5G - What Will it Be: The Tactile Internet

Gerhard P. Fettweis – Vodafone Chair Professor

ICC 2013 – Budapest

G. Fettweis

**A 5G Wireless Communications Vision**, 2012-12-15, Microwave Journal

[www.microwavejournal.com/articles/print/18751-a-5g-wireless-communications-vision](http://www.microwavejournal.com/articles/print/18751-a-5g-wireless-communications-vision)
The Team
- 1 professor
- 8 senior scientists/lecturers/post-docs
- 32 Ph.D. students
- 15+ Master students
- 4 program managers
- 8 start-up incubator employees
- 5 secretaries
- 5 lab engineers

Accomplishments
- Scientific:
  - 62 Ph.D. grads
  - 200+ Ms. grads
  - 700+ publications
  - 9,000+ citations
  - 200+ patent appl.
  - 60+ patents
  - 85+ patent families
- Innovation:
  - 10 spin-outs
  - 350 engineers
  - Funding:
    - € 50M Chair
    - € 50M VC
    - € 1/3B projects

IPP Sponsors

Project Partners
The Vodafone Chair’s Startup History

- **Founded 1999**: OnDSP™ based WLAN chip-sets
- **Founded 2000**: SON systems
- **2003**: Broadband Wireless HW (LTE, …)
- **2004**: Module and reference board design
- **2005**: MPSoC semiconductor IP
- **2007**: Wireless audio
- **2008**: Network performance measurement
- **2008**: LTE Cellular Handset Chip IP
- **2010**: Satellite Communications
- **2013**: Assisted living
- **2012**: Startbahn Venture Fund
ELECTRONICS FUTURE
Center for Advancing Electronics Dresden

Gerhard P. Fettweis (coordinator)
60+ Investigators and Teams
Enabling the information processing of electronics

Organic electronics for information

Managing heterogeneity in large-scale systems

Reliable computing with unreliable components

Reconfigurable from software to hardware interconnects

Learning from nature’s information processing

More-Shots-on-Goal

CMOS (industry focus)

Silicon Nanowires

Carbon

Organic

Biomolecular Assembly

Chemical

Orchestration

Resilience

HAEC: Highly Adaptive Computing 

Biological Systems

• Reconfigurable circuits

• Nanosensing

CNT transistors as radiofrequency amplifiers

Organic electronics for information processing

Using DNA scaffolds to build advanced electronic devices

Enabling the information processing of biology
ELECTRONICS ROADMAP
Tomahawk SoC (130nm CMOS): Single-Chip LTE Baseband & H.264

In 28 nm CMOS:
- Complete LTE BB
- < 10mm²
- < 100mW

PCB – printed circuit board

IC 1

IC 2

Interposer

PCB – printed circuit board
State-of-Art: 16 Chip-lets In a Stack

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© Samsung

Demonstrated full sequence of wafer bonding/thinning/backside processing, wafer taping, debonding and cleaning on tape of active CMOS wafers
TUD/MI TwinLab: 3D Chip-Stack Intraconnects

3D-Integrated µel. for Minimum Energy Design

Research Topic


Institute

TU Dresden

Masdar Institute

Dahlem, Dimas, Elfadel, Gougam, Henschel, Khilo, Nayfeh, Saadat, Sammoura, Yoo, Shabra, Viegas

Principal Investigators

Fettweis, Bartha, Ellinger, Plettemeier, Schöffny

TSV Intraconnects

Wireless Inductive

Wireless Optical

VCSEL

Interposer

PD

30.07.2013
90Gb/s Results

A Source-Synchronous 90Gbit/s Capacitively Driven Serial On-Chip Link over 6mm in 65nm CMOS in Proc.59th ISSCC’12
The „Tommy“ System-on-Chip

- 7.03 mm² die with 17 million transistors (65nm TSMC LP process)
- GALS SoC Approach
- 300Mbps @ 40mW Detection & 370mW Decoding

Highly Adaptive Energy-Efficient Computing

DFG SFB 912
(German Science Foundation Collaborative Research Center)
In operations since July-1, 2011

Gerhard P. Fettweis (coordinator)
Wolfgang Lehner (vice coordinator)
Wolfgang Nagel (vice coordinator)
Highly Adaptive Energy-Efficient Computing
High-Rate Inter-Chip Communications

Optical Interconnect
- adaptive analog/digital circuits for e/o transceiver
- embedded polymer waveguide
- packaging technologies (e.g. 3D stacking of Si/III-V hybrids)
- 90° coupling of laser

Radio Interconnect
- on-chip/on-package antenna arrays
- analog/digital beamsteering and interference minimization
- 100Gb/s
- 220GHz carrier / 25GHz channel
- 3D routing & flow management
Highly Adaptive Energy-Efficient Computing

Simulation & Prototyping

Information Processing

- Application
- Middleware
- Runtime
- Operating Sys.

Processor

Devices & Circuits

- Server level
- Wireless
- Optical
- Board level

Flexible Software

Flexible Hardware Interconnects

Energy Control Loop
The Outlook: The **HAEC** Box in 2020+

- Assume 128K processors per chip
- 128x chips stacked in 3D
- 4x4 chip-stacks on board
- 4x boards in a box

in 10x10x10 cm³ (1 liter)
8192 chips

⇒ 10⁹ processors!
⇒ 10⁵x performance of today!
TU Dresden’s Mission in Challenging Roadblocks of Electronics

✓ Integration Plateau
✓ Interconnect Bottleneck

€100M program
> 50 startups
Interim Conclusion

The Semiconductor Story Continues Until 2040!

It drives data ➔ the wireless roadmap!!
Coverage: Cellular

- GSM
- GPRS
- 3G R99 / EDGE
- HSDPA
- HSPA
- LTE
- LTE Advanced

Short links (1m)
- USB 1.0
- USB 2.0
- UWB intention

WLAN (10m)
- 802.11
- 802.11b
- 802.11ag
- 802.11n
- 802.11ac/ad

Cellular (100m)
- 802.11
- 802.11b
- USB 1.0
- USB 2.0
- USB 3.0
- UWB intention
- 802.15.3c
- 100Gb/s
- 10Gb/s
- 1Gb/s
- 100Mb/s
- 10Mb/s
- 1Mb/s
- 100Kb/s
- 10Kb/s

Timeline:
- 1995
- 2000
- 2005
- 2010
- 2015
>2020 Outlook

Graph showing the projected bandwidths from 1995 to 2030.
2005/4/4 – Via Della Conciliazione

Source: http://www.spiegel.de/panorama/bild-880031-473266.html
2013/3/12 – Via Della Conciliazione

Source: http://www.spiegel.de/panorama/bild-889031-473242.html
Watch Out!

http://static.o2.co.uk/www/img/iphone-device/4_phones.png
THE TACTILE INTERNET

G. Fettweis

A 5G Wireless Communications Vision, 2012-12-15, Microwave Journal

www.microwavezjournal.com/articles/print/18751-a-5g-wireless-communications-vision
Physiology and Psychology
Gaming...

http://popular-pics.com/Cool_World_RecordLAN_Event_Computer_Pictures__5
http://gametaffy.com/imho-the-lan-party/
Professional Audio

Remote Heli

http://ds_product_photos.s3.amazonaws.com/large/9756.jpg
Today’s urban Traffic

Example: Urban Traffic at Arc de Triomphe

Future Vision
Platooning 2.0

- 1ms examples of today’s cars: ESP, ABS

- Tomorrow: Platooned ESP & ABS
Traffic Control
Wireless Airbags

Crash to impact: 10-15ms
- Crash sensor
- Trigger
- Air bag
Exoskeletons – “Power Limbs”

http://news.cnet.com/8301-17938_105-57532729-1/nasa-exoskeleton-suit-is-half-way-to-iron-man/
Health / Physiotherapy

http://www.medindia.net/patients/patientinfo/images/physiotherapy.jpg
Virtual Overlay

http://googlesystem.blogspot.de/2009/12/google-goggles-mobile-visual-search.html
Sports

Smart Grid

Paradigm of 5G Cellular: Control

Traffic / Sports / Education / Health&Care / Manufacturing / Games / Smart Grid..
SmartRAN

Distributed Compute
Within Distributed Cloud

Data Center
Steering & Ctrl Center

router
Content Communications

Steering & Control Communications
Additional (non-functional) Requirements

- Accountability & Archiving
- Authorization
- Failure Resilience
- Attacker Resilience
- Eavesdropping Security
10ms $\Rightarrow$ 1ms Impact

Latency Goals:

$\Sigma = 0.3$ ms

Air Interface

$\Sigma = 0.2$ ms

Terminal $\Rightarrow$ Base Station

$\Sigma = 0.5$ ms
Multicarrier $\rightarrow$ spectrum agility

Short TTI $\rightarrow$ e.g. 32µs
- Symbols, e.g. 4µs
- Subcarrier spacing, e.g. 250kHz
- Frequency selectivity on subcarriers

Cannot be OFDM in its classical way
Overview of Multi-Carrier Schemes

Filtered Multicarrier Systems

- OFDM (Orthogonal Frequency Division Multiplexing)
- BFDM (Biorthogonal Frequency Division Multiplexing)
- FBMC (Filter Banks Multicarrier)
- UFMC (Universal Filtered Multicarrier)
- GFDM (Generalized Frequency Division Multiplexing)

5GNOW

Dresden, 05 June 2013
Nicola Michailow
Multi-carrier scheme

Block based approach

Circular signal structure (time and frequency)

Pulse shaped sub-carriers

Overlapping sub-carriers
Transmitter Description

\[ x = W_N^H M \sum_{k=0}^{K-1} P(k) \Gamma_T^{(L)} R^{(L)} W_M d_k \]

- **Transmit samples**
- **Transform to time domain**
- **Superposition = upconversion**
- **Pulse shaping**
- **Repetition = upsampling**
- **Transform to freq. domain**
- **Complex data**

- \( W_M = \{ w_{i,j} \}_{M \times M} \), where \( w_{i,j} = e^{-j2\pi \frac{i}{M}} \) with \( i, j = 0, \ldots, M-1 \)

- \( R^{(L)} = \begin{pmatrix} I_M & I_M & \cdots \end{pmatrix}^T \)

- \( \Gamma_T^{(L)} = \text{diag}(W_{LMF_T}^{(L)}) \)

- \( P^{(0)} = \begin{pmatrix} I_M/2 & 0_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\ 0_{LM/2} & I_M/2 & \cdots & 0_{LM/2} & 0_{LM/2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0_{LM/2} & 0_{LM/2} & \cdots & I_M/2 & 0_{LM/2} \end{pmatrix}^T \)

- \( P^{(1)} = \begin{pmatrix} 0_{LM/2} & I_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\ I_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \end{pmatrix}^T \)

- \( k \) sub-carrier index
- \( M \) number of time slots per block
- \( L \) width of the filter (freq. domain)
- \( N \) total number of sub-carriers
Receiver Description

\[
\hat{d}_k = \mathbf{W}_M^H \left( \mathbf{R}^{(L)} \right)^\top \Gamma_{\text{Rx}}^{(L)} \left( \mathbf{P}^{(k)} \right)^\top \mathbf{W}_{NM} \mathbf{y}
\]

Received data

\[
\mathbf{R}^{(L)} = \begin{bmatrix} \mathbf{I}_M & \mathbf{I}_M & \cdots \end{bmatrix}_L
\]

Receive filter

\[
\Gamma_{\text{Tx}}^{(L)} = \text{diag} \left( \mathbf{W}_{LMg_{\text{Tx}}}^{(L)} \right)
\]

Sub-carrier selection

\[
\begin{align*}
\mathbf{W}_M &= \{w_{i,j}\}_{M \times M}, \text{ where } w_{i,j} = e^{-j2\pi \frac{i}{M}} \\
\mathbf{P}^{(0)} &= \begin{bmatrix} \mathbf{I}_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\
0_{LM/2} & \mathbf{I}_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\
0_{LM/2} & 0_{LM/2} & \cdots & \mathbf{I}_{LM/2} & 0_{LM/2} \\
0_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & \mathbf{I}_{LM/2} \end{bmatrix}^\top \\
\mathbf{P}^{(1)} &= \begin{bmatrix} \mathbf{I}_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\
0_{LM/2} & \mathbf{I}_{LM/2} & \cdots & 0_{LM/2} & 0_{LM/2} \\
0_{LM/2} & 0_{LM/2} & \cdots & \mathbf{I}_{LM/2} & 0_{LM/2} \\
0_{LM/2} & 0_{LM/2} & \cdots & 0_{LM/2} & \mathbf{I}_{LM/2} \end{bmatrix}^\top
\end{align*}
\]

Receive samples

\[k\] sub-carrier index

\[M\] number of time slots per block

\[L\] width of the filter (freq. domain)

\[N\] total number of sub-carriers
Per sub-carrier successive interference cancellation (IC) can be performed in frequency domain.

Receiver with IC
Rayleigh multipath

64QAM, RRC, $a=0.2$
64QAM, RRC, $a=0.4$
256QAM, RRC, $a=0.4$
For realtime information please visit the ICC booth of

NATIONAL INSTRUMENTS

5GNOW
Let Us Begin

Physical Limit
- $c = 300,000 \text{ km/s}$
- 30 km in 0.1 ms

Tactile Internet
- $\leq 1 \text{ ms}$

LTE
- $\sim 50 \text{ ms}$

How to get there
- Small frames /TTIs
- Fast hardware (22nm)
- Realtime protocols & RRM
- Realtime operating systems
- Optimized routing
Communications ➔ Monitoring ➔ Control

- **Speed**: >10 Gb/s
- **Response**: <10 ms
- **MONITORING**: >10 years, 10b/s (1Ah)
Motivation
Cellular Roadmap

2G – 1992
Voice Messages

3G – 2002
+ Data
+ Positioning

4G – today
+ Video Conferencing
+ 3D Graphics

5G – 2020
+ Control
+ Things 2.0
Thanks to Vodafone for 18 years of continued support!

www.vodafone-chair.org

cfaed.tu-dresden.de
www.tu-dresden.de/sfb912
www.twinlab3d.org