Autonomous Self-deployment of Wireless Access Networks in an Airport Environment*

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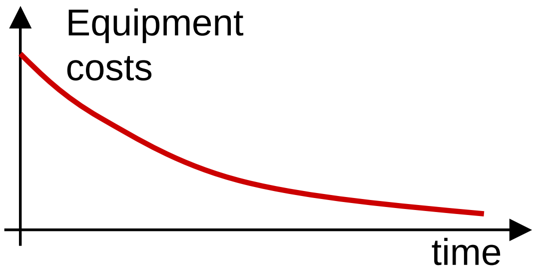
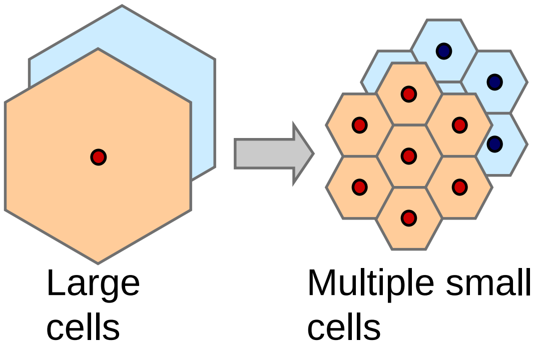
Introduction

Why self-deployment & self-configuration? (Civilian use)

Emerging trends for wireless access networks:

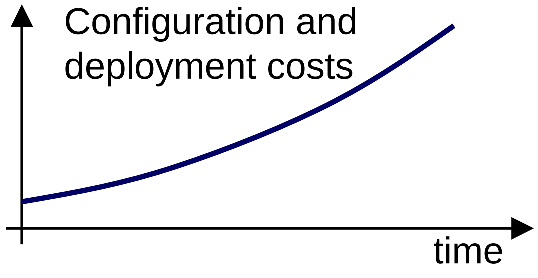
- Reduction in equipment costs.
- Reduction in cell size to increase capacity. This is accompanied with an increase of the total number of cells.
- Additional complexity as interoperability between heterogeneous systems (e.g. different access technologies) becomes economically critical.





Implications:

- Increase of the relative costs for deployment and configuration.
- Self-configuration helps to control the costs.
- Strong need for additional novel concept of self-deploying network.



Introduction

Why self-deployment & self-configuration? (Military use)

Requirements for tactical wireless access networks:

- Fast and autonomous deployment of high-speed data and voice networks in unknown terrain.
- High flexibility to react to changes in traffic and user locations.
- High robustness of the network against failing nodes.
- Coverage required in high-risk areas
  ⇒ unmanned deployment preferred.

Implications:

- De-centralised control required for robustness.
- Autonomous self-deployment allows network coverage anywhere and anytime.
- Self-configuration adapts the network to changes in the environment.
- Self-recovery to deal with failing nodes.

Introduction

Self-deployment process in future networks

1. Network identifies the need for changes

- The network measures its current performance.
- The network identifies the need for new base stations and their optimal positions.
- The network identifies the optimal positions for all deployed base stations in the network.
- The network identifies the optimal configurations of all deployed base stations.

2. Assess proposed changes

- Assess (manual/autonomous) if the expected gain resulting from the proposed changes is higher than the associated costs.

3. Deployment & configuration

- Manual or autonomous deployment of new base stations at the requested locations, if economically viable.
- Manual or autonomous re-deployment of currently deployed base stations, if economically viable.
- Manual or autonomous configuration of the base station, if economically viable.

Problem formulation

- Investigate the influence of a self-deploying network with mobile base stations on the required number of base stations in an airport environment with highly dynamic user demand.
- Solve the problem of cell site selection and configuration based on the environment, the user demand, and the user positions (statistics or current values).

Difficulty:

- Finding the optimal position is an NP-hard optimisation problem.
- Most of the required system knowledge is unknown.
- The optimal positions change constantly due to changes in user demand, user positions, and base station positions.

Requirements:

- Radically distributed processing that results in self-organising behaviour.
- Find globally near-optimum solutions with limited local system knowledge.
- No direct communications between base-stations to allow:
  - interoperability with unknown systems
  - technology independent operation

Approach

The use of stigmergy for BS information exchange

Communication between base stations:

- Direct communication is not always possible, but some communication (indirect) is necessary among the peer group.
- Use indirect communication (universal language, technology independent) through modification of the network environment.
- This indirect communication is known in biology as stigmergy and is used by social insects for coordination and optimisation of tasks.
  (e.g. ants use decaying pheromone trails to find shortest paths)
- The connections of the mobiles define the network environment. They depend on the channels and the load balancing technique used.
  (e.g. strongest received pilot signal)
- The connections provide information on the own cell, but also on other cells
  (e.g. coverage, demand, …)

Questions:

- Does the approach of indirect communication provide sufficient information for efficient self-deployment?
- Does this approach provide the scalability, flexibility & robustness required for future generation networks?

Approach

Self-deployment

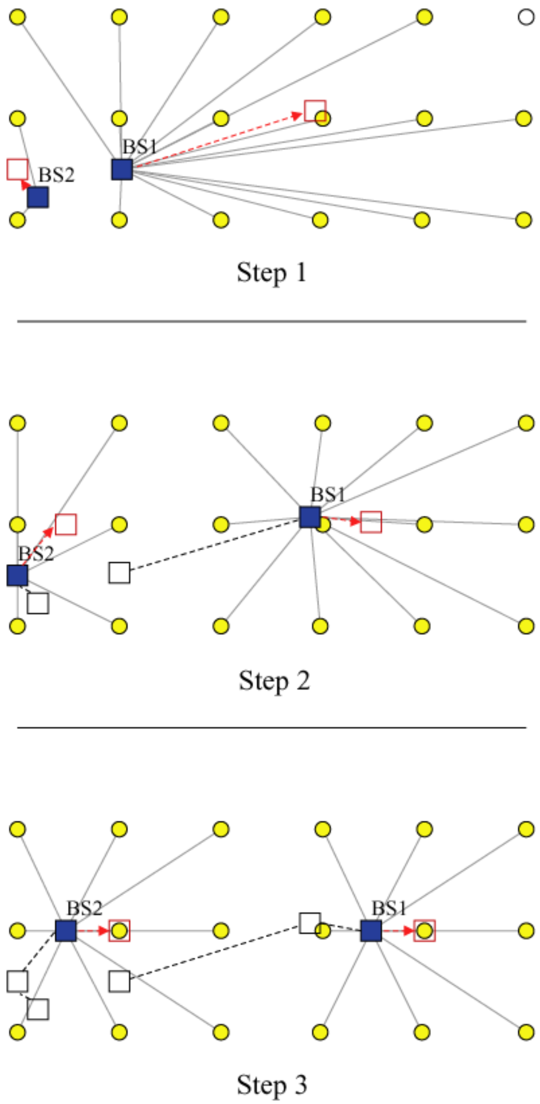
Start conditions:

- All mobiles connect to base stations (BS) dependent on the connection rule. This defines the current network environment.

Self-deployment process:

1. In each step, the optimal positions for all BS are calculated, based on the current network environment.
2. All BS move to the predicted optimum position.
3. The new BS positions trigger a change in the connections to the mobiles. This modification of the network environment is an indirect way of communication between BS.
   (provides information on coverage, position, …)

– Base stations are shown as solid blue squares
– Mobiles are shown as yellow circles with a line to the connected base station
– The optimal base station positions are shown as red squares

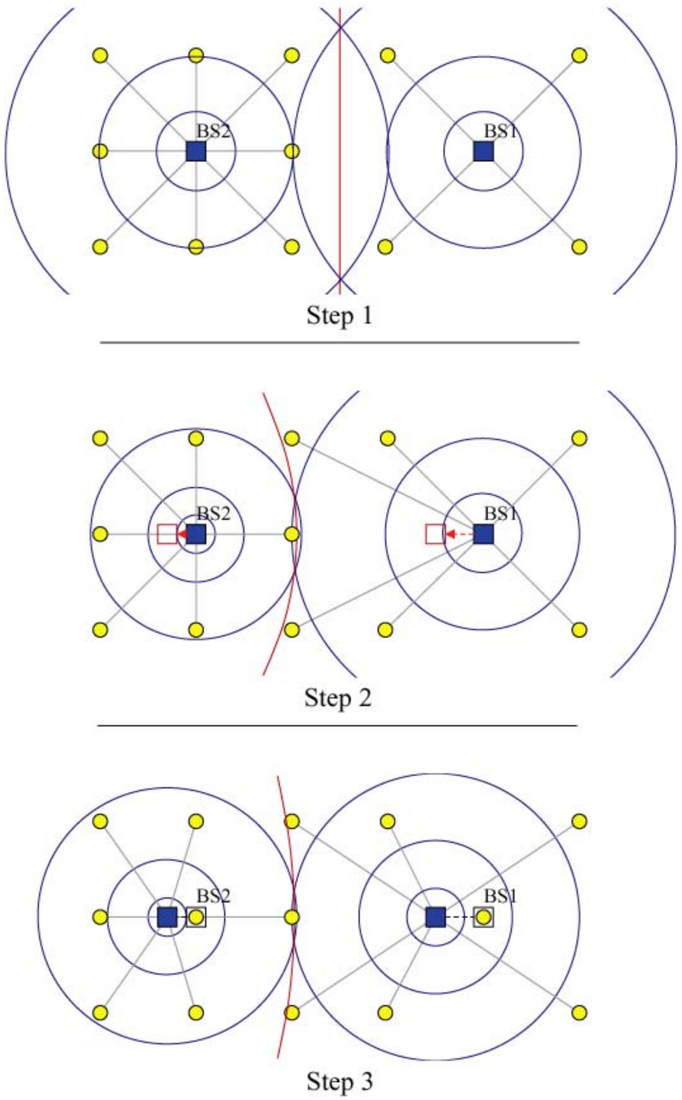


Approach

Load balancing using base station re-positioning

Start conditions:

- All mobiles connect to base stations (BS) dependent on the connection rule.
- New optimisation constraint: target resource usage



Load balancing process (via pilot power):

1. In each step, the optimal pilot powers for all BS are calculated, based on the current resource usage and network environment.
2. All BS adapt their pilot power to the predicted optimum value.
3. The new BS pilot powers results in a change of the network environment (connections) and trigger a re-positioning process.

– The blue contour plots illustrate the received pilot power.
– The red lines illustrate the cell boundaries.

Optimal positioning

Definition

- Important factors for positioning: optimum use of radio resources, but also costs, environment, regulations,…

Optimal positioning rules:

Rule 1: The optimal position for an individual base station allows it to sustain all requested connections with the minimum possible transmit power.

Rule 2: The optimal positions of all base stations in a network allow the network to sustain all requested connections with the minimum possible transmit power.

- The above rules are subject to constrains (other important factors).
- Optimum position of a single base station of Rule 1 is not necessarily equivalent to the position of the same base station in a globally optimised network based on Rule 2.
- To satisfy minimum possible transmit power, the network has to operate at the channel capacity limit (or close to).

Optimal positioning

Based on channel capacity

- With recent advances in coding theory (LDPC codes/turbo codes) communication close to the capacity limit became possible.
- Use Shannon capacity limit as optimisation point:

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

C = capacity
B = bandwidth
S = received signal power
N = received noise power

In terms of Tx-power S_{tx}, the capacity equation can be written as:

$$C = B\log_2\left(1+\frac{S_{\text{tx}}}{NL}\right)$$

S_{tx} = transmitted signal power
L = channel loss

Then, the required minimum transmit power per link is:

$$S_{\text{tx}} = NL\left(2^{C/B}-1\right)$$

Note: assuming operation at q dB from the capacity limit, C may be replaced by: $C \times 10^{(q/10)}$

Optimal positioning

Globally optimum solution

Optimisation (Rule 2):

- The total required transmit power S_{net} in the system can be written as

$$S_{\text{net}}(\mathbf{x}_{\text{BS}}, \mathbf{y}_{\text{BS}}) = \sum_{m=1}^{M} \sum_{k=1}^{K} S_{\text{tx},m}^{(k)}(x_m, y_m)$$

M = number of base stations
K = number of connections

- Find set of positions $(\mathbf{x}_{\text{BS}}, \mathbf{y}_{\text{BS}})$ which minimises $S_{\text{net}}(\mathbf{x}_{\text{BS}}, \mathbf{y}_{\text{BS}})$:

$$(\mathbf{x}_{\text{opt}}, \mathbf{y}_{\text{opt}}) = \underset{(\mathbf{x}_{\text{BS}}, \mathbf{y}_{\text{BS}})}{\arg\min} \left\{ S_{\text{net}}(\mathbf{x}_{\text{BS}}, \mathbf{y}_{\text{BS}}) \right\}$$

Note: $S_{\text{net}}(\mathbf{x}_{\text{BS}}, \mathbf{y}_{\text{BS}})$ must be evaluated for all possible combinations of BS positions $(\mathbf{x}_{\text{BS}}, \mathbf{y}_{\text{BS}})$

Characteristics:

- Centralised control
- Complete system knowledge is required, but in reality not all parameters are known.
- Prohibitive computational complexity (NP-hard problem)

Example: M=16 base-stations, 10×10 km area, resolution 1m ($N = 10^8$ position options)
search states: $N^M = 10^{128}$
computation time: $3{,}17 \times 10^{117}$ years (1ms per cycle)

Optimal positioning

Locally optimum solution

Optimisation (Rule 1):

- The required transmit power S_{BS} at each base station be written as

$$S_{\mathrm{BS}}(x,y)=\sum_{k=1}^{K}S_{\mathrm{tx}}^{(k)}(x,y)$$

- Find BS position (x, y) which minimises $S_{\mathrm{BS}}(x, y)$:

$$(x_{\mathrm{opt}},y_{\mathrm{opt}})=\arg\min_{(x,y)}\left\{S_{\mathrm{BS}}(x,y)\right\}$$

Characteristics:

- De-centralised control
- Only local system knowledge is required, but in reality not even all local parameters are known (e.g. channels & interference at new positions).
- Manageable computational complexity

Positioning with limited system knowledge

Solution for unknown channels & interference

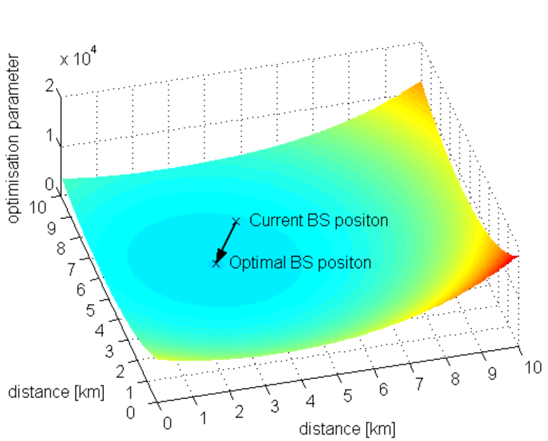
Simplified optimisation (Rule 1):

- new optimisation criterion:

$$\varphi(x,y) = L_{\mathrm{p}}\left(2^{C/B} - 1\right)$$

- Find BS position (x, y) which minimises $\varphi(x, y)$:

$$(x_{\mathrm{opt}}, y_{\mathrm{opt}}) = \arg\min_{(x,y)} \left\{ \sum_{k=1}^{K} \varphi^{(k)}(x,y) \right\}$$



Optimisation surface

Characteristics:

- De-centralised control
- Only known local system knowledge is required.
- Manageable computational complexity
- Simple optimisation surface ⇨ solution: conjugate gradient method

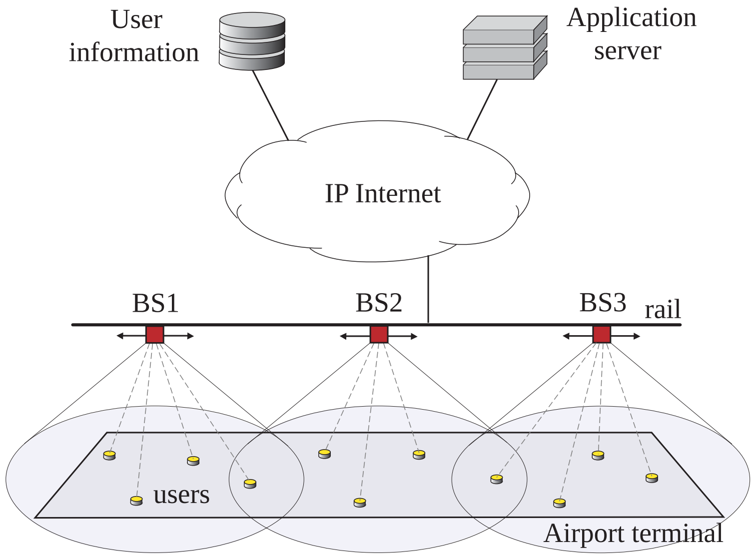
Question: Does local optimisation + stigmergy result in globally satisfactory behaviour for self-deployment?

Self-deployment in an Airport Environment

Test scenario: Athens International Airport

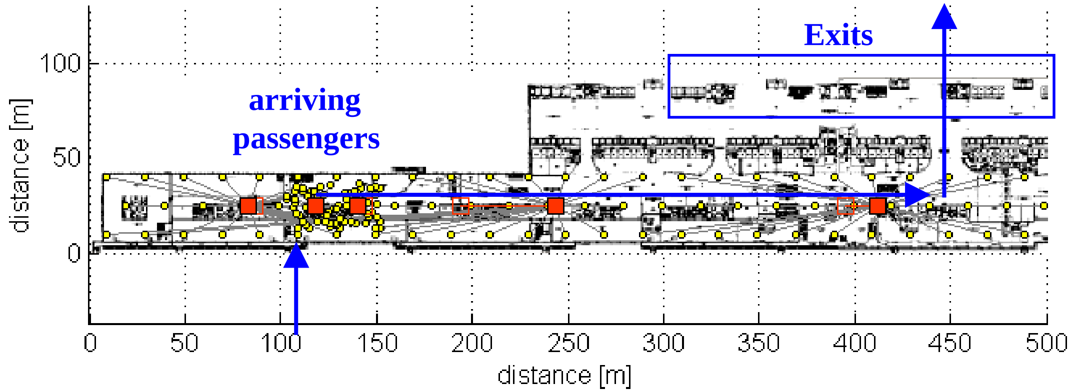
Deployment:

- Mobile base stations are deployed on a rail at the ceiling of the terminal building



Simulated steps:

1. Uniform user distribution along the gates
2. A plane arrives and the passengers create a user hot-spot.
3. The arriving passengers move along the corridor to the airport exits
4. Arriving at the exits, the users Leave the airport (hot-spot disappears)



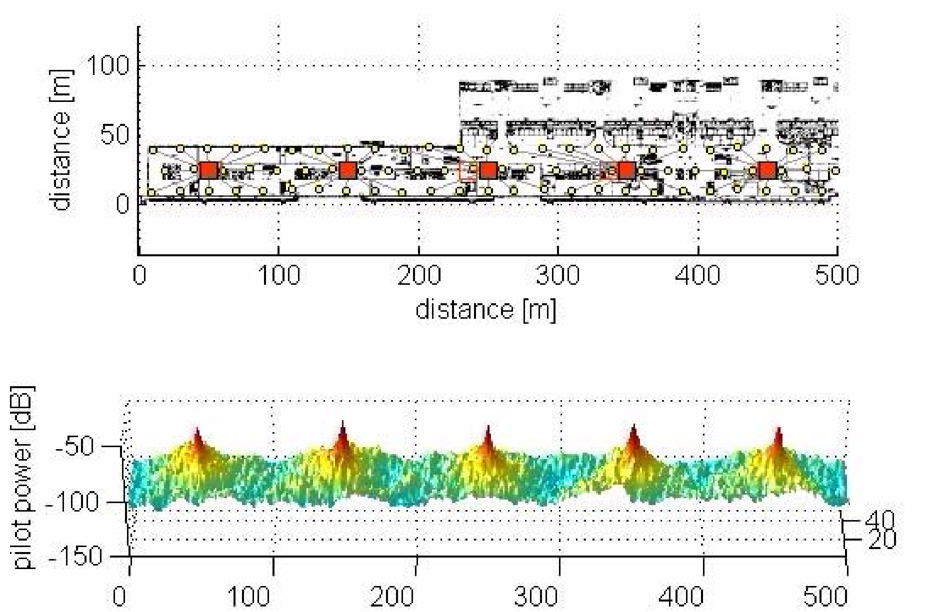
Self-deployment in an Airport Environment

Simulation results

Autonomous self-deployment

- 5 mobile self-deploying base stations are required to provide service within the transmit power budget of 200 mW

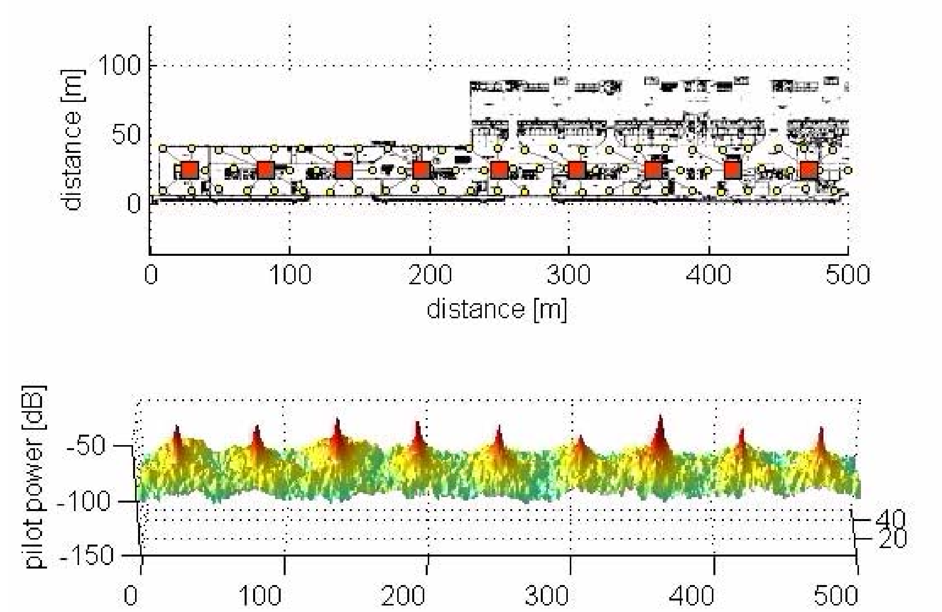
Click on image to start video



Reference: Fixed base station positions

- 9 base stations are required to provide the same performance as the self-deploying network.

Click on image to start video

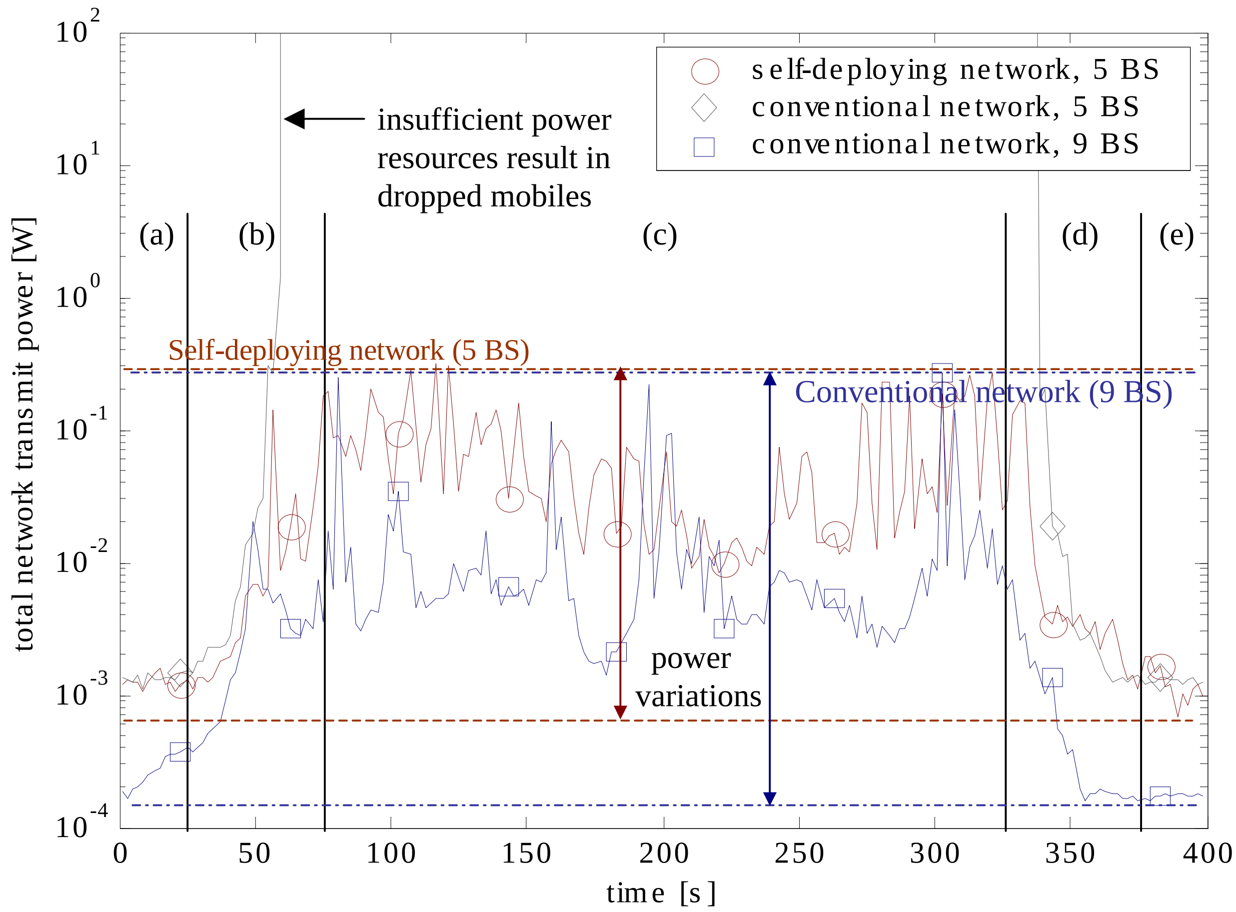


Self-deployment in an Airport Environment

Performance comparison

Results:

- A self-deploying network with 5 base stations offers equivalent performance as a static network with 9 base stations in the investigated scenario.
- A static network with 5 base stations is not able to deal with the user demand in the investigated scenario.
- Self-deployment reduces variations of the required network transmit power.



Summary & Conclusions

- Distributed algorithms for self-deployment were proposed based on the channel capacity that can provide the scalability, flexibility & robustness required for future generation networks.
- Self-deploying networks can outperform conventional networks with fixed positions since they can adapt to:
  - user demand
  - user locations
  - environment
  - base station failure
- Self-deployment with mobile base stations results in a significant reduction of the required base stations in dynamic environments with changing user demand and user locations.