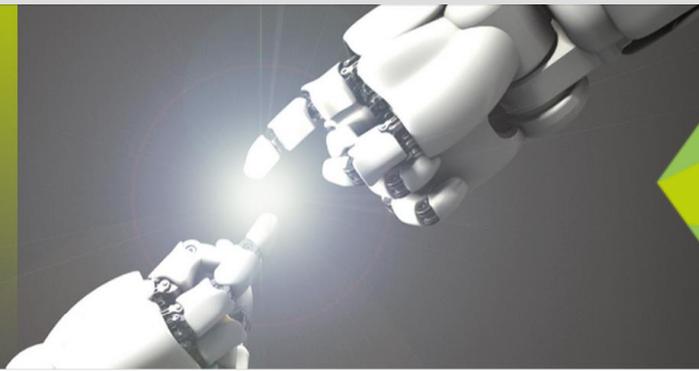




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DRESDEN



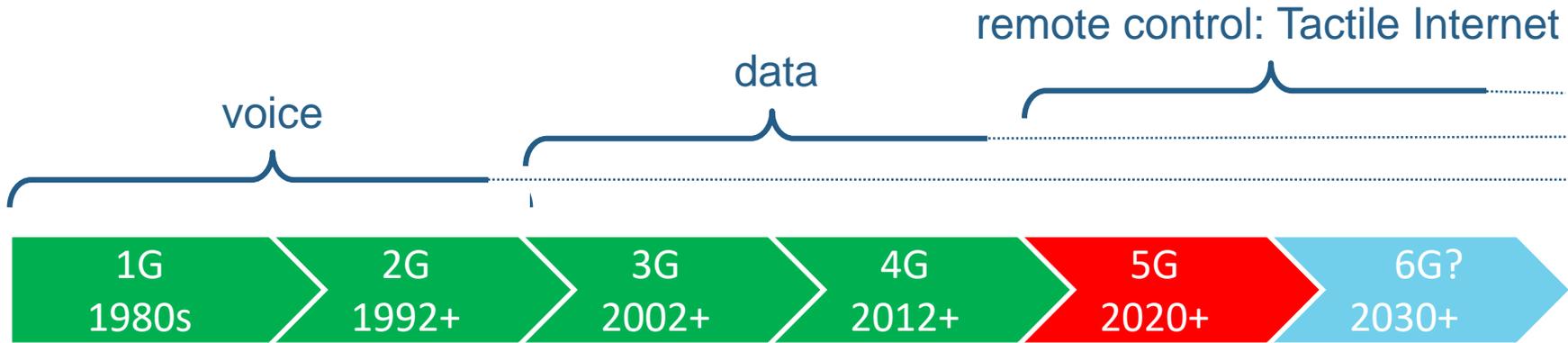
**5G+LAB**  
GERMANY

## Beyond 5G – What Could It Be – 6G?

**Gerhard P. Fettweis**

Vodafone Chair Professor - TU Dresden  
CEO Barkhausen Institute  
coordinator 5GLab Germany

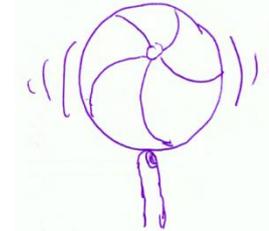
# 1G to 6G Cellular Networking



Today 100ms



1ms  
(1/1000 s)





# Revolution Ahead: The Tactile Internet



5G:  
Ubiquitous  
Steering & Control  
Communications

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



$\leq 4G$ :  
Ubiquitous  
Content  
Communications

IoT  
Internet of Things  
...

# Update 5G Lab Germany Members



## HARDWARE & WIRELESS



Frank Ellinger



Gerhard Fettweis



Karlheinz Bock



Dirk Plettemeier



Christian Mayr



Michael Schröter



Kambiz Jamshidi

## NETWORK & CLOUD



Thorsten Strufe



Frank Fitzek



Hermann Härtig



Diana Göhringer



Christof Fetzer



Eduard Jorswieck



Wolfgang Nagel



Christel Baier



Jürgen Weber

## TACTILE INTERNET APPLICATIONS



Uwe Aßmann



Thomas Herlitzius



Jens Krzywinski



Klaus Janschek



Leon Urbas

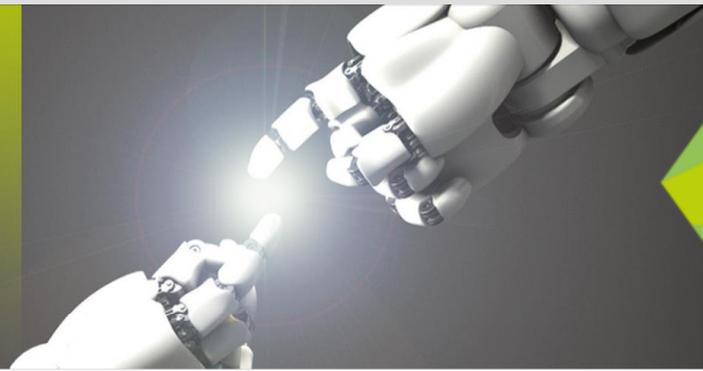


Peter Birkholz

[Team of 600+ Researchers]



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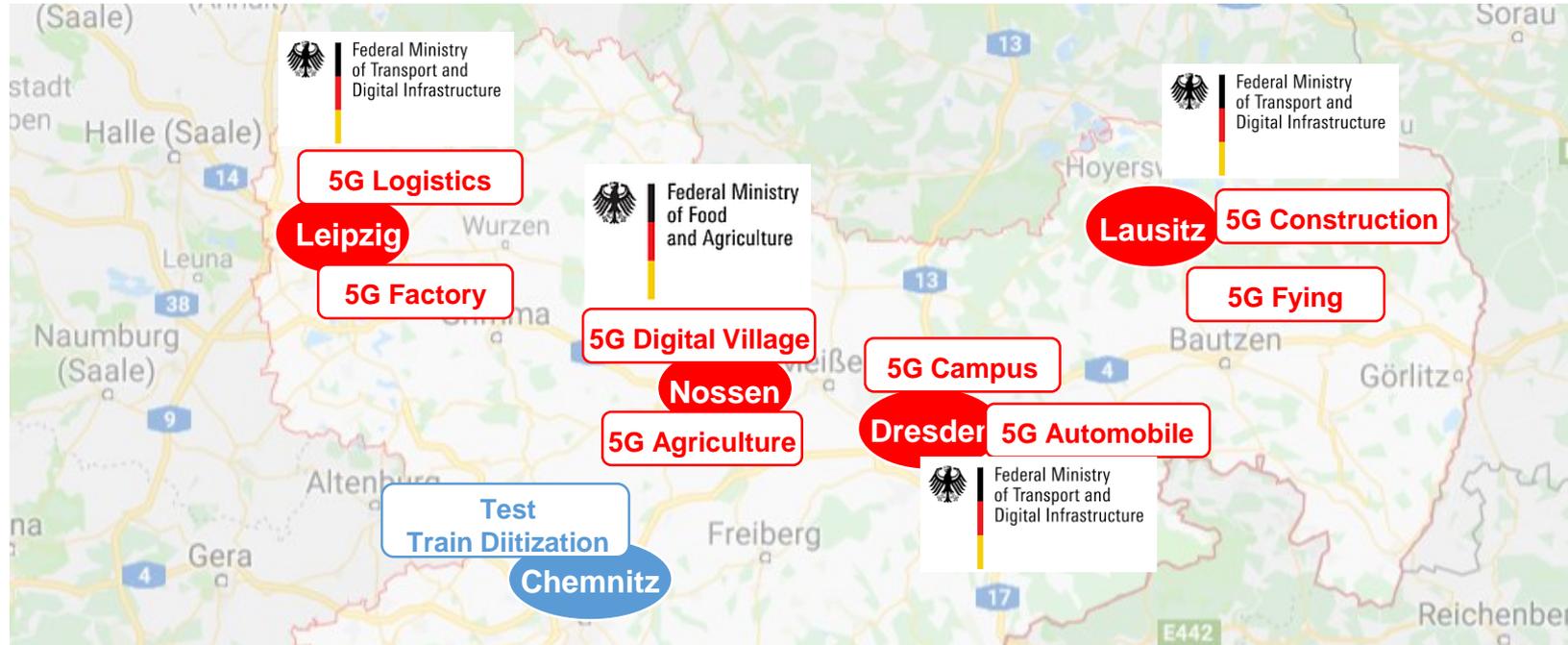


5G LAB  
GERMANY

## 5G Lab Germany – Partners



# “Our” 5G Testbeds Locations and Application Focus



And Now?

# 6G's Evolutionary Challenges “Stretching 5G”



- Reduce latency → below 5ms end-2-end (e.g. for robotics)
- Increase data rate → beyond 10Gb/s (e.g. for VR)
- Expand coverage → connect 4B people missed-out
- Scalable HW/SW → enable cost-efficient applications (e.g. verticals)
- Cleanup NFV → entangle NFV & Openstack (e.g. “lean NFV”?)

“faster, higher, stronger...” 😞😊

# 6G's Non-Evolutionary Challenges: Energy Challenge



E. Matus



R. Wittig



S. Moriam



S. Nam



M. Hasler



N. Grygorian



M. Radi



S. Damjancevic



M. Dörpinghaus



S. Bender



M. Schlüter



P. Neuhaus



Y. Zou



F. Diehm



E. Bolza-Sch.

# Energy Challenge



**Terminal @ 500Gb/s:**

**Analog-Digital Converter 100x power?**

(rate increase by 100x over 5G)



Our proposal:

ZXM Zero Crossing Modulation



- [1] G. Fettweis et al., Zero Crossing Modulation for Communication with Temporally Oversampled 1-Bit Quantization, *Proc. of Asilomar Conf. 2019*
- [2] G. Fettweis et al., Architecture and Advanced Electronics Pathways Toward Highly Adaptive Energy-Efficient Computing, *Proceedings of the IEEE, Jan 2019*

**RAN/Edge Cloud @ 500Gb/s:**

**100\*10\*10\*2/10=2000x power?**

(rate \* COTS \* #gNodeB \* massiveMIMO / Moore)



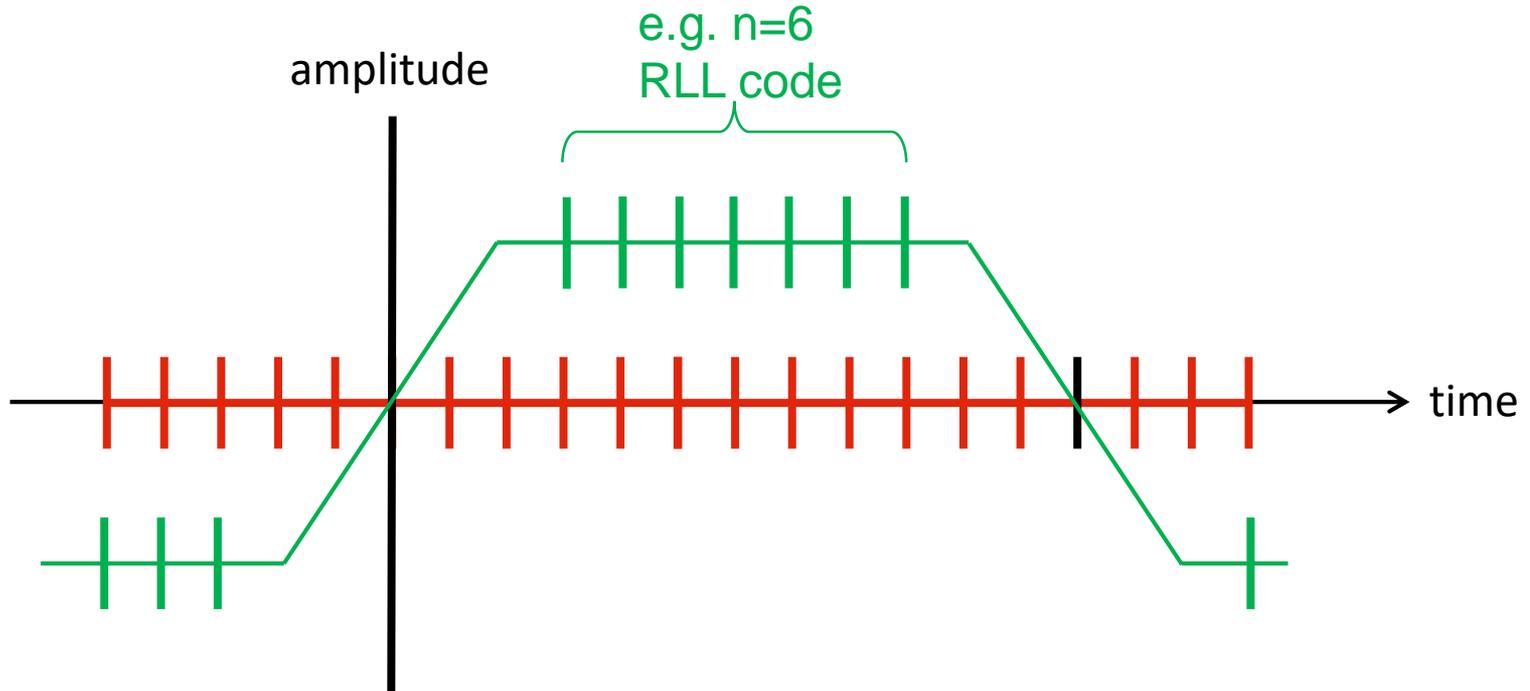
Our proposal:

Domain Specific computing platforms

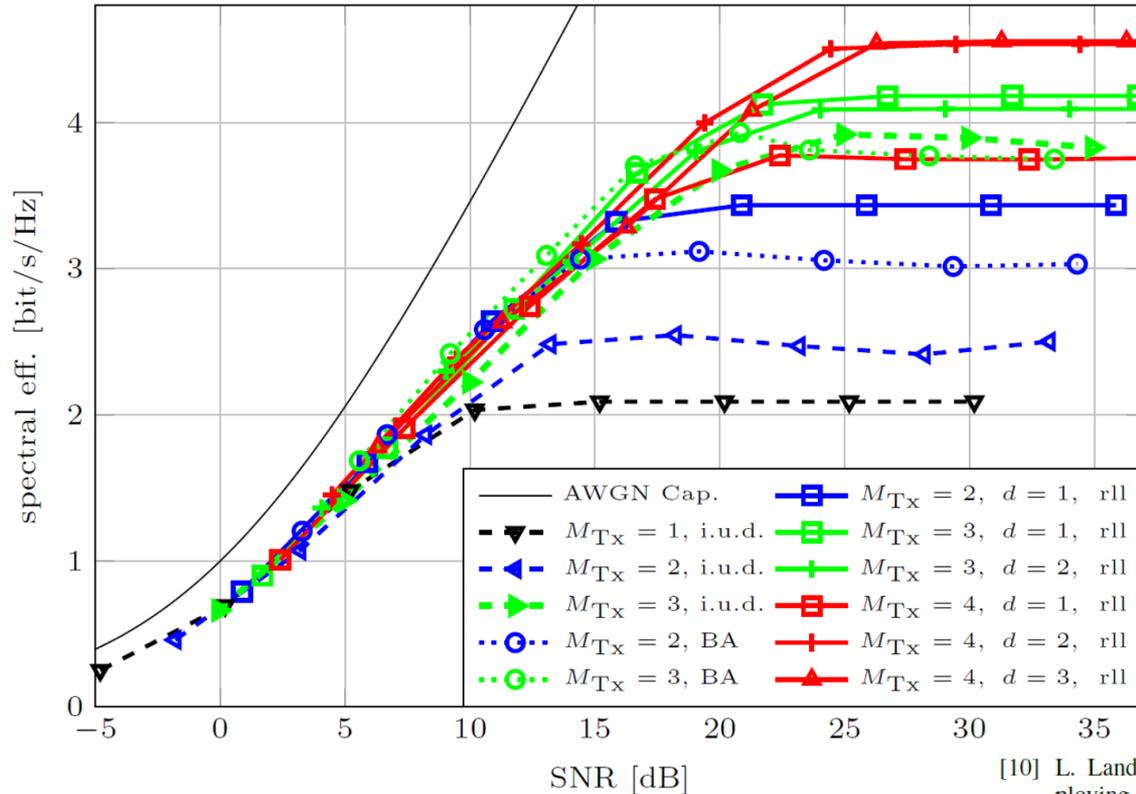


- [2] G. Fettweis et al., Architecture and Advanced Electronics Pathways Toward Highly Adaptive Energy-Efficient Computing, *Proceedings of the IEEE, Jan 2019*
- [3] G. Fettweis et al., A Low-Power Scalable Signal Processing Chip Platform for 5G and Beyond – Kachel, *Proc. of Asilomar Conf. 2019*

# ZXM: Zero Crossing Modulation



# Spectral efficiency versus SNR with FTN



Initial results:

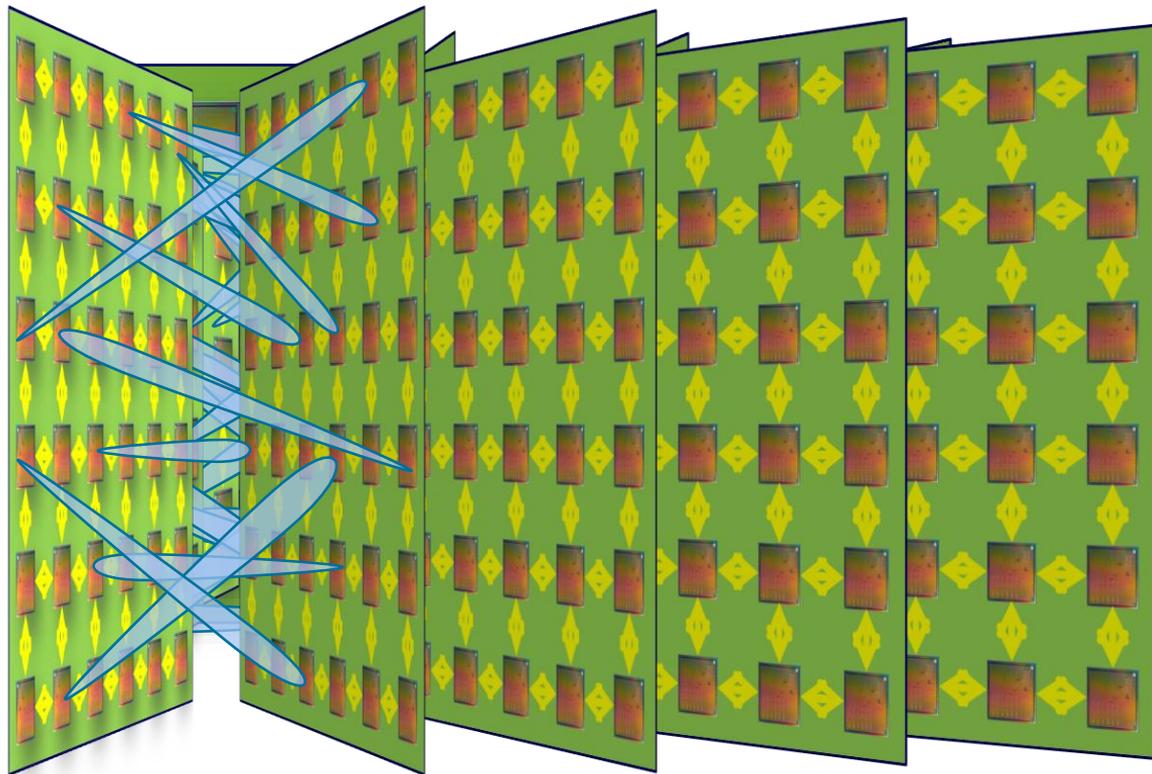
[10] L. Landau, M. Dörpinghaus, and G. Fettweis, "Communications employing 1-bit quantization and oversampling at the receiver: Faster-than-Nyquist signaling and sequence design," in *Proc. IEEE Int. Conf. Ubiquitous Wireless Broadband (ICUWB)*. Montreal, QC, Canada: IEEE, 2015, pp. 1–5.

# Highly Adaptive Energy-Efficient Computing

## High-Rate Inter-Chip Communications



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



### Optical Interconnect

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

### Wireless Interconnect

- on-interposer/on-package
- 8x8 antenna arrays
- beam-switching via Butler matrix
- 100Gb/s
- 30 GHz channel @ 180GHz carrier

# Adaptivity

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

### Communications today:

100% powered-on but @1% transfer activity (measured)



**Communications HAEC:**  
exploit P/100 through adaptivity

### Processing today:

Memory and processors linked via high bandwidth connection and cache



**Processing HAEC:**  
adaptive near-memory

computing (P/?)

# Lab Demos @ 180 GHz

IEEE 5G Summit Dresden 2018



1/100 achievable?!



[www.tu-dresden.de/sfb912](http://www.tu-dresden.de/sfb912)

# 6G's Non-Evolutionary Challenges: Integrity Challenge



A. Noll



T. Hößler



A. Haider



P. Schulz



J. Chaudhary



A. Kumar



B. Khodapanah



Barkhausen I.



T. Hentschel



P. Sen



M. Matthé

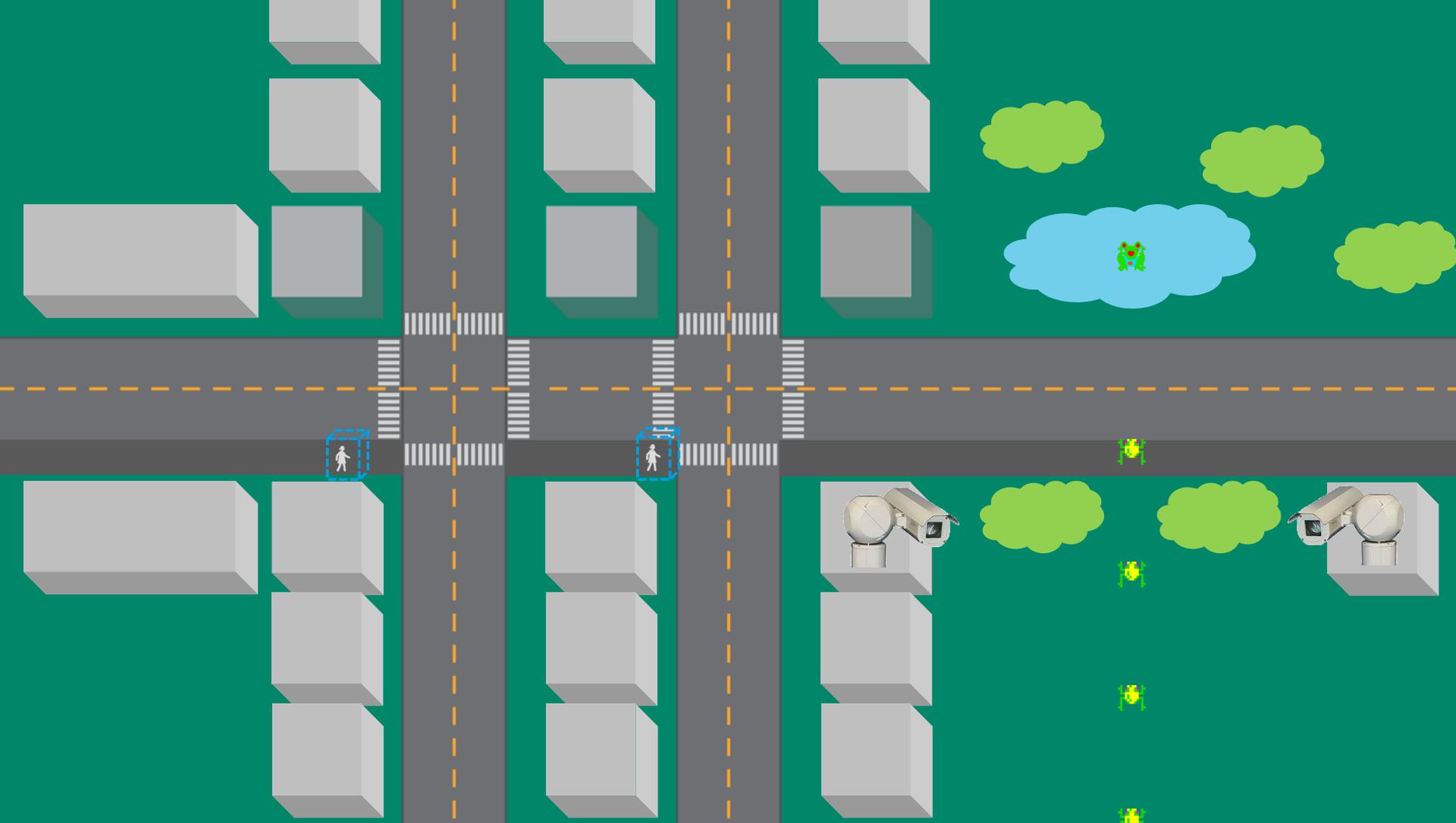


M. Roitzsch

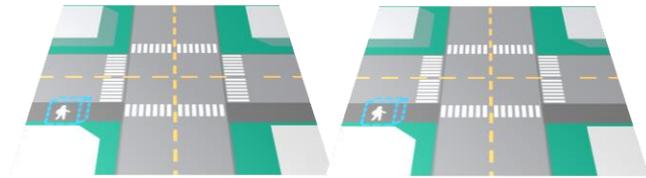


A. Noll

... and many more @ ! 

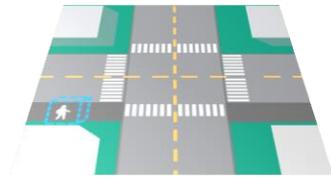


# Wireless Campus Networks: Massive Deployment

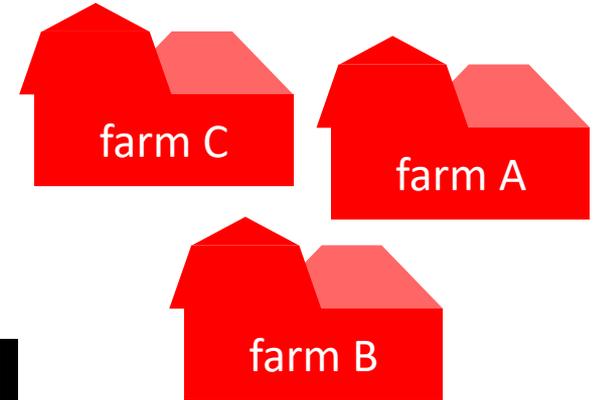
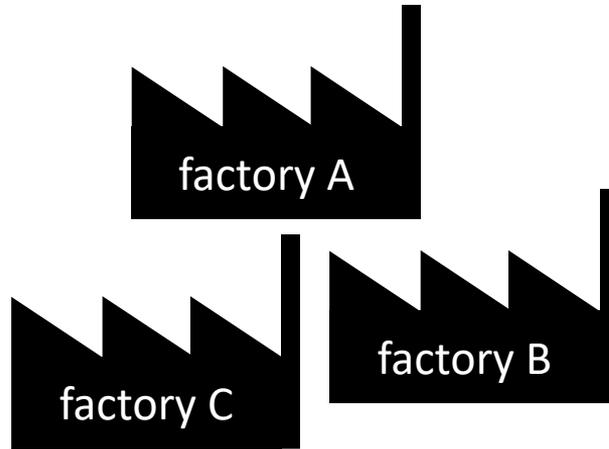


crossing A

crossing B

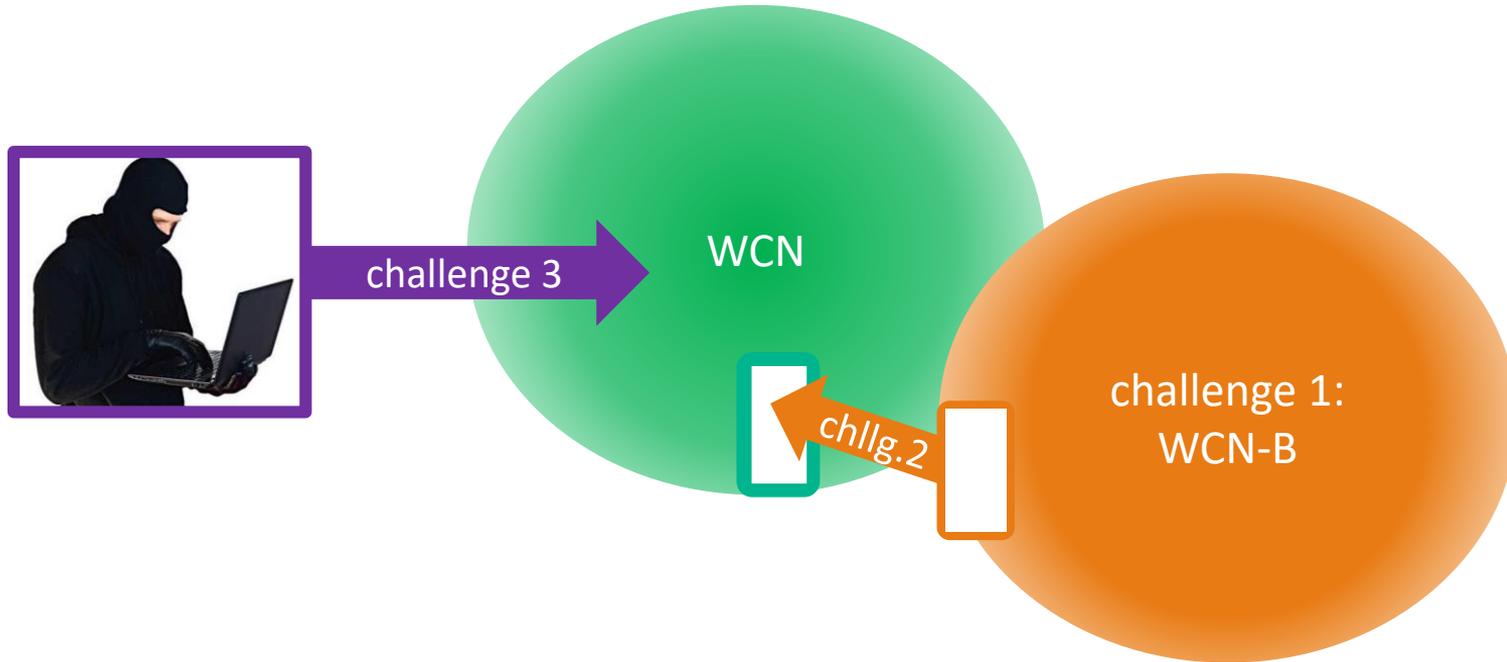


crossing C

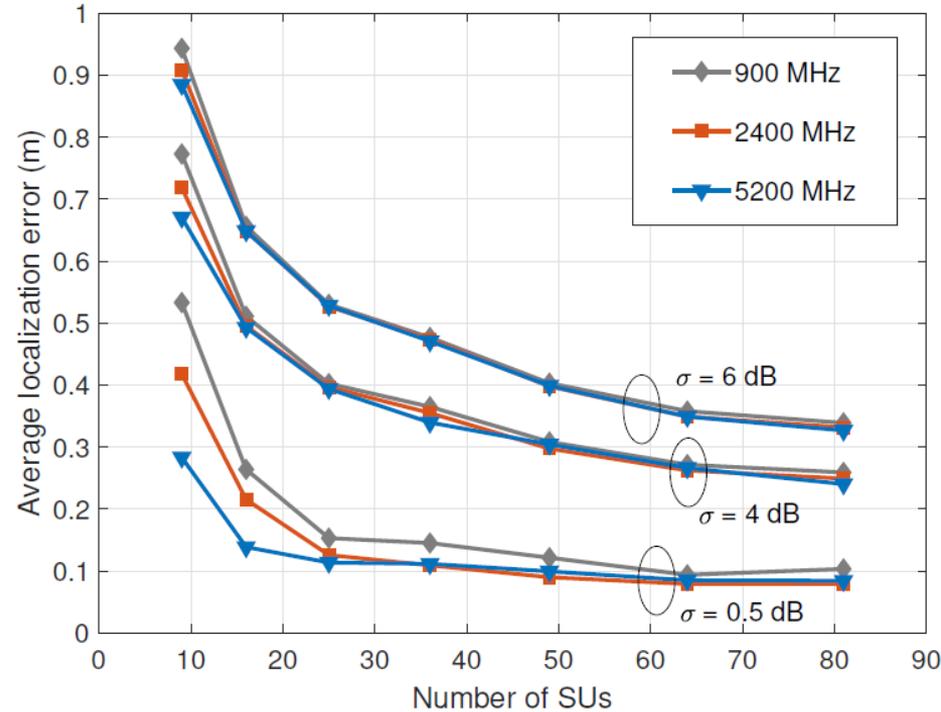
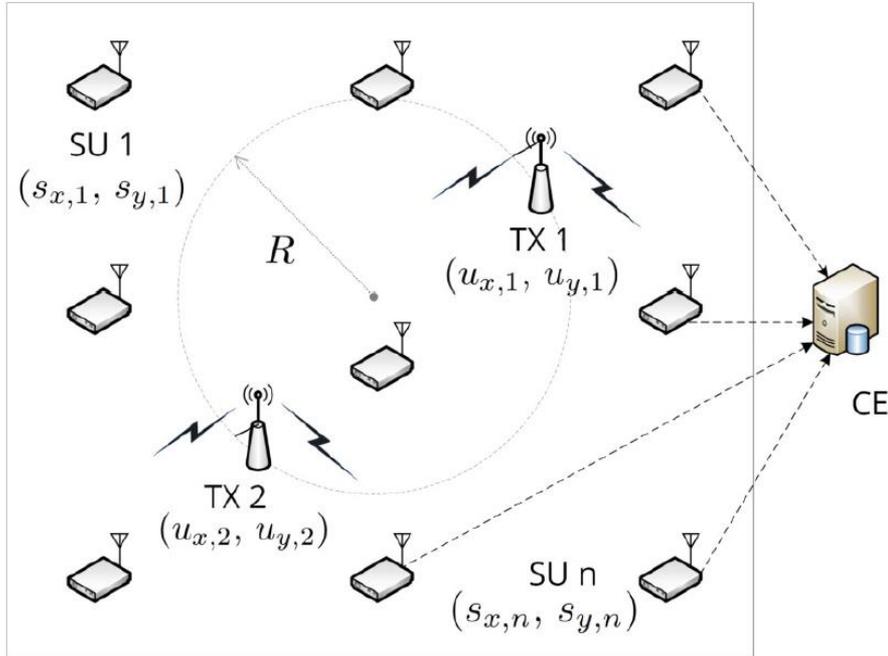


# Wireless Campus Networks

## 3 Examples of Unsolved Challenges



# Finding the Interferer (with ML)



# Integrity Challenge

## Network Management

Radio Access Network

Core Network

## Service Integrity Management

Radio Access Network  
RF Resilience

Core Network  
Privacy, Trust

## Service Delivery (Layer 7 to 1, from application to PHY)

Radio Access Network

Core Network

# 6G's Non-Evolutionary Challenges: Functionality Challenge



N. Franchi



L. Scheuvens



A. Gonzales



A. Villamil



E. Schmitt



A. Traßl



W. Anwar



N. Schwarzenberg



W. Rave



M. Khalili



X. Song



P. Neuhaus



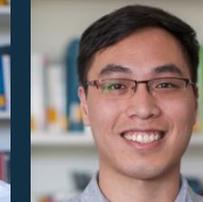
I. Bizon



C. Jans



T. Kadur



P. Guang

# 7ms Impact → Limited Tactile Internet Control





125µs EtherCAT

# Understanding the Challenge

## Example – Industrial Robots

E.g. KUKA



STOP @

3 contiguous packets lost

E.g. FRANKA



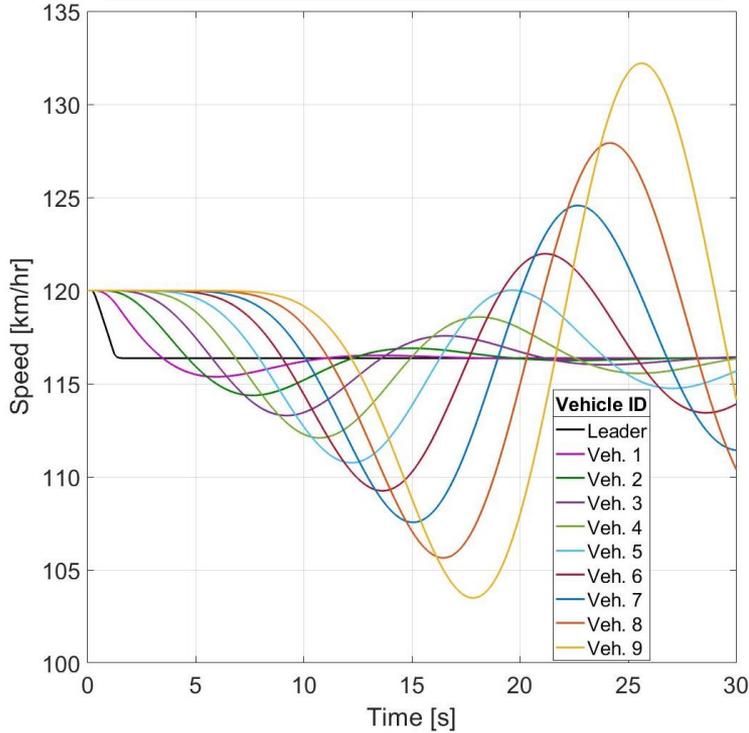
STOP @

5 contiguous packets lost

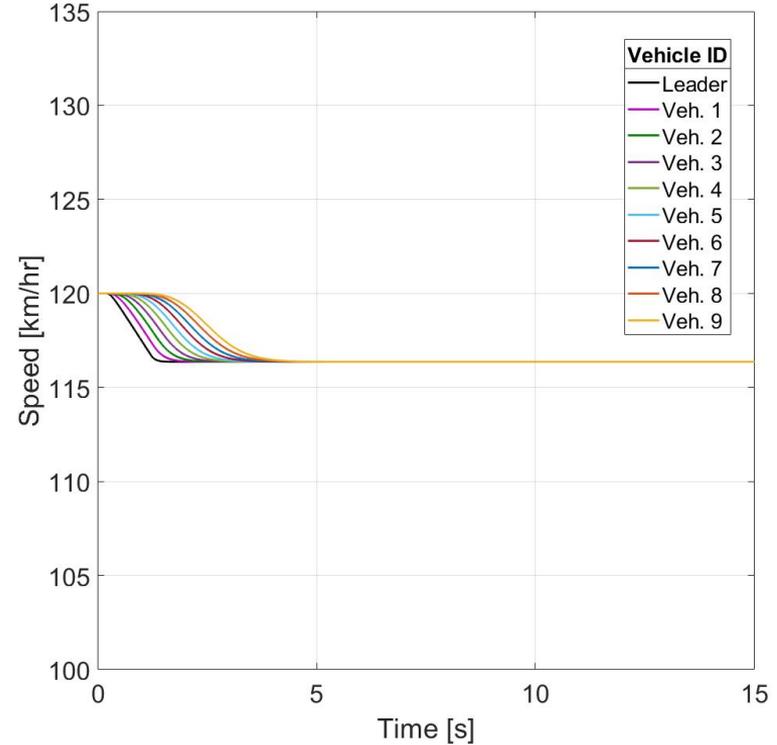


# Communication is key!

## Sensor-Only Automated Driving



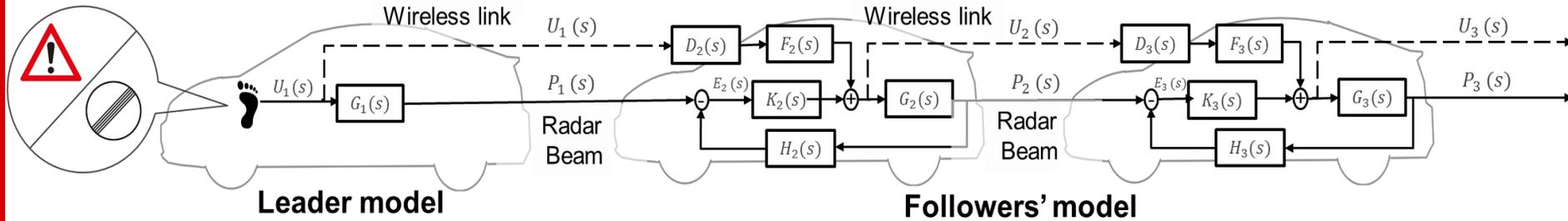
## Sensor+(Perfect) Communication Automated Driving



# How?

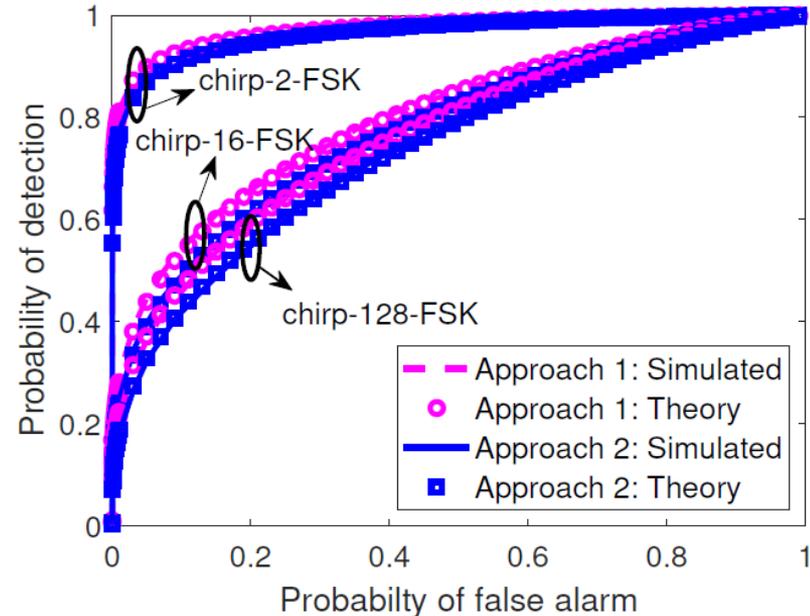
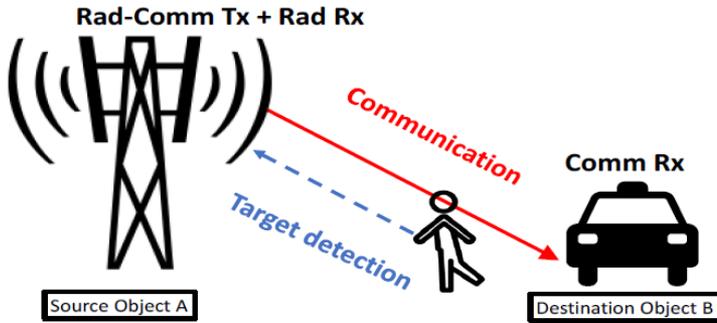
## Anticipate the action of the previous vehicle...

... by transmitting the control input (desired acceleration) to the immediate follower



# Huge Challenge – Full Duplex?

## First Results w/o Full Duplex Transceiver



(b)

Saumya Dwivedi, Andre Noll Barreto, Padmanava Sen, and Gerhard Fettweis, "Target Detection in Joint Frequency Modulated Continuous Wave (FMCW) Radar-Communication System," IEEE 5G World Forum 2019

# Communications Control Codesign



**A. Traßl, L. Scheuvs, T. Hößler, N. Franchi, G. Fettweis**, On Dependability Metrics for Wireless Industrial Communications - Applied to IEEE 802.11ax in Proceedings of *IEEE 5G World Forum (WF-5G 2019)*

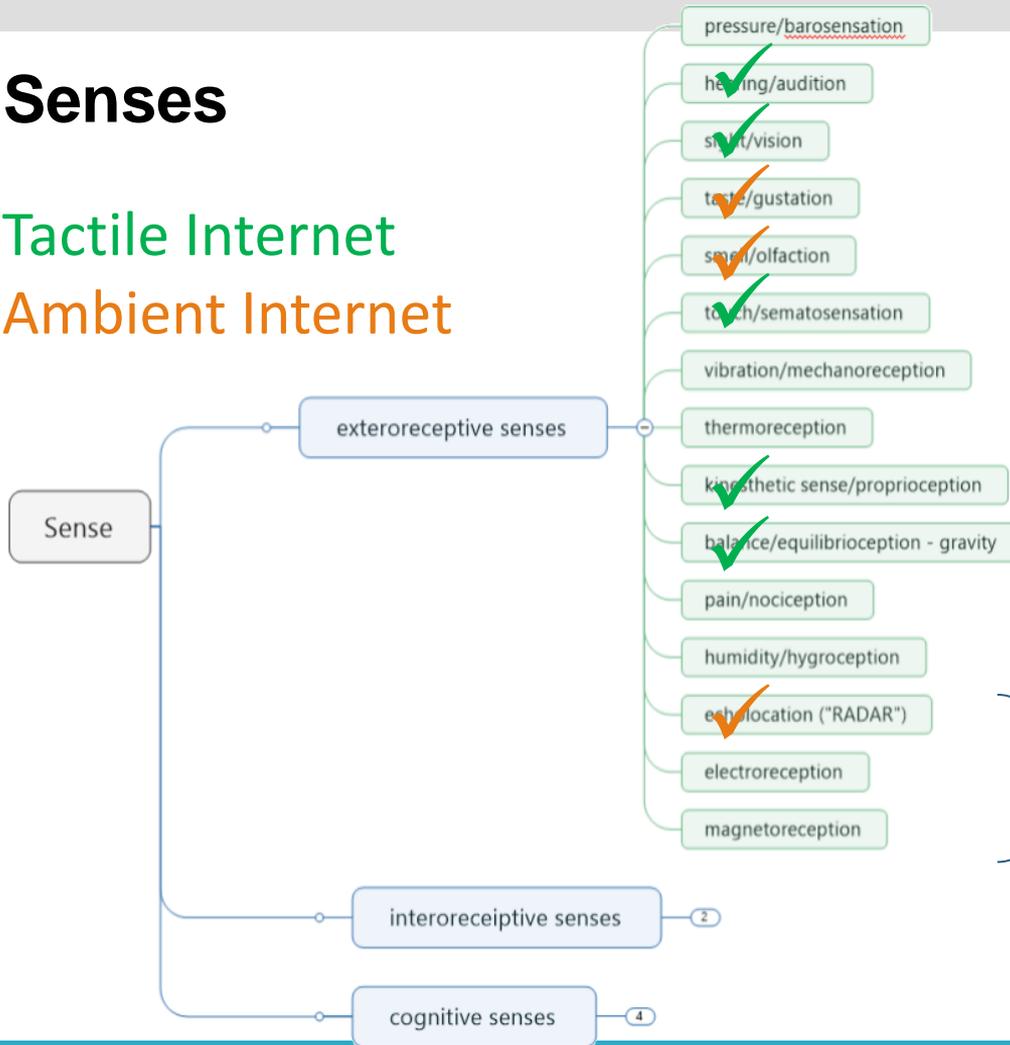
**A. González, A. Villamil, N. Franchi, G. Fettweis**, „String Stable CACC under LTE-V2V Mode 3: Scheduling Periods and Transmission Delays,“ in Proceedings of *IEEE 5G World Forum (WF-5G 2019)*

**N. Schwarzenberg, F. Burmeister, A. Wolf, N. Franchi, G. Fettweis**, „Joint Synchronization in Macro-Diversity Multi-Connectivity Networks,“ in Proceedings of *IEEE 90th Vehicular Technology Conference (VTC Fall 2019)*

# Senses

Tactile Internet

Ambient Internet



Aristotelian senses

Tactile/haptic senses

Non human senses



# Tactile Internet requires Ambience Intelligence



## RadCom: Radar & Communications

- Share one spectrum
- Share one channel
- Share one modem
- Exploit massive MIMO
- ➔ 6G will be RadCom in one system
- ➔ One standard/protocol embracing both needs!
- ➔ 3D imaging & ambience intelligence
- ➔ 3D spectroscopy:  
object & material classification
- ➔ 3D gesture detection for HMI

**“Ambient Internet”**

# 6G's Non-Evolutionary Tactile Internet Challenges!



## Energy Challenge

- Terminal data rate requires new PHY
- RAN and Edge Cloud requires new HW architecture – impacting NFV and more?



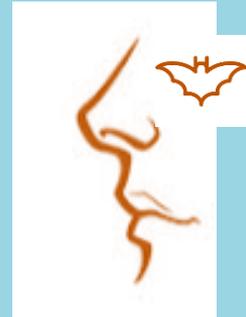
## Integrity Layer Challenge

- Privacy (Core Network)
- Resilience (RAN)
- Trust (trusted network with untrusted components)

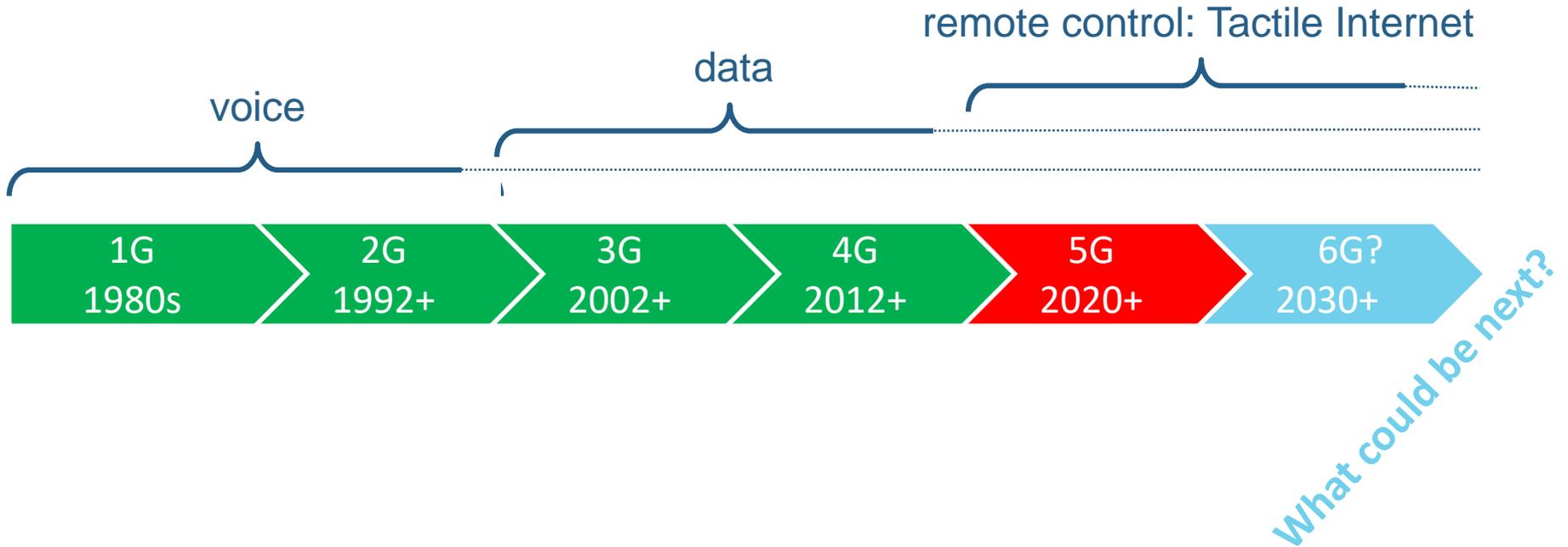


## Functionality Challenge

- CoCoCo
  - RadCom
  - Spectroscopy
  - Gesture
  - "7 senses"
- } **enabling the "Tactile Internet"**
- } **towards an "Ambient Internet"**



# 1G to 6G Cellular Networking

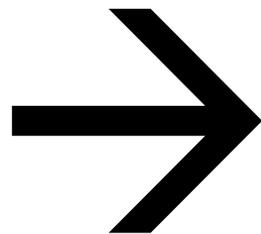


5G – Only The Beginning:

“The Carl Benz Automobile” for the Tactile Internet → Ambient Internet



**5G**

The text "5G" in a bold, black, sans-serif font, with a green signal wave icon above the "G".

**6G**

The text "6G" in a bold, black, sans-serif font, with a blue signal wave icon above the "G".



**vodafone**



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Thank you Vodafone for **25 years** of continued support of the **Vodafone Chair at TU Dresden** !

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