

5G: And Its Impact on Electronics

Gerhard P. Fettweis

Vodafone Chair Professor

coordinator



**5G LAB
GERMANY**



serial entrepreneur

Via Della Conciliazione



2005/4/4



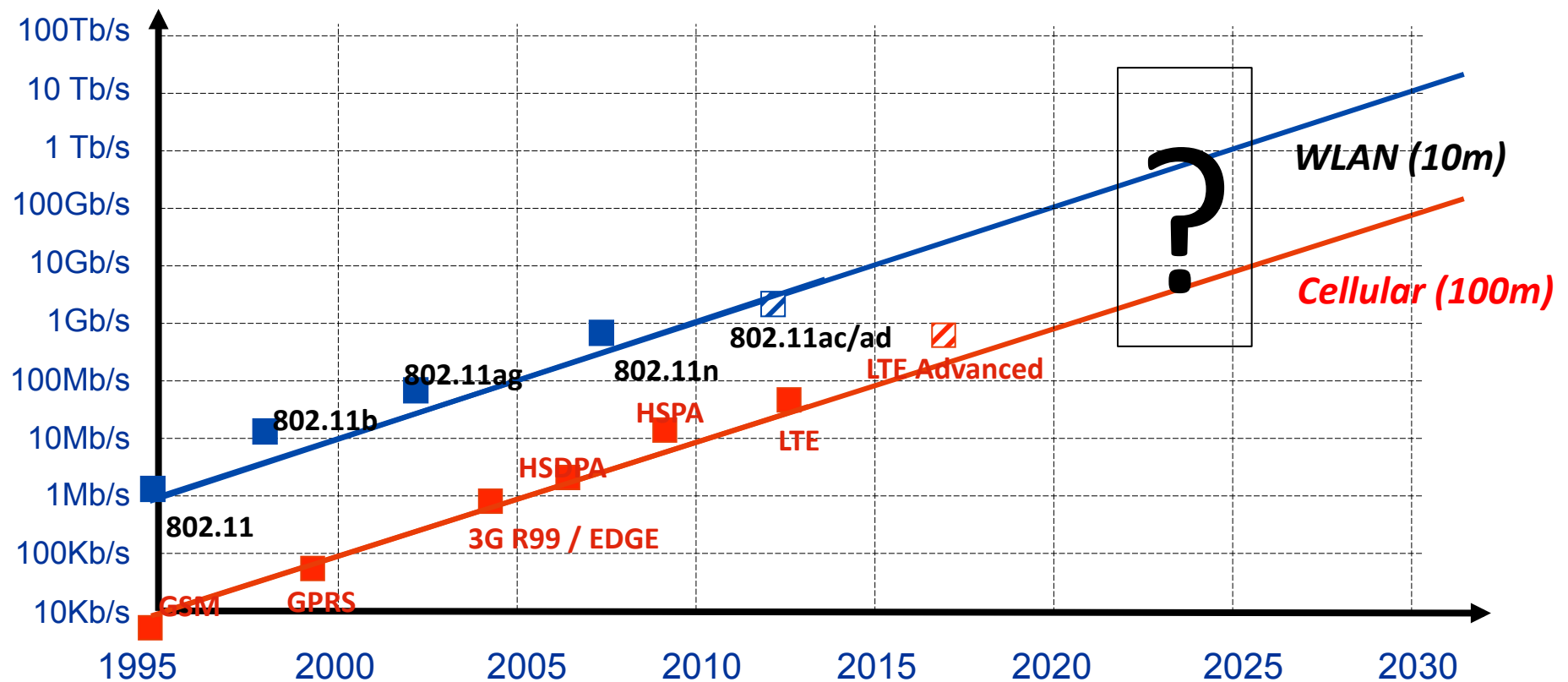
Source: <http://www.spiegel.de/panorama/bild-889031-473266.html>

2013/3/12



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

Wireless >2020 Outlook





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)

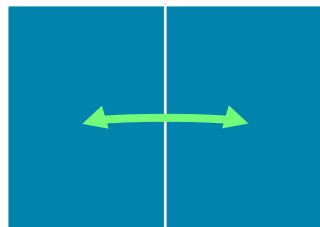


HAEC

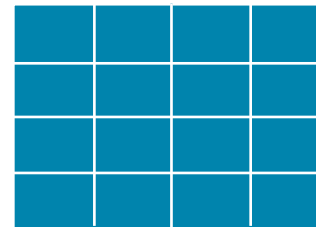
The Communication Bottleneck of Parallel Computing



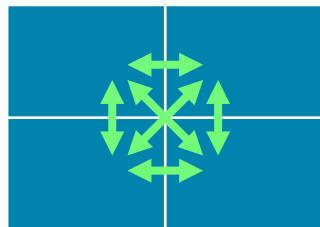
Collaborative Research Center 912: HAEC — Highly Adaptive Energy-Efficient Computing



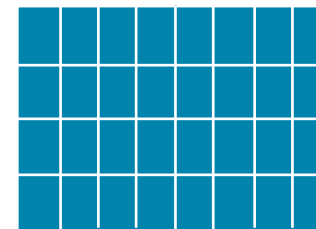
Parallelism = 2
Comm. links = 1



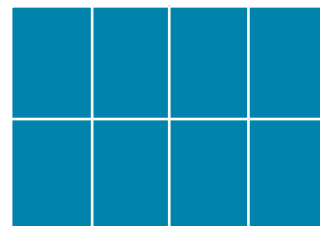
P=16
C=120



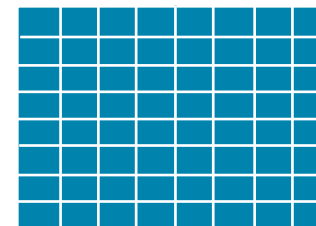
P=4
C=6



P=32
C=496



P=8
C=28



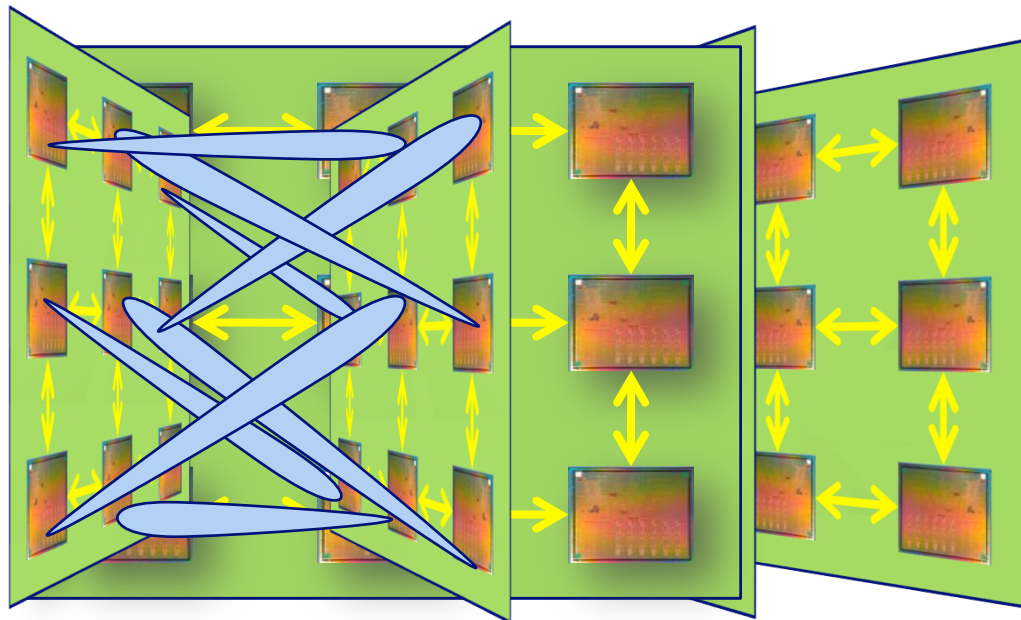
P=64
C=2016

Highly Adaptive Energy-Efficient Computing

Inter-Chip Communications



Collaborative Research Center 912: HAEC — Highly Adaptive Energy-Efficient Computing

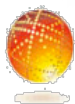


Optical Interconnect

- 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

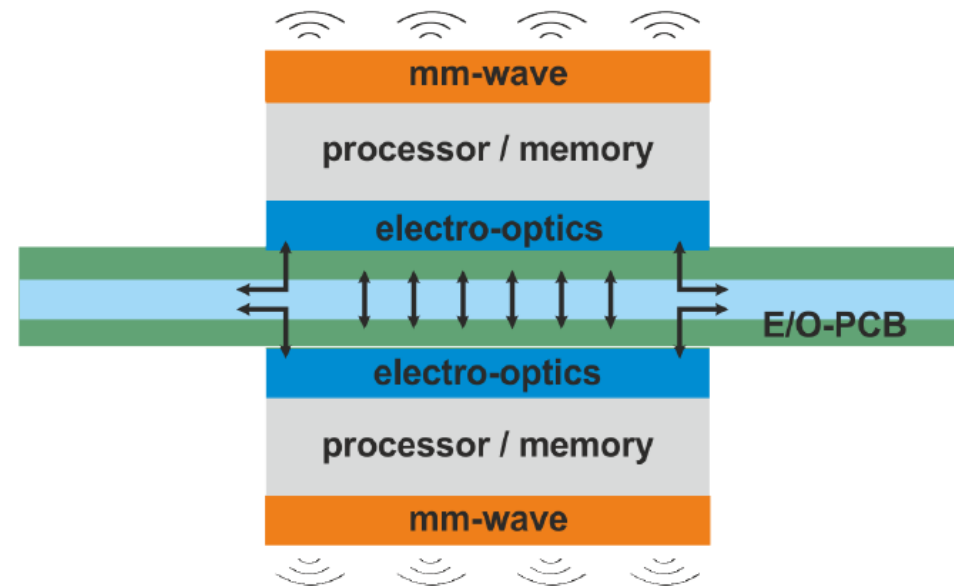
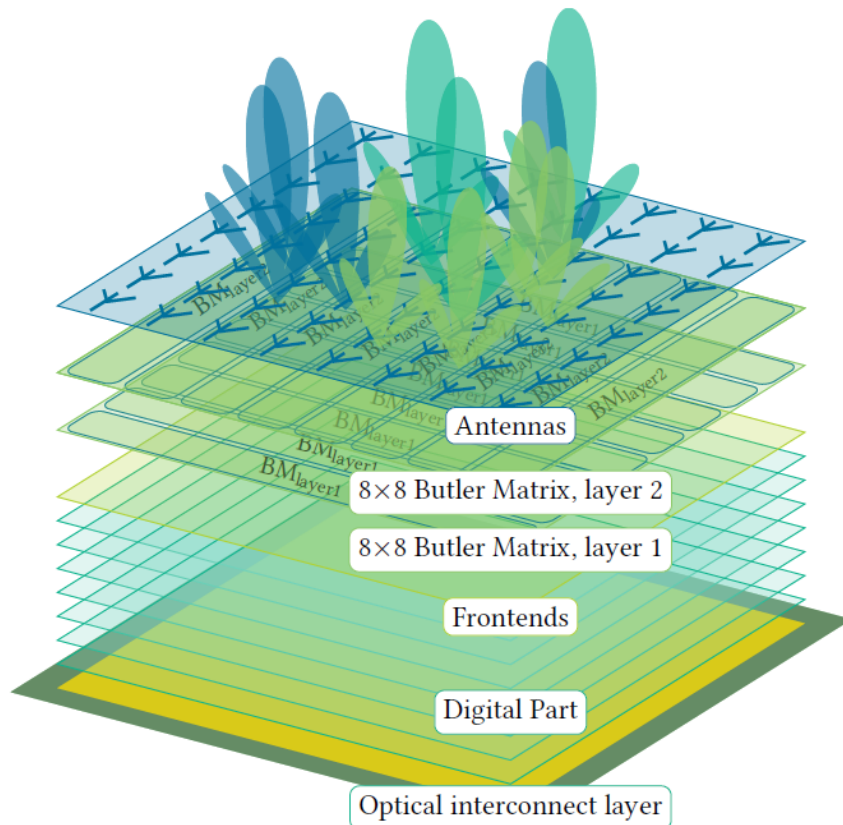


Some 3D Details of the HAEC Box



7

Collaborative Research Center 912: HAEC — Highly Adaptive Energy-Efficient Computing



The Outlook: The HAEC Box in 2030+

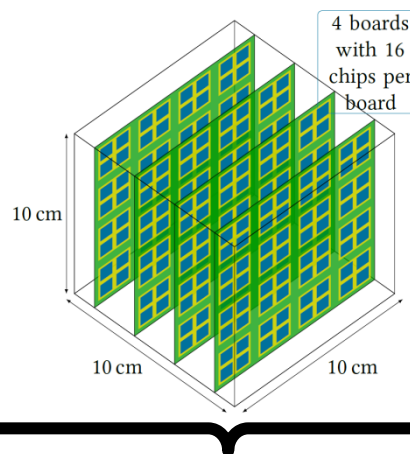
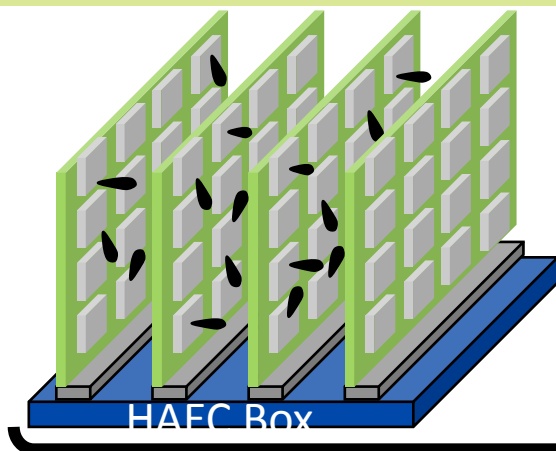


Slide 8

Collaborative Research Center 912: HAEC — Highly Adaptive Energy-Efficient Computing

Assume 64K processors per chip
128x chips stacked in 3D

2x 4x4 chip-stacks on board
4x boards in a box



in $10 \times 10 \times 10 \text{ cm}^3$ (1 liter)

1636 proc.+ 14746 memory chips

→ 10^8 processors!

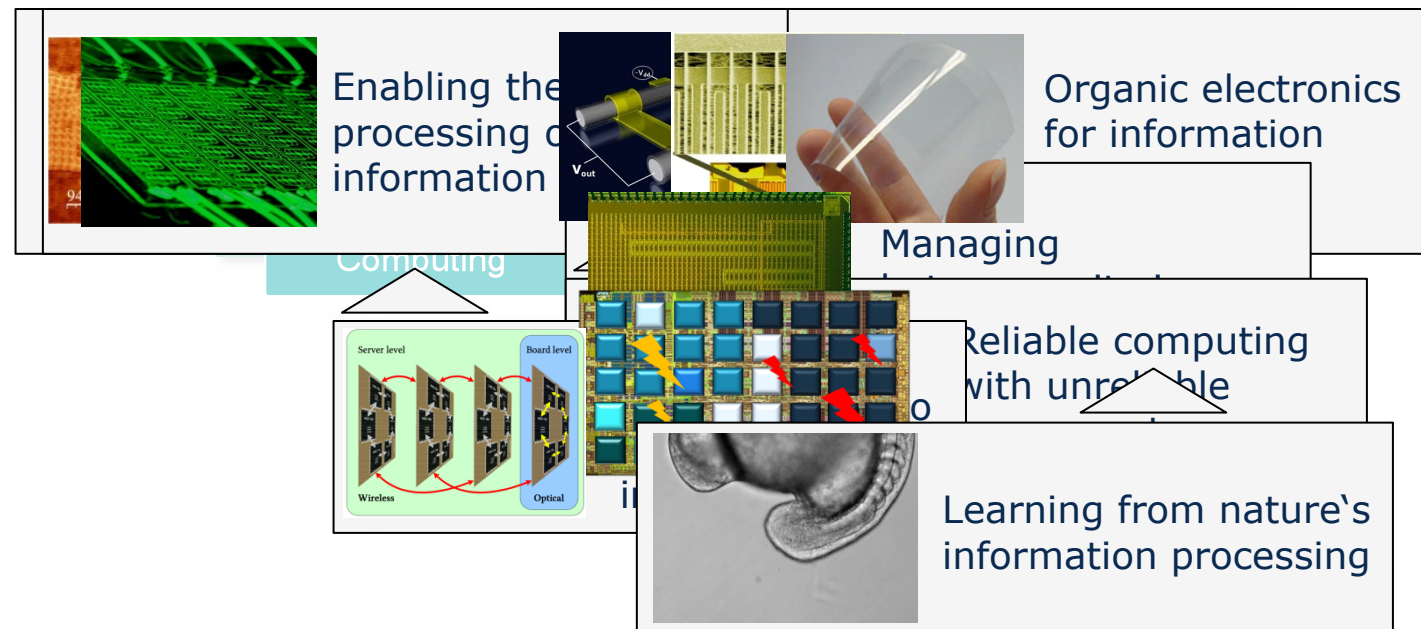
→ $10^4 \times$ performance of today!

Center for Advancing Electronics Dresden



Comprehensive Approach

"More-Shots-on-Goal"



A Future for Synchronous Clocks?



New Journal of Physics

The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft  DPG | IOP Institute of Physics

Synchronization in networks of mutually delay-coupled phase-locked loops

Alexandros Pollakis^{1,3}, Lucas Wetzel^{2,3}, David J Jörg^{2,3}, Wolfgang Rave^{1,3},
Gerhard Fettweis^{1,3} and Frank Jülicher^{2,3}

¹ Technische Universität Dresden, Vodafone Chair, Dresden, Germany

² Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

³ Center for Advancing Electronics Dresden cfaED, Dresden, Germany

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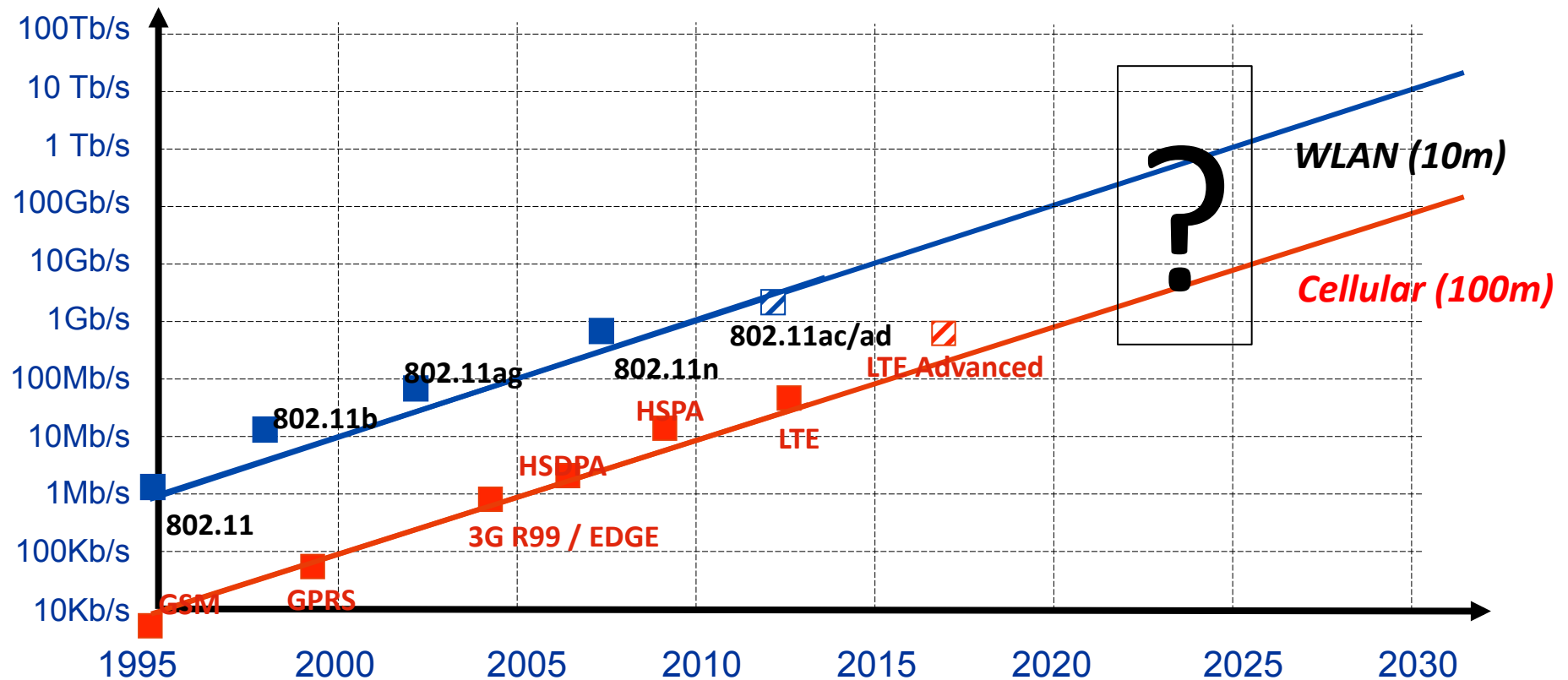
Accepted for publication 18 September 2014

Published 4 November 2014

New Journal of Physics **16** (2014) 113009

doi:[10.1088/1367-2630/16/11/113009](https://doi.org/10.1088/1367-2630/16/11/113009)

Wireless >2020 Outlook







Quelle: japantimes.co.jp/news/2014/09/30/asia-pacific/hong-kong-democracy-protesters-set-deadline-for-demands/

Slide 14



Quelle: japantimes.co.jp/news/2014/09/30/asia-pacific/hong-kong-democracy-protesters-set-deadline-for-demands/



7
Billion Devices
2014

500
Billion Devices
2022

Quelle: japantimes.co.jp/news/2014/09/30/asia-pacific/hong-kong-democracy-protesters-set-deadline-for-demands/



The Tactile Internet And Its Millisecond

The Tactile Internet



Moving from 25ms RTT → 1ms tomorrow



<http://ostsee-spezial.de/?p=148>
Gerhard Fettweis

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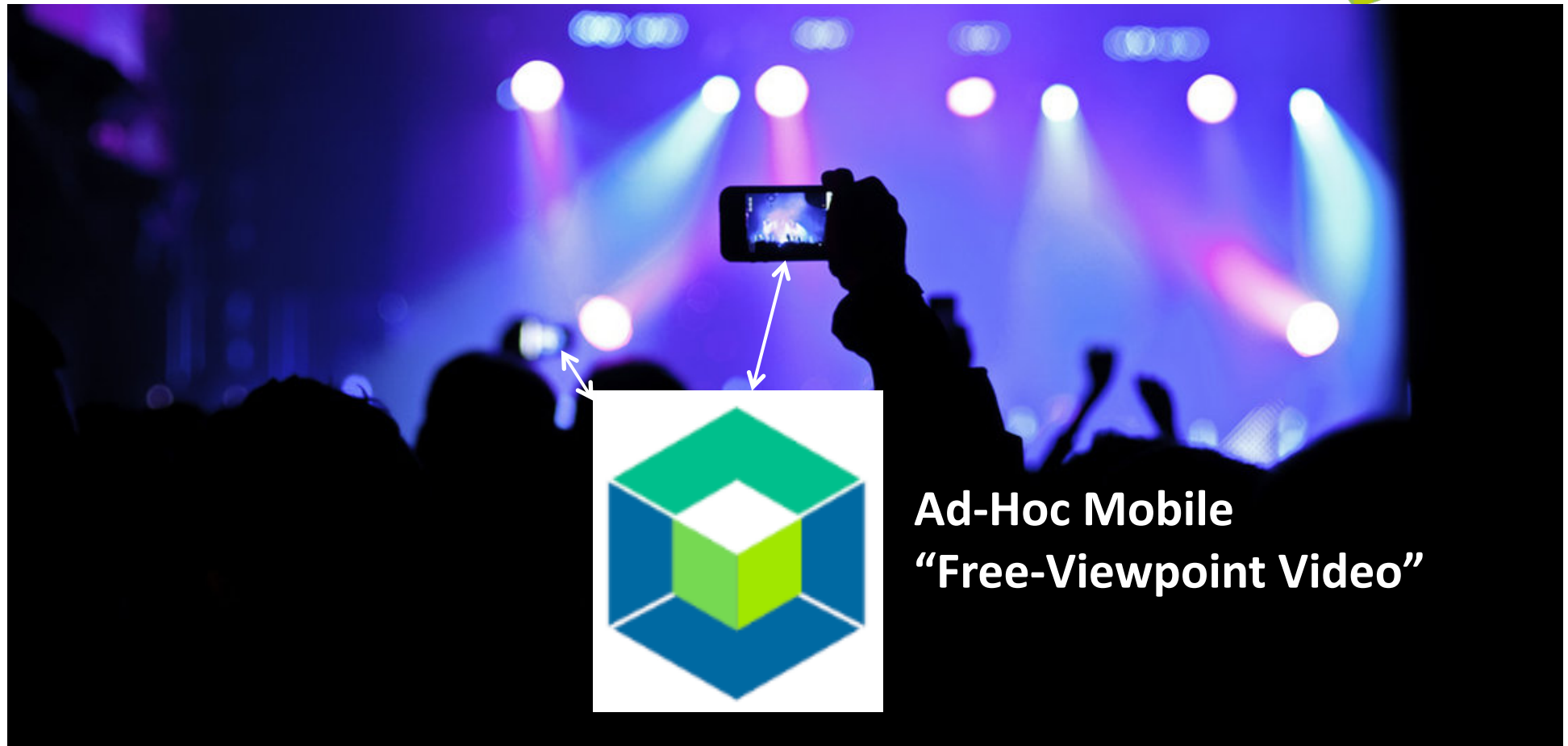
Gaming...



Pedelec: Tactile Control

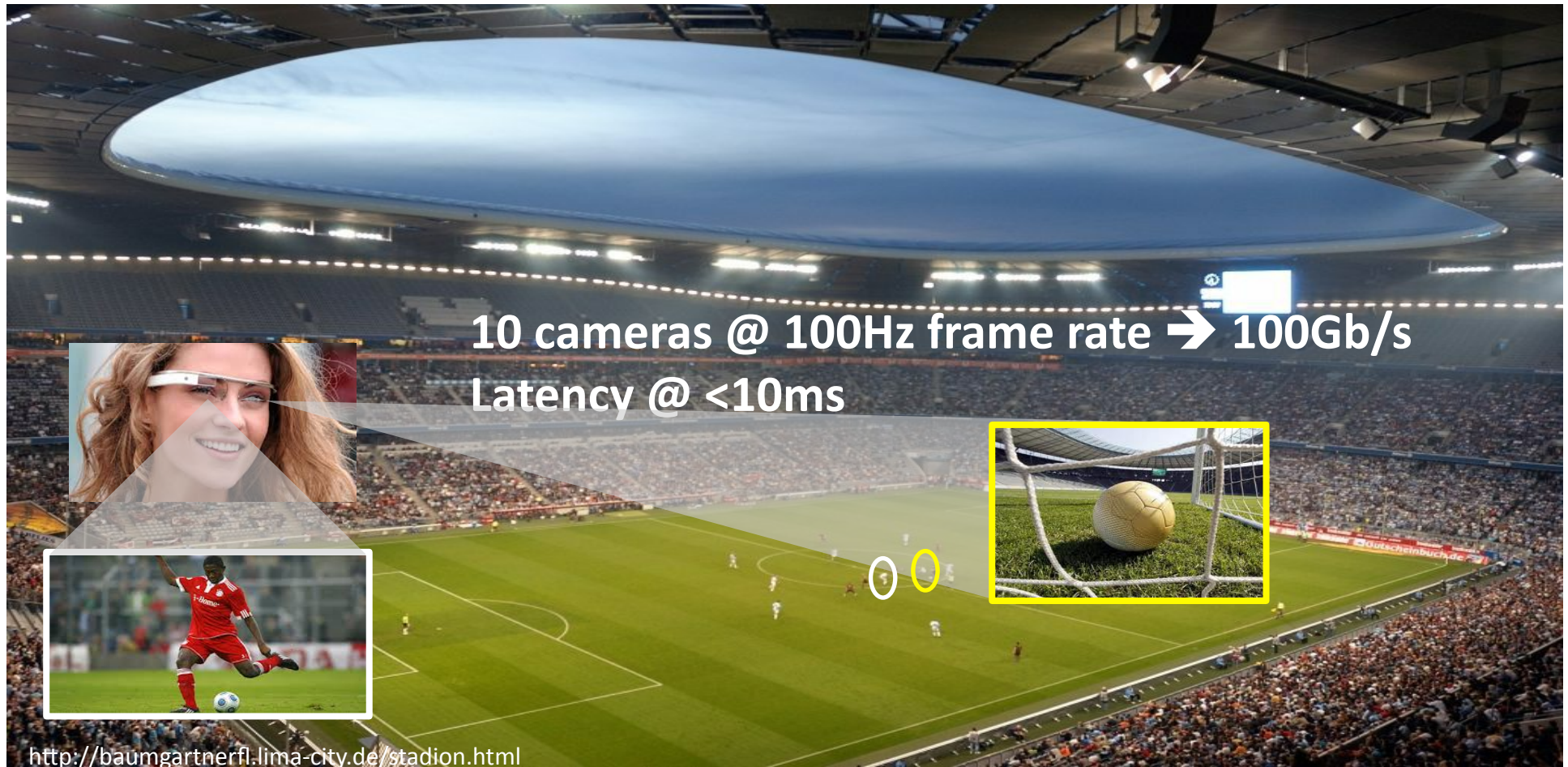


Free-Viewpoint Video



**Ad-Hoc Mobile
"Free-Viewpoint Video"**

Tactile Internet Killer App: Free Viewpoint Video



Reinventing “Latin Classes”



The Tactile Internet: Remote Controlled Humanoid Robots



http://images.gizmag.com/hero/8456_51207105642.jpg



Gerhard Fettweis

Human Touch



The Tactile Internet

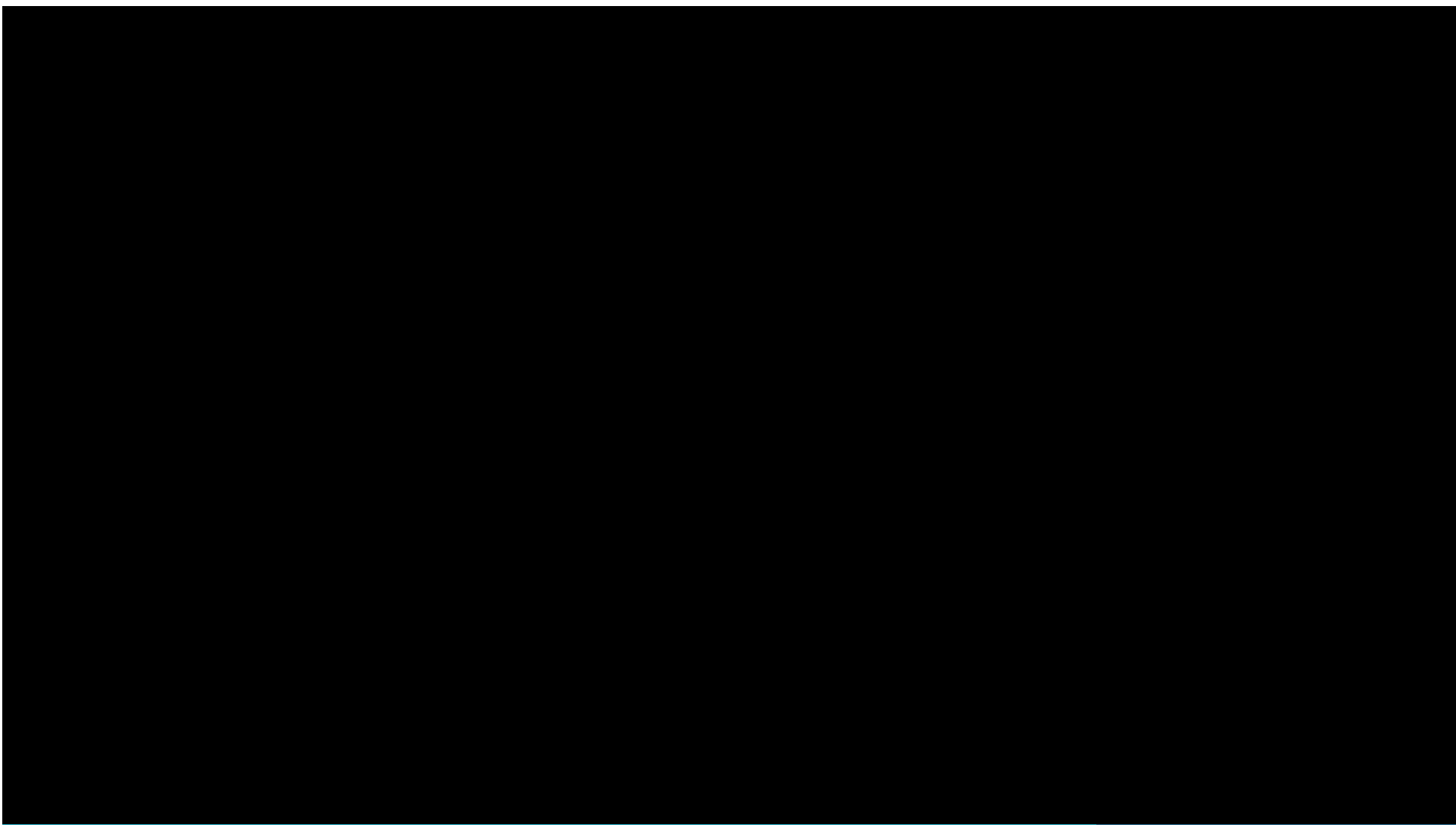
The Manufacturing Revolution Ahead



Design Service: A Job Machine







Revolution Ahead: The Tactile Internet

≤ 4G:
Content
Communications

5G:
Steering & Control
Communications

Health & Care
Traffic & Mobility
Sports & Gym
Edutainment
Manufacturing
Smart Grid
...



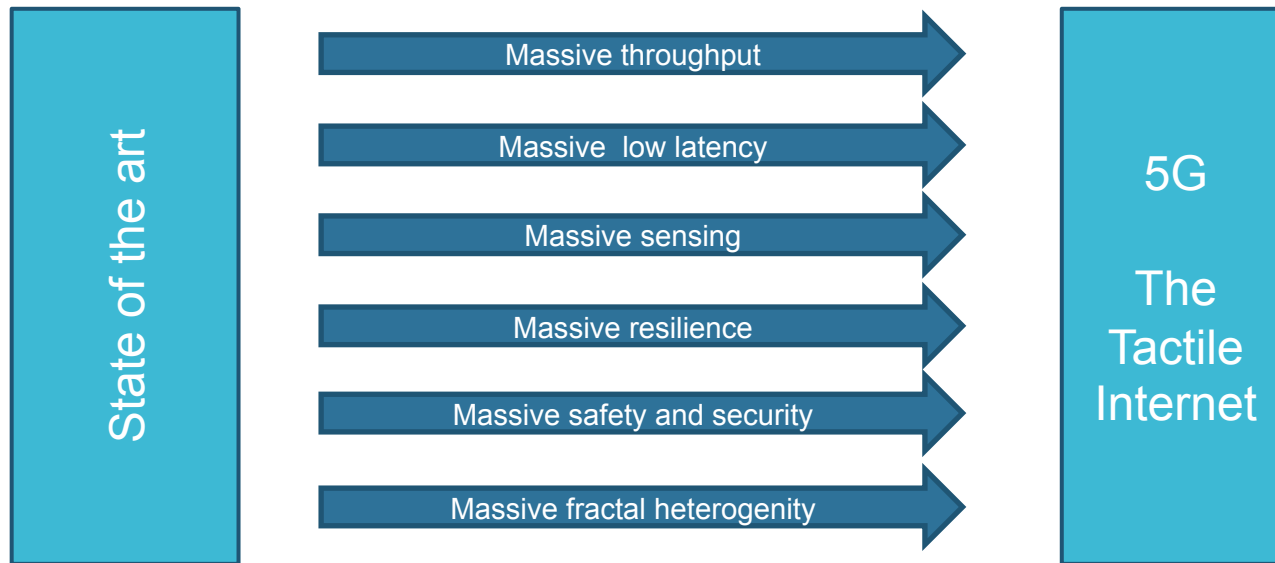
**5G LAB
GERMANY**

5G CHALLENGES

5G – “Massive” Requirements



5G – “Massive” Requirements



> 10Gbit/s per user



< 1ms RTT



> 10k sensors per cell



< 10^{-8} outage

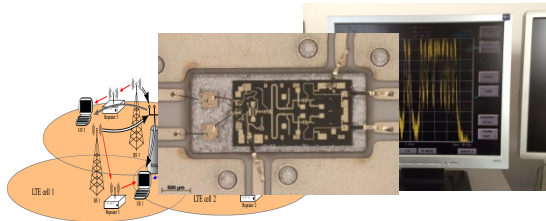


< 10^{-12} security

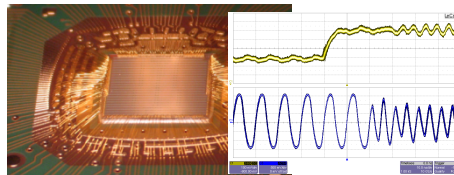


10x10 heterogeneity

5G Research on four Tracks



Wireless



Silicon systems



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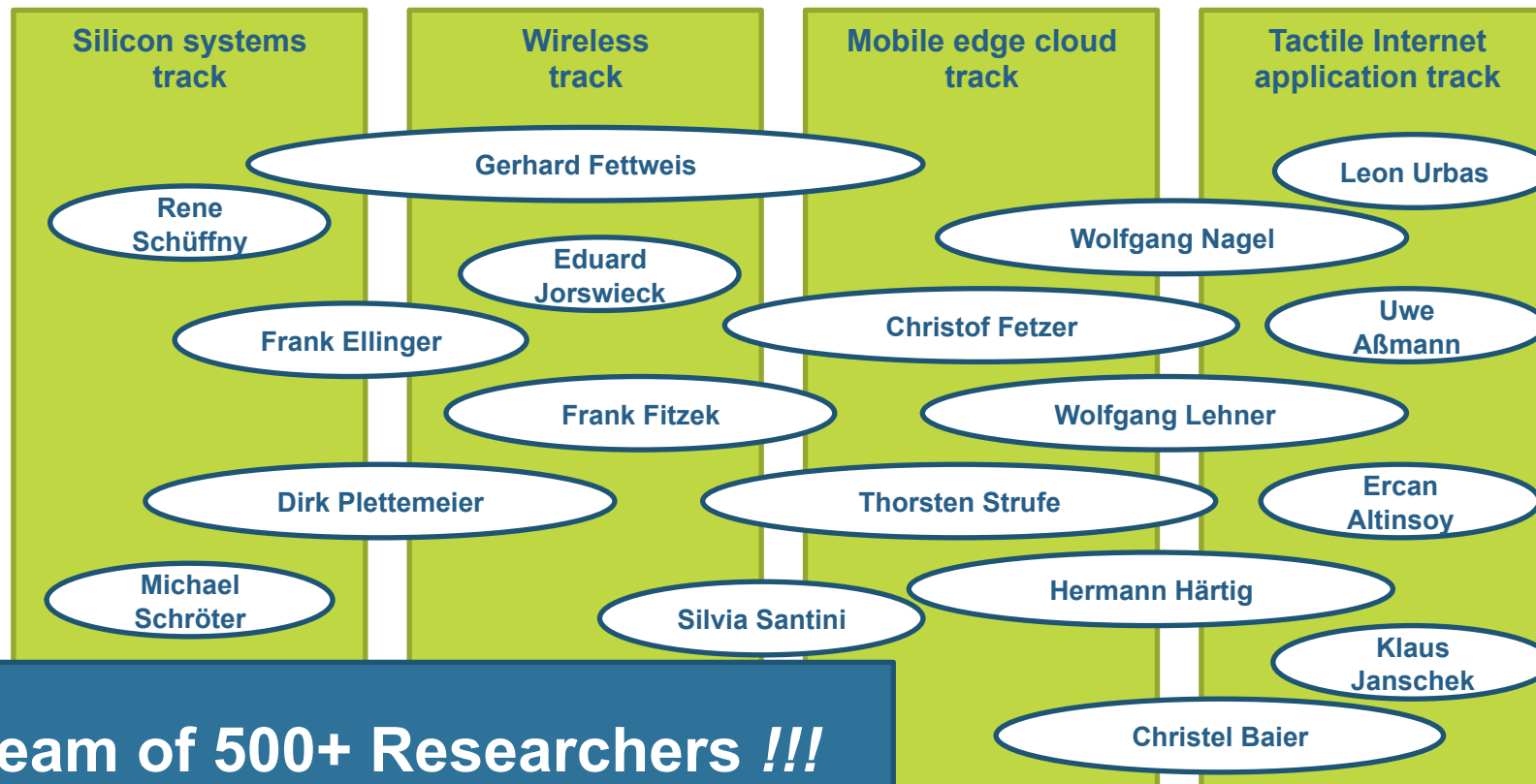


Tactile Internet applications



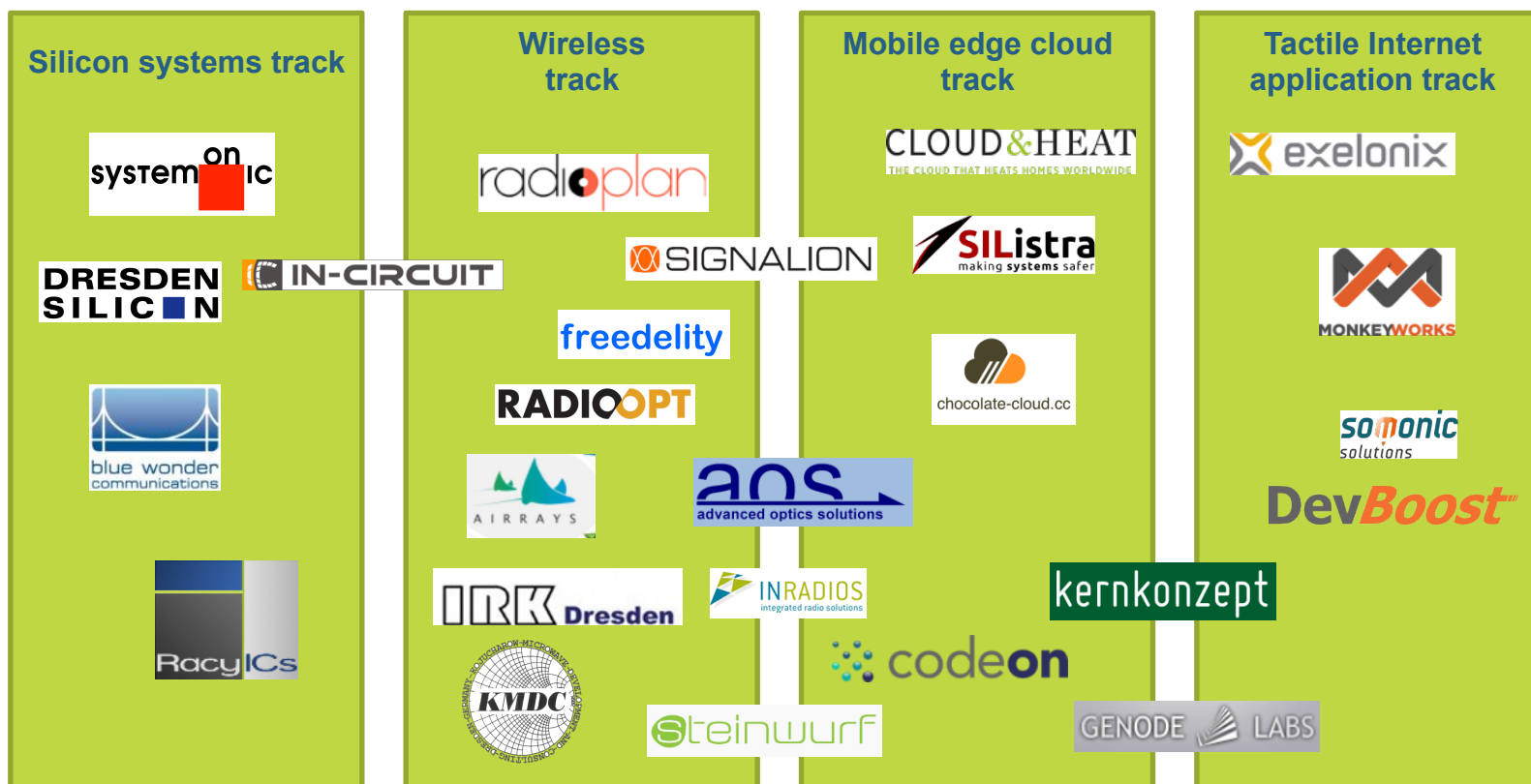
Mobile edge cloud

Members on Tracks



Team of 500+ Researchers !!!

Relevant Startups Generated by Team



Currently Connected Partners







TECHNISCHE
UNIVERSITÄT
DRESDEN

5G Research Laboratory Sponsored by



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iano Mendes



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Slide 40

fast **a**ctuators **s**ensors & **t**ransceivers



Coordinators: Frank Ellinger, (Gerhard Fettweis), TU Dresden
Starting 2014, appox. €75M project size, 60+ partners



Bundesministerium
für Bildung
und Forschung

fast
value chain
sales &
service
systems,
networks,
software
circuits
components
semi-
conductors



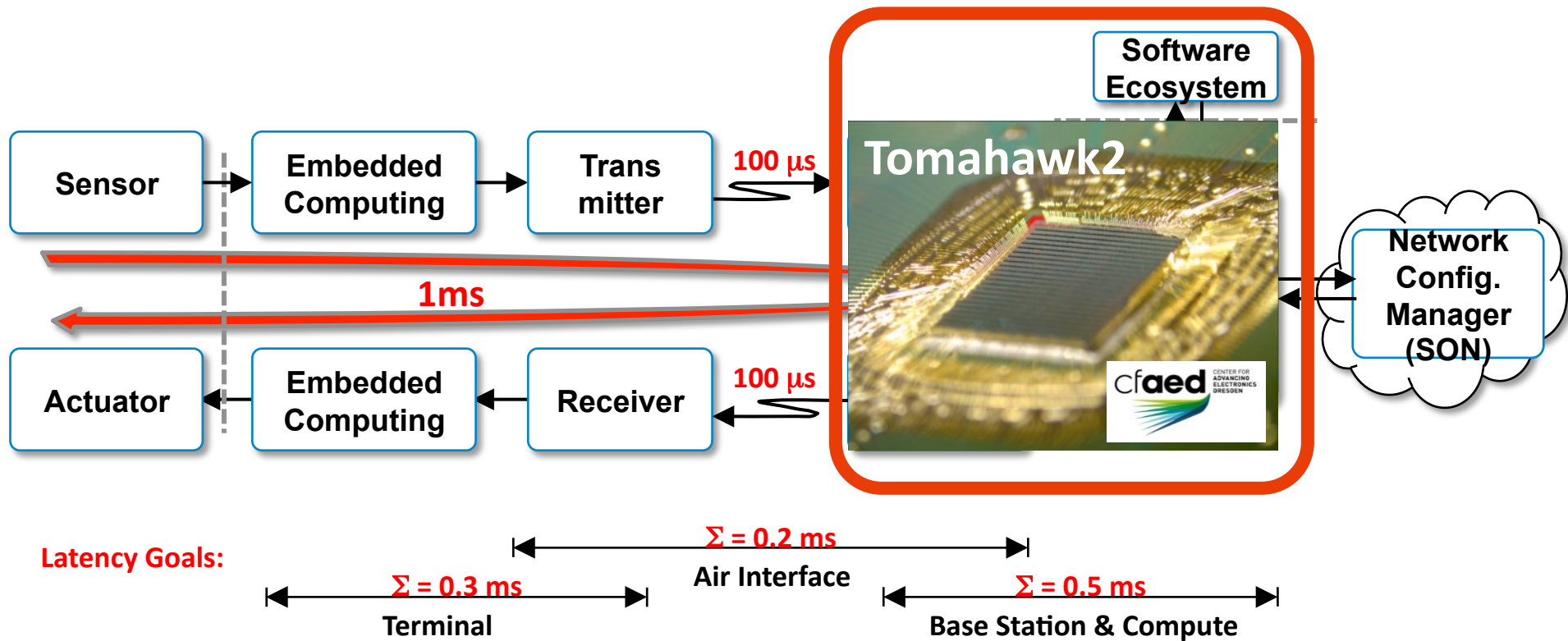
fast
network of
states
Berlin
Brandenburg
Mecklenburg
Vorpommern
Saxony-Anhalt
Saxony
Thuringia
Baden-Württ.
Lower Saxony
Bavaria



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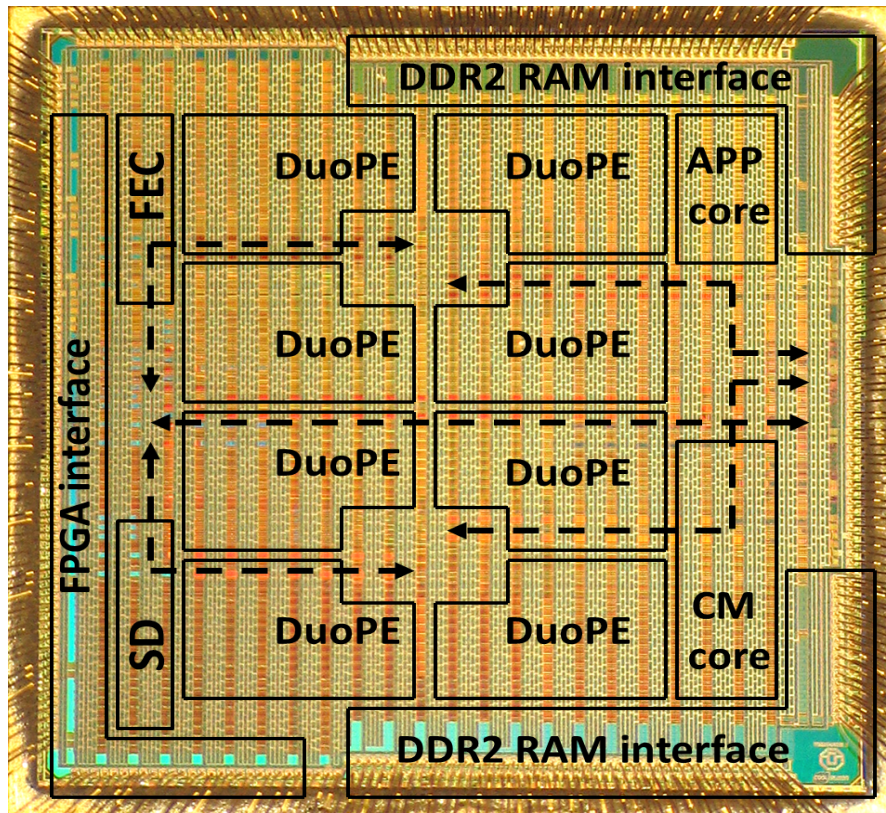
THE MILLISECOND

1ms Impact



Tommahawk2

(ISSCC 2014)



serial on-chip link (72Gbit/s)

local ADPLL clock generator

TSMC 65nm LP CMOS
6mm x 6mm

Pads: 465

Gates: 10,2 Millionen

SRAM: 750 kByte

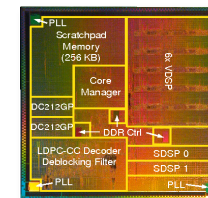
Cores: 20 processor elements

Power 150mW typical

Tapeout: 04/2013

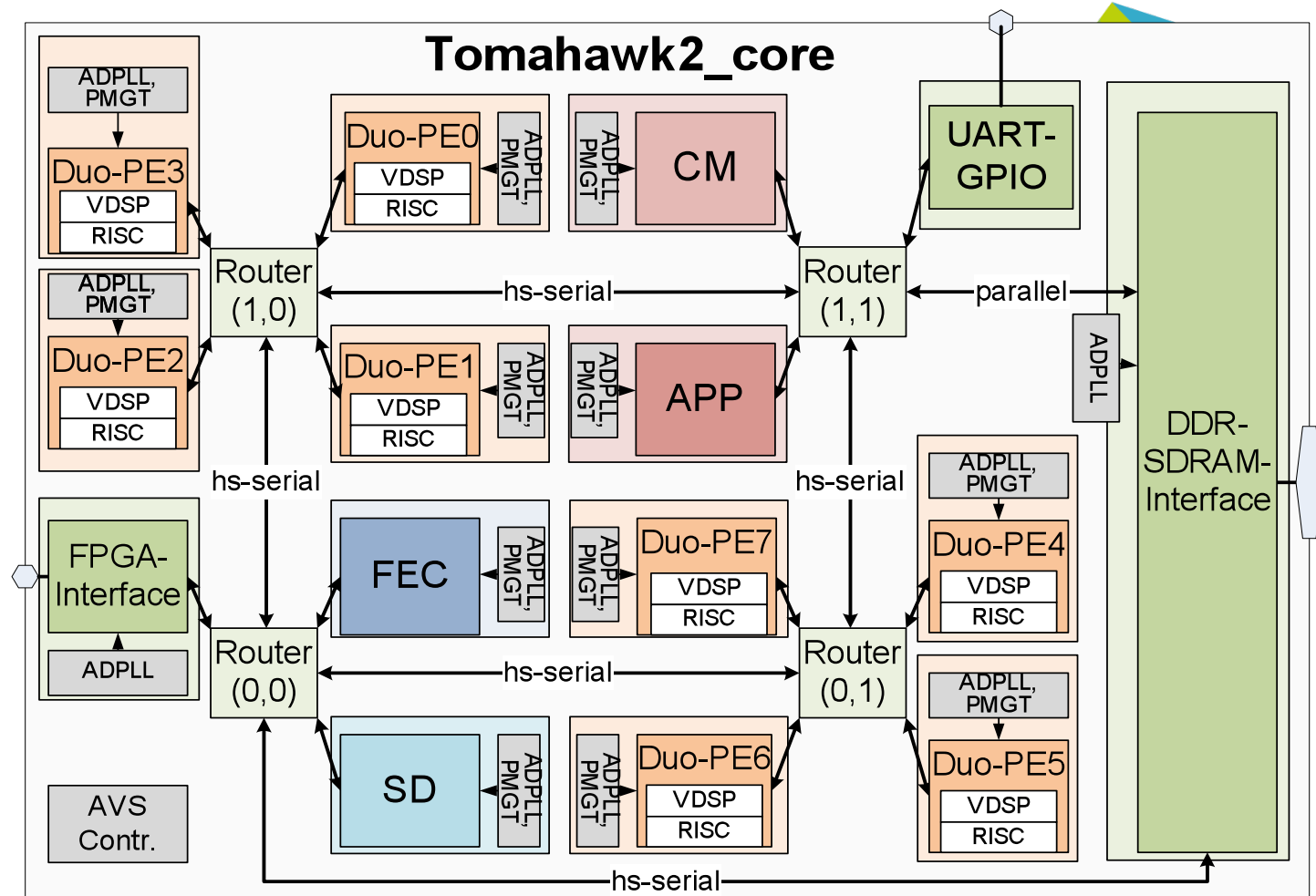
Dresden: 06/2013

Successor of Tomahawk1 (2007):

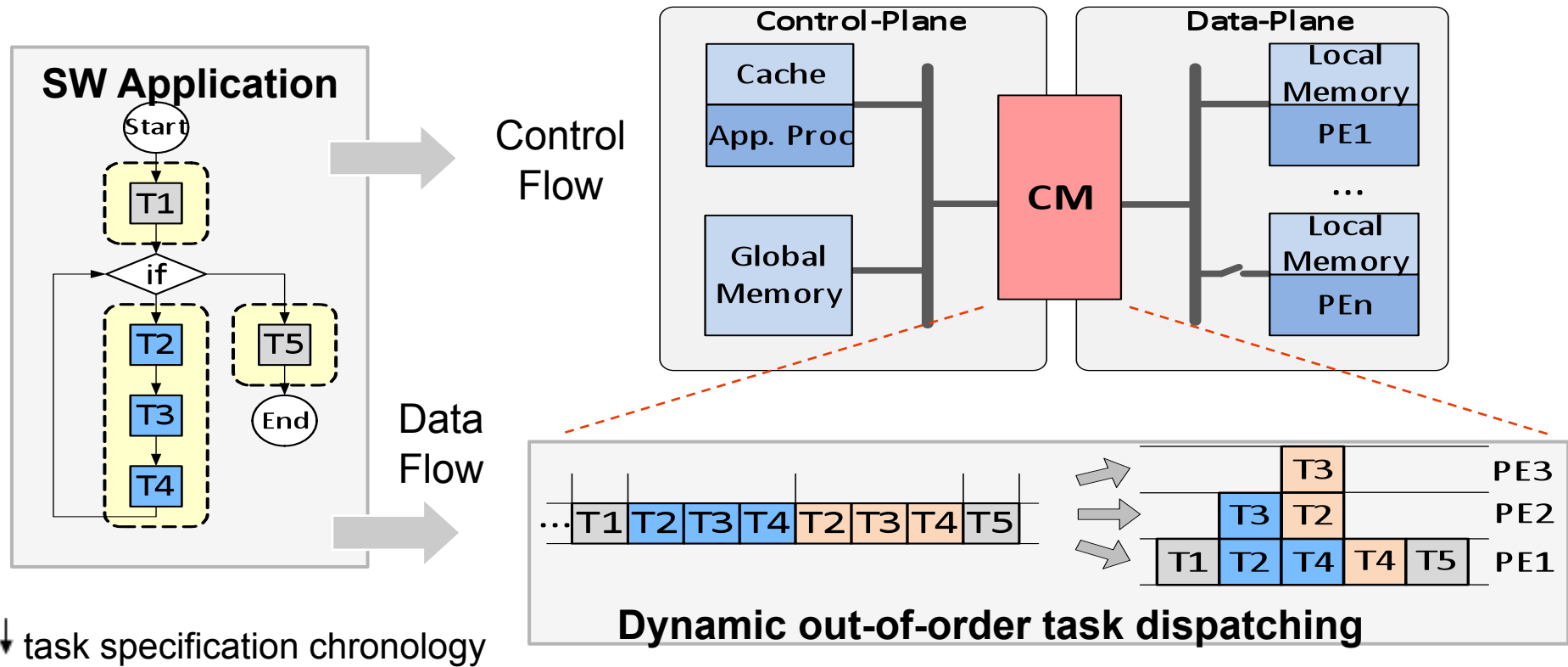


Winner of 2009 DAC/ISSCC Student Design Contest

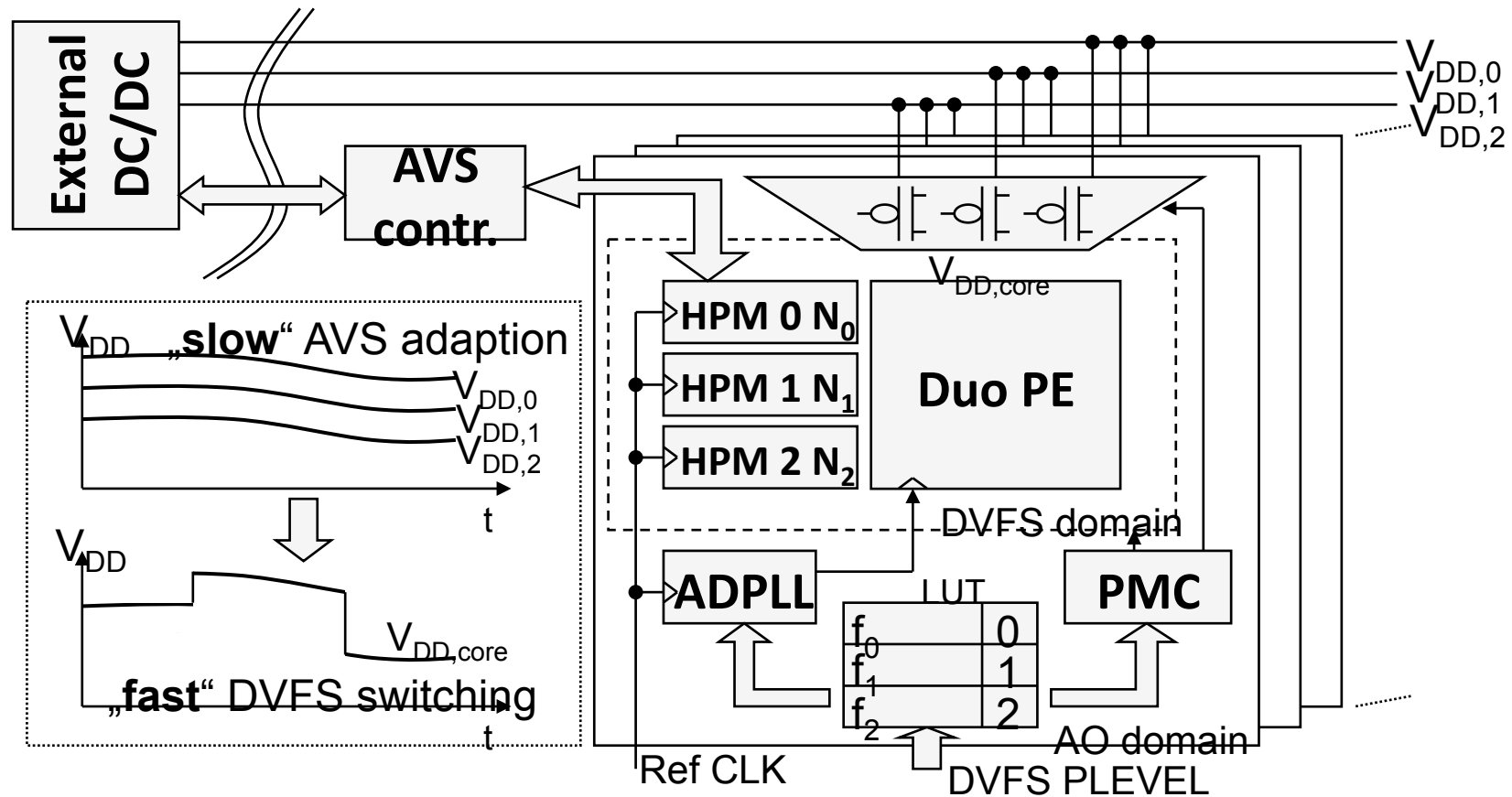
Block Diagram



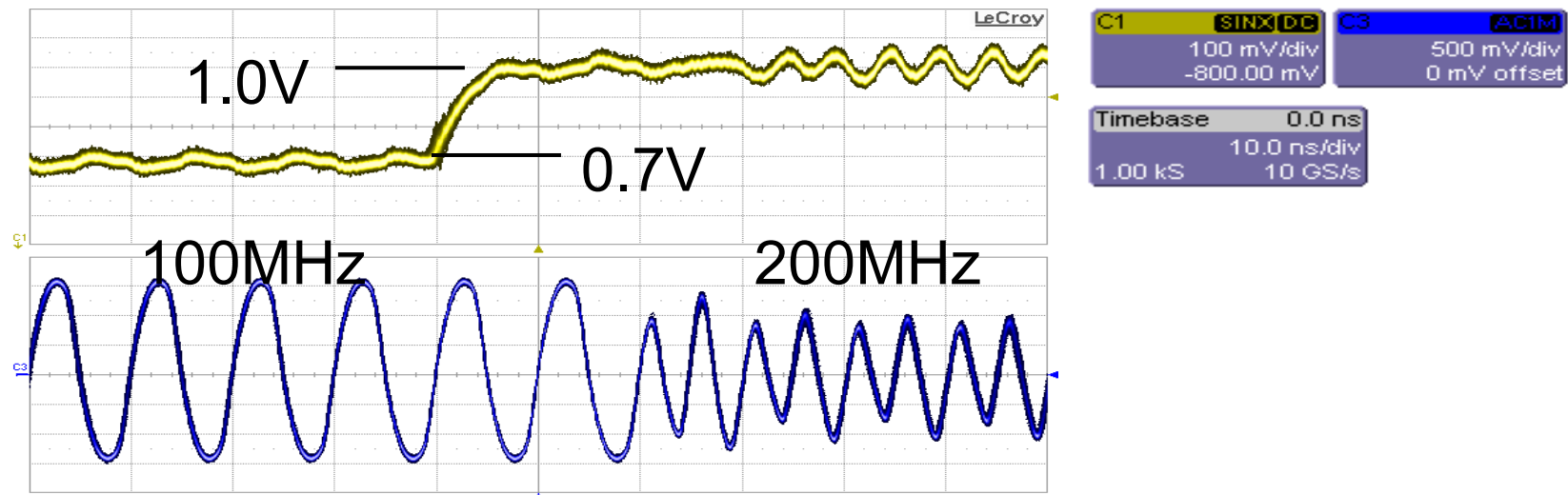
Tomahawk Architecture Framework



Power Management Architecture



Fast DVFS Measurement Result



- Ultra fast DVFS level change of Duo-PE in <20ns

SDR Architectures for MIMO 3GPP-LTE/WiMAX



	Tomahawk2	Magali [6]	Tomahawk [3]
Clocking and Power Management	GALS, local DVFS and AVS, power-gating	GALS, local DFS	Global clock
Scheduling	Dynamic (flexible, energy adaptable)	Static	Dynamic (fixed algorithm)
Peak Performance	105 GOPS (3.6 GFLOPS)	37 GOPS	40 GOPS
Application for power measurements	4x4 MIMO 3GPP baseband, 60 Mbps	2x2 MIMO Tx, 10.8 Mbit/s	LTE/WiMAX
Power consumption	480 mW @ 1.15V	477 mW @ 1.2V	1.2W @ 1.3V
NoC Throughput (per link)	80 Gbit/s	17 Gbit/s	5.47 Gbit/s
Die size	36mm ²	29.6 mm ²	100 mm ²
Technology	65nm	65nm	130nm

150mW typical

[6] Clermidy, *et al.*, A 477mW NoC-based digital baseband for MIMO 4G SDR, *ISSCC Dig. Tech. Papers*, pp. 278-279, 2010

RESILIENCE

Carrier Grade Wireless: Use cases



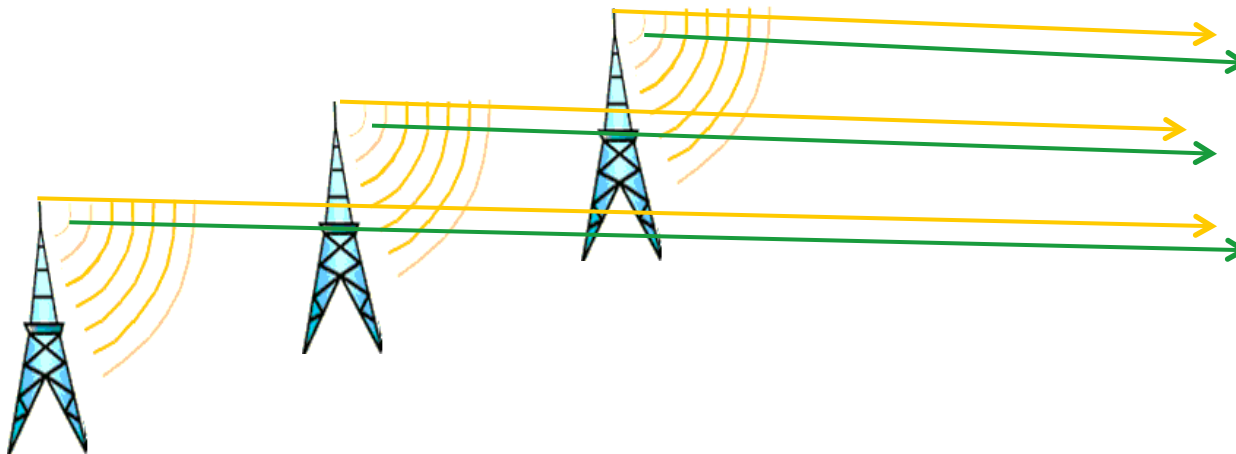
		Availability (time)	Latency	Coverage/ Availability (space)	Speed
Traffic safety & efficiency		> 99.999%	< 1ms	≈100%	< 500kmh
Industrial automation (Motion control)		> 99.999999%	< 1ms	≈100%	n/a
Telesurgery		> 99.999%	< 1ms	n/a	n/a
Emergency Communication		> 99.999%	n/a	≈100%	n/a

Others: Power Networks / Smart Grid, Real-Time Remote Computing, Platooning, ESP, Exoskeleton [1]

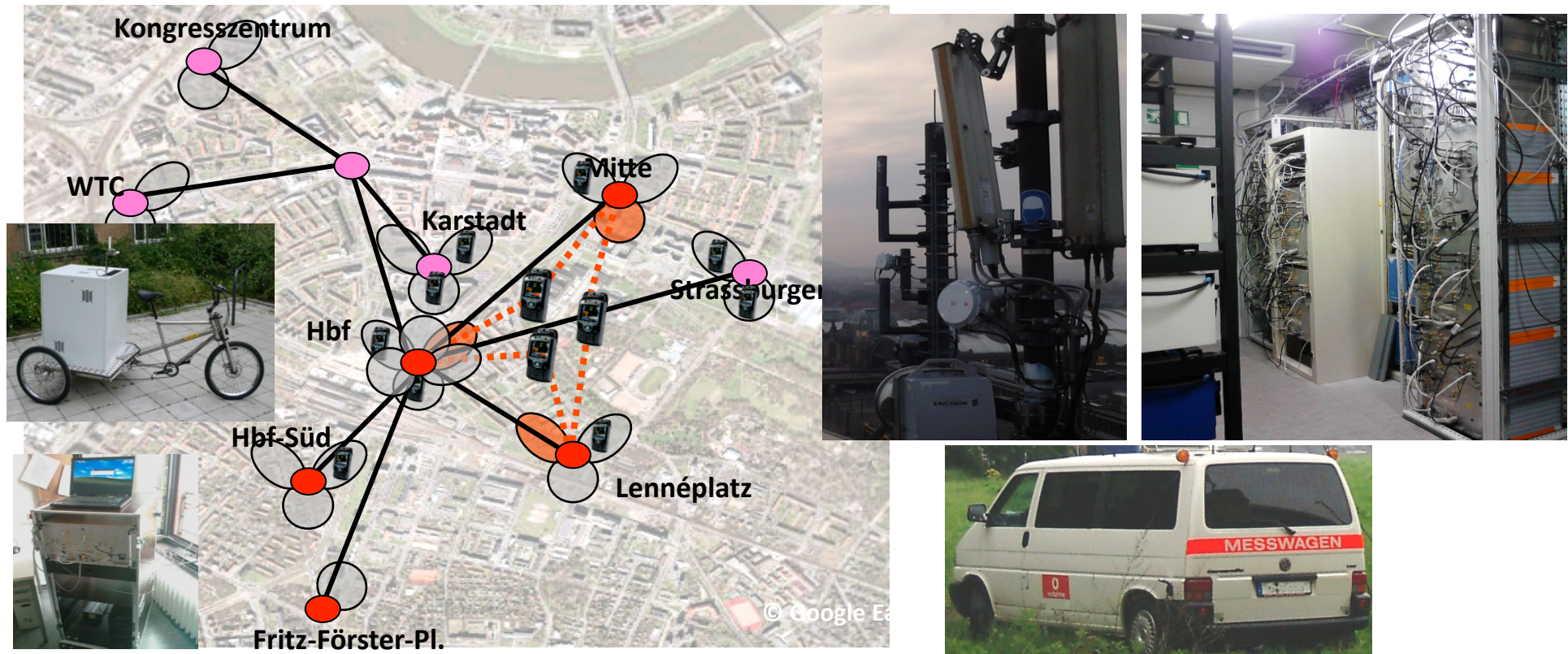
[1] Fettweis, G., "The Tactile Internet: Applications and Challenges," *Vehicular Technology Magazine, IEEE*, vol.9, no.1, pp.64,70, March 2014.

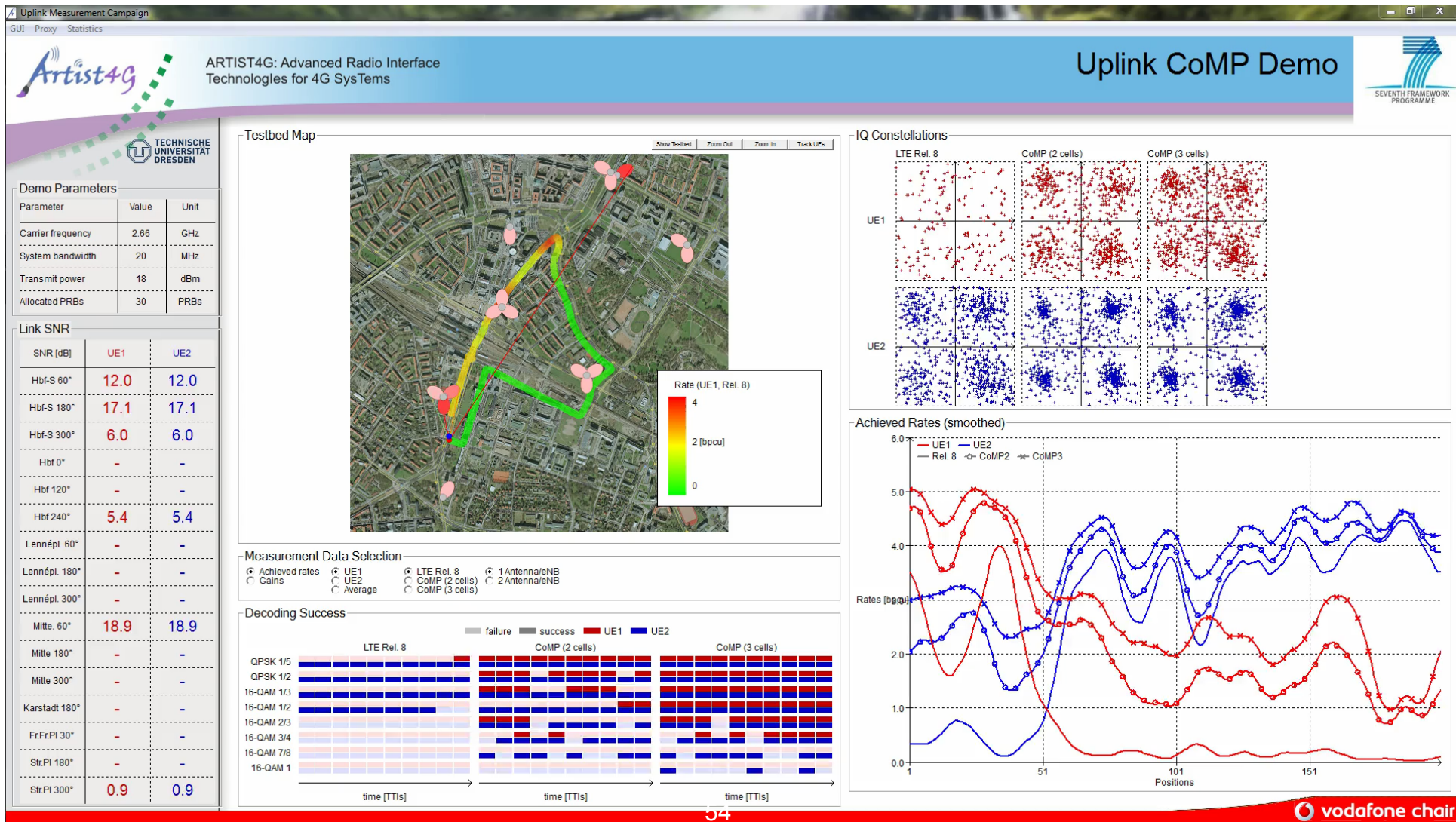
Serious Carrier Grade: 10^{-x} via Diversity

# indep. channels	1
outage	3%



2007-2013: World's Largest Operational LTE-Advanced CoMP Algorithm Testbed





Combining multiple Rayleigh-fading links



Setting:

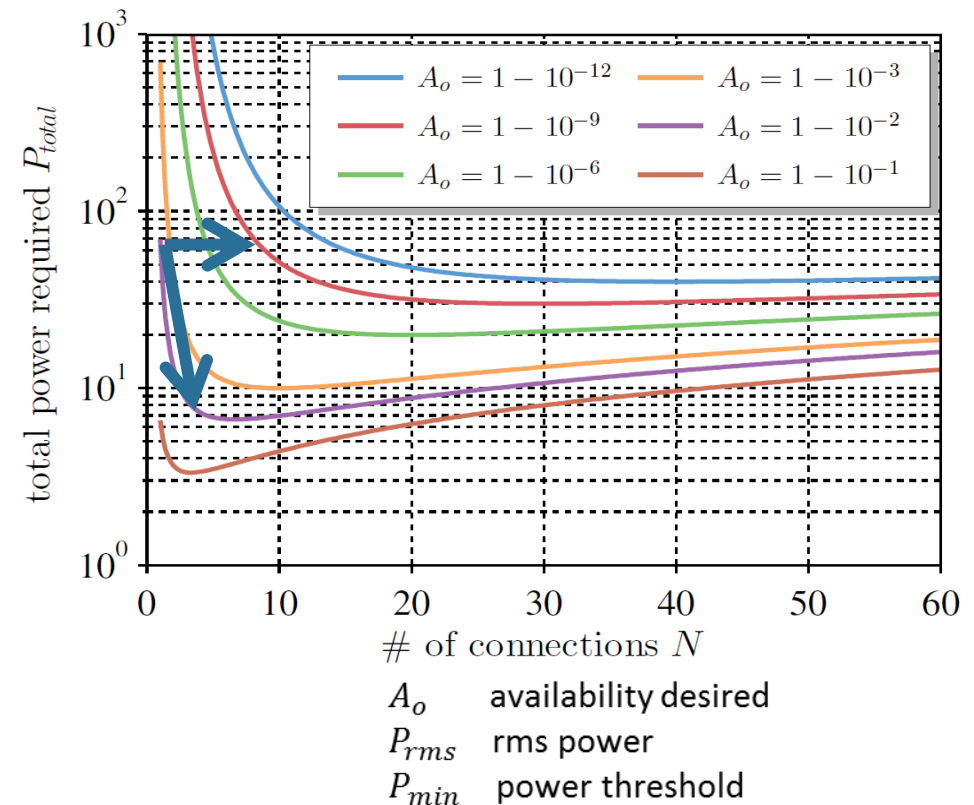
- N power-controlled links
→ only small scale fading matters
- No line of sight → Rayleigh fading

Total power required
for achieving overall availability

$$P_{total} = N \frac{P_{rms}}{P_{min}} = -\frac{N}{\ln(1 - (1 - A_o)^{1/N})}$$

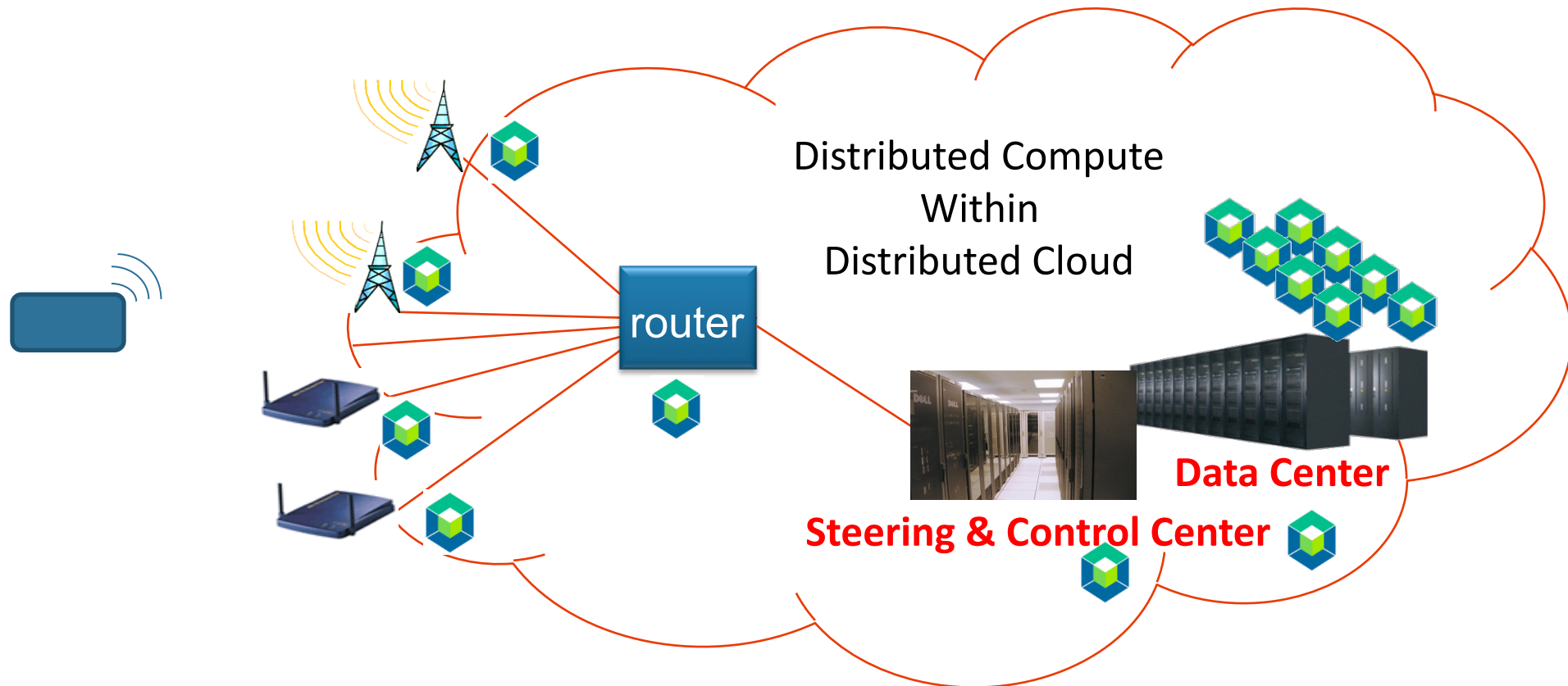
Results:

- In terms of power consumption,
utilizing multiple links is beneficial
- Different optimal operating points exist

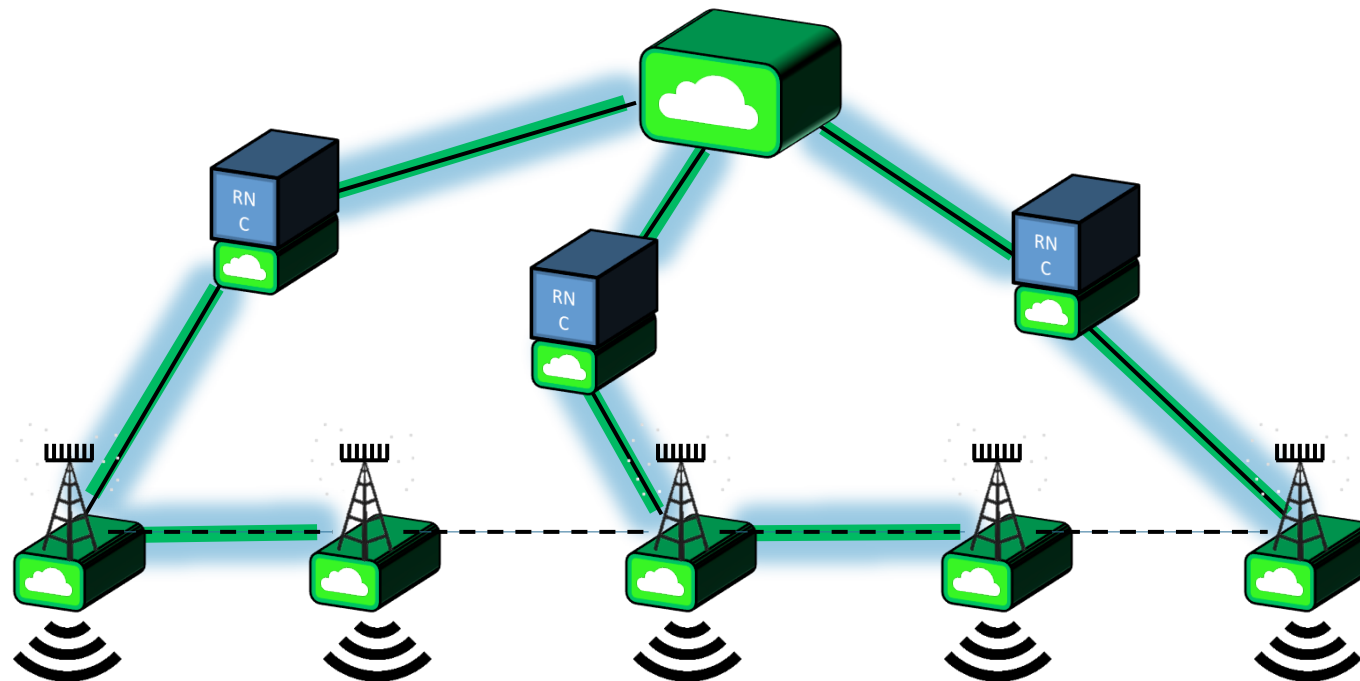


HANDOFF REVISITED

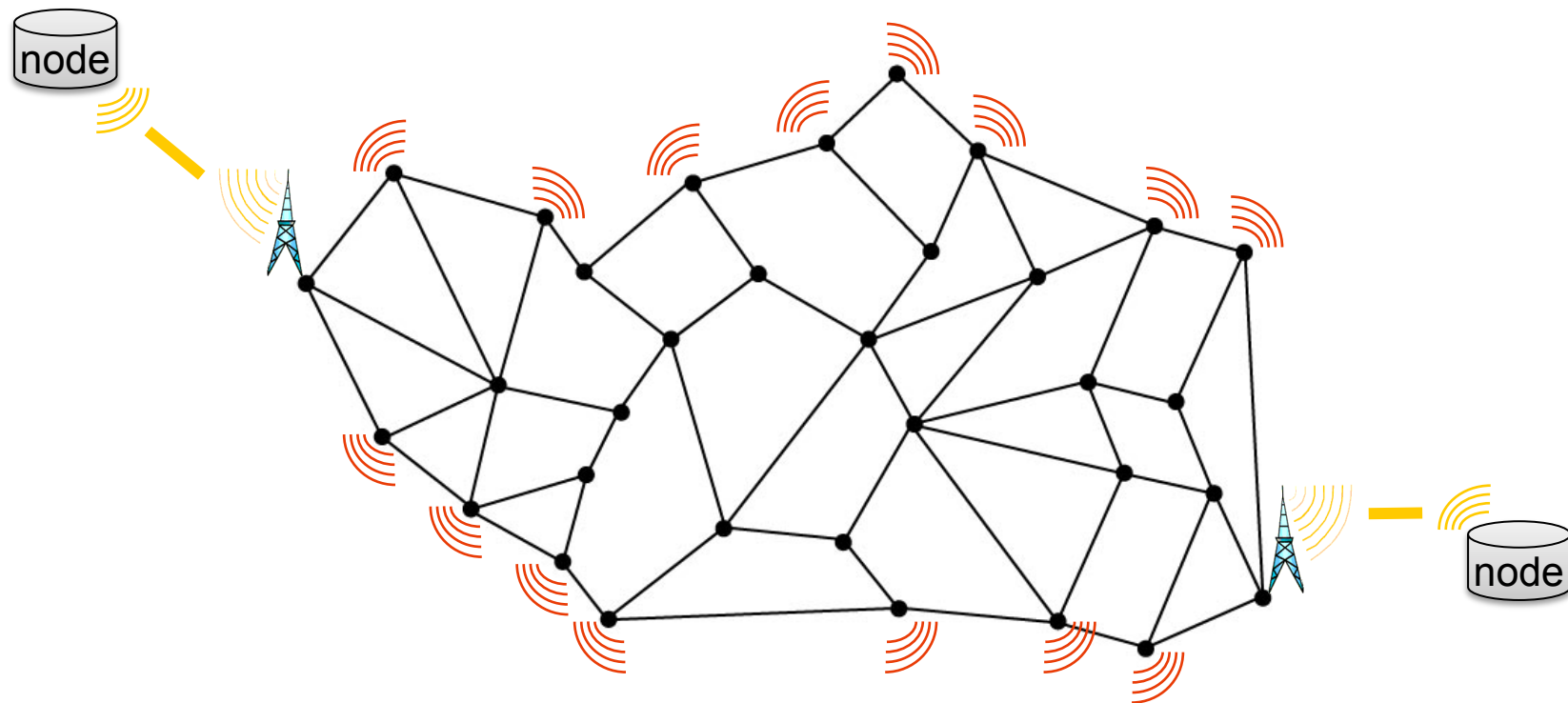
Mobile Edge Cloud / Micro Cloud / Cloud



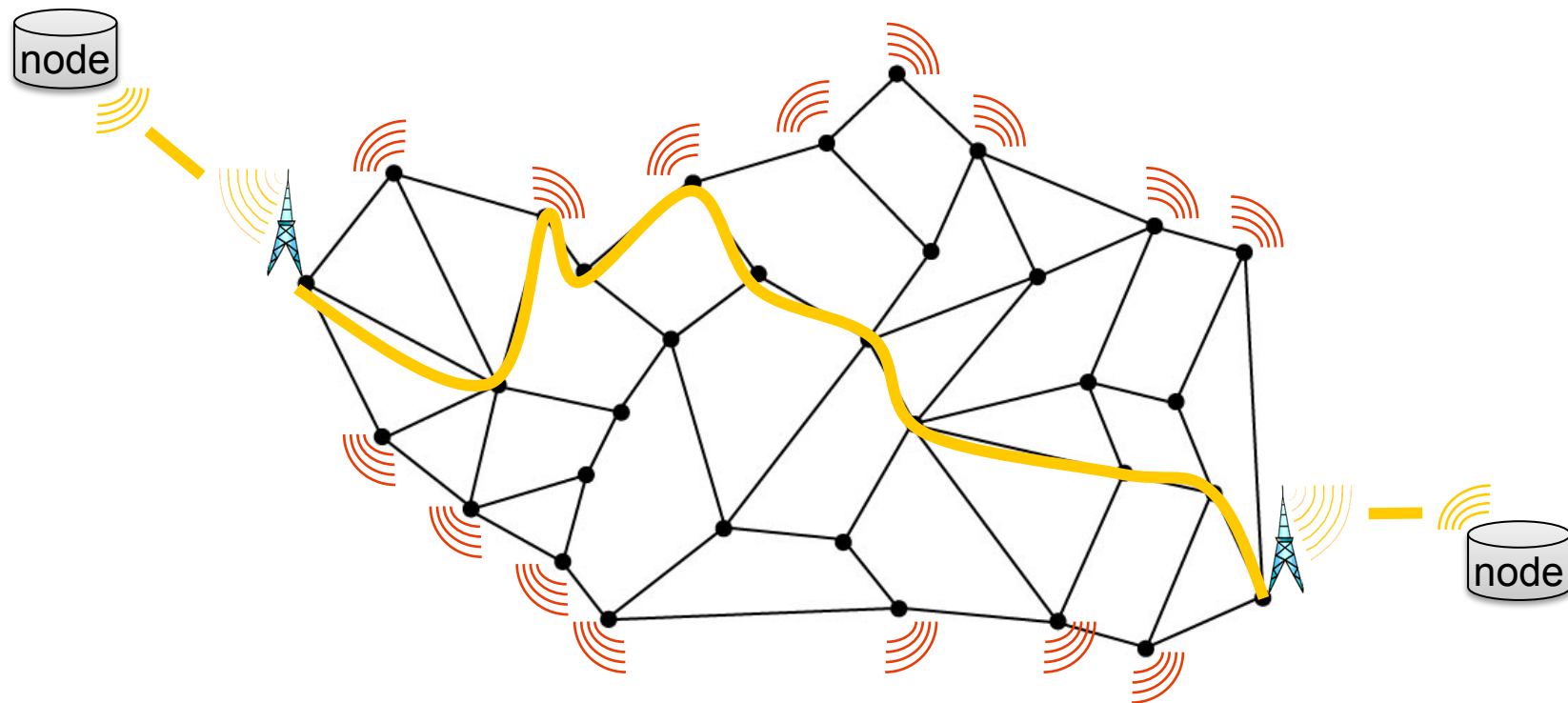
Mobile Edge Cloud / Micro Cloud / Cloud



Networking The Connection

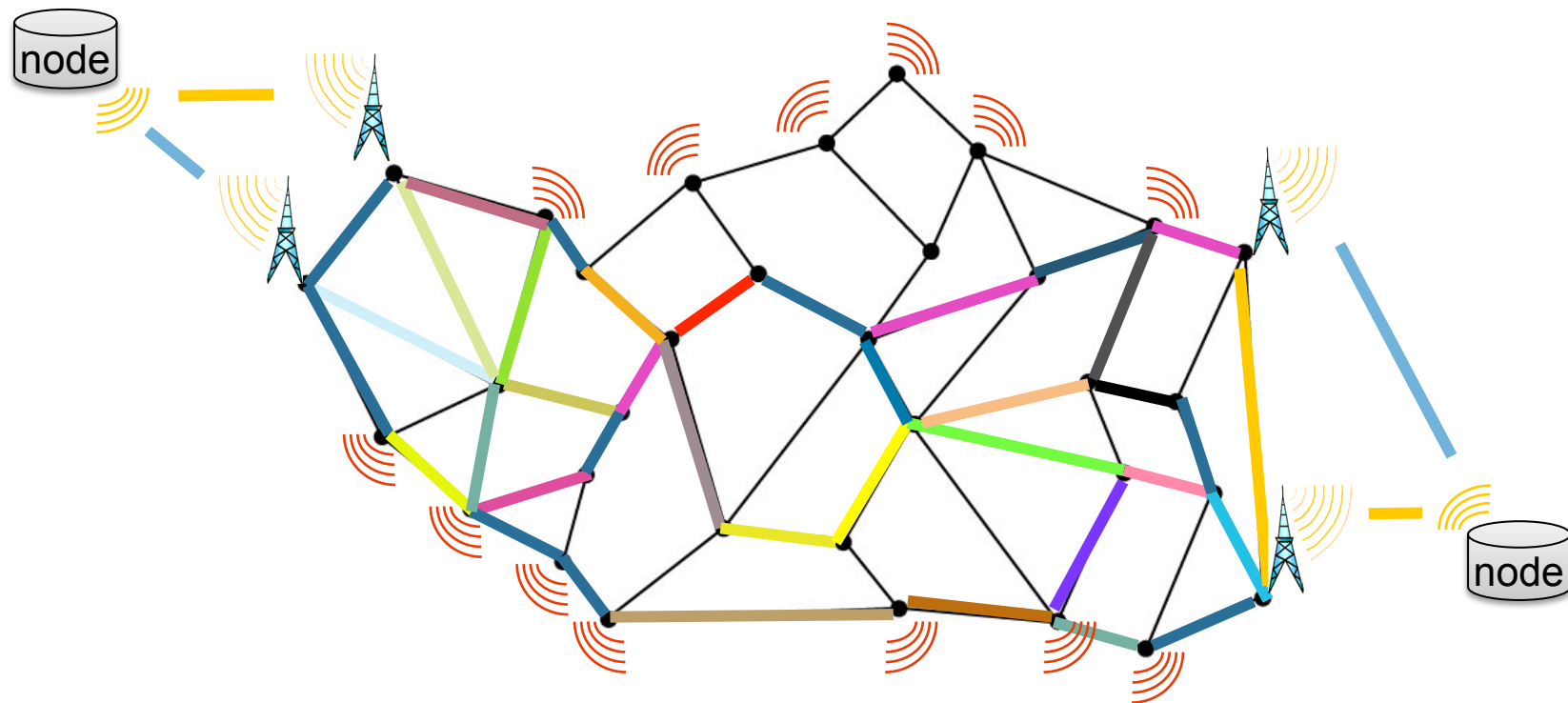


Single Path



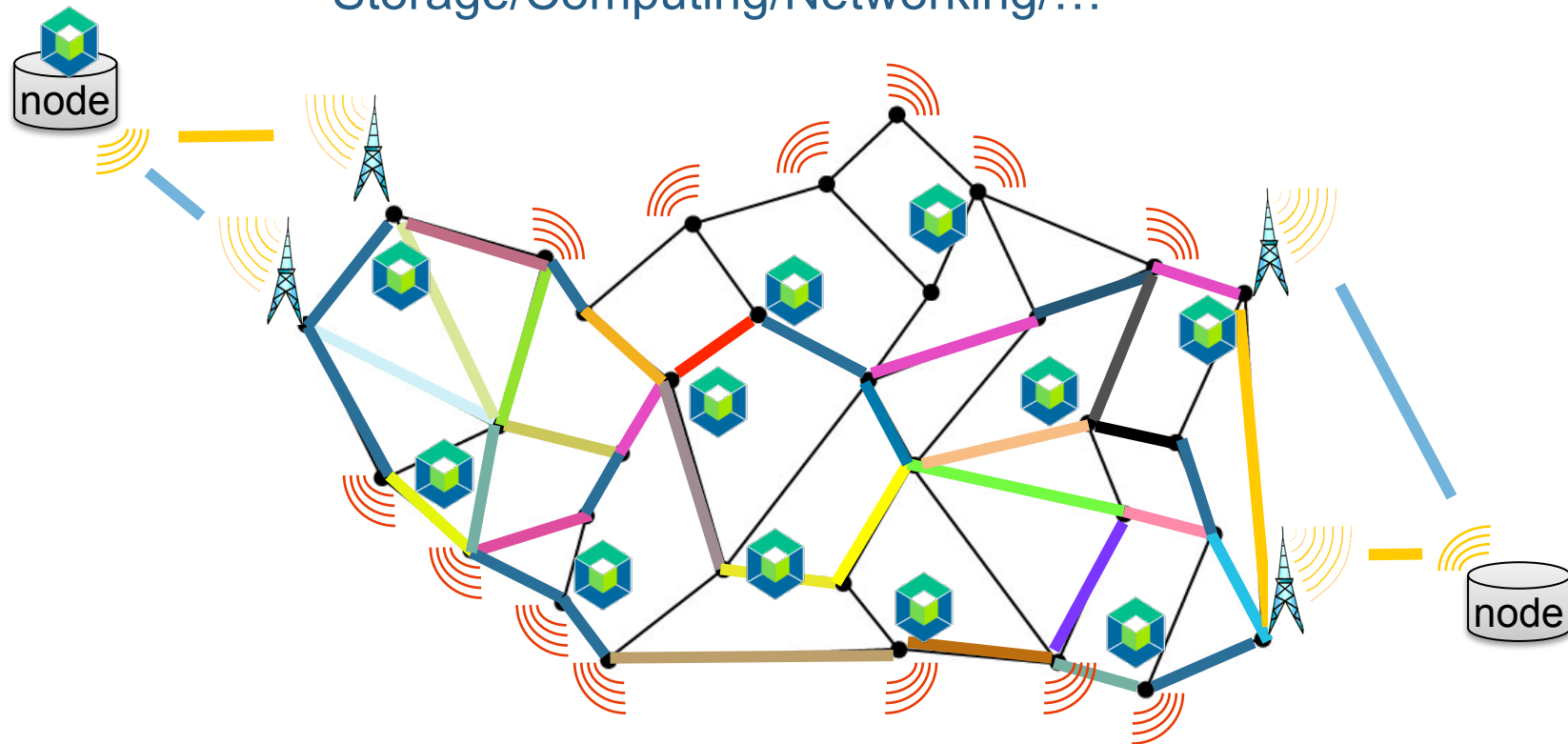
Revolution → Compute & Forward

(Disintergration of packet)

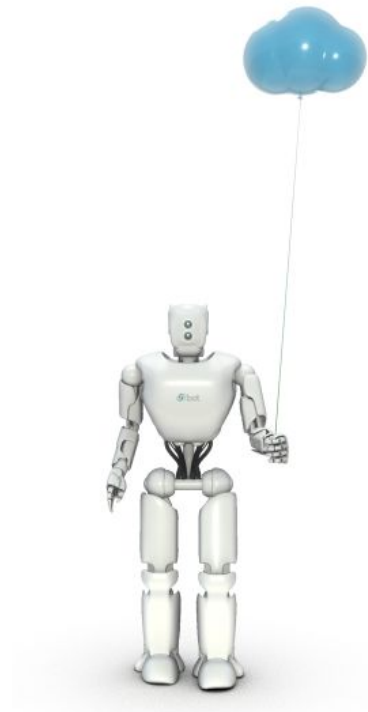


Revolution → Distributed Everything

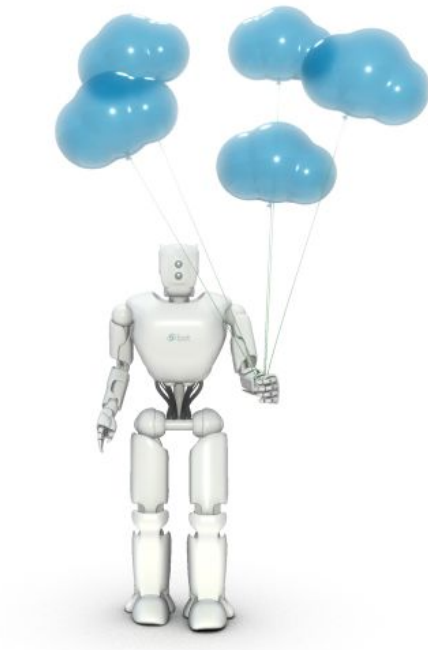
Storage/Computing/Networking/...



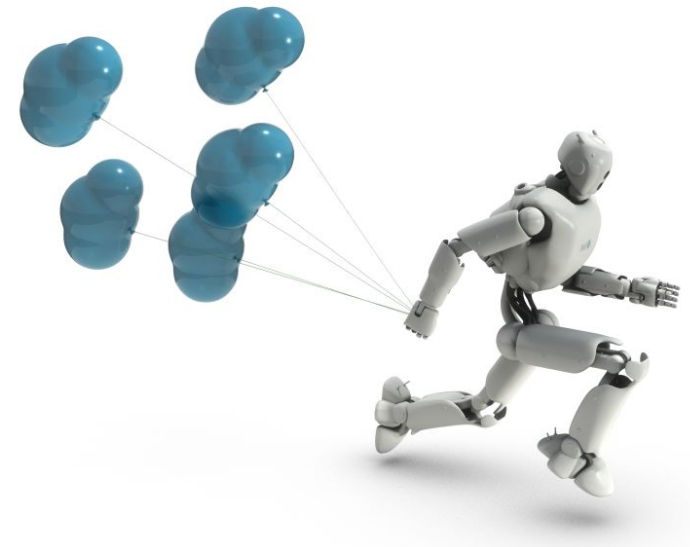
Cloud Evolution



Single/Static



Distributed/Static



Distributed/Agile



CONCLUSIONS

Telco Markets: A First Glimpse At Germany



care	German ambulatory care ~€35B → TAM €10B/a	Europe's chance!!! x20 x10 =200x =\$20T
manufacturing	German industrial interconnect revenue → TAM €10B/a	
events	German event/concert/... → TAM €10B/a	
'edutainment'	German ... entertainment (€11B) → TAM €10B/a	
mobility	... €5B, → TAM €10B/a	
smart grid	Smart grid ICT market €27B, \$47B by 2020 → TAM €10B/a	
emerging	e.g. drones, agriculture, and new gadgets → TAM €10B/a	

Cellular Roadmap of USPs



2G – 1992
Voice
Messages



3G – 2002
+ Data
+ Positioning



4G – 2012
+ Video everything
+ 3D Graphics



5G – 2022
+ Tactile Internet

**\$20T
GDP
boost**

**\$200B
Si
chance**



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contact@Dresden5GLab.org

Related publications



[1] Fettweis, Gerhard, and Siavash Alamouti. "[5G: Personal Mobile Internet beyond What Cellular Did to Telephony](#)"
Communications Magazine, IEEE 52.2 (2014): 140-145.

[2] Fettweis, G. "[The Tactile Internet: Applications and Challenges.](#)"
Vehicular Technology Magazine, IEEE 9.1 (2014): 64-70.

[3] Fettweis et al. „Positionspapier Das Taktile Internet“, VDE ITG

[4] Fettweis et al. „Tactile Internet“, ITU Tech Watch report, 2014,
<http://www.itu.int/en/ITU-T/techwatch/Pages/tactile-internet.aspx>

[4] HUAWEI. „[5G: A Technology Vision](#)“