Wireless Gigabit With Dirty RF

Gerhard Fettweis

vodafone Chair, TU Dresden

www.vodafone-chair.com
Dresden: No. 1 Semiconductor Site in Europe

TU Dresden: No. 1 EE Department in Germany (CHE)
Chair and Its Partners

Projects

Sponsors

Cooperation

IPP 2004:
Oct-06

Technische Universität Dresden

1 professor
3 secretaries
4 sen. scientists
1 post-doc
2 system adm.
24 Ph.D. students
25+ Ms students

EADS
Lucent
MEDAV
Nokia
T-Mobil

TH Aachen
TU Berlin
U Bremen
U Dortmund
U Erlangen
TU Ilmenau
U Karlsruhe
TU Munich
FhG-HHI Berlin
FhG-EAS Dresden
IHP Frankfurt/O
Mission

- Provide leading research results teaming with academic and industrial partners
- Create a great resource of human capital
- Enable startups to be founded
Main Research Topics

- Wireless Gigabit & 100Mb/s cellular
  - MIMO, precoding, demodulation, synchronization

- Dirty RF
  - Nonlinearities, phase noise, sampling problems

- Digital front-end (SDR)
  - Sampling rate, channelization filtering

- Vector Digital Signal Processors
  - Algebra based processor design, compiler-friendly
Startup History

1999  OnDSP™ based WLAN chip-sets

2000  UMTS/3G network optimization and planning

2003  Real-time hardware for developing the wireless future

2004  Module and reference board design
Systemonic Company Profile

Fabless Semiconductor Vendor
Founded: July 1999

Funding:
- $5M / €5M Round One,
- $30M / €35M Round Two
- Investors: ATLAS Venture, APAX, Krone mt., Robertson Stephens, Lehman Bros, Raytheon, Sony Venture Capital Europe, TBG

Acquired Complete Radio Solution from Raytheon Company in Oct 2001

Offices:
- Dresden, Germany
- San Jose, CA
- Marlboro, MA

Head count ~100
74 patents / pending

Acquired by Philips Semiconductors in 12'2002
Radioplan

Provider of Integrated Solutions for:

- Scalable high speed ray tracing (RPS, selected for 4G development in Japan)
- Automated optimization of 3G networks based on planning and measurement data
- Quality of service validation of UTRA/FDD networks based on dynamic and hybrid simulation
- 3G Network verification by drive test measurement solutions

Spin-off from Vodafone Chair at Dresden University of Technology, founded in 2000

Partners:

Panasonic
SIEMENS

Forsk
Radioplan Today

- Headquarters: Dresden/Germany
- Customers in Asia / Europe / America
- Customers in over 20 countries
- Leader in 3G network optimization
- Main supporter of B3G development

Visit at www.radioplan.com
Signalion Mobile Solutions

System Design

Software Defined Radio
MIMO
Standards (e.g. IEEE 802.11, UMTS)
Codecs (Audio & Video), Speech Processing

Simulation, Measurement & Modelling

Matlab, CoCentric, C

Application Specific HW/SW Codesign

HW-Modeling (VHDL, SystemC)
DSP-Programming (C, C++, Assembler)
FPGA-Prototyping (Xilinx, Altera)
Product Performance

- 2 Mb/s, 1994
- 11 Mb/s, 1998
- 54 Mb/s, 2002
- ¼ Gb/s, 2006
- 1 Gb/s, 2010

IEEE 802.11 WLAN
WIGWAM
Wireless Gigabit With Advanced Multimedia Support
www.wigwam-project.com

Coordinator: Gerhard Fettweis

Sponsor: €8M, plus industry with €7M ➔ total €15M

Main Partners:
- Technische Universität Dresden
- Vodafone Chair
- Alcatel
- Siemens
- Daimler Chrysler
- Philips
- Nokia
- Infineon Technologies
- ihp
Consortium

Main Contractors
- Technische Universität Dresden (Vodafone Chair)
- ALCATEL
- Infineon Technologies
- PHILIPS
- SIEMENS
- DAIMLERCHRYSLER
- MEDAV
- NOKIA
- TELEFUNKEN

Sub Contractors
- RWTH Aachen (Walke)
- TU Berlin (Wolisz)
- Univ. Bremen (Kammeyer)
- Univ. Erlangen (Weigel)
- TU Ilmenau (Haardt)
- TU Ilmenau (Thomä)
- TU Karlsruhe (Wiesbeck)
- TU Karlsruhe (Zitterbarth)
- TU Munich (Eberspächer)
- Univ. Ulm (Lindner)
- FhG HHI (Boche)
- FhG IAS (Reichl)
Requirements (1)

△ data rate of 1 Gbit/s
Some WIGWAM Features

PHY/DLC Parameters
- QoS enabled MAC: up to 1Gb/s cumulative user rate
- Carrier: 5GHz \( (n \times 20\text{MHz channel}) \)
- Transmit power: 100/1000mW
- Coding & modulation: open (OFDM with MC-CDMA overlay?)
- Transceiver size: MiniPCI or smaller
- Antennas: minimum 2

Network Parameters
- IP packet & streaming & VoIP network
- Integration into 3GPP IMS (all IP) Core Network

Cost Parameters
- Terminal chip-set goal: €10 (low)
- Base Station / Access point goal: €100 (indoor)
### Project Structure

#### Project Coordination

<table>
<thead>
<tr>
<th>AP 1: System Concept</th>
<th>AP 2: Hardware Platform</th>
<th>AP 3: Physical Layer</th>
<th>AP 4: Data Link Control / Radio Link Control</th>
<th>AP 5: Network Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUD</td>
<td>Infineon</td>
<td>Siemens</td>
<td>Philips</td>
<td>Alcatel</td>
</tr>
</tbody>
</table>

#### System Concept Group (TUD, Infineon, Siemens, Philips, Alcatel)

1.1 System Concept

1.2 Standardisation

1.3 Applications/Scenarios

2.1 Architecture and Models

2.2 Implementation

3.1 PHY

3.2 MIMO

4.1 MAC

4.2 Centralized/Non-Centralized Networks

4.3 Heterogenous Networks / MxRRM / Frequency Coordination

5.1 Mobility Management

5.2 IP layer protocols

5.3 Demonstrators

### All Partners

- **Daimler Chrysler/ Uni Erlangen**
- **EADS**
- **IHP**
- **Infineon/ Uni Erlg.**
- **Nokia/ Uni KA**
- **TUD**

- **EADS / U Ulm**
- **HHI**
- **MEDAV / TU IL**
- **NOKIA**
- **Siemens**
- **TUD**

- **Alcatel**
- **IHP**
- **Philips / TH AC**
- **Siemens / TU M**
- **TUD**

- **Alcatel / U KA**
- **EADS / TU Berlin**
- **Philips**

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Technische Universität Dresden

**Vodafone Chair**
Mobile Communications Systems

03-2003, Gerhard Fettweis
Requirements (2)

Assuming

- a sample rate of 100 MSps
- a channel bandwidth of 100MHz

→ we need spectral efficiency of 10 bit/s/Hz

What do we have today

- IEEE 802.11a @ 54Mb/s: 3.3 bit/s/Hz
- extended 802.11a @ 72Mb/s: 4.4 bit/s/Hz
Implications as to Standardization Activities
IEEE 802.11 – IEEE 802.16 – IEEE 802.20

IEEE .11 1Gb/s Standard Proposals Expected
IEEE .16 High-Speed Standard Proposals Expected

WIGWAM System Specs Ready
WIGWAM 1st System Definition Ready
WIGWAM System Definition Ready
WIGWAM System Details Ready

BMBF WIGWAM-project

IEEE 802.16
WIGWAM System Specs
Ready
WIGWAM 1st System Definition Ready
WIGWAM System Definition Ready
WIGWAM System Details Ready

IEEE 802.11
1Gb/s Standard Proposals Expected

2003 2004 2005 2006 2007
1 Gbit/s at Home!

Ad-Hoc “Self Configuring” Home Network
Key Home Scenario Parameters

△ Terminal Parameters
   - Velocity 1 m/s (4km/h)
   - Size restriction maximum miniPCI, better Flash-Card
   - Energy constraint 0.5-2.0 Ah
   - Operating temperature 0-50°C

△ Traffic & MAC
   - Acceptable latency 10 / 1000 ms
   - Delay jitter < 1ms
   - Access points asynchronous

△ Features
   - Localization no
   - Fallback 802.11
   - Range typ. 20m

△ Channel
   - Typical delay 0.3 μs
   - Delay spread 0.015 / 0.03 μs
   - Channel exponent 2.5 / 3.5
   - Doppler spread 200 Hz (f_c = 60Ghz)
we are used to: fixed 100 Mbit/s access:
- average on working day in 4-people-office: 1 Mbit/s
- peak in 4-people-office: 10 Mbit/s and more
→ very high “crest factor”
Key Office Scenario Parameters

Terminal Parameters
- Velocity: 1 m/s (4km/h)
- Size restriction: maximum miniPCI, better Flash-Card
- Energy constraint: 0.5-2.0 Ah
- Operating temperature: 0-50°C

Traffic & MAC
- Acceptable latency: 10 / 1000 ms
- Delay jitter: < 1ms
- Access points: asynchronous

Features
- Localization: no
- Fallback: 802.11
- Range: typ. 20m

Channel
- Typical delay: 1 µs
- Delay spread: 0.15 / 0.3 µs
- Channel exponent: 2.5 / 3.5 @ 5Ghz, 2.5 / 5.0 @ 60GHz
- Doppler spread: 200 Hz (f_c = 60Ghz)
1 Gbit/s for Public Access?

“hot spots”, e.g. lounges with 
50 users at 80 m²

△ connect “local” computers 
(100m range)

△ Internet backbone provides 
best-effort service

△ vertical & horizontal hand-off

△ dramatic variation of max 
transmission bit rate during 
hand-off
Key Public Scenario Parameters

▲ Terminal Parameters
  - Velocity
  - Size restriction
  - Energy constraint
  - Operating temperature
  0-5 km/h / 3-10 km/h / 60-100km/h
  maximum miniPCI, better Flash-Card
  0.6 Ah (PDA) – 6.0 Ah (laptop)
  -10°C – +50°C

▲ Traffic & MAC
  - Acceptable latency
  - Delay jitter
  - Access points
  10 / 1000 ms
  2-3ms streaming / 500ms packets
  asynchronous

▲ Features
  - Localization
  - Fallback
  - Range
  yes
  UMTS
  up to 500m

▲ Channel
  - Typical delay
  - Delay spread
  - Channel exponent
  - Doppler spread
  1 µs
  0.15 / 0.3 µs
  open
  520 Hz (f_c = 5Ghz)
1 Gbit/s at High Velocity

Freeway & Track information access
Key High Velocity Parameters

△ Terminal Parameters
- Velocity 250 km/h – 600 km/h
- Size restriction ~ 1 liter
- Energy constraint “none”
- Operating temperature -40°C – +80°C

△ Traffic & MAC
- Acceptable latency 10 / 100 ms
- Delay jitter 10/100 ms
- Access points asynchronous

△ Features
- Localization yes (0.5m accuracy)
- Fallback GSM (UMTS)
- Range up to 3000m

△ Channel
- Typical delay open
- Delay spread open
- Channel exponent 2 – 3
- Doppler spread 20 kHz ($f_c = 38$Ghz)
1 Gbit/s and Mobility?

△ using the IBMS-approach:
trade-off data rate vs. mobility
Key Challenges

▲ Challenge
  – 1Gb/s on the air
  – 1Gb/s implementation
  – 1Gb/s networked into infrastructure
  – Standardization impact

▲ MAC ↔ PHY

▲ PHY

▲ Dirty RF
A MAC-PHY Idea
A Basic Idea

MIMO OFDM

Multi-Carrier Spread Spectrum

Multi-Carrier Spread Spectrum
High bit-rate
  - MIMO
  ➔ OFDM

Signaling & synchronization pilots
  - Low bit rate

Solution
  - MIMO-OFDM (>10bit/s/Hz)
  - Plus overlaid MC-CDMA
  - Layered “interference” canceling receiver
Dirty RF

Gerhard Fettweis
Tim Hentschel, Wolfgang Rave, Heinrich Nuszkowski,
Michael Löhning, Denis Petrovic, Marcus Windisch,
Peter Zillmann, Ernesto Zimmermann

Chair, TU Dresden
www.vodafone-chair.com
Prof. Zinkernagel, Uni Zürich, 5. 3. 2004

“Früher war alles besser – Selbst die Zukunft!”

“Everything used to be better – even the future!”
A Large Amount of Places To Pick-Up „Dirt“

Phase noise  Nonlinear PA  Nonlinear LNA  Phase noise

Aperture jitter
Clock jitter
I/Q imbalance
RRC mismatch
Flicker noise
Phase Noise
The non-logarithmic spectrum can be expressed by:

\[ S_{SSB} \approx (1 + \gamma) \frac{kT}{P_{\text{sig}}} \frac{\omega_0^2}{Q^2 \Delta\omega^2} \]

In detail:

\[ S_{SSB} \approx (1 + \gamma) \frac{kT}{P_{\text{sig}}} \frac{\omega_0^2}{Q^2 \Delta\omega^2} \]

Hence, it depends on Vdd as:

\[ S_{SSB} \sim \frac{1}{V_{DD}^2} \]
Simulation Results and Cut-off Rate

AWGN Channel, $r = \frac{1}{2}$ Standard convolutional code
QPSK, 16-QAM, 64-QAM modulation schemes
$\Delta f_{3\text{dB}}/\Delta f_{\text{car}} = \{0, 0.016, 0.032, 0.064, 0.160\}$
Simulation Results

Phase noise influence on higher order modulations
Comparison: EKF + Decision feedback (DF) vs. Ideal Common Phase Error Correction

![Graph showing simulation results for phase noise influence on modulations.](image)
Phase Noise: MIMO RF-IC
- **Idea**
  - Apply Dirty RF concept for a product development

- **Problem**
  - How does MIMO impact the specification for an RF-IC?
  - How to architect the RF?
  - How to make use of “Dirty RF” concepts to develop a low-cost & low-power solution

- **Projected outcome**
  - MIMO RF-IC architecture & specification for WLAN
First Outcome of Dirty RF Concept: Coping With Phase Noise

- Classical solution:
  - Phase noise should be uncorrelated on each branch
  - Separate oscillators help improve performance
  - $M$ antennas
    $\Rightarrow$ $M \times$ RF complexity

- Dirty RF solution
  - Phase noise should be correlated on each branch to improve tracking performance
  - Single oscillator preferred
  - $M$ antennas
    $\Rightarrow$ $M \times$ RF signal chain complexity increase only
Power Amplifier & LNA
Baseband Model:

- Matched RRC Filtering
- Saleh PA Model
- QPSK, 16-QAM, 16-PSK

16-QAM Constellation at $y(n)$
Closed-Form Solution:

- Polar Coordinates
- Bayesian Estimation of Magnitude only
- Approximation of $|y(t)|$ by Noise Projection

Performance Example:

- 2048 OFDM Carriers
- IBO = 3 dB
- 16-QAM
I/Q Imbalance
Problem Definition

- Ideal
  - 90° Phase
  - I & Q-amplitude equals 1

- Realistic
  - Phase imbalance
  - Amplitude imbalance
The beautiful world of theory:

- Equal amplitude
- Perfect phase match (90°)
The brute world of reality:

- Desired channel
- Strong adjacent channel

\[ X(f) \]

\[ Y(f) \]

\[ Z(f) \]

\[ x(t) \]

\[ y(n) \]

\[ z(n) \]

Mismatches in:
- amplitude
- phase

Serious interference by the image signal
SNR performance limits due to:

- thermal noise
- aperture jitter
  - sampling time errors
- comparator ambiguity
  - quantization errors due to limited comparator speed

For an effective resolution bandwidth (ERBW) range of about 1 MHz to 1 GHz **aperture jitter** is the dominating effect that limits the SNR of high resolution wideband ADCs.

**Clock Jitter** has a similar effect on the SNR of (memoryless) ADCs.
Practically relevant case: \( |f_{i_{\text{max}}}| \ll \sigma_{\text{jitter}}^{-1} \)

- input signal: mix of **two sine waves** with frequencies of 10 MHz and 100 MHz

- **constant** error PSD (white noise floor) (independent of the input signal spectrum)

- **oversampling** increases the jitter dependent SNR in a given frequency band (limit determined by line components)

- weighted lines of the input PSD + Lorentzian spectra around them

- oversampling **does not** help

- **different** error power / SNR for equal-power spectral input components
Finally
- Picking up "dirt"

Dirty RF phenomena include:
- Aperture Jitter
- Ambiguity
- I/Q Imbalance
- RRC mismatch
- Flicker Noise
- Phase noise

Nonlinear PA
Nonlinear LNA

1-S-QAM Constellation at $y(n)$

Phase noise

Graphs showing SNR vs. SNR cut-off rate $R_0$ and Power Spectral Density in dB.
Today

- Baseband guys require RF to be “perfect”
- RF guys try to design best effort to achieve specifications

RF Reality & Outlook

- “Dirty RF” is becoming reality
- Challenging task: Combined RF-baseband solutions to become possible
And Now?

⇒ Putting thing together to achieve 1Gb/s
At low cost
Thanks!
10 Years Support

www.vodafone-chair.com
IST Mobile Summit 2005 Announcement