Coexistence in Heterogeneous Networks

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Thanks to Salam Akoum, Marios Kountouris, Arun Ghosh, and Anthony Soong
inspiration from Jeff Andrews FemNet 2010 talk
It is (still) an Exciting Time in Wireless

Almost 2X / year growth in data traffic projected for years to come

Huge fraction is mobile video

40% of mobile data at home
35% of mobile data at work
25% of mobile data is mobile

How are cellular systems evolving to meet performance demands?
Traditional Cellular: Cell Splitting

Decrease radius by 2x, get 4x capacity increase

Cellular density reaching practical limits in urban deployments
Heterogeneous Networks

Cellular networks are becoming more complex

- New kinds of infrastructure
- More coordination and management of interference
- More advanced PHY technologies
State of Research in HetNets

Research often considers infrastructure in isolation:

- Cellular systems with fixed relay(s)
- Cellular systems with distributed antennas
- Cellular with femtocell overlay
- Out-of-cell interference may or may not be included

How will all this infrastructure co-exist?
Outline

👀 Review different technologies
- Femtocells
- Distributed antenna systems
- Base station coordination
- Relays
- Comparison

👀 Hybrid framework for co-existence studies
👀 Impact of heterogeneous interference
👀 Conclusions
What is a Femtocell?

Customer deployed personal base station
- Connects to the core cellular network through last-mile backhaul
  - Ex: residential DSL or cable modem or WiMax
- Shares the same spectrum as cellular system
- New sources of interference: cross-tier and co-tier
## Femtocells - Why?

<table>
<thead>
<tr>
<th>Operator</th>
<th>Subscriber</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-80% of traffic offload</td>
<td>Cell phone finally works at home</td>
</tr>
<tr>
<td>CAPEX/OPEX saving $$$</td>
<td>Lower transmit power (health)</td>
</tr>
<tr>
<td>Customer loyalty &amp; reduce churn</td>
<td>Longer battery life</td>
</tr>
<tr>
<td>Multi-play bundled services</td>
<td>Free data / calls</td>
</tr>
</tbody>
</table>

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Femtocells in Research

- Experiencing significant growth
  - 610 related publications on IEEExplore
  - JSAC, JCN, Communication Magazine special issues, workshops

- Why is there growth for a deployed “mature” technology?
  - Being deployed out of necessity, optimum configuration not yet known

- Unique features in femtocell research
  - Cross-tier and co-tier interference, not present in cellular systems
  - Backhaul is less reliable than cellular: more delay and lower capacity
  - Access control is different
  - Distributed interference management
  - Energy efficiency is a concern

IEEE JSTSP
Special Issue with Deadline of June 10 coming up!!
Femtocells in Practice

AT&T 3G MicroCell
Handoff from femto, not to femto
GPS for initial setup
Closed access
$150

Many vendors:
Ubiquisys, Airvana,
ip.access, Samsung,
Cisco, Alcatel-Lucent,
Huawei, etc

Commercial wireless systems
- Femtocell specific 3GPP, 3GPP2 and WiMAX standards have been completed

Market status
- US operators have deployed femtocells: AT&T, T-mobile, Sprint, Verizon
- Japanese operators have deployed femtocells: NTT DoCoMo, Softbank, kDDI

Forecast
- 1.7M deployed now, 47M by 2014, Sprint already has 250,000 in US

Femtocells are already deployed in many countries
### Femtocells & Picocells & Small cells

<table>
<thead>
<tr>
<th>Femtocell</th>
<th>Metrocell / Picocell / Small cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Consumer deployed</td>
<td>□ Operator or enterprise solution</td>
</tr>
<tr>
<td>□ Lower quality backhaul connection</td>
<td>□ Higher quality backhaul</td>
</tr>
<tr>
<td>□ Lower TX power, ex: 20dBm</td>
<td>□ Higher TX power, ex: 30dBm/37dBm</td>
</tr>
<tr>
<td>□ Closed / hybrid access</td>
<td>□ Open access</td>
</tr>
<tr>
<td>□ Less aggressive coordination</td>
<td>□ More aggressive coordination</td>
</tr>
<tr>
<td>□ More random deployment</td>
<td>□ Structured deployment</td>
</tr>
<tr>
<td>□ Home, apartment</td>
<td>□ Office, train station</td>
</tr>
</tbody>
</table>
Outline

- Review different technologies
  - Femtocells
  - Distributed antenna systems
  - Base station coordination
  - Relays
  - Comparison

- Hybrid framework for co-existence studies
- Impact of heterogeneous interference
- Conclusions
What are Distributed Antenna Systems?

- Operator deployed distributed antennas
  - Distributed antennas connected via cable
  - Remote radio heads with power amplifiers, connected via radio-over-fiber
  - Used with a conventional base station tower or to replace a base station
- Initially used for coverage, evolving for capacity

Out-of-cell interference

DAS

Equipment
Hotel

Radio over fiber or coax
## DAS Deployment Scenarios

<table>
<thead>
<tr>
<th>Outdoor</th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Stadium, city</td>
<td>□ Malls, airports, rail stations</td>
</tr>
<tr>
<td>□ Neutral deployment, telephone poles or lamp posts</td>
<td>□ Common DAS deployed by building owner</td>
</tr>
<tr>
<td>□ Likely to use fiber for distribution</td>
<td>□ Fiber or coax for distribution</td>
</tr>
<tr>
<td>□ Coverage solution</td>
<td>□ Coverage solution</td>
</tr>
</tbody>
</table>
DAS in Research

🌟 Growth in papers
- Around 500 papers on IEEE Xplore
- Renewed interest with deployment of MIMO

🌟 Research insights
- Distributed MIMO w/ DAS can outperform centralized MIMO
- Downlink DAS with antenna selection has higher capacity than multicast DAS
- DAS can reduce uplink and downlink transmit power
- DAS works well with sectored antennas placed at the cell edge
- Multiuser MIMO can exploit DAS for high performance
- DAS is a practical way to implement network MIMO, ease coordination
# Distributed Antenna Evolution

<table>
<thead>
<tr>
<th>Early DAS Concept</th>
<th>More Recent DAS Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1990’s to mid 2000)</td>
<td>(mid 2000 to present)</td>
</tr>
<tr>
<td>□ Antennas multi-cast signal</td>
<td>□ More sophisticated use of antennas</td>
</tr>
<tr>
<td>□ Used for better indoor coverage</td>
<td>□ Higher capacity and coverage</td>
</tr>
<tr>
<td>□ No support for MIMO</td>
<td>□ Some MIMO support</td>
</tr>
<tr>
<td>□ No interference management</td>
<td>□ Realizing network MIMO</td>
</tr>
<tr>
<td>□ Coax signal distribution</td>
<td>□ Radio over fiber signal distribution</td>
</tr>
<tr>
<td>□ No significant green component</td>
<td>□ Reduced power, green wireless</td>
</tr>
</tbody>
</table>
DAS in Practice

COMMSCOPE
Ion-B remote

❖ Commercial wireless systems
  ❖ Type 1 DAS: cell with remote distributing antennas (conventional DAS)
  ❖ Type 2 DAS: each remote radio head is its own base station (DAS as CoMP)

❖ Market status
  ❖ US operators have deployed DAS: AT&T, Sprint, Verizon
  ❖ Largest US deployment by InnerWireless Las Vegas CityCenter 13.5M sq.ft.

❖ Forecast
  ❖ 2010 about 10,000 outdoor DAS units, 100,000 indoor DAS


DAS deployments are underway
Outline

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  - Base station coordination
  - Relays

- Hybrid framework for co-existence studies

- Impact of heterogeneous interference

- Conclusions
What is Network MIMO?

- **Coordinated transmission from multiple base stations**
  - Known as CoMP or Cooperative MIMO or base station coordination
  - Includes many interference management & coordination strategies
  - Exploits presence of a good backhaul connection
- **Used to improve area spectral efficiency, system capacity**
Network MIMO Architectures

Coordinate over backhaul

Like DAS uses local coordination

Processing for many base stations using cloud

Coordination clusters

Dynamic coordination

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Network MIMO in Research

• Growth in papers
  - Maybe 1,000 papers on IEEE Xplore (different terminology, hard to track)
  - Area of intensive research, JSAC special issue, sessions at conferences

• Established results
  - Coordination provides higher sum capacity under various assumptions

• Current research directions
  - Capacity with coordination under backhaul capacity limitations
  - Centralized vs. distributed coordination clustering
  - Limited feedback, codebooks, adaptive codebooks
  - Alignment vs. data sharing vs. fractional reuse
  - Scheduling and power control
  - Tools: optimization, game theory, random matrix theory
Network MIMO in Practice

Many interested companies: Samsung, Alcatel-Lucent, Huawei, Qualcomm, NEC, Panasonic, etc

Commercial wireless systems
- Known as CoMP (multicell coordinated multipoint transmission)
- Being studied by 3GPP RAN1 for Release 1: e.g. simulations, techniques, latency
- Renewed interest thanks to Cloud RAN, cloud-based baseband processing

Market status
- No commercial deployments, some prototyping, possible carrier trials (Orange)

Forecast
- Unclear if it will just be DAS+ or more coordination

Theory is promising, still in development
Outline

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  ○ Comparison

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❖ Conclusions
What is a Fixed Relay?

- Operator deployed infrastructure
- Uses multiple hops to convey signals between mobile & base stations
- No wired connection to the cellular network, backhaul alternative
- Inband (cellular spectrum) or outband (different spectrum)
- Deployed for coverage
Common Relay Architectures

One-way relay

Multiuser relay

Two-way relay

Shared relay

Many other architectures, types of processing, antennas
Relays in Research

❖ Huge number of existing papers
  • Likely more than 10,000 related publications on IEEExplore
  • ~1,000 papers on relays & cellular, ~150 papers on fixed relays
  • JSAC, JCN, Communication Magazine special issues

❖ Much relay research is detached from cellular implementation
  • May not consider the impact of out-of-cell interference
  • Gains in system level simulations often discouraging (10%)

❖ Challenges with relays in cellular
  • How to work with out-of-cell interference
  • Resource allocation, when & how to use relay
  • Transparent versus non-transparent operation
  • Optimum relay processing and preferred relay architectures
Relays in Practice

 степени Commercial wireless systems
- Active or passive distribution widely deployed (simple amplify-and-forward)
- Standardized as part of IEEE 802.16j, not part of WiMax
- Type I relay (non-transparent) supported in 3GPP LTE Adv. Release 10
- Type II relay (transparent) is still under development

Market status
- Carriers focused on capacity, concerned about extra delays, vendors ready
- Some interest for second-tier markets which are not capacity limited
- Possible field trials in 2012

Future is not clear

Relays are widely researched but not widely deployed
Outline

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**Comparison** of Key Features

<table>
<thead>
<tr>
<th></th>
<th>Femtocells</th>
<th>DAS</th>
<th>CoMP</th>
<th>Relays</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deployment</strong></td>
<td>User / owner</td>
<td>Carrier / owner</td>
<td>Carrier</td>
<td>Carrier</td>
</tr>
<tr>
<td><strong>Coverage</strong></td>
<td>home, office</td>
<td>mall, airport</td>
<td>all</td>
<td>tunnel, buildings</td>
</tr>
<tr>
<td><strong>Capacity/km²</strong></td>
<td>increase</td>
<td>depends</td>
<td>increase</td>
<td>depends</td>
</tr>
<tr>
<td><strong>CAPEX</strong></td>
<td>reduce lot</td>
<td>reduce little</td>
<td>same</td>
<td>reduce lot</td>
</tr>
<tr>
<td><strong>OPEX</strong></td>
<td>reduce lot</td>
<td>reduce little</td>
<td>increase</td>
<td>reduce</td>
</tr>
<tr>
<td><strong>Green potential</strong></td>
<td>yes</td>
<td>some</td>
<td>no</td>
<td>some</td>
</tr>
<tr>
<td><strong>Disaster relief</strong></td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

* Comparison versus deploying more base stations

** Of course the best answer almost surely is “it depends”
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⭐ Hybrid framework for co-existence studies

⭐ Impact of heterogeneous interference

⭐ Conclusions
HetNets: Transmission Possibilities

Baseline

MU MIMO

MU MIMO DAS

Relay w/ selection

Femtocell

Network MIMO
HetNets: Interference Scenarios

- Multiple signal and interference scenarios
- Coupling between signal and interference strategies
- Site-specific and model specific results

How to study impact of different technologies?
Proposed Hybrid Framework

Fixed Geometry
Multiple tiers of interferers

Hybrid Approach
Typical cell, guard zone, poisson interferer locations

Stochastic Geometry
Everything random
See e.g. Andrews FemNet10
Comparison of Methodologies

- **Fixed geometry**
  - Requires simulating multiple tiers of interferers, possible wrapping
  - Performance depends on interferer strategies and locations
  - Widely used

- **Stochastic geometry**
  - Describe interference using Poisson Point Process or other process
  - Some analytical results, applied to cellular, femto, DAS, multi-tier
  - Extension to heterogenous networks still under investigation
  - Used by many including Bacelli, Andrews, Haenggi, Ganti, etc.

- **Hybrid approach**
  - Abstract heterogeneous interference into multiple interfering processes
  - Study performance of specific in-cell strategies
  - Leverage approximations of signal and interference distributions to simplify results
Interference Models

- Model interference using Poisson point process
  - Guard region keeps cell dimensions proper
  - Higher density for DAS as there are more transmitters
  - No guard region for femto, there are everywhere
Mathematical Approach 1/2

Compute received interference power on a ring

- Transform into an equivalent RX with guard zone model
- Use results from [AndrewsGantiBaccelli2011] to compute power
\[ C_r = \mathbb{E} \ln \left( 1 + \frac{S_r}{I_r + \sigma^2} \right) \]

\[ S_r = \frac{H}{\ell(r)} \quad \text{Gamma small-scale} \quad \text{& Log-normal shadow fading} \]

\[ I_r = I^{(b)}_{R+R_g-r} + I^{(d)}_{R+R_d-r} + I^{(f)} \]

\[ I^{(b)}_{R+R_g-r} = \sum_{k \in \Phi/m_o \cup B(\Delta+R+R_g-r)} \frac{G_k}{\ell(R_k)} \quad \text{Excludes guard region} \]

\[ I^{(f)} = \sum_{k \in \Phi/m_o} \frac{F_k}{\ell(R_k)} \quad \text{No exclusion region (femtocells)} \]
Approaches for Analysis

 мн Determine Gamma parameters from configuration
  Scale=1, Shape=1 corresponds to Rayleigh fading
  Scale=Nt-U+1, Shape = Pt/U corresponds to MU MIMO

 мн Approximate Gamma x Shadow with another Gamma
  Used by several authors, e.g. Yanikomeroglu

 мн Use Poisson distribution to simplify interference calculations
  Use results from [BaccelliBlaszczyszyn] or [HaenggiGanti] or [AndrewsEtAl]
  Approximate distribution with Gamma or inverse Gamma
  Approximate sums with Gamma or inverse Gamma see e.g. [HeathEtAl]
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Simulation Parameters

System model
- Rayleigh fading, log-normal shadowing w/ 6dB
- 3GPP path loss model, $n=3.76$, 35m reference distance
- No penetration losses, indoor-outdoor channel, etc
- Cell radius of 300m

Transmission techniques
- Baseline single user, 40 W
- Multiuser MIMO with $N_t=4$ transmit antennas and $U=1,...,4$, 40 W
- Multiuser MIMO DAS with 6 remote ratio units & base, $U=1,...,7$, 7 W per TX
- Relay with 6 relay stations, select closest, 20 W per relay
- Network MIMO with cluster of 7 cells, $N_t=1$ transmit antennas and $U=1,...,7$
- Femtocell with 1 antenna, 0.1W, variable density typically 45 per cell
Baseline Case

Cellular Comparison for 2 Users with 45 femtos

- base
- base + relay
- base + das
- base + 45 femto
- all + 45 femto

Per User Capacity (nats/s/Hz) vs. Radius
MU MIMO DAS Comparison for 2 Users with 45 femtos

Per User Capacity (nats/s/Hz)

- base
- base + relay
- base+das
- base +45 femto
- all +45 femto

Radius
Performance Comparison

with 45 femtos

each femto has 0.6 bits/s/Hz/m² but 0.25% of macro area

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Out-of-cell interference

- Heterogenous networks have more than femtocells
- Hybrid approach has potential for evaluating HetNets
- Even more heterogeneity is coming

Thank You!

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