TECHNISCHE UNIVERSITÄT DRESDEN
Vodafone Chair Mobile Communications Systems, Prof. Dr.-Ing. Dr. h.c. G. Fettweis
vodafone chair

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

vodafone chair at TU Dresden

Key Facts and Figures

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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

IPP Sponsors

actix, ALTERA, Alcatel·Lucent, AsahiKASEI, BOSCH, HUAWEI, Intel Mobile Communications, NATIONAL INSTRUMENTS, Nokia Siemens Networks, ROHDE&SCHWARZ, SIGNALION, tensilica, SYNOPSYS, XILINX

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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

Project Partners

NATIONAL INSTRUMENTS, vodafone, GWT forschung+innovation, actix, Alcatel·Lucent, BT, Fraunhofer Heinrich Hertz Institute, NEC, SAGEMCOM, ST ERICSSON, 7 2007 - 2013, Deutsche Forschungsgemeinschaft DFG, Bundesministerium für Bildung und Forschung, Freistaat Sachsen Staatsministerium für Wissenschaft und Kunst

The Vodafone Chair's Startup History

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			founded
systemonic	2002	NXP founded by Philips	1999 OnDSP™ based WLAN chip-sets
radioplan	2006	actix	2000 SON systems
SIGNALION	2012	NATIONAL INSTRUMENTS	2003 Broadband Wireless HW (LTE,…)
IN-CIRCUIT	2006	IN-CIRCUIT	2004 Module and reference board design
DRESDEN SILICON	2007	SIGNALION	2005 MPSoC semiconductor IP
freedelity			2007 Wireless audio
RADIOOPT			2008 Network performance measurement
blue wonder communications	2010	intel	2008 LTE Cellular Handset Chip IP
INRADIOS integrated radio solutions			2010 Satellite Communications
exelonix			2013 Assisted living
STARTBAHN Venture Fonds			2012 Startbahn Venture Fund

ELECTRONICS FUTURE

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DRESDEN concept

Center for Advancing Electronics Dresden

Gerhard P. Fettweis (coordinator)
60+ Investigators and Teams

cfaed CENTER FOR ADVANCING ELECTRONICS DRESDEN

Fraunhofer

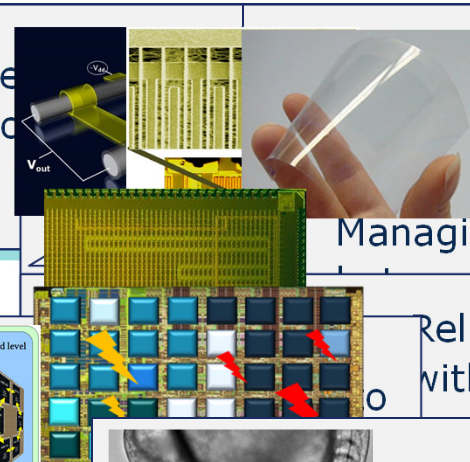
MAX-PLANCK-GESELLSCHAFT

Leibniz Gemeinschaft

HELMHOLTZ GEMEINSCHAFT

Comprehensive Approach: 9 Paths

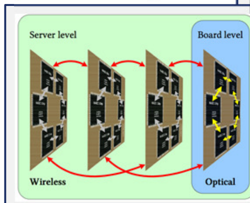
Enabling the
processing o
information

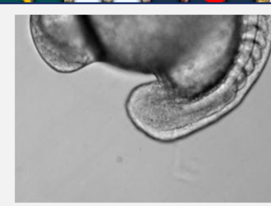


Organic electronics
for information

Managing

Reliable computing
with unre ble

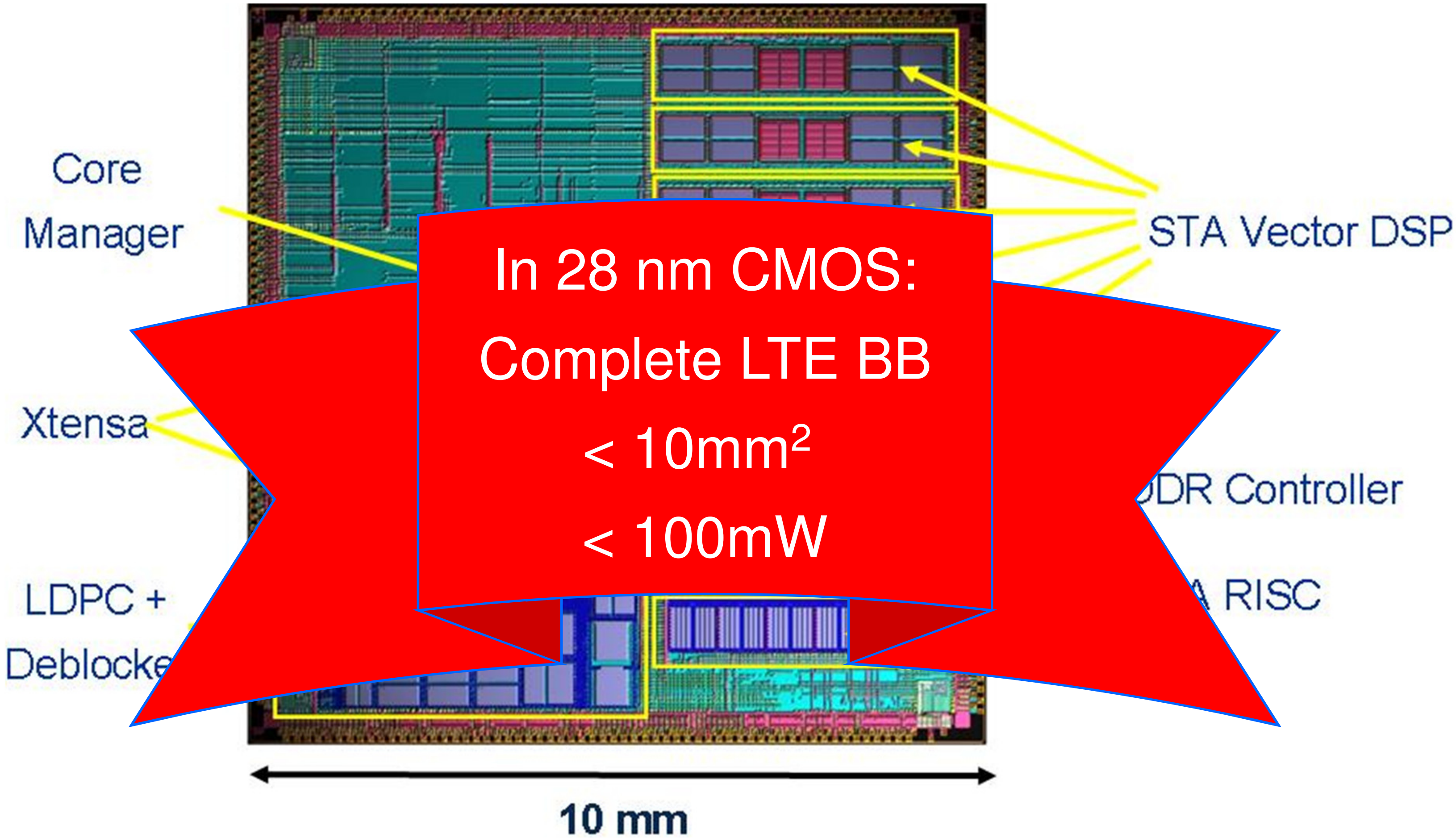




Learning from nature's
information processing

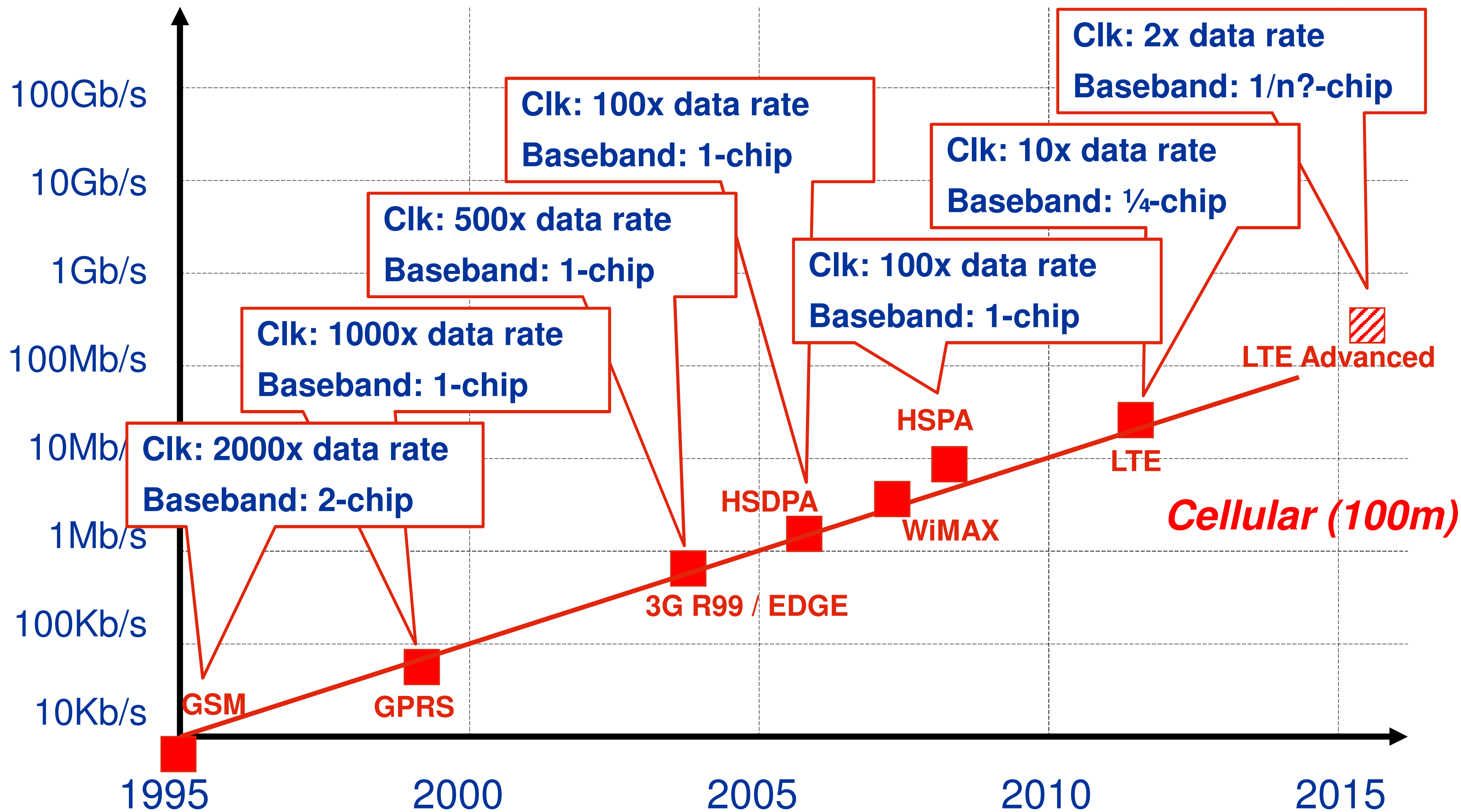
ELECTRONICS ROADMAP

Tomahawk SoC (130nm CMOS): Single-Chip LTE Baseband & H.264



Limberg, T., Winter, M., Bimberg, M., Klemm, R., Tavares, M.B., Ahlendorf, H. ; Matus, E. ; Fettweis, G. ; Eisenreich, H. ; Ellguth, G., Schlüssler, J.: A Heterogeneous MPSoC with Hardware Supported Dynamic Task Scheduling for Software Defined Radio. 46th DAC, ISSCC Student Design Contest Winner, 2009

Moore Versus Cellular



Moore Versus Cellular

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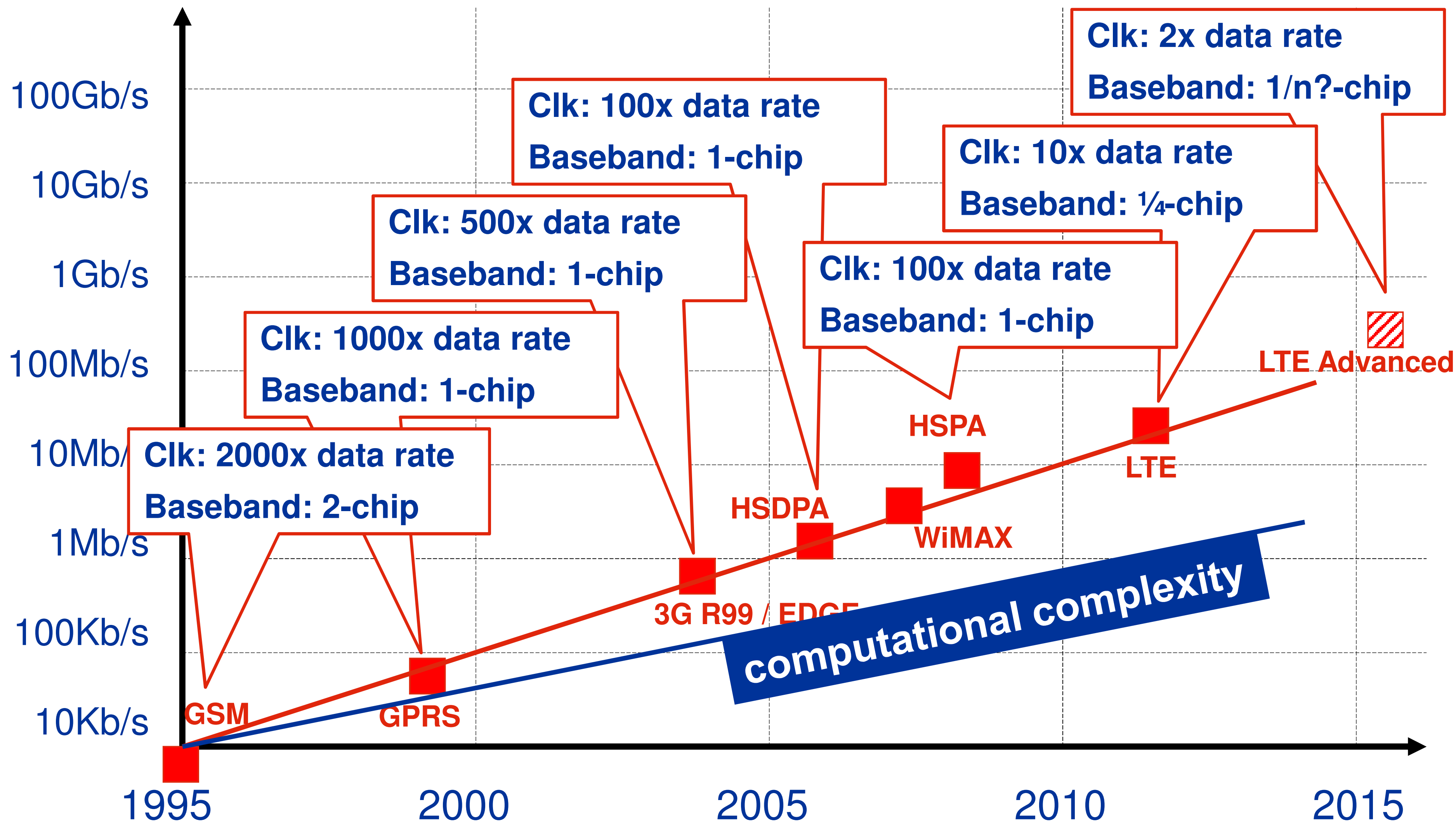
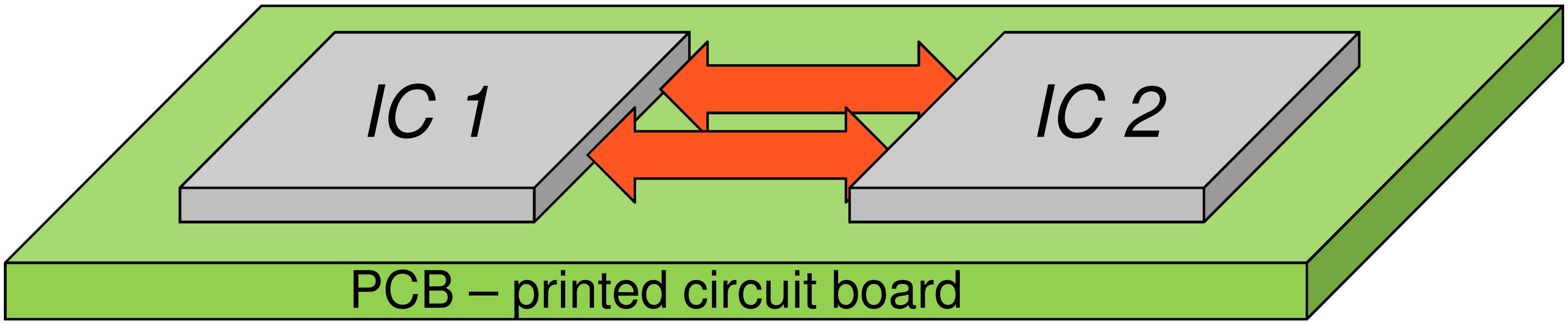
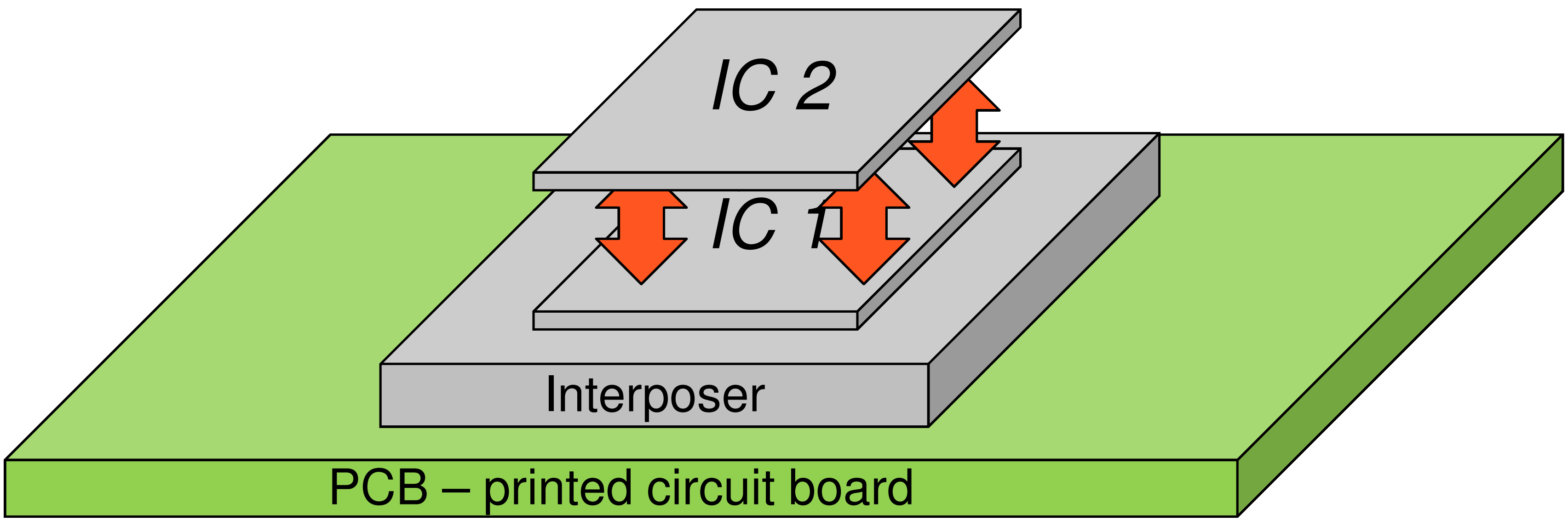
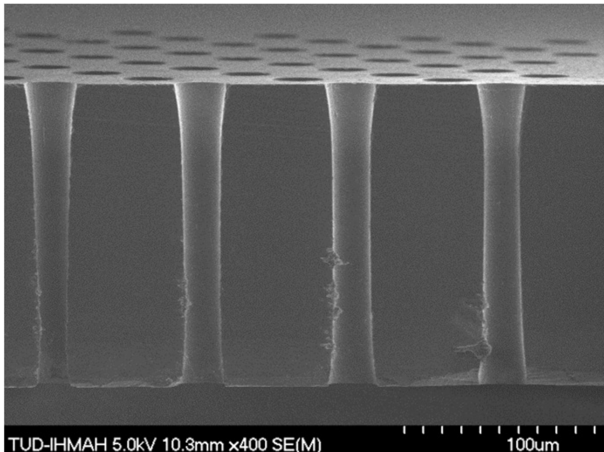


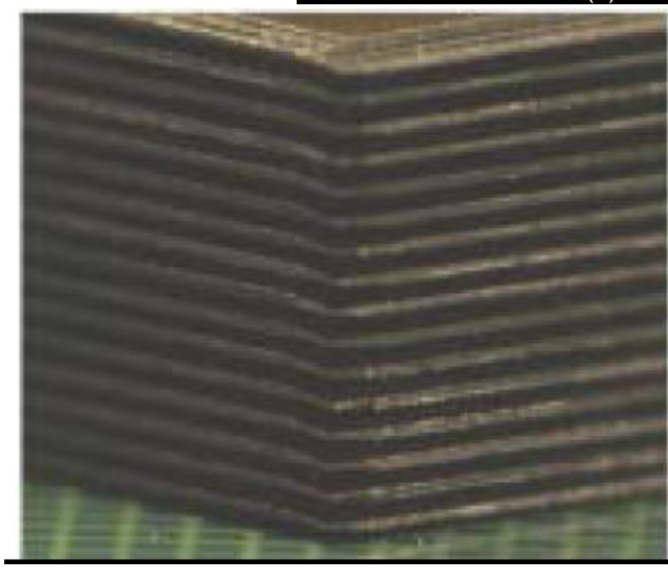

IC 1
IC 2
PCB – printed circuit board


IC 2
IC 1
Interposer
PCB – printed circuit board

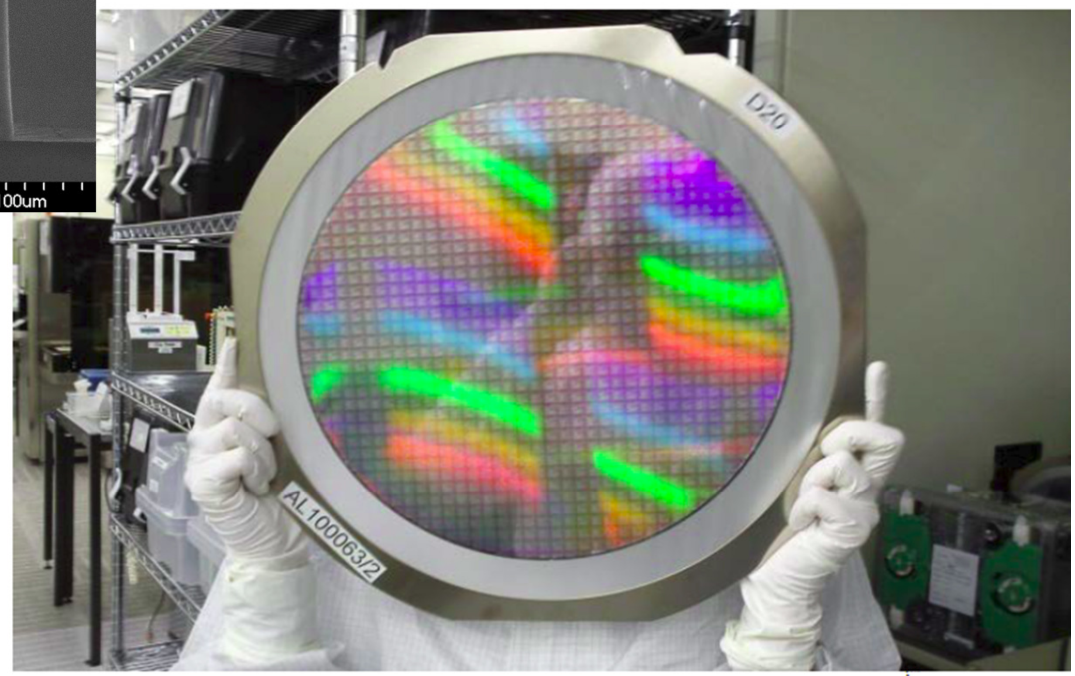
State-of-Art: 16 Chip-lets In a Stack

© TU Dresden





© Samsung



Demonstrated full sequence of wafer bonding/ thinning/ backside processing, wafer taping, debonding and cleaning on tape of active CMOS wafers

imec ERIC BEYNE - ITF 2013 BRUSSELS

TUD/MI TwinLab:
3D Chip-Stack Intraconnects

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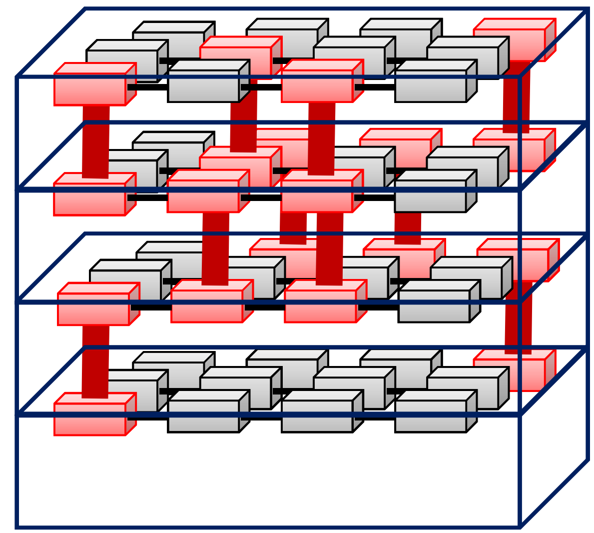
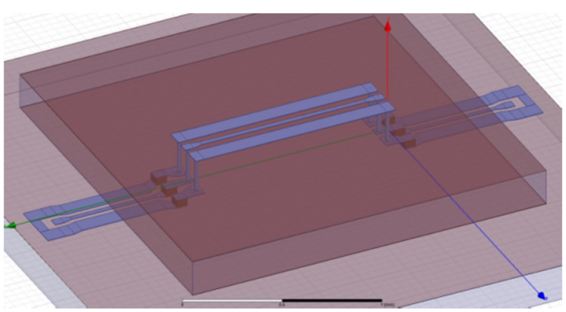
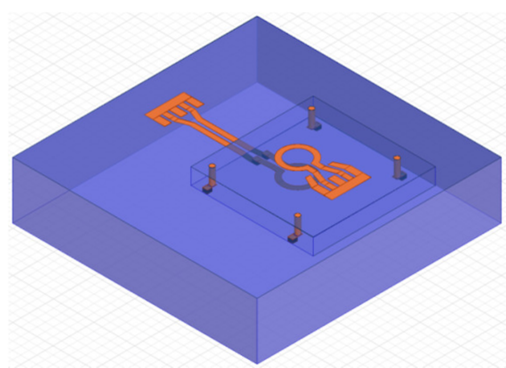
ATIC Abu Dhabi	3DCSI	Saxony
3D-Integrated µel. for Minimum Energy Design	Research Topic	3D Chip Stack Intraconnects for Energy/Bandwith Opt.
Masdar Institute	Institute	**TU Dresden**
Dahlem, Dimas, **Elfadel**, Gougam, Henschel, Khilo, Nayfeh, Saadat, Sammoura, Yoo, Shabra, Viegas	Principal Investigators	**Fettweis**, Bartha, Ellinger, Plettemeier, Schüffny



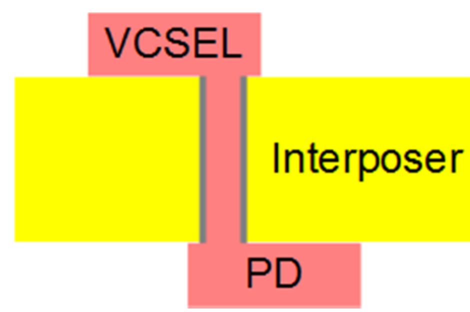
TSV Intraconnects



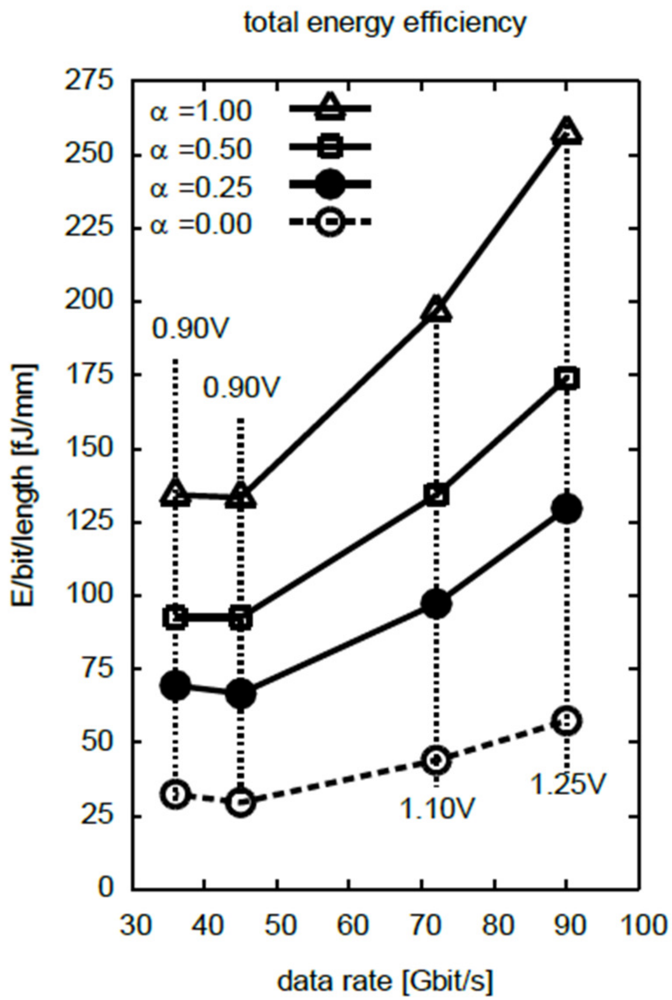
Wireless Inductive

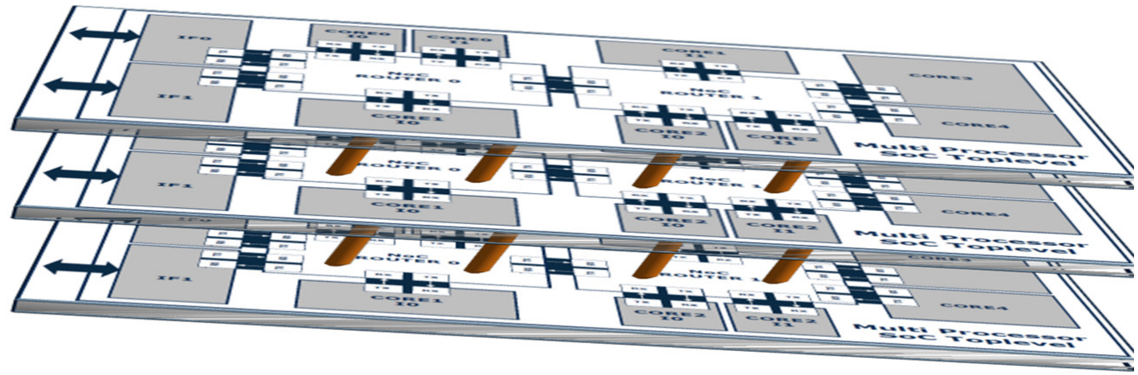


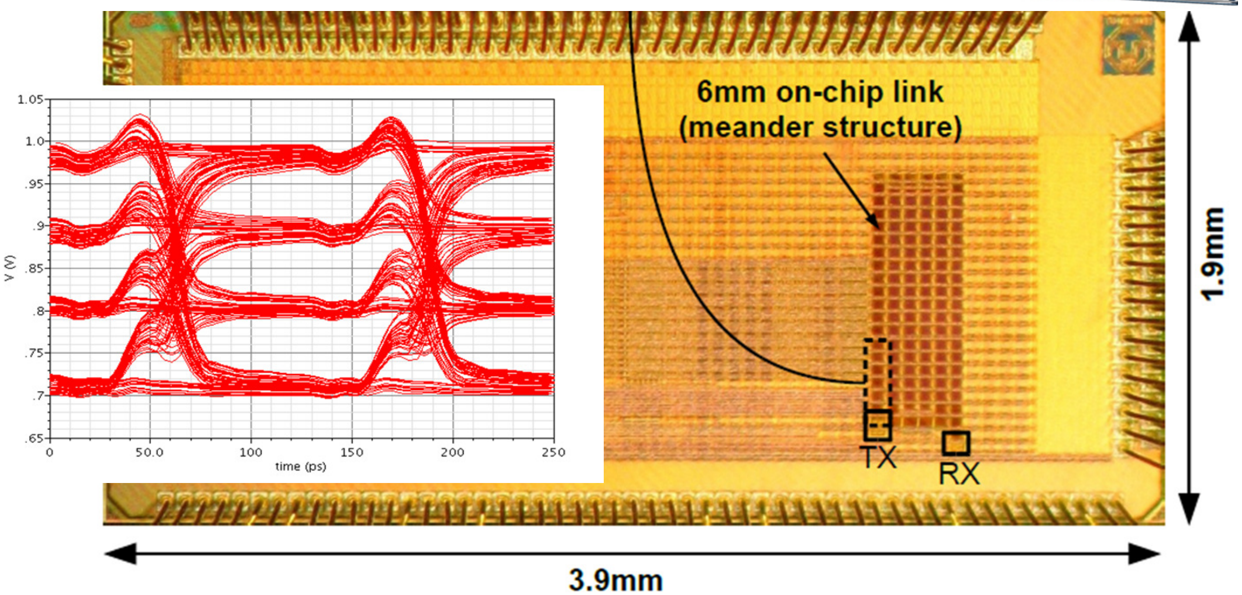
Wireless Optical



90Gb/s Results



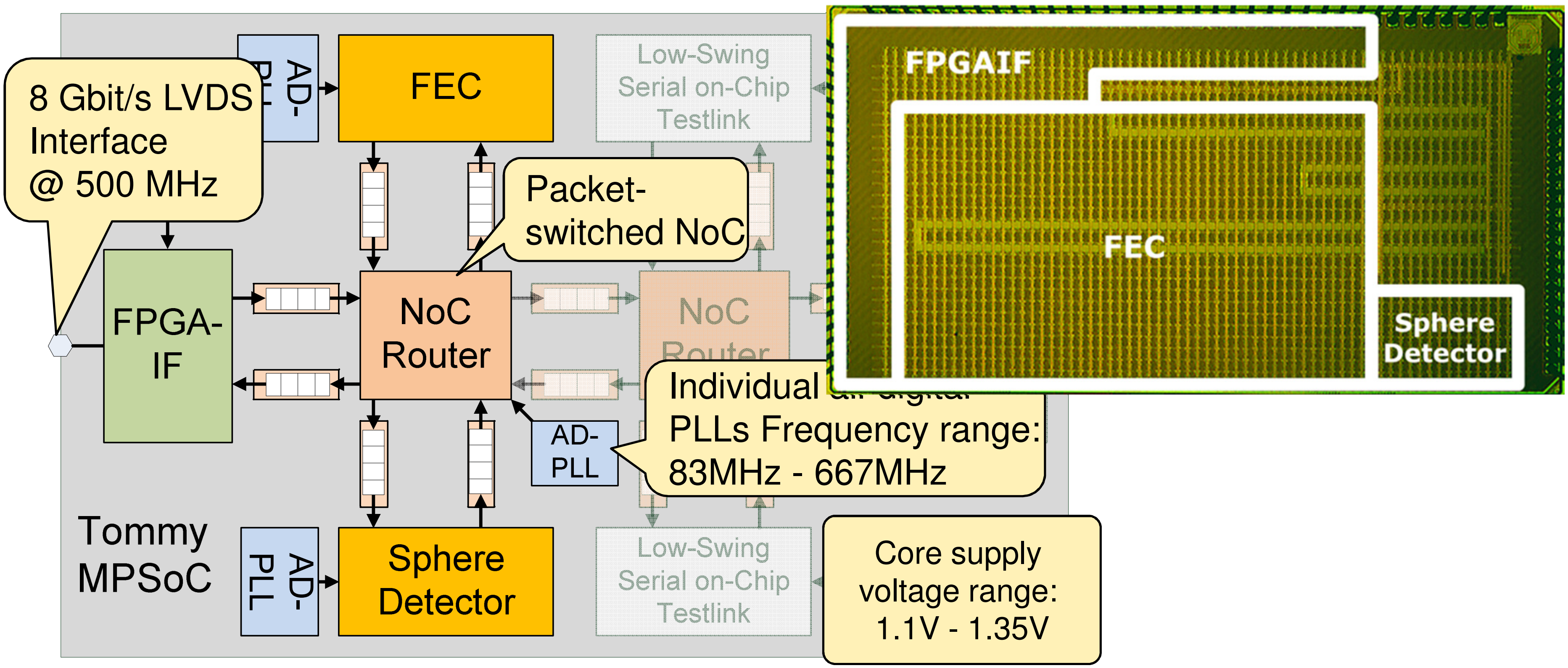




D. Walter, S. Höppner, H. Eisenreich, G. Ellguth, S. Henker, S. Hänzsche, R. Schüffny, M. Winter and G. Fettweis
A Source-Synchronous 90Gbit/s Capacitively Driven Serial On-Chip Link over 6mm in 65nm CMOS in *Proc.59th ISSCC'12*

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



: M. Winter, S. Kunze, E. Pérez Adeva, B. Mennenga, E. Matus, G. Fettweis, H. Eisenreich, G. Ellguth, S. Höppner, S. Scholze, R. Schüffny and T. Kobori. „A 335Mb/s 3.9mm² 65nm CMOS Flexible MIMO Detection-Decoding Engine Achieving 4G Wireless Data Rates.“ IEEE ISSCC 2012

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HAEC

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

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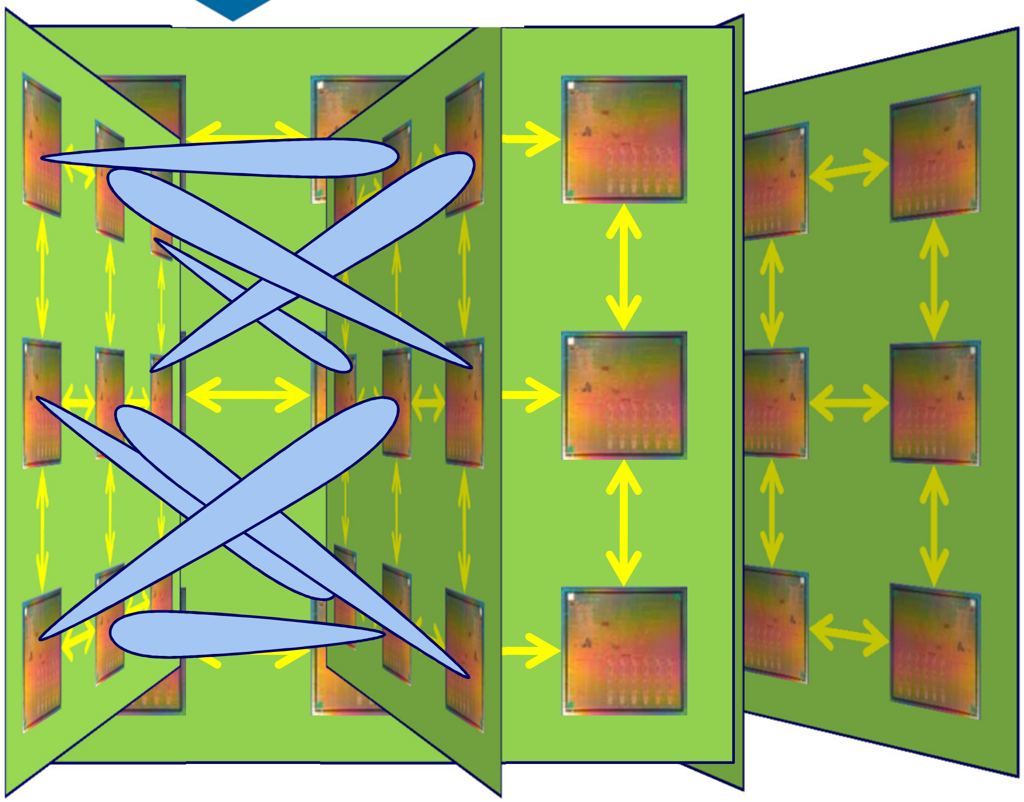

Optical Interconnect
- adaptive analog/digital circuits for e/o transceiver
- embedded polymer waveguide
- packaging technologies (e.g. 3D stacking of Si/III-V hybrids)
- 90° coupling of laser

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

GLOBALFOUNDRIES IBM AMD The future is fusion

HAEC Highly Adaptive Energy-Efficient Computing

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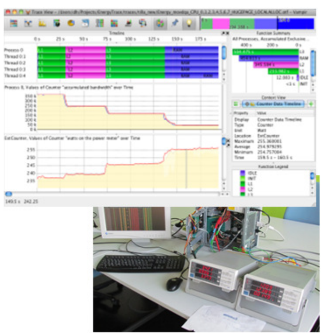
Simulation & Prototyping

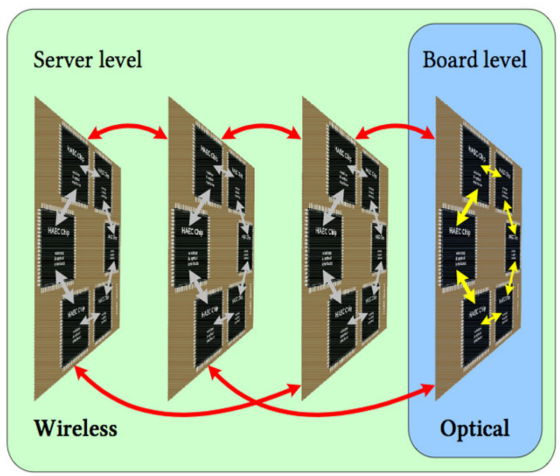


Information Processing

- **Application**
- **Middleware**
- **Runtime**
- **Operating Sys.**

Devices & Circuits

- **Processor**



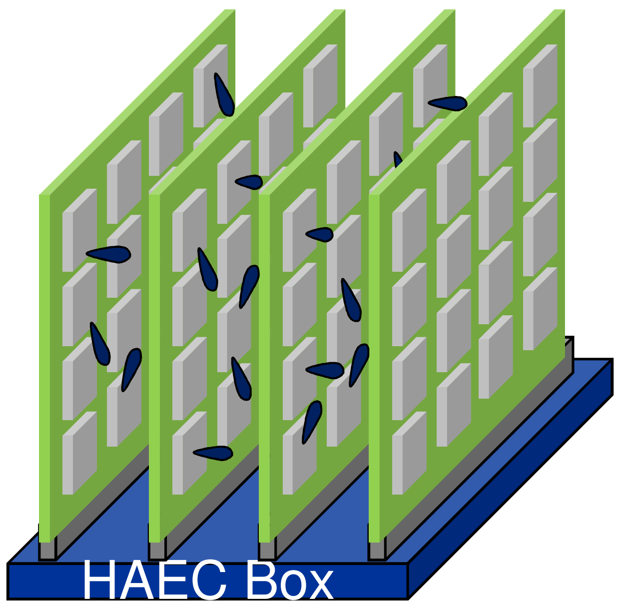
Flexible Software

Energy Control Loop

Flexible Hardware Interconnects

The Outlook: The HAEC Box in 2020+

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



in 10x10x10 cm³ (1 liter)	➔ 10^9 processors!
8192 chips	➔ 10^5x performance of today!

TU Dresden's Mission in Challenging Roadblocks of Electronics

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- ✓ **Integration Plateau**

  cfaed CENTER FOR ADVANCING ELECTRONICS DRESDEN

- ✓ **Interconnect Bottleneck**

  HAEC 3DCSI

€100M program

€100M program

> 50 startups

Interim Conclusion

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The Semiconductor Story Continues Until 2040 *!*

It drives data ➔ the wireless roadmap *!!*

WIRELESS ROADMAP

Coverage: Cellular

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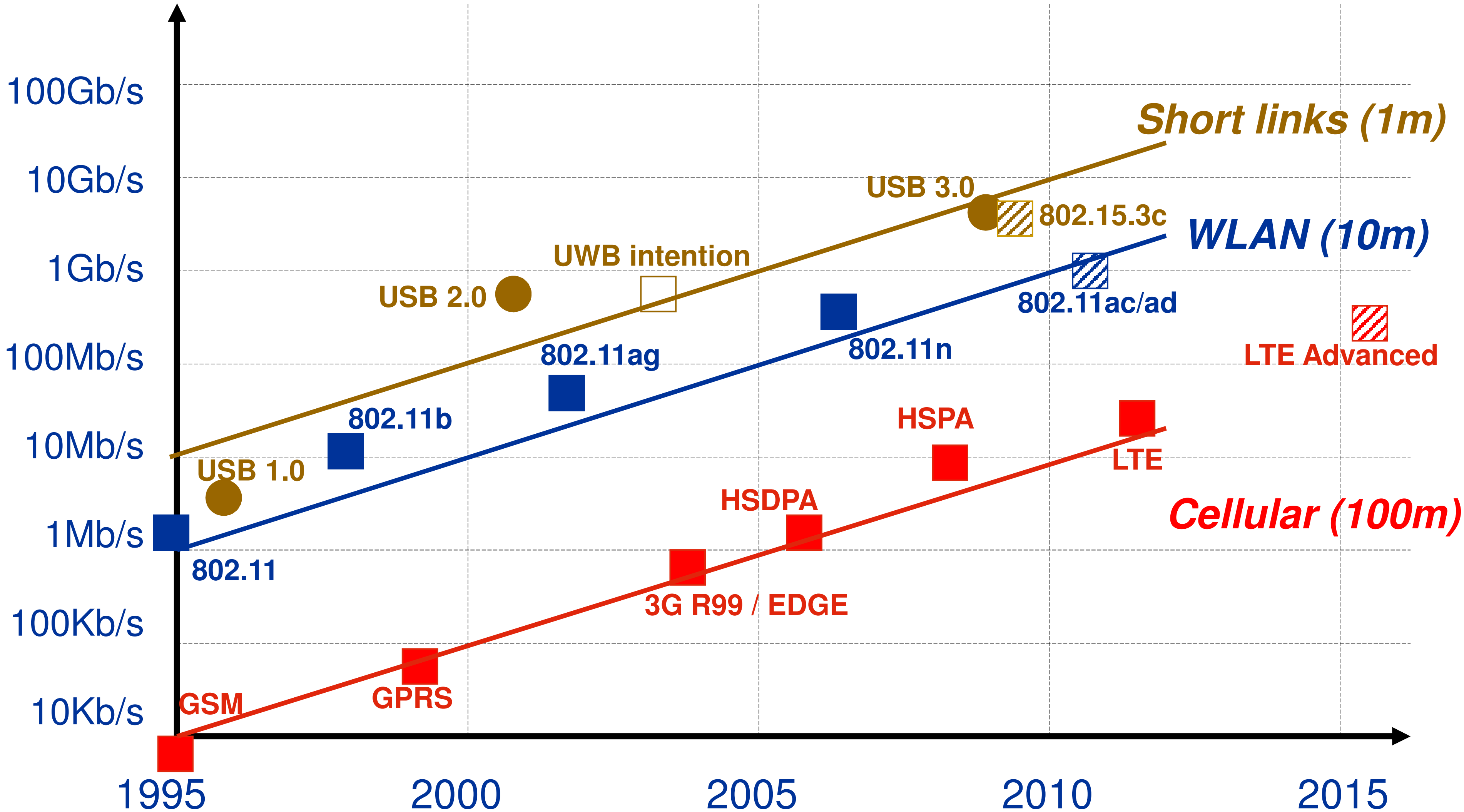

>2020 Outlook

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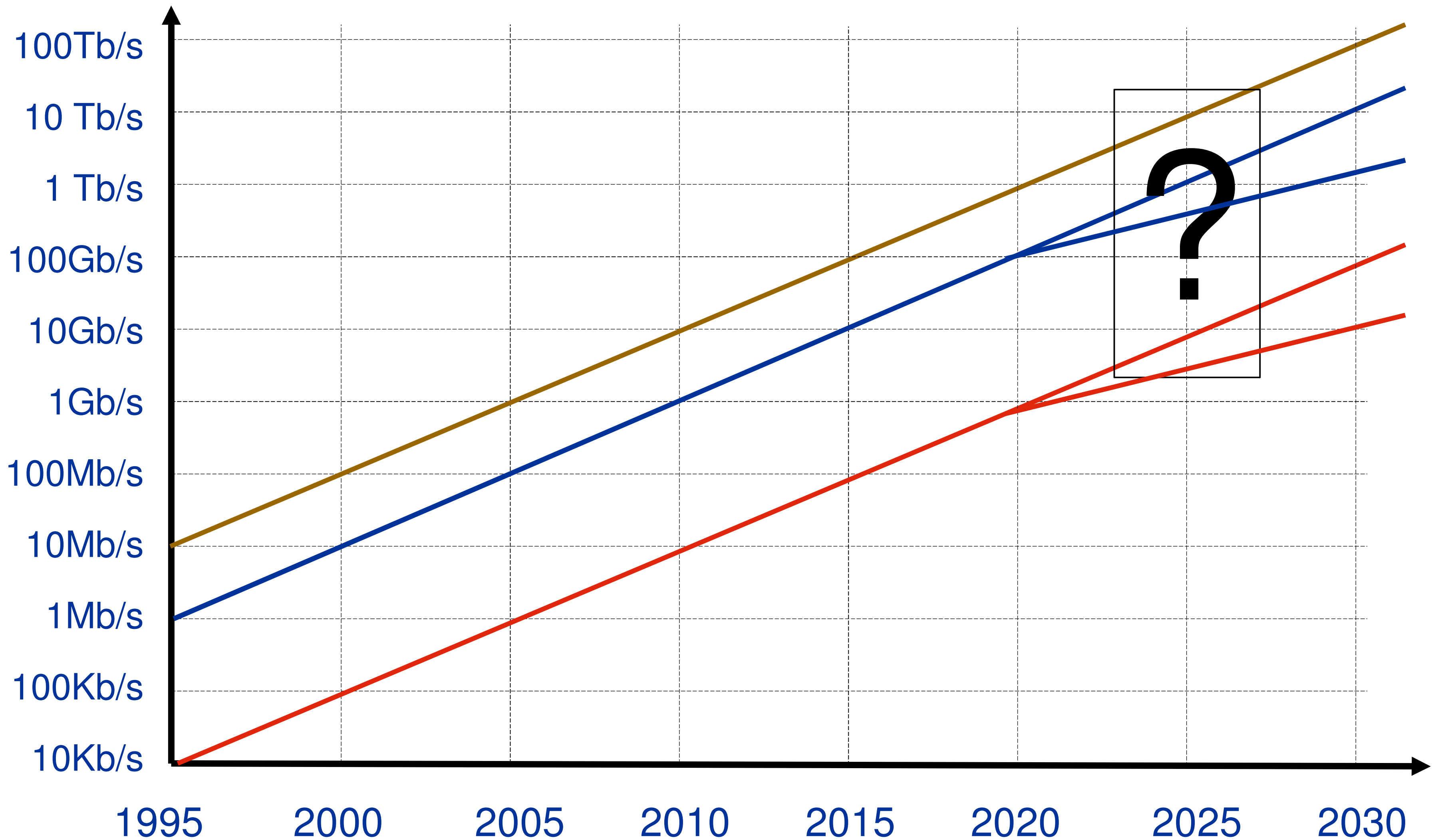

2005/4/4 – Via Della Conciliazione

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Source: http://www.spiegel.de/panorama/bild-889031-473266.html

2013/3/12 – Via Della Conciliazione

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

Watch Out !

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

http://www.iclarified.com/images/news/28607/111946/111946-1280.png

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5G

THE TACTILE INTERNET

G. Fettweis

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

www.microwav ejournal.com/articles/print/18751-a-5g-wireless-communications-v ision

Physiology and Psychology

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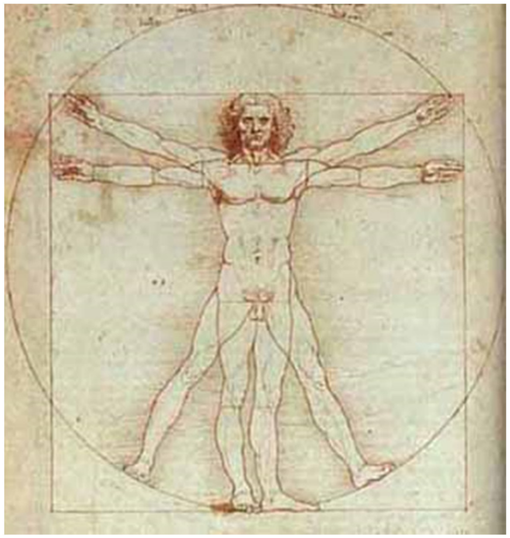
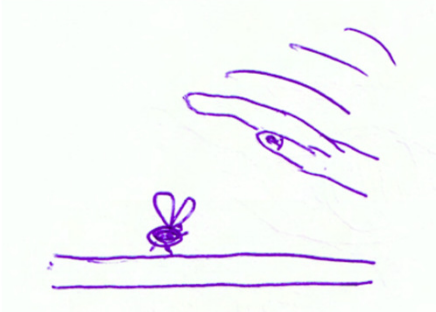
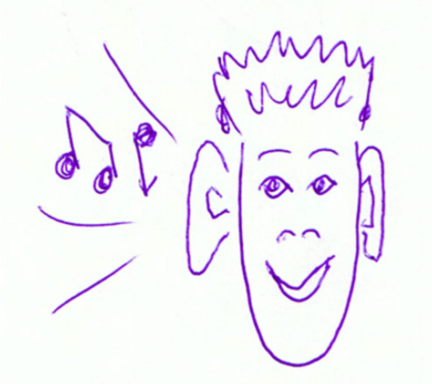


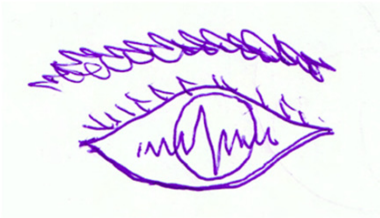
1 sec



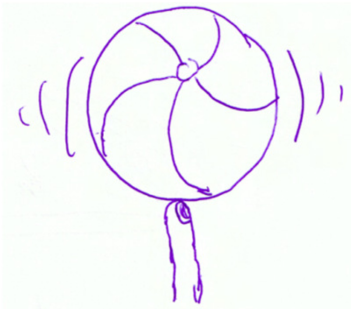
100ms



10ms



1ms



Physiology and Psychology

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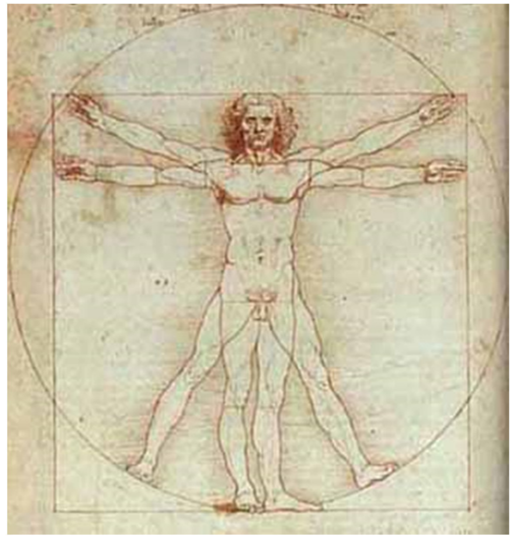

1 sec

100ms

10ms

1ms

Gaming…

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http://popular-pics.com/Cool_World_Record_LAN_Event_Computer_Pictures__5
http://gametaffy.com/imho-the-lan-party/

Professional Audio

http://www.germanpulse.com/wp-content/uploads/2013/02/HerbertGroenemeyerGuitarPhotoByAliKepenek.jpg

Remote Heli

http://ds_product_photos.s3.amazonaws.com/large/9756.jpg

FITS – Future Intelligent Things and Systems
Usage Scenario Autonomous Vehicles

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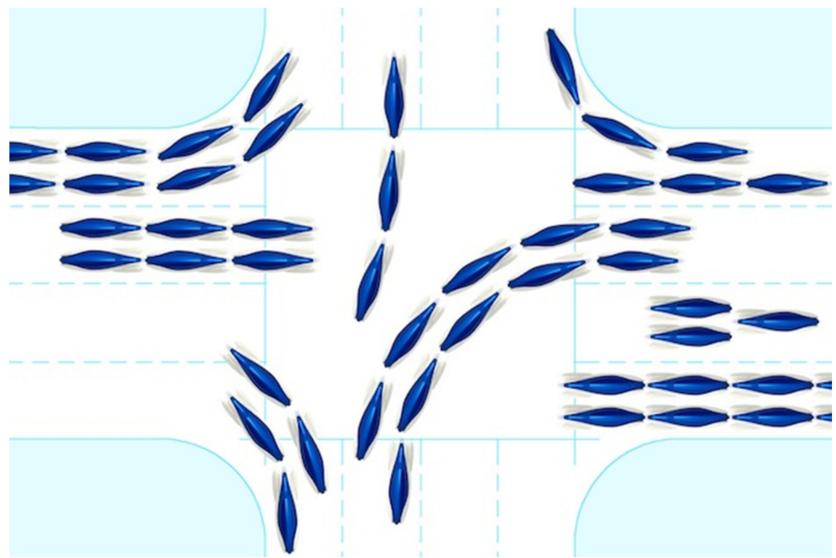
- Today's urban Traffic

Example: Urban Traffic at Arc de Triomphe

- Future Vision



Remote Driving 2.0

Platooning 2.0

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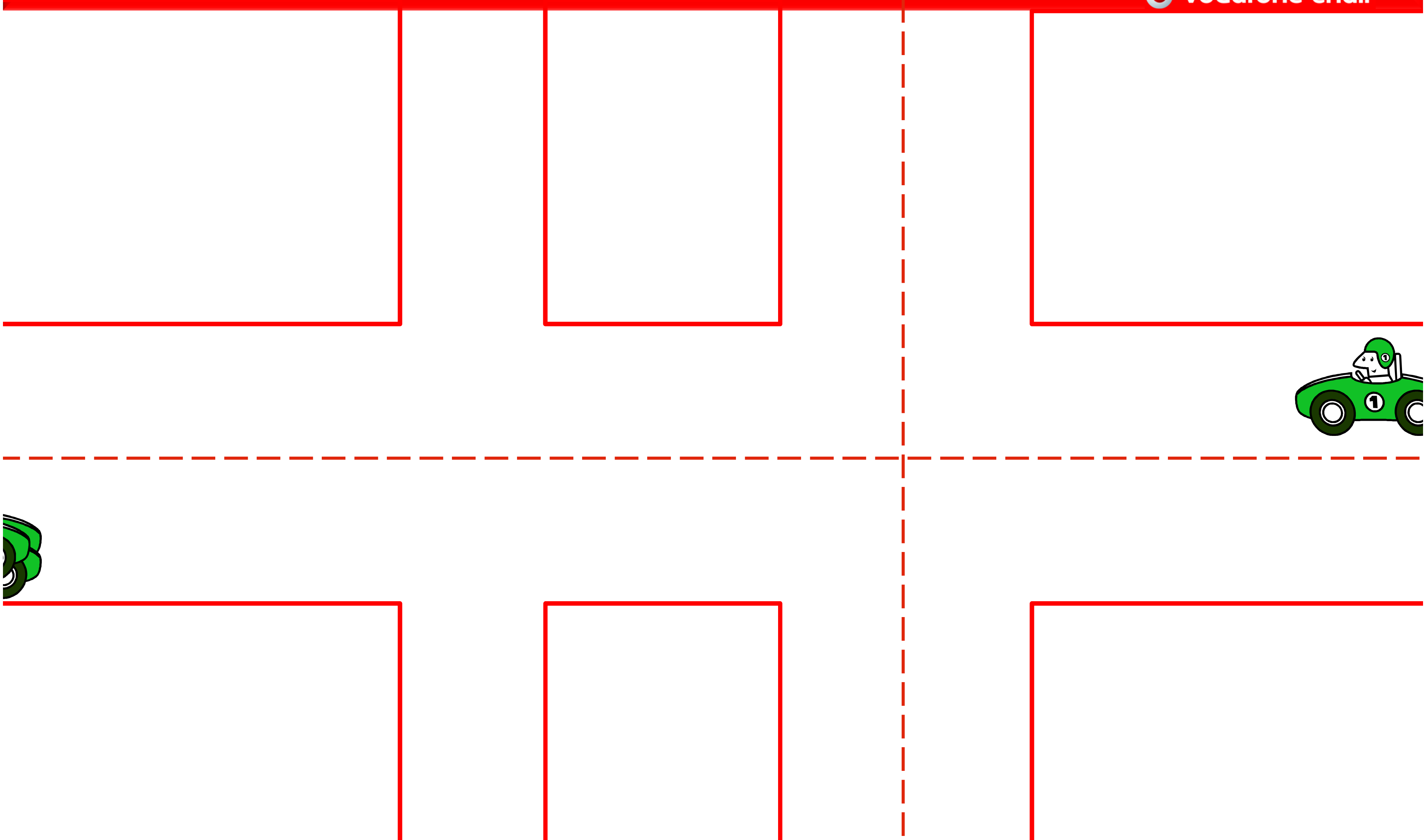
- 1ms examples of today's cars: ESP, ABS

- Tomorrow: platooned ESP & ABS

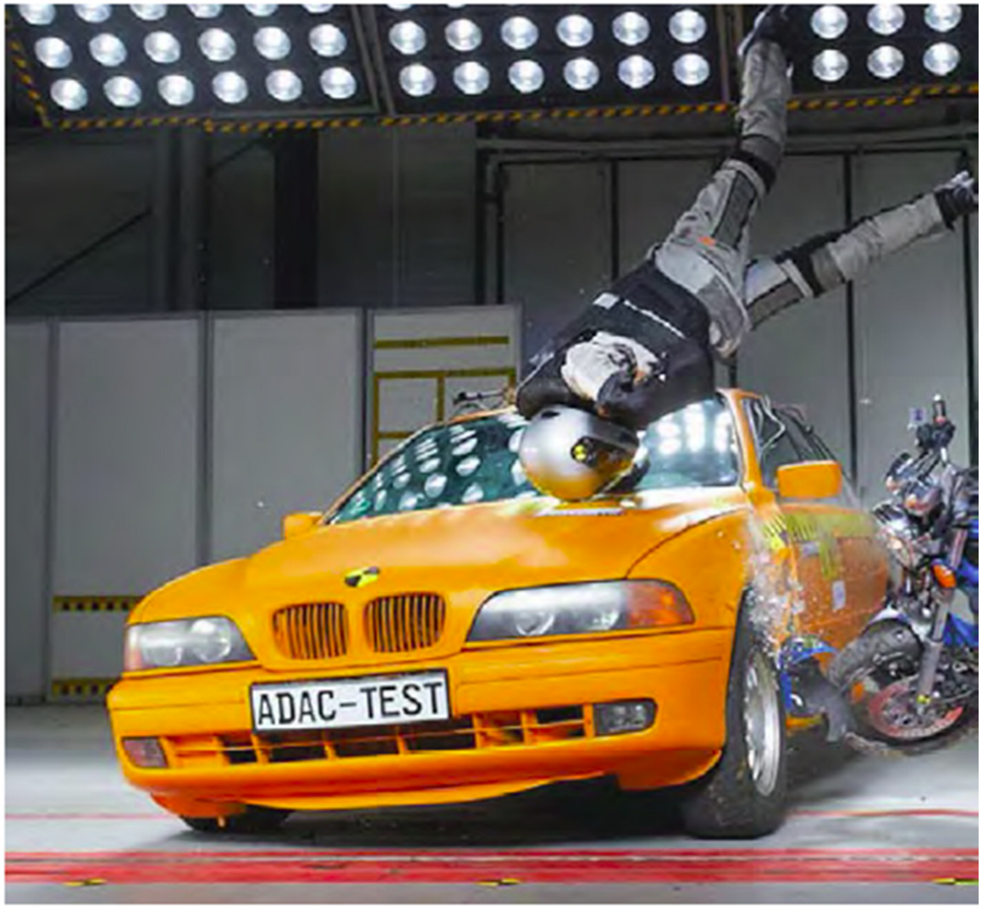
Traffic Control



Wireless Airbags

Crash to impact: 10-15ms

- Crash sensor
- Trigger
- Air bag



Exoskeletons – "Power Limbs"

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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

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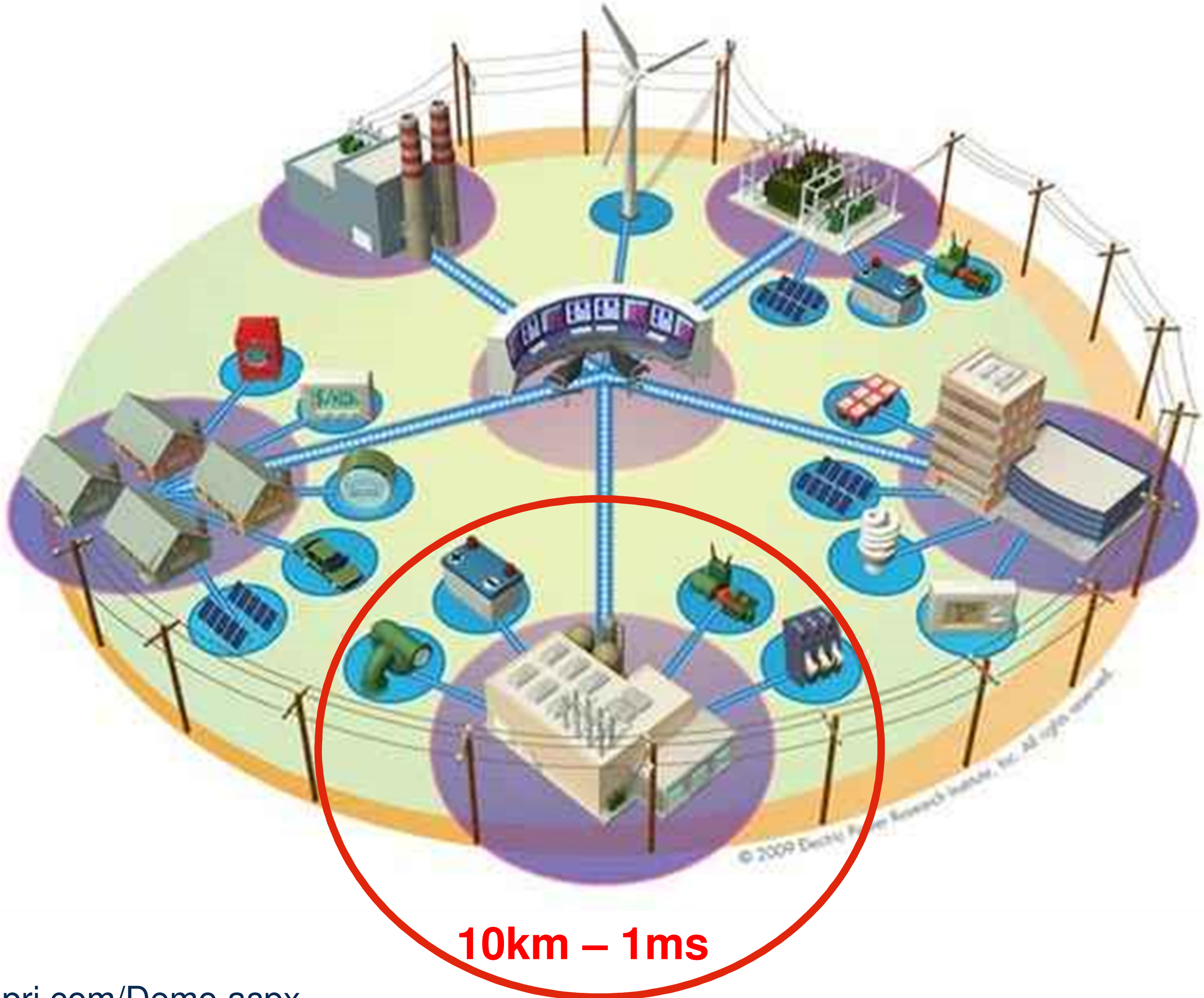
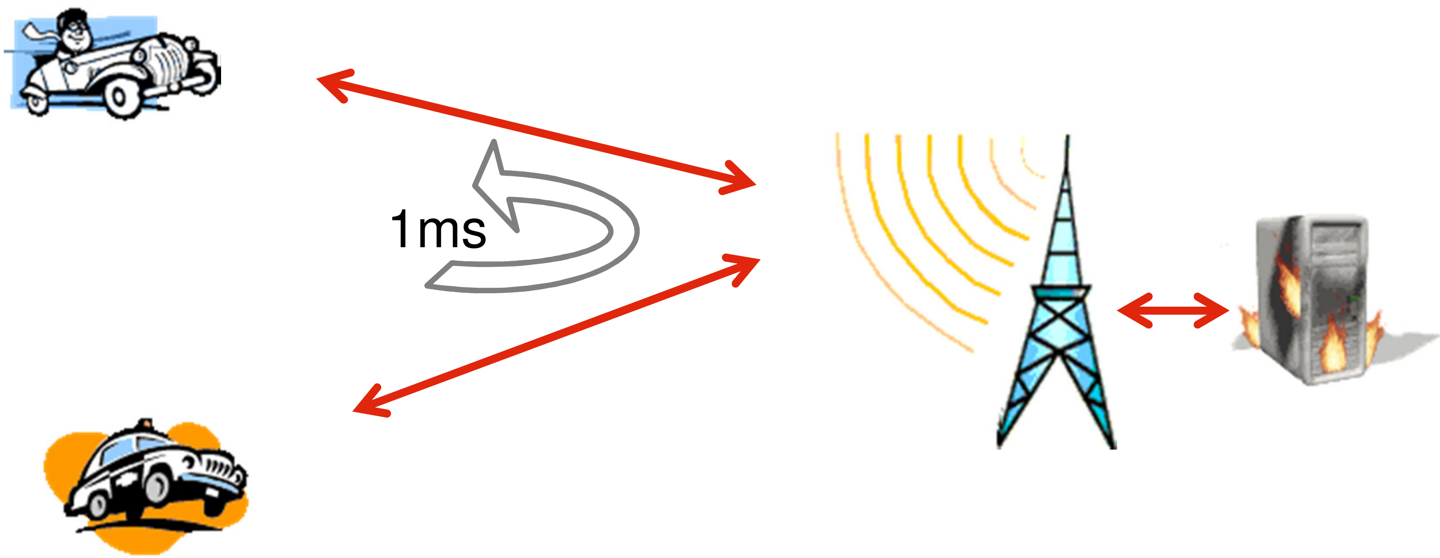
http://www.spox.com/de/sport/olympia/0807/Artikel/Terminplaene/zeitplan-kanu.html

Smart Grid



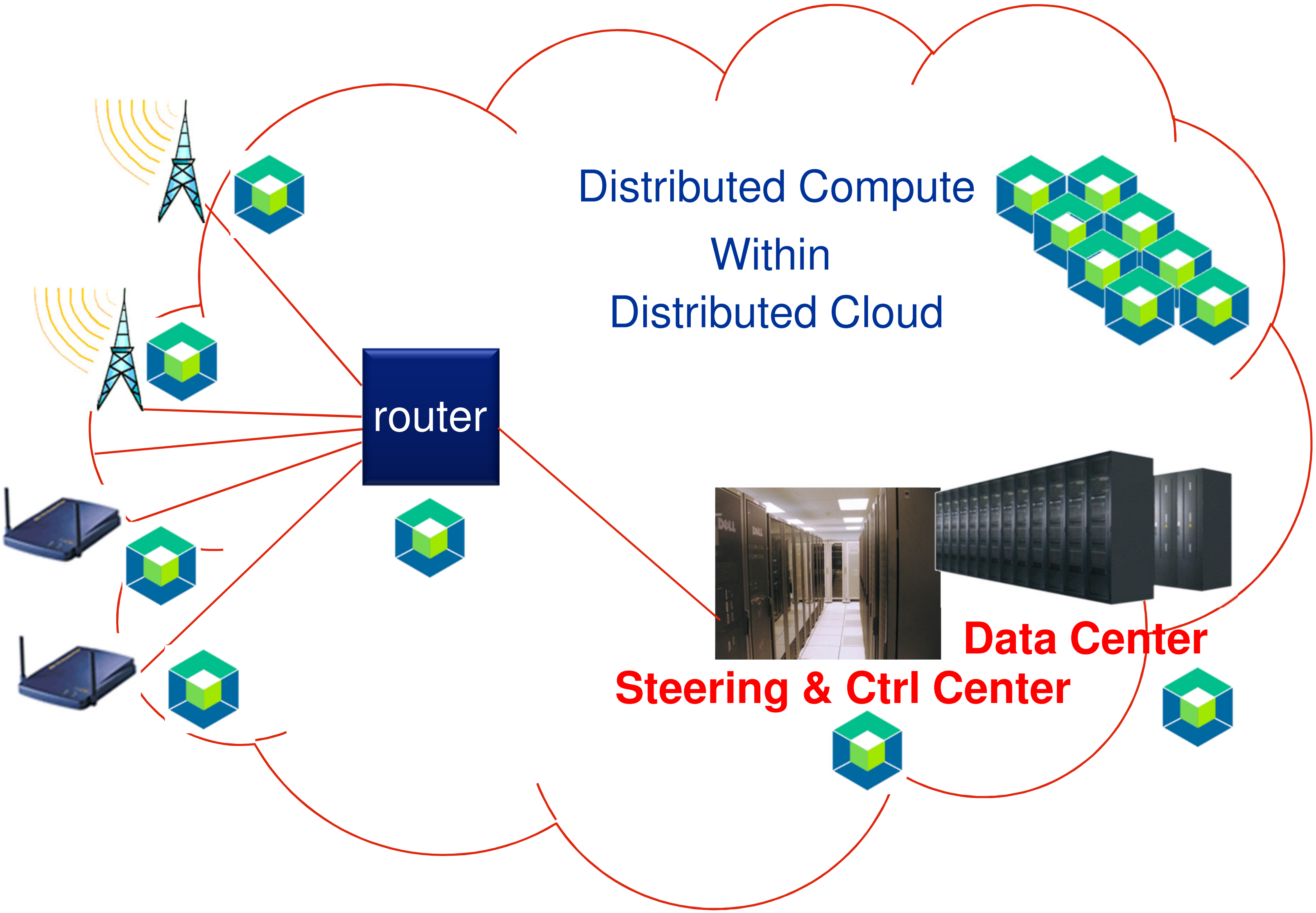
http://smartgrid.epri.com/Demo.aspx

Paradigm of 5G Cellular: Control

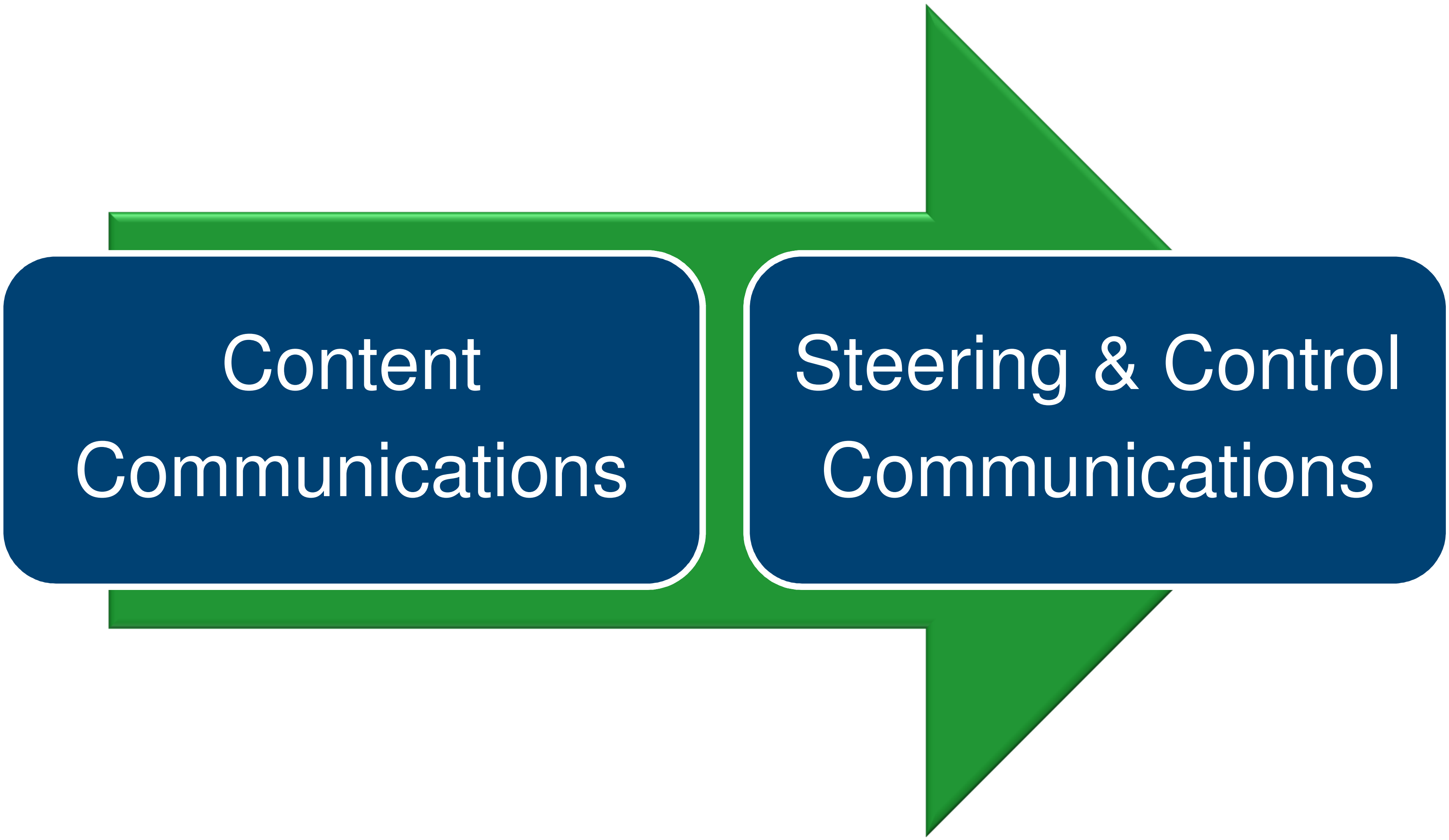


Traffic / Sports / Education / Health&Care / Manufacturing / Games / Smart Grid..

SmartRAN



Distributed Compute
Within
Distributed Cloud
router
Data Center
Steering & Ctrl Center


Content Communications
Steering & Control Communications

Additional (non-functional) Requirements

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- Accountability & Archiving

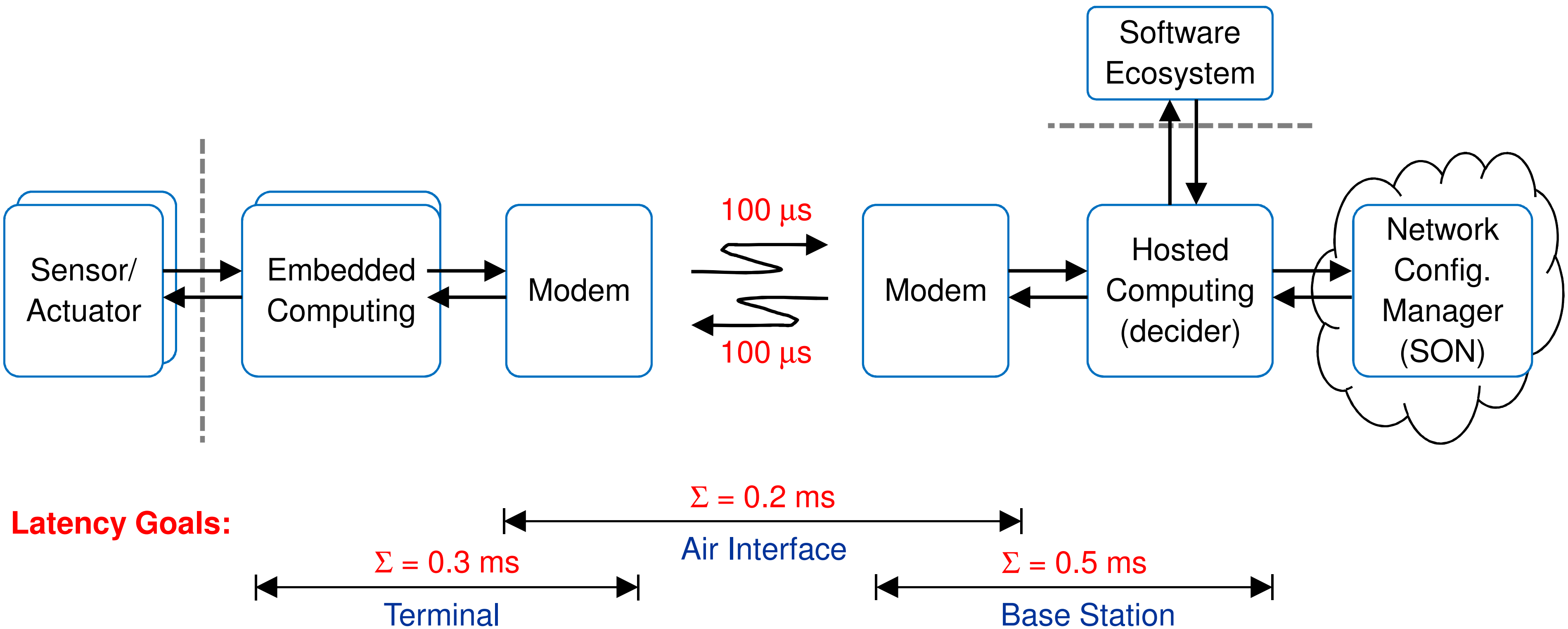
- Authorization

- Failure Resilience

- Attacker Resilience

- Eavesdropping Security

10ms ➔ 1ms Impact



PHY Requirement

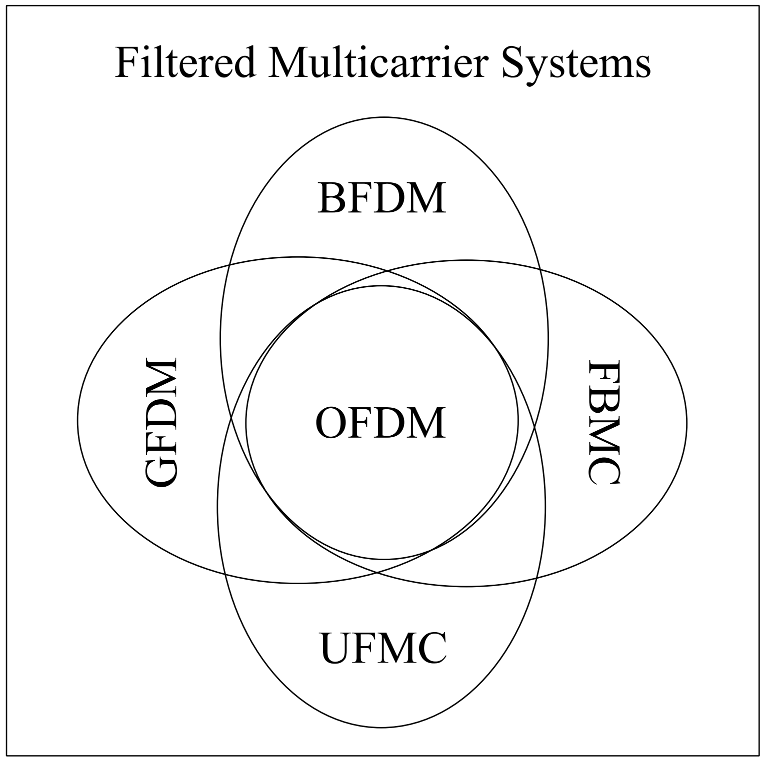
Multicarrier → spectrum agility

Short TTI → 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



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

GFDM Signal Properties

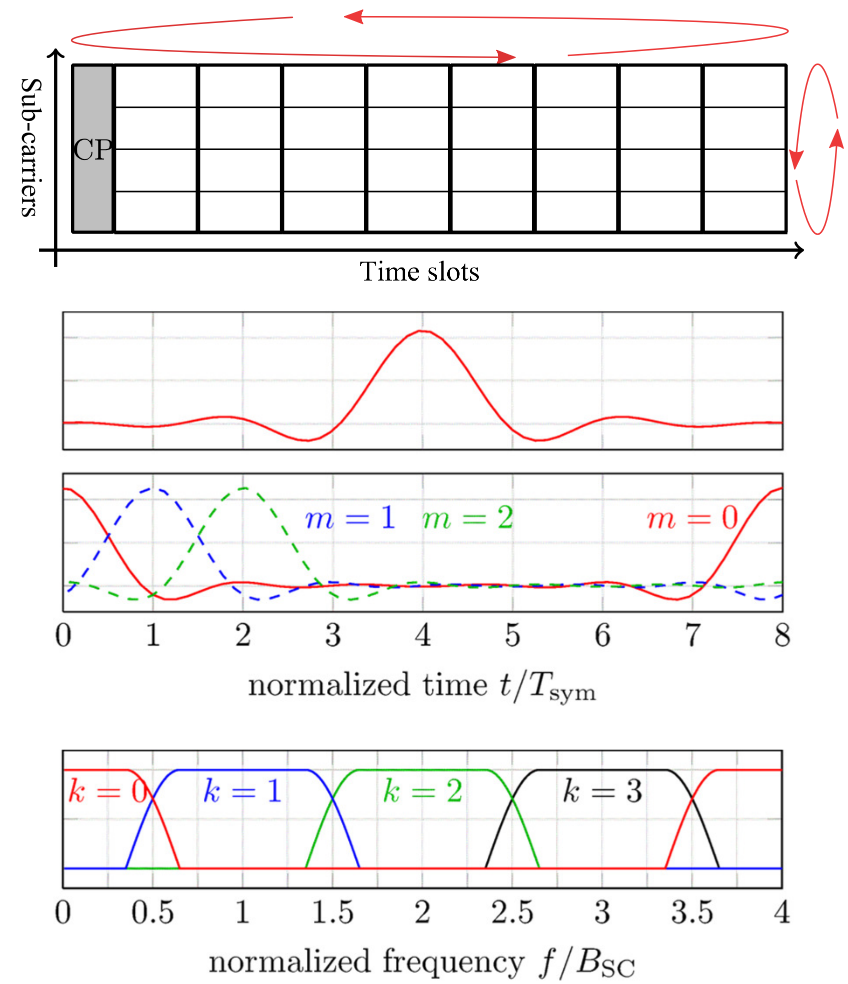
Multi-carrier scheme

Block based approach

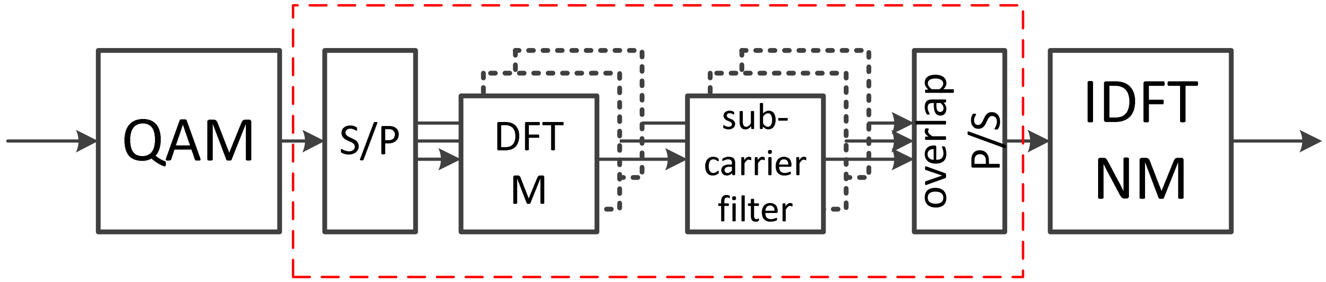
Circular signal structure (time and frequency)

Pulse shaped sub-carriers

Overlapping sub-carriers



Transmitter Description



$$\mathbf{x} = \mathbf{W}_{NM}^{\mathrm{H}} \sum_{k=0}^{K-1} \mathbf{P}^{(k)} \mathbf{\Gamma}_{\mathrm{Tx}}^{(L)} \mathbf{R}^{(L)} \mathbf{W}_M \mathbf{d}_k$$

- transmit samples
- transform to time domain
- superposition
- permutation = upconversion
- pulse shaping
- repetition = upsampling
- transform to freq. domain
- complex data

$$\mathbf{W}_M = \{w_{i,j}\}_{M\times M}, \text{ where } w_{i,j} = e^{-j2\pi\frac{ij}{M}} \text{ with } i,j = 0,\ldots,M-1$$

$$\mathbf{R}^{(L)} = \underbrace{\begin{pmatrix} \mathbf{I}_M & \mathbf{I}_M & \ldots \end{pmatrix}}_{L}^{\mathrm{T}}$$

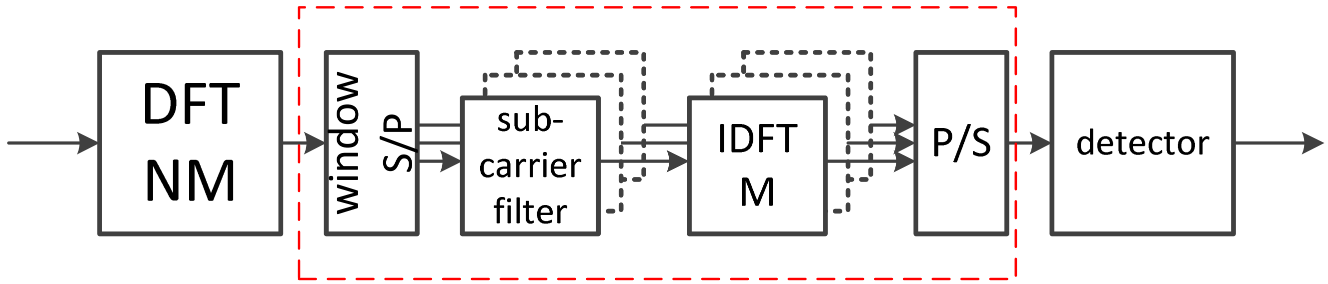
$$\mathbf{\Gamma}_{\mathrm{Tx}}^{(L)} = \mathrm{diag}\left(\mathbf{W}_{LM}\mathbf{g}_{\mathrm{Tx}}^{(L)}\right)$$

$$\mathbf{P}^{(0)} = \begin{pmatrix} \mathbf{I}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \\ \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{I}_{LM/2} \end{pmatrix}^{\mathrm{T}}$$

$$\mathbf{P}^{(1)} = \begin{pmatrix} \mathbf{0}_{LM/2} & \mathbf{I}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \\ \mathbf{I}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \end{pmatrix}^{\mathrm{T}}$$

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



$$\hat{\mathbf{d}}_k = \mathbf{W}_M^{\mathrm{H}} \left(\mathbf{R}^{(L)}\right)^{\mathrm{T}} \mathbf{\Gamma}_{\mathrm{Rx}}^{(L)} \left(\mathbf{P}^{(k)}\right)^{\mathrm{T}} \mathbf{W}_{NM}\, \mathbf{y}$$

received data — transform to time domain — decimation = downconversion — receive filter — sub-carrier selection — transform to frequency domain — receive samples

$$\mathbf{W}_M = \{w_{i,j}\}_{M\times M}, \text{ where } w_{i,j} = e^{-j2\pi\frac{ij}{M}} \text{ with } i,j = 0,\ldots,M-1$$

$$\mathbf{R}^{(L)} = \underbrace{\begin{pmatrix} \mathbf{I}_M & \mathbf{I}_M & \ldots \end{pmatrix}}_{L}^{\mathrm{T}}$$

$$\mathbf{\Gamma}_{\mathrm{Tx}}^{(L)} = \operatorname{diag}\left(\mathbf{W}_{LM}\mathbf{g}_{\mathrm{Tx}}^{(L)}\right)$$

$$\mathbf{P}^{(0)} = \begin{pmatrix} \mathbf{I}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \\ \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{I}_{LM/2} \end{pmatrix}^{\mathrm{T}}$$

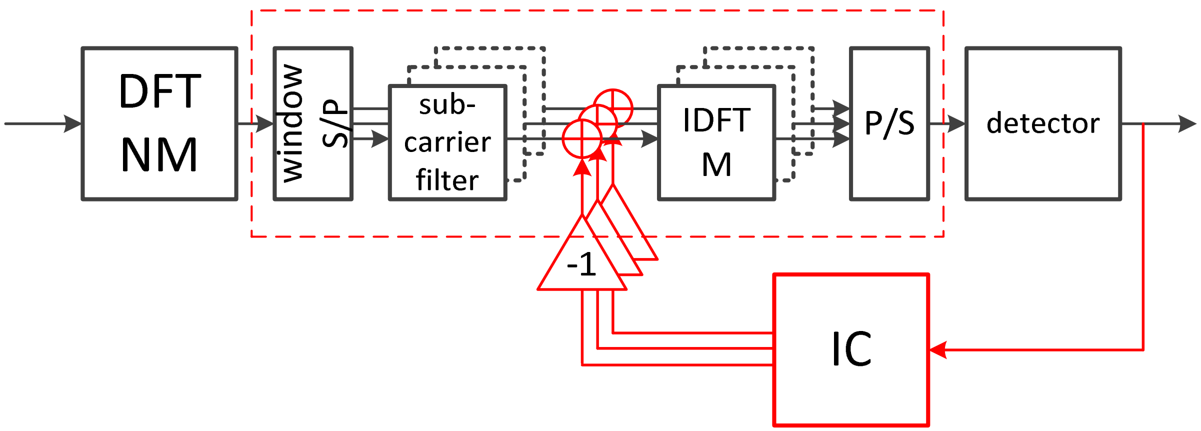
$$\mathbf{P}^{(1)} = \begin{pmatrix} \mathbf{0}_{LM/2} & \mathbf{I}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \\ \mathbf{I}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \end{pmatrix}^{\mathrm{T}}$$

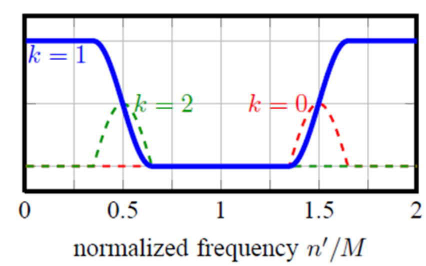
k	sub-carrier index
M	number of time slots per block
L	width of the filter (freq. domain)
N	total number of sub-carriers

Low Complexity Transceiver (2)

Per sub-carrier successive interference cancellation (IC) can be performed in frequency domain.

Receiver with IC

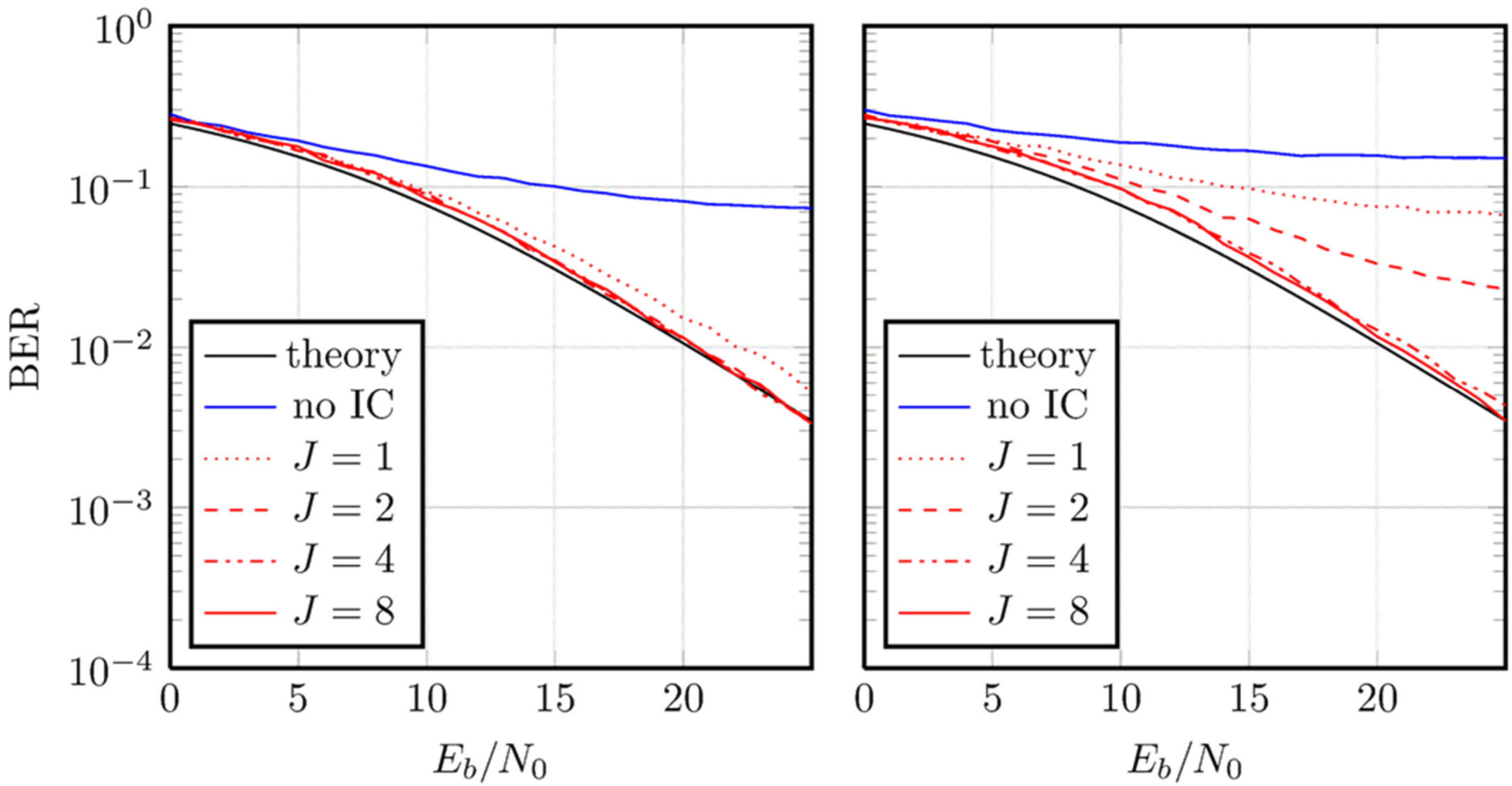




Bit Error Rate Performance

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 km/s

30 km in 0.1 ms

Tactile Internet

≤ 1 ms

LTE ~ 50 ms

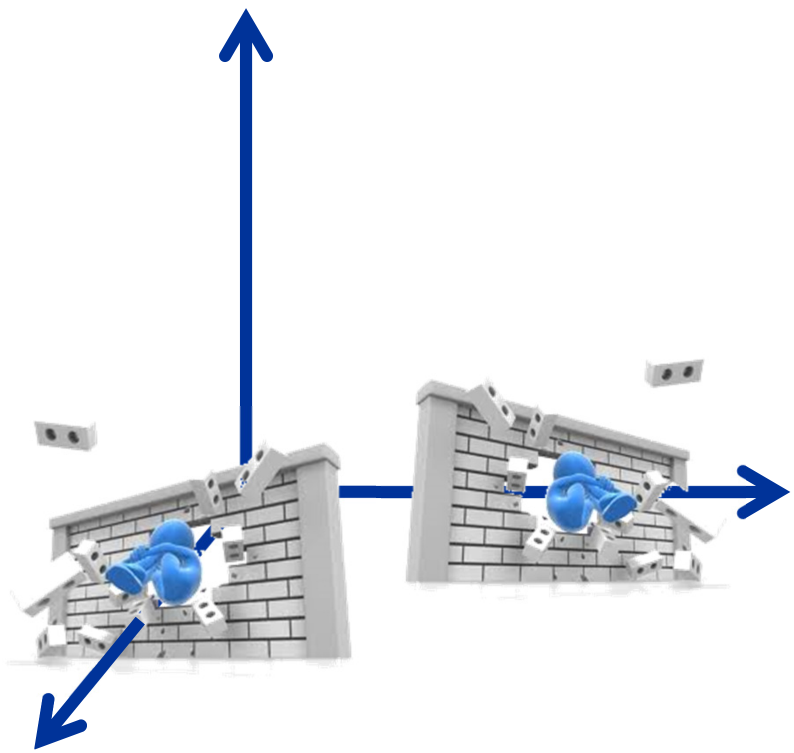
How to get there

- Small frames /TTIs
- Fast hardware (22nm)
- Realtime protocols & RRM
- Realtime operating systems
- Optimized routing

Communications → Monitoring →Control

Speed: >10 Gb/s

COMMUNICATIONS



MONITORING

>10 years, 10b/s (1Ah)

CONTROL

Response: <10 ms

Motivation
Cellular Roadmap

5G – 2020
+ Control
+ Things 2.0

4G – today
+ Video Conferencing
+ 3D Graphics

3G – 2002
+ Data
+ Positioning

2G – 1992
Voice
Messages

Thanks to Vodafone for 18 years of continued support !

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