PhD Thesis Defense on

Optimization and Self-optimization for LTE Networks

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Context

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

Example: Orange France

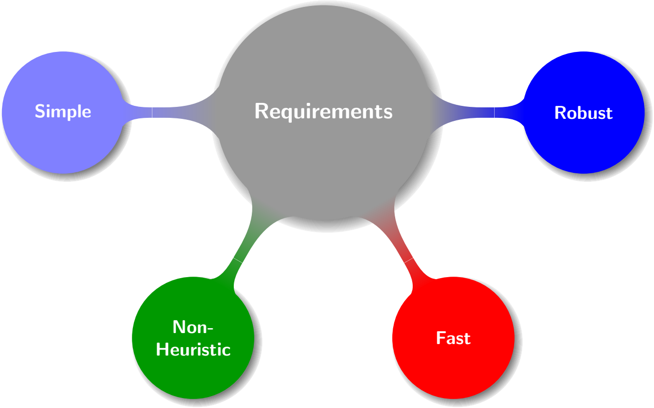
- Sites: 19000+ 2G, 19000+ 3G, 7000+ 4G
- Frequency bands: 700 MHz, 800 MHz, 900 MHz, 1.8 GHz, 2.1 GHz and 2.6 GHz
- Indoor femto-cells

Challenge: Optimize resource utilization and Control the OPEX.

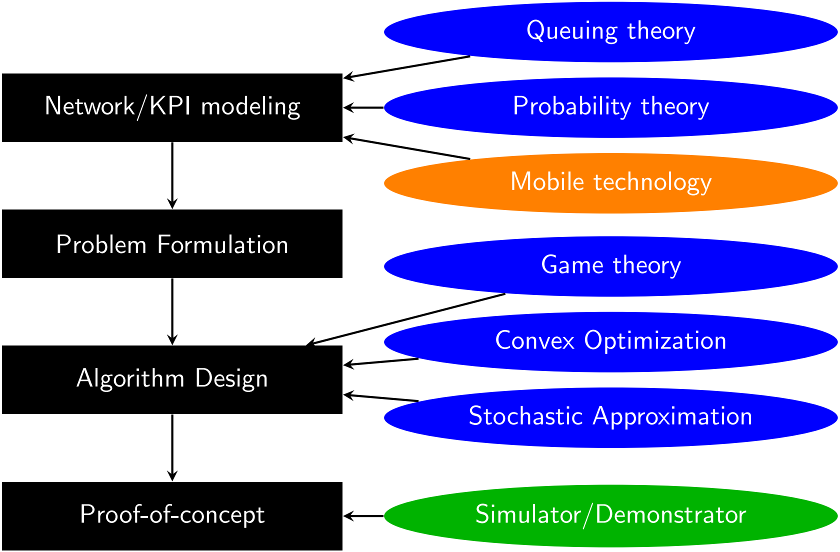
Enabler: **Automation with Self-Organizing Network (SON)** for self-configuration, self-optimization and self-healing.

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

Queuing theory

Probability theory

Mobile technology

Game theory

Convex Optimization

Stochastic Approximation

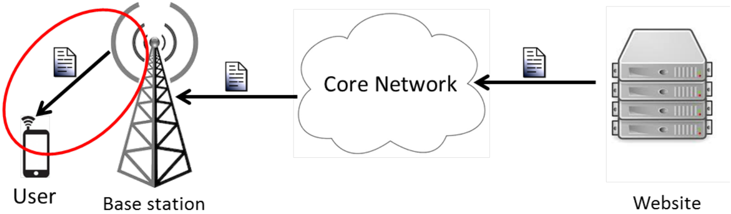
Simulator/Demonstrator

Overview

Overview

1. Introduction
2. **Background**
3. Heterogeneous Networks
4. Active Antenna Systems
5. SON Coordination
6. Conclusion & Perspectives

Flow level network model



- Base station modeled as M/G/1 PS queue
- User's data rate $R(r) = min(R_{\max}, \eta \log_2(1 + SINR(r)))$
- 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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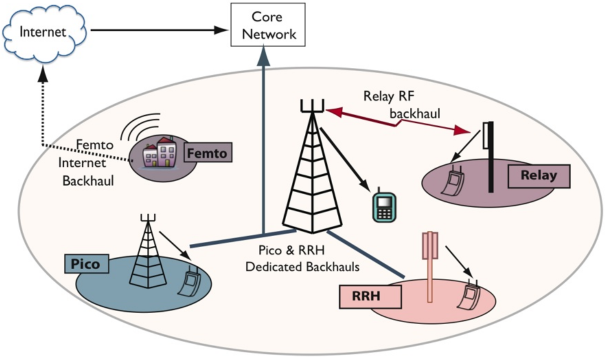
Introduction

- 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:

$$s_u^* = \text{argmax}_s R_{u,s}(1-\rho_s)^\alpha \tag{1}$$

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

$\Longrightarrow$ Minimizes $\sum_s \frac{(1-\rho_s)^{1-\alpha}}{\alpha-1}$.

R. Combes et al., IEEE INFOCOM 2012:

$$P_s(k+1) = P_s(k)(1+\epsilon_k(\rho_1(k)-\rho_s(k))) \tag{2}$$

with P (pilot power).

$\Longrightarrow$ Minimizes $\max_s \rho_s$

End-to-end load model

Classical BS load definition:

$$\rho = \min\left(1, \int_A \frac{\lambda(r)\mathbb{E}(\sigma)}{R(r)} dr\right), \tag{3}$$

End-to-end load definition

$$\rho_g = \min\left(1, \int_A \frac{\lambda(r)\mathbb{E}(\sigma)}{\min(C_{BH}, R(r))} dr\right). \tag{4}$$

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).

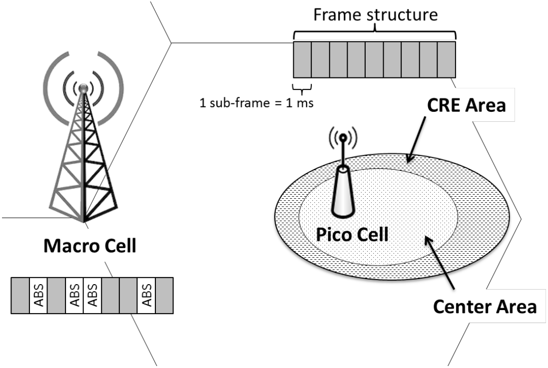


Illustration of Almost Blank Sub-Frames in a HetNet

ABS-based interference coordination (eICIC)

Opimization Problem: trade-off between small cells' users SINR and macro cells' capacity.

θ: 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: α-fair utility of users' throughput

$$U_\alpha(\theta) = \begin{cases} \sum_{\text{all users}} \log R_u & \text{if } \alpha = 1 \\ \sum_{\text{all users}} \frac{R_u^{1-\alpha}}{1-\alpha} & \text{otherwise} \end{cases} \tag{5}$$

Lower-bound PF utility for low complexity algorithm

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

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

Lower bound utility:

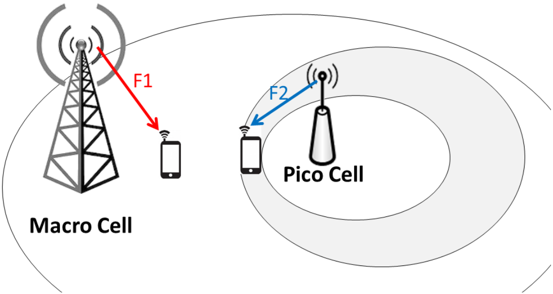
$$\begin{aligned} U_{\text{PF\_approx}}(\theta) = \sum_{m=1}^{M} \sum_{u \in m} \log((1-\theta)\bar{R}_{u,m}) &+ \sum_{u \in p} \frac{1}{2} \log(2(1-\theta)\bar{R}_{u,p}^{\text{no ABS}}) \\ &+ \sum_{u \in p} \frac{1}{2} \log(2\theta \bar{R}_{u,p}^{\text{ABS}}) \end{aligned} \quad (7)$$

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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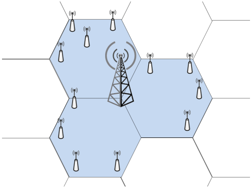
Numerical results - Scenario

Network parameters	
Number of macro BSs	3
Number of small BSs	12
Number of interfering macros	6 × 3 sectors
Macro Cell layout	hexagonal trisector
Small Cell layout	omni
Intersite distance	500 m
Bandwidth	10MHz
Scheduling	Round-Robin
Channel characteristics	
Thermal noise	-174 dBm/Hz
Macro Path loss (d in km)	$128.1 + 37.6 \log_{10}(d)$ dB
Small cell Path loss (d in km)	$140.7 + 36.7 \log_{10}(d)$ dB
Algorithms Parameters	
SON update frequency	**every event**
Step size of ABSrO	10^{-4}
Step size of FSO	5.10^{-5}



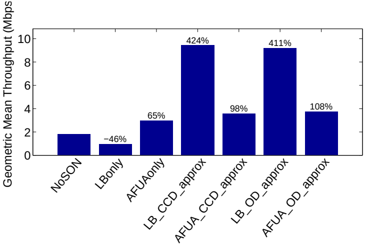
Network layout scenario

Numerical results - Scenario cont'd.

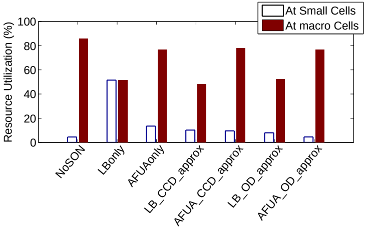
Traffic spatial distribution	uniform
λ	14 users/s/km^2
λ_h	6 users/s/km^2
Service type	FTP
Average file size	6 Mbits

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.

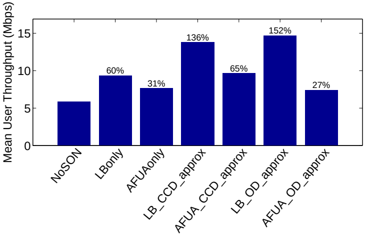
Numerical results - Performance



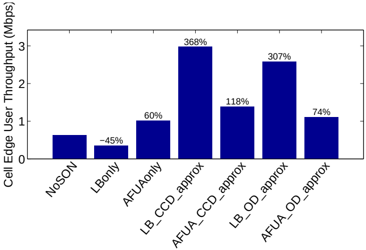
α-fair utility ($\alpha = 1$)



Loads

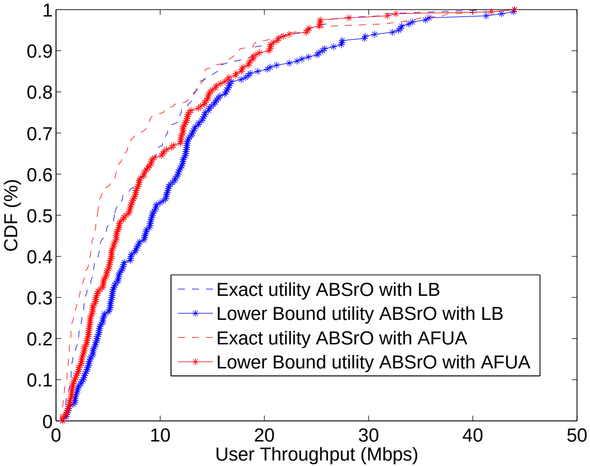


Mean User Throughput



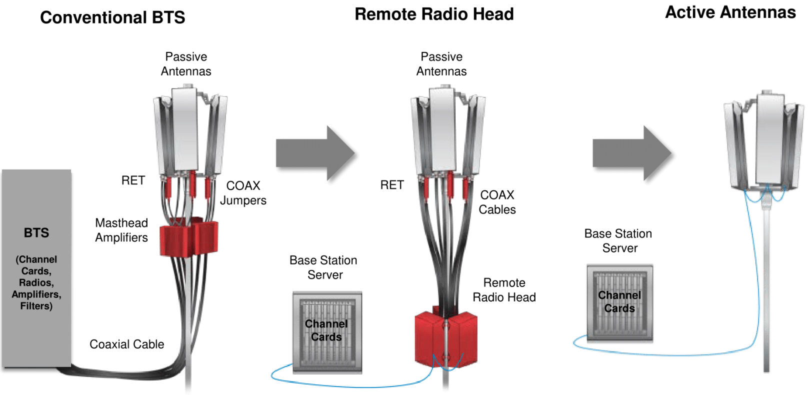
Cell Edge throughput

Exact vs Approximate algorithms



Overview

Introduction



Base Station architecture evolution

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   - Virtual Sectorization
   - Multilevel Beamforming
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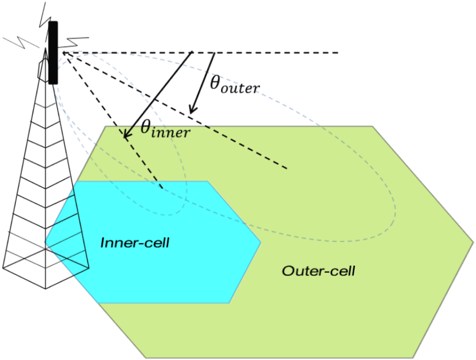
Vertical Sectorization (VeSn) description

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

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

Decision Boundary

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

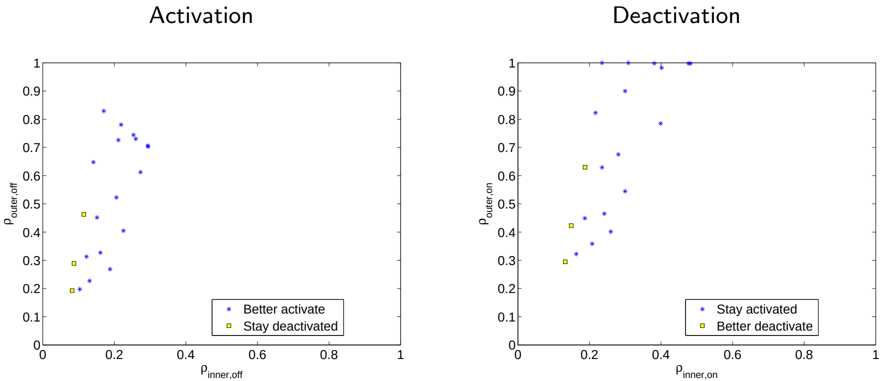
$$(\textbf{VSOFF}) : a_1\rho_i^2 + b_1\rho_i\rho_o + c_1\rho_o^2 + d_1\rho_i + e_1\rho_o = 0 \quad (11)$$

$$(\textbf{VSON}) : a_2\rho_i^2 + b_2\rho_i\rho_o + c_2\rho_o^2 + d_2\rho_i + e_2\rho_o = 0 \quad (12)$$

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.

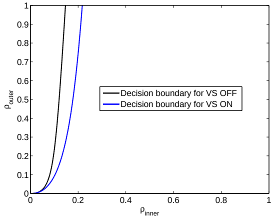
VeSn activation controller calibration

Data from realistic network simulator

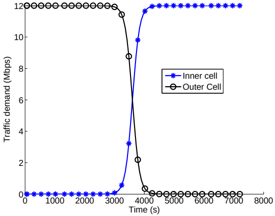


Data used to estimate parameters of the decision boundaries: classification problem.

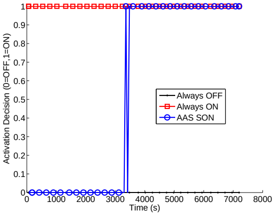
VeSn activation controller performance



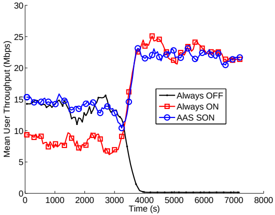
Activation controller



Traffic scenario



Activation decisions



User performance

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: δ - proportion of bandwidth allocated to inner cell.

Criteria: Alpha-fair utility of all users throughputs

$$U_\alpha(\delta) = \begin{cases} \sum_{u \in \mathcal{U}_i} \log\left(\delta \bar{R}_u\right) + \sum_{u \in \mathcal{U}_o} \log\left((1-\delta)\bar{R}_u\right) & \alpha = 1 \\ \sum_{u \in \mathcal{U}_i} \frac{\left(\delta \bar{R}_u\right)^{1-\alpha}}{1-\alpha} + \sum_{u \in \mathcal{U}_o} \frac{\left((1-\delta)\bar{R}_u\right)^{1-\alpha}}{1-\alpha} & \alpha \neq 1 \end{cases}$$

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

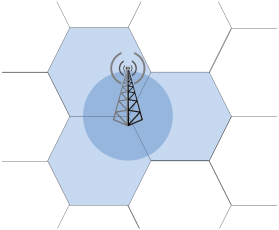
$$\delta = \frac{N_i}{N_i + N_o} \qquad (13)$$

with $N_i = |\mathcal{U}_i|$ and $N_o = |\mathcal{U}_o|$.

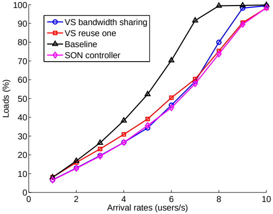
- For general α:

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

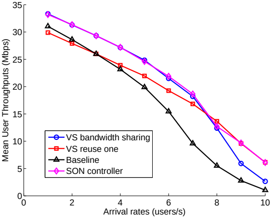
VeSn with bandwidth sharing performance



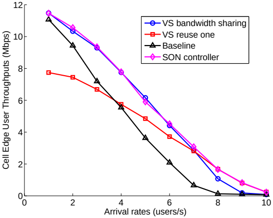
Network layout



Maximum loads



Mean User Throughput

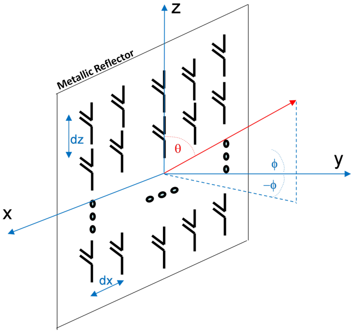


Cell Edge throughput

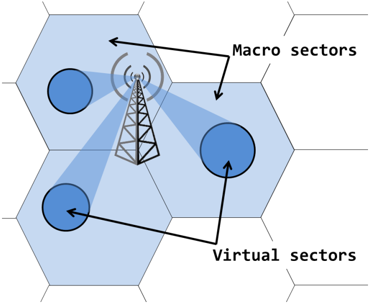
Overview

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).

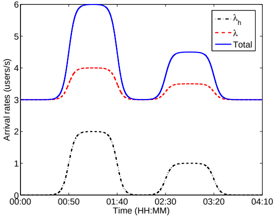


Antenna Array

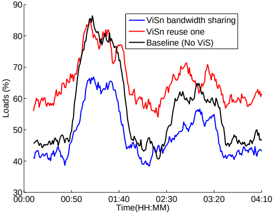


Network layout

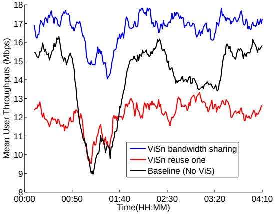
ViSn performance results



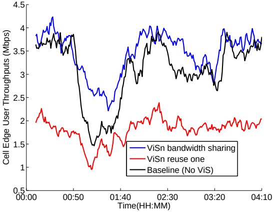
Traffic profile



Maximum loads



Mean User Throughput



Cell Edge throughput

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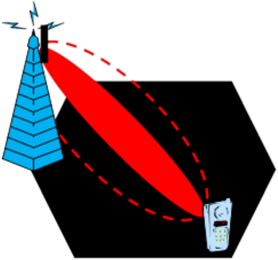
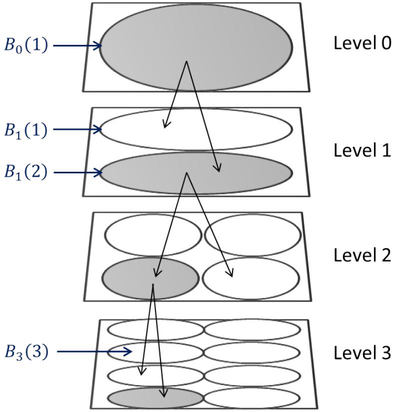
Introduction to multilevel beamforming

- 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 $\Longrightarrow$ Beam planning.



Multilevel beamforming idea

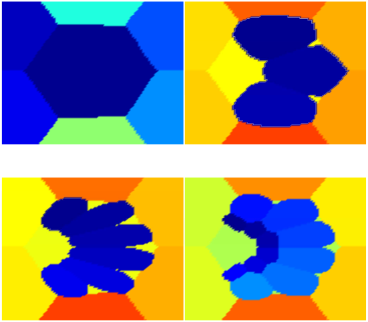


Example of beam hierarchy

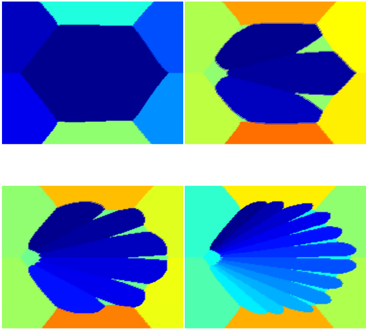
- Design the codebook hierarchically.
- Find the best beam available by navigating iteratively through the codebook.
- Tree search (logarithmic complexity)

Beam planning for each type of environment

Dense Urban

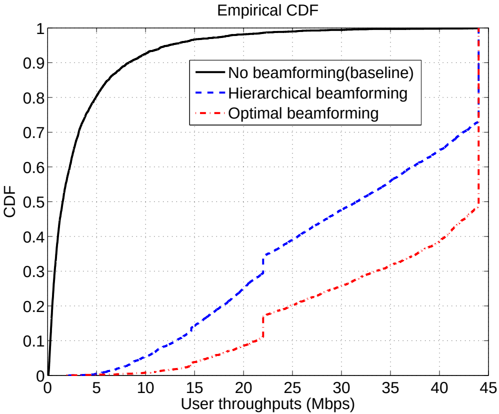


Rural



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

Multilevel beamforming performance

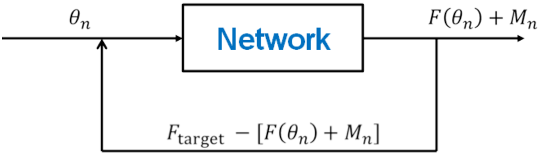


User throughput CDFs comparison

Data rate function: $R = \min(R_{max}, \eta \log_2(1 + SINR))$

Overview

SON model as control loops



- Generic formulation of stochastic approximation algorithms

$$\theta_{n+1} = \theta_n + \epsilon(F(\theta_n) + M_n) \tag{14}$$

  where
  - θ: parameters,
  - $F(\cdot)$: search directions,
  - M_n: noise.
- Mean behavior described by the limiting Ordinary Differential Equation (ODE):

$$\dot{\theta} = F(\theta) \tag{15}$$

Stability and coordination

- Jacobian of $F(\theta)$ defined as $G_\theta = JF(\theta)$ where

$$G_\theta(i,j) = \frac{\partial F_i(\theta)}{\partial \theta_j} \tag{16}$$

- Rosen's sufficient condition for stability:

Theorem

If the matrix $G_\theta + G_\theta^T$ is negative definite for every θ 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

$$\begin{aligned} &minimize \; \|C + A^{-1}\|_F \\ &s.t. \; (CA)^T + CA \prec 0; \, C \in \mathcal{C} \end{aligned} \tag{17}$$

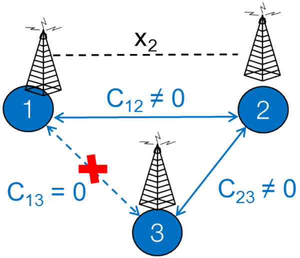
where

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

$$\dot{\theta}_i = F_i(\theta)$$

$$\Downarrow$$

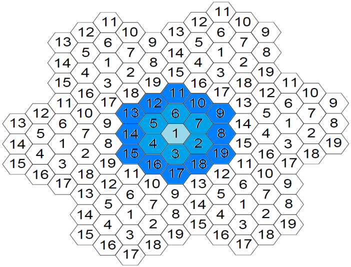
$$\dot{\theta}_i = \sum_j C_{i,j} F_j(\theta)$$



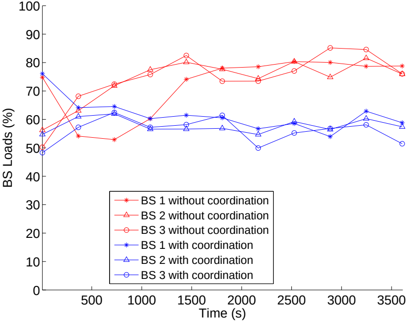
System constraints

Use case description

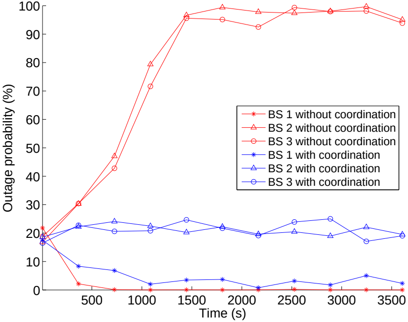
SON function	Parameters	KPIs
Load balancing	Transmit pilot power P_{pilot}	Load of the cell ρ
Outage Probability minimization	Transmit data power P_{TCH}	Coverage probability of the cell K
Blocking Rate minimization	Admission threshold AT	Blocking rate of the cell b



Performance results



Loads



Coverage probabilities

Overview

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 α in α-fair utilities?
- Coordination of highly non-linear systems of SON functions

Thank you!

Questions are welcome.