Feeding the Smart Phone

The Limits of Spatial Reuse in Picocells

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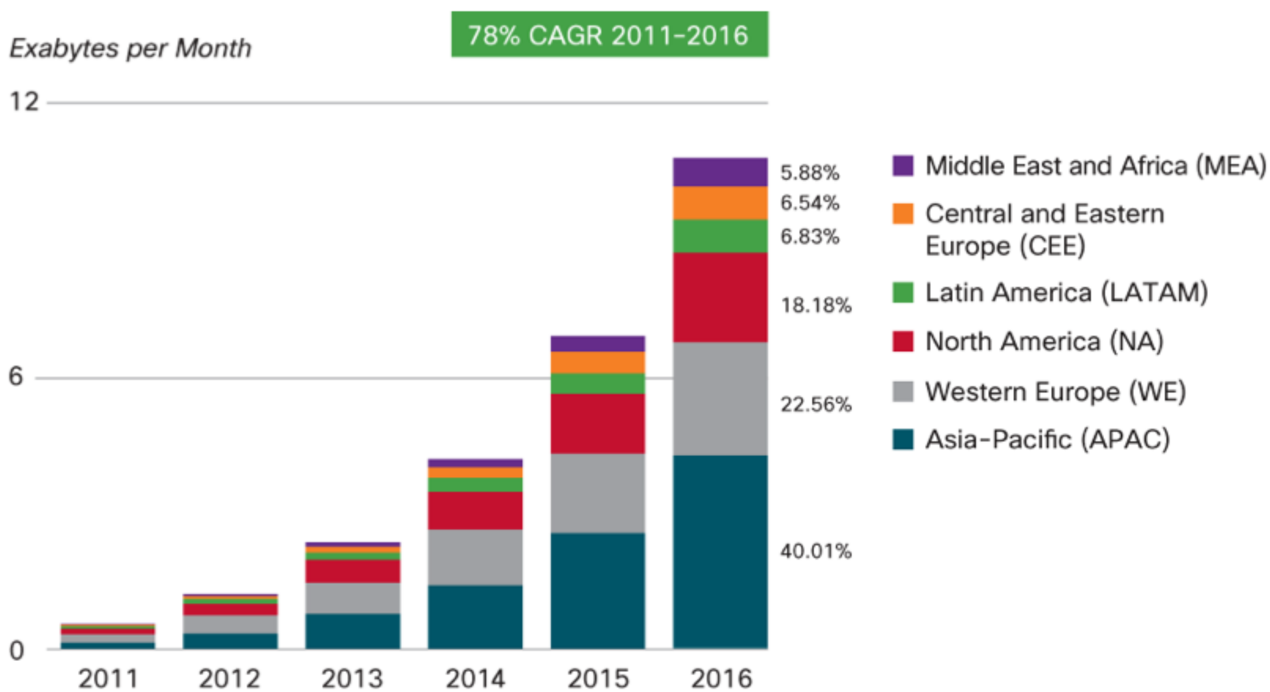
Work actually done by

Dinesh Ramasamy

The wireless industry who cried wolf

- After years of hype, exponential growth in wireless data hits with a vengeance

Figure 2. Global Mobile Data Traffic Forecast by Region

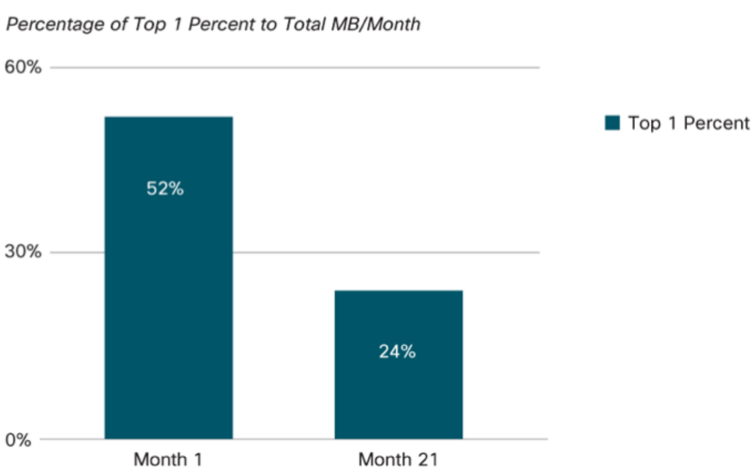


Source: Cisco VNI Mobile, 2012

Irreversible trends

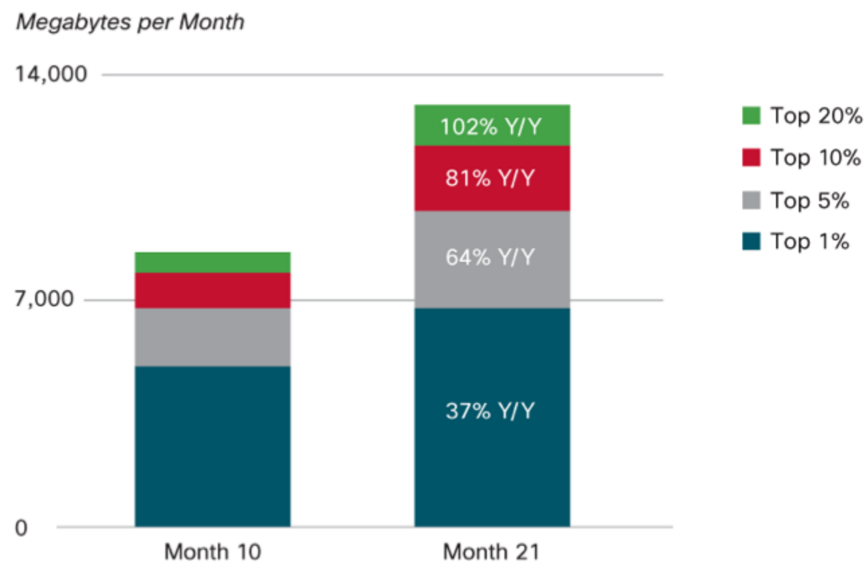
- iPhone/Android, Pandora/Spotify, Netflix/Amazon
- Tiered pricing can only go so far
  - Mice are becoming elephants

Figure 10. Top 1 Percent Generates 24 Percent of Monthly Data Traffic in Month 21 Compared to 52 Percent in Month 1



Source: Cisco VNI Mobile, 2012

Figure 11. Top 20 Percent Growing at a Faster Rate of 102 Percent Year-to-Year



Source: Cisco VNI Mobile, 2012

How to feed the smart phone?

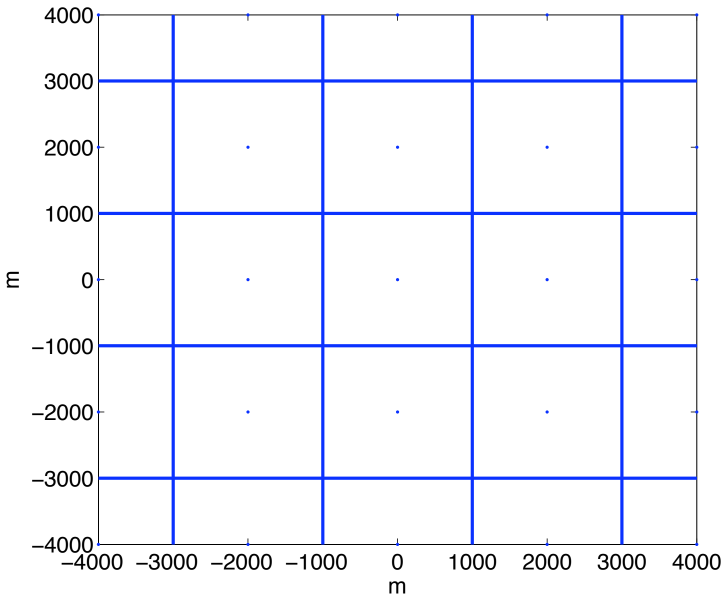
- Need exponential growth in network capacity
- Possible answers
  - Spatial reuse: cell size reduction
  - Offload to WiFi (or co-opt WLAN into cellular network via femtocell)
  - Advanced cross-layer techniques
- Today's talk: how far can picocells take us?

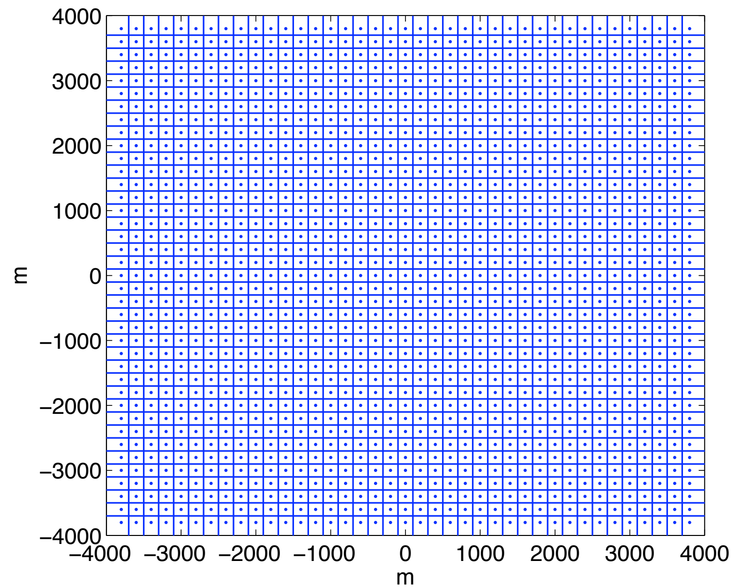
  can we provide wire-like determinism?

  how decentralized can resource management be?

  how much does network MIMO help?

The promise of shrinking cells





- •Cell radius shrinks from 1km to 100m
  - 100 picos where there was one macro
- •100X throughput gains?

$$SIR = \frac{r_{desired}^{-\alpha}}{\sum_i r_i^{-\alpha}}$$

Performance would be scale-invariant for fixed path loss exponent

But is the assumption of fixed power law path loss valid?

Revisiting path loss models

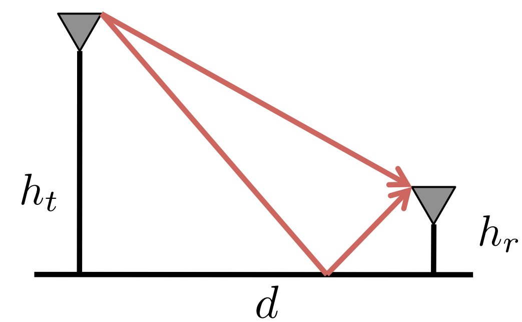
The perils of power laws

- $d^{-\alpha}$ predicts path loss locally (not for all d)
  - Depends on distance relative to geometry of TX, RX, environment
- Small cells (e.g., lamppost based base stations)
  - Signal from serving BS is near-LOS ➔ $\alpha=2$ a good fit
  - Is $\alpha=2$ a good guess for interference from other cells?
    - Yes for nearby cells (i.e., for aggressive reuse)
    - But not for far-away cells (blocked by buildings)

The fourth power model: LOS & ground reflection

- Power law "regime change" reported in measurements; justified via ground reflections

$$PL(d) = \begin{cases} -20\log_{10}(4\pi d/\lambda_c) & d \le d_f \\ -20\log_{10}(4\pi d_f/\lambda_c) - 40\log_{10}(d/d_f) & d > d_f \end{cases}$$



Fresnel breakpoint

$$d_f \approx \frac{4h_t h_r}{\lambda_c}$$

At 1.9GHz, Rx height 1.7m, predicted regime change at:

Tx mounted 13.2m high is 573m

Tx mounted 3.7m high is 159m

d_f

M. J. Feuerstein, K. L. Blackard, T. S. Rappaport, S. Y. Seidel, and H. H. Xia, "Path loss, delay spread, and outage models as functions of antenna height for microcellular system design," *ITVT* '94.

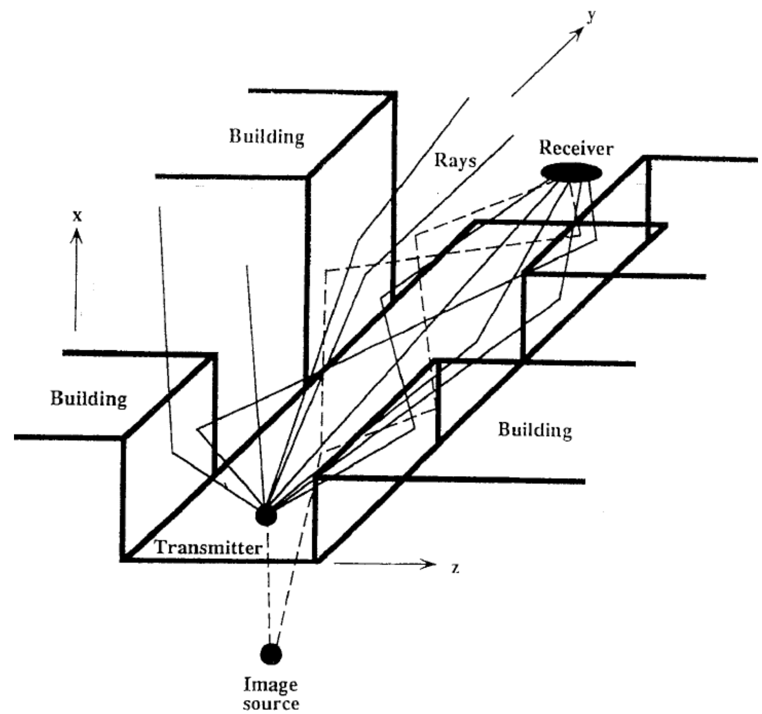
Second power + exponential: multi-slit waveguide

- Urban scenarios, along the street with BS
- Channel model:

$$PL(d) = -20\log_{10}\left(\frac{4\pi d}{\lambda_c}\right) - 4.3\eta d$$

- Random slit positions give exp falloff
- Breakdown distance depends on environment

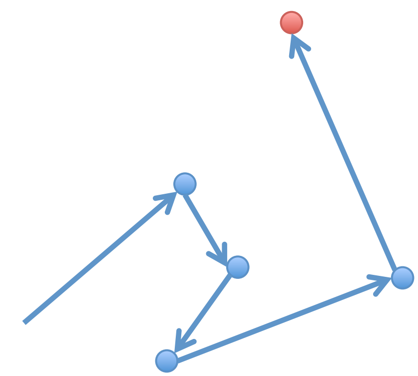
$$\eta^{-1} \approx 150\text{m} - 500\text{m}$$



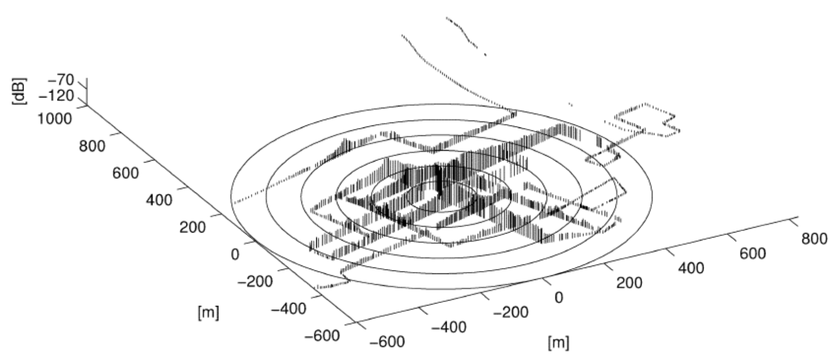
N. Blaunstein, R. Giladi, and M. Levin, “Characteristics’ prediction in urban and suburban environments,” ITVT ’98.

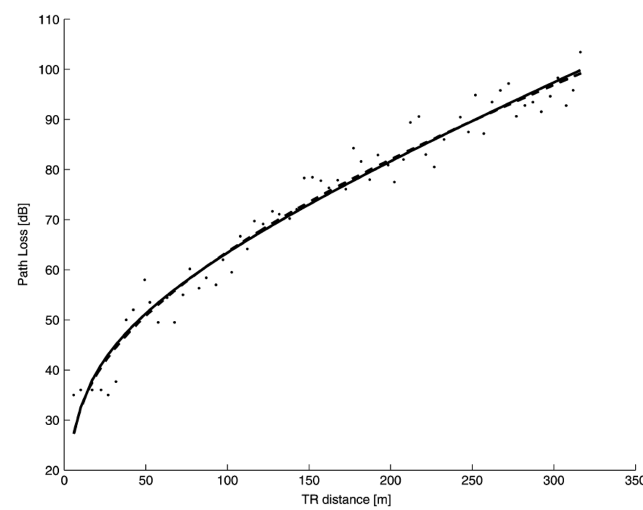
Second power + exponential via wandering photons

- Intuitively well matched to below rooftop BS (picos) in built-up areas
- Exp power loss model; exponent η depends on clutter



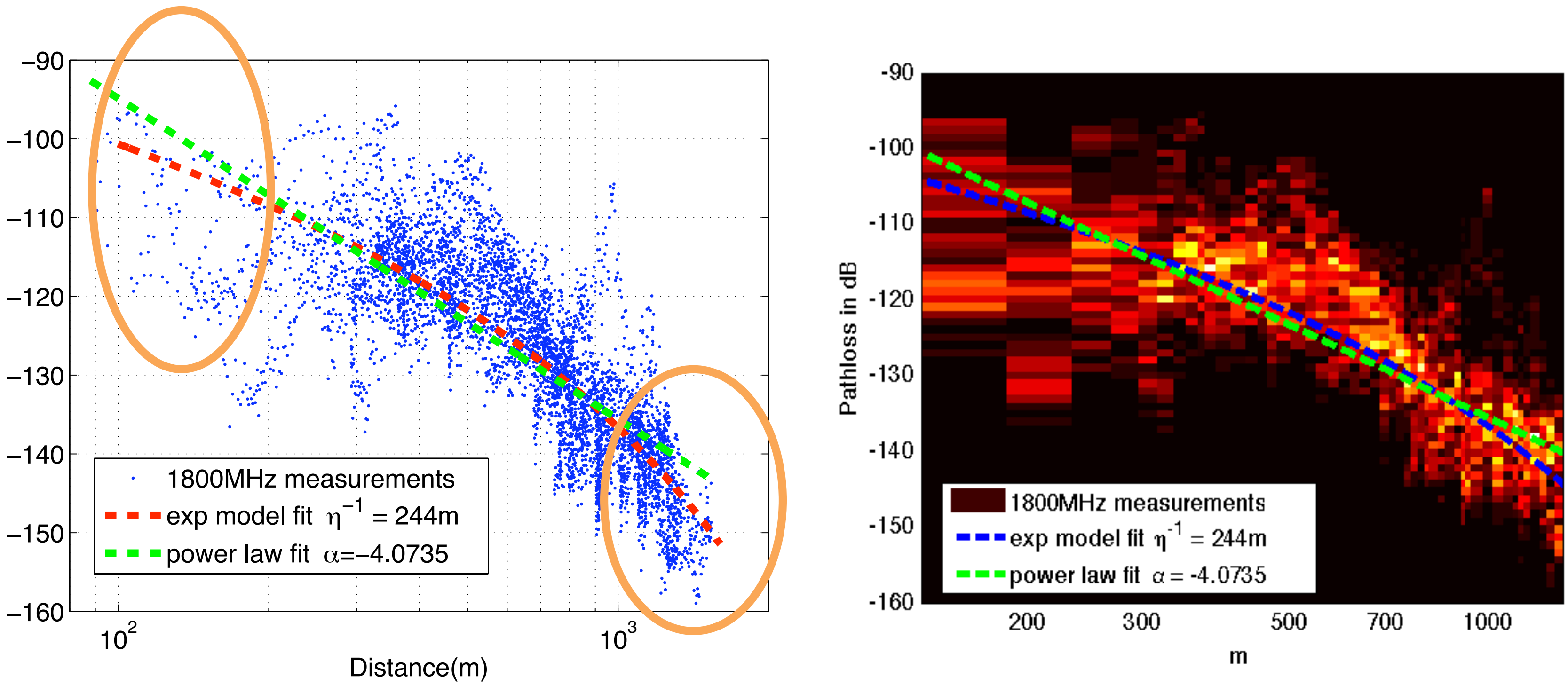
$$PL(d) = -20\log_{10}\left(\frac{4\pi d}{\lambda_c}\right) - 4.3\eta d$$





M. Franceschetti, J. Bruck, and L. J. Schulman, “A random walk model of wave propagation,” ITAP ’04

Second power + exponential as a unified model?



B. Van Laethem, F. Quitin, F. Bellens, C. Oestges, and P. De Doncker, "Correlation for multi-frequency propagation in urban environments," *Progress In Electromagnetics Research Letters, '12.*

Exponential model fits measurement data well over a much larger range than any single power law

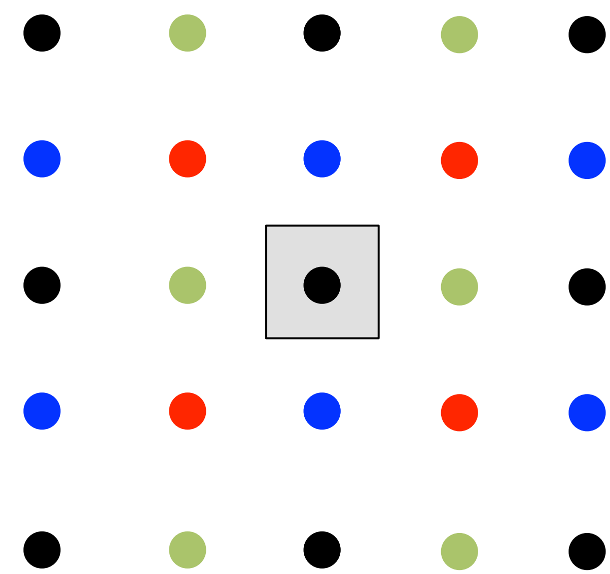
Limits of spatial reuse

Model

- Channel model
  - Second power + exp path loss model
  - phase due to LOS beam

$$h(d) = 10^{PL(d)/20} e^{j2\pi d/\lambda_c}$$

$$PL(d) = -20\log_{10}\left(\frac{4\pi d}{\lambda_c}\right) - 4.3\eta d$$

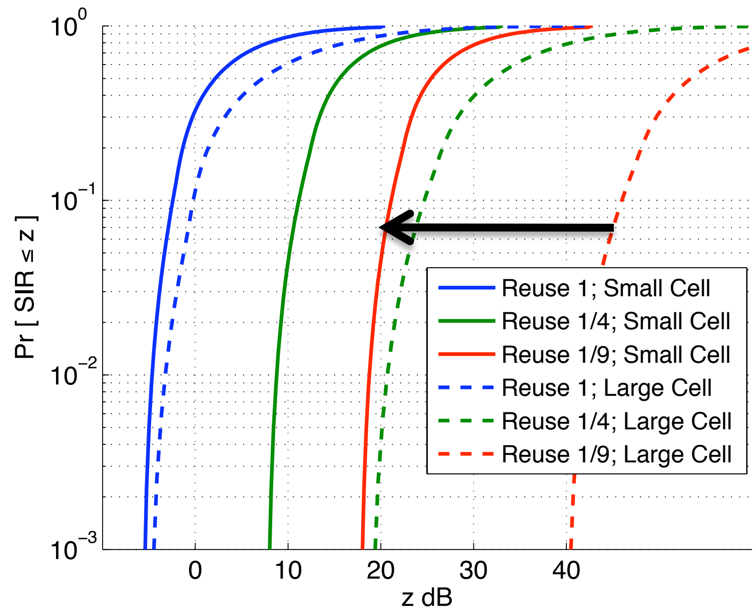


Reuse ¼

- Square grids; regular reuse; random user locations
- Carrier frequency 2GHz

Shrinking cells alone is not enough

- Shrinking cells
  - Relative strength of nearby interference increases
  - "LOS-like" interference
- For same SIR (say 20dB)
  - Less aggressive reuse; 1/4 to 1/9
  - 100X cell division gains are offset by 4/9 reuse backoff



Small cell:

$$R_e = 100\mathrm{m} \quad \eta^{-1} = 150m$$

Large cell:

$$R_e = 1000\mathrm{m} \quad \eta^{-1} = 500m$$

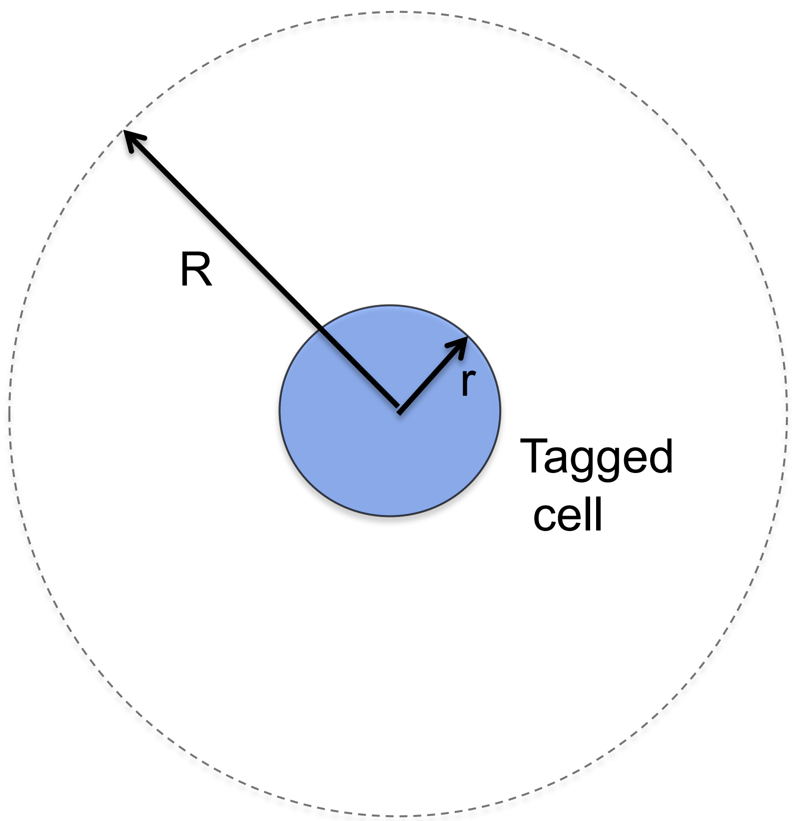
Need smarter sharing strategies for picocells

Design approach for small cells

- High peak rates
  - high bandwidth efficiency, high SIR target
- Quasi-deterministic performance
  - Towards zero outage
  - Feasible in near-LOS environments
- Must coordinate with nearby picocells
  - Single interferer can wipe you out in near-LOS environment
  - But naïve orthogonalization is too costly
- "Far-away" picocells set interference floor

A Scalable Architecture

Nearby interference causes too much damage in near-LOS environments
➔must coordinate with neighboring cells
Cells *outside* coordination region set interference floor
Strategy inside coordination region affects interference floor



r= cell radius
R= coordination radius
(no coordination with cells
outside coordination radius)

Analytical model: example interference computation

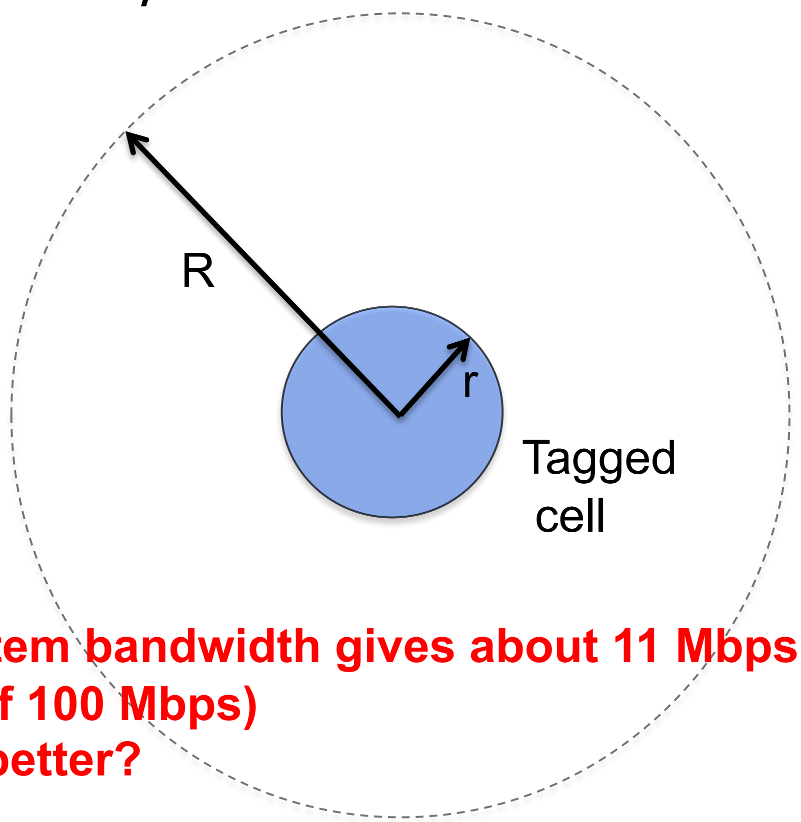
Interference floor calculation
(orthogonalizing in coordination region)

$$I = \int_R^\infty \rho \frac{1}{r^2} e^{-\eta r} 2\pi r\, dr \leq \frac{2\pi\rho}{\lambda R} e^{-\eta R}$$

Signal strength $S = \frac{1}{r^2} e^{-\eta r}$

$$K = \frac{R^2}{r^2}, \rho = \frac{K}{\pi r^2}$$

K= reuse factor
R = cell radius



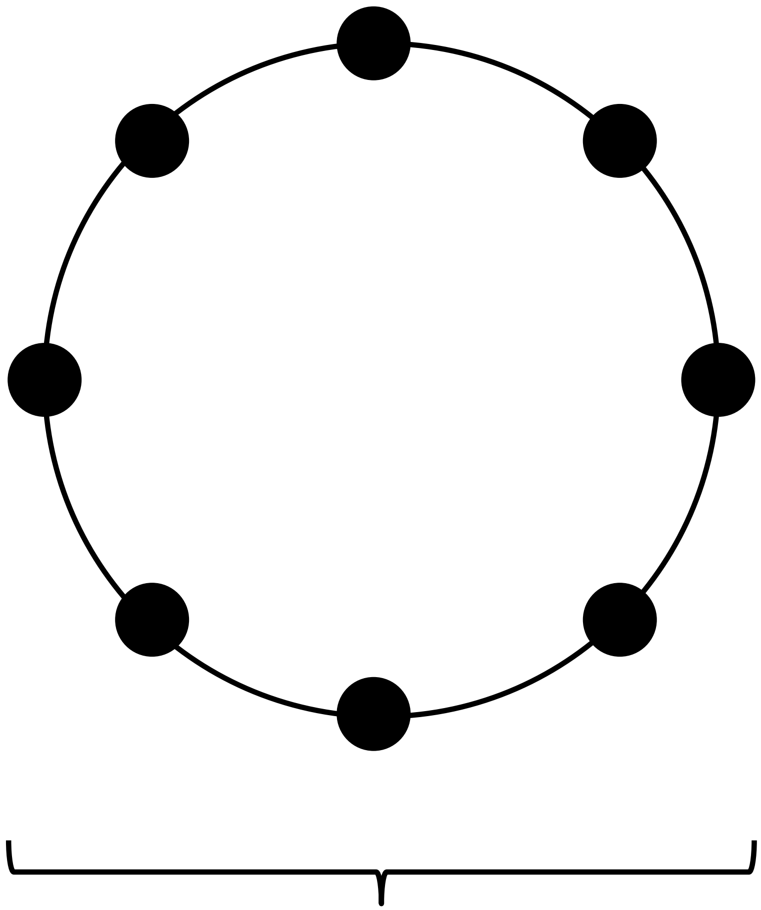
Example
K = 9
r = 100m
λ^{-1} = 150m
SIR = 15.3 dB
BW efficiency = 5.13bps/Hz

20 MHz system bandwidth gives about 11 Mbps per picocell
(peak rate of 100 Mbps)
Can we do better?

How to get back spatial reuse in picocells

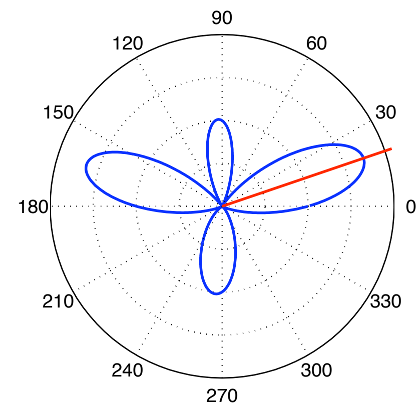
- Why is spatial reuse impaired in picocells?
  - Near-LOS interference can wipe you out
  - But naïve orthogonalization really hurts capacity
- Can we reduce nearby interference?
  - Beamforming
- Can we turn nearby "interference" into "desired signal"?
  - Collaborative beamforming (CoMP)

Base station antenna arrays

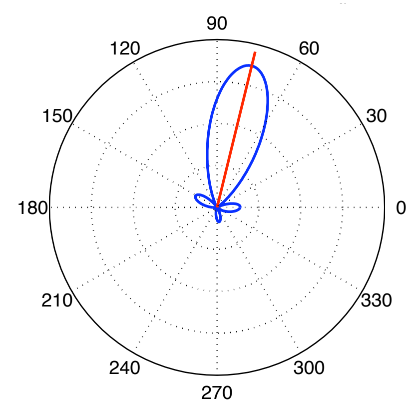


Diameter = λ_c = 15cm

Focus power when transmitting



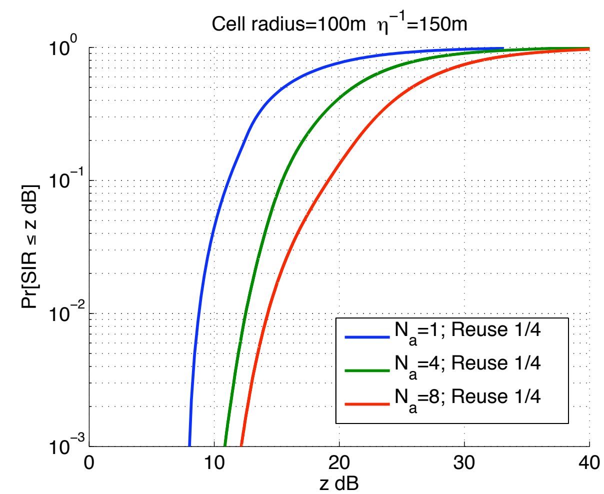
4 element array

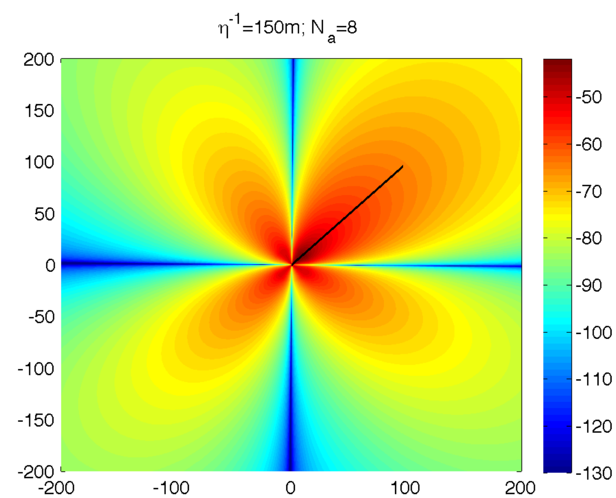


8 element array

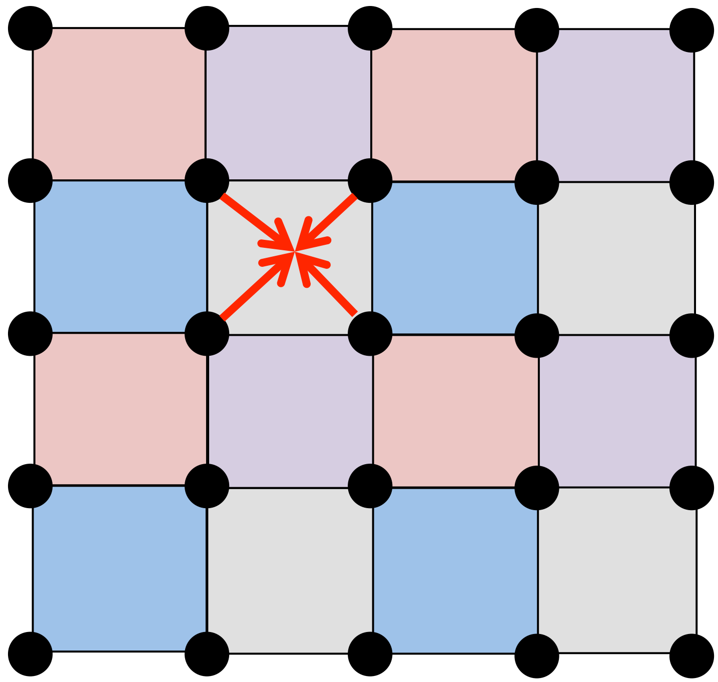
Beamforming

- Particularly effective in near-LOS settings
  - Focus power, improve SIR
  - Freq-flat beamforming
- 8 element pico approaches SIR CDF of omni large cell
  - Can avoid reuse back off
    - Reuse ¼ gives median SIR 20 dB
  - But performance not “deterministic”
    - 1% outage for 15 dB SIR target
  - Determinism with larger arrays? (higher carrier freqs)

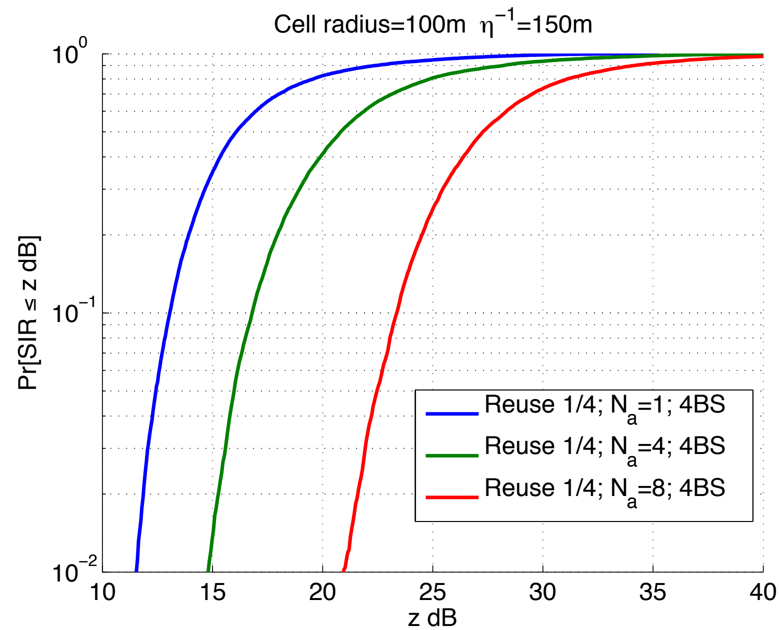




CoMP Beamforming



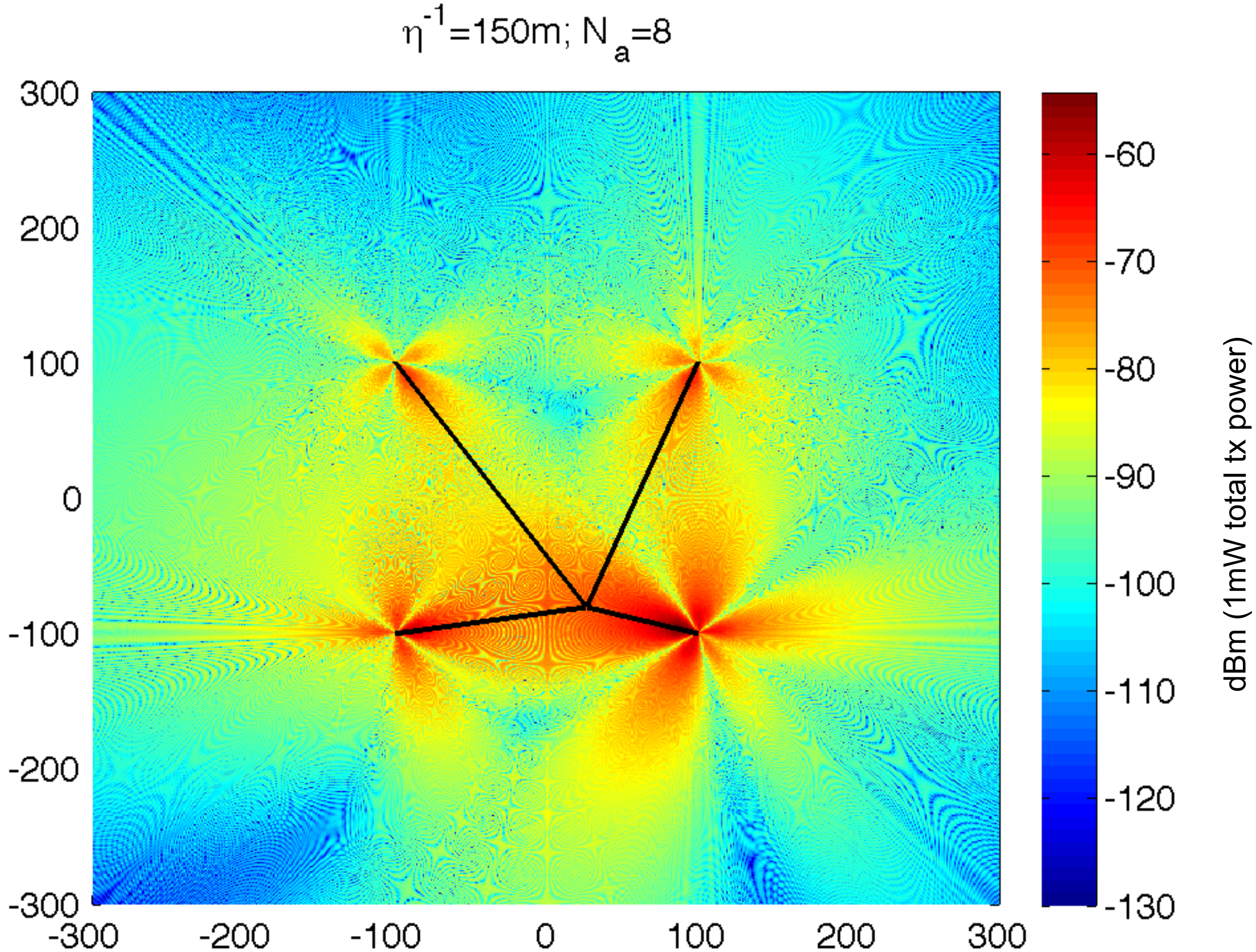
Reuse 1/4



Define “virtual cells” based on cluster of collaborating BS

-8 Element array with CoMP better than large cell reuse ¼
-Performance getting more “deterministic”

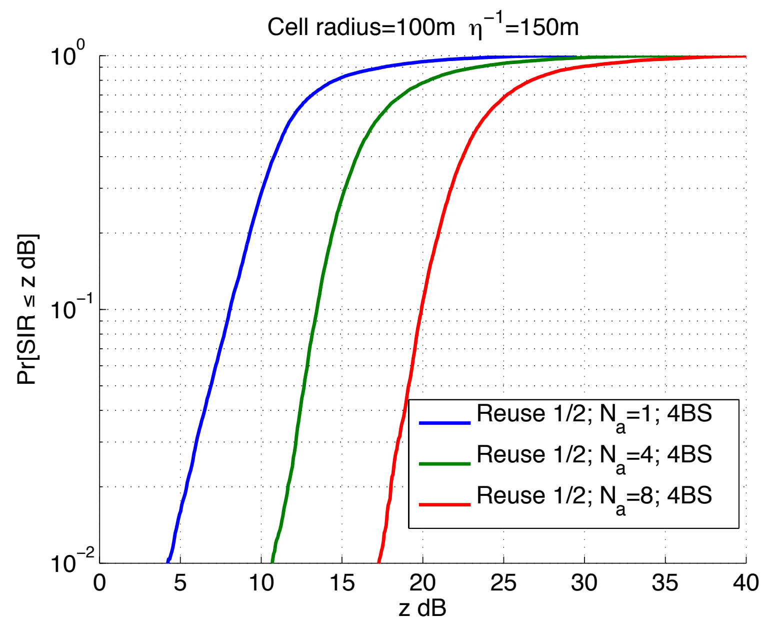
CoMP beam pattern



Leakage mainly contained to adjacent virtual cells, so reuse ¼ works

CoMP Multiplexing

- Serve 2 users per virtual cell
  - "Effective reuse" rate ½
  - SIR > 15dB
- 1.5X better than large cell (omni; naïve) per cell
  - **150X network capacity gain**



Median rates

Omni; naïve

Reuse	Large cell SIR	Small cell SIR	Large cell rates	Small cell rates
1	7.4dB	2.2dB	54 Mbps	28 Mbps
1/4	32dB	15.5dB	53 Mbps	26 Mbps
1/9	53.5dB	25.5dB	39.5Mbps	19Mbps

Small cells; Reuse 1/4

Arrays at BS

Antenna elements	SIR	Rates
4	21dB	35Mbps
8	25.9dB	43Mbps

CoMP; collaborative BF and Mux.

Antenna elements	BF only SIR	BF only rates	BF+ZF SIR	BF+ZF rates
4	21dB	35Mbps	17dB	56Mbps
8	27.4dB	46Mbps	23dB	77Mbps

Three nines (0.1% outage) rates

Omni; naïve

Reuse	Large cell SIR	Small cell SIR	Large cell rates	Small cell rates
1	-4.1dB	-5.3dB	9.4Mbps	7.5Mbps
1/4	20dB	8dB	33.3Mbps	14.3Mbps
1/9	40dB	18dB	29.5Mbps	13.3Mbps

Small cells; Reuse 1/4

Arrays at BS

Antenna elements	SIR	Rates
4	11dB	19Mbps
8	12dB	21Mbps

CoMP; collaborative BF and Mux.

Antenna elements	BF only SIR	BF only rates	BF+ZF SIR	BF+ZF rates
4	13.5dB	23Mbps	7.5dB	27Mbps
8	19dB	32Mbps	14.5dB	49Mbps

What we have learnt

- Fixed power law models can be misleading
- 2nd power/exponential promising model
  - Interference is "amplified" as we shrink cell size
  - Naïve orthogonalization gives away scaling gains
  - Local coordination is critical
- Beamforming can help
  - Still need to enforce reuse
- Collaborative beamforming can really help!
  - Requires very tight coordination with neighbors
  - Still need to enforce reuse

Many open issues

- Statistical characterization of performance
  - Randomness mainly due to desired mobile location (fading less important for near-LOS links)
  - Can we get quasi-deterministic performance?
- Dealing with SIR "outage"
  - Reactive coordination for adaptive reuse?
  - Adaptive modulation?
- Realizing the promise of CoMP
  - Convincing solutions for sync and coordination
  - Leverage recent progress on dist. beamforming
- How much mobility can we handle?

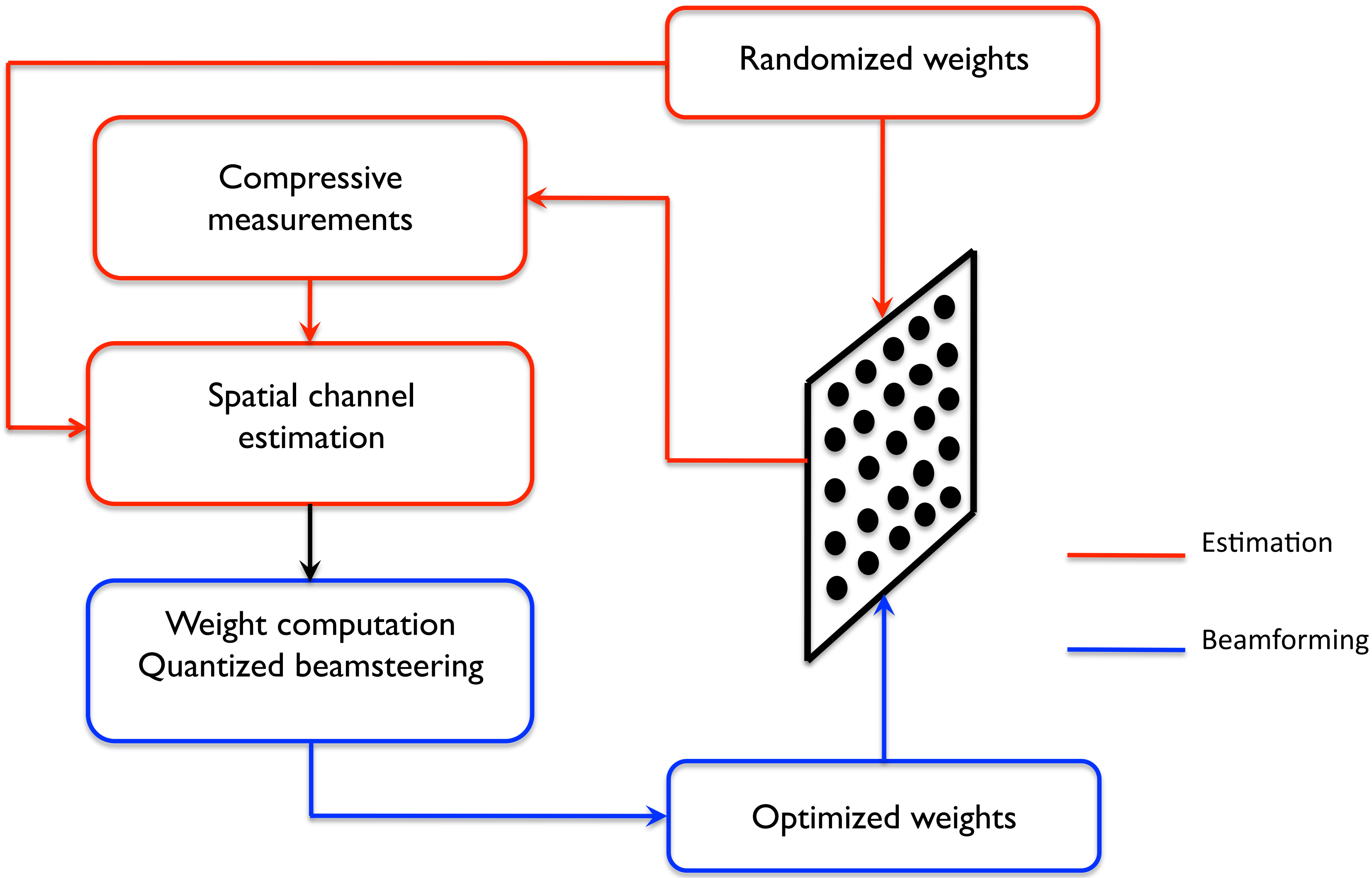
A Couple of Asides

The Role of 60 GHz

Beamforming to the limit

- Very large arrays at picocellular basestations give reuse one without CoMP
- 60 GHz to the mobile?
  - Attractive once WiGig makes it into smart phones
- Host of issues
  - Adapting large arrays (promising recent progress)
  - Shadowing
  - Mobility management

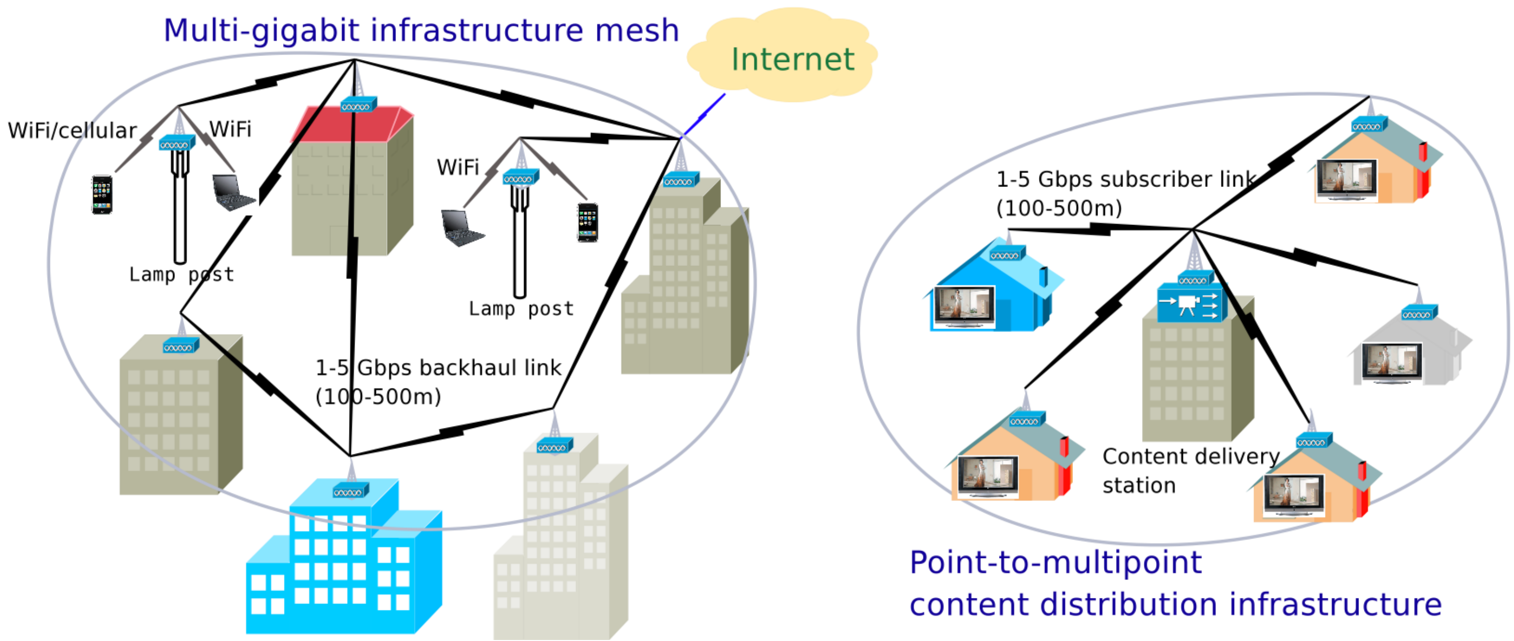
Compressive Adaptation of 1000 element arrays



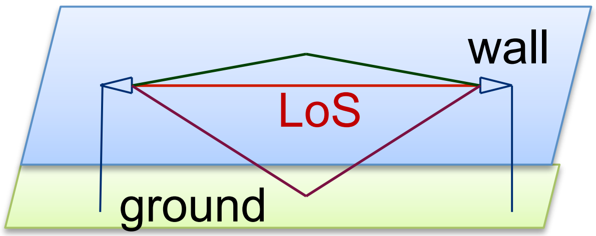
Ramasamy, Venkateswaran, Madhow, ITA 2012

What about backhaul?

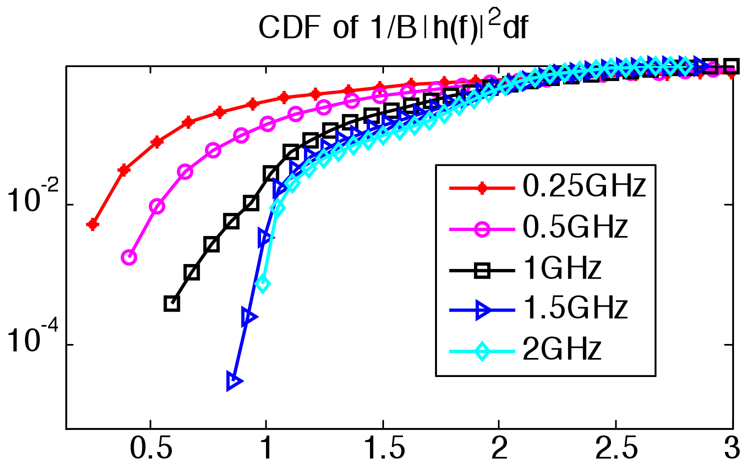
60 GHz again! (as advocated in CTW 2010)

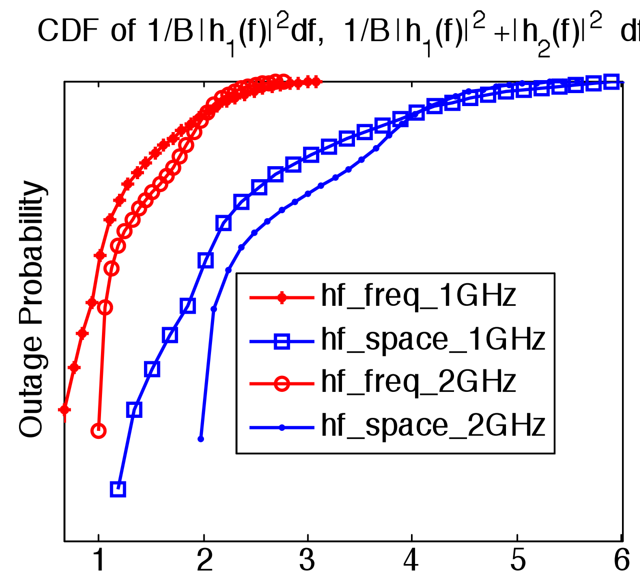


Determinism in the backhaul



Deterministic diversity for sparse multipath (Zhang and Madhow, recent results)





Freq diversity enough if
BW > 1/(smallest differential delay)

Spatial diversity provides determinism
even if BW < 1/(smallest differential delay)

Determinism: steep rise in CDF of average channel power gain

Final thoughts

- Yes we can!
  - the smart phone need not go hungry
- But it will need work
  - Tight coordination between neighbors for CoMP
  - Decentralized, scalable protocols for resource sharing and mobility tracking
  - MultiGigabit backhauls
  - 60 GHz to the mobile
- All good news for the wireless researcher!
  - Redoing digital cellular 20 years later