# Coverage in Heterogeneous Networks

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UC4G Beijing Workshop August 2010

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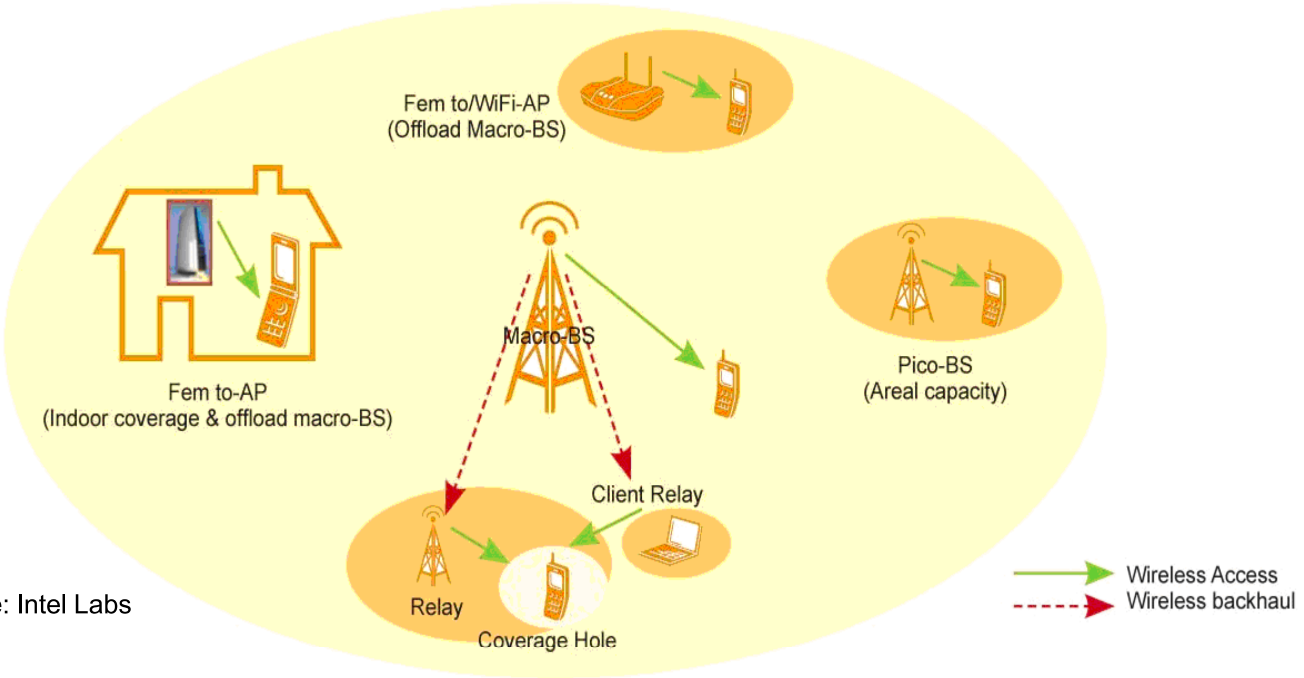
# Introduction

# 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.



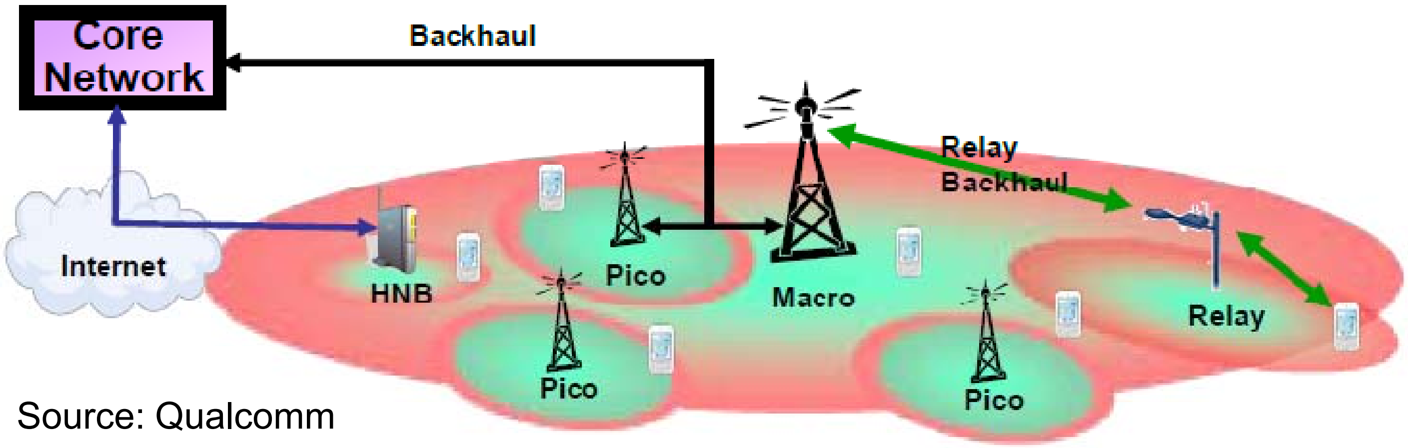

Source: Intel Labs

# Heterogeneous Networks

- Macrocells
  - Operator-deployed BSs use dedicated backhaul
  - Open to public access
  - $P_{\mathrm{Tx}}$ ~ 43 dBm, $G$ ~ 12-15 dBi
- Picocells
  - Operator-deployed BSs use dedicated backhaul
  - Open to public access
  - $P_{\mathrm{Tx}}$ ~ 23-30 dBm, $G$ ~ 0-5 dBi
- Femtocells
  - User-deployed BSs use user's broadband connection as backhaul
  - Open access, closed access, or a hybrid access policy
  - $P_{\mathrm{Tx}} \leq$ 23 dBm, $G$ ~ 0-2 dBi
- Relays
  - Operator-deployed BSs use over-the-air link to MBS as backhaul
  - $P_{\mathrm{Tx}}$ ~ 23-30 dBm, $G$ ~ 0-5 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



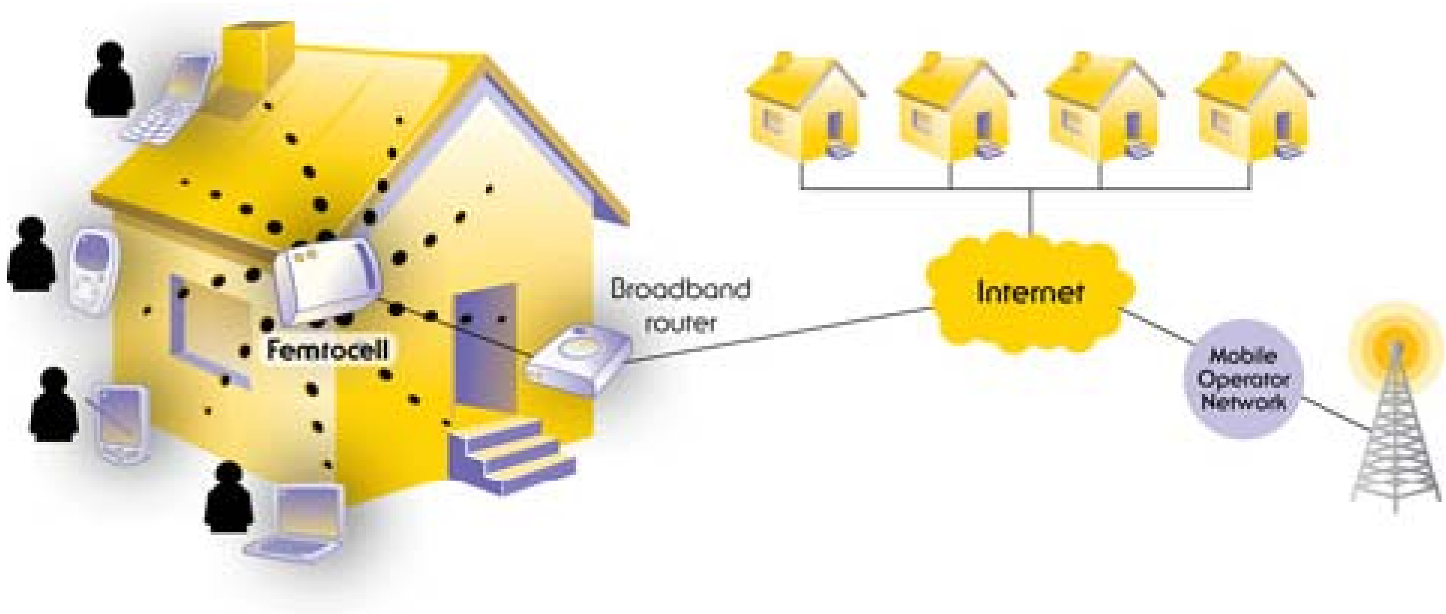

Source: Qualcomm

# 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 $r_{\mathrm{M}}$
  - Femtocells of radius $r_{\mathrm{F}}$ are randomly distributed on $\mathbb{R}^2$ as a spatial Poisson point process (SPPP) with a density of $\lambda_{\mathrm{F}}$.
  - $N_{\mathrm{F}}$ femtocells per cell site on average
  - $U_{\mathrm{F}}$ indoor UEs per femtocell, each located on cell edge
  - MBS transmit power is $P_{\mathrm{M,Tx}}$ per RB
  - FAP transmit power is $P_{\mathrm{F,Tx}}$ per RB
  - Each FAP transmits with a probability $\rho$ within each RB.
  - Spatial intensity of simultaneously transmitting co-channel FAPs is $u_{\mathrm{F}} = \lambda_{\mathrm{F}}\rho$.

# Channel Model

- Each subchannel sees Rayleigh flat fading and lognormal shadowing
- Path loss follows the IMT-2000 channel model
  - MBS to outdoor UE

$$\mathrm{PL}_{\mathrm{M}} = \phi_{\mathrm{M}} D_{\mathrm{M}}^{\alpha_{\mathrm{M}}} = 10^{-7.1} f_{\mathrm{c}}^{3} D_{\mathrm{M}}^{\alpha_{\mathrm{M}}}$$

  - MBS to indoor UE

$$\mathrm{PL}_{\mathrm{FM}} = \phi_{\mathrm{FM}} D_{\mathrm{FM}}^{\alpha_{\mathrm{FM}}} = \phi_{\mathrm{M}} \xi D_{\mathrm{FM}}^{\alpha_{\mathrm{FM}}} = 10^{-7.1} f_{\mathrm{c}}^{3} \xi D_{\mathrm{FM}}^{\alpha_{\mathrm{FM}}}$$

  - Home FAP to indoor UE

$$\mathrm{PL}_{\mathrm{F}} = \phi_{\mathrm{F}} D_{\mathrm{F}}^{\alpha_{\mathrm{F}}} = 10^{3.7} D_{\mathrm{F}}^{\alpha_{\mathrm{F}}}$$

  - FAP to outdoor UE

$$\mathrm{PL}_{\mathrm{MF}} = \phi_{\mathrm{MF}} D_{\mathrm{MF}}^{\alpha_{\mathrm{MF}}} = \phi_{\mathrm{F}} \xi D_{\mathrm{MF}}^{\alpha_{\mathrm{MF}}}$$

  - Interfering FAP to indoor UE

$$\mathrm{PL}_{\mathrm{FF}} = \phi_{\mathrm{FF}} D_{\mathrm{FF}}^{\alpha_{\mathrm{FF}}} = \phi_{\mathrm{F}} \xi^{2} D_{\mathrm{FF}}^{\alpha_{\mathrm{FF}}}$$

  - $\xi$ denotes wall-penetration loss

# Femtocell DL SIR

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

$$\mathrm{SIR}_{\mathrm{F}} = \frac{P_{\mathrm{F}}\phi_{\mathrm{F}}^{-1}H_{\mathrm{F}}Q_{\mathrm{F}}r_{\mathrm{F}}^{-\alpha_{\mathrm{F}}}}{P_{\mathrm{M}}\phi_{\mathrm{FM}}^{-1}H_{\mathrm{FM}}Q_{\mathrm{FM}}D_{\mathrm{FM}}^{-\alpha_{\mathrm{FM}}} + \sum_{i\in\Phi} P_{\mathrm{F}}\phi_{\mathrm{FF}}^{-1}H_{\mathrm{FF}i}Q_{\mathrm{FF}i}D_{\mathrm{FF}i}^{-\alpha_{\mathrm{FF}}}}$$

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

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# Macrocell DL SIR

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

$$\mathrm{SIR}_{\mathrm{M}} = \frac{P_{\mathrm{M}}\phi_{\mathrm{M}}^{-1} H_{\mathrm{M}} Q_{\mathrm{M}} D_{\mathrm{M}}^{-\alpha_{\mathrm{M}}}}{\sum_{i\in\Phi} P_{\mathrm{F}}\phi_{\mathrm{MF}}^{-1} H_{\mathrm{MF}i} Q_{\mathrm{MF}i} D_{\mathrm{MF}i}^{-\alpha_{\mathrm{MF}}}}$$

  - $D_{\mathrm{M}}$ is the distance from the MBS to the MUE, $D_{\mathrm{MF}i}$ is the distance from FAP $i$ to the MUE;
  - $\alpha_{\mathrm{M}}$ and $\alpha_{\mathrm{MF}}$ are path loss exponents from the MBS and an FAP to the MUE;
  - $H_{\mathrm{M}}$ and $H_{\mathrm{MF}i}$ denote unit-mean exponential channel power gains;
  - $Q_{\mathrm{M}} \sim \mathrm{LN}(\zeta\mu_{\mathrm{M}}, \zeta^2\sigma_{\mathrm{M}}^2)$ and $Q_{\mathrm{MF}i} \sim \mathrm{LN}(\zeta\mu_{\mathrm{MF}}, \zeta^2\sigma_{\mathrm{MF}}^2)$ denote lognormal shadowing.

# Femto Outage Probability

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

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

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

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

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

$$\sum_{n=1}^{N} \sum_{m=1}^{M} \frac{w_n v_m \left\{ 1 - \exp\left[ -\kappa_F u_F \left( e^{\sqrt{2 a_n + 2\tilde{\chi}(b_m)}\tilde{\sigma}_F + \breve{\mu}_F} - \gamma_F e^{\sqrt{2}\tilde{\sigma}_{FM} b_m + \breve{\mu}_{FM}} \right)^{-\frac{2}{\alpha_{FF}}} \right] \right\}}{2\pi \sqrt{a_n + \tilde{\chi}(b_m)} e^{\tilde{\chi}(b_m)}}$$

# Macro Outage Probability

- Outage probability of an MUE w.r.t. the target SIR $\gamma_{\mathrm{M}}$

$$\mathrm{P}\left(\mathrm{SIR}_{\mathrm{M}} < \gamma_{\mathrm{M}}\right) = \mathrm{P}\left( \frac{S_{\mathrm{M}}}{\sum_{i \in \Phi} P_{\mathrm{F}} \phi_{\mathrm{MF}}^{-1} H_{\mathrm{MF}i} Q_{\mathrm{MF}i} D_{\mathrm{MF}i}^{-\alpha_{\mathrm{MF}}}} < \gamma_{\mathrm{M}} \right)$$

- Based on the stochastic geometry theory and for an MUE at a distance $d_{\mathrm{M}}$ from the MBS,

$$\mathrm{P}\left(\mathrm{SIR}_{\mathrm{M}} < \gamma_{\mathrm{M}} \middle| D_{\mathrm{M}} = d_{\mathrm{M}}\right) \approx 1 - \sum_{m=1}^{M} \frac{v_m}{\sqrt{\pi}} \exp\left[ -\kappa_{\mathrm{M}} u_{\mathrm{F}} \exp\left( -\frac{2\sqrt{2}\tilde{\sigma}_{\mathrm{M}} b_m}{\alpha_{\mathrm{MF}}} - \frac{2\breve{\mu}_{\mathrm{M}}}{\alpha_{\mathrm{MF}}} \right) \right]$$

$$\kappa_{\mathrm{M}} = \pi \left( \frac{P_{\mathrm{F}} \gamma_{\mathrm{M}}}{\phi_{\mathrm{MF}}} \right)^{\frac{2}{\alpha_{\mathrm{MF}}}} \exp\left( \frac{2\tilde{\mu}_{\mathrm{MF}}}{\alpha_{\mathrm{MF}}} + \frac{2\tilde{\sigma}_{\mathrm{MF}}^2}{\alpha_{\mathrm{MF}}^2} \right)$$

# Minimum MBS-to-FAP Distance

- For an FUE at a distance $d_{\mathrm{FM}}$ from the MBS,

$$\mathrm{P}\left(\frac{S_{\mathrm{F}}}{I_{\mathrm{FM}}} < \gamma_{\mathrm{F}} \middle| D_{\mathrm{FM}} = d_{\mathrm{FM}}\right) = \mathrm{P}\left(\frac{H_{\mathrm{F}} Q_{\mathrm{F}}}{H_{\mathrm{FM}} Q_{\mathrm{FM}}} < \frac{P_{\mathrm{M}} \phi_{\mathrm{F}} r_{\mathrm{F}}^{\alpha_{\mathrm{F}}} \gamma_{\mathrm{F}}}{P_{\mathrm{F}} \phi_{\mathrm{FM}} d_{\mathrm{FM}}^{\alpha_{\mathrm{FM}}}}\right)$$

$$\approx F_{\vartheta}\left(\frac{P_{\mathrm{M}} \phi_{\mathrm{F}} r_{\mathrm{F}}^{\alpha_{\mathrm{F}}} \gamma_{\mathrm{F}}}{P_{\mathrm{F}} \phi_{\mathrm{FM}} d_{\mathrm{FM}}^{\alpha_{\mathrm{FM}}}}; \tilde{\mu}_{\mathrm{F}} - \tilde{\mu}_{\mathrm{FM}}, \sqrt{\tilde{\sigma}_{\mathrm{F}}^2 + \tilde{\sigma}_{\mathrm{FM}}^2}\right)$$

  - $\vartheta = H_{\mathrm{F}} Q_{\mathrm{F}} / (H_{\mathrm{FM}} Q_{\mathrm{FM}}) \sim$ lognormal distribution

- Minimum $d_{\mathrm{FM}}$ for $\mathrm{P}(S_{\mathrm{F}}/I_{\mathrm{FM}} < \gamma_{\mathrm{F}} | D_{\mathrm{FM}} = d_{\mathrm{FM}}) \le \varepsilon_{\mathrm{F}}$,

$$d_{\mathrm{FM,min}} \approx \left[\frac{P_{\mathrm{F}} \phi_{\mathrm{FM}} F_{\vartheta}^{-1}\left(\varepsilon_{\mathrm{F}}; \tilde{\mu}_{\mathrm{F}} - \tilde{\mu}_{\mathrm{FM}}, \sqrt{\tilde{\sigma}_{\mathrm{F}}^2 + \tilde{\sigma}_{\mathrm{FM}}^2}\right)}{P_{\mathrm{M}} \phi_{\mathrm{F}} r_{\mathrm{F}}^{\alpha_{\mathrm{F}}} \gamma_{\mathrm{F}}}\right]^{-\frac{1}{\alpha_{\mathrm{FM}}}}$$

- Any UE less than $d_{\mathrm{FM,min}}$ from the MBS should be associated with the macrocell.

# Maximum Femto Density

- Maximum intensity of simultaneous co-channel femtocell transmissions at a distance $d_{\mathrm{M}}$ ($\leq r_{\mathrm{M}}$) from the MBS for $\mathrm{P}(\mathrm{SIR}_{\mathrm{M}} < \gamma_{\mathrm{M}} | D_{\mathrm{M}} = d_{\mathrm{M}}) \leq \varepsilon_{\mathrm{M}}$

$$\breve{u}_{\mathrm{F}}(d_{\mathrm{M}}) \stackrel{\Delta}{=} F^{-1}_{\mathrm{SIR}_{\mathrm{M}}}(\varepsilon_{\mathrm{M}}, P_{\mathrm{F}}, d_{\mathrm{M}})$$

$$F_{\mathrm{SIR}_{\mathrm{M}}}(u_{\mathrm{F}}, P_{\mathrm{F}}, d_{\mathrm{M}}) = \mathrm{P}(\mathrm{SIR}_{\mathrm{M}} < \gamma_{\mathrm{M}} | D_{\mathrm{M}} = d_{\mathrm{M}}) = \varepsilon_{\mathrm{M}}$$

- Maximum effective femtocell density at a distance $d_{\mathrm{FM}}$ ($\geq d_{\mathrm{FM,min}}$) from the MBS for $\mathrm{P}(\mathrm{SIR}_{\mathrm{F}} < \gamma_{\mathrm{F}} | D_{\mathrm{FM}} = d_{\mathrm{FM}}) \leq \varepsilon_{\mathrm{F}}$

$$\tilde{u}_{\mathrm{F}}(d_{\mathrm{FM}}) \stackrel{\Delta}{=} F^{-1}_{\mathrm{SIR}_{\mathrm{F}}}(\varepsilon_{\mathrm{F}}, P_{\mathrm{F}}, d_{\mathrm{FM}})$$

$$F_{\mathrm{SIR}_{\mathrm{F}}}(u_{\mathrm{F}}, P_{\mathrm{F}}, d_{\mathrm{FM}}) = \mathrm{P}(\mathrm{SIR}_{\mathrm{F}} < \gamma_{\mathrm{F}} | D_{\mathrm{FM}} = d_{\mathrm{FM}}) = \varepsilon_{\mathrm{F}}$$

- For $d_{\mathrm{FM,min}} \leq d \leq r_{\mathrm{M}}$, $u_{\mathrm{F}}(d) \leq \min\{\breve{u}_{\mathrm{F}}(d), \tilde{u}_{\mathrm{F}}(d)\}$

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# FAP Transmit Power

- Maximum allowed $P_{\mathrm{F}}$ at a distance $d_{\mathrm{M}}$ ($\leq r_{\mathrm{M}}$) from the MBS s.t. $\mathrm{P}(\mathrm{SIR}_{\mathrm{M}} < \gamma_{\mathrm{M}} | D_{\mathrm{M}} = d_{\mathrm{M}}) \leq \varepsilon_{\mathrm{M}}$

$$\breve{P}_{\mathrm{F}}(d_{\mathrm{M}}) \overset{\Delta}{=} F^{-1}_{\mathrm{SIR}_{\mathrm{M}}}(\varepsilon_{\mathrm{M}}, u_{\mathrm{F}}, d_{\mathrm{M}})$$

- Minimum required $P_{\mathrm{F}}$ at a distance $d_{\mathrm{FM}}$ ($\geq d_{\mathrm{FM,min}}$) from the MBS s.t. $\mathrm{P}(\mathrm{SIR}_{\mathrm{F}} < \gamma_{\mathrm{F}} | D_{\mathrm{FM}} = d_{\mathrm{FM}}) \leq \varepsilon_{\mathrm{F}}$

$$\widetilde{P}_{\mathrm{F}}(d_{\mathrm{FM}}) \overset{\Delta}{=} F^{-1}_{\mathrm{SIR}_{\mathrm{F}}}(\varepsilon_{\mathrm{F}}, u_{\mathrm{F}}, d_{\mathrm{FM}})$$

- At a distance $d$ ($d_{\mathrm{FM,min}} \leq d \leq r_{\mathrm{M}}$) from the MBS,
  - if $\widetilde{P}_{\mathrm{F}}(d) \leq \breve{P}_{\mathrm{F}}(d)$, then $\widetilde{P}_{\mathrm{F}}(d) \leq P_{\mathrm{F}}(d) \leq \breve{P}_{\mathrm{F}}(d)$;
  - otherwise, no femtocell coverage and have to reduce $u_{\mathrm{F}} = \lambda_{\mathrm{F}}\rho$.

# Simulations and Results

# Simulation Setup

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

- $\xi = 5$ dB, 10 dB
- $\alpha_{\mathrm{M}} = 4$
- $\alpha_{\mathrm{F}} = 3$
- $\alpha_{\mathrm{FM}} = \alpha_{\mathrm{M}}$
- $\alpha_{\mathrm{FF}} = 3.5$
- $\alpha_{\mathrm{MF}} = \alpha_{\mathrm{FF}}$
- $\sigma_{\mathrm{M}} = 8$ dB
- $\sigma_{\mathrm{F}} = 4$ dB
- $\sigma_{\mathrm{FF}} = 12$ dB
- $\sigma_{\mathrm{MF}} = 10$ dB
- $\sigma_{\mathrm{FM}} = 10$ dB
- $f_{\mathrm{c}} = 2000$ MHz
- $P_{\mathrm{M,Tx}} = 43$ dBm
- $P_{\mathrm{F,Tx}} \leq 23$ dBm
- $G_{\mathrm{MBS}} = 15$ dBi
- $G_{\mathrm{FAP}} = 2$ dBi
- $G_{\mathrm{UE}} = 0$ dBi
- $r_{\mathrm{M}} = 1000$ m
- $r_{\mathrm{F}} = 30$ m
- $U_{\mathrm{F}} = 2$
- $\gamma_{\mathrm{M}} = 3$ dB
- $\gamma_{\mathrm{F}} = 5$ dB
- $\varepsilon_{\mathrm{M}} = \varepsilon_{\mathrm{F}} = 0.1$
- $M = N = 12$

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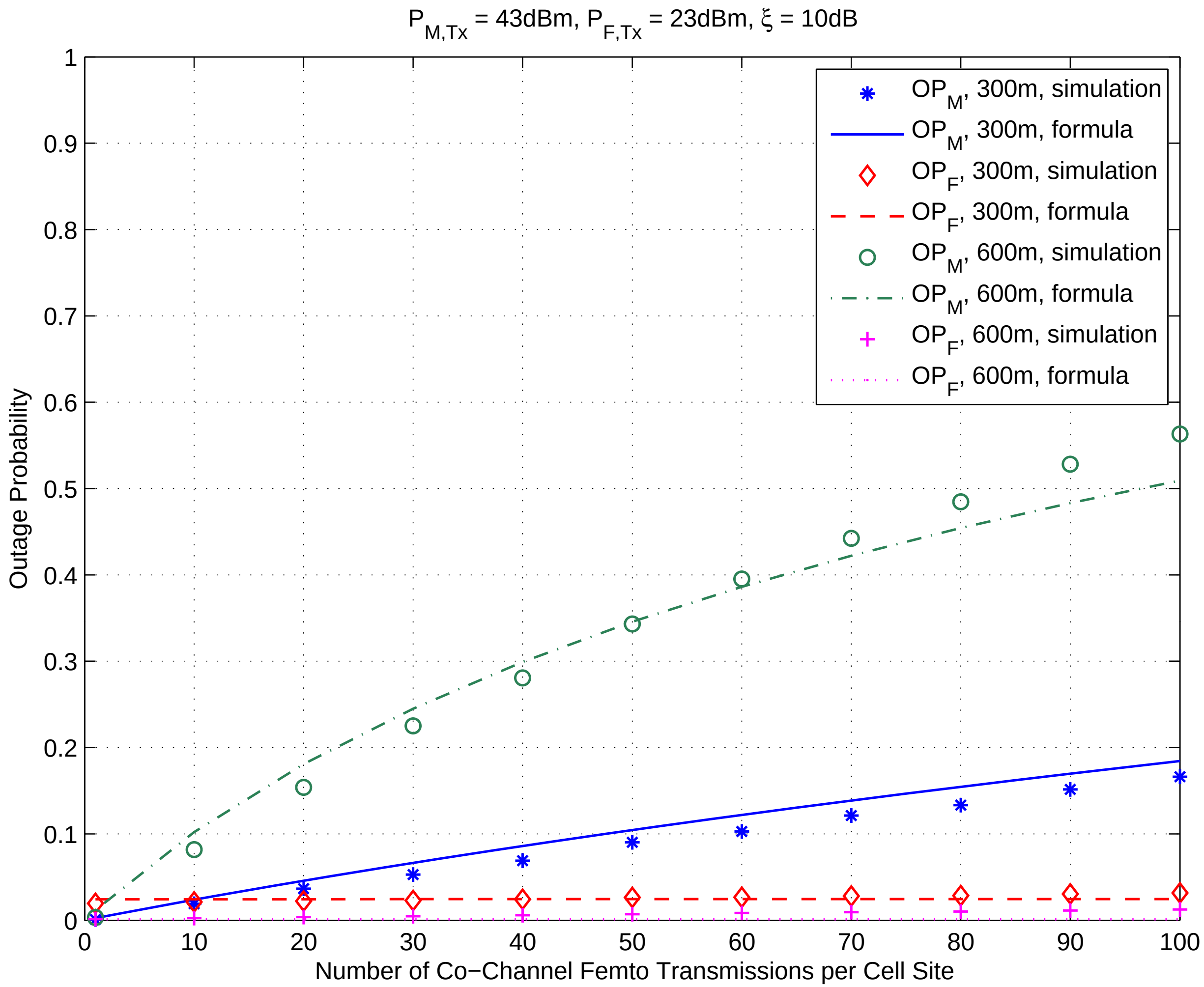
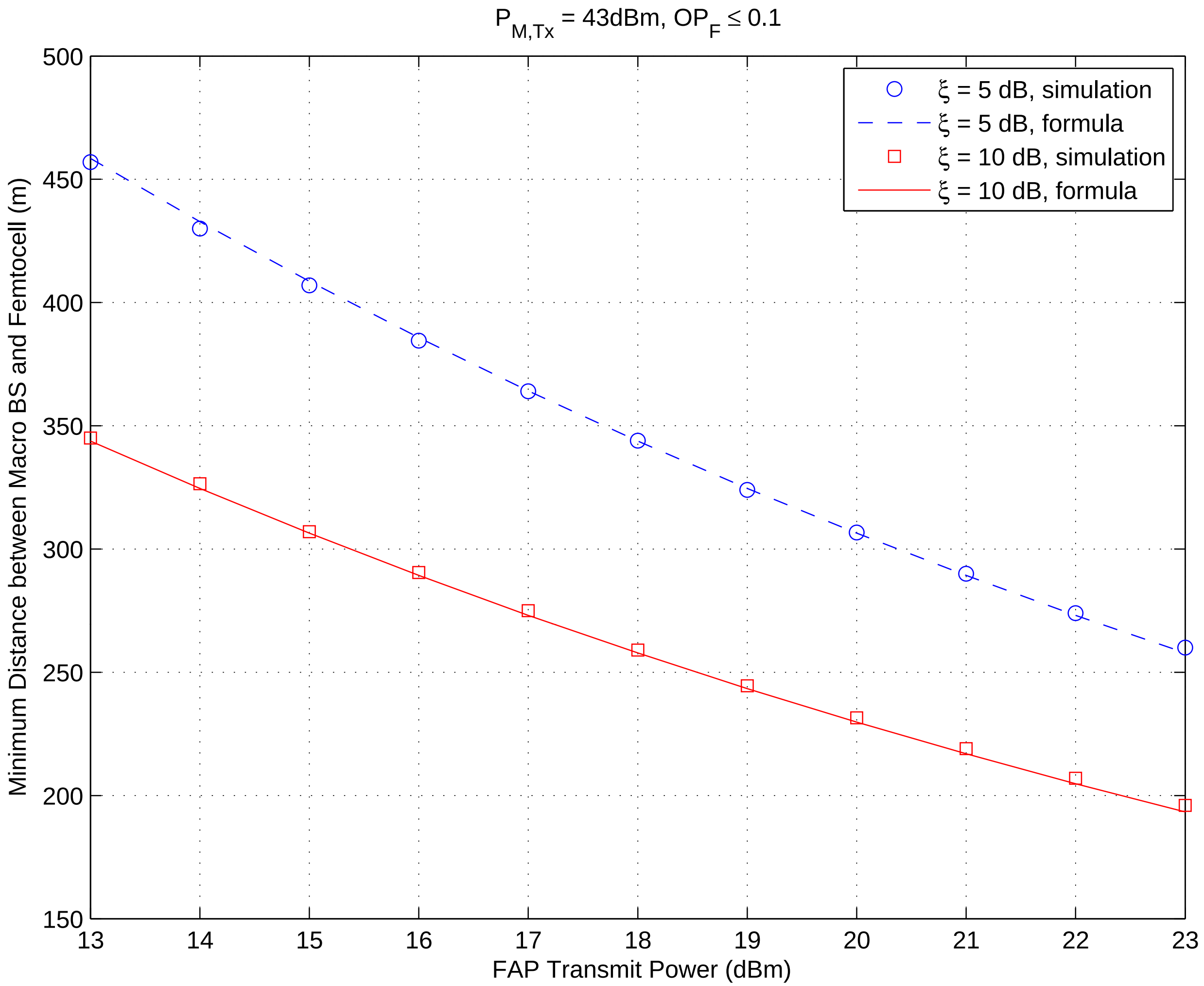
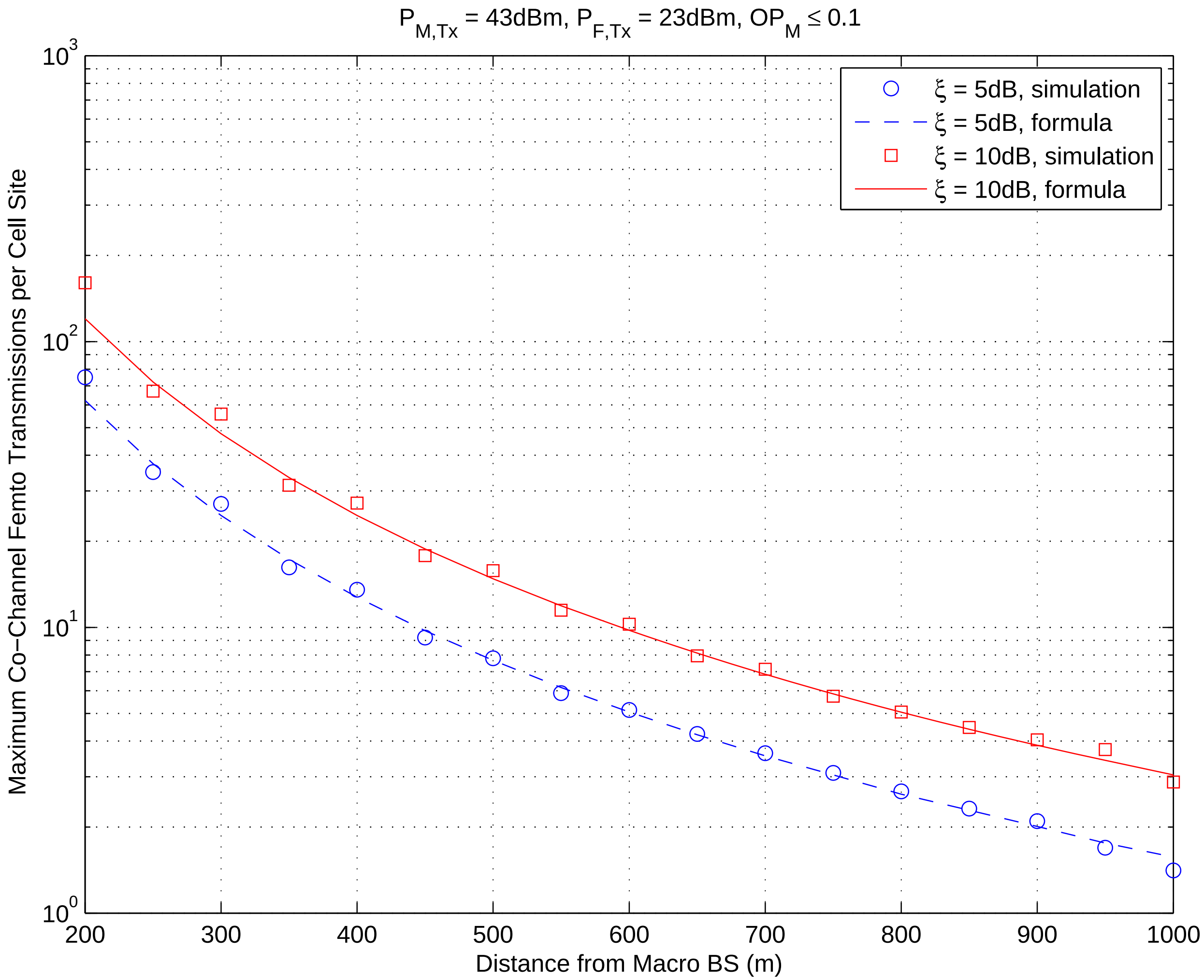
# Outage Probability



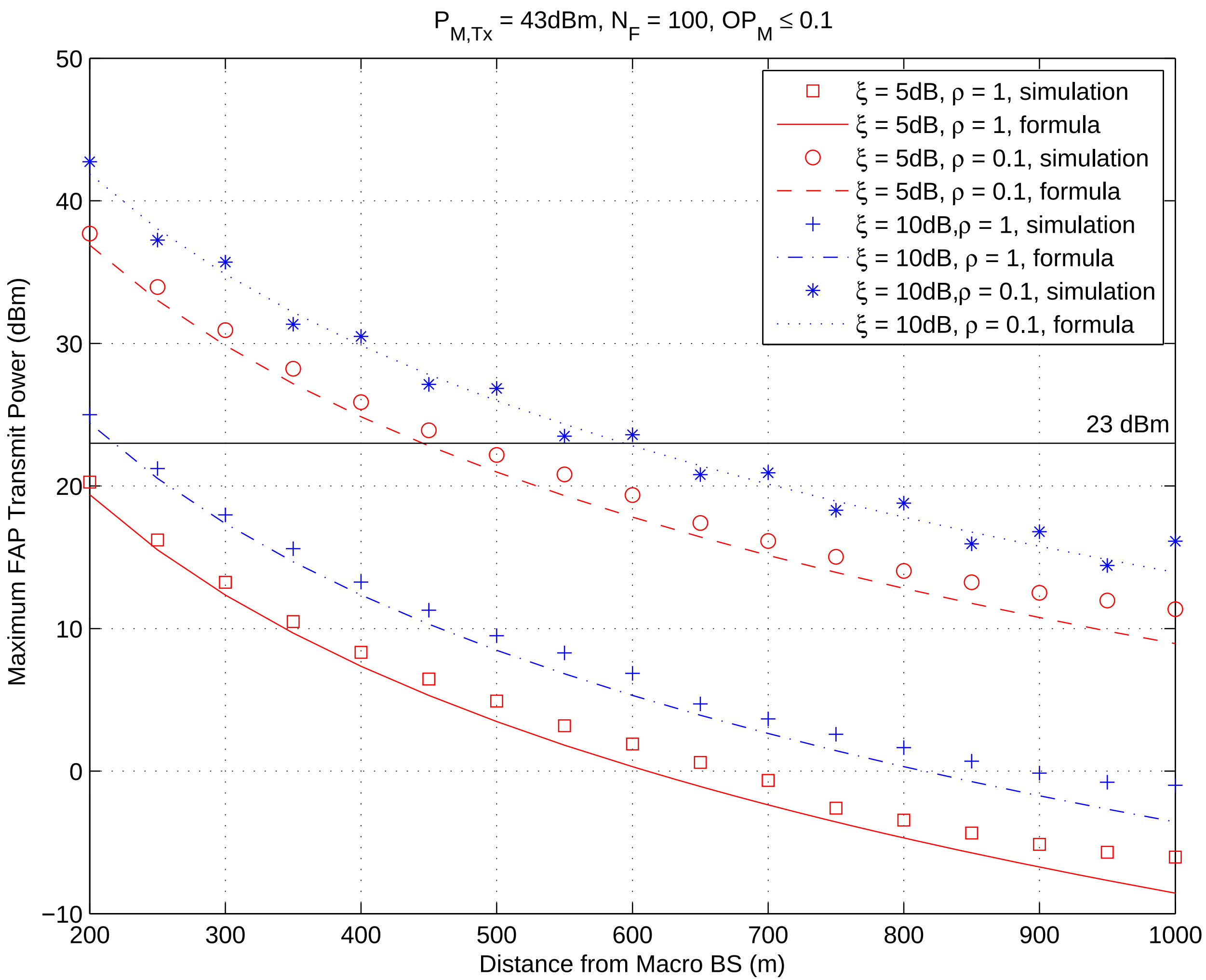
# Minimum MBS-to-FAP Distance



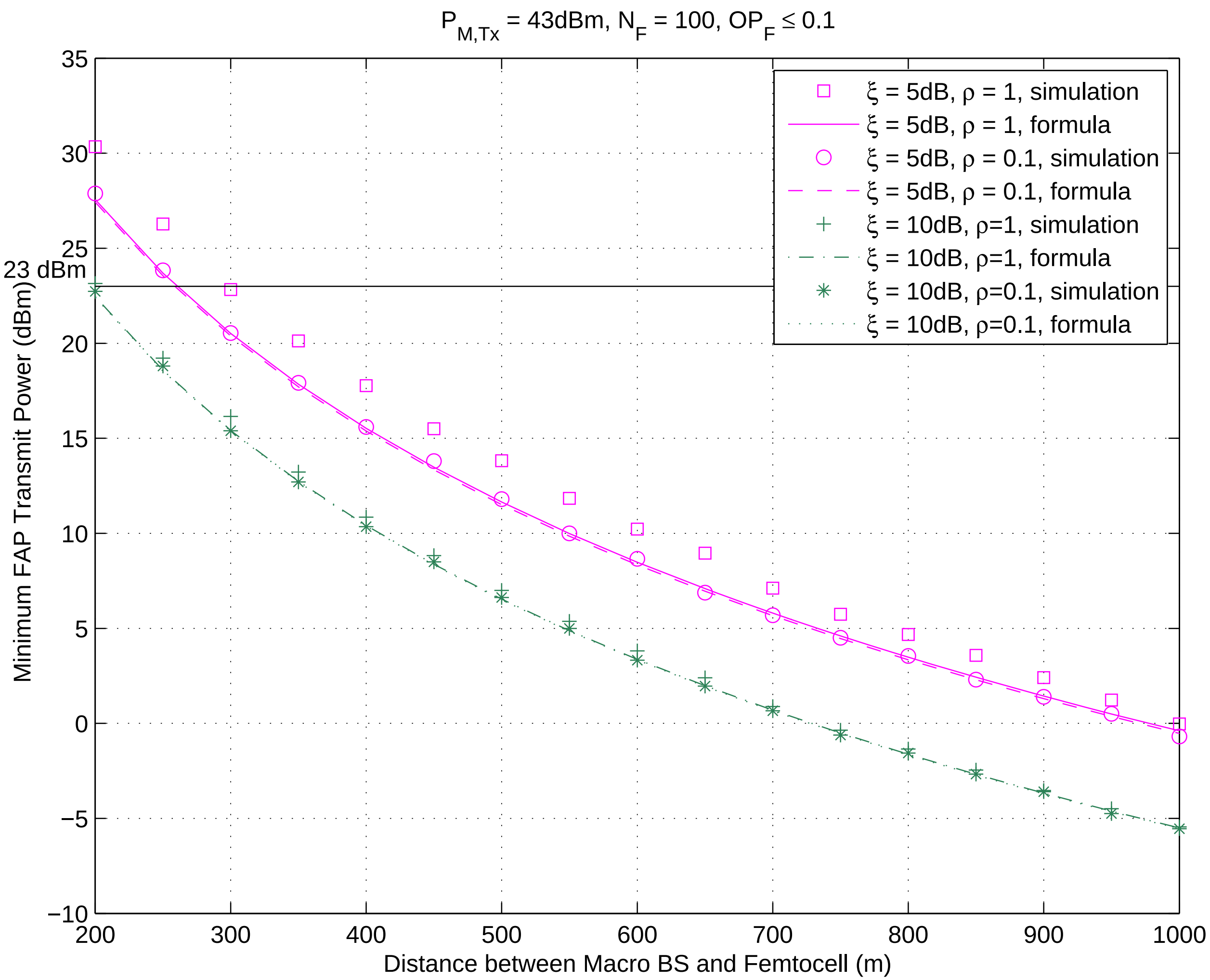
# Maximum Femto Density



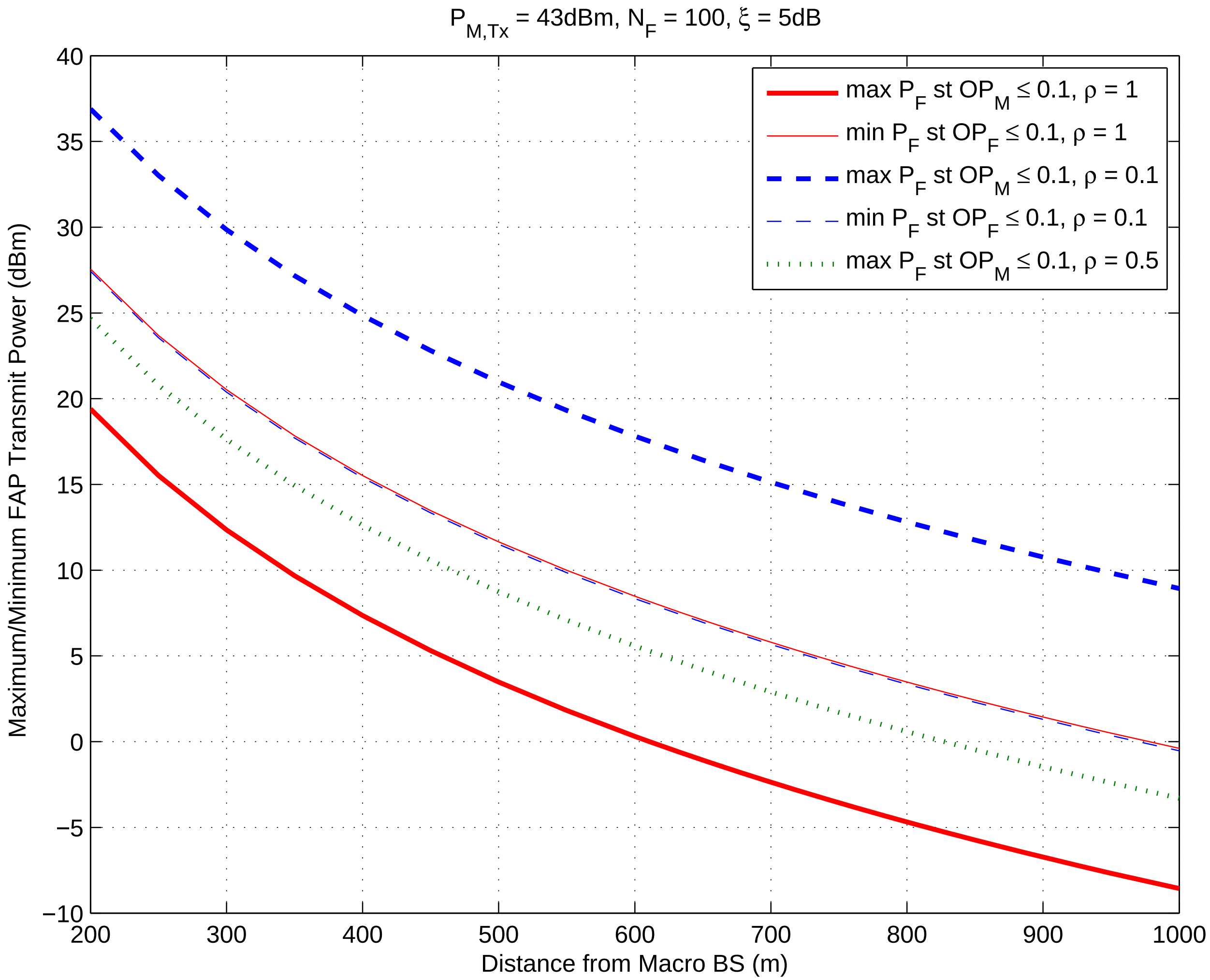
# Maximum Allowed $P_{F,Tx}$



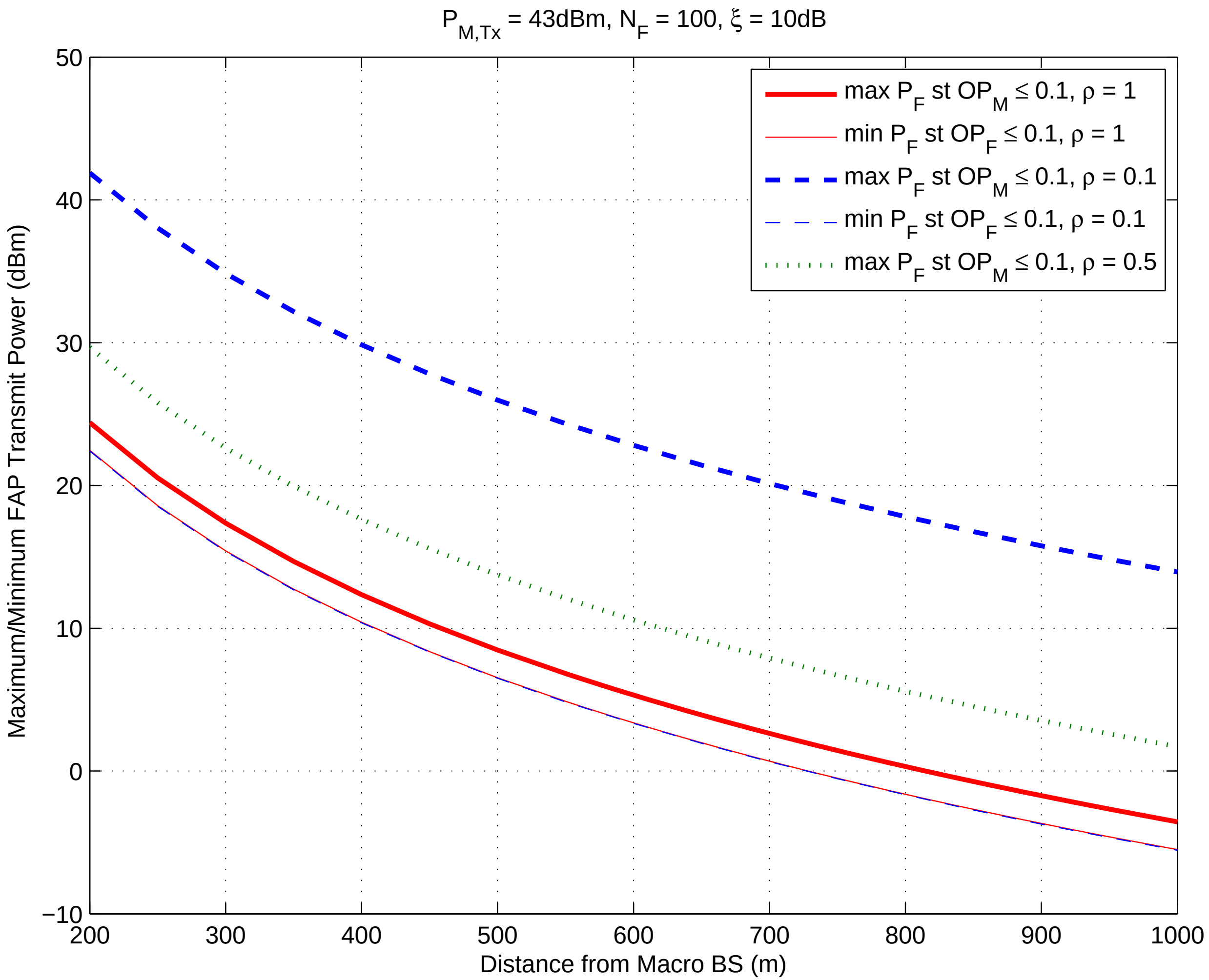
# Minimum Required $P_{F,Tx}$



# $P_{F,Tx}$ under Low Attenuation



# $P_{F,Tx}$ under High Attenuation



# 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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