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.
24th August 2018
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Global Mobile Data Traffic Forecast 2013-2018

- 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

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**Mobile data traffic growth prediction [1]**

Exabytes per month (1 EB = $10^{18}$ bytes)

- **Smartphones**
- **Mobile PCs, tablets, etc.**

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[1] Ericsson Mobility Report, November 2017
Heterogeneous Cellular Networks

1. Introduction

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.

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

- High power efficiency for battery powered devices
- Reduce interference

Interfering users can be closer to a BS than its associated user
Uplink Transmit Power Control in HetNet: Problem Statement

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

\[ P_z = f(\rho, z, y, \alpha, h_{zy}, P_{max}) \]

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

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

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

\( \rho \) — reference transmitted power, \( l(z, y) \) — path loss (power gain)
Uplink System Model and Assumptions:

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

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

\[
P_c(T) = 2\sqrt{\pi} \lambda \sum_{i=1}^{L} \zeta_i \int_{0}^{\infty} r_{z_0} \exp \left( -\pi r_{z_0}^2 - \frac{N_0 T \exp \left(-\sqrt{2}\sigma v_i \right)}{\rho r_{z_0}^{\alpha(\eta-1)}} \right) \mathcal{L}_{I_{\Phi \setminus 0}} \left( s = \frac{T \exp \left(-\sqrt{2}\sigma v_i \right)}{\rho r_{z_0}^{\alpha(\eta-1)}} \right) dr_{z_0} + \epsilon_L,
\]

where,

\[
\mathcal{L}_{I_{\Phi \setminus 0}}(s) = \exp \left( -\frac{2\pi^{\frac{1-x}{2}}}{\alpha - 2} s \rho \frac{v_{z_0}^{\alpha - 2}}{\alpha - 2} \sum_{j=1}^{M} \kappa_j \exp(\sqrt{2}\sigma x_j) \sum_{q=1}^{Q} \beta_q \right)
\times 2F_1 \left( 1, \frac{\alpha - 2}{\alpha}, \frac{2 - 2}{\alpha}, \frac{-s \rho \exp(\sqrt{2}\sigma x_j) \delta_q^{\frac{\alpha n}{2}}}{r_{z_0}^{\alpha n}(\pi \lambda)^{\frac{\alpha n}{2}}} \right) + R_{MQ}
\]

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

- Severe shadowing (higher standard deviation) degrade coverage.
- When shadowing is less severe, all three Schemes achieve similar performance.
- At low SINR thresholds and severe 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.

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

2.1 uplink power control
Coverage Probability dependence on the Power Control Factor: Scheme 1

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

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

2.1 uplink power control
Coverage Probability dependence on the Power Control Factor: Scheme 2

- At low SINR thresholds, $\eta = \theta = 1$ (complete compensation of shadowing and path loss), gives the highest coverage.
- At high threshold SINR, $\eta = 0$ (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.

BS density $\lambda = 0.5$ BS/km$^2$, Path loss exponent $\alpha = 3.5$, $\sigma_{dB} = \xi_{dB}$, $N_0 = 0$. 
Coverage Probability of BS Densities and TPC Schemes

2.1 uplink power control

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

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

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

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

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

\[
P_{th} = P_t \left[ \frac{\lambda \pi}{\Gamma_{\text{in}}^{-1}(n, (n-1)!(1-q))} \right]^{\frac{\alpha}{2}}
\]
2.2 Limited candidate cell association

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

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

\[
+ 2\pi \lambda_p \int_0^{\left(\frac{P_p}{P_{th}}\right)^{\frac{1}{\alpha_p}}} r \exp \left(-\frac{T_p N_0}{P_p r^{-\alpha}}\right) \exp \left(-\frac{2\pi^2 \lambda_p T_p^{\frac{2}{\alpha_p}} r^2}{\alpha_p \sin \left(\frac{2\pi}{\alpha_p}\right)} - \frac{2\pi^2 \lambda_m (T_p P_m/P_p)^{\frac{2}{\alpha_m}} r^2}{\alpha_m \sin \left(\frac{2\pi}{\alpha_m}\right)}\right) \, dr
\]

\[
\mathcal{L}_I(s) = \exp \left(-2\pi \lambda_m P_m t^{2-\alpha_m} s \, _2F_1\left[1, \frac{\alpha_m - 2}{\alpha_m}; 2 - \frac{2}{\alpha_m}, \frac{-P_m s}{t^{\alpha_m}}\right]\right) / (\alpha_m - 2)
\]

\[
- 2\pi \lambda_p P_p^{\frac{2}{\alpha_p}} P_{th}^{\frac{1}{\alpha_p}} s \, _2F_1\left[1, \frac{\alpha_p - 2}{\alpha_p}; 2 - \frac{2}{\alpha_p}, -s P_{th}\right] / (\alpha_p - 2)
\]

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

A similar result has been derived for case 2
2.2 Limited candidate cell association

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

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

  \[
  R_{1\text{-tier}} = \ln(1 + T) + \frac{1}{P_c(T)} \int_{\ln(1+T)}^{\infty} P_c(e^z - 1) \, dz
  \]

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

  \[
  R_{2\text{-tier}} = \ln(1 + T) + \frac{1}{P_c(T,T)} \int_{\ln(1+T)}^{\infty} P_c(e^z - 1, e^z - 1) \, dz
  \]
2.2 Limited candidate cell association

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, $\alpha_m = 3.5$, $\alpha_p = 3.8$, $n = 1$, $q = 0.7$, $T_m = T_p = T$, $\lambda_m = 0.5$ BSs/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