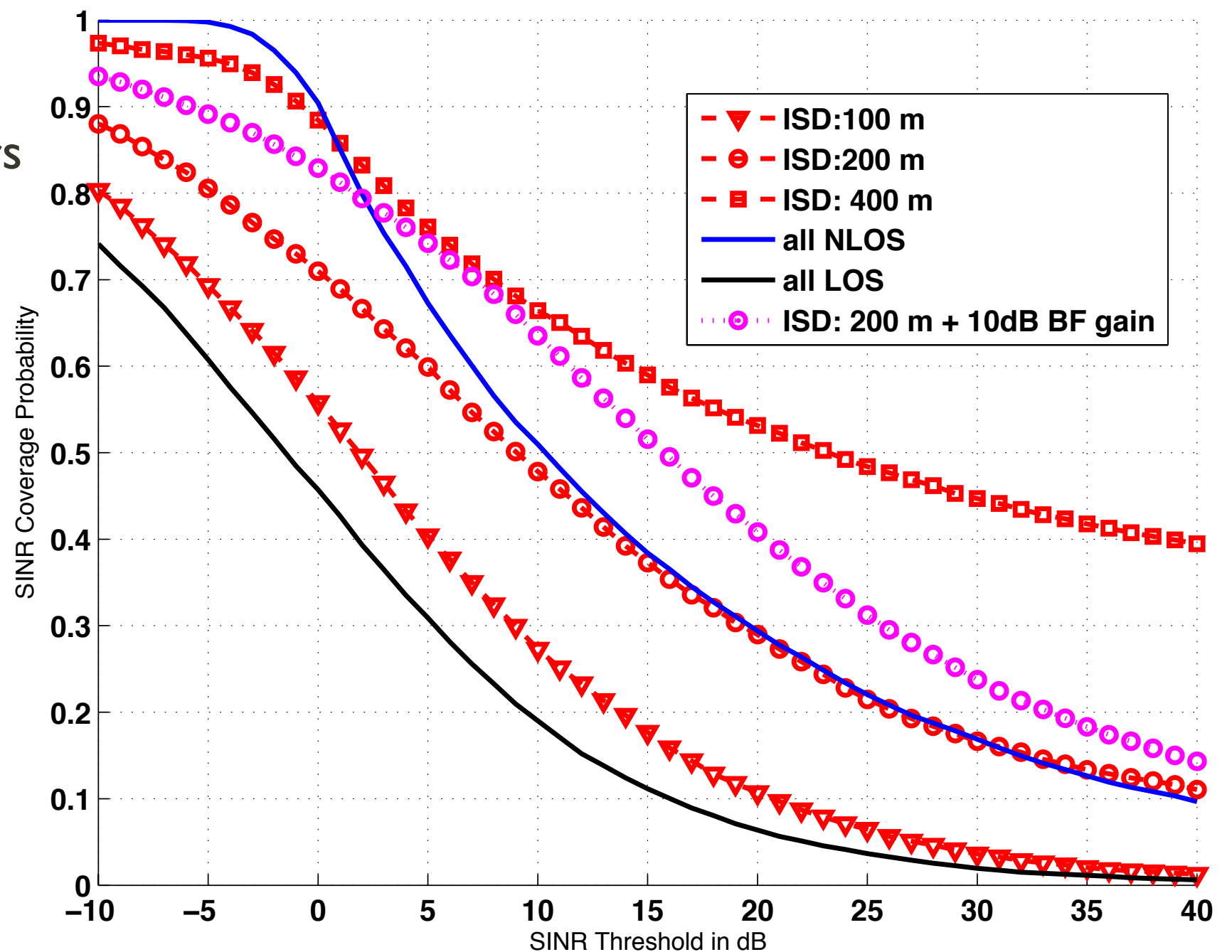NLOS has better asymptotic SINR than LOS, due to large path loss exponent

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- ISD:100 m
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- all LOS
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SINR Coverage Probability (y-axis)

SINR Threshold in dB (x-axis)

MS beamforming improve SINR
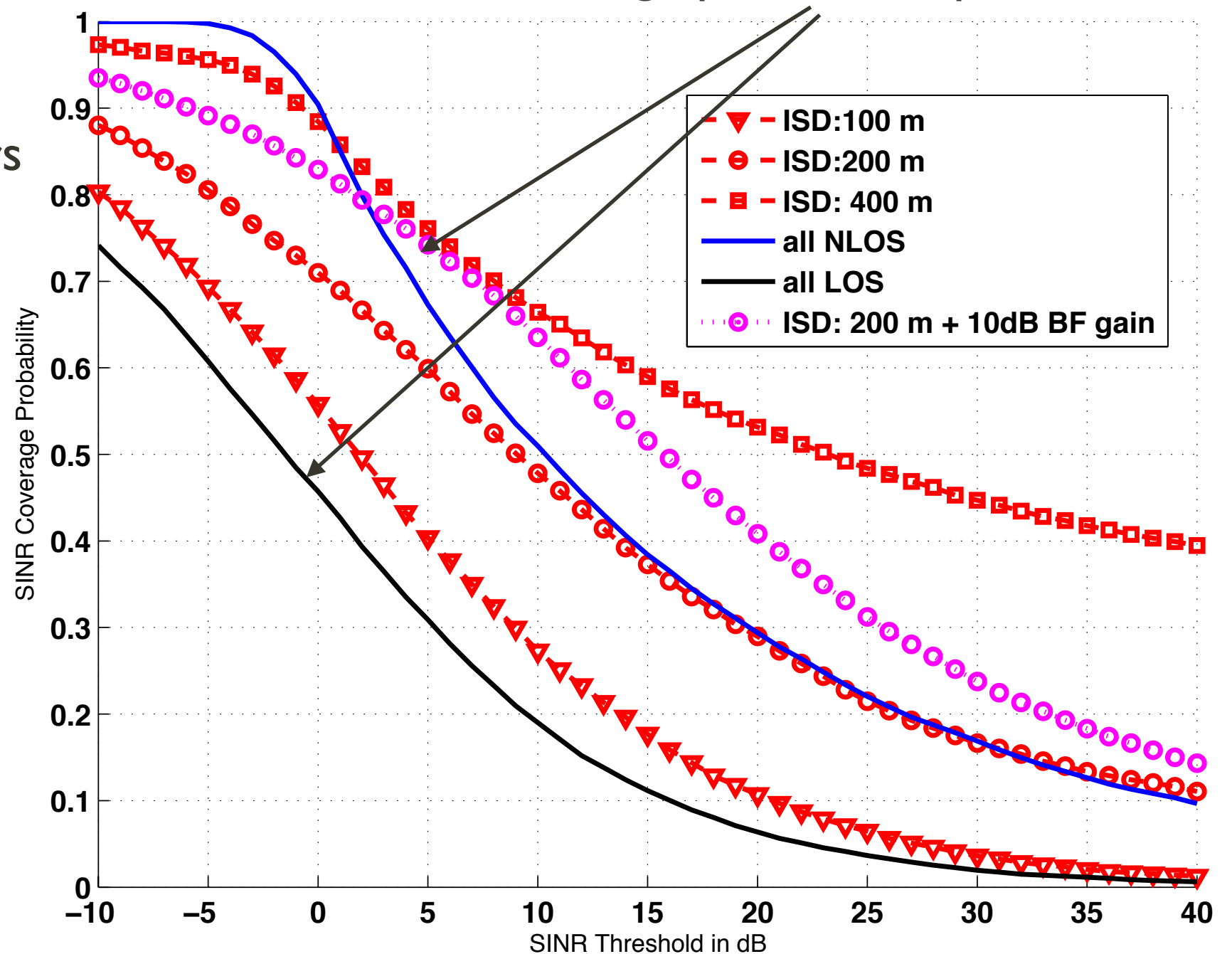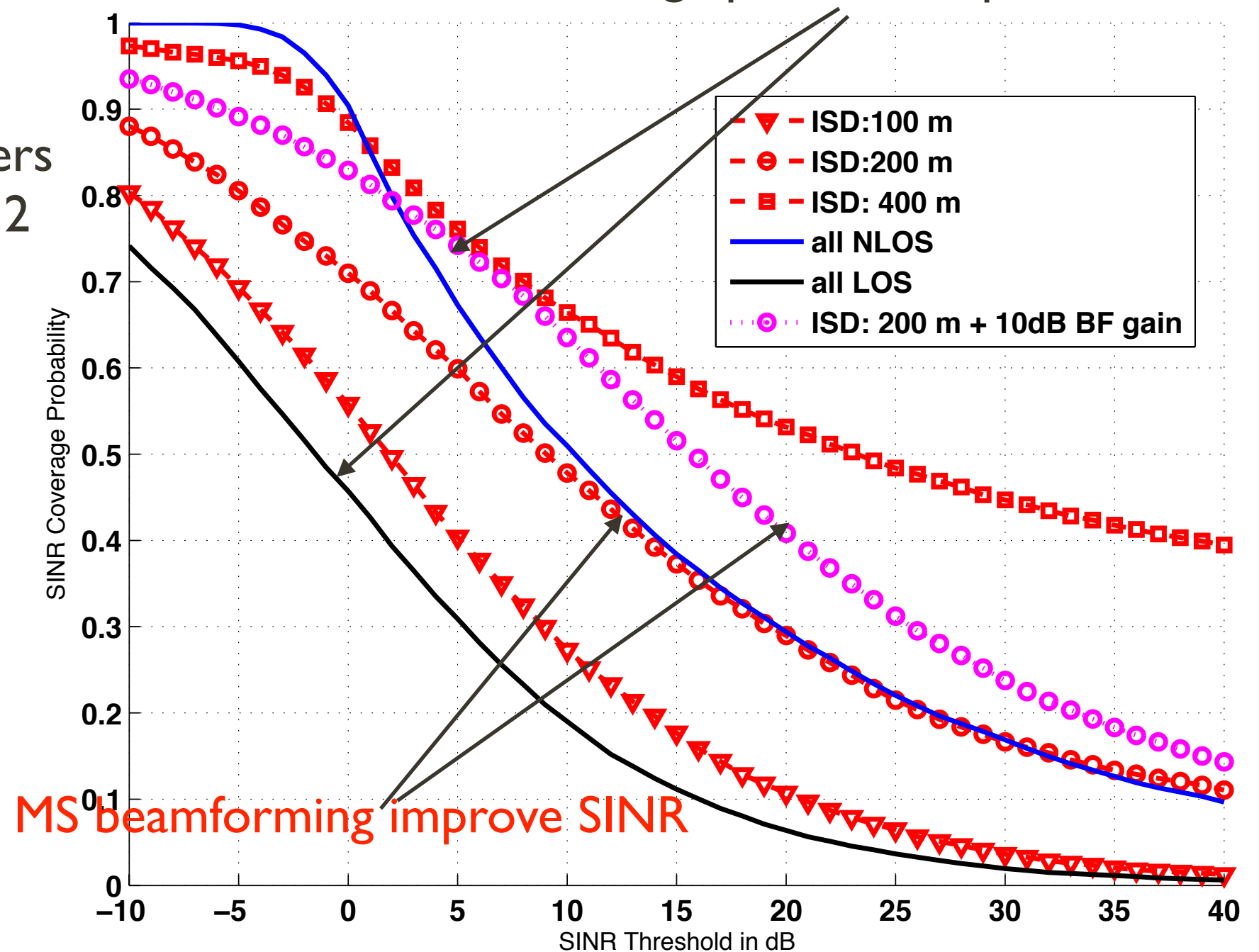
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Legend:
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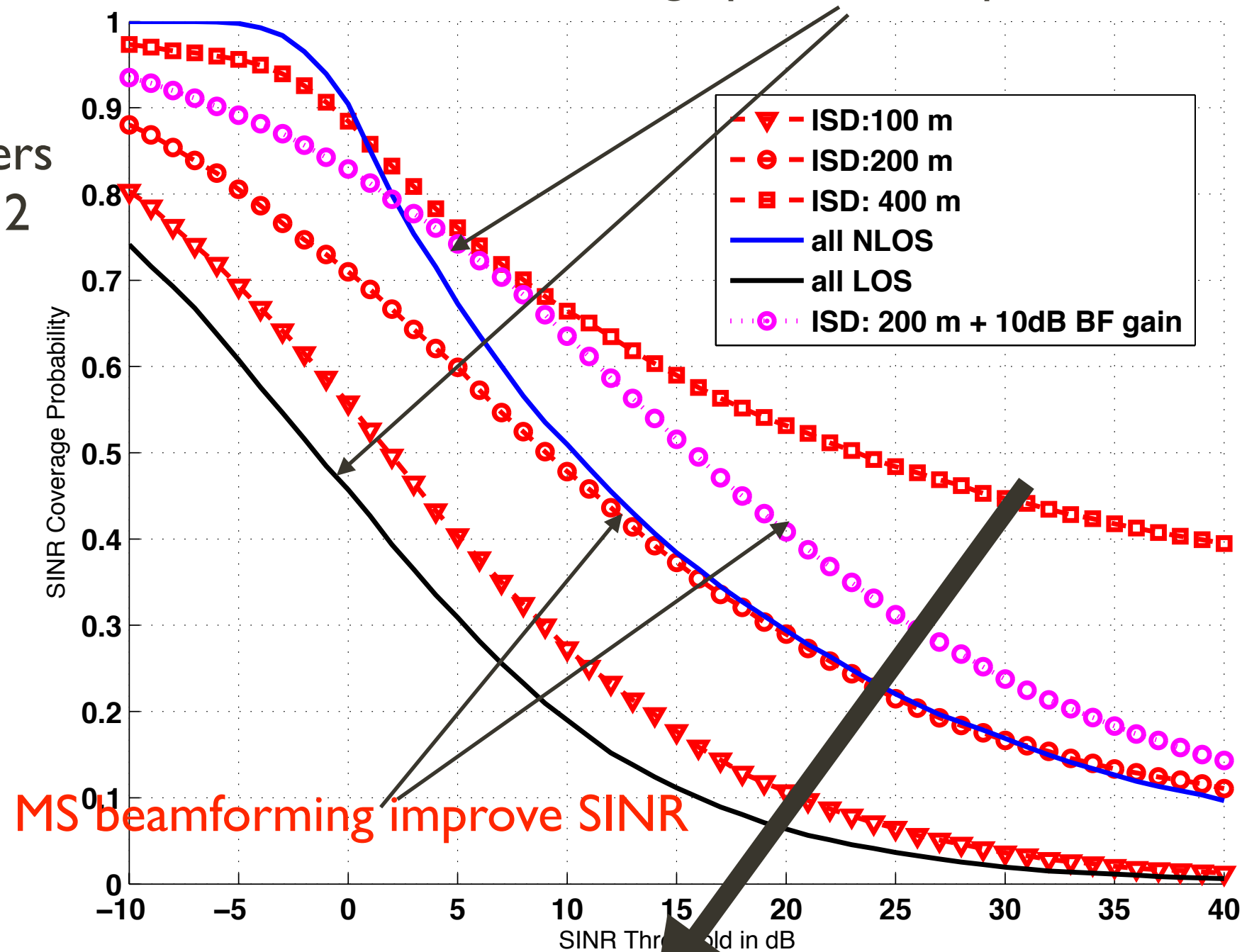- ISD: 200 m
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- all NLOS
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SINR Coverage Probability (y-axis)
SINR Threshold in dB (x-axis)

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

mmWave is worse in low SINR

Microwave not sensitive to blockages

Apply blockage model to microwave for fair comparison

Legend:
- mmWave
- mmWave+MS beamforming
- microwave+blockages
- microwave

Y-axis: SINR Coverage Probability
X-axis: SINR Threshold in dB
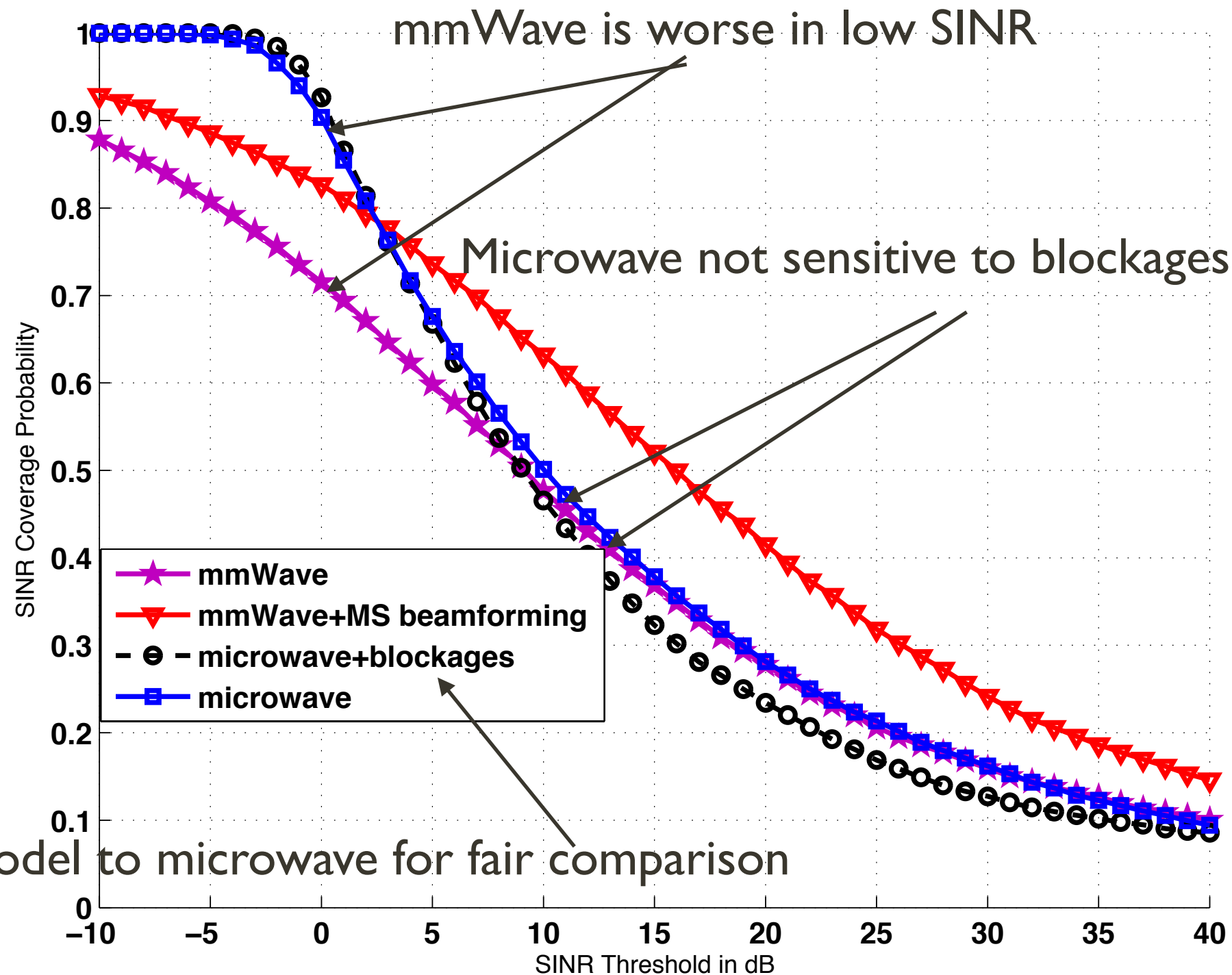
# Coverage with Finite Antennas

mmWave blockage model
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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



Legend:
- Microwave 64 antennas
- MmWave 16 antennas
- MmWave 128 antennas

Gain from larger # of antennas

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

X-axis: SINR threshold in dB
Y-axis: SINR Coverage Probability
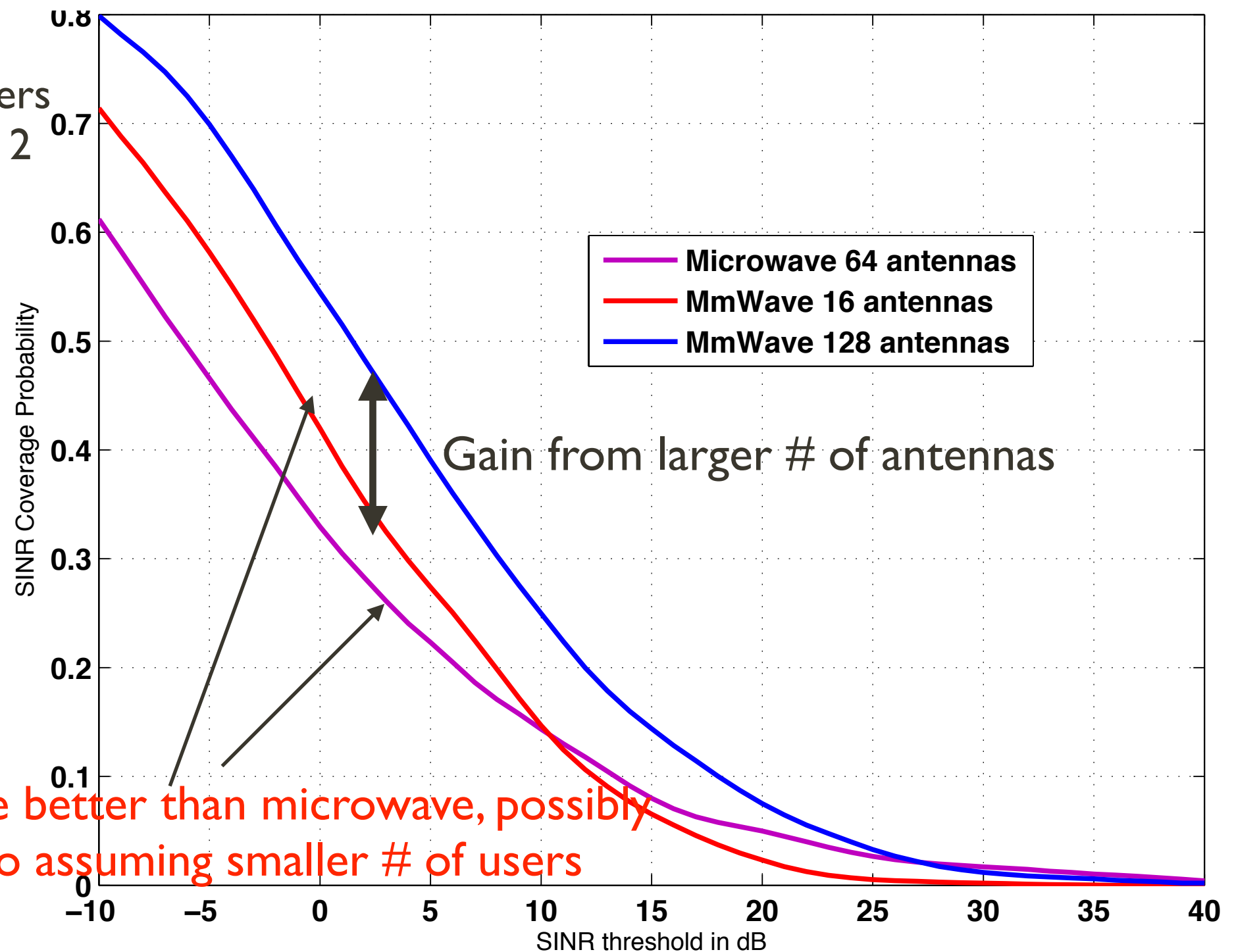
# Training Overhead

| | BW (MHz) | $T_{\text{OFDM}}$ OFDM symbol time ($\mu$s) | $T_{\text{g}}$ CP length ($\mu$s) | $T_{\text{c}}$ Coherent time ($\mu$s) | 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 $\tau$ OFDM symbol as training, max. # of simultaneous users**

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

✳ Given per user rate $R_{\text{u}}$, cell throughput can be computed as

$$R_{\text{cell}} = R_{\text{u}} K_{\text{max}} \left(1 - \frac{\tau T_{\text{OFDM}}}{T_{\text{c}}}\right) \left(1 - \frac{T_{\text{g}}}{T_{\text{OFDM}}}\right)$$

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 |
| Micro 64 antennas | 1.2 | 10 | 30*80.0% | 288.0 | 400 | 2292 |
| Micro 64 antennas | 1.2 | 10 | 30*80.0% | 288.0 | 200 | 9172 |
| MmWave 16 antennas | 1.4 | 4 | 500*77.8% | 2178.4 | 200 | 69376 |
| MmWave 128 antennas | 2.2 | 4 | 500*77.8% | 3423.2 | 200 | 109019 |

20x

4x

7x        7x

1.6x

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

Still notably large gain with finite antennas

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# Conclusion

## Go Massive