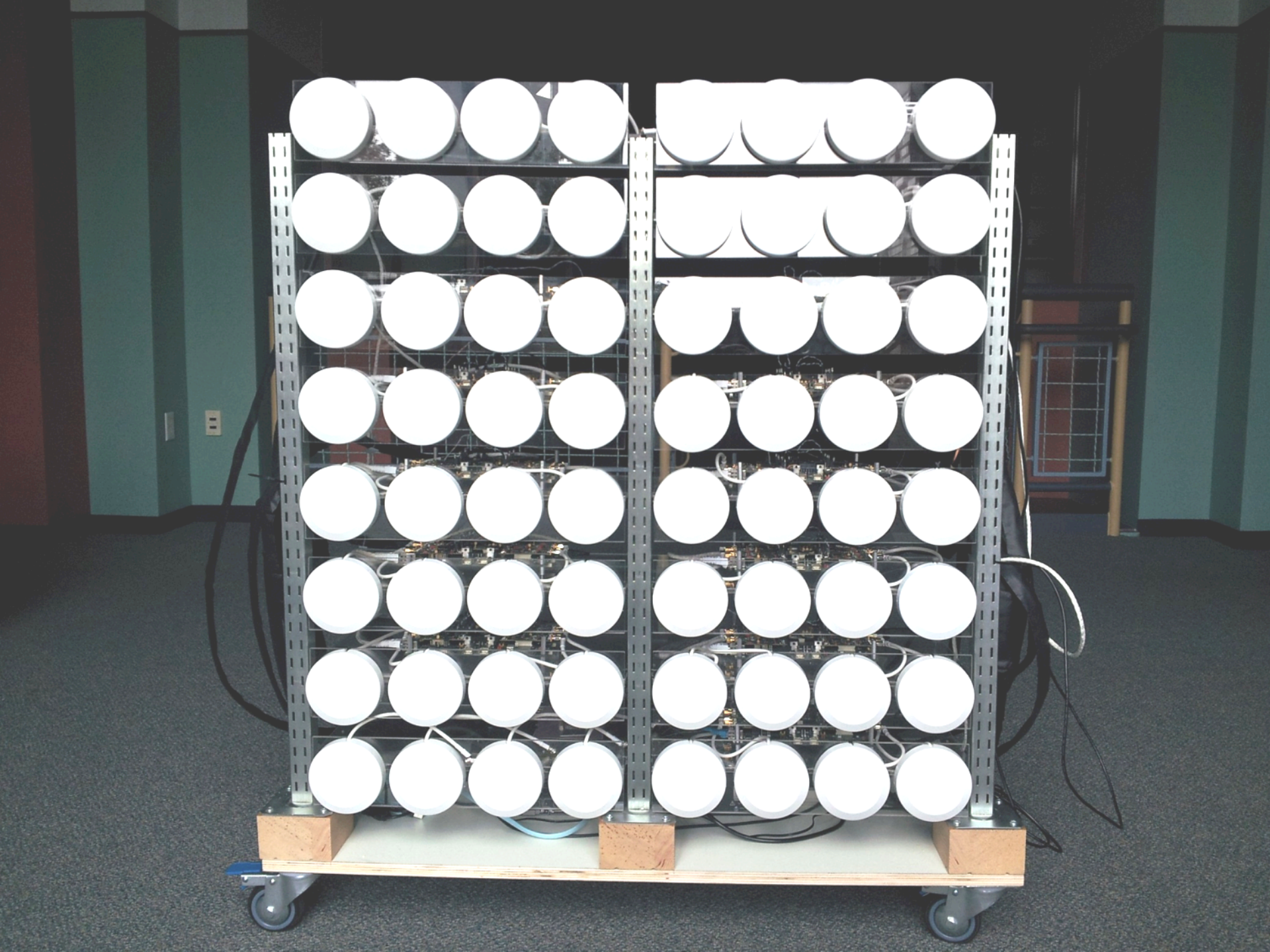
Many-antenna base stations are interesting systems

Lin Zhong
http://recg.org

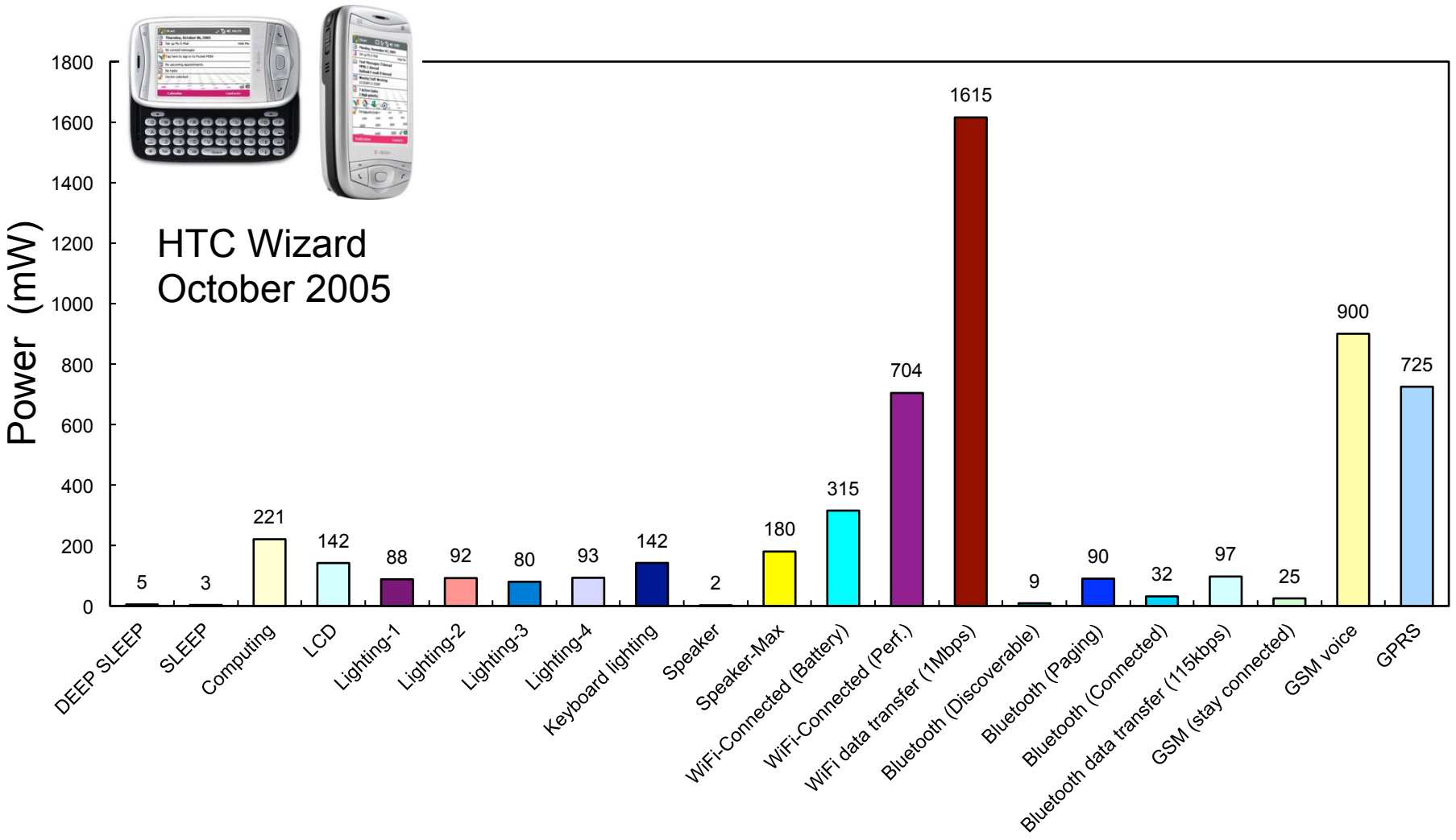


- How we got started
- Why many-antenna base station
- What we have learned
- What we are doing now

How we started

Why a mobile system guy got interested in massive MIMO

Wireless consumes a lot of power



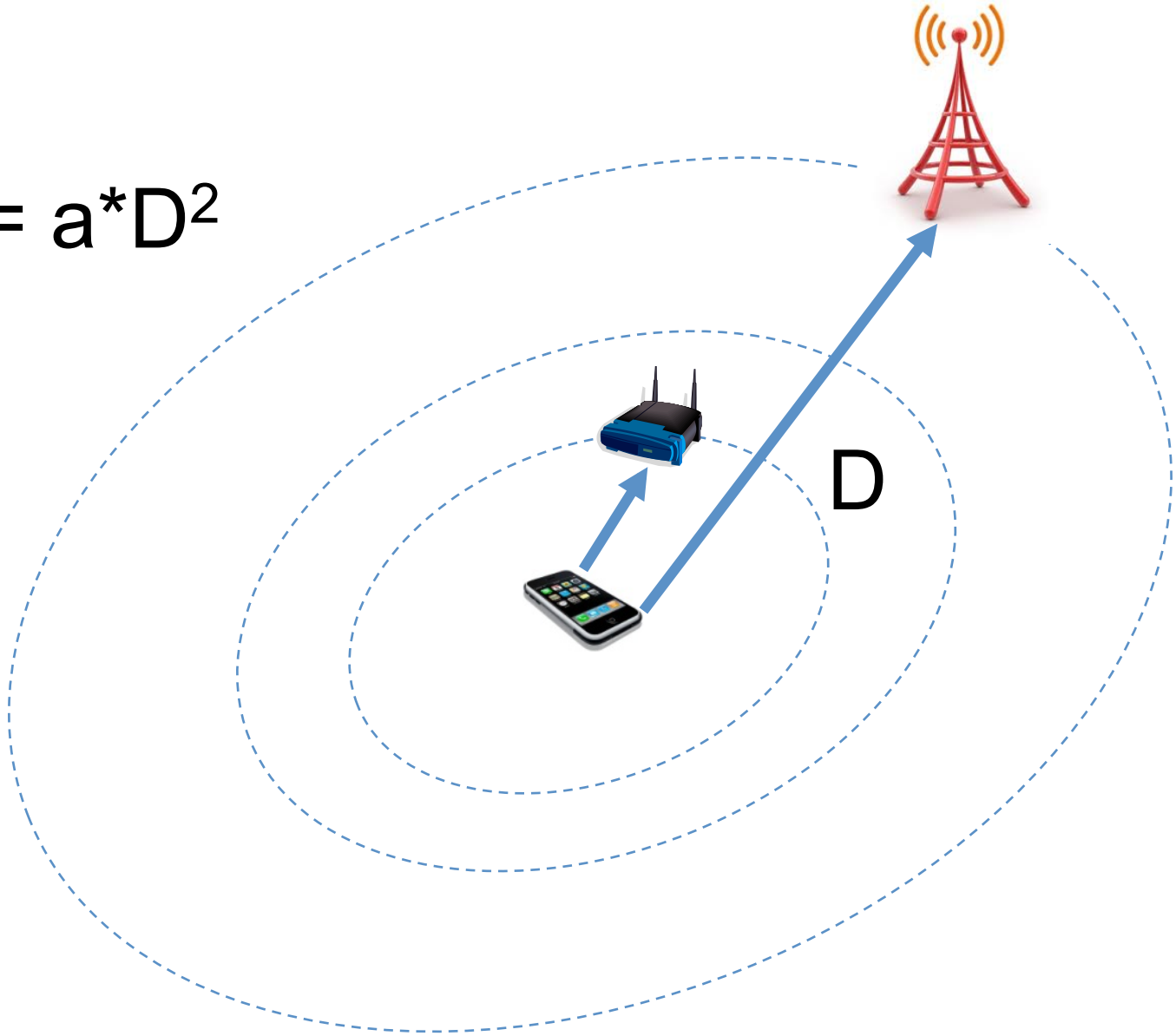
Power profile !=Energy profile

First insight

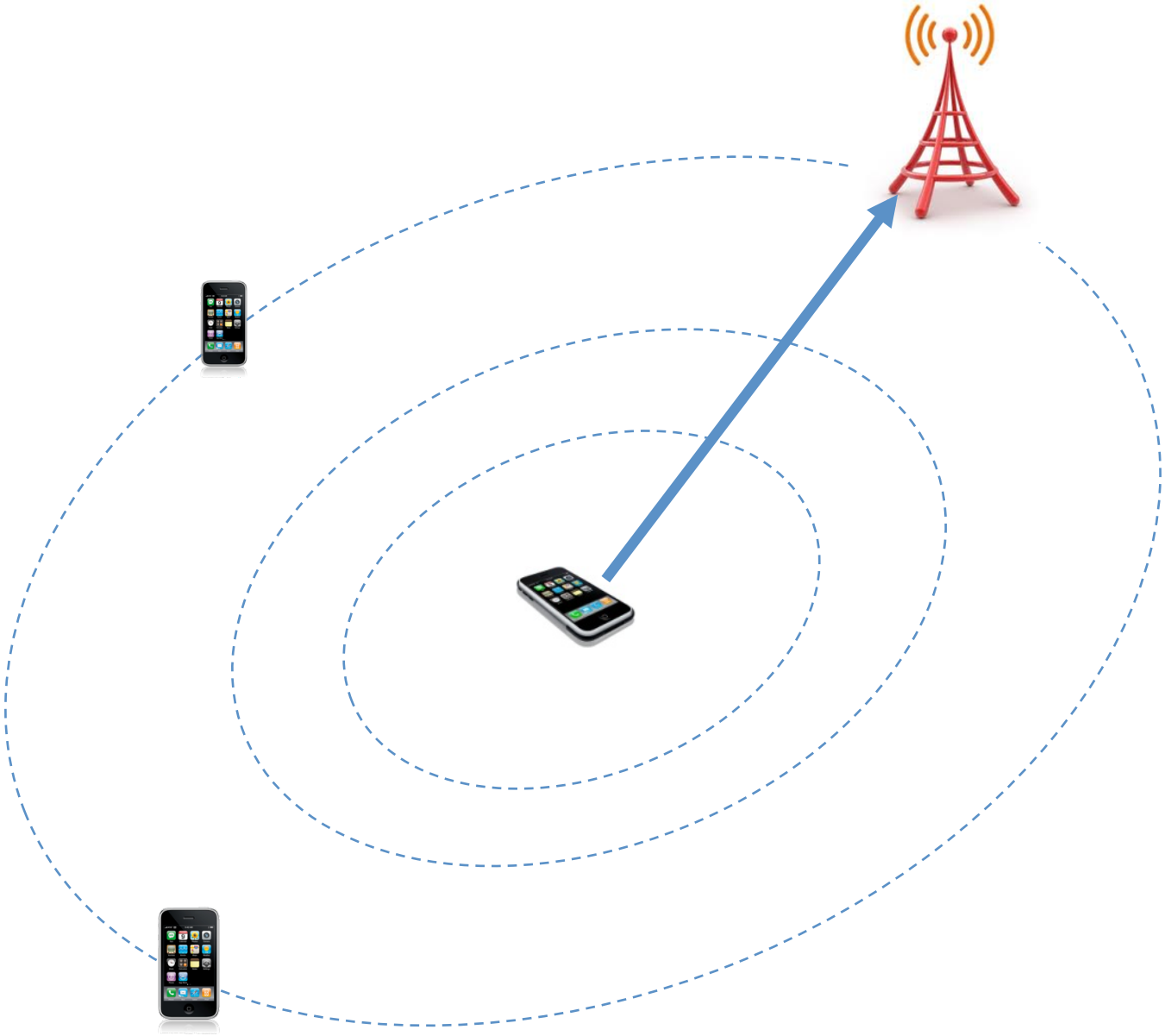
- Wi-Fi more efficient than cellular
  - MobiSys'07

Why is Wi-Fi more efficient?

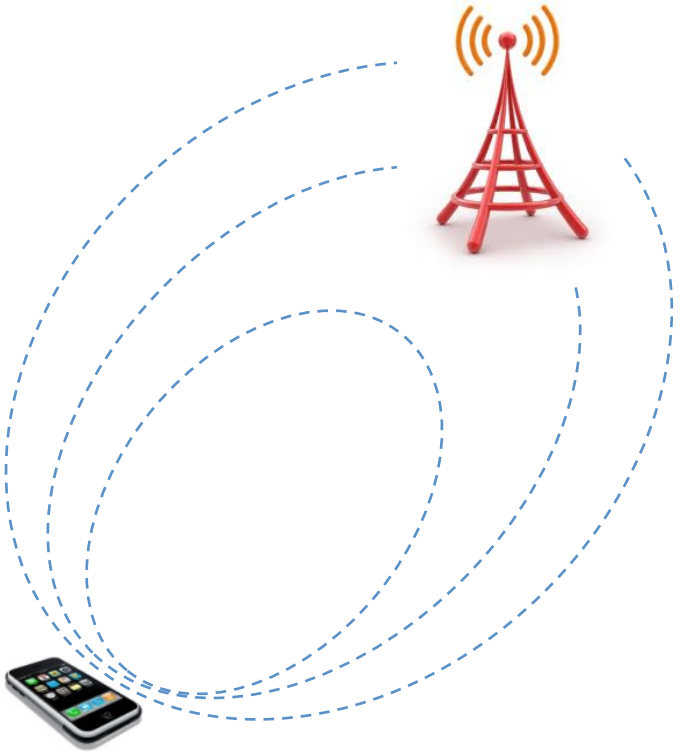
$P_{TX} = a*D^2$



Horribly wasteful



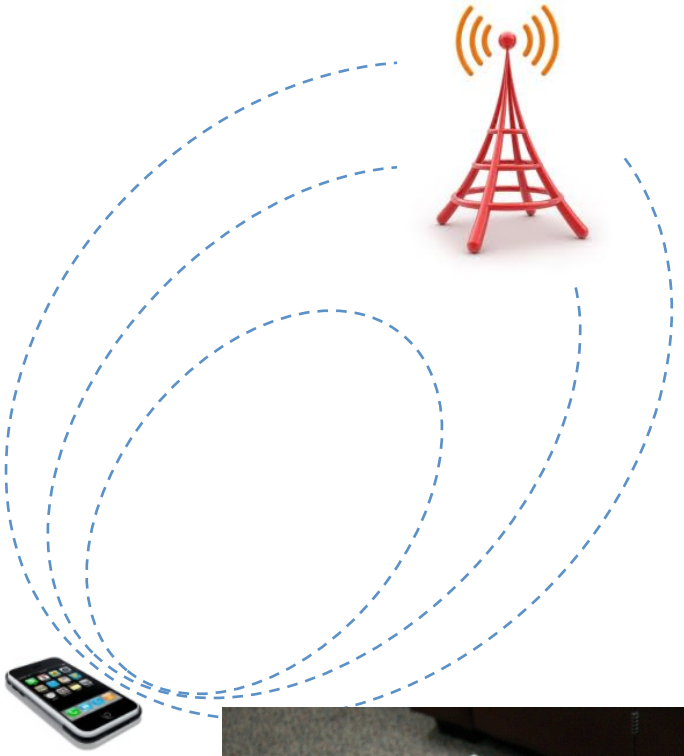
Directional transmission!

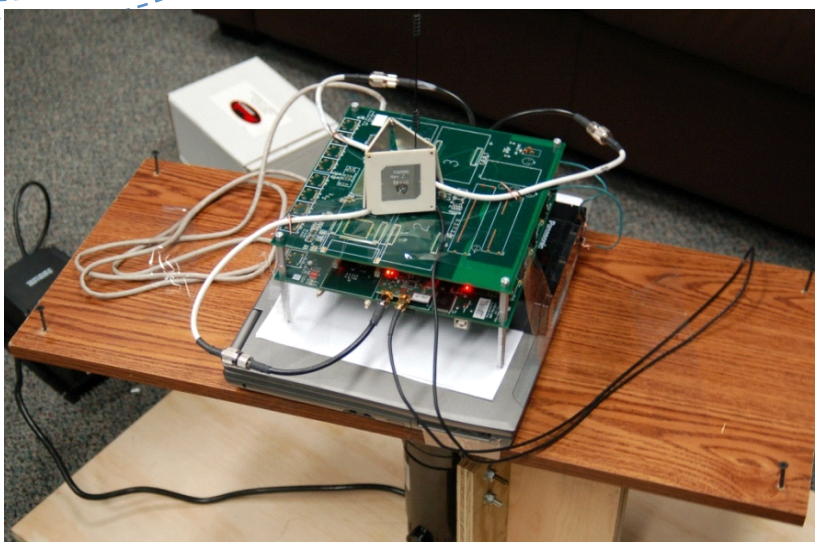


Passive directional antenna to save energy

(MobiCom'10)

- No power overhead
- Fixed bean patterns

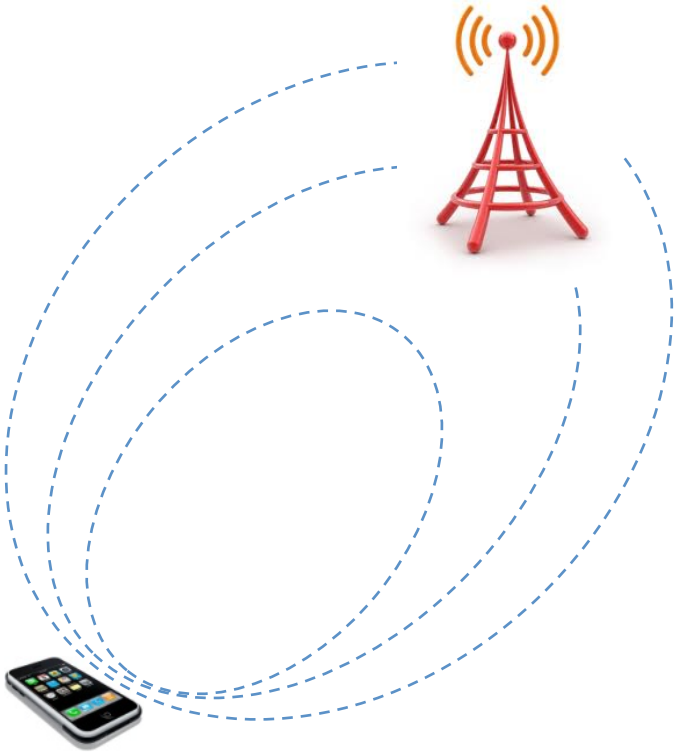




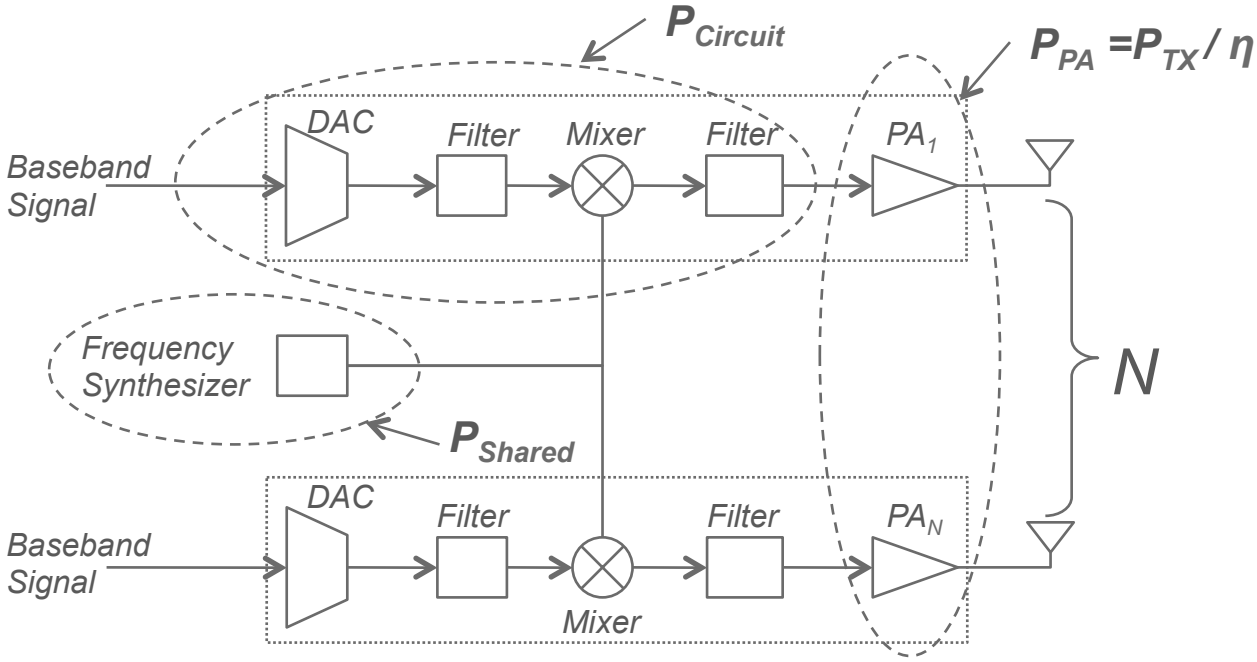
Beamforming to save energy

(MobiCom'11)

- Extra transceivers
- Steerable beams



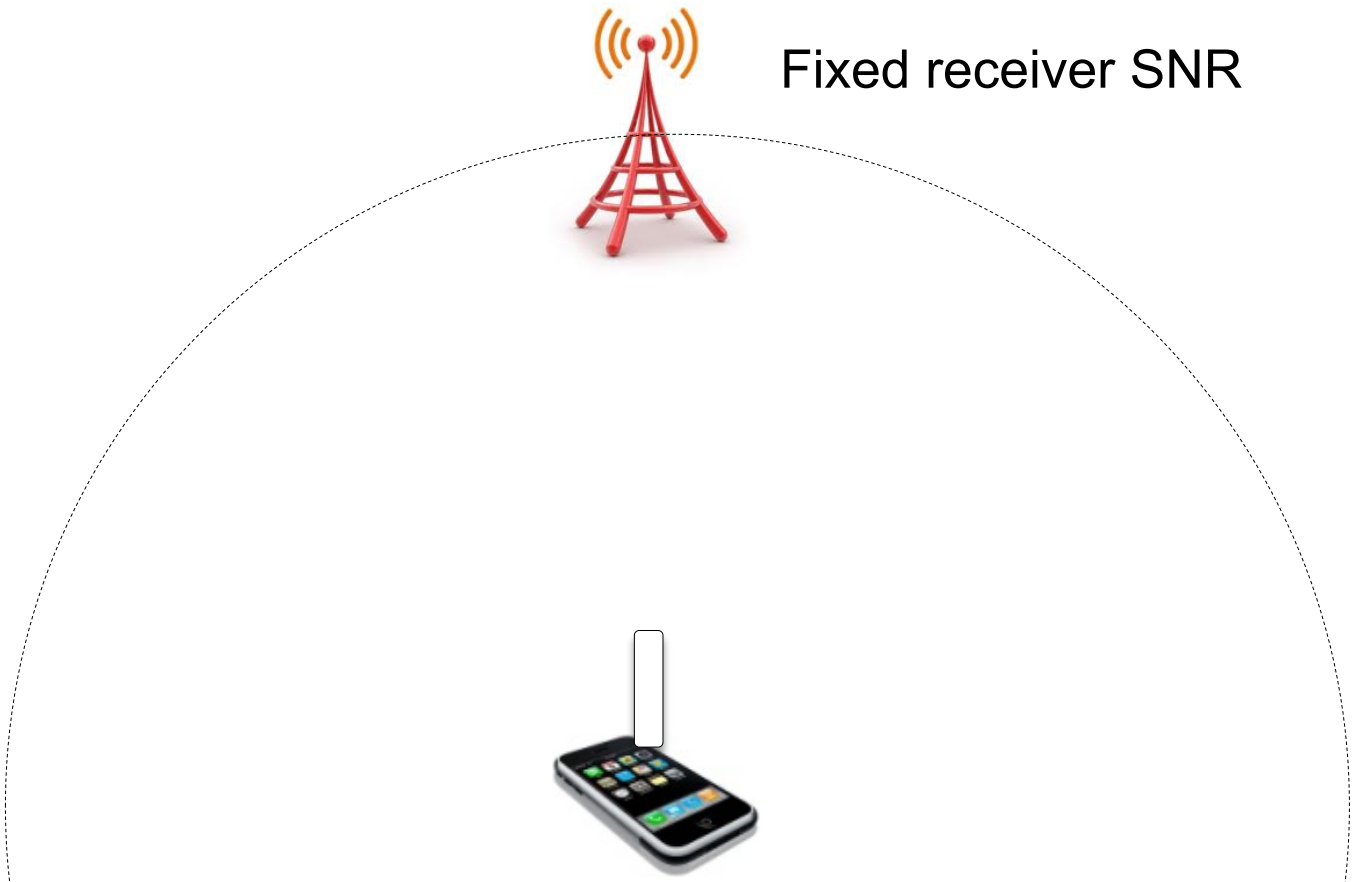
Power by multi-antenna systems (uplink)



$$P = P_{shared} + N \cdot P_{Circuit} + P_{TX} / \eta$$

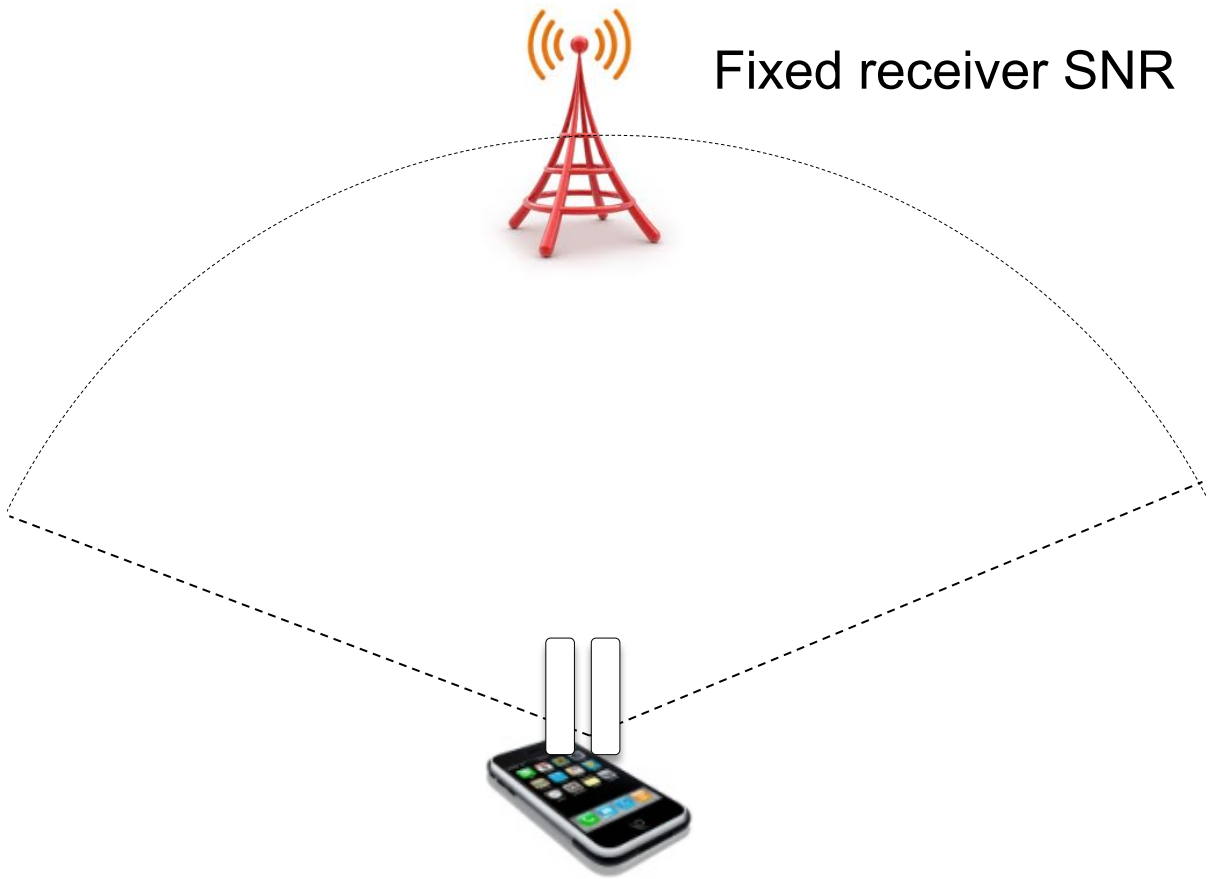
Circuit vs. radiation power tradeoff

$$P = P_{shared} + \mathbf{1} \cdot P_{Circuit} + P_{TX} / \eta$$



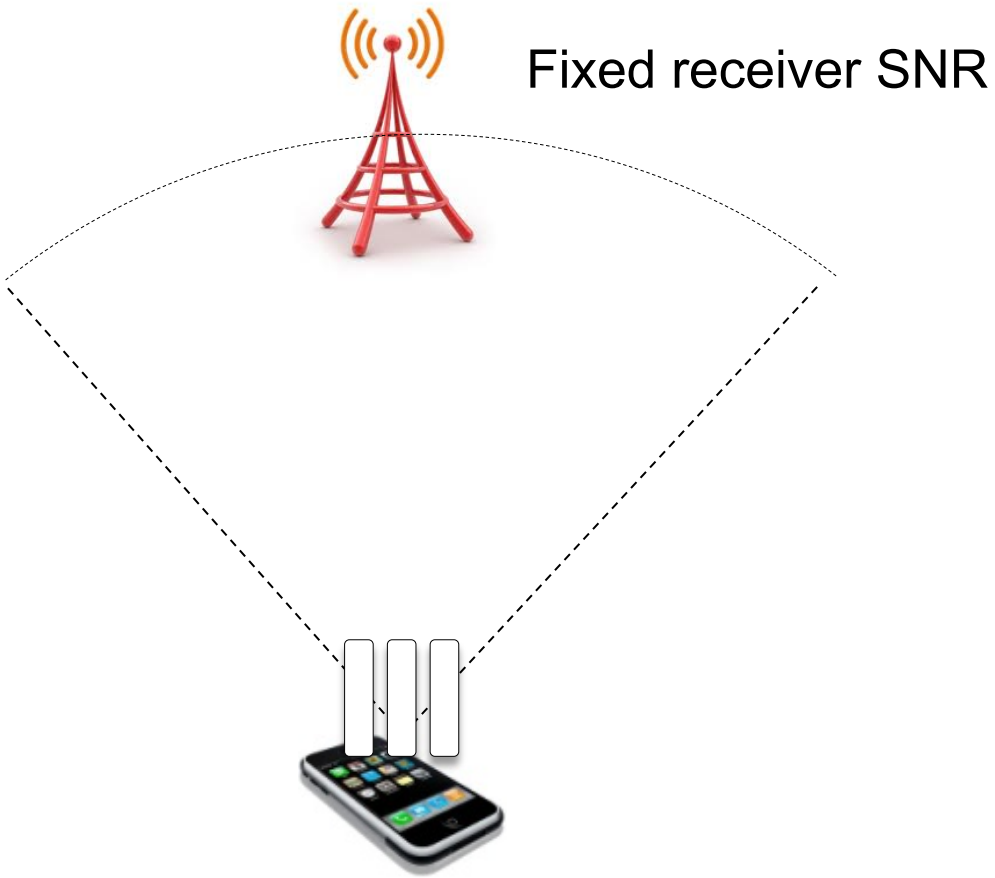
Circuit vs. radiation power tradeoff

$$P = P_{shared} + \mathbf{2} \cdot P_{Circuit} + P_{TX} / \eta$$



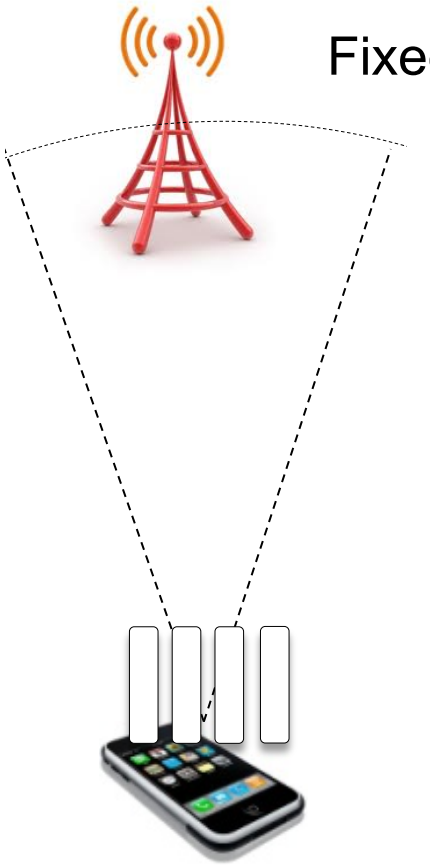
Circuit vs. radiation power tradeoff

$$P = P_{shared} + 3 \cdot P_{Circuit} + P_{TX} / \eta$$



Circuit vs. radiation power tradeoff

$$P = P_{shared} + \mathbf{4} \cdot P_{Circuit} + P_{TX} / \eta$$

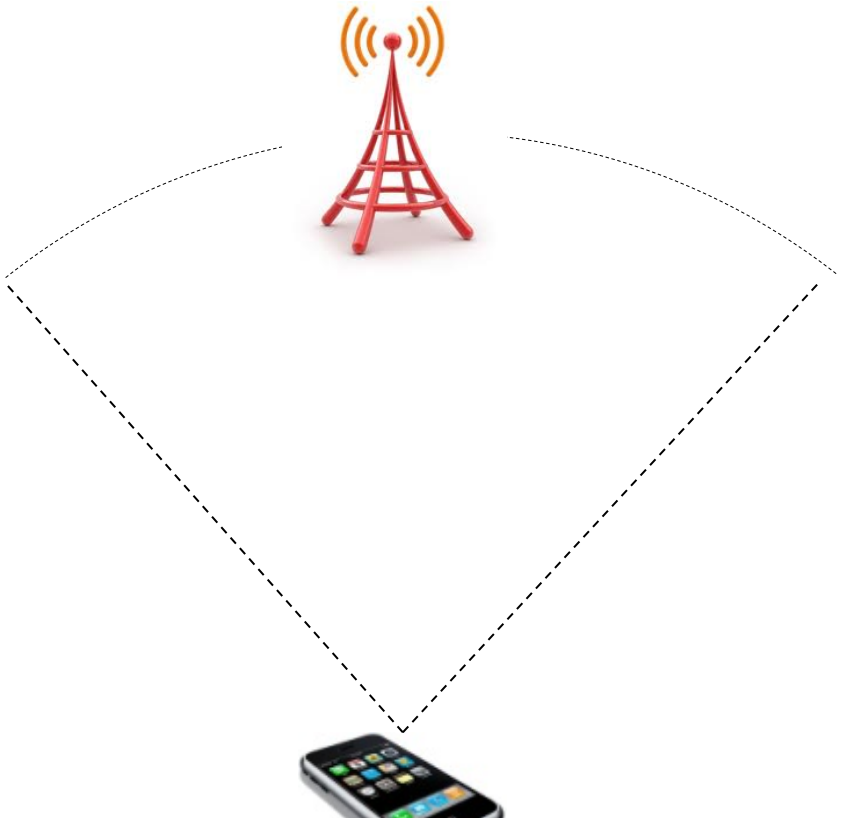


Fixed receiver SNR

Circuit vs. radiation power tradeoff

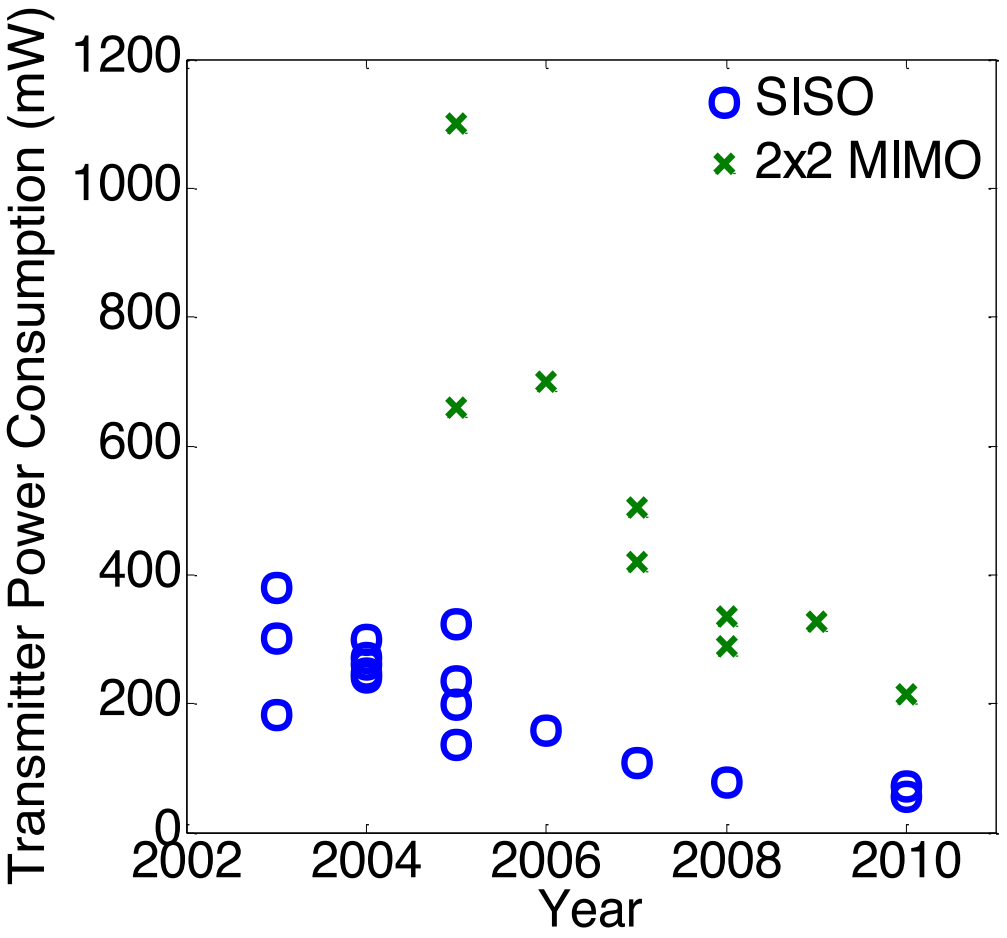
- Optimal number of antennas for efficiency

$$N_{opt} = a \cdot \sqrt{P_O / P_{Circuit}} - b \cdot P_O$$



Hardware is cheap & getting cheaper

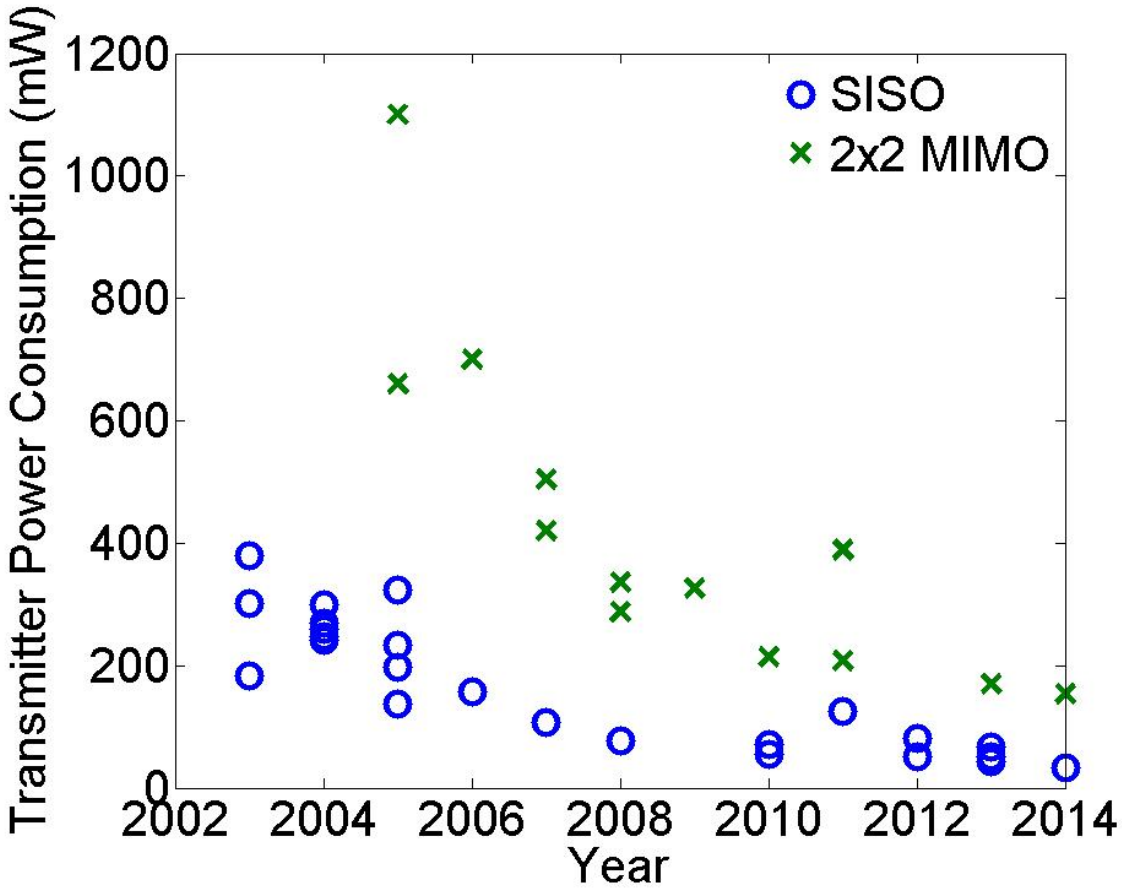
$$P = P_{shared} + N \cdot P_{Circuit} + P_{TX} / \eta$$



Sources: IEEE Int. Solid-State Circuits Conferences (ISSCC) and IEEE Journal of Solid-State Circuits (JSSC)

Hardware is cheap & getting cheaper

$$P = P_{shared} + N \cdot P_{Circuit} + P_{TX} / \eta$$



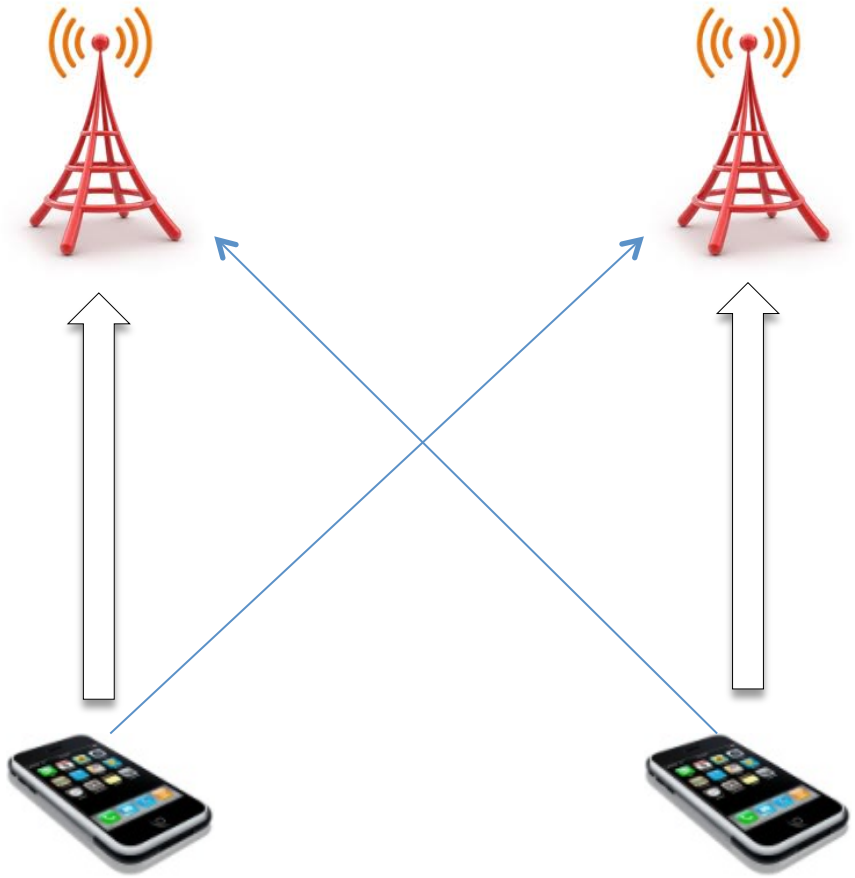
Sources: IEEE Int. Solid-State Circuits Conferences (ISSCC) and IEEE Journal of Solid-State Circuits (JSSC)

Circuit vs. radiation power tradeoff is increasingly profitable

$$N_{opt} = a \cdot \sqrt{P_O / P_{Circuit}} - b \cdot P_O$$

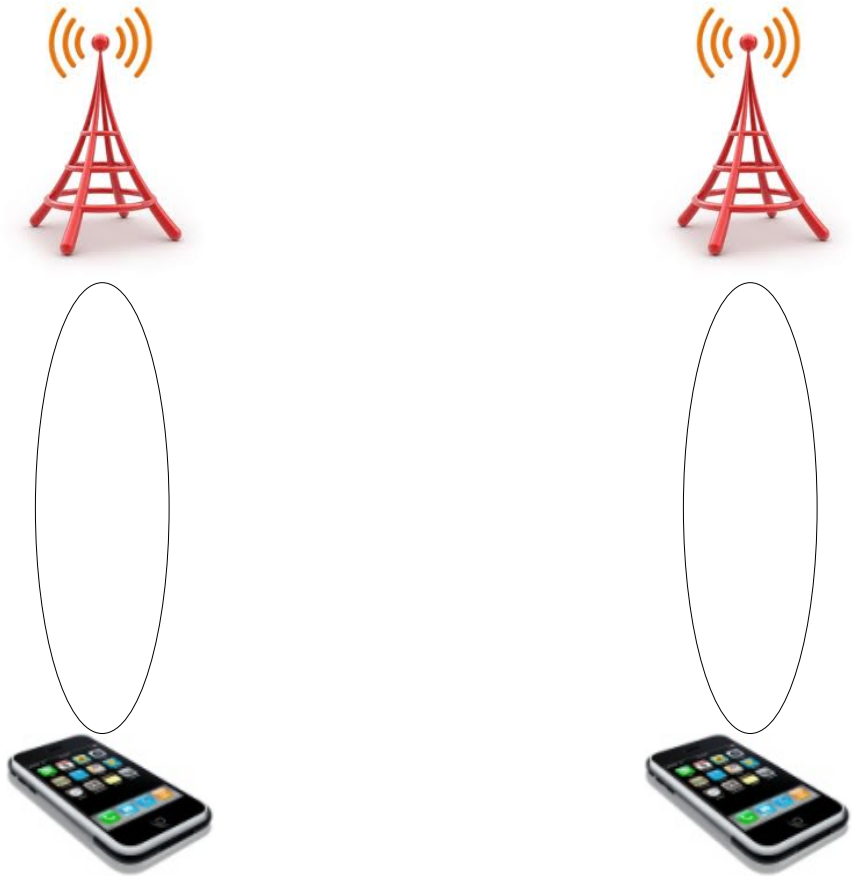
- The most energy-efficient way is to use all the antennas

Beyond a single link



What the carrier wants:

Use all your antennas!



Guiding principles distilled

- Spectrum is scarce
- Hardware is cheap, and getting cheaper

You can’t really fit a lot of antennas in a mobile device ☹

Got a call from Erran Li, Bell Labs

Spring 2011

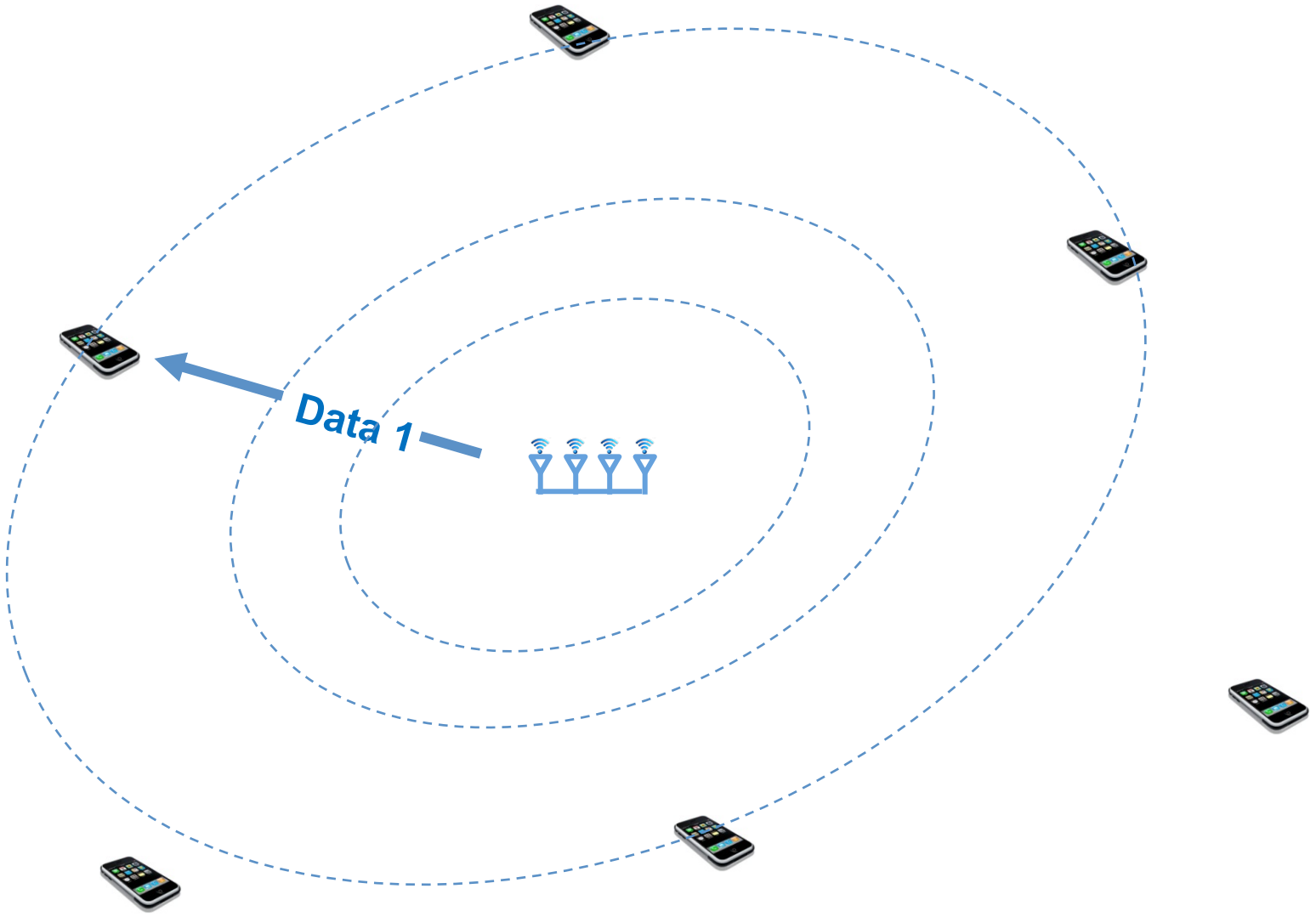
Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas

Thomas L. Marzetta

Clay Shepard went to Bell Labs Summer 2011

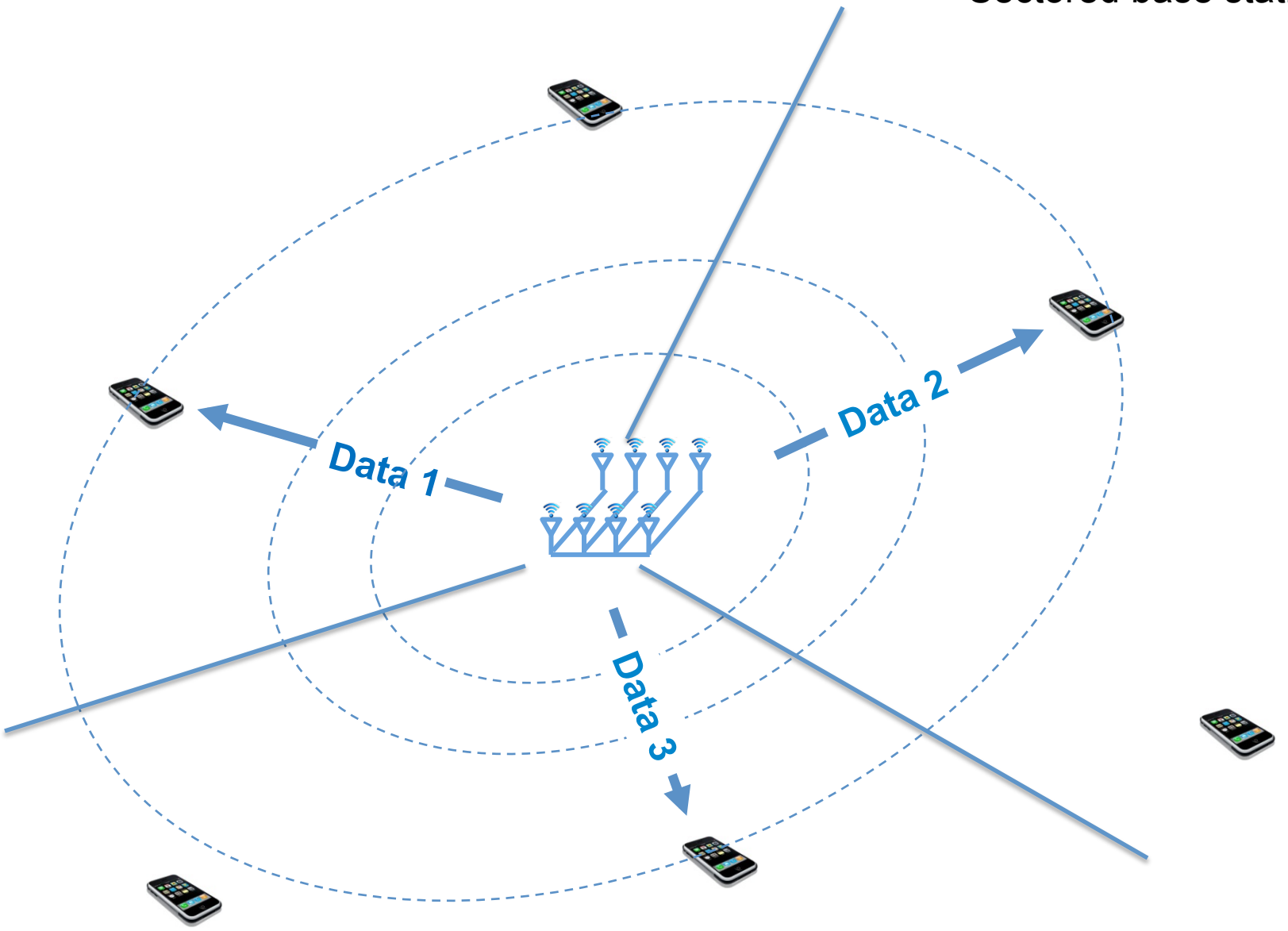
Why many-antenna base station?

Omni-directional base station

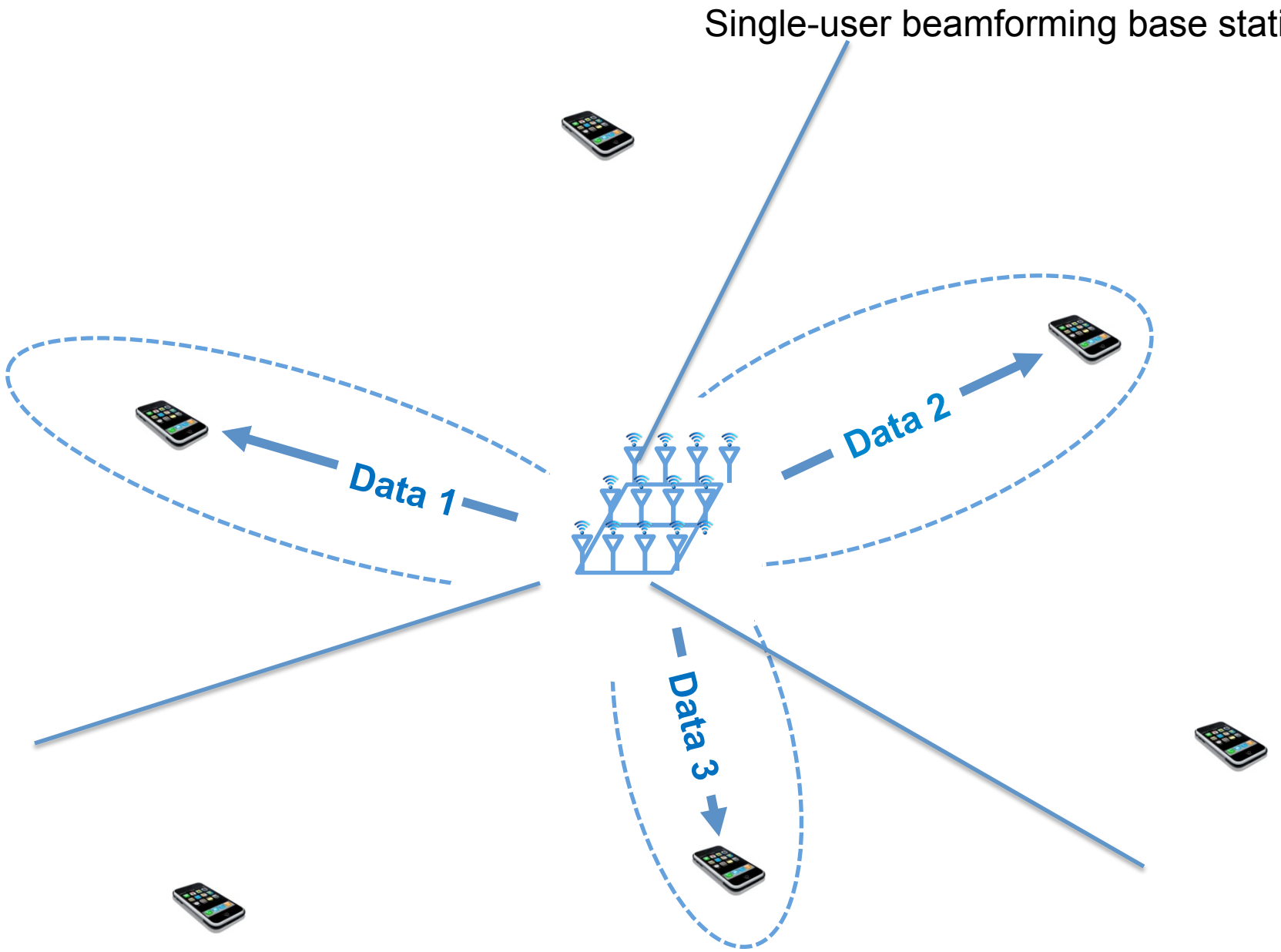


Poor spatial reuse; poor power efficiency; high inter-cell interference

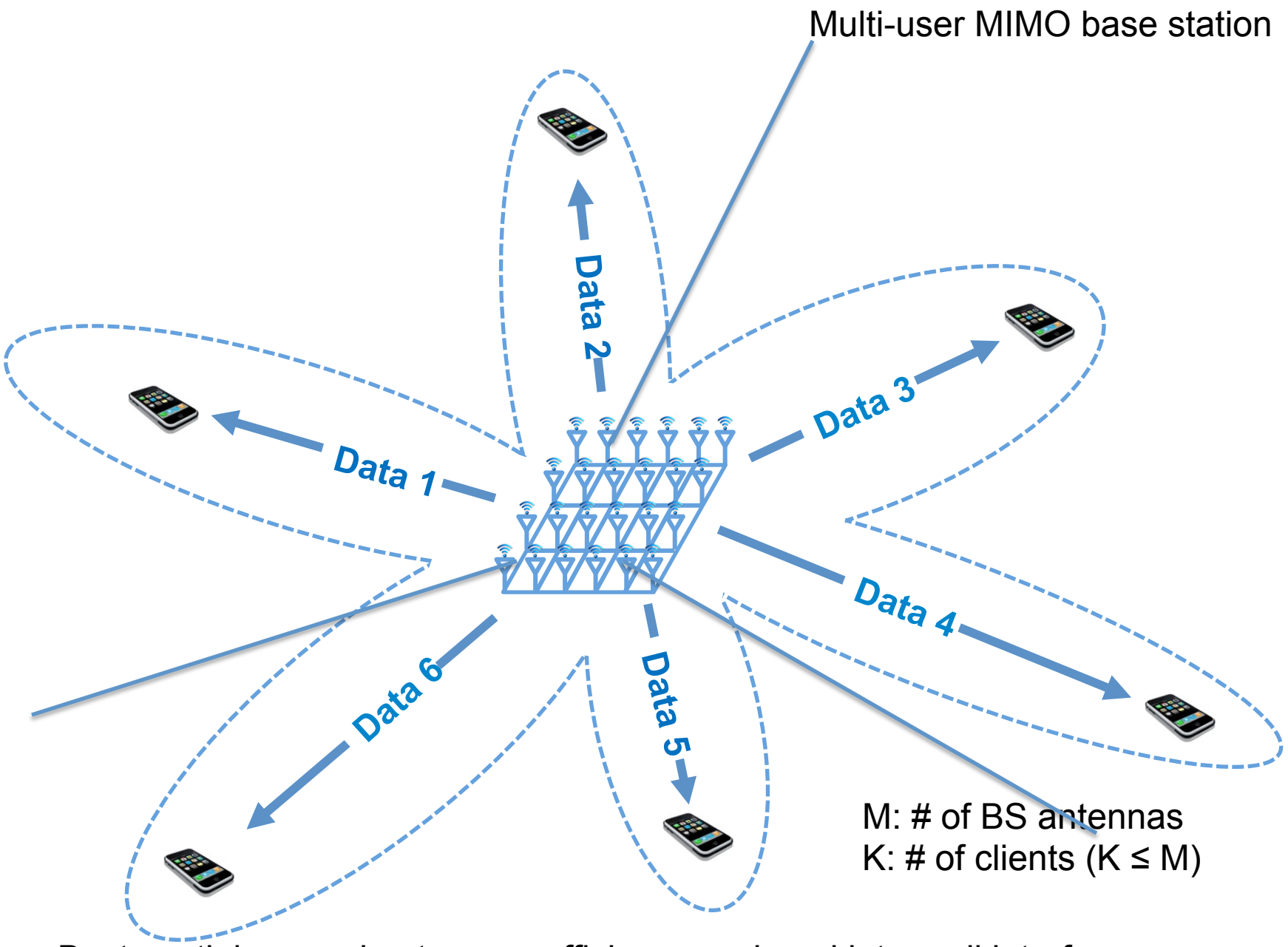
Sectored base station



Better spatial reuse; better power efficiency; high inter-cell interference



Better spatial reuse; best power efficiency; reduced inter-cell interference



Best spatial reuse; best power efficiency; reduced inter-cell interference

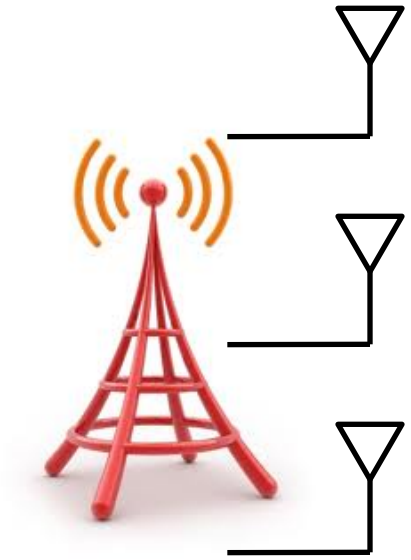
Why ***massive***?

- More antennas ➔ Higher spectral efficiency
- More antennas ➔ Higher energy efficiency

- Marzetta's key result
  - Simple baseband technique becomes effective

T.L. Marzetta. Noncooperative cellular wireless with unlimited numbers of base station antennas. IEEE Trans. on Wireless Comm., 2010.

How multi-user MIMO works



H

M: # of BS antennas

K: # of clients

M ≥ K

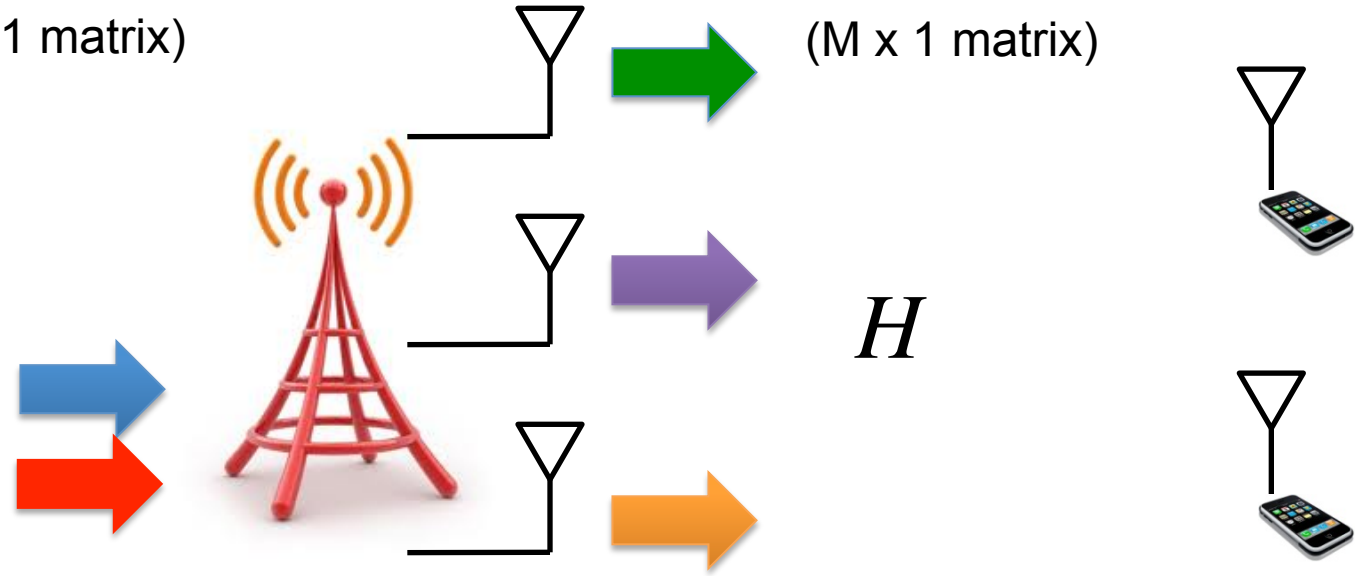
Multi-user MIMO: Precoding

s

(Kx1 matrix)

$\mathrm{s}' = f(\mathrm{s}, \mathrm{H})$

(M x 1 matrix)



H

M: # of BS antennas

K: # of clients

M ≥ K

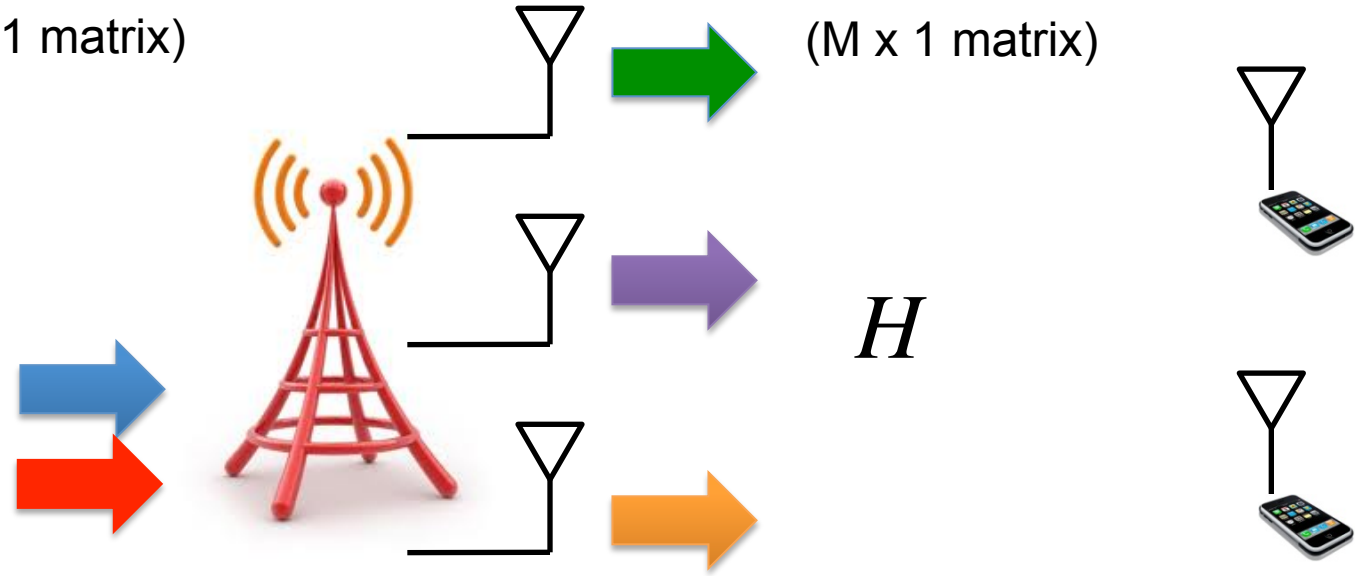
Linear Precoding

$$s' = W \cdot s$$

s

(Kx1 matrix)

(M x 1 matrix)



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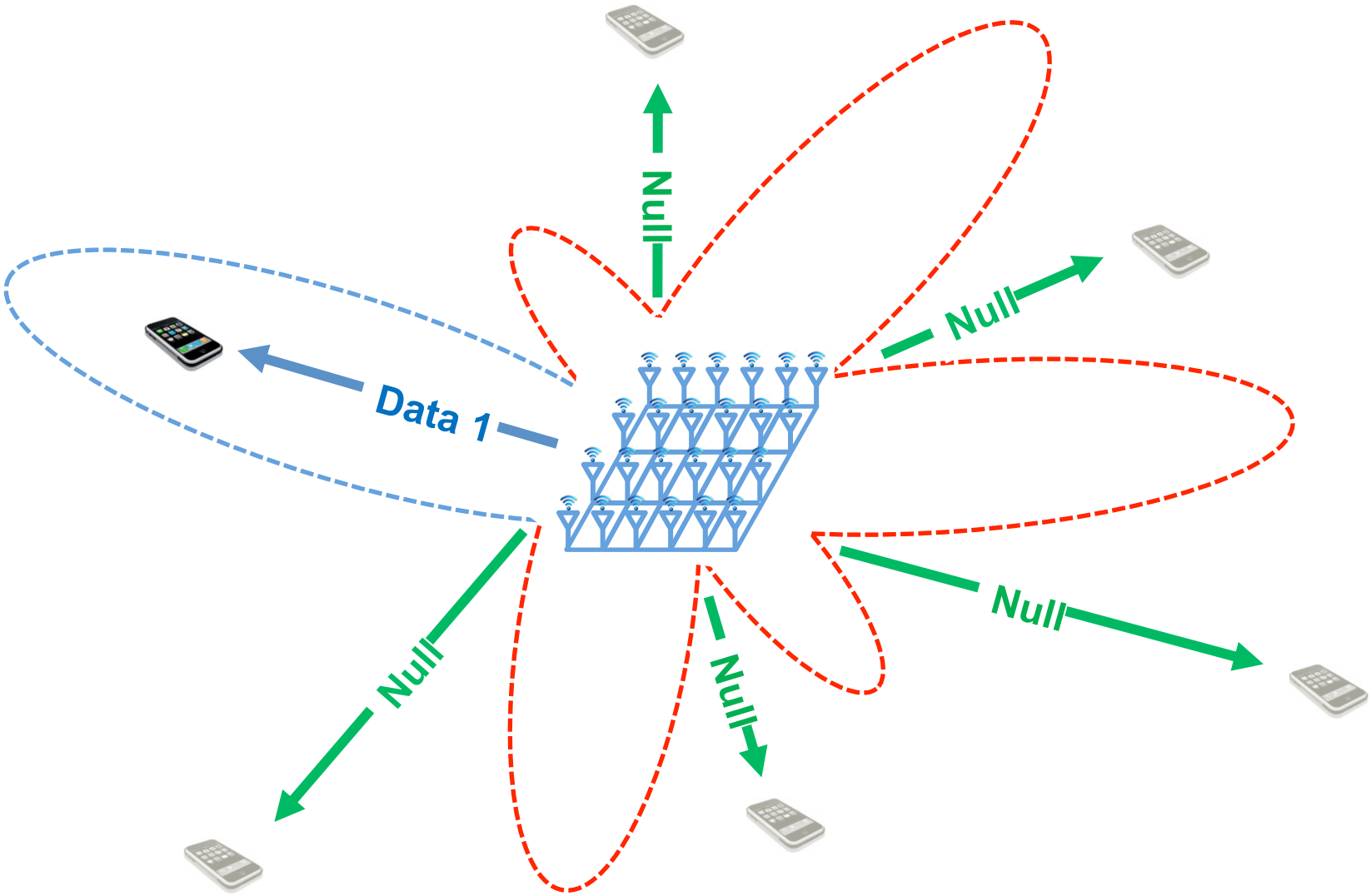
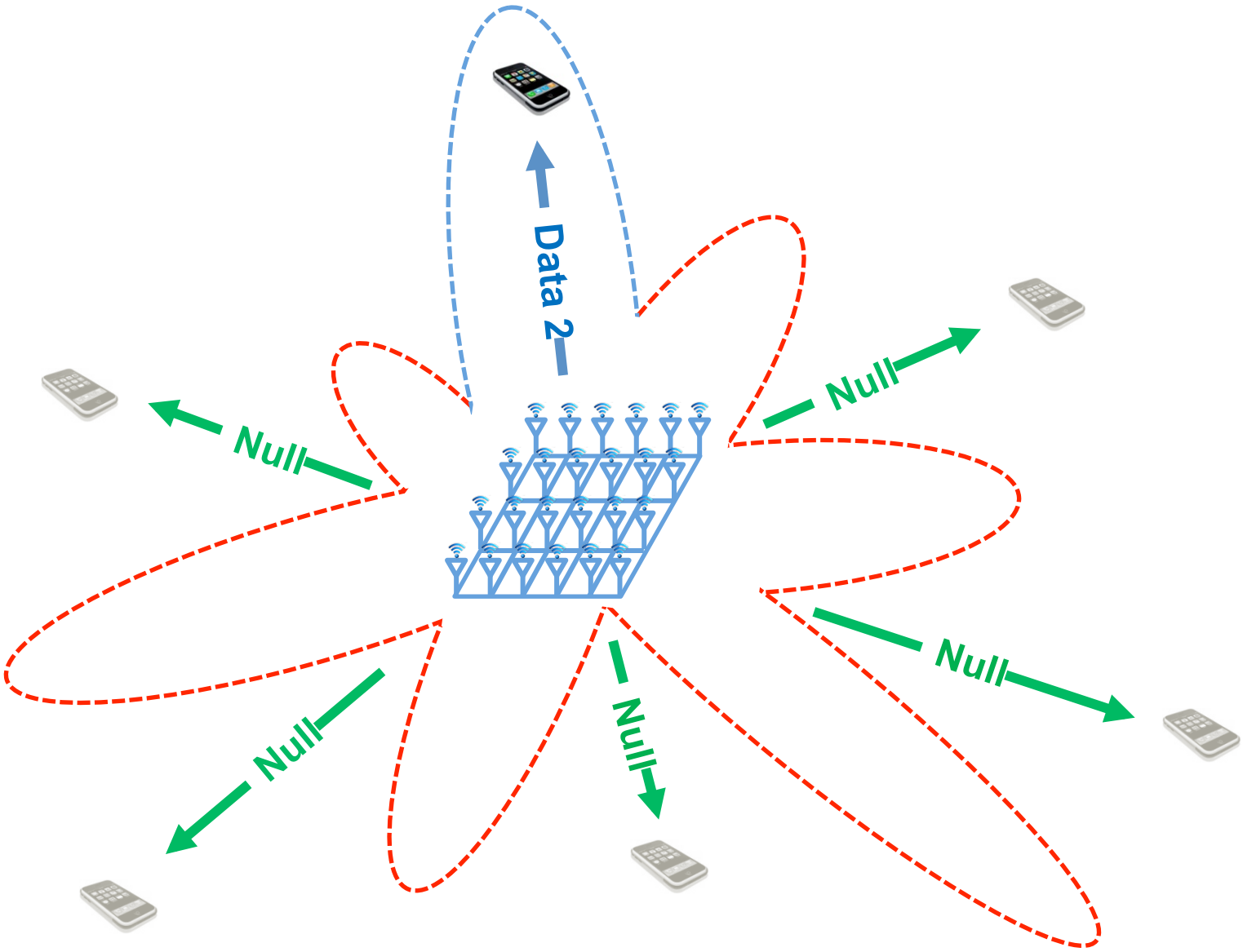
Linear Precoding I: Zero-forcing Beamforming

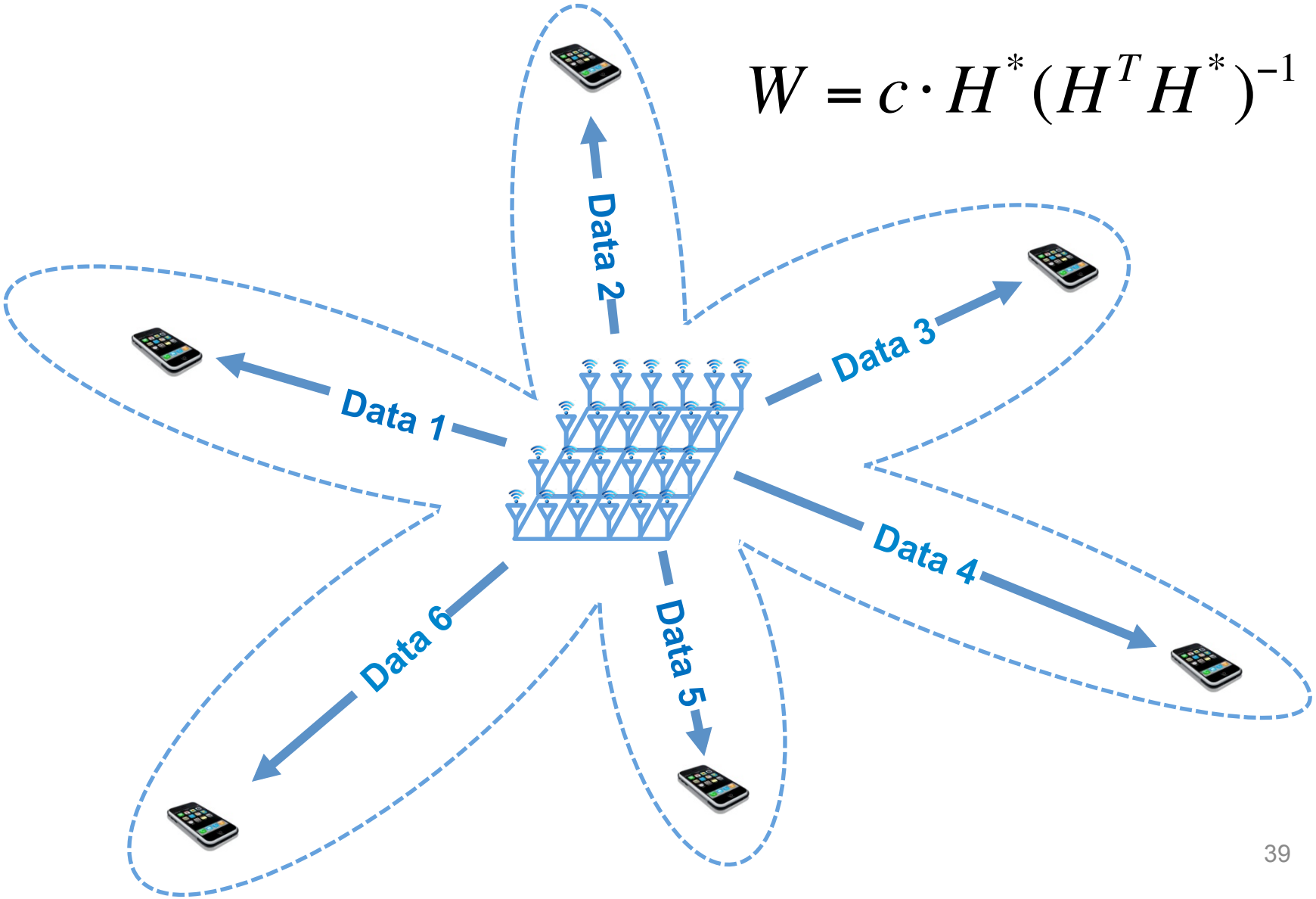


Zero-forcing Beamforming



Zero-forcing Beamforming

$$W = c \cdot H^{*}(H^{T}H^{*})^{-1}$$



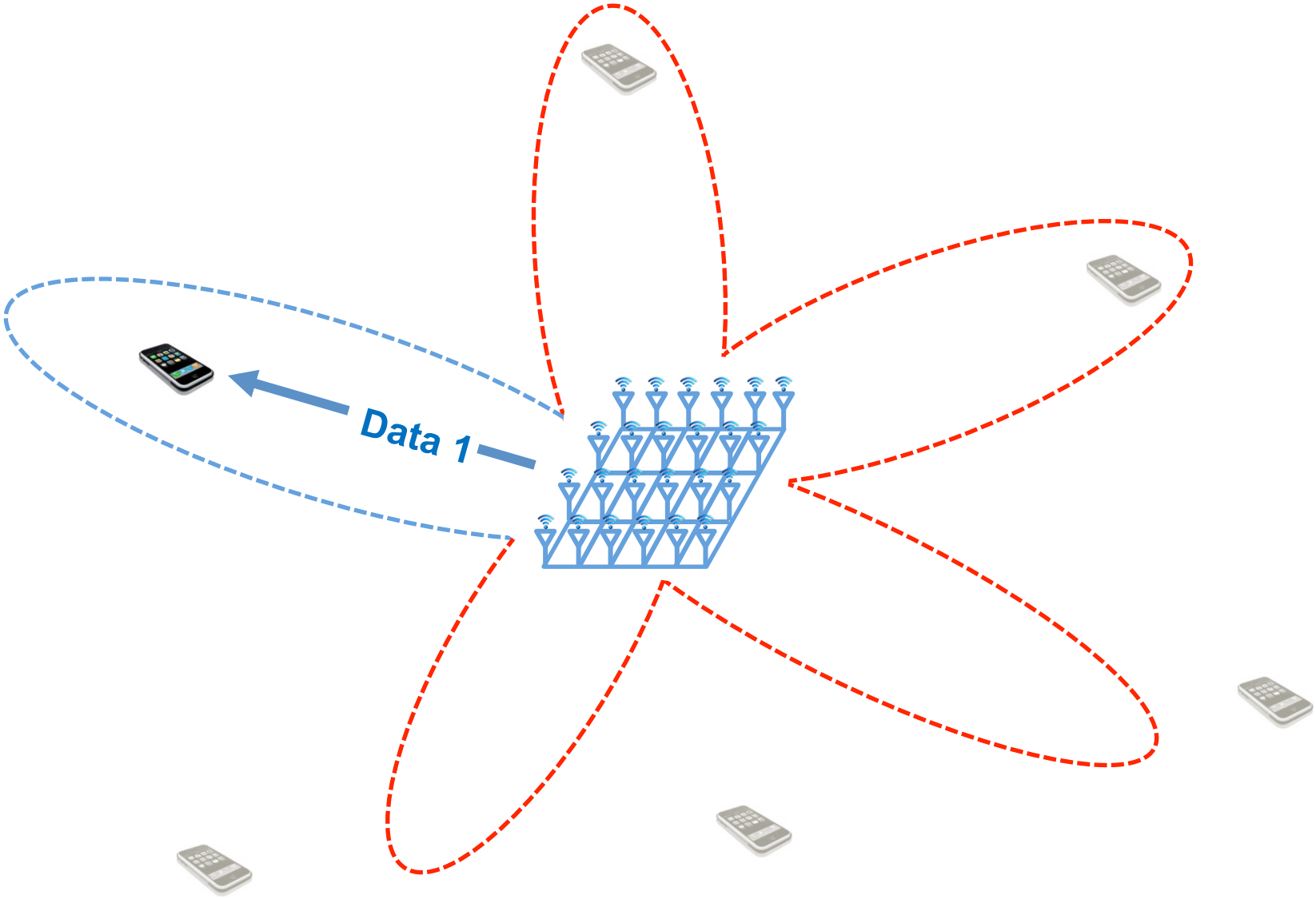
Zero-forcing does not scale well

$$W = c \cdot H^{*}(H^{T}H^{*})^{-1}$$

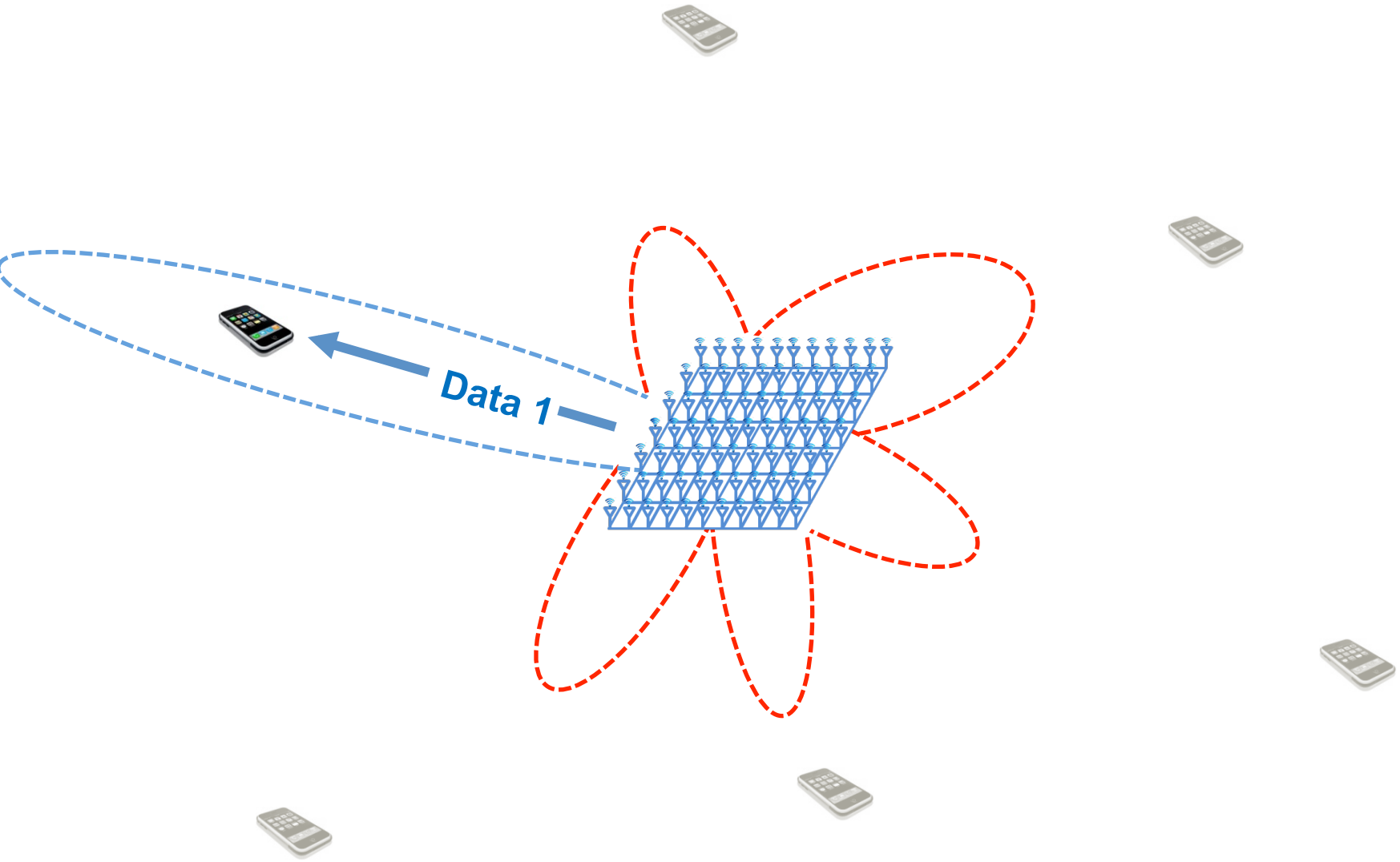
Inversion of M X M matrix

$O(M*K^2)$

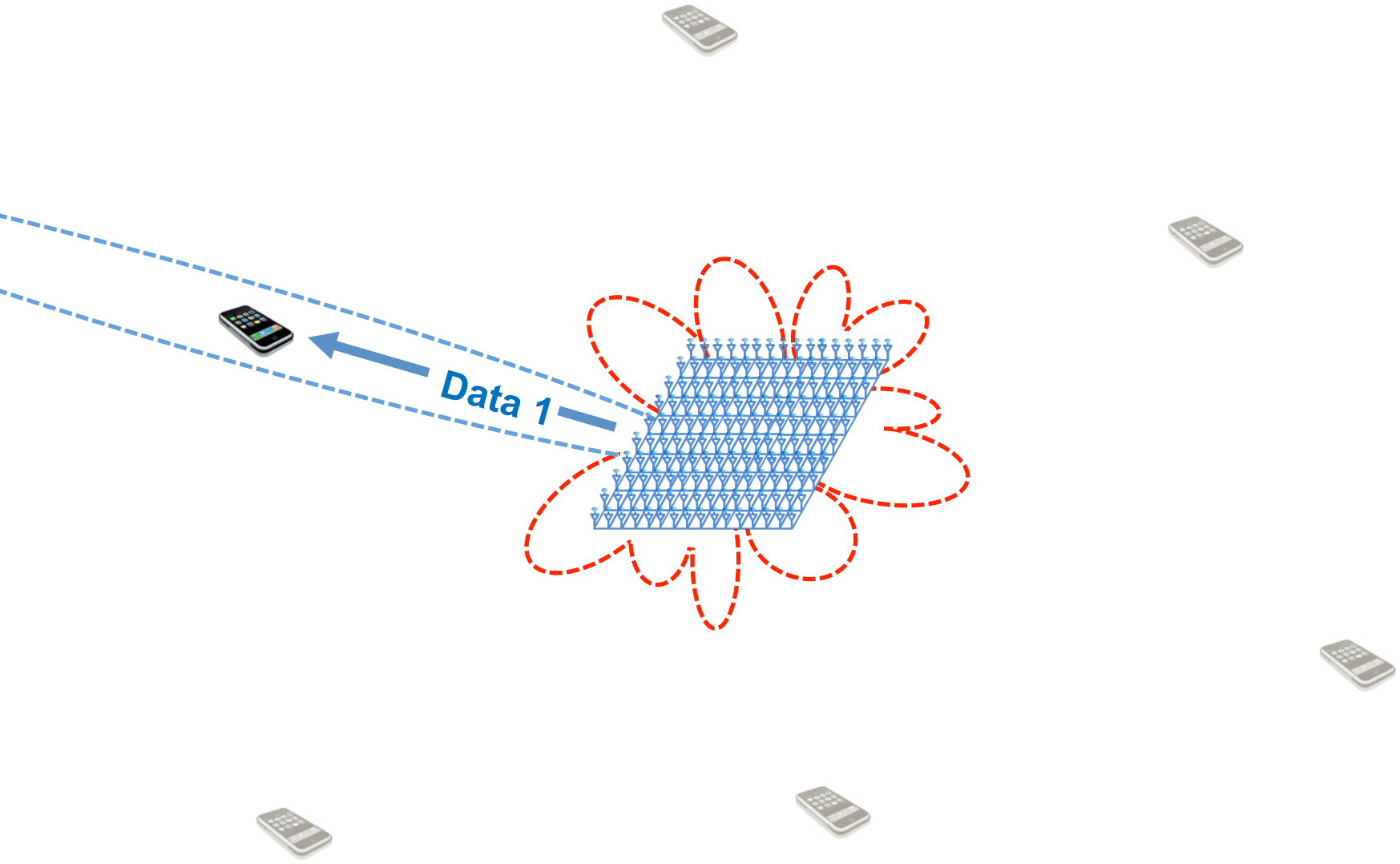
Linear precoding II: Conjugate Beamforming



With more antennas

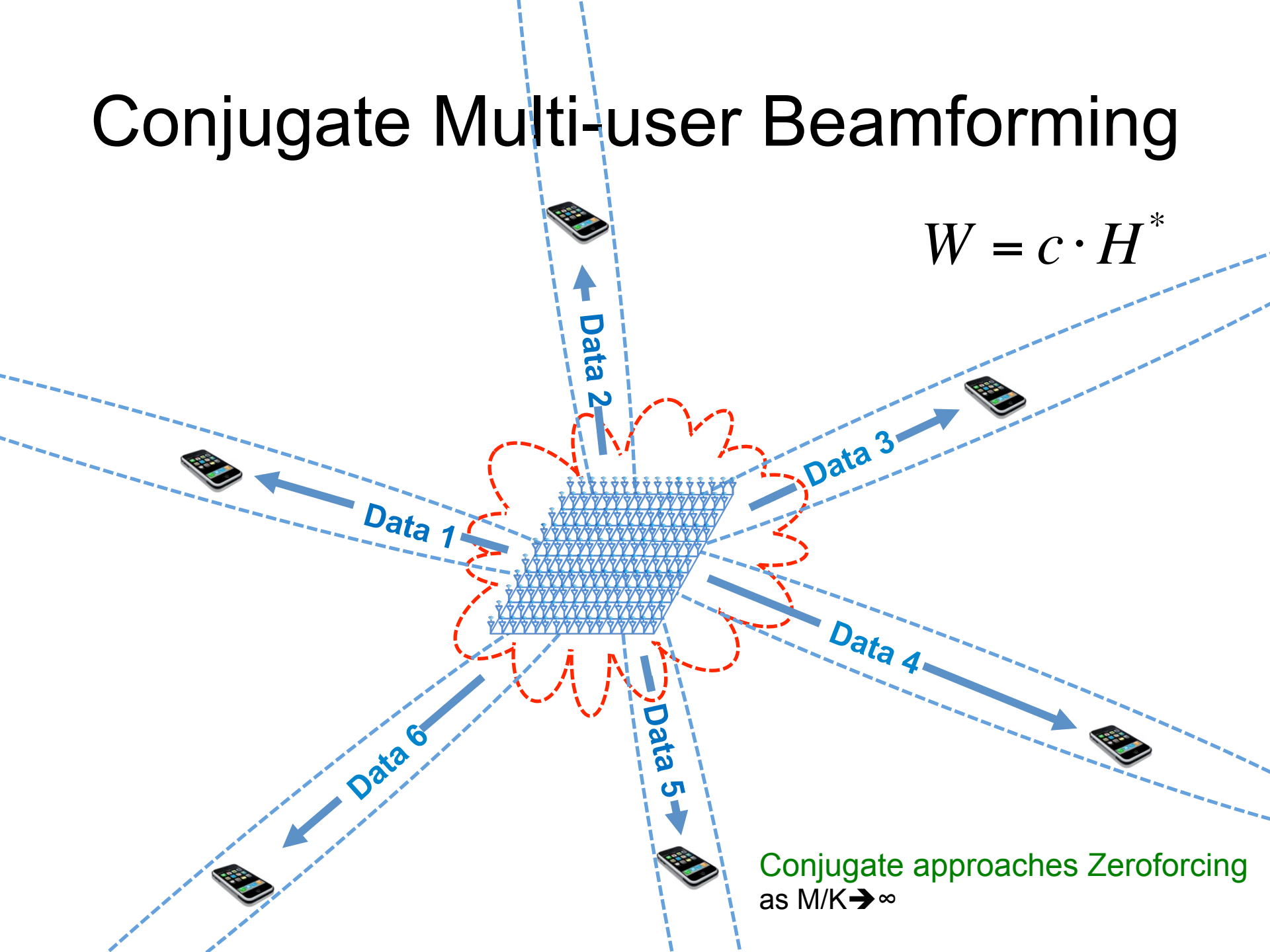


With even more antennas



Conjugate Multi-user Beamforming

$$W = c \cdot H^{*}$$



Conjugate approaches Zeroforcing as M/K➔∞

Conjugate scales very well

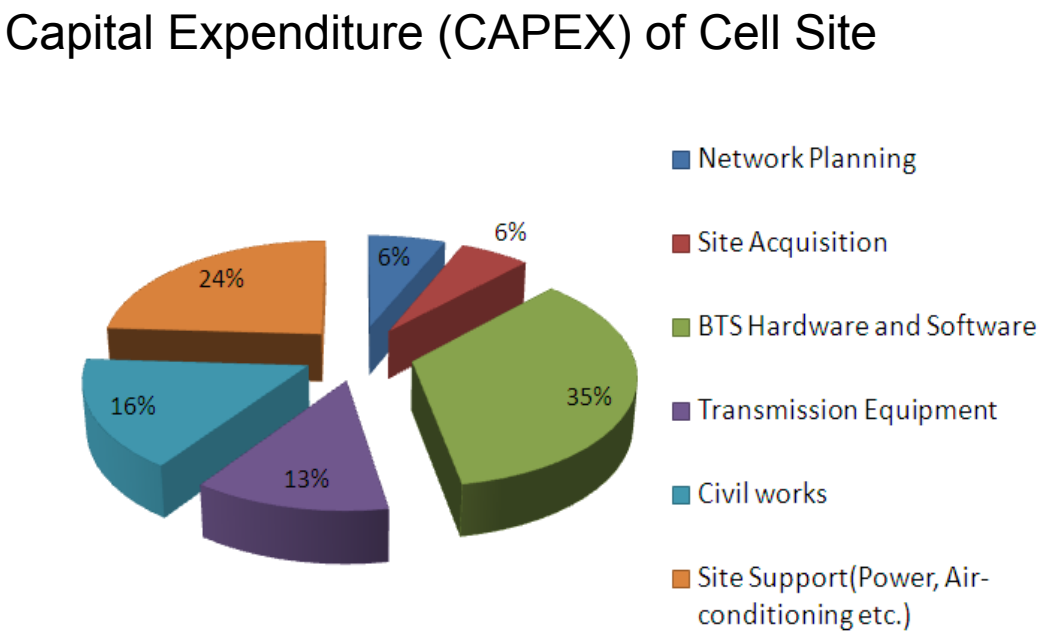
$$W = c \cdot H^{*}$$

O(K) per antenna

Marzetta's key result:

Conjugate approaches Zeroforcing as M/K➔∞

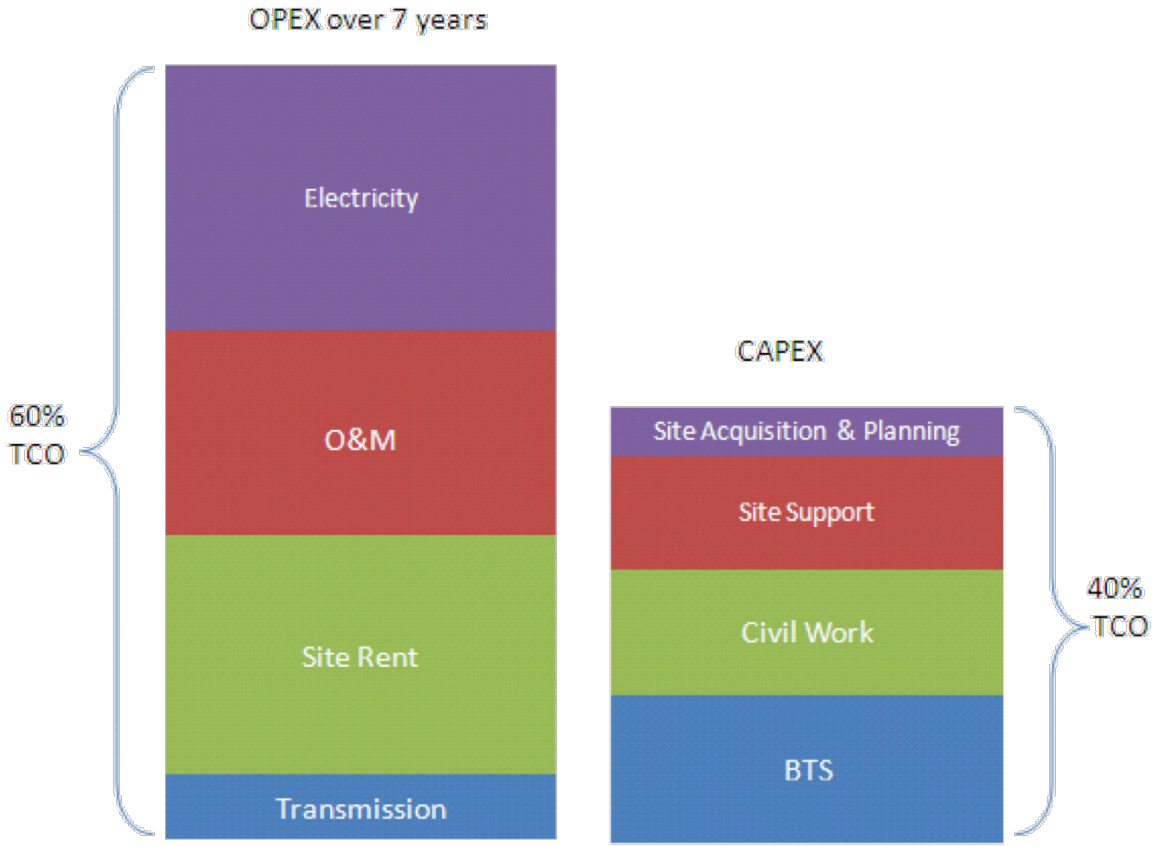
Many-antenna vs. small cell



- Major wireless equipment only 35%
- Just get the site to work: >50%

China Mobile White Paper: C-RAN: The Road Towards Green RAN (Oct, 2011)

Total Cost of Ownership (TCO)



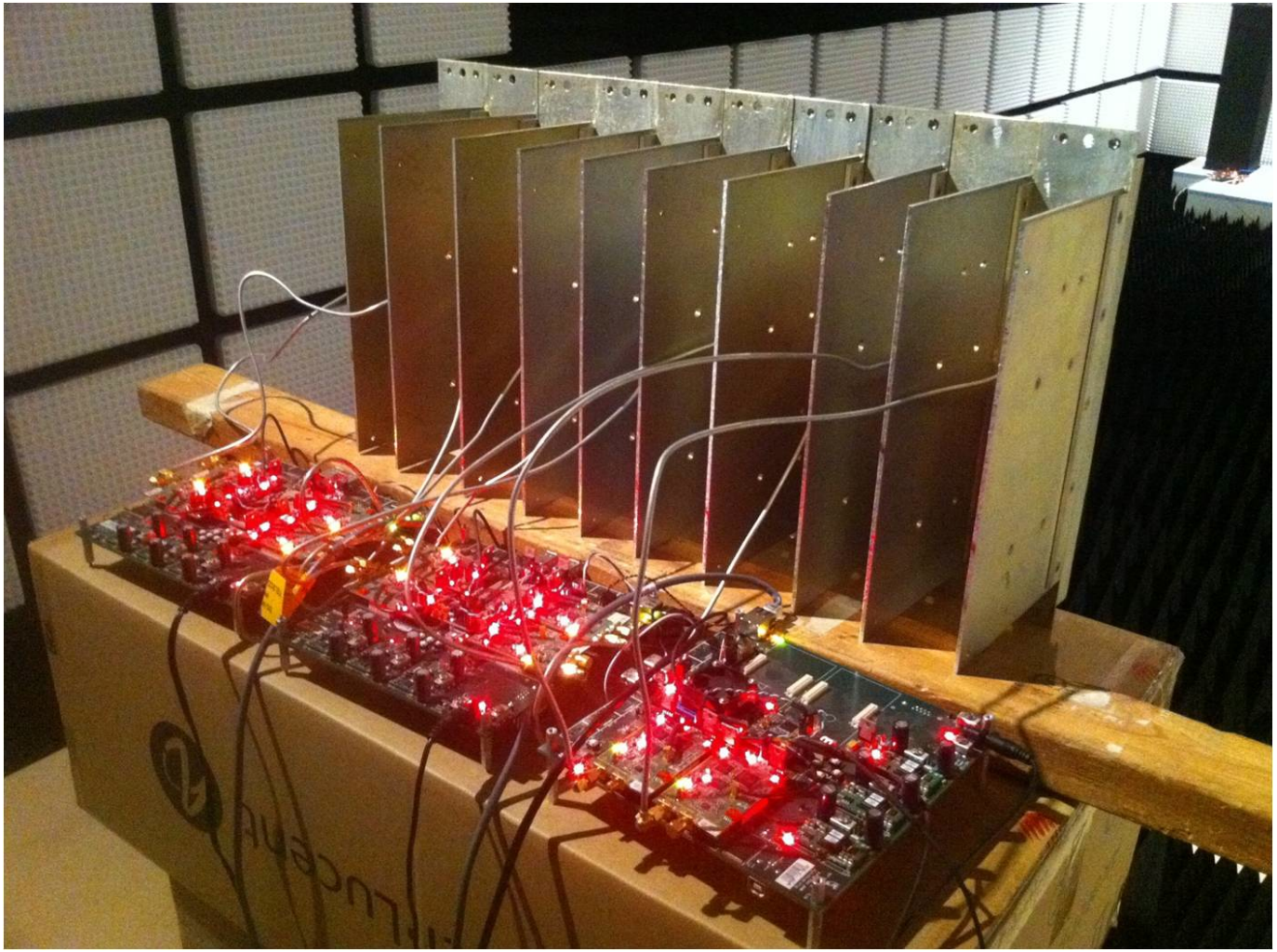
- Operating & Maintenance (O&M)
- Operating Expenditure (OPEX)

"The most effective way to reduce TCO is to decrease the number of sites."

China Mobile White Paper: C-RAN: The Road Towards Green RAN (Oct, 2011)

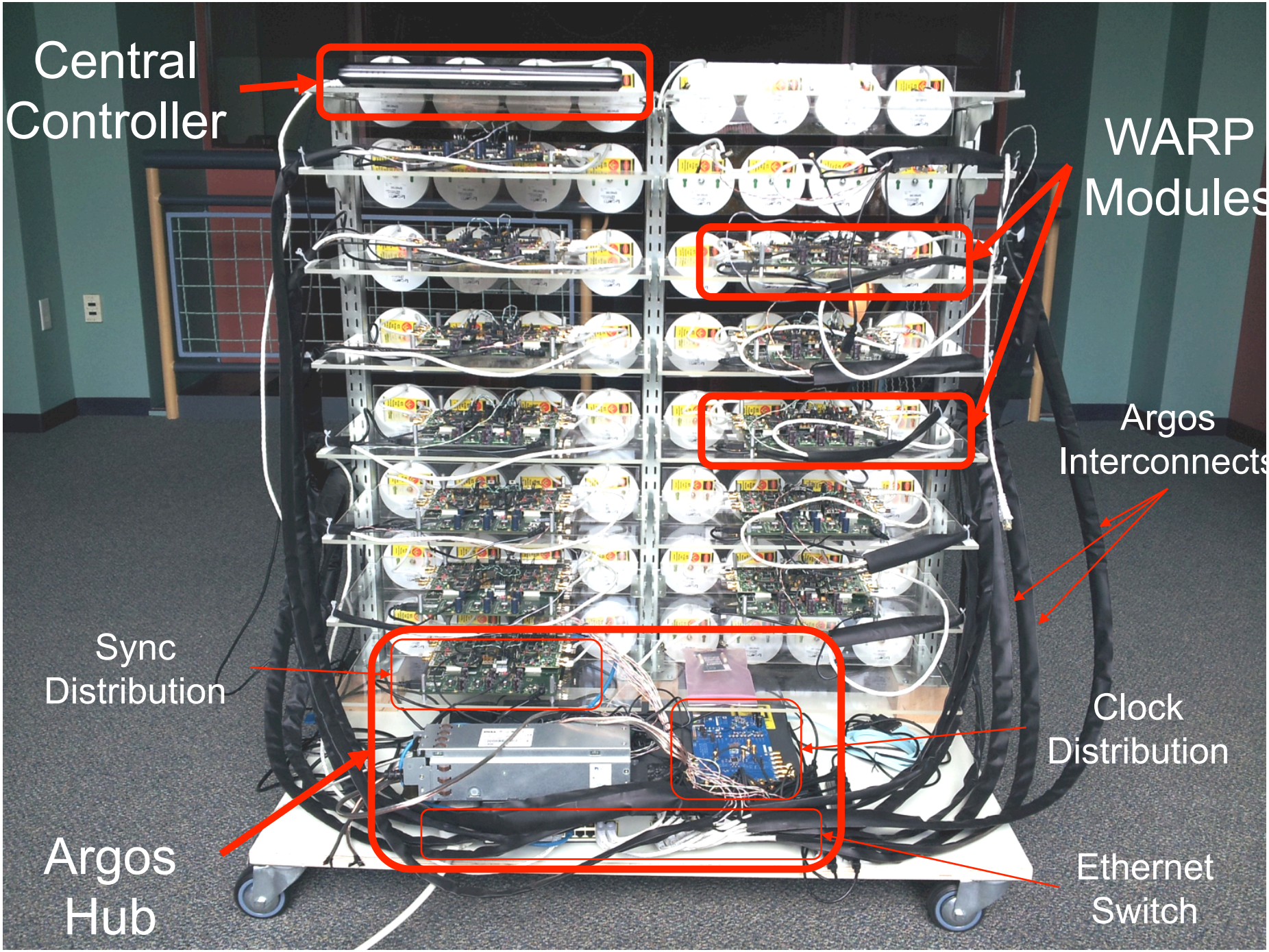
If you’ve got a site, better use as many antennas as you can

After a summer at Bell Labs



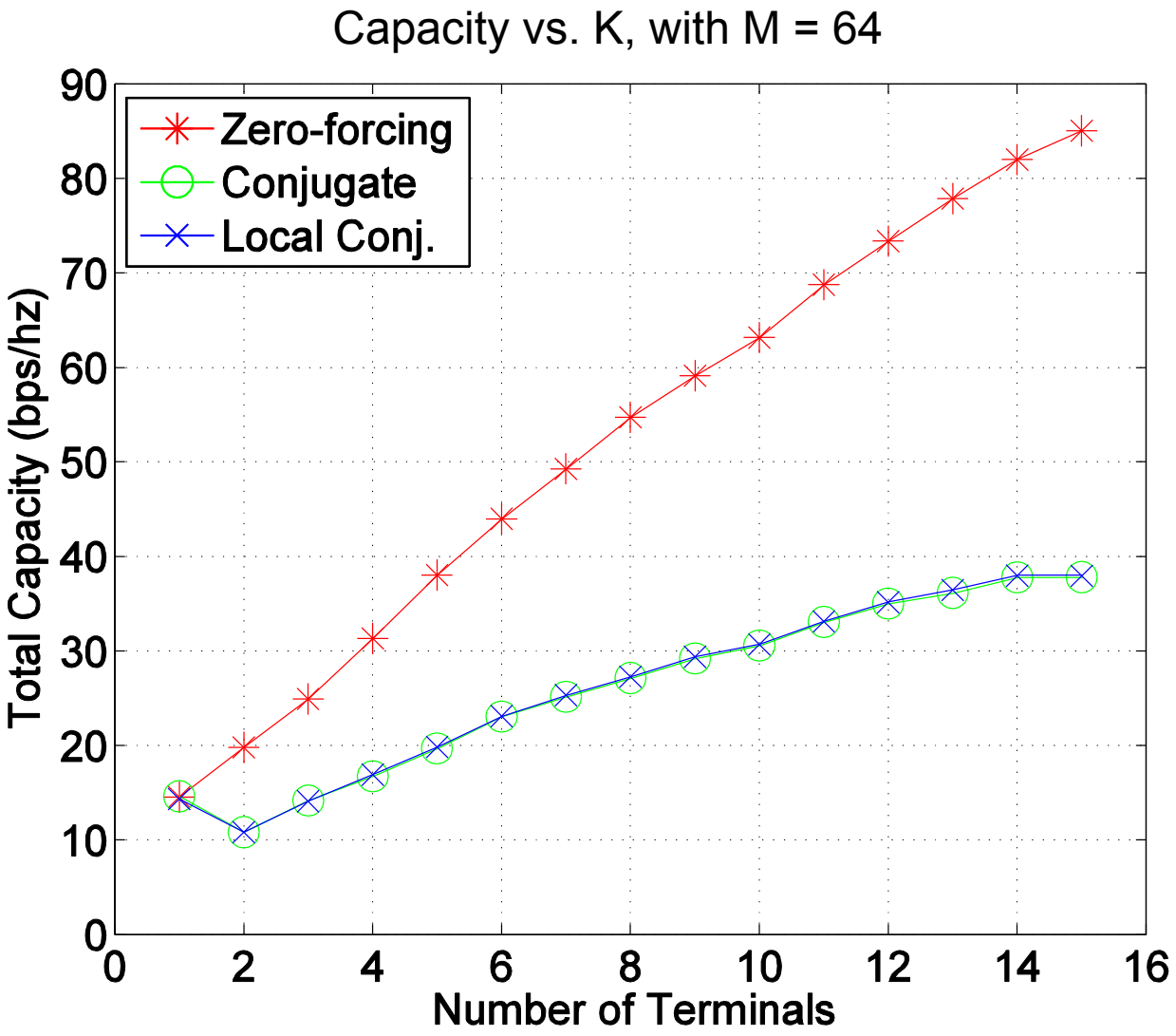
10-antenna prototype in the anechoic chamber at Bell Labs

ArgosV1
(MobiCom'12)


Central Controller
WARP Modules
Argos Interconnects
Sync Distribution
Clock Distribution
Argos Hub
Ethernet Switch

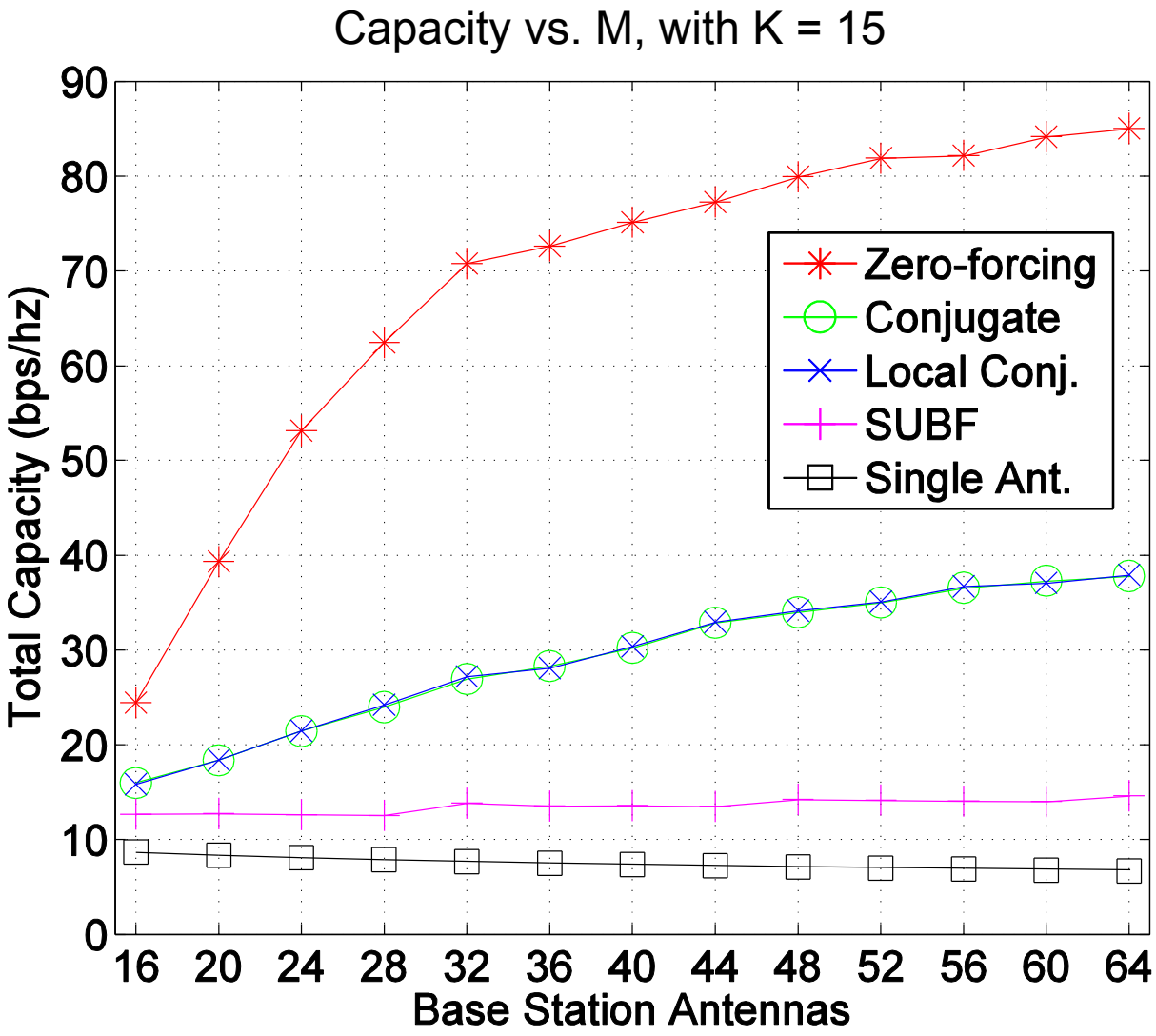
What we have learned

Good news:
Linear gains as # of users increases

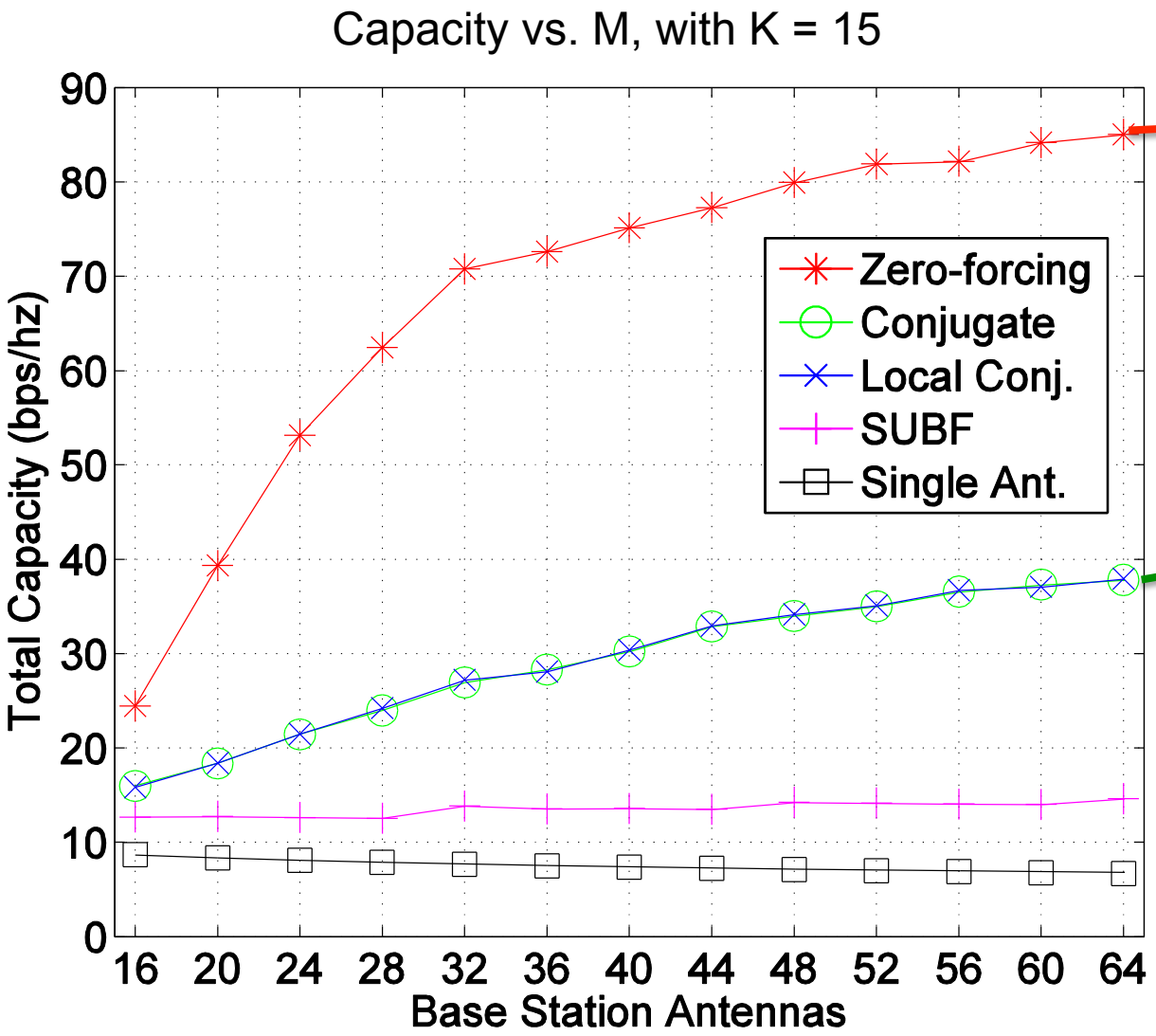


Linear gains as # of BS antennas increases

even as total P_{TX} scaled with 1/M



Disappointment: Conjugate not approaching Zero-forcing up to 64 antennas



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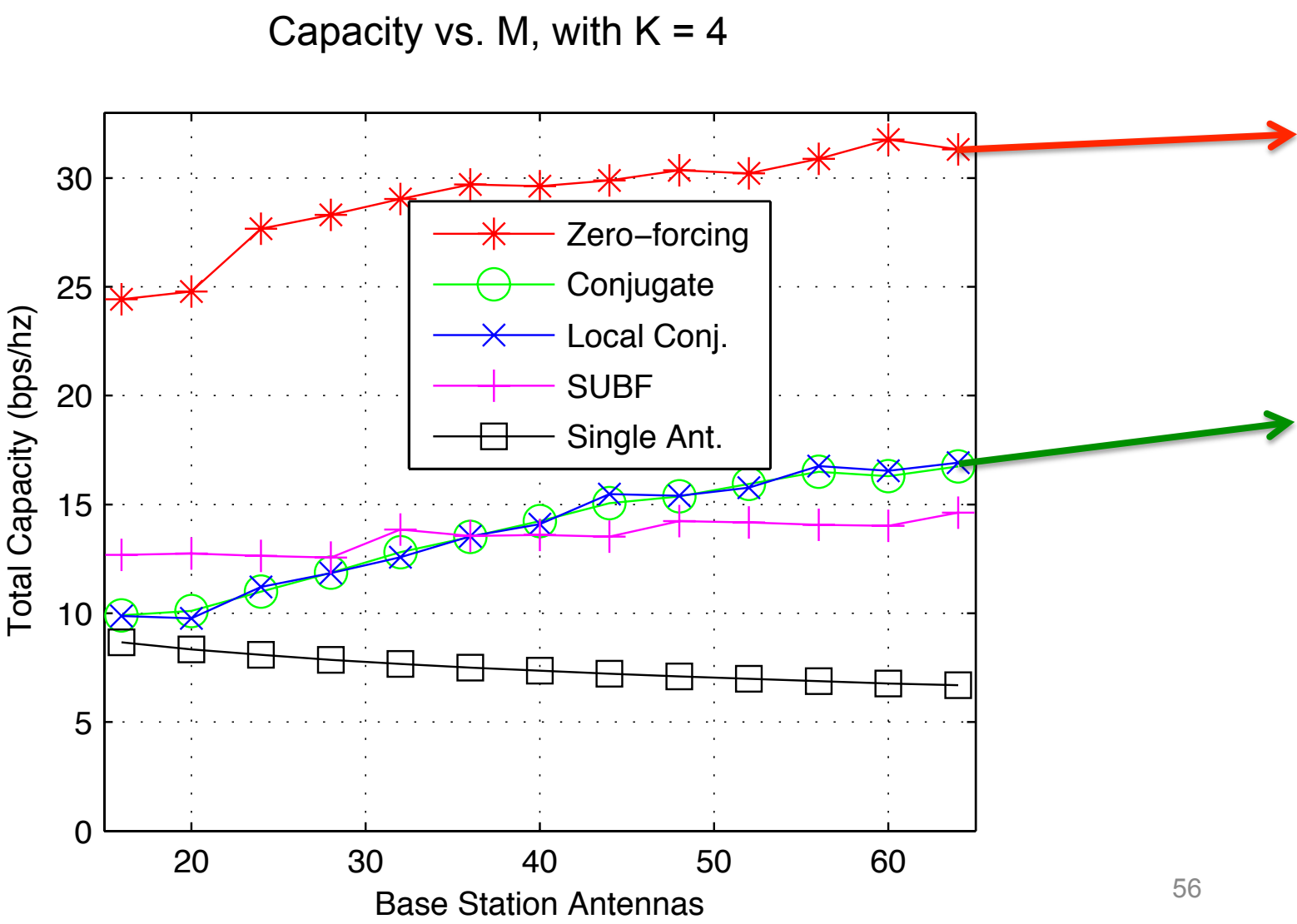


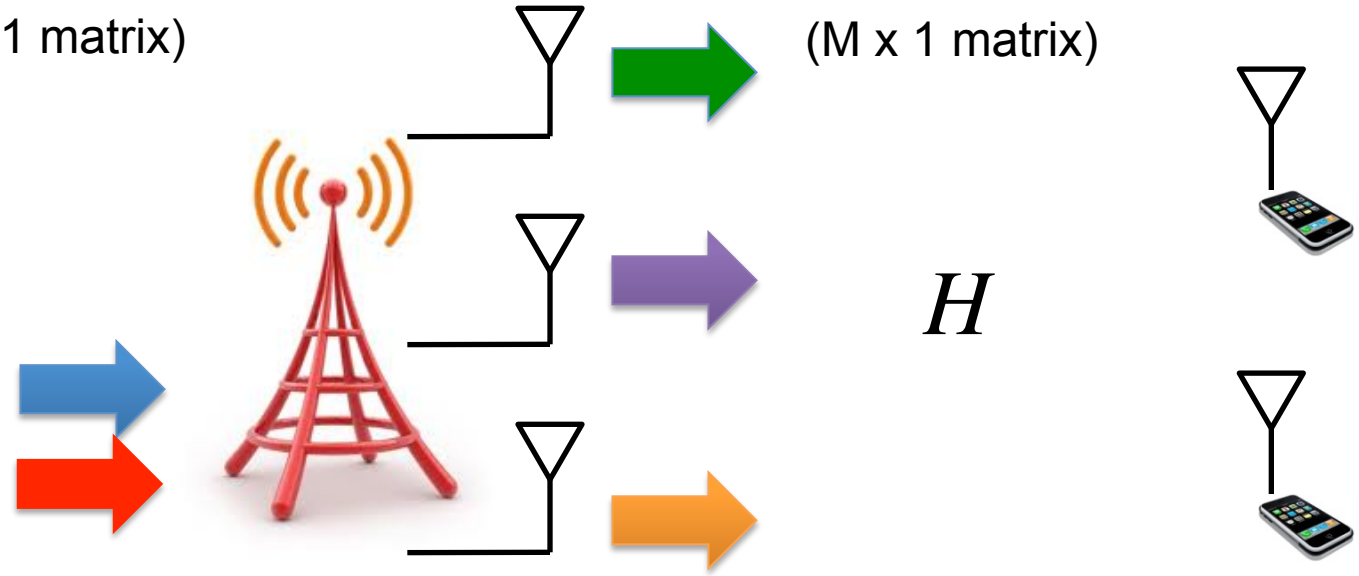
The dirty secret of massive MIMO

s

(Kx1 matrix)

$\mathrm{s}' = f(\mathrm{s}, \mathrm{H})$

(M x 1 matrix)



H

M: # of BS antennas

K: # of clients

M ≥ K

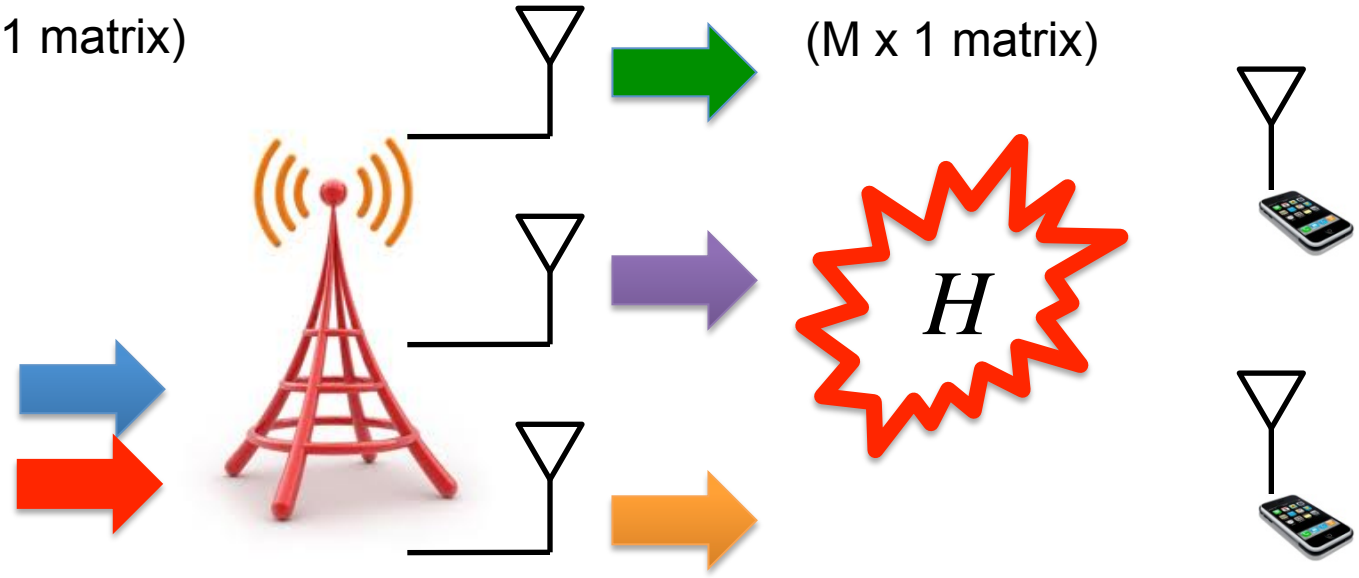
The dirty secret of massive MIMO

$\mathbf{s}$

(Kx1 matrix)

$\mathbf{s}' = f(\mathbf{s}, \mathbf{H})$

(M x 1 matrix)



M: # of BS antennas

K: # of clients

M ≥ K

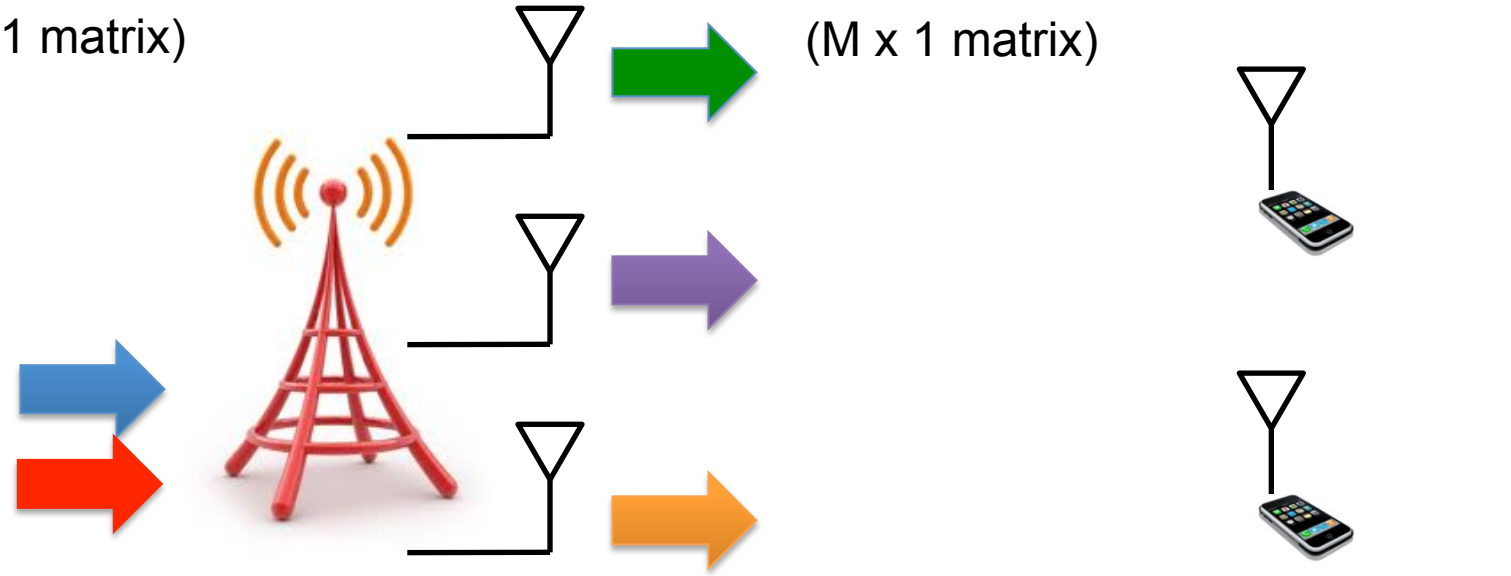
Sounding-feedback does not scale

s

(Kx1 matrix)

$\mathrm{s}' = f(\mathrm{s}, \mathrm{H})$

(M x 1 matrix)



M: # of BS antennas

K: # of clients

M ≥ K

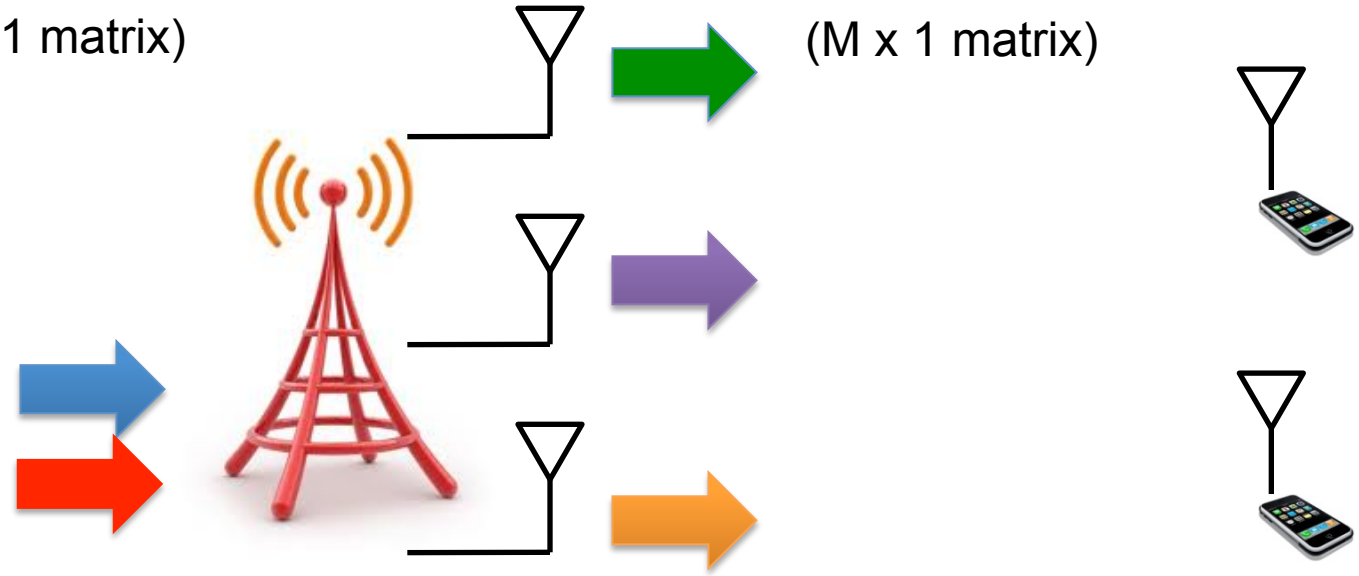
One must use time-division duplex and client-sent pilot

$\mathbf{s}$

(Kx1 matrix)

$\mathbf{s}' = f(\mathbf{s}, \mathbf{H})$

(M x 1 matrix)

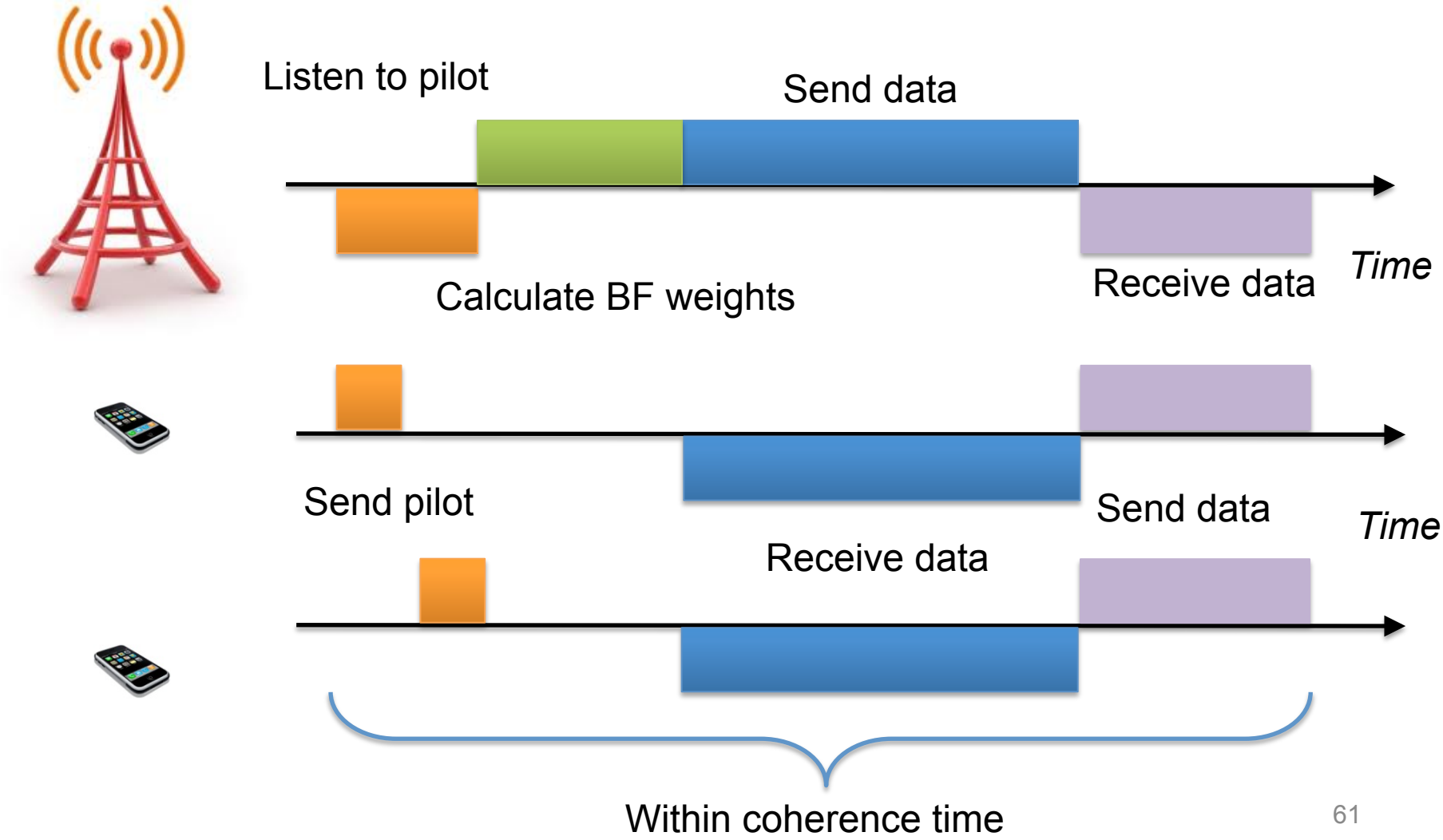


M: # of BS antennas

K: # of clients

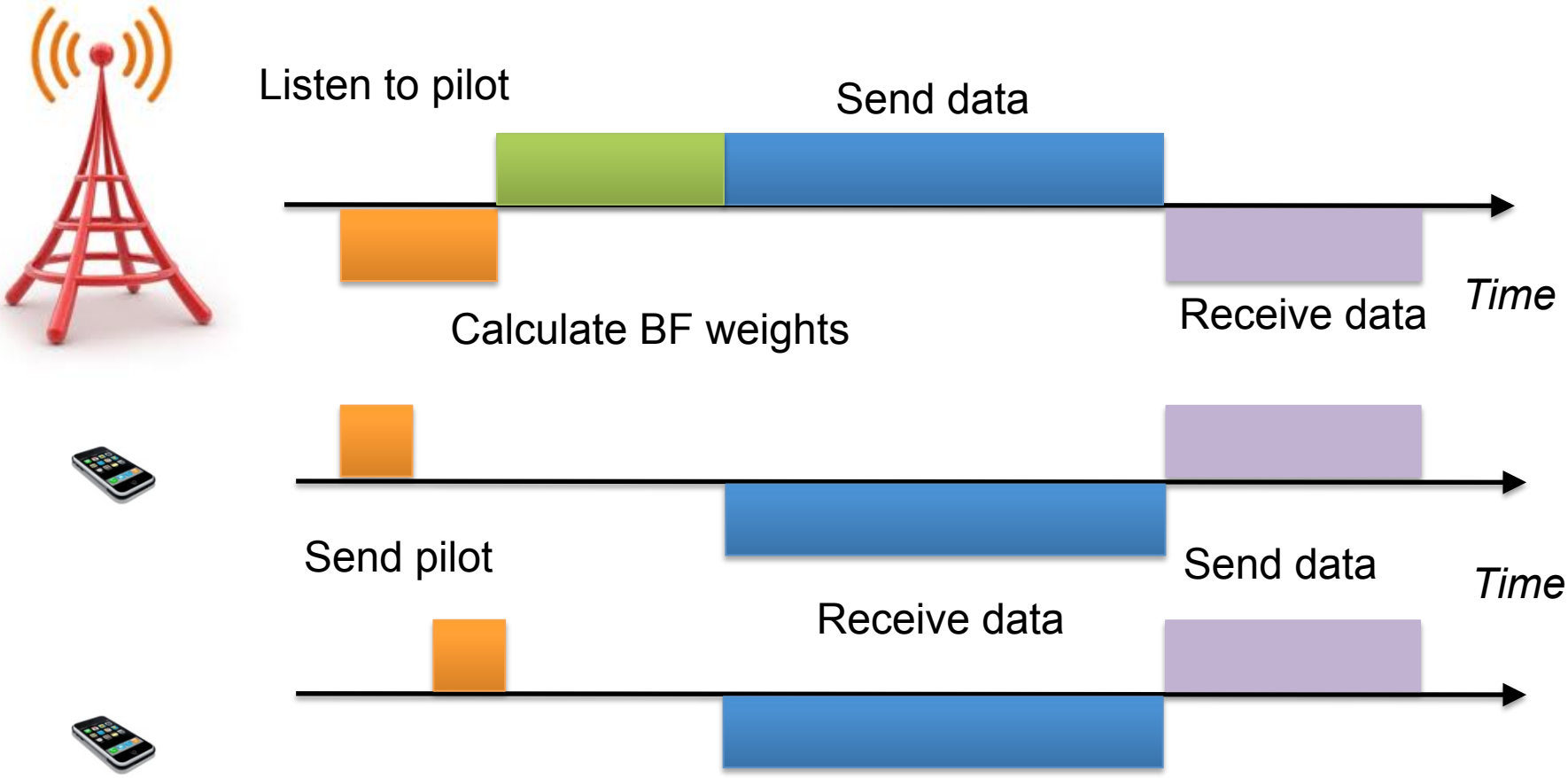
M ≥ K

What happens in a single coherence period



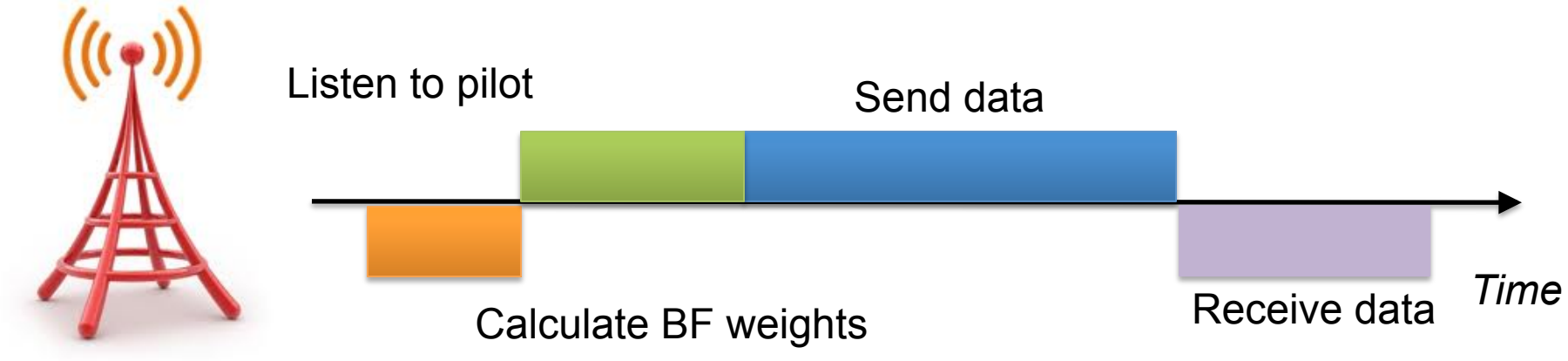
Both theory and our experiments only consider……

What if we factor all in?



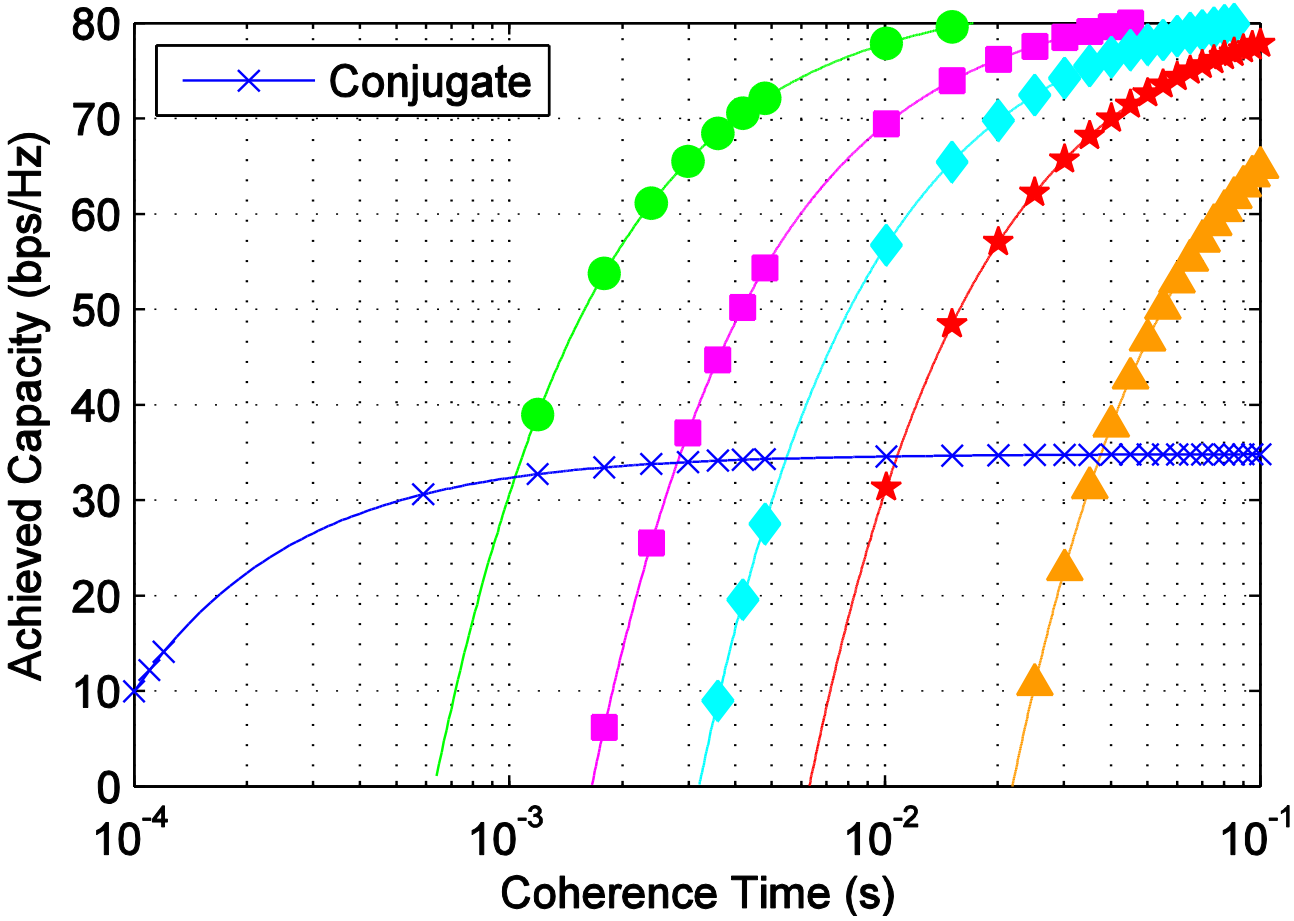
The base station can receive during calculation but the opportunity is limited due to downlink/uplink asymmetry

What if we factor all in?



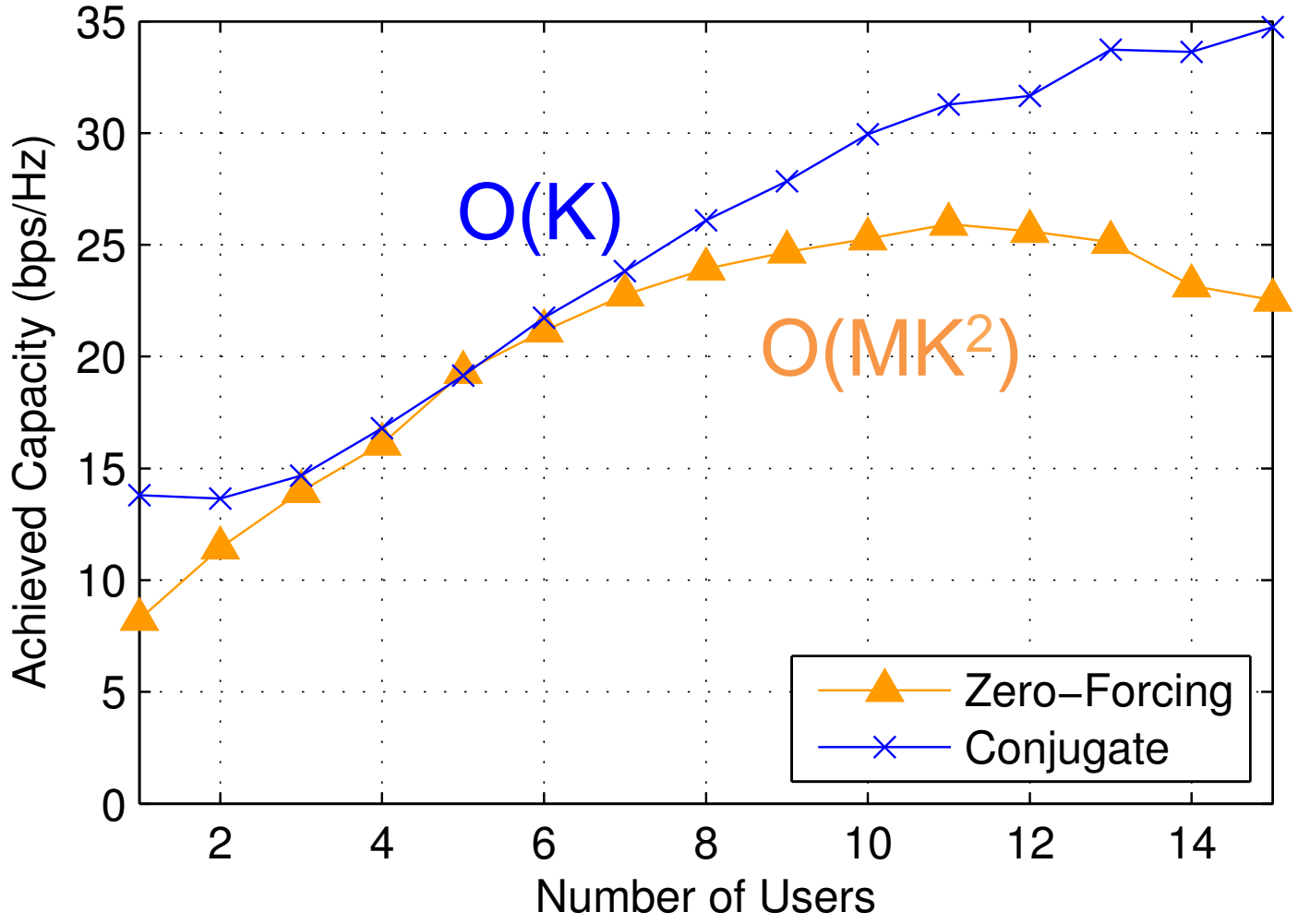
- Client mobility
  - Channel coherence time
- Number of clients
  - Time to listen to pilot
- Computation hardware on base station
  - Time to calculate BF weights

M = 64 K = 15



	Type	S	L	Inv. Type	Sym.
Super	Infiniband	40 Gbps	1 μs	FPGA	●
Cluster	4x10GbE	40 Gbps	20 μs	8xIntel i7	■
High	2x10GbE	20 Gbps	20 μs	4xIntel i7	◆
Mid	10GbE	10 Gbps	20 μs	2xIntel i7	★
Low	GbE	1 Gbps	20 μs	Intel i7	▲

Zeroforcing with various hardware configurations



Fixed coherence time of 30 ms with low-end hardware.

What we have learned

- Computational resources matter significantly
- Simplistic Conjugate beamforming works
  - Not in Marzetta's theoretical sense
- Need adaptive solutions
  - # of clients; client mobility
  - Precoding methods: Conjugate vs. Zero-forcing

What we are working on

Going for more antennas

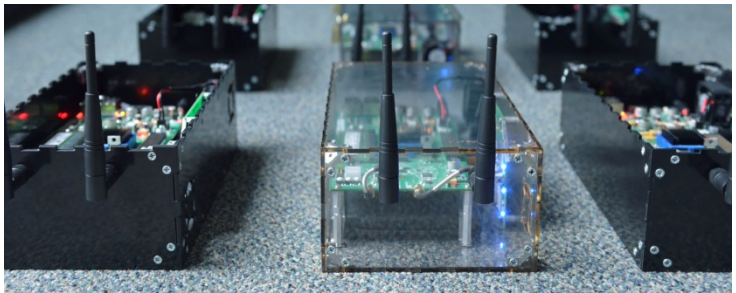
ArgosV2 (2013)

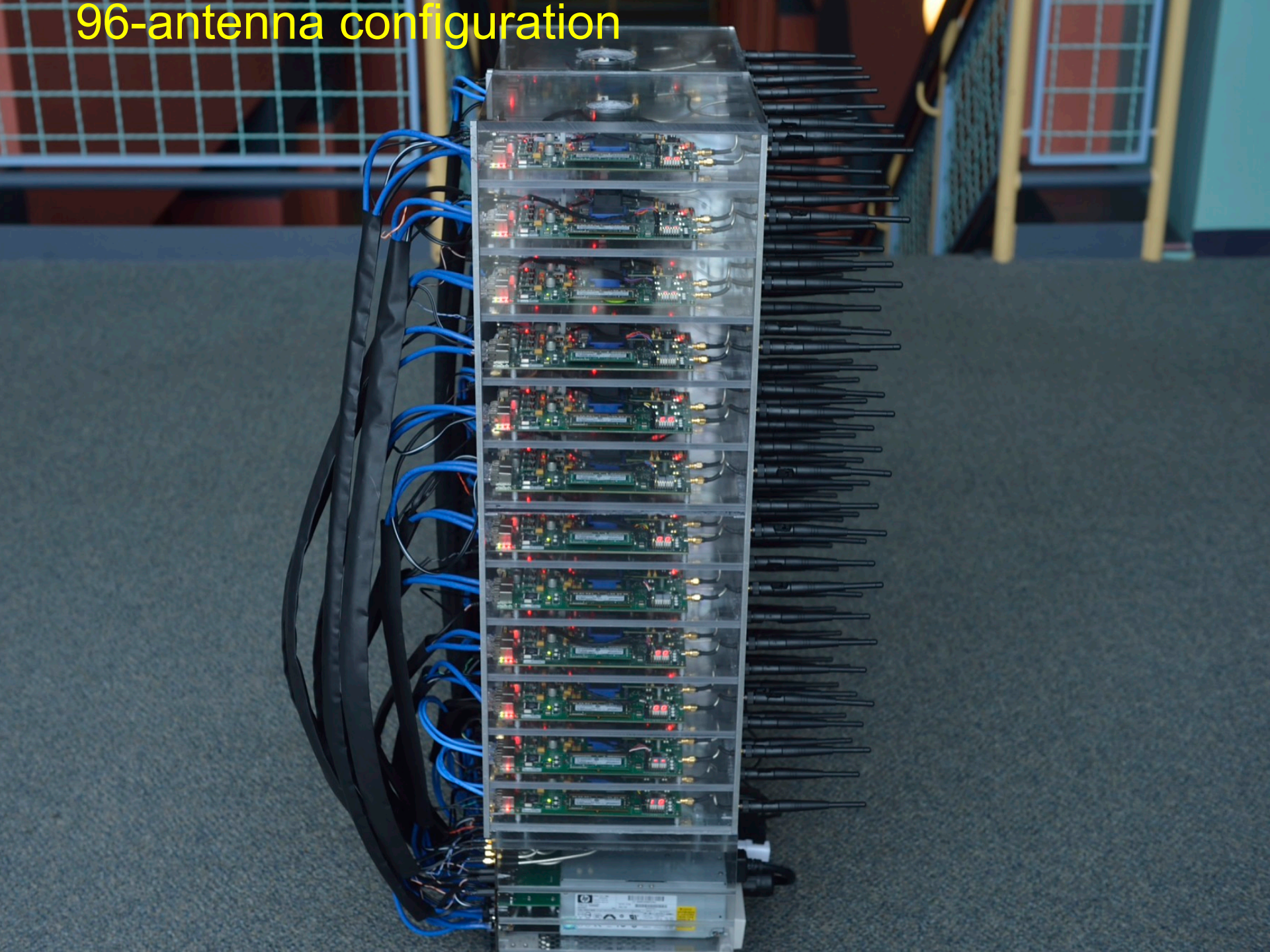
12 WARP V3 (48 antennas) per rack

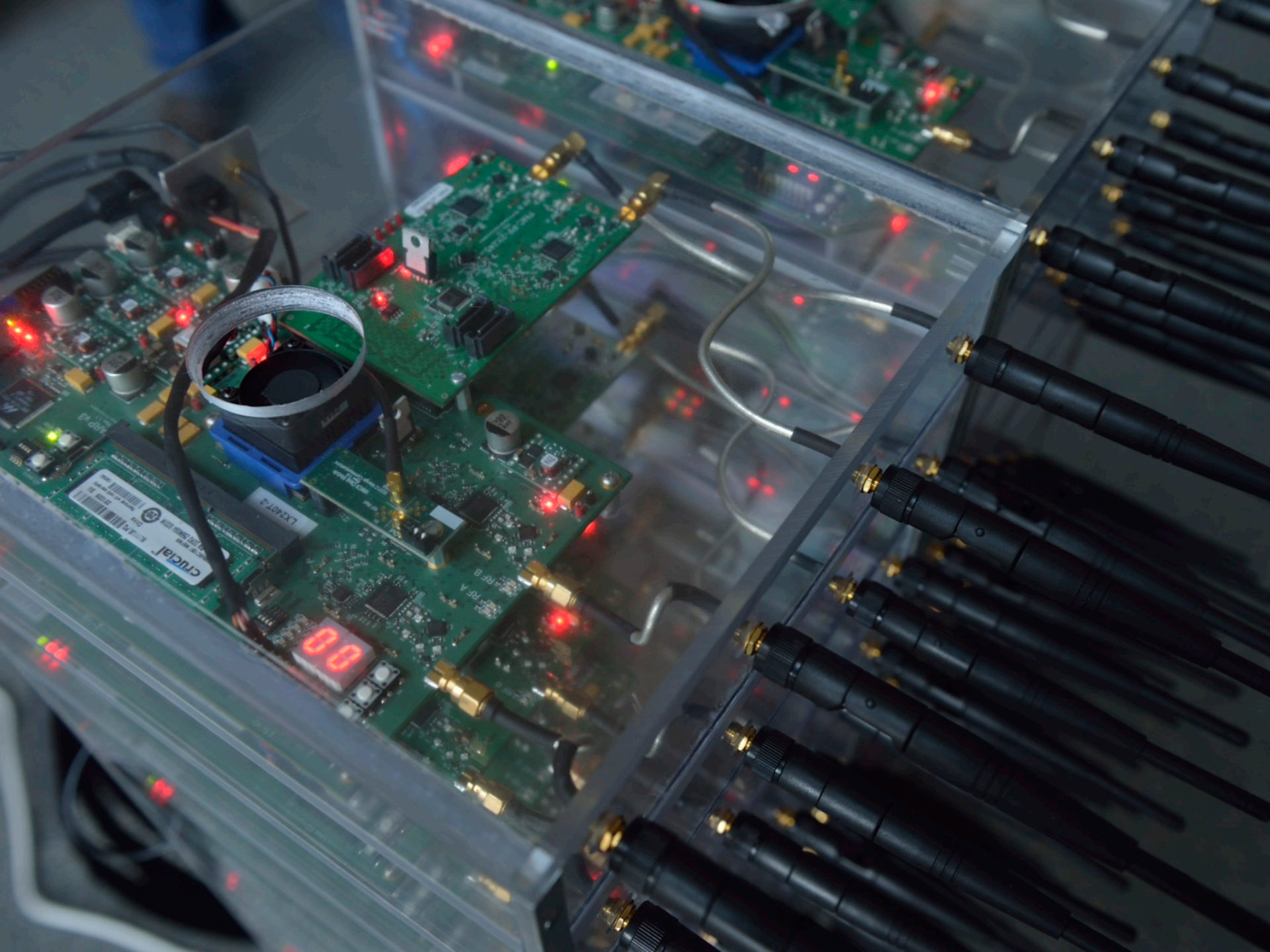
Polycarbonate, dado-style shelf

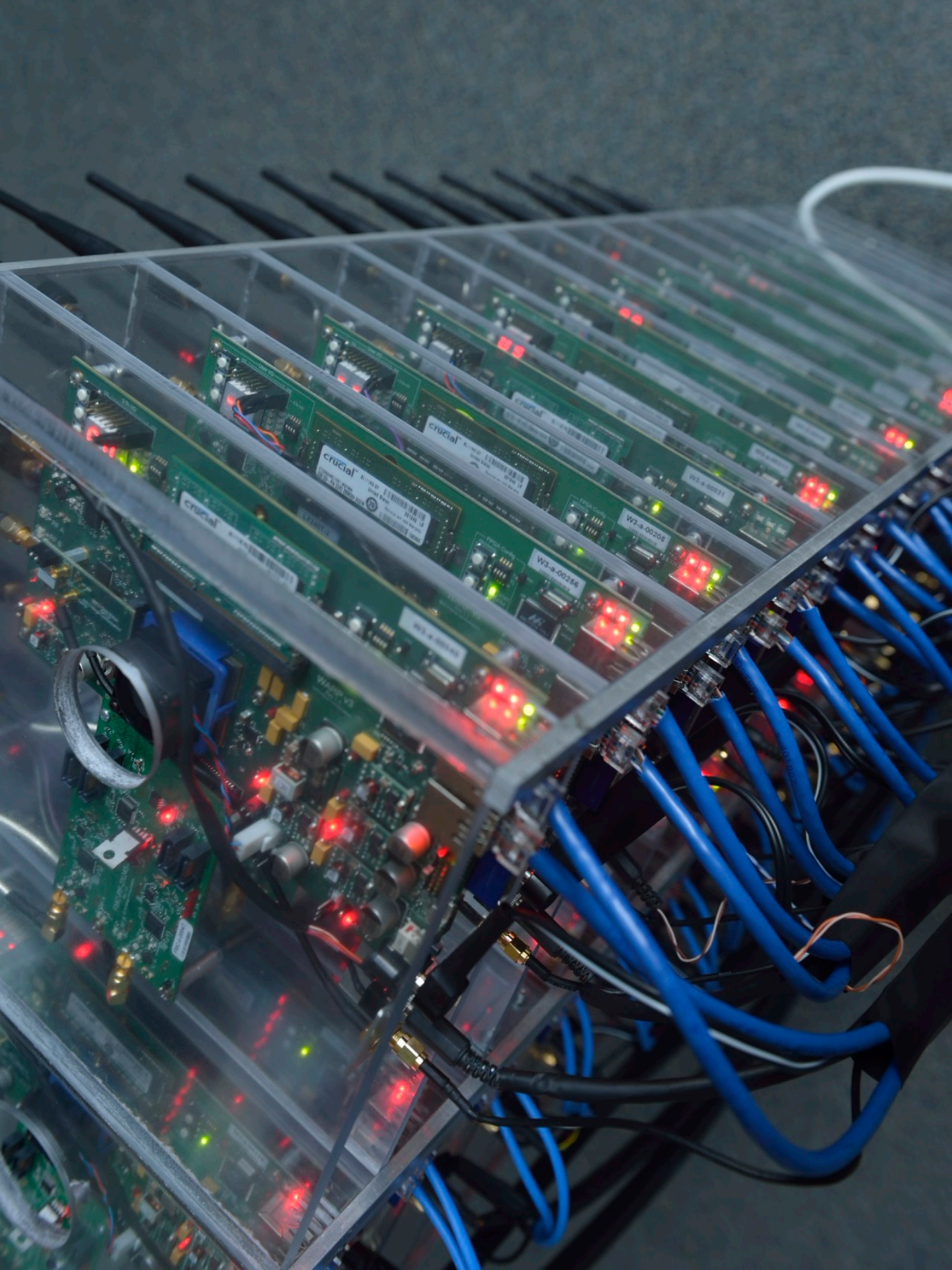
Anti-static spray and thermal vent

Battery-powered ArgosMobile




96-antenna configuration

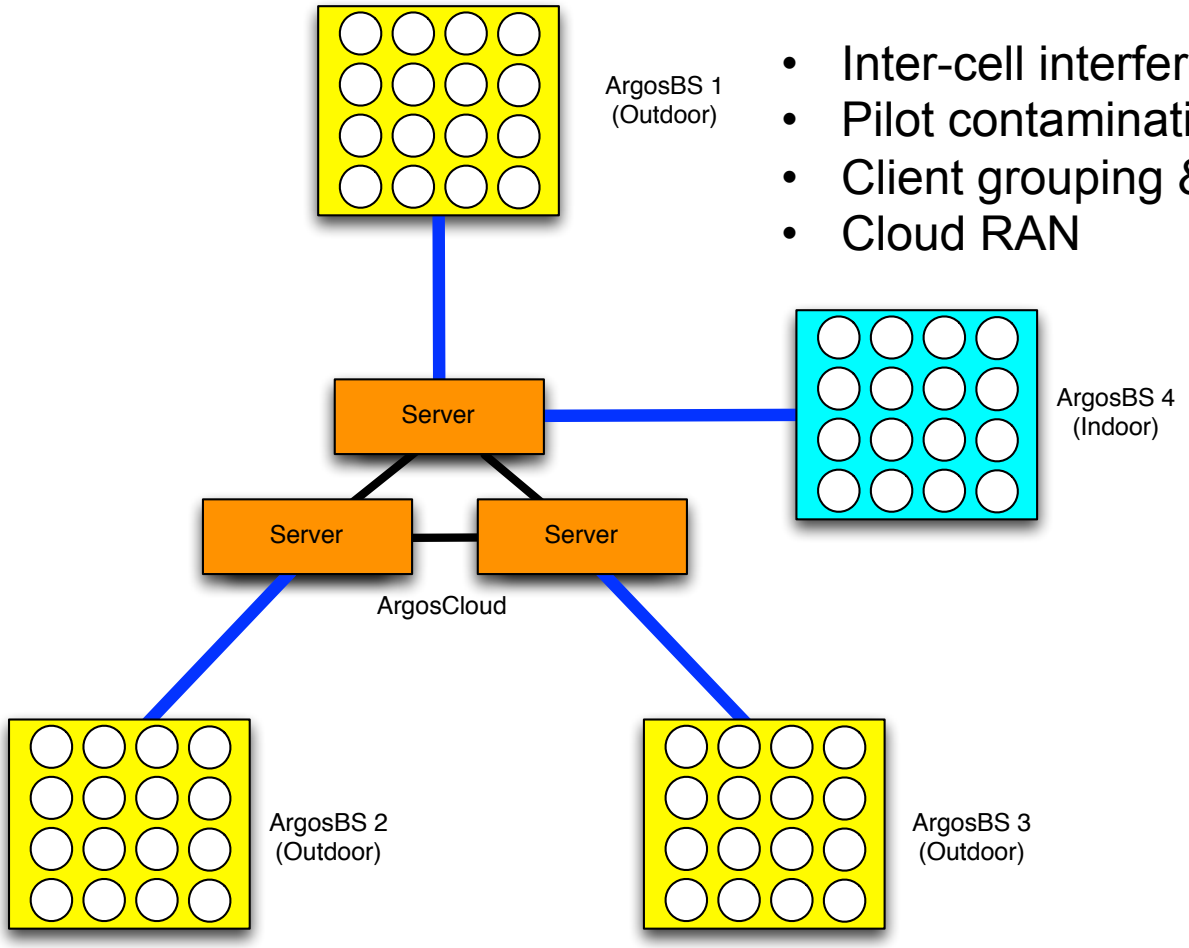



crucial
W3-a-00306
W3-a-00284

Ongoing Work: ArgosLab

- Software Framework for Rapid Prototyping
- Out-of-the-box Functionality
  - Time/Frequency Synchronization
  - Calibration
  - CSI Collection
- Scheduled frame-based real-time Transmission

From Argos to ArgosNet

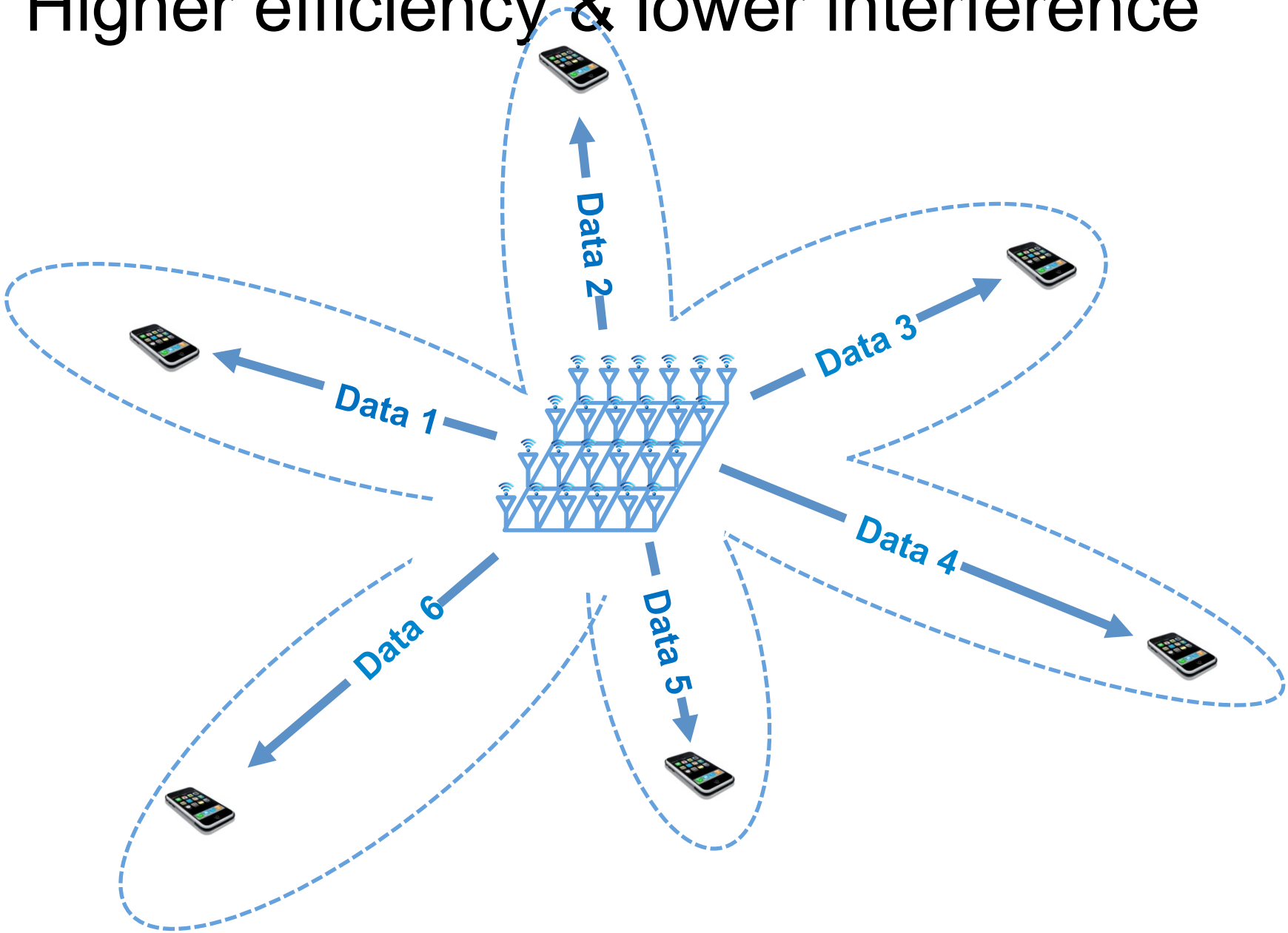


- Inter-cell interference management
- Pilot contamination
- Client grouping & scheduling
- Cloud RAN

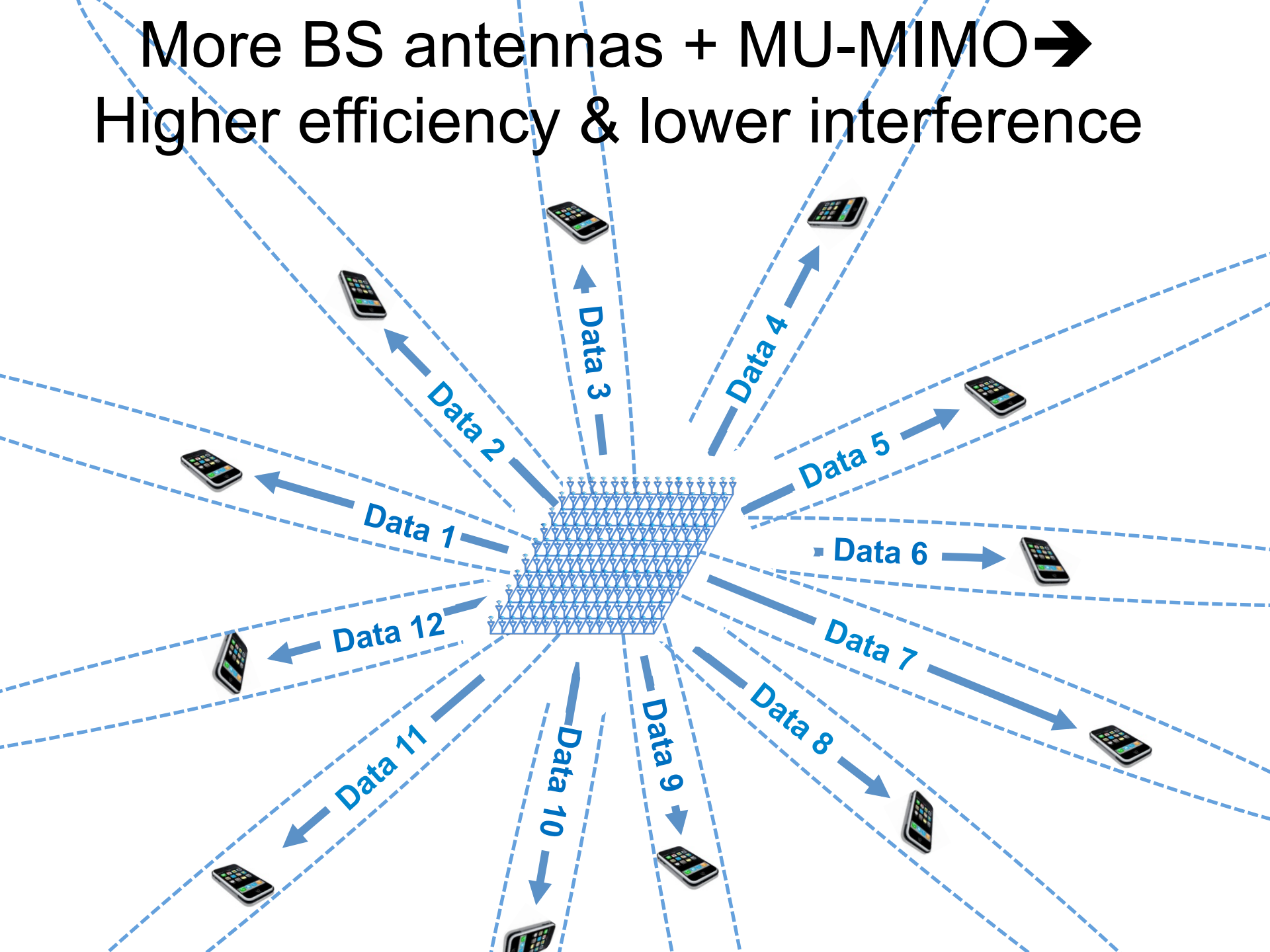
A network of massive MU-MIMO base stations

In summary……

More BS antennas + MU-MIMO➔ Higher efficiency & lower interference



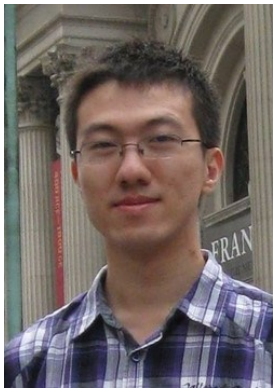
More BS antennas + MU-MIMO➔ Higher efficiency & lower interference



Guiding Principles

- Spectrum is scarce
- Hardware is cheap, and getting cheaper

Acknowledgments



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