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Backhaul Requirements for Inter-site Cooperation in Heterogeneous LTE-Advanced Networks *(invited)*

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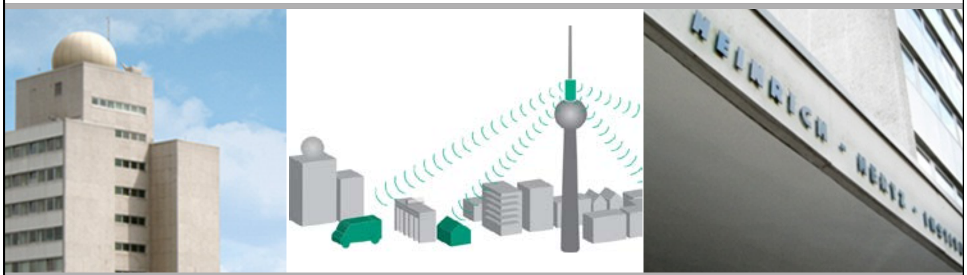

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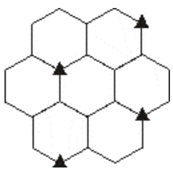
Outline

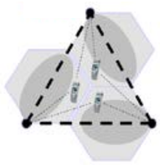
Wireless Communication and Networks

- Introduction
  - Cooperative base stations
  - Challenges for integrated fixed-wireless network
- Network architecture
  - Heterogeneous mobile network
  - LTE backhaul for flexible clustering
- Traffic for adaptive cooperation
  - Clustering and user selection
  - Single-cell and aggregate results
- Feedback delay
  - Over-the-air and network propagation delays
  - SIR improvement by channel prediction
- Backhaul-assisted synchronization
- Conclusion

Introduction

Wireless Communication and Networks





- Mobile networks reuse frequency again and again
- Intercell interference is a major bottleneck
- Coordinated Multipoint (CoMP)
  - Distributed base stations = multiple inputs
  - Terminals in multiple cells = multiple outputs
  - Joint processing of adjacent base station signals
  - **CoMP needs a powerful backhaul**
- Integrated fixed and mobile network
  - **What are the requirements for CoMP?**

Cooperation in clusters

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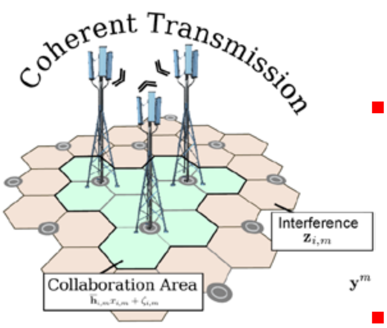

- Full cooperation
  - All cells cooperate → No more interference
  - Reaches theoretical limits
  - Infinite pilot, feedback and backhaul overhead
- Clustering
  - Only few selected base stations cooperate
  - Let others create interference
  - Terminal suggest its most relevant cells
  - Clusters are formed with flexible size
  - → **Overhead scales with the cluster size**
- User selection
  - Crucial step in MAC protocol for CoMP
  - We start with random users
  - Exchange users until all gain from cooperation

Principle and trials (2010)

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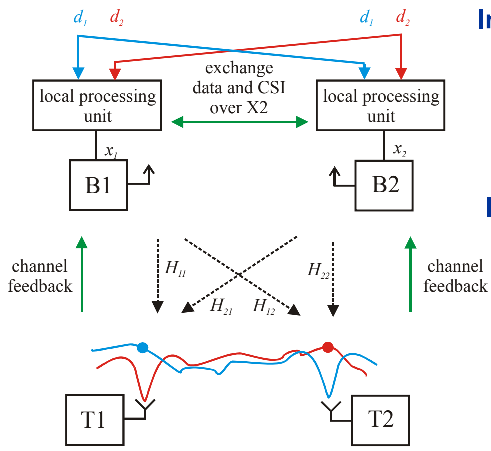
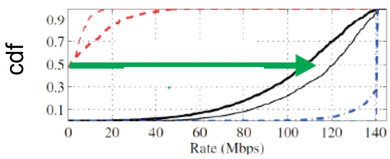
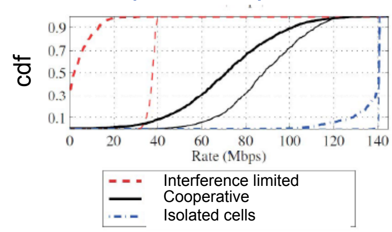


In the lab



In the field (500m ISD)



- **Huge gains both, in the lab and in the field, despite high interference.**

Challenges for integrated network

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- Data + CSI exchange between small and macro cells
  - → **Increased backhaul overhead**
- Flexible reorganization of the network: Who talks to whom
  - → **Selective multicast inside the cluster**
- Nearly perfect channel state information (CSI) at the base stations
  - → **Delays: Minimize channel aging, use channel prediction**
- Coherent placement of zeros in space
  - → **Almost perfect synchronization**

Heterogeneous mobile network

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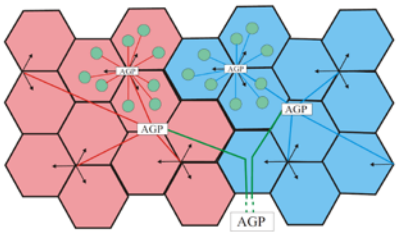

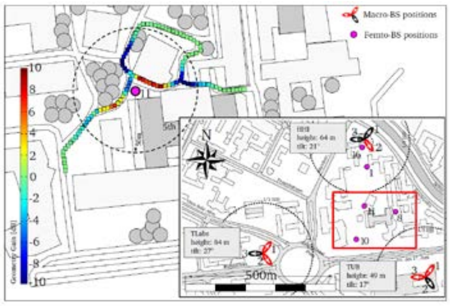

- Small cells embedded into large cells
- Exchange can be passed over multiple aggregation nodes
- Right: Measurements in Berlin testbed
- 3 macro-sites, two sectors active at each site, 5 distributed small cells
- Change of geometry factor *E*(S)/*E*(I) around a small cell (right)
- **Difficult interference → Cooperation between small- and macro-cells**

LTE backhaul

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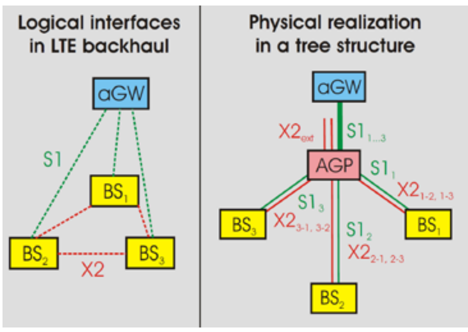

- Long-Term Evolution (LTE) has a specific backhaul architecture
- Individual feeder link (S1)
  - from advanced gateway (aGW) to each base station (BS)
  - logical star
- Interconnects (X2)
  - exchange between the BSs
  - logical mesh
- Physically realized as a tree (right)
  - Ethernet-based
  - S1 and X2 are multiplexed
  - **Active aggregation nodes**

Flexible clustering

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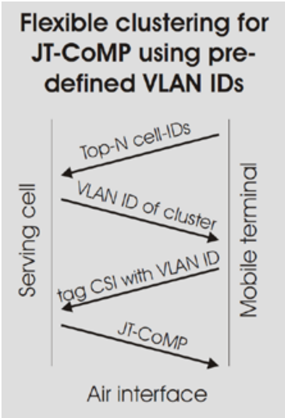

- **Why flexible?**
  - Terminal have to suggest the right cluster
  - According to the Top-N interferers
- **VLAN using predified cluster IDs**
  - All possible clusters are preconfigured
  - Each cluster has a specific ID
  - Terminal send Top-N list
  - Cluster ID is broadcast to all terminals
  - Channel feedback is tagged with cluster ID
  - Reaches all base stations in the cluster
  - Similar for data exchange
- **Active switches at aggregation nodes**

Traffic estimation

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1. **Clusters are build using strongest base stations at the terminal**
   - Yields a variable cluster size → statistical problem!
2. **Successive user selection**
   - Finds suitable users in all cooperative cells
   - Rule: Each user gains from cooperation (win-win situation)
   - Needs 3-4 iterations, on average
3. **Backhaul traffic estimation**
   - Simulate over-the-air performance in the cluster
   - Compute S1 and X2 traffic statistics, accordingly
   - Use peak and average values according to NGMN recommentations
4. **Obtain single-cell and aggregate backhaul results**
   - Only inter-site traffic contributes to the real backhaul load

Single-cell results

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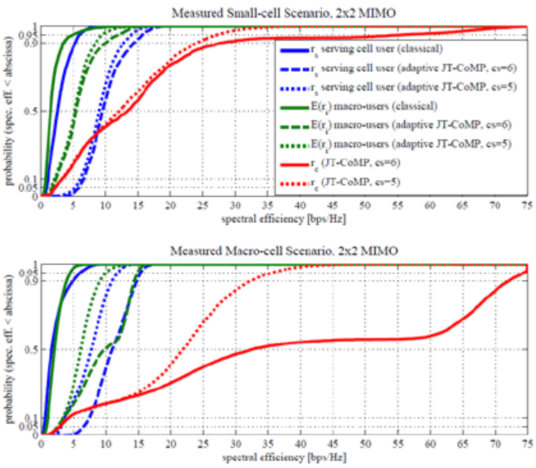

- Results are based on multi-cell channels measured at 2.6 GHz in the field
- Significant gains due to adaptive cooperation
- Factor 3.6-3.8
- Backhaul is related to red curves
- Limited cluster size cs=5 is useful for small cells to reduce the backhaul load

Aggregate results

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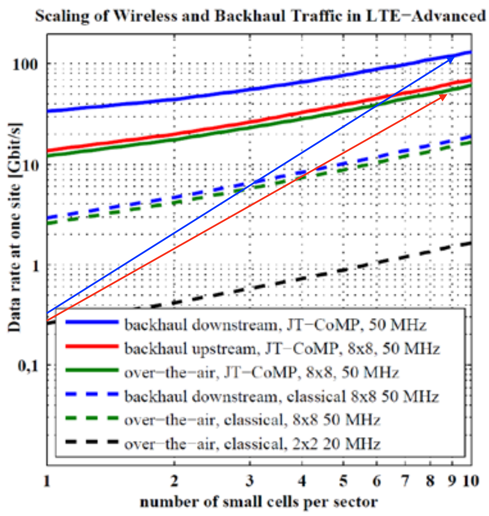

- Heterogeneous network with adaptive cooperation
- Using all technology options in LTE-Advanced
  - No. of small cells (abscissa)
  - Carrier aggregation
  - Higher-order MIMO (8x8)
  - Cooperative base stations
- Over-the-air: Factor 300
- Backhaul: Factor 1,000
- **LTE-A is nicely scalable if enough backhaul is available**

Feedback delay

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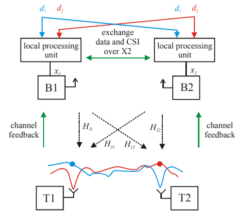
- Cooperation is based on channel feedback
- If feedback is delayed, the gains go down
- There are many contributions to the delay



$$t_{delay} = t_t + t_{air} + p \cdot \left(\frac{1}{r_{up}} + \frac{1}{r_{X2}} \right) + t_{rout} + t_b$$

- Main contributions
  - Packet processing delays at terminal and base station $t_t + t_{air} + t_t > 4$ *ms*
  - Packet size p → can be reduced by feedback compression > 1 *ms*
  - Routing delays t_{rout} in the backhaul < 1 *ms*
- Compensate the delay by channel prediction

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Network delays are small

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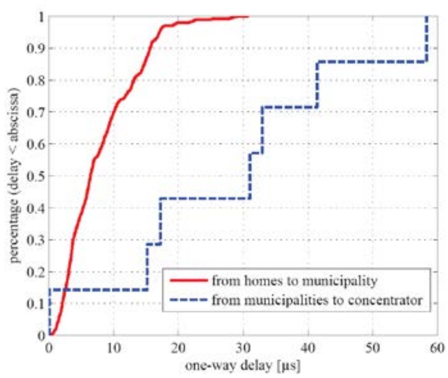

- **Assuming Ethernet switches at all aggregation points (AGP)**
- FTTx network in 7 rural municipalities
- Cumulative delays over 1st and 2nd aggregation level $t_{rout} < 180\ \mu s$
- Average switching delays < 0.5 ms
- **Delays in the network < 1 ms**
- Reduced over-the-air delays need changes in the standard

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Feedback compression

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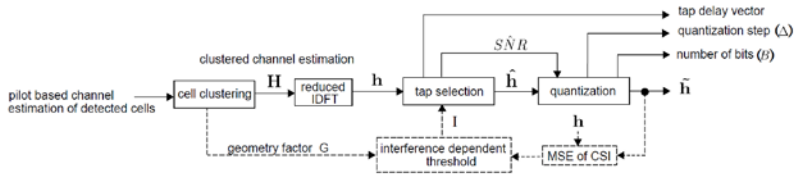
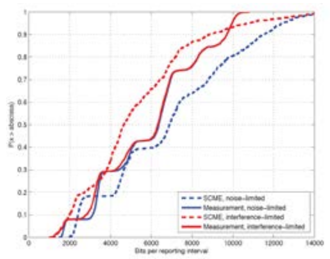


- Major approaches
  - Select the strongest cells (clustering)
  - Select the strongest multi-paths (taps)
  - Quantize complex amplitudes adaptively
  - Take out-of-cell interference into account



- **CSI packet is 15 times smaller, on average**
- Thus, the feedback delay is reduced

Channel prediction

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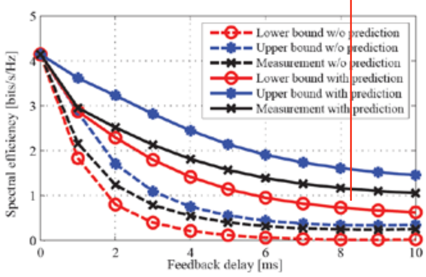
- **New concept based on Doppler-delay analysis (best paper award VTC-Spring)**
  - Estimate delays and Doppler frequencies from channel history
  - Insert estimated values into multi-path channel model
  - Predict the channel into the future

Results for 30 km/h

- **Results are based on random matrix theory**
  - upper/lower bounds for i.i.d. Rayleigh fading/orthogonal users, respectively
  - measured results include clustering and user selection

$$SIR = \left(\sum_u \frac{MSE}{\lambda_u^2}\right)^{-1} \qquad \gamma = \frac{N_b}{N_u}$$

$$\frac{\gamma - 1}{MSE} \leq E(SIR) \leq \frac{\gamma}{MSE}$$



- Delay axis is „streched“ by prediction

Network-assisted synchronization

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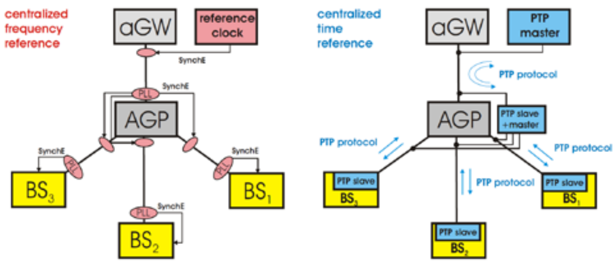
- Cooperative base stations need tight synchronization
- Field trials used GPS, but operators want network-assisted synchronization
- Two main approaches:
  - IEEE 1588v2 precision time protocol (PTP)
  - Synchronous Ethernet, using the bit clock
  - Mobile aggregation nodes have to support this



Conclusions

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- We summarized major backhaul requirements for future mobile networks.
  - Significantly higher data rates
  - Flexible reconfiguration, Reduced delays
  - Network-assisted synchronization
- We proposed several new techniques of cooperative base stations.
  - Flexible clustering and successive user selection
  - Adaptive feedback compression
  - Channel prediction
- Challenge is an integrated fixed-wireless access network.

Contact info

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Thanks for your interest. I am looking forward to your questions.

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SODALES FP7 Call 8 project (2012-2015)

Wireless Communication and Networks

- Targets
  - Integration of fixed and mobile access
  - Open access for very different network operators
  - Energy-efficient, low cost, universal, scaleable
- Proposed solution
  - new **active remote node** (ARN) between CO and end user
  - multiple ARNs/commercial users/RBS served using WDM
  - ARN is essentially an active Ethernet switch
    - significant oversubscription
    - statistical multiplex reduces the uplink rate
    - shortcuts mobile backhaul traffic for cooperation between macro-RBS and small cells
  - Co-located CPRI switch for multiple remote antennas

SODALES Architecture with ARN

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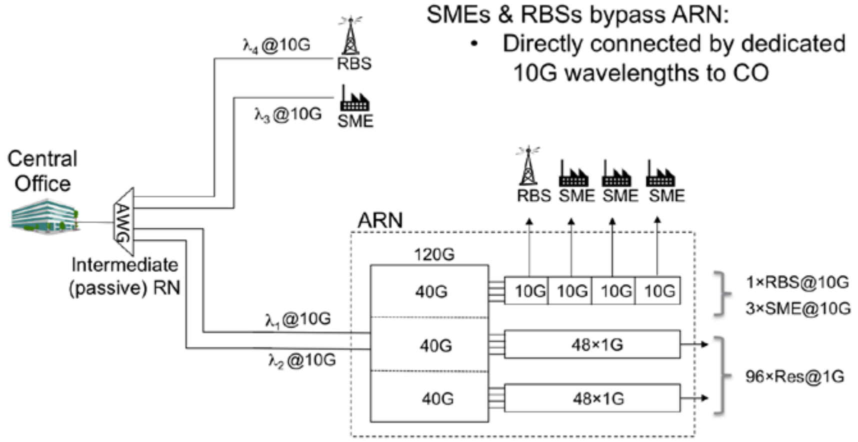

Points for panel discussion

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- Integrated fixed and mobile access network.
- 100 Gbit/s at first aggregation node, evtly. co-located with macro-RBS.
- Centralized versus distributed architecture (Cloud-RAN vs. All-Ethernet).
- CPRI/ORI using Ethernet PHY.
- The need for wireless fiber replacements (10-100 Gbit/s, 60-240 GHz).
- New potential for radio over fiber (RoF) as feeder for mm-wave radio.
- Heterogeneous backhaul (fixed/wireless).