Coverage in Heterogeneous Networks

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Outline

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Introduction
Why Heterogeneous?

• Needs for substantial improvements in cellular capacity and coverage
  ▫ Radio link improvement alone cannot meet increasing demands
  ▫ Traffic demand and channel condition vary with time and location

• Improve spectral efficiency/area/cost
  ▫ Need to increase cell density cost-effectively
  ▫ Network topology provides gains beyond radio technology

• Heterogeneous networks
  ▫ Deploy macro-, pico-, femto-cells, and relays in the same spectrum
  ▫ Improve coverage and capacity through better spatial reuse
  ▫ Address hot-spot needs and coverage holes
  ▫ Lower traffic load on macrocells
Deployment

- Initial coverage with macro base stations (MBS)
- Add pico, femto and relay stations for capacity increase, hot spots, indoor coverage, etc.
- Pico, femto and relay stations require lower power, offer flexible site acquisition, and add little or no backhaul expense.

Source: Intel Labs
Heterogeneous Networks

- **Macroc Elle s**
  - Operator-deployed BSs use dedicated backhaul
  - Open to public access
  - $P_{\text{Tx}} \sim 43 \text{ dBm}, G \sim 12-15 \text{ dBi}$

- **Picocells**
  - Operator-deployed BSs use dedicated backhaul
  - Open to public access
  - $P_{\text{Tx}} \sim 23-30 \text{ dBm}, G \sim 0-5 \text{ dBi}$

- **Femtocells**
  - User-deployed BSs use user’s broadband connection as backhaul
  - Open access, closed access, or a hybrid access policy
  - $P_{\text{Tx}} \leq 23 \text{ dBm}, G \sim 0-2 \text{ dBi}$

- **Relays**
  - Operator-deployed BSs use over-the-air link to MBS as backhaul
  - $P_{\text{Tx}} \sim 23-30 \text{ dBm}, G \sim 0-5 \text{ dBi}$
HN Characteristics

- Coexistence of potentially different access technologies
- Different cell scales: macro > micro > pico > femto
- BSs owned by operators, enterprises and consumers
- Wired or wireless backhaul with guaranteed or best-effort QoS
- Femtocells potentially offer coverage only to subscribed UEs

Source: Qualcomm
Challenges

• Maintain uniform user experience
  ▫ More cell-edges created
  ▫ Near-far effect
  ▫ Closed-access femtocells in co-channel deployments
  ▫ Relay stations may have different duplexing schedules

• Handoff decisions have to consider backhaul capacity, especially for relays and femtocells

• Optimized use of radio resources

• Inter-cell interference management
  ▫ Lack of coordination between cells
  ▫ Scalability, security and limited backhaul bandwidth
Femtocells

- Femtocells are low-power wireless access points that operate in licensed spectrum to connect standard mobile devices to a mobile operator’s network using residential DSL or cable broadband connections [Source: Femto Forum].
Coverage

• Inter-cell interference creates dead spots where UE QoS cannot be guaranteed.
  ▫ Location w.r.t. MBS
  ▫ Path loss, shadowing, fading

• Minimum distance of an FAP from the MBS s.t. a femto outage probability (OP) constraint

• Maximum density of simultaneously transmitting co-channel femtocells meeting a macro/femto OP constraint

• Maximum allowed transmit power of FAPs s.t. a macro OP constraint

• Minimum required transmit power of FAPs s.t. a femto OP constraint
Coverage Analysis
System Model

- OFDMA downlink of collocated spectrum-sharing macrocell and closed-access femtocells
  - A central MBS covers a disc area with radius $r_M$
  - Femtocells of radius $r_F$ are randomly distributed on $\mathbb{R}^2$ as a spatial Poisson point process (SPPP) with a density of $\lambda_F$.
  - $N_F$ femtocells per cell site on average
  - $U_F$ indoor UEs per femtocell, each located on cell edge
  - MBS transmit power is $P_{M,Tx}$ per RB
  - FAP transmit power is $P_{F,Tx}$ per RB
  - Each FAP transmits with a probability $\rho$ within each RB.
  - Spatial intensity of simultaneously transmitting co-channel FAPs is $u_F = \lambda_F \rho$. 
Channel Model

- Each subchannel sees Rayleigh flat fading and lognormal shadowing
- Path loss follows the IMT-2000 channel model
  - MBS to outdoor UE
    \[ \text{PL}_M = \phi_M D_M^{\alpha_M} = 10^{-7.1} f_c^3 D_M^{\alpha_M} \]
  - MBS to indoor UE
    \[ \text{PL}_{FM} = \phi_{FM} D_{FM}^{\alpha_{FM}} = \phi_M \xi D_{FM}^{\alpha_{FM}} = 10^{-7.1} f_c^3 \xi D_{FM}^{\alpha_{FM}} \]
  - Home FAP to indoor UE
    \[ \text{PL}_F = \phi_F D_F^{\alpha_F} = 10^{3.7} D_F^{\alpha_F} \]
  - FAP to outdoor UE
    \[ \text{PL}_{MF} = \phi_{MF} D_{MF}^{\alpha_{MF}} = \phi_F \xi D_{MF}^{\alpha_{MF}} \]
  - Interfering FAP to indoor UE
    \[ \text{PL}_{FF} = \phi_{FF} D_{FF}^{\alpha_{FF}} = \phi_F \xi^2 D_{FF}^{\alpha_{FF}} \]
  - \( \xi \) denotes wall-penetration loss
Femtocell DL SIR

- For a given RB, the received SIR at an FUE is

\[
\text{SIR}_F = \frac{P_F \phi_F^{-1} H_F Q_F r_F^{-\alpha_F}}{P_M \phi_{FM}^{-1} H_{FM} Q_{FM} D_{FM}^{-\alpha_{FM}}} + \sum_{i \in \Phi} P_{FF} \phi_{FF}^{-1} H_{FFi} Q_{FFi} D_{FFi}^{-\alpha_{FF}}
\]

- \( P_F = P_{F,Tx} G_{FAP} G_{UE} \), \( P_M = P_{M,Tx} G_{MBS} G_{UE} \);
- \( D_{FM} \) is the distance from the MBS to the FUE, \( D_{FFi} \) is the distance from interfering FAP \( i \) to the FUE;
- \( \alpha_F, \alpha_{FM} \) and \( \alpha_{FF} \) are path loss exponents from the home FAP, the MBS and an interfering FAP to the FUE, respectively;
- \( H_F, H_{FM} \) and \( H_{FFi} \) are unit-mean exponential channel power gains;
- \( Q_F \sim \text{LN}(\mu_F, \sigma_F^2), \ Q_{FM} \sim \text{LN}(\mu_{FM}, \sigma_{FM}^2) \) and \( Q_{FFi} \sim \text{LN}(\mu_{FF}, \sigma_{FF}^2) \) denote lognormal shadowing, \( \zeta = 0.1 \ln 10 \);
- \( \Phi \) is the set of FAPs transmitting in the given RB, with intensity \( u_F \).
Macrocell DL SIR

- Co-channel interference from neighboring macrocells is ignored.
- For a given RB, the received SIR at an MUE is

\[
\text{SIR}_M = \frac{P_M \phi_M^{-1} H_M Q_M D_M^{-\alpha_M}}{\sum_{i \in \Phi} P_F \phi_{MF}^{-1} H_{MF_i} Q_{MF_i} D_{MF_i}^{-\alpha_{MF}}}
\]

- \( D_M \) is the distance from the MBS to the MUE, \( D_{MF_i} \) is the distance from FAP \( i \) to the MUE;
- \( \alpha_M \) and \( \alpha_{MF} \) are path loss exponents from the MBS and an FAP to the MUE;
- \( H_M \) and \( H_{MF_i} \) denote unit-mean exponential channel power gains;
- \( Q_M \sim \text{LN}(\mu_M, \sigma_M^2) \) and \( Q_{MF_i} \sim \text{LN}(\mu_{MF}, \sigma_{MF}^2) \) denote lognormal shadowing.
Femto Outage Probability

• Outage probability of an FUE w.r.t. the target SIR $\gamma_F$

$$P(SIR_F < \gamma_F) = P\left( \frac{S_F}{I_{FM} + \sum_{i \in \Phi} P_F \phi_{FF}^{-1} H_{FF_i} Q_{FF_i} D_{FF_i}^{-\alpha_{FF}}} < \gamma_F \right)$$

$$= P\left( \frac{S_F}{I_{FM}} < \gamma_F \right) + P\left( SIR_F < \gamma_F, \frac{S_F}{I_{FM}} \geq \gamma_F \right)$$

• Based on the stochastic geometry theory and for an FUE at a distance $d_{FM}$ from the MBS,

$$P(SIR_F < \gamma_F | D_{FM} = d_{FM}) \approx F_{\phi}\left( \frac{P_M \phi_F r_F^{\alpha_F} \gamma_F}{P_F \phi_{FM} d_{FM}^{\alpha_{FM}}} ; \tilde{\mu}_F - \tilde{\mu}_{FM}, \sqrt{\tilde{\sigma}_F^2 + \tilde{\sigma}_{FM}^2} \right) +$$

$$W_n W_m \left\{ 1 - \exp\left[ -\kappa_F u_F \left( e^{\sqrt{2a_n + 2\tilde{\chi}(b_m)\sigma_f} + \tilde{\mu}_F} - \gamma_F e^{\sqrt{2\tilde{\sigma}_{FM} b_m + \tilde{\mu}_{FM}}} \right) \right] \right\}$$

$$\sum_{n=1}^{N} \sum_{m=1}^{M} \frac{2\pi \sqrt{a_n + \tilde{\chi}(b_m)} e^{\tilde{\chi}(b_m)} \right\}$$

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Macro Outage Probability

- Outage probability of an MUE w.r.t. the target SIR $\gamma_M$

$$P(SIR_M < \gamma_M) = P\left(\sum_{i \in \Phi} P_F \phi_{MF}^{-1} H_{MF_i} Q_{MF_i} D_{MF_i}^{\alpha_{MF}} < \gamma_M\right)$$

- Based on the stochastic geometry theory and for an MUE at a distance $d_M$ from the MBS,

$$P(SIR_M < \gamma_M | D_M = d_M) \approx 1 - \sum_{m=1}^{M} \frac{\nu_m}{\sqrt{\pi}} \exp\left[-\kappa_M u_F \exp\left(-\frac{2\sqrt{2}\tilde{\sigma}_M b_m}{\alpha_{MF}} - \frac{2\tilde{\mu}_M}{\alpha_{MF}}\right)\right]$$

$$\kappa_M = \pi \left(\frac{P_F \gamma_M}{\phi_{MF}}\right)^\frac{2}{\alpha_{MF}} \exp\left(\frac{2\tilde{\mu}_{MF}}{\alpha_{MF}} + \frac{2\tilde{\sigma}^2_{MF}}{\alpha^2_{MF}}\right)$$
Minimum MBS-to-FAP Distance

• For an FUE at a distance $d_{FM}$ from the MBS,

$$P\left(\frac{S_F}{I_{FM}} < \gamma_F | D_{FM} = d_{FM}\right) = P\left(\frac{H_FQ_F}{H_{FM}Q_{FM}} < \frac{P_M\phi_F r_F^{\alpha_F} \gamma_F}{P_F\phi_{FM} d_{FM}^{\alpha_{FM}}}\right)$$

$$\approx F_\vartheta\left(\frac{P_M\phi_F r_F^{\alpha_F} \gamma_F}{P_F\phi_{FM} d_{FM}^{\alpha_{FM}}}; \bar{\gamma}_F - \bar{\mu}_F, \sqrt{\bar{\sigma}_F^2 + \bar{\sigma}_{FM}^2}\right)$$

$\vartheta = \frac{H_FQ_F}{H_{FM}Q_{FM}} \sim \text{lognormal distribution}$

• Minimum $d_{FM}$ for $P(S_F/I_{FM} < \gamma_F | D_{FM} = d_{FM}) \leq \epsilon_F$,

$$d_{FM, min} \approx \frac{1}{P_M\phi_F r_F^{\alpha_F} \gamma_F} \left[P_F\phi_{FM} F_\vartheta^{-1}\left(\epsilon_F; \bar{\gamma}_F - \bar{\mu}_F, \sqrt{\bar{\sigma}_F^2 + \bar{\sigma}_{FM}^2}\right)\right]^{-\frac{1}{\alpha_{FM}}}$$

• Any UE less than $d_{FM, min}$ from the MBS should be associated with the macrocell.
Maximum Femto Density

- Maximum intensity of simultaneous co-channel femtocell transmissions at a distance $d_M \leq r_M$ from the MBS for $P(SIR_M < \gamma_M|D_M = d_M) \leq \varepsilon_M$

$$\tilde{u}_F(d_M) = F_{SIR_M}^{-1}(\varepsilon_M, P_F, d_M)$$

$$F_{SIR_M}(u_F, P_F, d_M) = P(SIR_M < \gamma_M|D_M = d_M) = \varepsilon_M$$

- Maximum effective femtocell density at a distance $d_{FM} \geq d_{FM, min}$ from the MBS for $P(SIR_F < \gamma_F|D_{FM} = d_{FM}) \leq \varepsilon_F$

$$\tilde{u}_F(d_{FM}) = F_{SIR_F}^{-1}(\varepsilon_F, P_F, d_{FM})$$

$$F_{SIR_F}(u_F, P_F, d_{FM}) = P(SIR_F < \gamma_F|D_{FM} = d_{FM}) = \varepsilon_F$$

- For $d_{FM, min} \leq d \leq r_M$, $u_F(d) \leq \min\{\tilde{u}_F(d), \tilde{u}_F(d)\}$
FAP Transmit Power

- Maximum allowed $P_F$ at a distance $d_M$ ($\leq r_M$) from the MBS s.t. $P(SIR_M < \gamma_M|D_M = d_M) \leq \varepsilon_M$

$$\tilde{P}_F(d_M)^{\Delta} = F_{SIR_M}^{-1}(\varepsilon_M, u_F, d_M)$$

- Minimum required $P_F$ at a distance $d_{FM}$ ($\geq d_{FM,\text{min}}$) from the MBS s.t. $P(SIR_F < \gamma_F|D_{FM} = d_{FM}) \leq \varepsilon_F$

$$\tilde{P}_F(d_{FM})^{\Delta} = F_{SIR_F}^{-1}(\varepsilon_F, u_F, d_{FM})$$

- At a distance $d$ ($d_{FM,\text{min}} \leq d \leq r_M$) from the MBS,
  - if $\tilde{P}_F(d) \leq \bar{P}_F(d)$, then $\tilde{P}_F(d) \leq P_F(d) \leq \bar{P}_F(d)$;
  - otherwise, no femtocell coverage and have to reduce $u_F = \lambda_F \rho$. 
Simulations and Results
Simulation Setup

- One MBS in the center
- FAPs and MUEs are randomly dropped within the macrocell coverage following independent SPPPs.

- $\xi = 5 \text{ dB}, 10 \text{ dB}$
- $\alpha_M = 4$
- $\alpha_F = 3$
- $\alpha_{FM} = \alpha_M$
- $\alpha_{FF} = 3.5$
- $\alpha_{MF} = \alpha_{FF}$
- $\sigma_M = 8 \text{ dB}$
- $\sigma_F = 4 \text{ dB}$
- $\sigma_{FF} = 12 \text{ dB}$
- $\sigma_{MF} = 10 \text{ dB}$
- $\sigma_{FM} = 10 \text{ dB}$
- $f_c = 2000 \text{ MHz}$
- $P_{M,Tx} = 43 \text{ dBm}$
- $P_{F,Tx} \leq 23 \text{ dBm}$
- $G_{MBS} = 15 \text{ dBi}$
- $G_{FAP} = 2 \text{ dBi}$
- $G_{UE} = 0 \text{ dBi}$
- $r_M = 1000 \text{ m}$
- $r_F = 30 \text{ m}$
- $U_F = 2$
- $\gamma_M = 3 \text{ dB}$
- $\gamma_F = 5 \text{ dB}$
- $\varepsilon_M = \varepsilon_F = 0.1$
- $M = N = 12$
Outage Probability

$P_{M, Tx} = 43\text{dBm}, P_{F, Tx} = 23\text{dBm}, \xi = 10\text{dB}$

Graph showing the outage probability as a function of the number of co-channel femto transmissions per cell site. The graph includes data points and lines for different distances and models (simulation vs. formula).
Minimum MBS-to-FAP Distance

\[ P_{M,Tx} = 43 \text{dBm}, \ OP_F \leq 0.1 \]

- \( \xi = 5 \text{ dB, simulation} \)
- \( \xi = 5 \text{ dB, formula} \)
- \( \xi = 10 \text{ dB, simulation} \)
- \( \xi = 10 \text{ dB, formula} \)

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Maximum Femto Density

\[ P_{M,Tx} = 43\text{dBm}, P_{F,Tx} = 23\text{dBm}, O_{PM} \leq 0.1 \]

- \( \xi = 5\text{dB}, \) simulation
- \( \xi = 5\text{dB}, \) formula
- \( \xi = 10\text{dB}, \) simulation
- \( \xi = 10\text{dB}, \) formula
Maximum Allowed $P_{F,Tx}$

$P_{M,Tx} = 43\text{dBm}, N_F = 100, \text{OP}_M \leq 0.1$

![Graph showing maximum allowed transmit power vs. distance from macro BS](image)

- $\xi = 5\text{dB}, \rho = 1$, simulation
- $\xi = 5\text{dB}, \rho = 1$, formula
- $\xi = 5\text{dB}, \rho = 0.1$, simulation
- $\xi = 5\text{dB}, \rho = 0.1$, formula
- $\xi = 10\text{dB}, \rho = 1$, simulation
- $\xi = 10\text{dB}, \rho = 1$, formula
- $\xi = 10\text{dB}, \rho = 0.1$, simulation
- $\xi = 10\text{dB}, \rho = 0.1$, formula

- Maximum FAP Transmit Power (dBm)
- Distance from Macro BS (m)
Minimum Required $P_{F,Tx}$

$P_{M,Tx} = 43\text{dBm}, N_F = 100, \text{OP}_F \leq 0.1$

Graph showing the minimum required FAP transmit power ($P_{F,Tx}$) as a function of the distance between the Macro BS and the Femtocell. The graph includes data points for different values of $\xi$ and $\rho$, indicating simulations and formulas for $P_{F,Tx}$ at various distances.
$P_{F,Tx}$ under Low Attenuation

$P_{M,Tx} = 43\text{dBm}, N_F = 100, \xi = 5\text{dB}$

![Graph showing maximum and minimum FAP transmit power (dBi) versus distance from Macro BS (m). The graph includes lines for different attenuation conditions and power levels: $\max P_{F \text{ st } OP_M \leq 0.1, \rho = 1}$, $\min P_{F \text{ st } OP_F \leq 0.1, \rho = 1}$, $\max P_{F \text{ st } OP_M \leq 0.1, \rho = 0.1}$, $\min P_{F \text{ st } OP_F \leq 0.1, \rho = 0.1}$, $\max P_{F \text{ st } OP_M \leq 0.1, \rho = 0.5}$, and $\min P_{F \text{ st } OP_F \leq 0.1, \rho = 0.5}$. The y-axis represents Maximum/Minimum FAP Transmit Power (dBi), and the x-axis represents Distance from Macro BS (m).]
\( P_{F,Tx} \) under High Attenuation

\( P_{M,Tx} = 43\text{dBm}, N_F = 100, \xi = 10\text{dB} \)

- \( \max P_F \text{ st } \text{OP}_M \leq 0.1, \rho = 1 \)
- \( \min P_F \text{ st } \text{OP}_F \leq 0.1, \rho = 1 \)
- \( \max P_F \text{ st } \text{OP}_M \leq 0.1, \rho = 0.1 \)
- \( \min P_F \text{ st } \text{OP}_F \leq 0.1, \rho = 0.1 \)
- \( \max P_F \text{ st } \text{OP}_M \leq 0.1, \rho = 0.5 \)

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Conclusions

• OFDMA downlink of collocated spectrum-sharing macrocell and closed-access femtocells
  ▫ Analytical expressions for outage probabilities
• It is possible to improve coverage by
  ▫ regulating femtocell transmit powers, which depend on the distance from the MBS;
  ▫ restricting the probability of each femtocell transmitting in each RB, which can be controlled in both frequency and time domains.
Future Work

• Mechanism for an FAP to infer its distance from the closest MBS, so that the FAP can adapt its transmit power accordingly to ensure satisfactory coverage.

• Associate UEs to cells intelligently
  ▫ UEs associated to a cell with least path loss
  ▫ Allow more UEs to benefit from low-power BSs

• Distributed adaptive resource partitioning
  ▫ BSs negotiate resource reservation with each other
  ▫ Resource request/grant messages sent over backhaul
  ▫ Based on load status and feedback from active UEs

• Coordinated multi-point transmission in the heterogeneous network
Thank You!

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