PhD Thesis Defense on

Optimization and Self-optimization for LTE Networks

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Introduction

Context

- More and more complex networks
- Highly competitive market with steadily decreasing prices/revenues

Example: Orange France

- Sites: 19000+ 2G, 19000+ 3G, 7000+ 4G
- Frequency bands: 700 MHz, 800 MHz, 900 MHz, 1.8 GHz, 2.1 GHz and 2.6 GHz
- Indoor femto-cells

Challenge: Optimize resource utilization and Control the OPEX.

Enabler: Automation with Self-Organizing Network (SON) for self-configuration, self-optimization and self-healing.
Thesis objectives

Design self-optimizing algorithms for use cases of interest: hetnets and active antenna systems.
SON design methodology

Network/KPI modeling

Problem Formulation

Algorithm Design

Proof-of-concept

Queueing theory

Probability theory

Mobile technology

Game theory

Convex Optimization

Stochastic Approximation

Simulator/Demonstrator
Overview

1. Introduction
2. Background
3. Heterogeneous Networks
   - Load balancing
   - Interference coordination
   - Numerical results
4. Active Antenna Systems
   - Vertical Sectorization
   - Virtual Sectorization
   - Multilevel Beamforming
5. SON Coordination
   - Concept
   - Problem formulation and Solution
   - Use case
6. Conclusion & Perspectives
   - Conclusion
   - Perspectives
Flow level network model

- Base station modeled as M/G/1 PS queue
- User’s data rate $R(r) = \min(R_{\text{max}}, \eta \log_2(1 + \text{SINR}(r)))$
- Key performance indicators:
  - Load: $\rho = \frac{\text{traffic demand}}{\text{service rate}}$
  - Mean user throughput: $\mu = R(1 - \rho)$
  - Others by simulation.
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Introduction

- Nodes with different transmit powers
- Nodes with different propagation conditions
- Nodes with low processing capabilities
- Dense network with more interference problems
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Literature review

H. Kim et al., IEEE INFOCOM 2010:

\[ s_u^* = \arg\max_s R_{u,s}(1 - \rho_s)^\alpha \]  

with \( R_{u,s} \) (data rate from BS \( s \) to user \( u \)), \( \rho \) (load) and \( \alpha \in \mathbb{R}_+ \).

\[ \Rightarrow \text{Minimizes } \sum_s \frac{(1-\rho_s)^{1-\alpha}}{\alpha-1}. \]

R. Combes et al., IEEE INFOCOM 2012:

\[ P_s(k + 1) = P_s(k)(1 + \epsilon_k(\rho_1(k) - \rho_s(k))) \]

with \( P \) (pilot power).

\[ \Rightarrow \text{Minimizes } \max_s \rho_s \]
End-to-end load model

Classical BS load definition:

\[ \rho = \min \left( 1, \int_{A} \frac{\lambda(r) \mathbb{E}(\sigma)}{R(r)} \, dr \right), \quad (3) \]

End-to-end load definition

\[ \rho_g = \min \left( 1, \int_{A} \frac{\lambda(r) \mathbb{E}(\sigma)}{\min(C_{BH}, R(r))} \, dr \right). \quad (4) \]

where

- \( C_{BH} \): backhaul capacity,
- \( \lambda(r) \): arrival rate at location \( r \),
- \( \mathbb{E}(\sigma) \): mean file size,
- \( R(r) \): peak rate at location \( r \).
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Almost Blank Subframe (ABS) mechanism

- Time-domain interference mitigation in heterogeneous networks.
- Used in conjunction with Cell Range Extension (CRE).

Illustration of Almost Blank Sub-Frames in a HetNet
**ABS-based interference coordination (eICIC)**

**Optimization Problem**: trade-off between small cells’ users SINR and macro cells’ capacity.

$\theta$: ABS ratio applied by the considered macro cells.

$R_u = (1 - \theta)\bar{R}_{u,m}$: Average data rate of macro user.

$R_u = (1 - \theta)\bar{R}_{u,p}^{\text{no ABS}} + \theta\bar{R}_{u,p}^{\text{ABS}}$: Average data rate of small cell user.

**Performance criteria**: $\alpha$-fair utility of users’ throughput

$$U_\alpha(\theta) = \begin{cases} 
\sum_{\text{all users}} \log R_u & \text{if } \alpha = 1 \\
\sum_{\text{all users}} \frac{R_u^{1-\alpha}}{1-\alpha} & \text{otherwise}
\end{cases}$$

(5)
Lower-bound PF utility for low complexity algorithm

Exact Proportional Fair ($\alpha = 1$) utility:

$$U_{PF\text{-}exact}(\theta) = \sum_{m=1}^{M} \sum_{u \in m} \log((1 - \theta)\bar{R}_{u,m}) + \sum_{u \in p} \log((1 - \theta)\bar{R}_{u,p}^{\text{no ABS}} + \theta\bar{R}_{u,p}^{\text{ABS}}) \quad (6)$$

Lower bound utility:

$$U_{PF\text{-}approx}(\theta) = \sum_{m=1}^{M} \sum_{u \in m} \log((1 - \theta)\bar{R}_{u,m}) + \sum_{u \in p} \frac{1}{2} \log(2(1 - \theta)\bar{R}_{u,p}^{\text{no ABS}})$$

$$+ \sum_{u \in p} \frac{1}{2} \log(2\theta\bar{R}_{u,p}^{\text{ABS}}) \quad (7)$$

Optimal ABS ratio in closed-form

$$\theta = \frac{N_p}{2(N_p + \sum_{m=1}^{M} N_m)} \quad (8)$$
Frequency splitting (orthogonal deployment)

- Orthogonal frequency used between macro cells and small cells
- Completely eliminates interference between macro cells and small cells at the price of reduced frequency reuse.
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### Numerical results - Scenario

<table>
<thead>
<tr>
<th>Network parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of macro BSs</td>
<td>3</td>
</tr>
<tr>
<td>Number of small BSs</td>
<td>12</td>
</tr>
<tr>
<td>Number of interfering macros</td>
<td>$6 \times 3$ sectors</td>
</tr>
<tr>
<td>Macro Cell layout</td>
<td>hexagonal trisector</td>
</tr>
<tr>
<td>Small Cell layout</td>
<td>omni</td>
</tr>
<tr>
<td>Intersite distance</td>
<td>500 m</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10MHz</td>
</tr>
<tr>
<td>Scheduling</td>
<td>Round-Robin</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal noise</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Macro Path loss (d in km)</td>
<td>$128.1 + 37.6 \log_{10}(d)$ dB</td>
</tr>
<tr>
<td>Small cell Path loss (d in km)</td>
<td>$140.7 + 36.7 \log_{10}(d)$ dB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Algorithms Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SON update frequency</td>
<td>every event</td>
</tr>
<tr>
<td>Step size of ABSrO</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Step size of FSO</td>
<td>$5.10^{-5}$</td>
</tr>
</tbody>
</table>
Numerical results - Scenario cont’d.

<table>
<thead>
<tr>
<th>Traffic spatial distribution</th>
<th>uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda )</td>
<td>14 users/s/km(^2)</td>
</tr>
<tr>
<td>( \lambda_h )</td>
<td>6 users/s/km(^2)</td>
</tr>
<tr>
<td>Service type</td>
<td>FTP</td>
</tr>
<tr>
<td>Average file size</td>
<td>6 Mbits</td>
</tr>
</tbody>
</table>

**NoSON**: baseline.

**LBonly**: load balancing only.

**AFUAonly**: alpha-fair user association (afua) only.

**LB-CCD-approx**: load balancing with approximate ABS-based eICIC.

**AFUA-CCD-approx**: afua with approximate ABS-based eICIC.

**LB-OD-approx**: load balancing with approximate frequency-based eICIC.

**AFUA-OD-approx**: afua with approximate frequency-based eICIC.
Numerical results - Performance

α-fair utility ($\alpha = 1$)

Mean User Throughput

Cell Edge throughput
Exact vs Approximate algorithms

- Exact utility ABSrO with LB
- Lower Bound utility ABSrO with LB
- Exact utility ABSrO with AFUA
- Lower Bound utility ABSrO with AFUA

User Throughput (Mbps) vs CDF (%)
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Introduction

Base Station architecture evolution
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Vertical Sectorization (VeSn) description

- Vertical separation of the two beams in the same sector
- Sector divided in two cells: inner and outer with resp. vertical tilts $\theta_{\text{inner}}$ and $\theta_{\text{outer}}$ with $\theta_{\text{inner}} > \theta_{\text{outer}}$

- Transmit powers: $P_i$ and $P_o$ for inner and outer cells resp. with $P_i + P_o = P_{\text{total}}$.
- Possible implementations: bandwidth sharing or full reuse.
VeSn with frequency reuse one

Description
- Inner and outer sectors reuse the whole available bandwidth.
- Power budget split equally between inner and outer sectors.

Advantages
- Increased capacity.
- Increased antenna gain for inner cell users.

Drawbacks
- Reduced transmit power.
- More interference.

Requirement: SON controller for VeSn feature activation.
VeSn feature activation problem

Activation rule

\[
\text{Action} = \begin{cases} 
\text{VeSn ON} & \text{if } \mu^\text{ON}(\rho_i, \rho_o) > \mu^\text{OFF}(\rho_i, \rho_o) \\
\text{VeSn OFF} & \text{otherwise (9)}
\end{cases}
\]

Decision Boundary

\[
\mu^\text{ON}(\rho_i, \rho_o) = \mu^\text{OFF}(\rho_i, \rho_o) \quad (10)
\]

(VSOFF) : \[a_1\rho_i^2 + b_1\rho_i\rho_o + c_1\rho_o^2 + d_1\rho_i + e_1\rho_o = 0\]  
(VSON) : \[a_2\rho_i^2 + b_2\rho_i\rho_o + c_2\rho_o^2 + d_2\rho_i + e_2\rho_o = 0\]

with \[a_1, a_2, b_1, b_2, c_1, c_2, d_1, d_2, e_1, e_2\]: parameters depending on traffic and data rate distributions in the sector.
VeSn activation controller calibration

Data from realistic network simulator

Data used to estimate parameters of the decision boundaries: classification problem.
VeSn activation controller performance

Activation controller

Traffic scenario

Activation decisions

User performance

Decision boundary for VS OFF
Decision boundary for VS ON

Traffic demand (Mbps)

Time (s)

Mean User Throughput (Mbps)

Time (s)

Always OFF
Always ON
AAS SON

Always OFF
Always ON
AAS SON
VeSn with bandwidth sharing

Description
- Total frequency bandwidth split between inner and outer sectors.
- Transmit power per Hz does not change.

Advantages
- No Inter-cell interference between inner and outer cells.
- Increased transmit power for each user compared to reuse one.
- Increased antenna gain for inner cell users.

Drawbacks
- Reduced capacity because there is no reuse.

**Problem:** Which sharing proportions for the frequency bandwidth?
Optimal bandwidth sharing

- Parameter: $\delta$ - proportion of bandwidth allocated to inner cell.

Criteria: Alpha-fair utility of all users throughputs

$$U_{\alpha}(\delta) = \begin{cases} 
\sum_{u \in U_i} \log (\delta \bar{R}_u) + \sum_{u \in U_o} \log ((1 - \delta) \bar{R}_u) & \alpha = 1 \\
\sum_{u \in U_i} \frac{(\delta \bar{R}_u)^{1 - \alpha}}{1 - \alpha} + \sum_{u \in U_o} \frac{(1 - \delta) \bar{R}_u)^{1 - \alpha}}{1 - \alpha} & \alpha \neq 1 
\end{cases}$$

- If $\alpha = 1$, optimal parameter in closed form:

$$\delta = \frac{N_i}{N_i + N_o} \quad (13)$$

with $N_i = |U_i|$ and $N_o = |U_o|$.

- For general $\alpha$:

$$\delta[k + 1] = \delta[k] + \epsilon \frac{\partial \hat{U}_{\alpha}(\delta[k])}{\partial \delta}$$
VeSn with bandwidth sharing performance

Network layout

Maximum loads

Mean User Throughput

Cell Edge throughput
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Virtual Sectorization (ViSn) description

- Evolution of vertical sectorization.
- Spatial separation of beam (both vertically and horizontally) using antenna arrays.
- Conservation of total power budget leading to resource allocation problems.
- Can be implemented with reuse one or frequency sharing (as in VeSn).
ViSn performance results

Traffic profile

Maximum loads

Mean User Throughput

Cell Edge throughput
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Introduction to multilevel beamforming

- Challenging topic in Massive MIMO community
- State of the art: channel matrix estimation and inversion
- Goal: low complexity processing for beamforming in TDD & FDD and low feedback in case of FDD.
- Our approach: Extend codebook idea to integrate coverage aspect \(\implies\) Beam planning.
Multilevel beamforming idea

- Design the codebook hierarchically.
- Find the best beam available by navigating iteratively through the codebook.
- Tree search (logarithmic complexity)

Example of beam hierarchy:

- $B_0(1)$ at Level 0
- $B_1(1)$ and $B_1(2)$ at Level 1
- $B_3(3)$ at Level 3
Beam planning for each type of environment

- Dense Urban
- Rural

Problem: automatic generation of beam codebook given basic cell information (size, antenna height, etc.). (future work)
Multilevel beamforming performance

Data rate function: $R = \min(R_{\text{max}}, \eta \log_2(1 + \text{SINR}))$
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SON model as control loops

\[ \theta_{n+1} = \theta_n + \epsilon(F(\theta_n) + M_n) \] (14)

where
- \( \theta \): parameters,
- \( F(\cdot) \): search directions,
- \( M_n \): noise.

Mean behavior described by the limiting Ordinary Differential Equation (ODE):
\[ \dot{\theta} = F(\theta) \] (15)
Stability and coordination

- Jacobian of $F(\theta)$ defined as $G_\theta = JF(\theta)$ where
  \begin{equation}
  G_\theta(i, j) = \frac{\partial F_i(\theta)}{\partial \theta_j}
  \end{equation}

- Rosen’s sufficient condition for stability:
  \begin{enumerate}
  \item Theorem
  \end{enumerate}
  If the matrix $G_\theta + G_\theta^T$ is negative definite for every $\theta$ in $\prod_{j=1}^N S_j$, then $\dot{\theta} = F(\theta)$ has a unique equilibrium point and it is asymptotically stable in $\prod_{j=1}^N S_j$.

- Local stability given by linearization: $F(\theta) = A\theta$ then $A^T + A$ negative definite is a sufficient condition.

- **Coordination idea**: Apply a coordination matrix $C$ (obtaining $\dot{\theta} = CF(\theta)$) such that $(CA)^T + CA$ is negative definite.
Coordination matrix computation

\[
\begin{align*}
\text{minimize} & \quad \| C + A^{-1}\|_F \\
\text{s.t.} & \quad (CA)^T + CA \prec 0; \quad C \in \mathcal{C}
\end{align*}
\]

where

- \( \| . \|_F \) is the Frobenius norm.
- \( \mathcal{C} \): the set of coordination matrices satisfying the system constraints.

\[
\dot{\theta}_i = F_i(\theta) \\
\dot{\theta}_i = \sum_j C_{i,j} F_j(\theta)
\]
## Use case description

<table>
<thead>
<tr>
<th>SON function</th>
<th>Parameters</th>
<th>KPIs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load balancing</td>
<td>Transmit pilot power $P_{pilot}$</td>
<td>Load of the cell $\rho$</td>
</tr>
<tr>
<td>Outage Probability minimization</td>
<td>Transmit data power $P_{TCH}$</td>
<td>Coverage probability of the cell $K$</td>
</tr>
<tr>
<td>Blocking Rate minimization</td>
<td>Admission threshold $AT$</td>
<td>Blocking rate of the cell $b$</td>
</tr>
</tbody>
</table>

![Hexagonal cellular network diagram](image)
Performance results

Loads

Coverage probabilities

- BS 1 without coordination
- BS 2 without coordination
- BS 3 without coordination
- BS 1 with coordination
- BS 2 with coordination
- BS 3 with coordination
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Conclusion

- SON algorithms for small cells
  - Load balancing (with constrained backhaul)
  - Alpha-fair Interference coordination

- SON algorithms for active antenna systems
  - VeSn feature activation
  - Alpha-fair bandwidth sharing for VeSn and ViSn
  - Beam selection algorithm for multilevel beamforming

- Which is the best option?
  - With low cost backhaul or for non-line-of-sight coverage areas: Small Cells
  - Others: Active Antenna Systems (multilevel beamforming)

- Systematic SON coordination framework
  - Tested for load balancing with interference coordination in small cells scenario.
Perspectives

- Extend algorithms to other use cases: D2D, energy saving, etc.
- Backhaul-aware SON functions
- Multi-armed bandits for AAS features activation
- Beam planning automation and application to more use cases
- Which $\alpha$ in $\alpha$-fair utilities?
- Coordination of highly non-linear systems of SON functions
Thank you!
Questions are welcome.