Current Frontiers in Wireless Communications: Fast & Green & Dirty

Gerhard Fettweis
<table>
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<tr>
<th>Chair and Its Partners</th>
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<tbody>
<tr>
<td><strong>32</strong> Ph.D. students</td>
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<tr>
<td><strong>25+</strong> Ms students</td>
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<tr>
<td><strong>4</strong> sen. scientists</td>
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<tr>
<td><strong>1</strong> post-doc</td>
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<tr>
<td><strong>1</strong> professor</td>
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<tr>
<td><strong>1</strong> project mgr</td>
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<tr>
<td><strong>2</strong> secretaries</td>
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<td><strong>4</strong> engineers</td>
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<td><strong>IPP 2008 Oct-1</strong></td>
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<th>Sponsors</th>
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<td>Agilent Technologies</td>
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<td>Asahi KASEI</td>
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<td>AMD</td>
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<td>CoWare</td>
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<td>ANALOG DEVICES</td>
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<td>ROHDE &amp; SCHWARZ</td>
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<td>ERICSSON</td>
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<td>Synopsys</td>
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<td>ST-NXP Wireless</td>
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<td>Altera</td>
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<td>Actix</td>
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<td>Alcatel-Lucent</td>
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<tr>
<td>NXP</td>
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<td>EPCOS</td>
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<td>Tyco Electronics</td>
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<td>NEC</td>
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<td>ZMD</td>
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<tr>
<td><strong>Scientific:</strong></td>
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<tr>
<td>44 Ph.D. grads</td>
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<td>175+ Ms. grads</td>
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<tr>
<td>500 publications</td>
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<tr>
<td>40+ patents</td>
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<td><strong>Innovation:</strong></td>
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<tr>
<td>8 spinouts</td>
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<tr>
<td>200 engineers</td>
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<td><strong>Funding:</strong></td>
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<td>€ +35M Chair</td>
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<td>€ +40M VC</td>
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<td>€ 250M projects.</td>
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The Vodafone Chair’s Startup History

- 1999: OnDSP™ based WLAN chip-sets
- 2000: UMTS/3G network optimization and planning
- 2003: LTE FDD & TDD test mobile
- 2004: Module and reference board design
- 2005: MPSoC semiconductor IP
- 2007: Wireless embedded technology
- 2008: Network performance measurement
- 2008: LTE Cellular Technology Provider
FAST
Embedded Mobile Memory: Single-Chip Flash Memory Trend
“The Wireless Roadmap”
Data Synchronization: Point-to-Point

- USB 1.0
- USB 2.0
- USB 3.0
- 802.15.3c
- UWB intention

Short links (1m)
Client Server Applications: WLAN

- Short links (1m)
- WLAN (10m)

- 802.11b
- 802.11ag
- 802.11n
- 802.11vht

Bandwidth:
- 100Gb/s
- 10Gb/s
- 1Gb/s
- 100Mb/s
- 10Mb/s
- 1Mb/s
- 100Kb/s
- 10Kb/s

Years:
- 1995
- 2000
- 2005
- 2010
- 2015
The Wireless Roadmap

- **Short links (1m)**
- **WLAN (10m)**
- **Cellular (100m)**

Driven By Moore’s Law

ITRS Roadmap: Continues until 2020

- 100Gb/s
- 10Gb/s
- 1Gb/s
- 100Mb/s
- 10Mb/s
- 1Mb/s
- 100Kb/s
- 10Kb/s

- 1995
- 2000
- 2005
- 2010
- 2015
The ITU “Van” Diagram
2004: Integration Nightmare Roadmap of Wireless Standards into Handsets

- **Status Today**
  - GSM/UMTS
  - Bluetooth
  - IrDA

- **IEEE 802.11b**: 11Mb/s wireless LAN @ 2.4GHz (up to 100m)
- **IEEE 802.11a/g**: 54Mb/s wireless LAN @ 2.4/5GHz (up to 100m)
- **IEEE 802.11n**: 250Mb/s wireless LAN @ 5GHz (up to 30m)
- **UWB (IEEE 802.15.3a)**: 480Mb/s wireless USB2.0 (typ. 1m)
- **WiMax (IEEE 802.16d/e)**: ~10Mb/s broadband wireless access
- **NFC**: Near Field Communications (RF-ID, wireless payment,…)
- **WiFi 802.11a**: 54Mb/s wireless LAN @ 5GHz (up to 100m)
- **WiFi 802.11g**: 54Mb/s wireless LAN @ 2.4GHz (up to 100m)
- **WiFi 802.11n**: 250Mb/s wireless LAN @ 5GHz (up to 30m)
- **WiFi 802.20**: ~10Mb/s broadband wireless access
- **ZigBee (IEEE 802.15.4)**: Sensor networks, remote control
  - Bluetooth
    - Version 2: TBD?
2009: Integration Cleanup Roadmap of Wireless Standards into Handsets

Status Today
- GSM/UMTS
- Bluetooth
- FM Radio
- WiFi 802.11bg
- GPS

Status Tomorrow
+ WiMax
+ WiFi 802.11
+ Galileo
+ WiFi 802.11n
+ Galileo
+ LTE / WiMAX
+ GPS / WiFi 802.11

Loosers:
- MediaFlow
- UWB
- DVB T/H
- NFC
- ZigBee
- 802.20
The Only Wireless Features We Need?

- Cellular Connectivity ➔ Fast
- Broadband Local Connectivity ➔ Fast
- Positioning
How to Achieve “FAST” in Cellular
Shaping the SINR Distribution

Active „shaping“ of SINR

- Interference Cancellation
- Power Control

Advantages

- High average SINR
  - High spectral efficiency
  - Enabler for MIMO
- Small Variance
  - High grade of fairness
Interference Cancellation: Fairness & High Data Rate
CoMP: Coordinated Multi-Point

- We thus believe that next generation systems will include multi-cell cooperative signal processing ("network MIMO" or CoMP):
Roadmap View

1st/2nd generation

• Interference avoidance through high reuse factors

3rd generation

• Interference suppression through classical MIMO

4th generation

• Interference shaping and exploitation through distributed MIMO and relaying
Potential Gains of CoMP

- Okumura-Hata pathloss model, ITU pedestrian A
- Link-to-system mapping (MIESM), 8 MCS schemes
- Spectral eff. losses through guard bands / intervals
- Assuming perfect channel est., 2 rx ant. per eNB

- Linear joint transmission, assuming perfect channel knowledge at the eNBs
- 2 tx ant. per eNB
We can easily observe how many interferers would have to be perfectly cancelled for a user at any location within a cell, to achieve a **capacity target**:

- **Target 3 bit/s/Hz/sector**
- **Target 4 bit/s/Hz/sector**

Note that we are assuming **perfect interference cancellation** (optimistic), but do not take into account increased diversity (pessimistic).
Spectral Efficiency

License Cost (GER)

- $1Hz \sim EUR~1000$
- $100Mb/s/\text{sector}$ required:
  - GSM: $1GHz \Rightarrow €1T$
  - LTE: $100MHz \Rightarrow €100B$
  - Theory: $10MHz \Rightarrow €10B$

**GAP**

20 YEARS Of Engineering
1987 - 2007

20 further YEARS Of Engineering
2007-2027?
Enablers for Ambient Services & Systems
Part C: Wide Area Coverage

EASY-C Update
Project Partners
Coordinator: Gerhard Fettweis

Volume:
€ +47M project
€ +27M funding
Current View on Network MIMO

- See the following challenges connected to network MIMO:
  - Channel estimation & Obtaining transmitter-side CSI at eNBs
  - Synchronization in time / frequency
  - Reducing Backhaul / Infrastructure Aspects
  - Scheduling
  - System partitioning
  - Impact of network MIMO on higher protocol layers
Project Workflow

1.1 Algorithm & Concept Exploration

1.2 Algorithm Classification & Selection

2.1 Specification

2.2 Implementation

2.3 Lab Test

2.4 Field Test

3.1 Specification

3.2 SoC Architecture

3.3 Implementation

3.4 Demonstrators

1.3 Assessment & Dissemination

Working Groups

WG 1
Algorithms & Concepts

WG 2
Technology Test Bed

WG 3
Hardware Architecture

Working Groups

Alcatel-Lucent
BNetzA
Dt. Telekom
Ericsson
FhG HHI
IFX/Comneon
Kathrein
NXP
Qualcomm
Radioplan
Signalion
TES
TU Dresden
Ubidyne
Uni Paderborn
Vodafone
Two sectors are installed on the roof of TUD building:
Lab Site:
- 2 sites at the chair
- Antenna: 1700-2700Mhz
- Microwave link between the sites

Mobile Lab UE:
- Sorbas UE
- 12V Battery
- Notebook
Field Test Berlin

Overview

- In Berlin, a second test bed is being set up, with a focus on services and applications.
Cellular After 2015
Testbed Dresden
Field Test

- LTE+ antennas co-located at real 3G sites (downtown, height of antennas 30-55m)
- Support from project partner (Vodafone, T-Mobile)
- Backhaul realized with Motorola Canopy PTP600 system (250 Mbit/s TDD system)
Additional Challenges:
“Lessons Learned”
OFDM for Downlink CoMP

$t = t_0 - \tau$

$t = t_0 - \tau$

$d \rightarrow \text{distance between cooperating base stations}$

$\tau \approx d/c$

Use CP to compensate?

LTE: $d=360m$
Carrier Phase Offset, Phase Noise

- Carrier Phase Offset (CPO)
  - Caused by LO imperfections
- Phase Noise (PN)
  - Caused by LO jitter due to non perfect sine generation
- CoMP $\rightarrow$ PN increased by 3-5dB
Sampling Clock Offset

- Sampling Clock Offset (SCO)
  - Sampling offset between ADC and DAC
  - Caused by LO imperfections
  - Range: $10^{-5}$ - 50ppm related to sampling rate
  - CoMP ⇒ “negligible asynchronous OFDM”

![Diagram of communication system with labels and arrows indicating various components such as ADC, DAC, PLL, BPF, LPF, VGA, AGC, Tx DFE, Rx AFE, Tx AFE, and Rx DFE.](image)

$h(t, \tau) \rightarrow$ Doppler Spread

© Vincent Kotzsch, 2008
Carrier Frequency Offset

- Carrier Frequency Offset (CFO)
  - Continuously phase shift over time
  - Caused by LO-imperfections and Doppler
  - Range: $10^{-5}$ - 50ppm related to $f_c$
  - CoMP $\Rightarrow$ “artificial Doppler”
Requirement “FAST” will not end soon
GREEN

cool
The Server Farms Are Growing

- Moore’s law for logic: 5x every 5 years
- Moore’s law for flash: 10x every 5 years

Result: 2x power consumption every 5 years
The Challenge

In 2007 the Energy supply of ICT produced CO₂-output at level of 25% of worldwide cars.
Paradigm Change

Computing
Internet-Server (Mio.)

Cellular
Customers (Mio.)

Energy Costs = Invest

2007

Energy Costs = Personnel
Energy Demand & CO$_2$ of ICT

- **Server farms & telco infrastructure**
  - Currently 3% of world electric energy consumption
  - Increasing by 16-20% / year
  - Doubling world el. energy consumption by 2030 driven by ICT

- **ICT: 10% of el. energy demand within industrialized nations**
  - 900 Bill. kWh / year = Central and South Americas
  - Worldwide proliferation: 40% of world el. energy production

→ Dramatic improvement in energy efficiency needed!
Cellular: What Do We Know

Cellular networks: 0.5% of world-wide electrical energy
- Handsets: 1% of total cellular energy consumption
- Network: 99% of total cellular energy consumption

Running the network:
- Expected energy bill: 3x (200%) over next 7 years
- 80% of energy consumed at base station site
  - 50% for cooling
  - E.g. UMTS CDMA: 25% power in “pilot pollution” !!!
  - “Always on” the wrong strategy?!

Need of “border-crossing” optimization:

*System Engineering*
Coordinator
Prof. Gerhard Fettweis

energy efficiency innovations
from silicon saxony
Key Facts of Cool Silicon

- **Partners**
  - Companies
    - Currently around 40 companies involved
  - Universities
    - TU Dresden
    - TU Chemnitz
    - HTW Dresden
  - Research Institutes

- **Money**
  - EUR 100M funding
  - EUR 150M total volume

- **Duration:** Feb-2009 to Feb 2014
How to Achieve “GREEN” in Handsets (& Base Stations)
LTE FDD & TDD / WiMAX Single-Chip SDR: Tomahawk – Block-Diagram

Our Testchip "TOMAHAWK": running silicon Jan 18, 2008
LTE FDD/ TDD/ WiMAX Single-Chip SDR: Tomahawk - Die Photo

In 45 nm CMOS:
Complete LTE BB
< 20mm²
< 200mW

130nm UMC
57M transistors

10 mm

Silicon on
Jan 18 2008

3x DDR Controller
2x STA SIOUX
PLL

Steel on
Jan 18 2008

STA Vector DSP

2x Xtensa
DC212GP

Scratchpad
Core
Manager

10 mm

2x STA SIOUX

LDPC Decoder/
Deblocker

STA

ASIP

PLL

TU Dresden
Gerhard Fettweis
Slide 48
Area & Power Efficiency

1. MIMO SVD ASIC
2. Consumer RISC
3. Multimedia DSP
4. FFT Processor
5. RISC CPU with Media Processor
6. Communications DSP
7. CAM LSI
8. Video Stream Multi-Processor
9. Hearing Aid DSP

Source: Markovic et. al., Power and Area Minimization for Multidimensional Signal Processing, IEEE J. Solid-State Circuits, vol. 42, no. 4, pp. 922-934, April 2007. Results scaled to 90 nm, operations are 12 bit add equivalents
How to Achieve “GREEN” in Networks
Some Issues

- Network topology
- Network architecture
- Network components
- Network interconnections
- Network supported features
- Network delivered bandwidth
DIRTY RF
Dirty RF

- Picking up “dirt”
  - Nonlinear LNA
  - Feedthrough
  - Coupling
  - Phase noise
  - Aperture Jitter
  - Ambiguity
  - I/Q Imbalance
  - RRC mismatch
  - Flicker Noise
  - Digital noise

Nonlinear PA

16-QAM Constellation at y(n)

Digital noise

DSP: Living With Dirty RF

- Jitter constant
- Sampling frequency
- Number of sampling points
- Block length
Transmit Leakage in FDD and Direct Conversion

Problem: Tx Leakage in FDD Terminals

- Limited Tx-Rx Isolation due to miniaturization and frequency agility
  → Tx Leakage (TxL)
  → Strong out-of-band interference in Rx branch

Approaches for Solution:

- Additional bandpass filter
- Adaptive filter in parallel to duplexer
- **Dirty RF**: Compensation of analog impairments by digital signal processing
  + Reconfigurable / standard independent / relaxed RF requirements

- Limited reconfigurability
- Increased analog complexity
Tx Leakage in Zero-IF Receivers

**Tx Leakage intermodulation products 2nd order (TxL-IM2)**

- Nonlinearity of I/Q down converter
  - Intermodulation product 2nd order of Tx Leakage (TxL-IM2)
- Low freq. TxL-IM2 interfering desired, down converted DL signal
Tx-Rx Isolation

Measurement with UMTS SAW Duplexer B7632 (EPCOS AG)

- Antenna nearfield distorted by metal interrupter moved within distance [0.036, 0.303] m to the antenna

![Graph showing Tx-Rx isolation with different frequency bands and values](image-url)
SNR loss due to TxL

OFDM susceptible to TxL for $\gamma_{\text{TxL}} < 30\text{dB}$
- digital TxL compensation
  suitable for $\gamma_{\text{TxL}} > 0\text{dB}$
  $\Rightarrow$ TxL can be mitigated digitally up to 30 dB

- ML reaches almost Genie Cmp. limit, but suffers from high min. SNR loss
  - LMS performance strongly depending on TxL channel property

Simulation Parameters:
- DL / UL: 802.11a, 16QAM
- DL channel: HiperLAN A
- CSF EQ in TxL Est.
- analog DC$^{-1}$
- ADC: 8-bit lin. mid-rise, $\eta=2$
- TxL: 6-tap exp PDP and meas. IR
  - TxL SIR $\gamma_{\text{TxL}} = 10\text{dB}$
  - no TxL I/Q mismatch
- TxL Est: $N_B=4000$, $\hat{L} = L$
**Phase Noise and Clipping**

- **Phase Noise:**
  - Kalman Tracking
  - Complete Sync

- **Clipping:**
  - Analogue PAPR
  - Saleh Model
  - AM/PM distortion

- **Clipping & PN:**
  - Rate
Phase Noise in OFDM
Rate under Phase Noise & Clipping

Setup:
IEEE 802.11a SISO
Exponential PDP, 8 taps
64-QAM f = 4GHz, IBO = 0dB

\[ c_{vco} = 3 \cdot 10^{-17} \]
Many Further Issues

“Estimation and Detection” algorithm design
- Nonlinearities
- Phase noise
- I/Q imbalance
- Sampling jitter
- Transmit leakage
- …
Conclusions
- **FAST** increasing data transmission rates
- **GREEN** much lower-power “cool communications”
- RF impairment estimation with **DIRTY RF** approach

→ We need much more further research!
Thanks!

Thank you Vodafone for the continued support of the chair

www.vodafone-chair.com