Next Generation Wireless Systems
Optimizing the Spatial and Spectral Degrees of Freedom

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From Ideas to Prototypes

Cellular Evolution of Adaptive MIMO-OFDM

First Gigabit MIMO-OFDM Demo
3GSM Mobile World Congress
Cannes 2005

First LTE Live Demo
ITU Telecom World
Hong Kong 2006

First Multiuser MIMO Demo
BMBF STC Meeting
Munich 2007

First LTE Field Trials
Berlin 2007/2008

Berlin
LTE Advanced Testbed
since 2008

First LTE Advanced Relaying
3GSM MWC, CTIA
Barcelona/Las Vegas 2009

First Downlink CoMP Trials
Berlin 2010

First H.264/SVC over LTE Demo
3GSM Mobile World Congress
Barcelona 2010

Cross-Layer Design
4 3 2 1
Wireless Communication
and Networks

Multi-Layer Multi-Cell Field Trial Environment

- Easy access to buildings, rooftops and antenna sites
- Typical urban heterogeneous radio network environment
- Radio overlays: 2G, 3G, 4G, WLAN
- Hierarchical cell deployments: Macro, Pico, Femto
- Fast inter-site optical fiber connections (X2, S1)
- Ultrafast broadband connection to DFN (German NREN)
- IP based seamless handover via EPC

Field Trials in Real World Radio Environments

- Outdoor drive tests with measurement van
- Outdoor to indoor coverage
- Indoor measurement campaigns
- Wireless radio link performance measurements
- Performance testing under multi-cell interference limitation
Wireless Access and Backhaul

- LTE / LTE-Advanced & beyond
- Relaying and multi-hop technologies
- Fiber and wireless backhauling techniques
- Distributed antenna systems (DAS) and remote radio heads
- HetNets, small cells and SON
- Carrier aggregation and multi-band techniques
- Higher order MIMO processing \{4,8,12\}-TRx
- Cooperative antenna systems: CoMP/Network MIMO
- Sensing techniques for cognitive radios
- Radio resource management (RRM) & cross-layer design for video over wireless
- C-RAN technologies
Spectrum – the Degree of Freedom #1

- Spectrum Efficiency
- Frequency Reuse / Frequency Planning / ICIC
- Multiband Carrier Aggregation
- New frequency bands / upto 300GHz
- Flexible Spectrum Usage
- Opportunistic Spectrum Access
- Dynamic Spectrum Management
- Spectrum Sharing
- Secondary Usage
- Cognitive Radio Systems
Applications
- Design and develop a holistic and rapidly deployable mobile network composed of
  - Aerial segment – AeNB
  - Terrestrial platform – TeNB
  - Satellite communications for serving institutional missions
- Demonstrate
  - High-capacity, low-latency and coverage capabilities of LTE-A solutions
  - Broadband emergency communications within disaster relief scenarios
  - Dynamic spectrum access and secure connectivity
  - Contribute to public safety domain in Europe

Resilient Flexible LTE-A Networks

http://www.absolute-project.eu/
Applications

- SDR platform supporting different communication standards with variable
  - signal bandwidths
  - carrier frequencies
  - transmit power
- Multiband, MIMO and beamforming operation using several radio units connected and synchronized via optical fiber
Thinking beyond one band per service or one band per MNO

**Concept:** Flexible frequency sharing between cells with shared coverage footprint for small cell deployments within one’s MNO spectrum domain between several MNOs with cell footprint overlap
- Micro-Economic spectrum trading driven by geo-location aware small scale traffic forecasts

**Advantages:**
- w/ site sharing: local immediate capacity shifts on demand
- w/o site sharing: easy shift of exclusive spectrum between cells
- based on CA mechanisms
- subscribers remain in native network (national roaming vs. spectrum sharing)
- additional cell deployments can be postponed
- follows concepts of DSM and SON based load balancing

**Options:**
obtain/ offer spectrum options based on load predictions specific in time and geo-location (introduce a convertible metric between eg MNOs)
Thinking beyond one band per service or one band per MNO

Spectrum Sharing for LTE-A Systems

Operator 1
- IP Rate: 29.94 MBit/s
- Max Rate: 26.19 MBit/s
- Rate in MBit/s

Operator 2
- IP Rate: 35.85 MBit/s
- Max Rate: 35.25 MBit/s
- Rate in MBit/s

Native Spectrum

Terminal 1
- 8 MBit/s VBR

Terminal 2
- 20 MBit/s VBR

Terminal 3

R

Terminal 1
- 20 MBit/s CBR

Terminal 2
- 20 MBit/s VBR

R

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Spectrum – shift spectrum to other cells temporarily

Manage Peak Load Imbalances between cells of shared footprint

Spectrum Sharing for LTE-A Systems

Operator 1
- IP Rate: 10.62 MBit/s
- Max Rate: 16.89 MBit/s
- Shared Spectrum

Operator 2
- IP Rate: 45.14 MBit/s
- Max Rate: 47.74 MBit/s

Terminal 1, Terminal 2, Terminal 3

8 MBit/s VBR

Terminal 1, Terminal 2, Terminal 3

20 MBit/s CBR

20 MBit/s VBR
Spectrum – shift spectrum to other cells temporarily

Manage Spectrum Demand Imbalances between cells of shared footprint

Spectrum Sharing for LTE-A Systems

Operator 1
IP Rate: 9.98 MBit/s
Max Rate: 13.95 MBit/s

Operator 2
IP Rate: 21.69 MBit/s
Max Rate: 26.44 MBit/s

Shared Spectrum

Terminal 1
Terminal 2
Terminal 3

8 MBit/s VBR

20 MBit/s CBR
Embedding secondary services in your own active bands

Scenario: narrow band / low rate services to be operated on LTE footprint; low complexity devices used

Concept: smart coexistence between LTE and systems with lower bandwidth and complexity (meters/sensors w/o LTE capability) → gray space comm

Primary system view:
embedding of secondary services air-interfaces in own spectrum
- based just on permit to operate, volume driven or event driven
- coordination with secondary’s aggregation points or control channels
- can cope with interference anyway, improved resilience by e.g. CoMP

Secondary system view:
- can be operated with low complexity coordination capabilities (simple, cost and energy efficient)
- Basic knowledge about LTE bands and structure is sufficient
Wireless sensor networks, M2M communications, internet of things
- energy-efficient transmission (maximum network lifetime)
- distributed in-network data processing including data and decision fusion, consensus algorithms, compression …
- opportunistic routing
- energy-efficient MIMO

Information flow

In-network data processing:
fusion, aggregation, classification

WSN: Wireless Sensor Network
CN: Collector Node
mm-Wave in Mobile Communication

- **Macro BTS for coverage**
- **Small cells for capacity enhancement**
- **mm-wave backhaul (point-to-point)**
- **Nanocells for Gbit/s offload**
- **mm-wave or THz access (mobile)**
- **mm-wave backhaul**

Diagrams:
- Macro base station
- Small base station
- Nanocell

4G

mm-Wave / THz
mm-Wave Challenges and Approaches

mm-Wave Backhaul
- Reliable and efficient communication for realistic environments (low antenna heights)
- Interference Management for license-free bands
- Installation
  - Advanced Modem and PHY-Design
  - Cognitive spectrum management
  - Beamforming, Self Organization

Nanocell Overlay
- User Mobility and Beam Tracking
- Handover between cellular network and overlay
  - Hybrid data link layer and control plane
Wireless Communication and Networks

Space – the Degree of Freedom #2

- Multi-Antenna Systems MIMO
- Spatial Multiplexing
- Beamforming
- Massive MIMO
- Multi-user MIMO
- CoMP/ Network MIMO

- Spatial Reuse
- Cellular layout
- Cell densification / HetNets
- Intercell Interference
Multi-cell field trials in Berlin LTE-Advanced Testbed

Coherent multicell measurements

- Base station sites are synchronized with GPS/Rubidium
- Cell-specific pilot grid (once per 10 ms radio frame)
- Full identification of the frequency-selective channel
- Pilot design allows up to 32 antennas
- Current limitation in signal processing
- 6 cells with 2x2 MIMO
Multi-cell field trials in Berlin LTE-Advanced Testbed

Extraction of channel parameters

- Channel is modeled as multi-path
  \[ r(t) = \sum_{l=1}^{L} a_l \cdot e^{j\phi_l} \cdot \delta(t - \tau_l) \]
- SAGE-like tap estimation
- Extracts most relevant paths from the measurements
- Can be used in system simulator
- Interpolation for use in Elektrobit F8 channel emulator
Performance Overview for Limited Feedback:

- **MIMO 2x4**
  - Is the desired setup in LTE and LTE-Advanced
  - Multi-user diversity gain is given
  - With less users, 5%-ile user rate improves, since more spectrum is available per user.

- **MIMO 4x2**
  - Improved capabilities for interference suppression in OC
  - 4 antennas at UE might difficult to realize

- **MIMO 4x4**
  - Gains from larger codebook decreases
  - Gains from SIMO to MIMO 4x4:
    - 23% → 60%, 75% → 87%, 120% → 180%, 196%, 200% (with respect to SISO)
Adaptive Cluster Size Selection for CoMP

- ISD 500 m
- Downtilt 1/3 ISD
- Correlated shadow fading
- Selection window 15 dB
Cluster Selection for BSs:

- User-centric vs. network-centric clustering
- It will be rather impractical to merge users reporting user-centric clusters
- Large-scale channel propagation conditions should not behave i.i.d. This would make network-centric clustering impossible.
**System Model for CoMP:**

\[
\begin{align*}
    y_{k,t} &= H_{c,k} \left( B_{c,k} \right)_{:,t} \sqrt{p_{c,t}} x_{c,t} \\
    &+ \sum_{j \in T_s \setminus \{t\}} H_{c,k} \left( B_{c} \right)_{:,j} \sqrt{p_{c,j}} x_{c,j} \\
    &+ \sum_{m \in M \setminus M_c} \sum_{j=1}^{N_t} H_{m,k} \left( B_{m} \right)_{:,j} \sqrt{p_{m,j}} x_{m,j} + n
\end{align*}
\]
CoMP Transmission Steps

**Phase I:**
- channel estimation at UE side based on CSI-RS
- CQI prediction
- acquisition of MISO-CSI and CQI data and feedback to serving base station

\[ \hat{H}_k = \gamma_k^H H_{c,k} \]

**Phase II:**
- user grouping and cluster selection
- distributed precoder calculation based on MISO-CSI
- link adaptation based on UE specific CQI

**Phase III:**
- demodulation using MRC or OC receiver

\[ \text{SINR}_k = \frac{\| w^H_{k,t} H_{c,k} [B_{c,k}^t]_{1:t} \sqrt{P_{c,t}} \|^2}{\sum_{j \in T_k \setminus \{t\}} \| w^H_{k,t} H_{c,k} [B_{c,j}]_{1:t} \sqrt{P_{c,t}} \|^2 + w^H_{k,t} [z_k z_k^H] w_{k,t}} \]

with \( w_{k,t} \) being the combining weights at the receiver, e.g. OC or MRC.
Indoor and outdoor CoMP measurements show:

- Coherent Interference Suppression is feasible
- Drastic cell edge performance improvement
  - No cell outage
  - High data rates with frequency reuse 1
Heterogeneous Networks - HetNets

- Coverage and capacity enhancements by cell densification
- Deployment of small cells: Macro – Pico – Femto – Relay – DAS
- Challenges:
  - Interference (Coordination, Cooperation)
  - Backhaul (Wireless Backhaul)
  - Scalability (complexity, cost issues)
  - Energy efficiency (distributed or virtual cells using AAS, directivity vs. spectrum)

from macro cells to dense deployments

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Self-Organization

- **Self-organizing (cellular) networks**
  - Different use cases: handover, load balancing, capacity, coverage, energy efficiency etc.
  - Interaction between different use cases/joint optimization

- **Methods**
  - Stochastic optimization
  - Machine learning and inference
  - Multi-objective optimization

- **Challenges in Heterogeneous Networks**
  - Large amount of measurements
  - Delayed & limited feedback
  - Unavailability of suitable (statistical) network models
Thank you for your attention!

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