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
Irreversible trends

- iPhone/Android, Pandora/Spotify, Netflix/Amazon
- Tiered pricing can only go so far
  - Mice are becoming elephants
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 $\Rightarrow \alpha=2$ 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

\[
PL(d) = \begin{cases} 
-20 \log_{10} \left( 4\pi d/\lambda_c \right) & d \leq d_f \\
-20 \log_{10} \left( 4\pi d_f/\lambda_c \right) - 40 \log_{10} \left( d/d_f \right) & d > d_f
\end{cases}
\]

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

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
  \[ \eta^{-1} \approx 150m - 500m \]

Second power + exponential via wandering photons

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

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

Second power + exponential as a unified model?

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

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

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

- **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

Need smarter sharing strategies for picocells

Small cell:
\[ R_e = 100m \quad \eta^{-1} = 150m \]

Large cell:
\[ R_e = 1000m \quad \eta^{-1} = 500m \]
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

\[ r = \text{cell radius} \]
\[ R = \text{coordination radius} \]
(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
\[ S = \frac{1}{r^2} e^{-\eta r} \]

Example
K = 9
r = 100m
\( \lambda^{-1} = 150m \)
SIR = 15.3 dB
BW efficiency = 5.13 bps/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 = $\lambda_c = 15\text{cm}$

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 $\frac{1}{4}$
-Performance getting more “deterministic”
Leakage mainly contained to adjacent virtual cells, so reuse ¼ works
CoMP Multiplexing

• Serve 2 users per virtual cell
  – “Effective reuse” rate $\frac{1}{2}$
  – SIR > 15dB

• 1.5X better than large cell (omni; naïve) per cell
  – 150X network capacity gain
## Median rates

### Omni; naïve

<table>
<thead>
<tr>
<th>Reuse</th>
<th>Large cell SIR</th>
<th>Small cell SIR</th>
<th>Large cell rates</th>
<th>Small cell rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.4dB</td>
<td>2.2dB</td>
<td>54 Mbps</td>
<td>28 Mbps</td>
</tr>
<tr>
<td>1/4</td>
<td>32dB</td>
<td>15.5dB</td>
<td>53 Mbps</td>
<td>26 Mbps</td>
</tr>
<tr>
<td>1/9</td>
<td>53.5dB</td>
<td>25.5dB</td>
<td>39.5Mbps</td>
<td>19Mbps</td>
</tr>
</tbody>
</table>

### Small cells; Reuse 1/4

#### Arrays at BS

<table>
<thead>
<tr>
<th>Antenna elements</th>
<th>SIR</th>
<th>Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>21dB</td>
<td>35Mbps</td>
</tr>
<tr>
<td>8</td>
<td>25.9dB</td>
<td>43Mbps</td>
</tr>
</tbody>
</table>

#### CoMP; collaborative BF and Mux.

<table>
<thead>
<tr>
<th>Antenna elements</th>
<th>BF only SIR</th>
<th>BF only rates</th>
<th>BF+ZF SIR</th>
<th>BF+ZF rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>21dB</td>
<td>35Mbps</td>
<td>17dB</td>
<td>56Mbps</td>
</tr>
<tr>
<td>8</td>
<td>27.4dB</td>
<td>46Mbps</td>
<td>23dB</td>
<td>77Mbps</td>
</tr>
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Three nines (0.1% outage) rates

Omni; naïve

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<th>Small cell rates</th>
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<tbody>
<tr>
<td>1</td>
<td>-4.1dB</td>
<td>-5.3dB</td>
<td>9.4Mbps</td>
<td>7.5Mbps</td>
</tr>
<tr>
<td>1/4</td>
<td>20dB</td>
<td>8dB</td>
<td><strong>33.3Mbps</strong></td>
<td><strong>14.3Mbps</strong></td>
</tr>
<tr>
<td>1/9</td>
<td>40dB</td>
<td>18dB</td>
<td>29.5Mbps</td>
<td>13.3Mbps</td>
</tr>
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Small cells; Reuse 1/4

Arrays at BS

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<th>Rates</th>
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</thead>
<tbody>
<tr>
<td>4</td>
<td>11dB</td>
<td>19Mbps</td>
</tr>
<tr>
<td>8</td>
<td>12dB</td>
<td>21Mbps</td>
</tr>
</tbody>
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CoMP; collaborative BF and Mux.

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</tr>
<tr>
<td>8</td>
<td>19dB</td>
<td><strong>32Mbps</strong></td>
<td>14.5dB</td>
<td><strong>49Mbps</strong></td>
</tr>
</tbody>
</table>
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

Compressive measurements → Spatial channel estimation → Weight computation
Quantized beamsteering

Randomized weights

Optimized weights

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