Technische Universität München
Lehrstuhl für Kommunikationsnetze
Prof. Dr.-Ing. J. Eberspächer

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„Cooperation and Self-Organization in
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Decentralized Interference Coordination for LTE

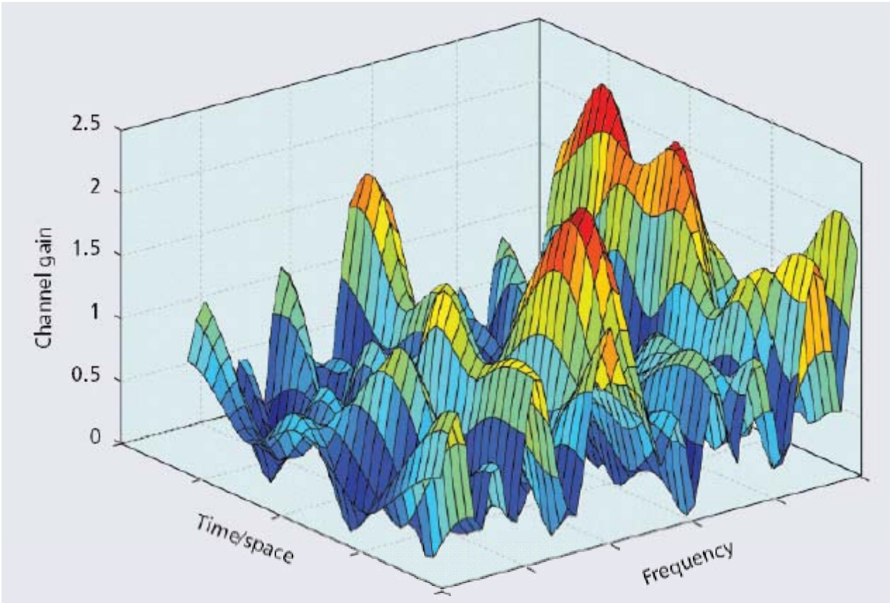
Christian Hartmann
hartmann@tum.de
Jan Ellenbeck
jan.ellenbeck@tum.de

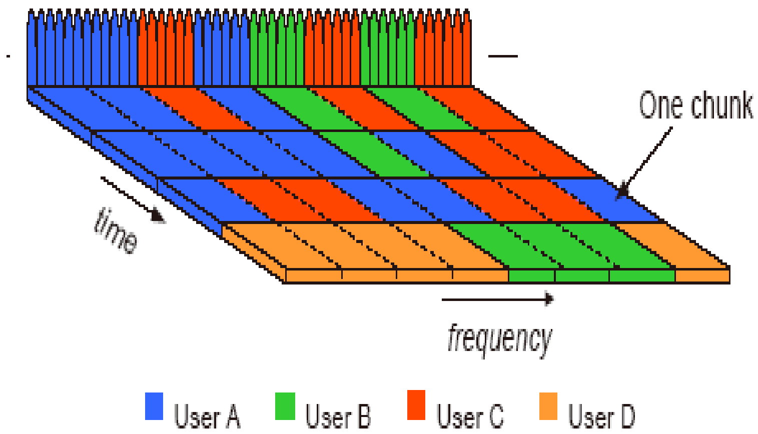
Agenda

- Motivation
- The Interference Avoidance Game
  - Convergence issues
  - Price of Anarchy
- Interference Coordination in LTE
  - Autonomous Scheme
  - Inter-Cell Signaling based Scheme
- Conclusions

LTE Resources

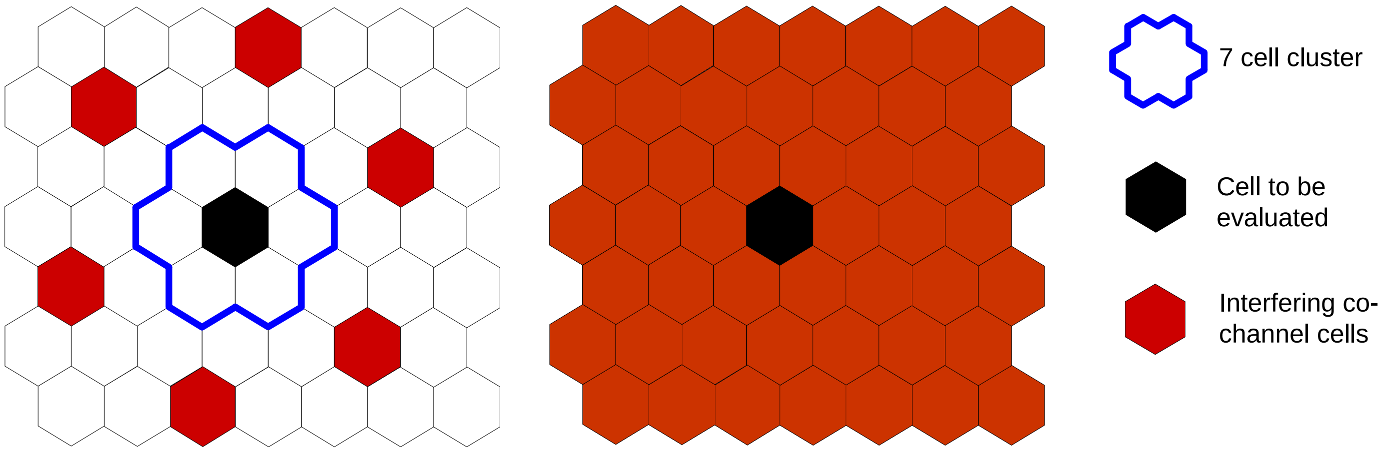
- Resource units: frequency-carrier-group per timeslot
- SINR-adaptive link adaptation and fast scheduling
- Main challenge (concerning throughput): inter-cell interference





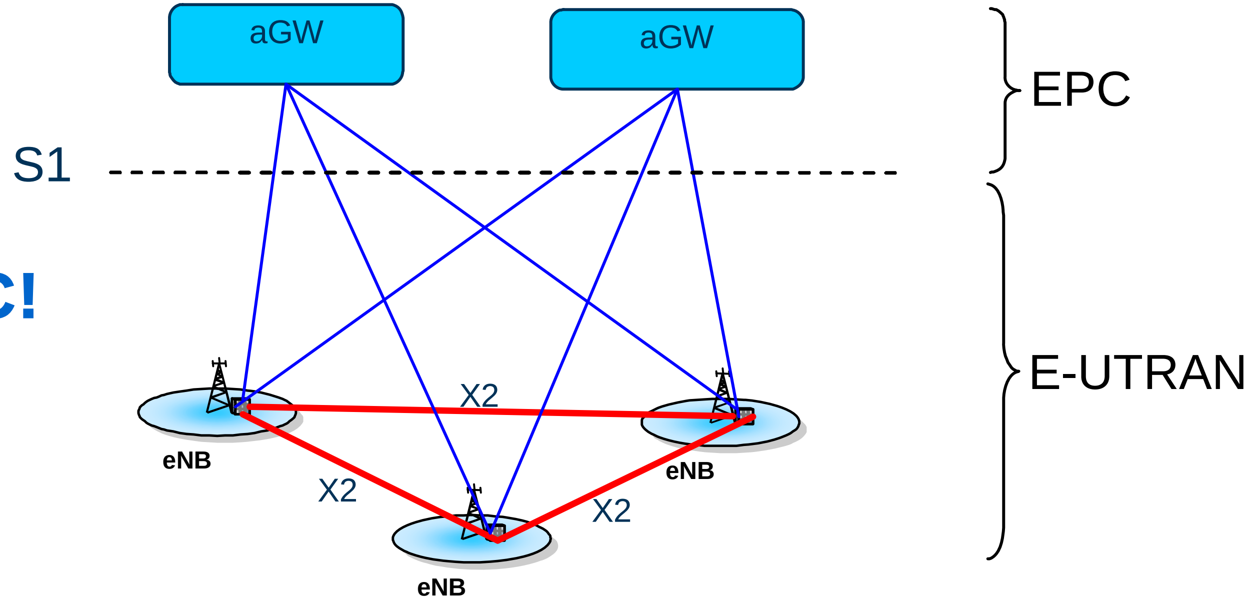
Inter-Cell Interference

- Reuse of one:
  - High number of resources per cell
  - Low SINR, low throughput per resource unit
- Reuse of seven or three:
  - Lower number of resources per cell
  - Higher SINR, higher throughput per resource unit



Which is best? It depends! So, do it adaptively.

LTE System Architecture



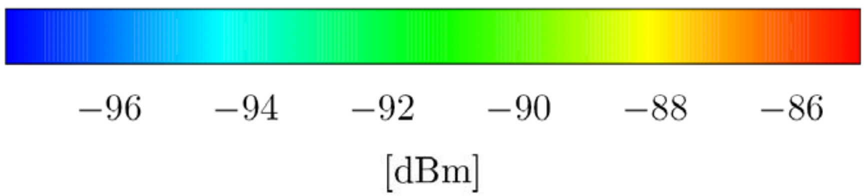
No RNC!

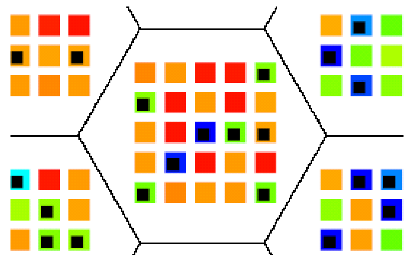
EPC:	Evolved Packet Core (Network)
aGW:	Access Gateway
E-UTRAN:	Evolved UTRAN (Universal Terrestrial Radio Access Network)
eNB (eNodeB):	Base Station of the E-UTRAN

No central control units! So, do it distributed.

Decentralized Interference Coordination – Idea

- In each cell measure inter-cell interference on each resource block (PRB)
- Allocate low interference resource subset to use for (fast) scheduling of users in each cell
- If resources are assigned by cells locally:
  - No central coordination necessary
  - Allows fast decision
  - Solely based on local information
  - Number of resources used per cell could be dynamically adjusted
- But will it work, will it be stable?
  - Each cell‘s allocation decision depends on the allocation decisions of its neighbors





Issues and Approach

Issues

- How do the cells choose their subset of resources?
  - utility function to evaluate allocation
- Do stable states exist?
- How could it be reached?
  - timing of decisions (simultaneously?)
- How far is the result from the global optimum?

Game Theoretical Modeling

⇨ Game model including utility function

⇨ Show existence of Nash Equilibrium

⇨ Learning in Games

(adjustment dynamics)

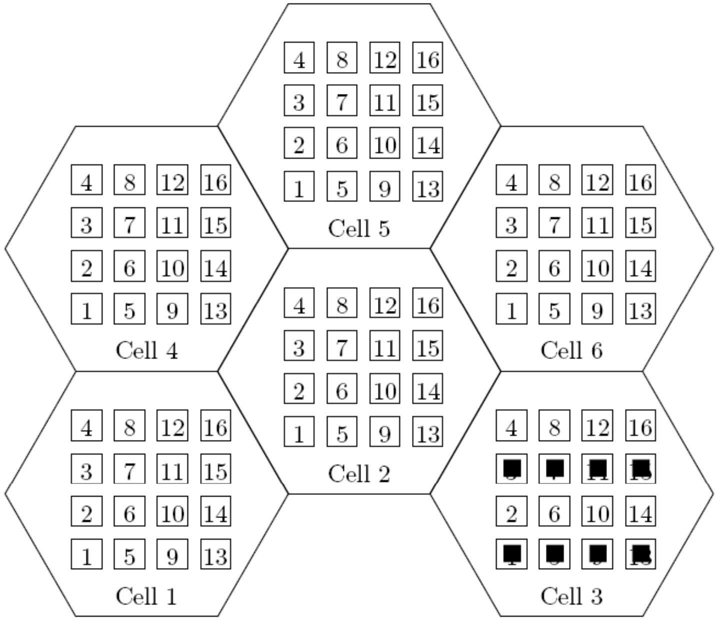
⇨ Determine *price of anarchy*

Normal Form Game in Non-Cooperative Game Theory

- Notation of Normal Form Game: $\Gamma = (N, (X_i)_{i \in N}, (U_i)_{i \in N})$
- Decision situations with *n* decision makers (players) $N = \{1, 2, \ldots, n\}$
  here: cells / base stations are decision makers = players
- Players are assumed to be rational and behave selfishly, aiming at maximizing their own utility U_i
- A decision $x_i \in X_i$ is some action or move by a player i
- An action profile $(x_1, x_2, \cdots, x_n)$ describes the action x_i chosen by each player in each round of the game. Also called the outcome of the game.
- Notation: $x_{-i} = (x_1, x_2, \cdots, x_{i-1}, x_{i+1}, \cdots, x_n)$ denotes the actions chosen by all players except player i.
- Utility functions $U_i(x_i, x_{-i})$ depend on own move x_i and on the moves $x_{-i} = (x_1, x_2, \cdots, x_{i-1}, x_{i+1}, \cdots, x_n)$ by all other players

⇨ **strategic interdependence**

System Model



Modeling assumptions:

- 1,…,n cells (players)
- Each allocates exactly D_i out of m resources
- A resource utilization in cell i causes interference in cell j
- Interference impact $h_{i,j}$ depends on geometric distance between cell centers (pathloss law)
- Interference is symmetric $h_{i,j} = h_{j,i}$
- An action by a cell is a vector indicating the chosen resources, e.g.:

$$\mathbf{x_3} = (1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0) \in \mathbb{B}^{16}$$

Interference Avoidance Game

- The total inter-cell interference on resource *k* can be written as:

$$I_{i,k}(\mathbf{x_{-i}}) = \sum_{j \in N \setminus \{i\}} h_{i,j} x_{j,k}$$

- If selecting resources so that the total inter-cell interference is minimized, the utility function is

$$U_i(\mathbf{x_i}, \mathbf{x_{-i}}) = -\sum_{k \in K} (x_{i,k} I_{i,k})$$
$$= -\sum_{k \in K} \left(x_{i,k} \sum_{j \in N \setminus \{i\}} h_{i,j} x_{j,k} \right)$$

- The utility is assumed to be additive: every selected resource contributes to the total utility

⇨ Now that we defined the game, what can we say about it?

Potential of the Game and Nash Equilibrium

- For the interference avoidance game, a so-called potential can be given by:

$$\Phi(\mathbf{x_i}, \mathbf{x_{-i}}) = -\sum_{i=1}^{n}\sum_{j=1}^{i}\sum_{k=1}^{m} h_{i,j} x_{i,k} x_{j,k}$$

- Defining property: $U_i(x_i', x_{-i}) - U_i(x_i, x_{-i}) = \Phi(x_i', x_{-i}) - \Phi(x_i, x_{-i})$
- Global function that depends on resource allocations of all cells
- Intuitive interpretation: the potential is (half) the system wide total interference
- Existence of potential guarantees so-called *finite improvement path* that leads to a Nash Equilibrium:
  - assume players act sequentially
  - each round, one player selects a best response to the current interference situation
  - by lowering its interference, the potential function value is also decreased
  - the potential thus monotonically decreases
  - until no player is able to unilaterally improve its utility ⇨ Nash Equilibrium

Timing and Response Algorithms are important

- If Nash Equilibrium exists, it can be reached via a finite improvement path

- But sequential adaptations are not practical:
  - sequential order in the whole cellular system would have to be established
  - only one cell able to adapt at a time

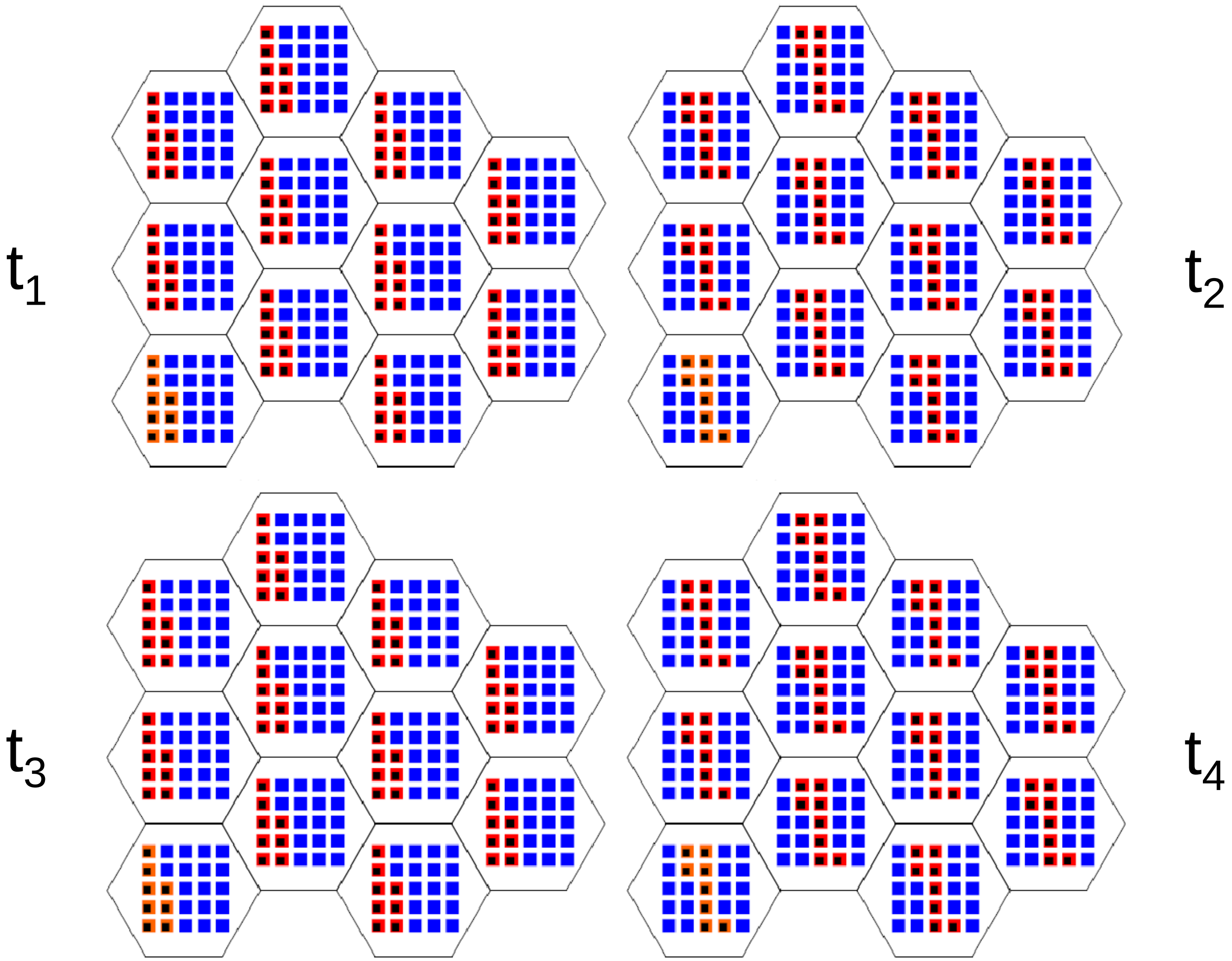
  ⇨ does not scale well for large cellular systems
- Simultaneous moves by all cells desired
  - would scale well
  - but neighboring cells might choose same previously less interfered resource resulting in high interference

  ⇨ no convergence

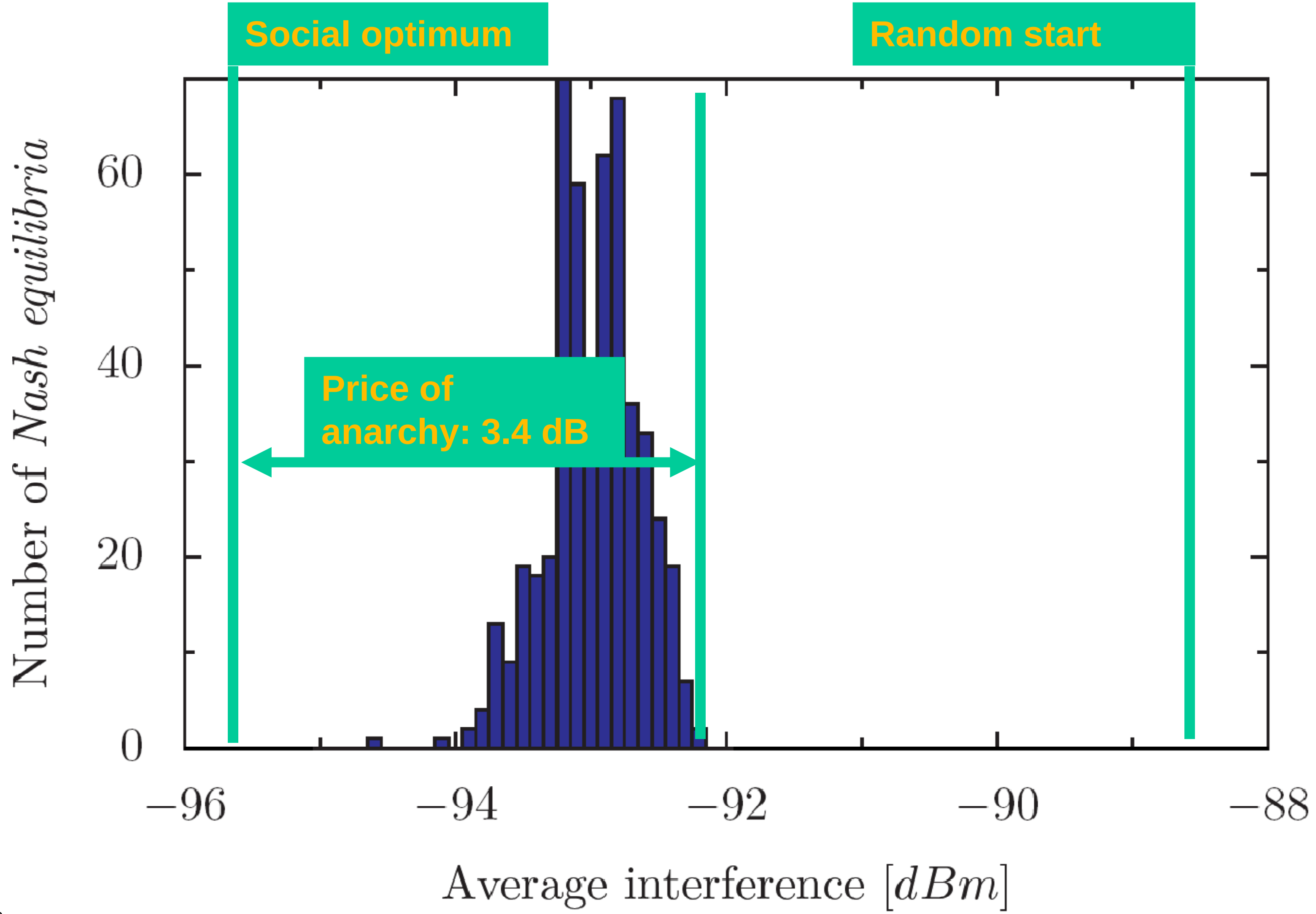
- Solution:
  - make a cell adopt a better resource only with probability *p*
  - for suitable values of p (e.g. around 1/10), with high probability only one cell in the vicinity switches to that resource

  ⇨ converges with high probability to Nash Equilibrium

Oscillation between two Worst Cases



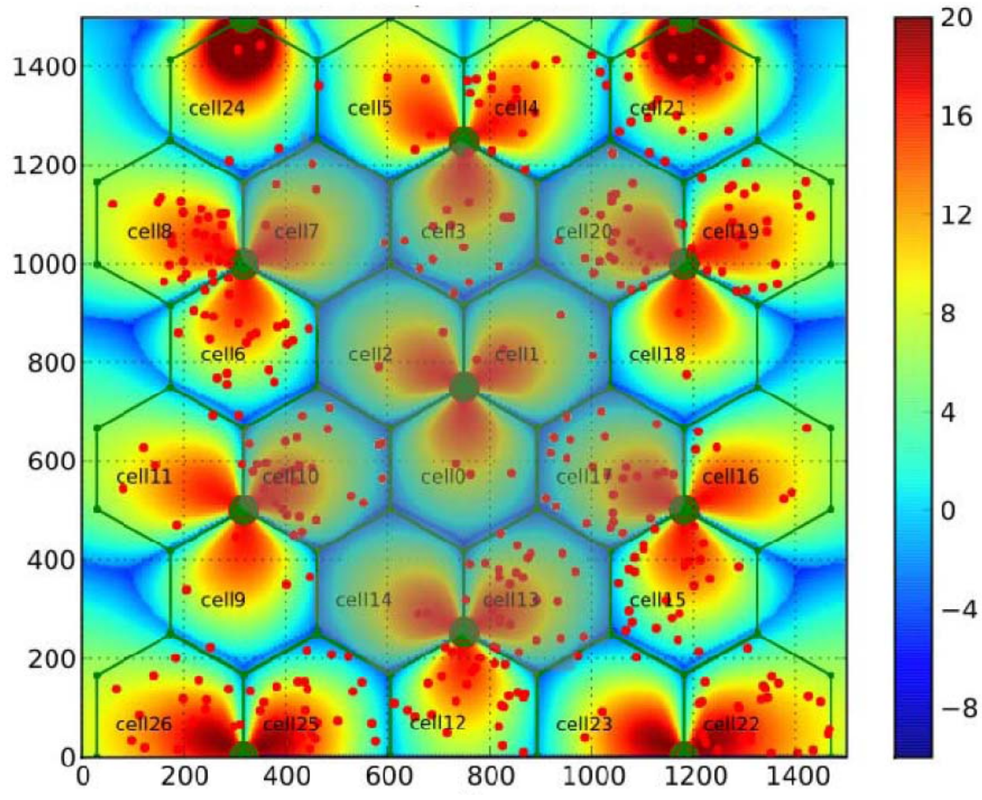
Histogram of Equilibrium Interference



Application to LTE?

Investigate the interference avoidance game in LTE-type environment

- Use of realistic sector antenna patterns
- Consider actual and inhomogeneous user positions
- Distinguish between uplink and downlink (here: uplink)
- Consider link adaptation (model from 3GPP)
- Model fast scheduling
- Power control (3GPP model)
- Compute average cell throughput



26 sector scenario, downlink reuse-1 SINR

Autonomous Scheme

- eNBs *i* periodically measure interference on PRB*k* $I_{i,k,t}$
- Since interference changes fast with intra-cell scheduling, exponentially averaged value is used:

$$\hat{I}_{i,k,t} = \alpha I_{i,k,t} + (1 - \alpha)\hat{I}_{i,k,t-1}$$

- Advantage: No signaling requirements
- Problem: Interference impact between pair of cells not symmetric

⇨ Lower interference on a PRB in *cell i* can still increase *systemwide* interference

⇨ Nash Equilibrium not provable

⇨ Convergence not guaranteed

⇨ Introduce hysteresis margin of $\Delta I = 1\,\mathrm{dB}$

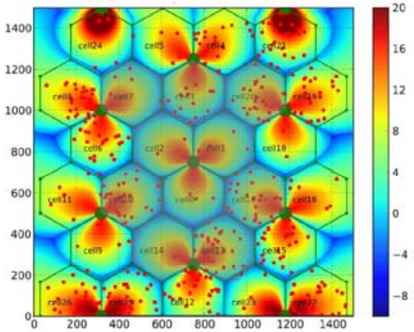
Inter-Cell Signaling Based Scheme

- Goal: Guarantee convergence
- Idea: Base game on virtual interference that is forced to be symmetric
- Precompute interference impact values that *eNB i* experiences, if a UE in the center of *cell j* uses the same PRB:

$$I_{i,j}^{center}$$

- However, due to sectorized cells, we have: $I_{i,j}^{center} \neq I_{j,i}^{center}$
- Force symmetry by pairwise averaging
- Assume, used PRBs can be communicated between eNBs via X2 interface
- Base game decisions on computed virtual interference
- No exponential smoothing required
- Convergence guaranteed

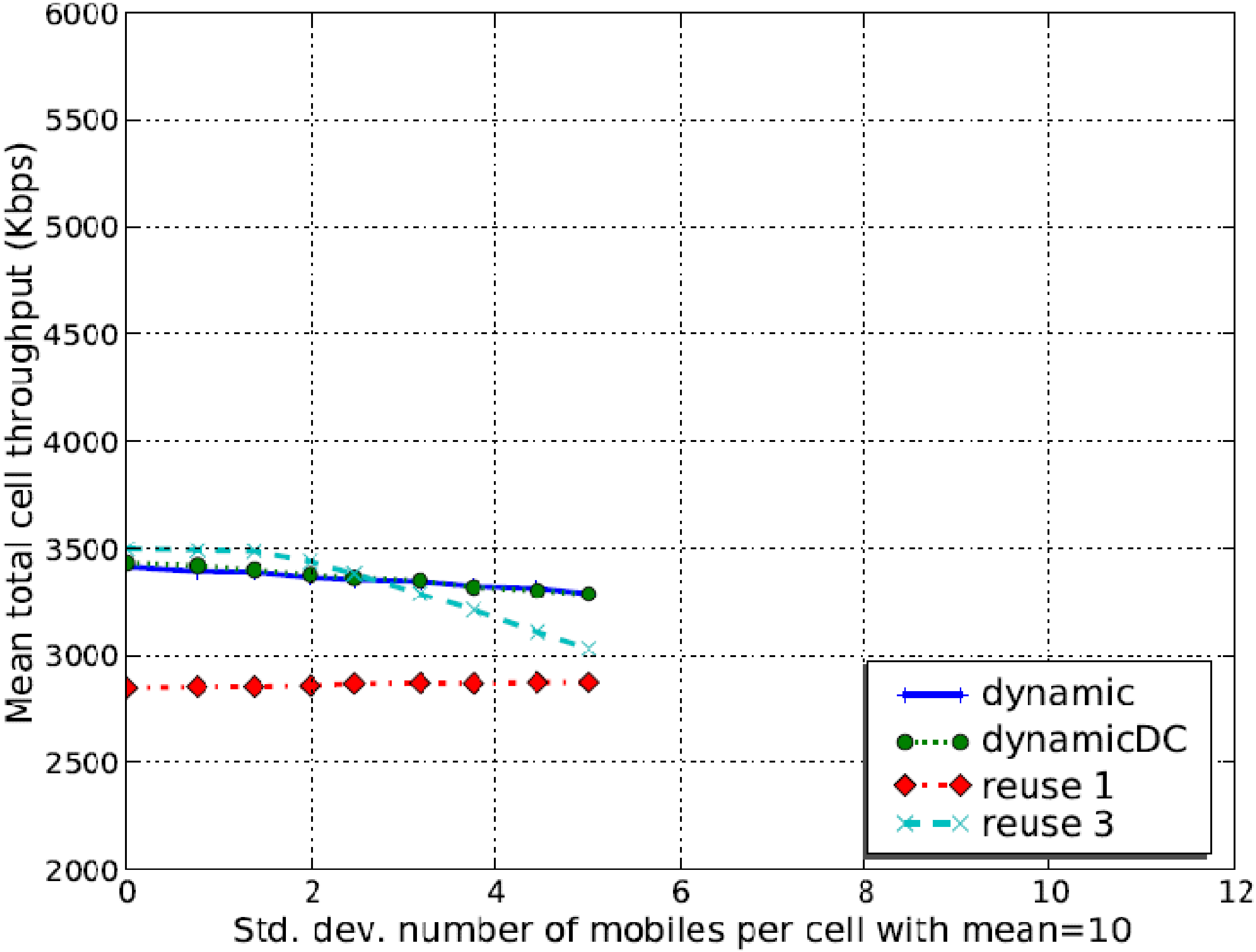
Additional Evaluations – Parameters



Parameter	Value
Carrier frequency	2000 MHz
Number of PRBs	36
Bandwidth per PRB	180 kHz
Thermal noise power	-121 dBm per PRB, 5 dB noise figure
eNB Antenna pattern [12]	$A(\Theta) = -\min\left\{12\left(\frac{\Theta}{\Theta_{3\text{dB}}}\right)^2, A_m\right\}$ $\Theta_{3\text{dB}} = 70°, \quad A_m = 20$ dB
Scenario size	1500 m x 1500 m
Number of eNBs	27 (9 sites with 3 cells/sectors each)
Number of UEs	10, 20, or 30 with 0% to 80% relocated between random cell pairs
Inter-site distance	500 m
Pathloss model [12]	$L = 128.1 + 37.6 \log_{10}(R[\text{km}])$ scenario (1) in [12]
Max. Tx Power in UL	$P_{max} = 24$ dBm per PRB
Uplink power control	$P = \min\{P_{max}, P_0 + \alpha L\}$ per PRB Open-Loop Power Control [10] [11] with $P_0 = -48$ dBm and $\alpha = 0.7$
Link-level performance model [9]	see equation (1) with these parameters: $\alpha = 0.4$ $\gamma_{min} = -10$ dB $Th_{max} = 2.0$ bps/Hz

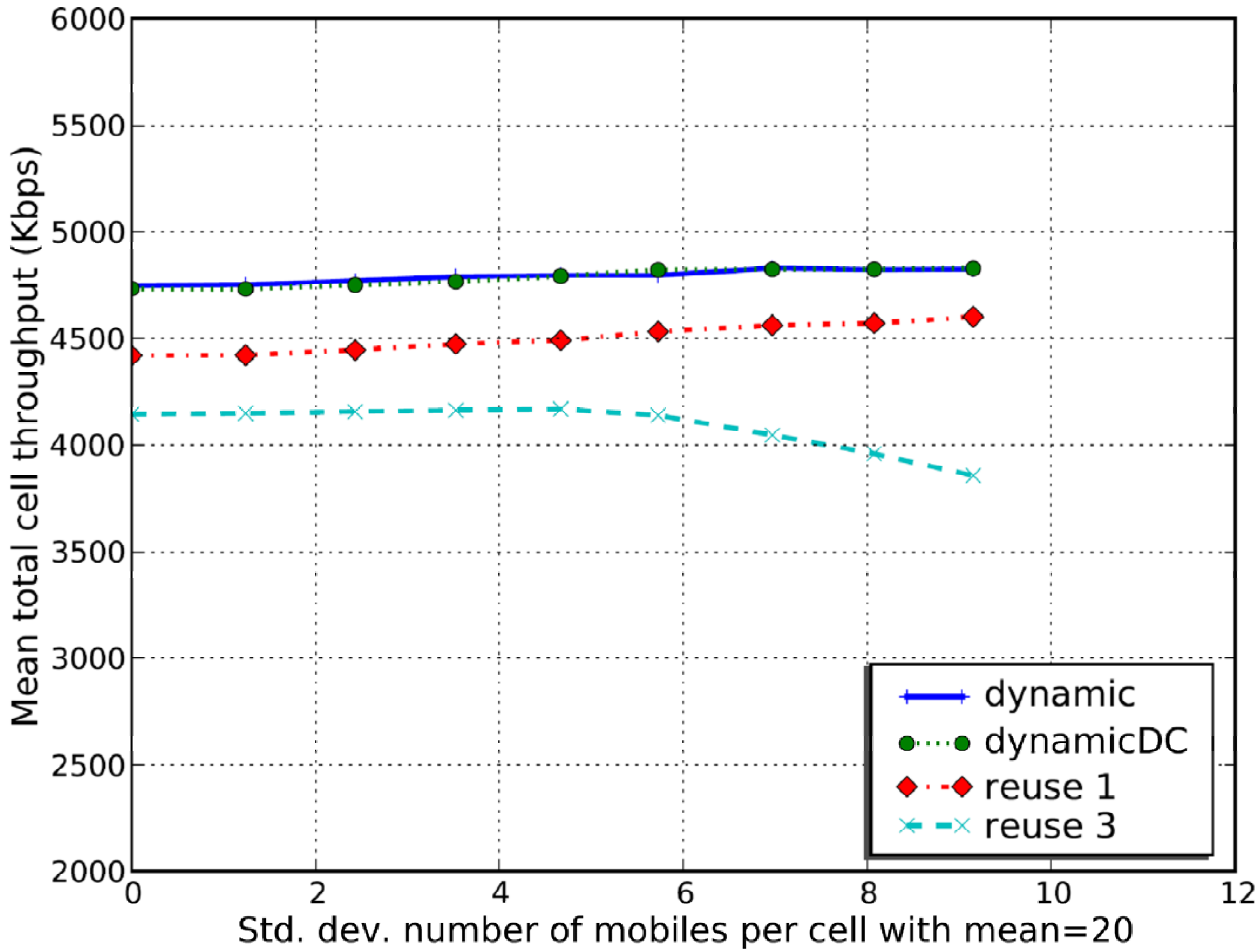
Results – 10 users per cell

Mean cell throughput versus increasing spatial user inhomogeneity



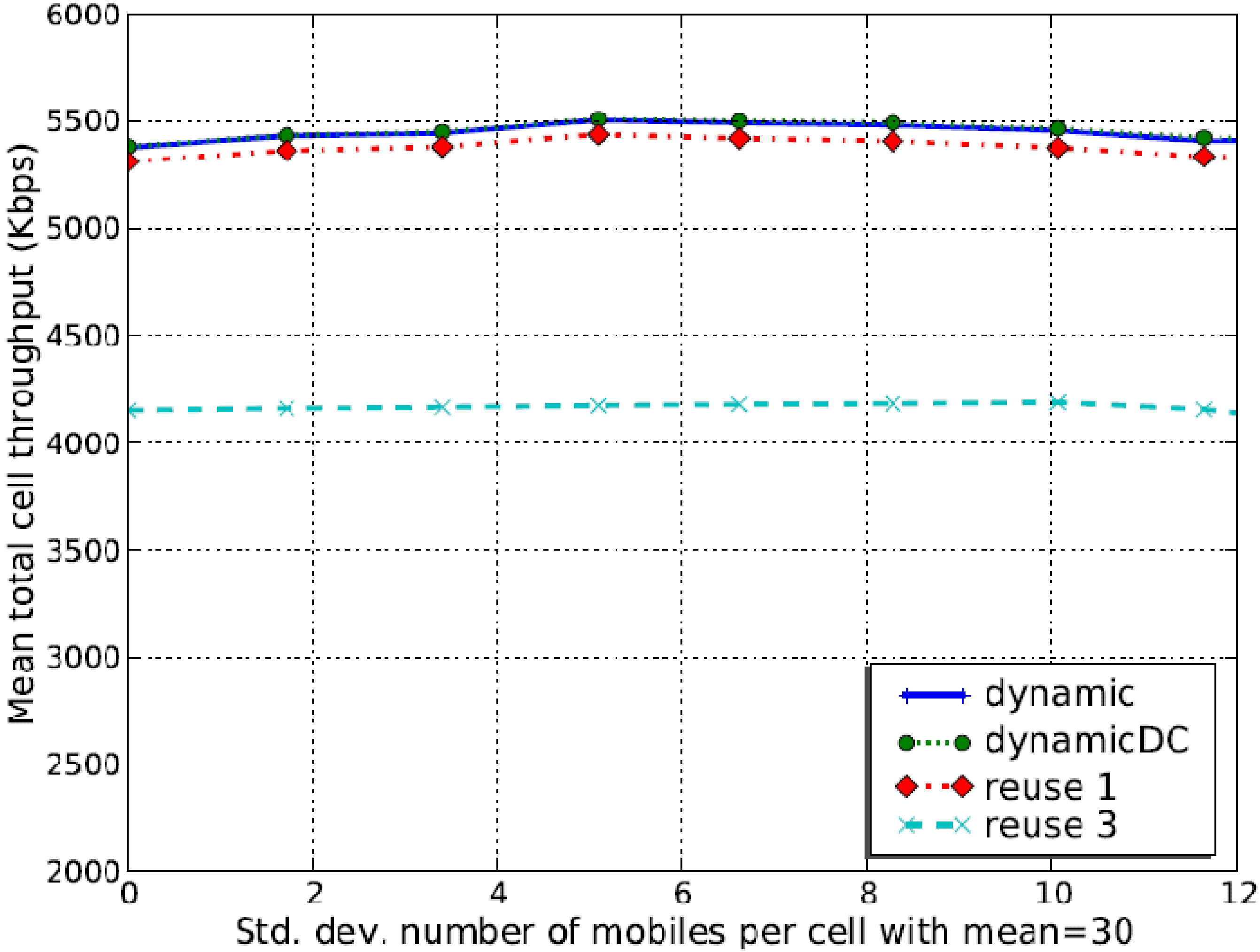
Results – 20 users per cell

Mean cell throughput versus increasing spatial user inhomogeneity



Results – 30 users per cell

Mean cell throughput versus increasing spatial user inhomogeneity



Conclusions

- Introduced interference avoidance game
- Investigated convergence and price of anarchy

- Extended game to be applied to LTE
- Autonomous scheme
- Inter-cell signaling based scheme

- Simulations show convergence
- Comparison to fixed schemes shows gain due to self adaptation

Future extensions

- Further improve modeling (schedulers, protocols)
- Combine with other approaches like *flexible reuse*

References

- Jan Ellenbeck, Christian Hartmann, Lars Berlemann: **Decentralized Inter-Cell Interference Coordination by Autonomous Spectral Reuse Decisions** *European Wireless 2008,* June 2008, Prague Czech Republic*.*
- Jan Ellenbeck, Hussein Al-Shatri, and Christian Hartmann **Performance of Decentralized Interference Coordination in the LTE Uplink** *2009 IEEE Vehicular Technology Conference,* September 2009, Anchorage, Alaska, USA, *accepted for publication*.

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