Performance Analysis of Power Control and Cell Association in Heterogeneous Cellular Networks

Prasanna Herath Mudiyanselage

PhD Final Examination

Supervisors: Witold A. Krzymień and Chintha Tellambura

Department of Electrical and Computer Engineering,
University of Alberta, Edmonton, Canada.
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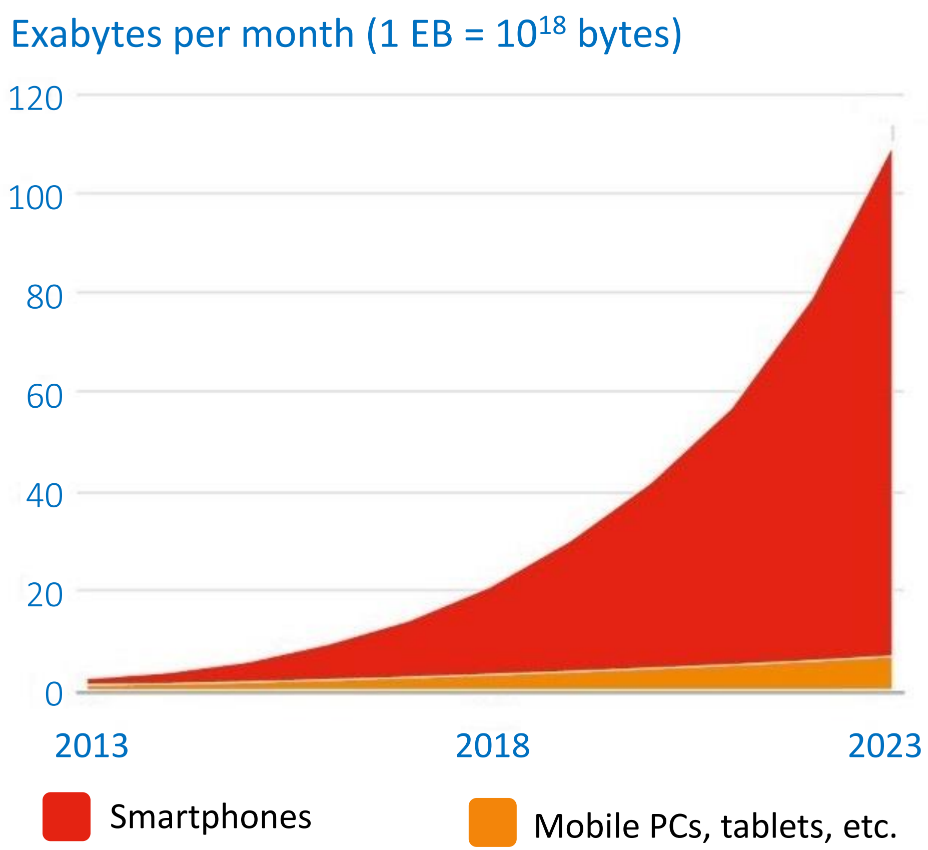
UNIVERSITY OF ALBERTA

Outline

Global Mobile Data Traffic Forecast 2013-2018

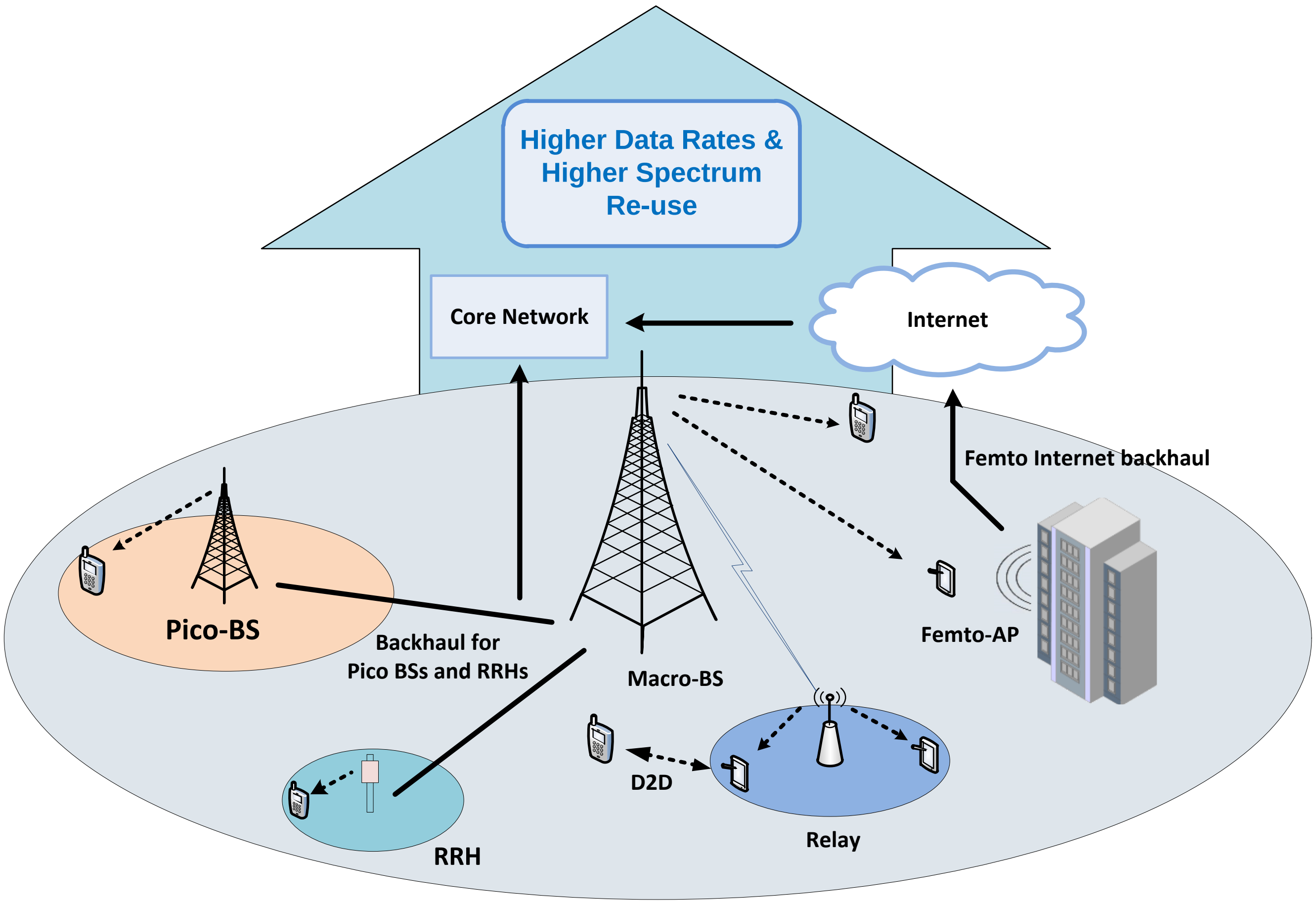
Mobile data traffic growth prediction [1]



- Compound annual growth rate (CAGR) of 42%
- Monthly traffic is expected to surpass 100 EB in 2023
- Smart phones will contribute 95% of the traffic in 2023

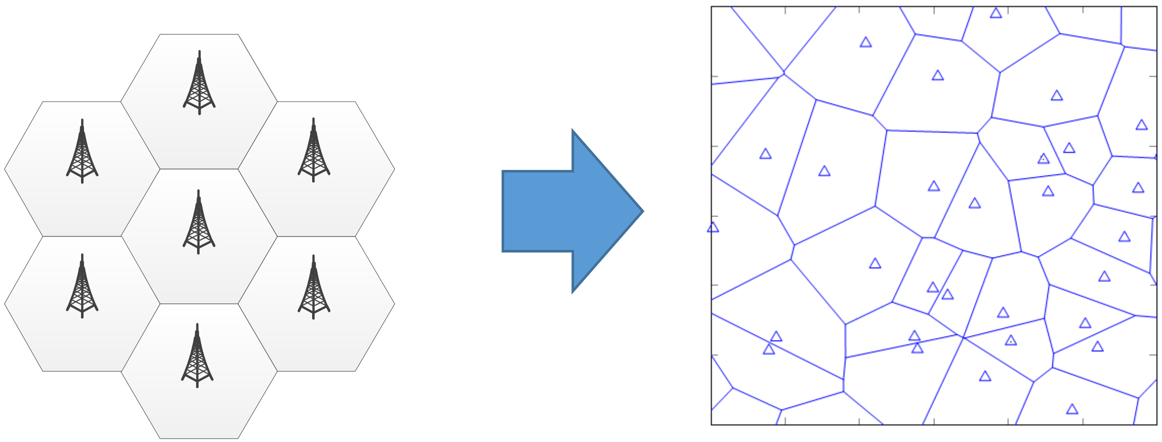
[1] Ericsson Mobility Report, November 2017

Heterogeneous Cellular Networks



BS: base station, **AP**: access point, **RRH**: remote radio head, **D2D**: device-to-device

Stochastic Geometry for Cellular HetNets



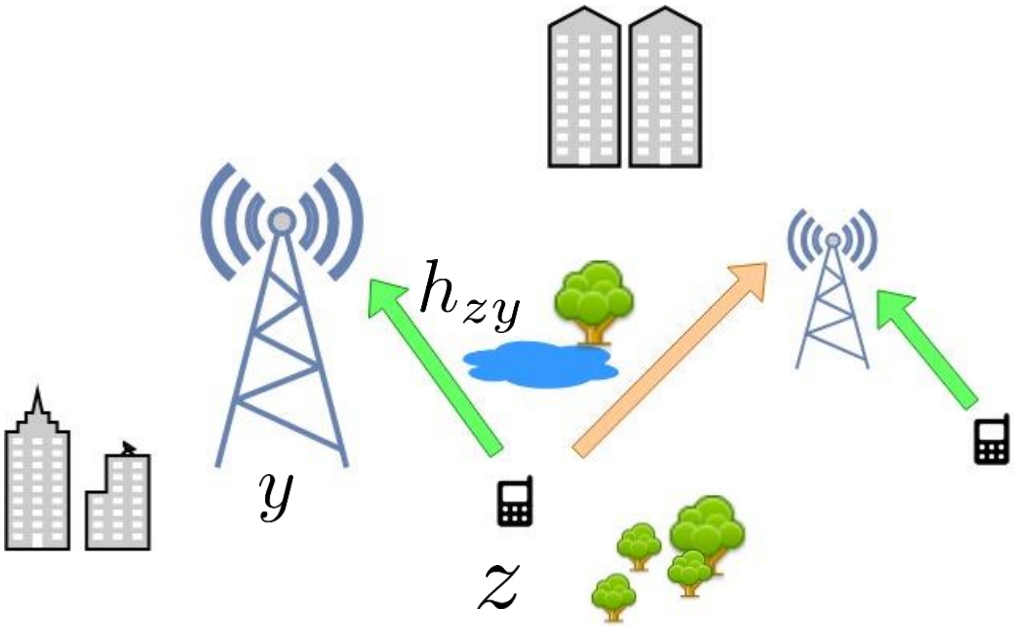
- Networks are evolving towards irregular spatial deployments and cell shapes.
  - Better modeled by random spatial processes [2]
- Spatial distribution of nodes and users affects performance [3]. System level analysis is essential.
- Stochastic geometry is a powerful tool for modeling and analysis of networks with random topologies.

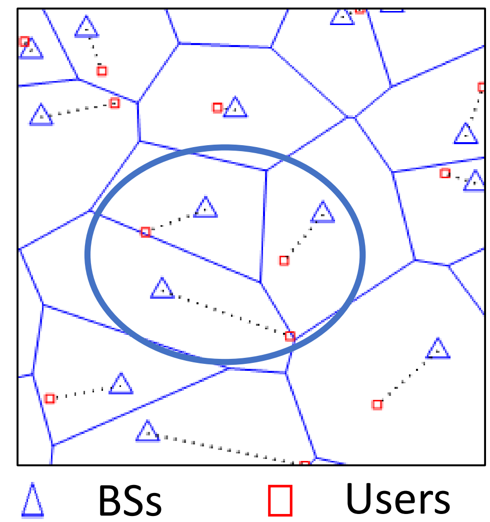
[2] J. Andrews, "Seven ways that HetNets are a cellular paradigm shift," *IEEE Commun. Mag.*, vol. 51, no. 3, pp. 136–144, Mar. 2013.
[3] M. Haenggi, *Stochastic Geometry for Wireless Networks*. New York, NY: Cambridge University Press, 2013.

Contributions of the Thesis

1. Three uplink transmit power control (TPC) schemes for HetNets
2. Simple cell association policy for dense HetNets (single-tier & two-tier)
3. Analytical tools to comprehensively capture practical conditions (spatial distribution of nodes, spatial dependency, different channel impediments), power control, and cell association.

Uplink Transmit Power Control in HetNet: Problem Statement





Interfering users can be closer to a BS than its associated user

- High power efficiency for battery powered devices
- Reduce interference

Uplink Transmit Power Control in HetNet: Problem Statement

How to design uplink TPC to minimize interference, improve power efficiency, and performance?

$$P_z = f\left(\rho, z, y, \alpha, h_{zy}, P_{max}\right)$$

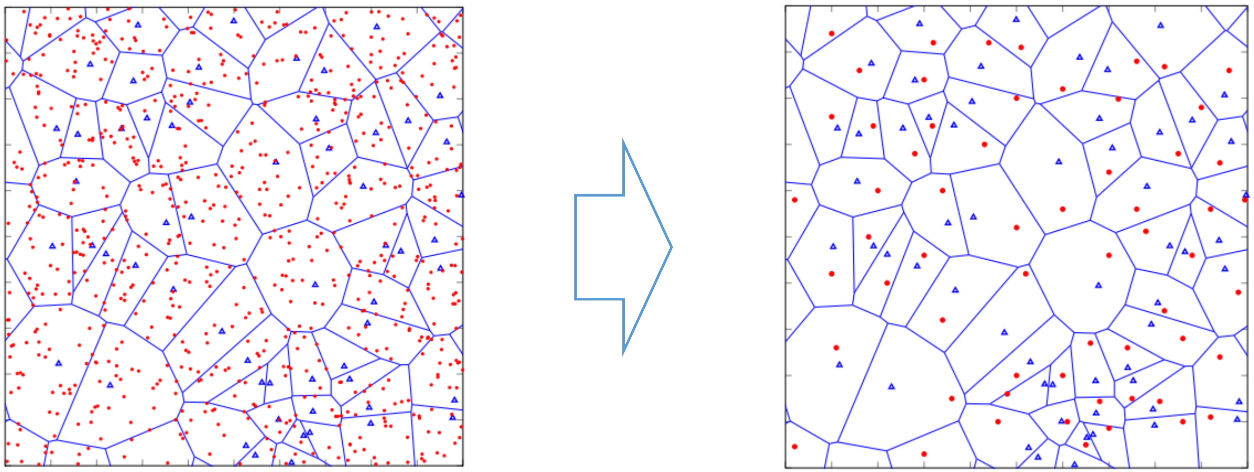
$$P_z = \rho l(z, y)^{-\eta} h_{zy}^{-\theta}$$

$$\eta \in (0, 1]$$

- **Scheme 1:** $\theta = 0$
- **Scheme 2:** $\theta = \eta$
- **Scheme 3:** $\theta = 1$

ρ – reference transmitted power, $l(z, y)$ – path loss (power gain)

Uplink System Model and Assumptions:



Random cellular network - all users

Random cellular network – active users in one resource block

- Orthogonal multiple access (OFDM or DFT-S-OFDM)
- Universal frequency reuse and fully loaded network
- Downlink equivalent model [4]

[4] T. Novlan, H. Dhillon, and J. Andrews, "Analytical modeling of uplink cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2669–2679, Jun. 2013

Coverage Probability Analysis

- Theorem (SNR coverage probability of TPC Scheme 1)

The uplink coverage probability of an MS in a single-tier cellular network under fractional path loss inversion power control is given by

$$P_c(T) = 2\sqrt{\pi}\lambda \sum_{i=1}^{L} \zeta_i \int_0^{\infty} r_{z_0} \exp\left(-\pi\lambda r_{z_0}^2 - \frac{N_0 T \exp\left(-\sqrt{2}\sigma v_i\right)}{\rho r_{z_0}^{\alpha(\eta-1)}}\right) \mathcal{L}_{I_{\Phi\setminus z_0}}\left(s = \frac{T\ \exp\left(-\sqrt{2}\sigma v_i\right)}{\rho r_{z_0}^{\alpha(\eta-1)}}\right) dr_{z_0} + \epsilon_L,$$

where,

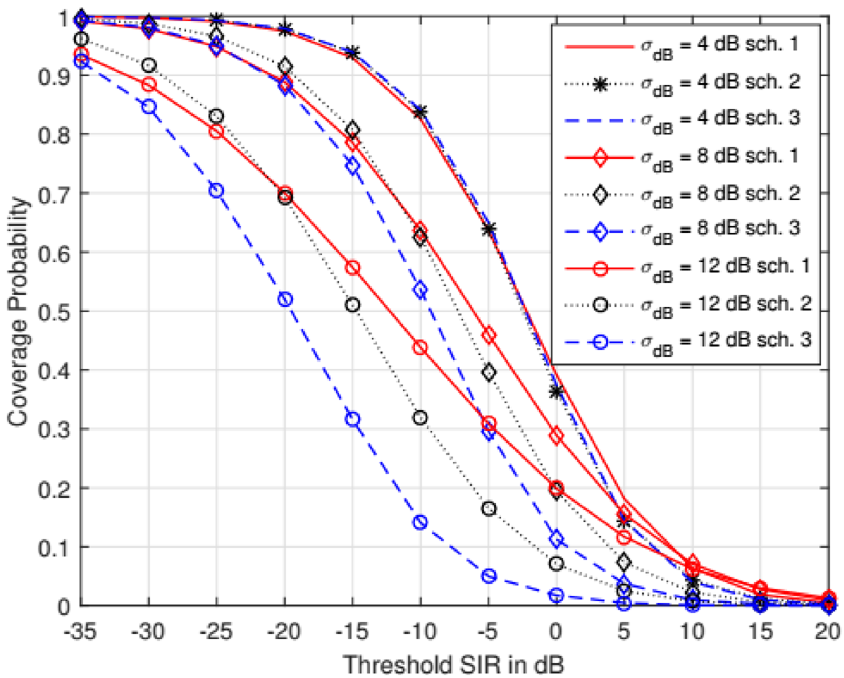
$$\mathcal{L}_{I_{\Phi\setminus z_0}}(s) = \exp\Bigg(\frac{-2\pi^{\frac{1-\alpha\eta}{2}} \lambda^{\frac{2-\alpha\eta}{2}} s\rho\ r_{z_0}^{2-\alpha}}{\alpha-2} \sum_{j=1}^{M} \kappa_j \exp\big(\sqrt{2}\sigma x_j\big) \sum_{q=1}^{Q} \beta_q \times {}_2F_1\left(1, \frac{\alpha-2}{\alpha}, 2-\frac{2}{\alpha}, \frac{-s\rho\ \exp\left(\sqrt{2}\sigma x_j\right) \delta_q^{\frac{\alpha\eta}{2}}}{r_{z_o}^{\alpha}\ (\pi\lambda)^{\frac{\alpha\eta}{2}}}\right)\Bigg) + R_{MQ}$$

$\zeta_i,\ v_i\ (\kappa_j,\ x_j)$: weights and nodes of the Gauss-Hermite quadrature of order L (M).

β_q, δ_q : weights and nodes of the Gauss-Laguerre quadrature of order Q

Similar theorems have been derived for the TPC Schemes 2 and 3.

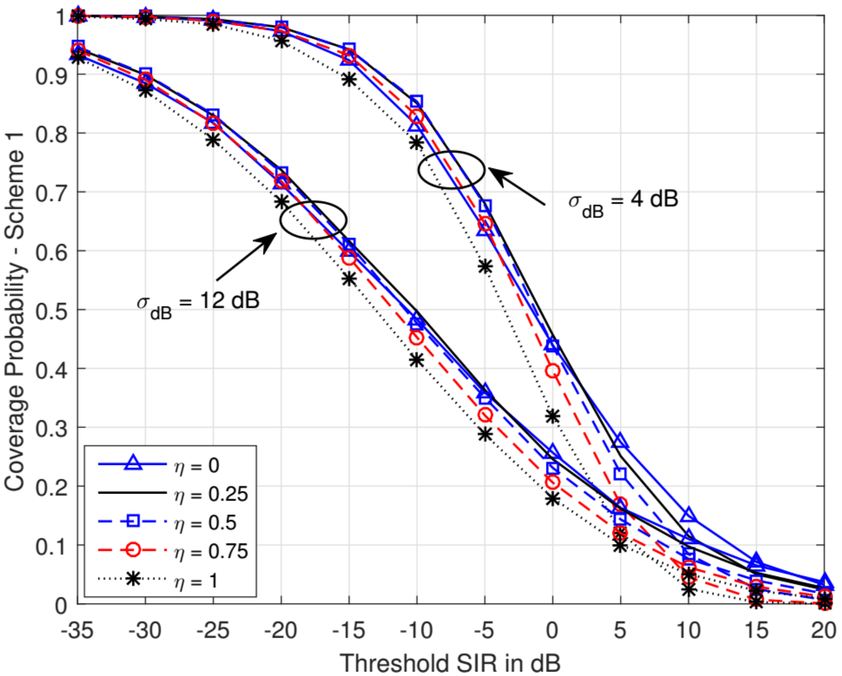
Coverage Probability of TPC Schemes



BS density $\lambda = 0.5\ \mathrm{BS/km^2}$, Power control factor $\eta = 0.5$, Path loss exponent $\alpha =\ 3.5,\ \sigma_{dB} = \xi_{dB}\ , N_0 = 0.$

- Severe shadowing (higher standard deviation) degrade coverage.
- When shadowing is less severe, all three Schemes achieve similar performance.
- At low SINR thresholds and sever shadowing, Scheme 2 (compensating for the aggregate effect of path loss and shadowing) improves coverage
- At high SINR thresholds, Scheme 1 (path loss inversion) provides better coverage.

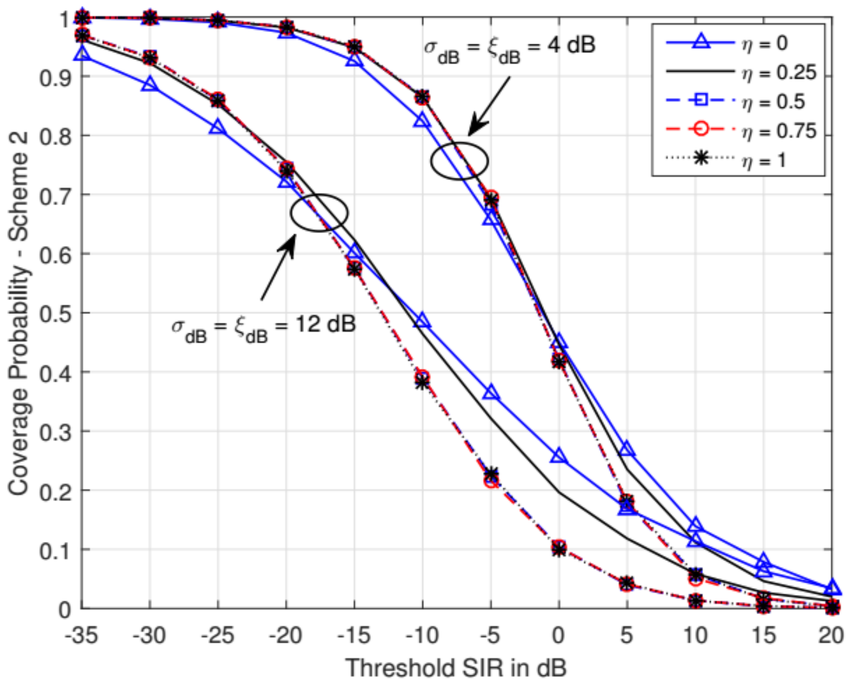
Coverage Probability dependence on the Power Control Factor: Scheme 1



BS density $\lambda = 0.5\ \mathrm{BS/km^2}$, Path loss exponent $\alpha = 3.5,\ \sigma_{dB} = \xi_{dB}, N_0 = 0.$

- Coverage is smallest when the path loss is completely compensated.
  - ✓ Higher η boost cell edge user SINR at the cost of higher network interference
- At high threshold SINR, the η = 0 (no power control), give better coverage
- Variation of coverage with η is similar for different levels of shadowing.

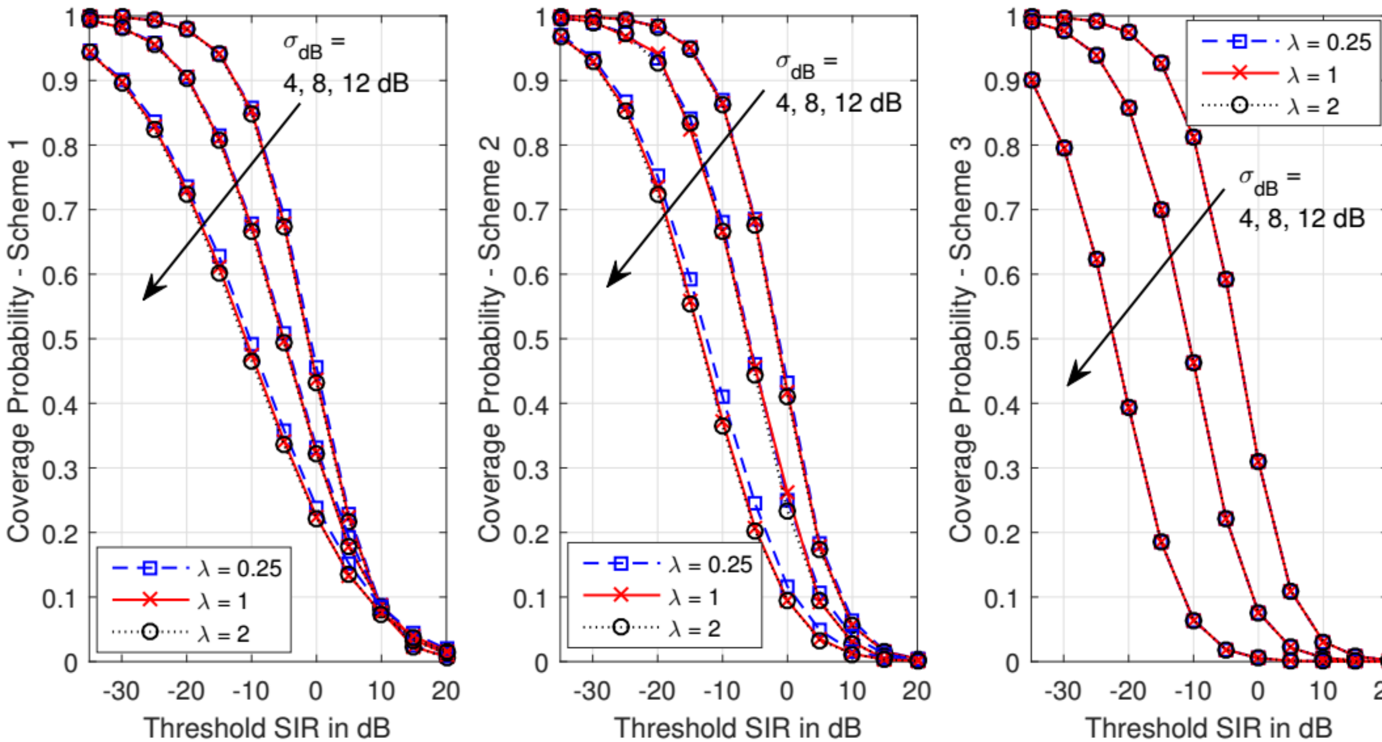
Coverage Probability dependence on the Power Control Factor: Scheme 2



BS density $\lambda = 0.5\ \mathrm{BS/km^2}$, Path loss exponent $\alpha = 3.5,\ \sigma_{dB} = \xi_{dB}, N_0 = 0.$

- At low SINR thresholds, $\eta = \theta = 1$ (complete compensation of shadowing and path loss), gives the highest coverage
- At high threshold SINR, η = 0 (no power control) give better coverage
- Performance variation widens when shadowing is increased
- Power control parameters have to be chosen based on the operating SINR

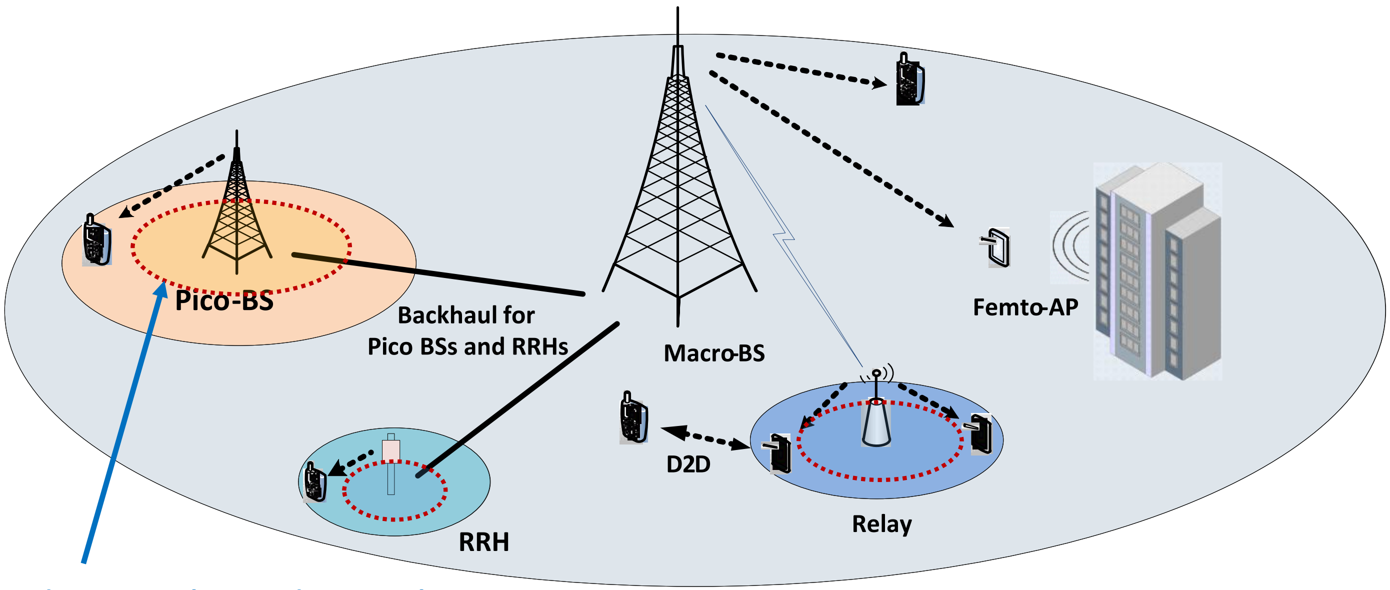
Coverage Probability of BS Densities and TPC Schemes



Power control factor $\eta = 0.5$, Path loss exponent $\alpha = 3.5$, $\sigma_{dB} = \xi_{dB}$, $N_0 = 0$.

- BS density has no significant impact on the coverage probability.

Cell Association in HetNet: Problem Statement

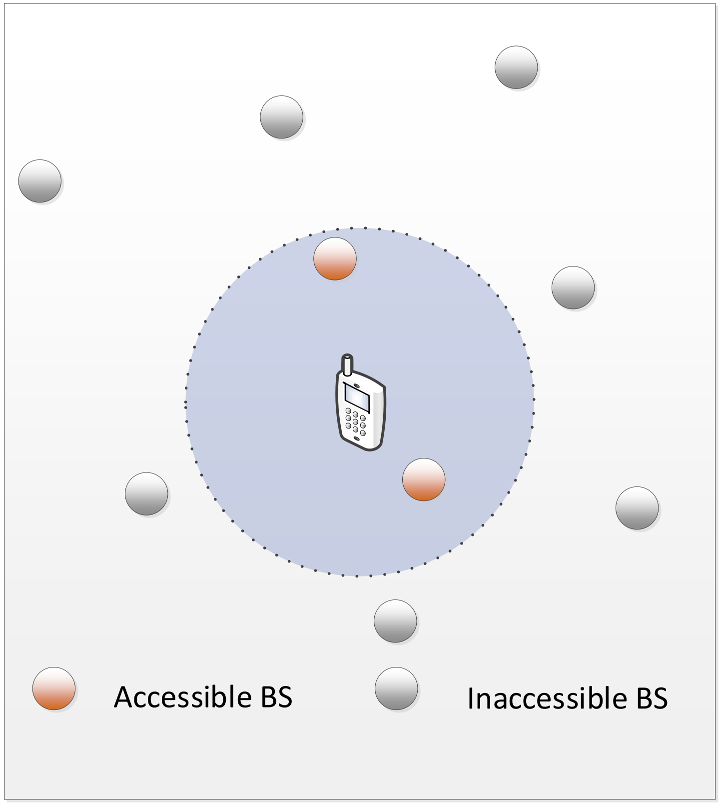


Cell boundary with traditional received power based cell association

Dense network with low-power low-cost BSs/APs

How to perform cell association with sparse network information and maximize the use of low-power BSs to increase the network capacity?

Cell Association with Limited Candidate Base Stations



- Solution
  - Select the highest instantaneous SINR BS out of BSs providing average received power above P_{th}
  - Select P_{th} appropriately to reduce the number of candidate BSs without compromising performance
  - Only requires SINR of few neighboring BSs

Coverage Probability Analysis: Single-Tier Network

- Theorem (SNR coverage probability)

In single-tier networks, coverage probability with limited candidate cell association is given by

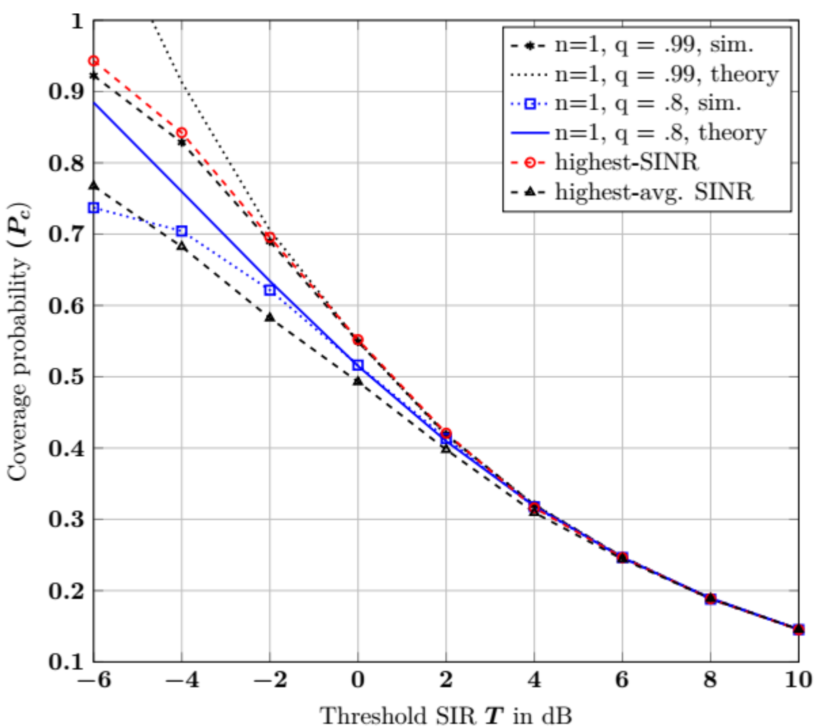
$$P_c(T) = \left[1 - \exp\left(\frac{-2\pi^2 \left(\frac{P_t T}{P_{th}}\right)^{\frac{d}{\alpha}} \lambda}{\alpha \sin\left(\frac{2\pi}{\alpha}\right)}\right)\right] \frac{\alpha \sin\left(\frac{2\pi}{\alpha}\right)}{2\pi T^{\frac{2}{\alpha}}}.$$

- Lemma (minimum average received power to become a candidate BS)

Minimum average received power to have n candidate BSs with probability q is given by

$$P_{th} = P_t \left[\frac{\lambda\pi}{\Gamma_{in}^{-1}\left(n, (n-1)!(1-q)\right)}\right]^{\frac{\alpha}{2}}$$

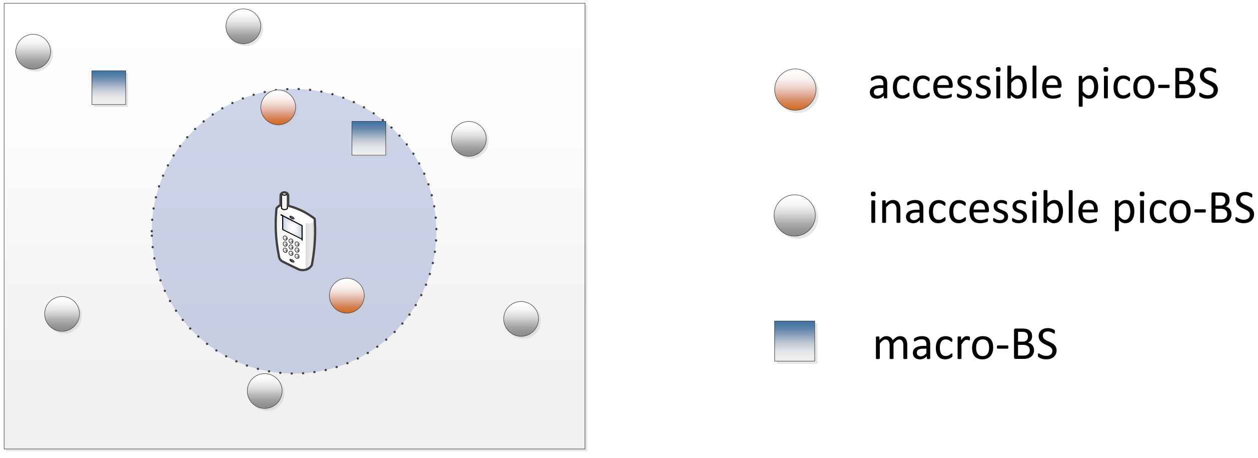
Coverage Probability-Single-Tier Network



- Improved coverage probability compared to average received power based cell association
- Close to the performance of highest-SINR association can be reached by proper selection of P_{th}

BS density $\lambda = 12$ BSs/km^2, Path loss exponent $\alpha = 3.5$, n BSs meet P_{th} requirement with probability q , $N_0 = 0$.

Cell Association in a Two-Tier Network



- **Case 1:** Both Instantaneous SINR and average received power of pico-BSs are available
  - Choose highest-SINR pico-BS if there is any meeting P_{th}. Select highest average SINR macro-BS otherwise.
- **Case 2:** Only average received power of pico-BSs are available
  - Choose highest average received power pico-BS if there is any meeting the P_{th}. Select highest average SINR macro-BS otherwise.
- Users can be offloaded to pico-BSs by adjusting P_{th}

Coverage Probability Analysis: Two-Tier Networks

- Theorem (SINR coverage probability)

When both instantaneous SINR and average received power of pico-BSs are available (case 1), the coverage probability of limited candidate cell association is given by

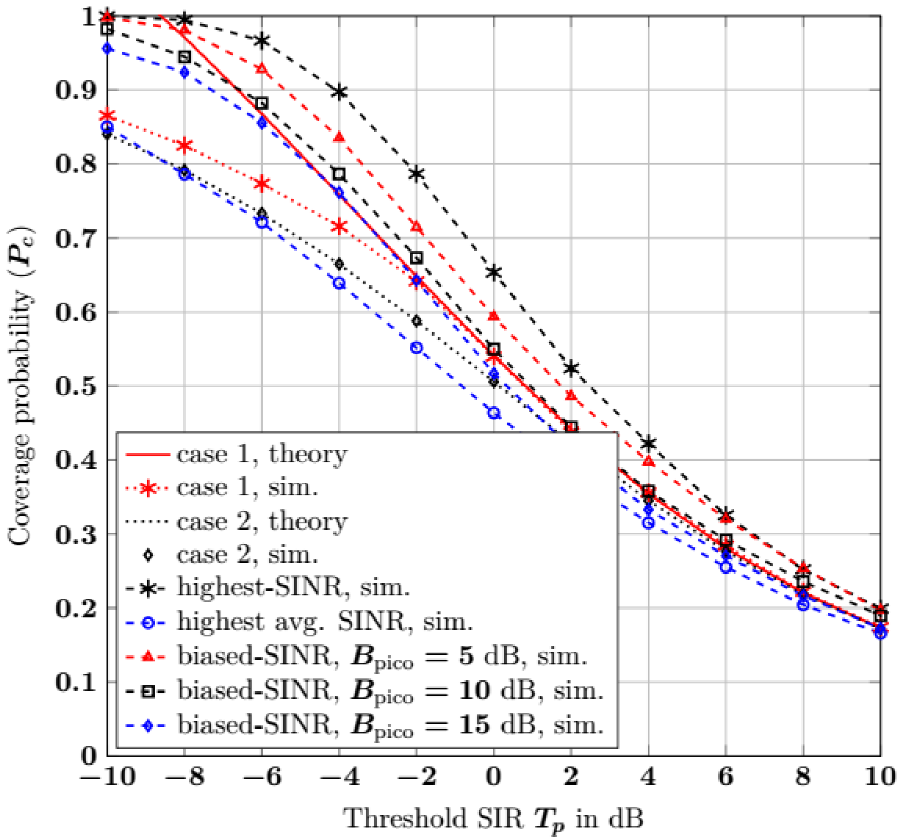
$$P_c(T_m, T_p) = \exp\left(-\lambda_p \pi \left(\frac{P_p}{P_{th}}\right)^{\frac{2}{\alpha_p}}\right) \int_0^\infty \exp\left(-\frac{T_m N_0}{P_m r_z^{-\alpha_m}}\right) \mathcal{L}_I\left(\frac{T_m}{P_m t^{-\alpha_m}}\right) f_{r_z}(t) dt$$
$$+ 2\pi\lambda_p \int_0^{\left(\frac{P_p}{P_{th}}\right)^{\frac{1}{\alpha_p}}} r \exp\left(-\frac{T_p N_0}{P_p r^{-\alpha}}\right) \exp\left(-\frac{2\pi^2 \lambda_p T_p^{\frac{2}{\alpha_p}} r^2}{\alpha_p \sin\left(\frac{2\pi}{\alpha_p}\right)} - \frac{2\pi^2 \lambda_m (T_p P_m / P_p)^{\frac{2}{\alpha_m}} r^2}{\alpha_m \sin\left(\frac{2\pi}{\alpha_m}\right)}\right) dr$$

$$\mathcal{L}_I(s) = \exp\Big(- 2\pi\lambda_m P_m t^{2-\alpha_m} s \; {}_2F_1\big[1, \frac{\alpha_m - 2}{\alpha_m}; 2 - \frac{2}{\alpha_m}, \frac{-P_m s}{t^{\alpha_m}}\big]/(\alpha_m - 2)$$
$$- 2\pi\lambda_p P_p^{\frac{2}{\alpha_p}} P_{th}^{1-\frac{2}{\alpha_p}} s \; {}_2F_1\big[1, \frac{\alpha_p - 2}{\alpha_p}; 2 - \frac{2}{\alpha_p}, -sP_{th}\big]/(\alpha_p - 2)\Big)$$

$$f_{r_z}(t) = 2\pi\lambda_m t \exp\left(-\lambda_m \pi t^2\right), \; t > 0$$

A similar result has been derived for case 2

Coverage Analysis: Two-Tier Networks



- Higher coverage probability compared to highest average SINR association
- Perform similar to biased SINR association in most of the operating SINR values

$P_m = 20$ W, $P_p = 2$ W, $\alpha_m = 3.5$, $\alpha_p = 3.8$, $n = 1$, $q = 0.7$, $T_m = T_p - 5$ dB, $\lambda_m = 0.5$ BSs/km^2 , $\lambda_p = 20$ BSs/km^2, $N_0 = 0$.

Achievable Rate Analysis of an MS in Coverage

- Theorem (single-tier network)

With limited candidate cell association in single-tier networks, achievable data rate by a user in coverage is given by

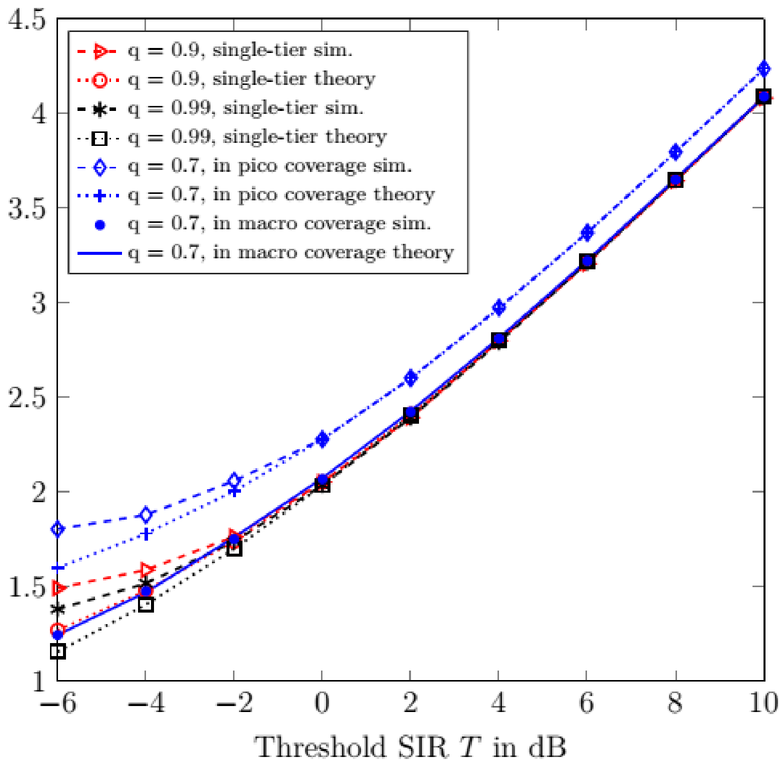
$$R^{\text{1-tier}} = \ln(1+T) + \frac{1}{P_c(T)} \int_{\ln(1+T)}^{\infty} P_c(e^z - 1)dz$$

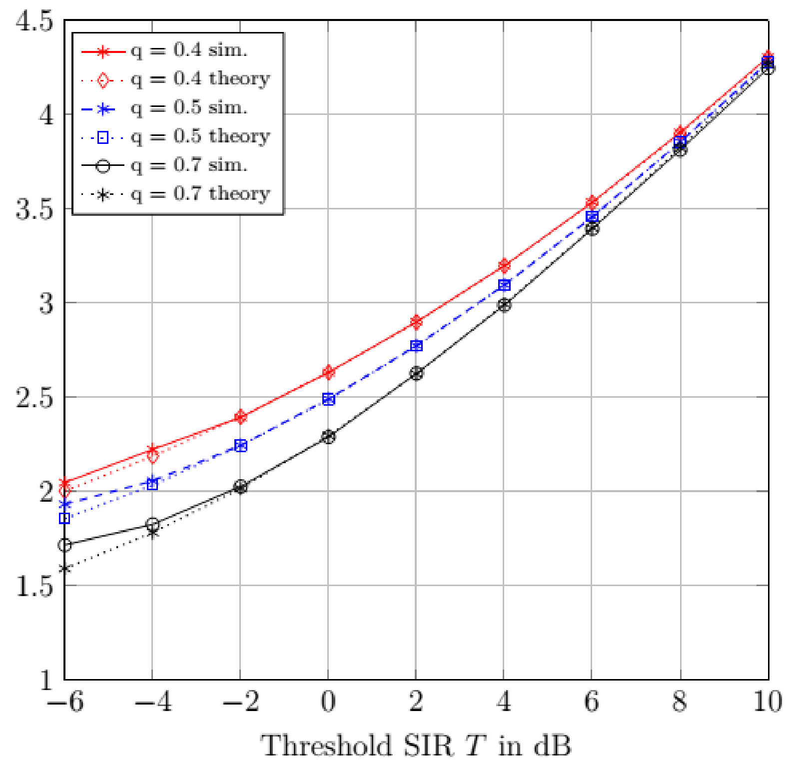
- Theorem (two-tier network)

With limited candidate cell association in two-tier networks, achievable data rate by a user in coverage is given by

$$R^{\text{2-tier}} = \ln(1+T) + \frac{1}{P_c(T,T)} \int_{\ln(1+T)}^{\infty} P_c(e^z - 1, e^z - 1)dz$$

Rate Analysis: Single- & Two-Tier Networks





Single-tier network: $\lambda = 12$ BSs/km^2 , $\alpha = 3.5, n = 1$.
Two-tier network: $P_m = 20$ W, $P_p = 2$ W, $\alpha_m = 3.5, \alpha_p = 3.8, n = 1,\ q = 0.7, T_m = T_p = T$, $\lambda_m = 0.5$ BSs/km^2 $\lambda_p = 20$ BSs/km^2, $N_0 = 0$.

Two-tier network: $P_m = 20$ W, $P_p = 2$ W, $\alpha_m = 3.5, \alpha_p = 3.8, n = 1,\ q = 0.7, T_m = T_p = T$, $\lambda_m = 0.5 \frac{\text{BSs}}{\text{km}^2}$, $\lambda_p = 20$ BSs/km^2, $N_0 = 0$.

Future Research Directions

- Mixed types of TPC based on operating SINR
- Impact of TPC in cellular networks on underlay communications: device-to-device and cognitive radio networks
- Evaluate gains of user off-loading in HetNet considering traffic models
- Considering different point process models to capture deployment scenarios

Summary of Contributions

1. Investigated three uplink TPC schemes
   - Effect of different TPC parameters, network densification, and channel impediments
2. Proposed and investigated a simple cell association policy for dense HetNet deployment (single-tier & two-tier)
   - Cell association with limited candidate BSs
3. Developed a comprehensive mathematical framework for system level analysis of cellular networks (downlink and uplink)
   - Spatial distribution of nodes and users, spatial dependency among users, different channel impediments, power control, cell association