Machine Learning for 5G

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Joint work with R.L.G. Cavalcante, M. Kasparick, S. Limmer and L. Miretti

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Mobile networks-From the first to the fifth generation

- **1G** • Analog voice services (car telephony)

Revolution: Analog → Digital

- **2G** • Digital voice services + SMS (globally available)

Evolution: Integration of data services (mobile web)

- **3G** • Voice (circuit switched) + data (packet switched)

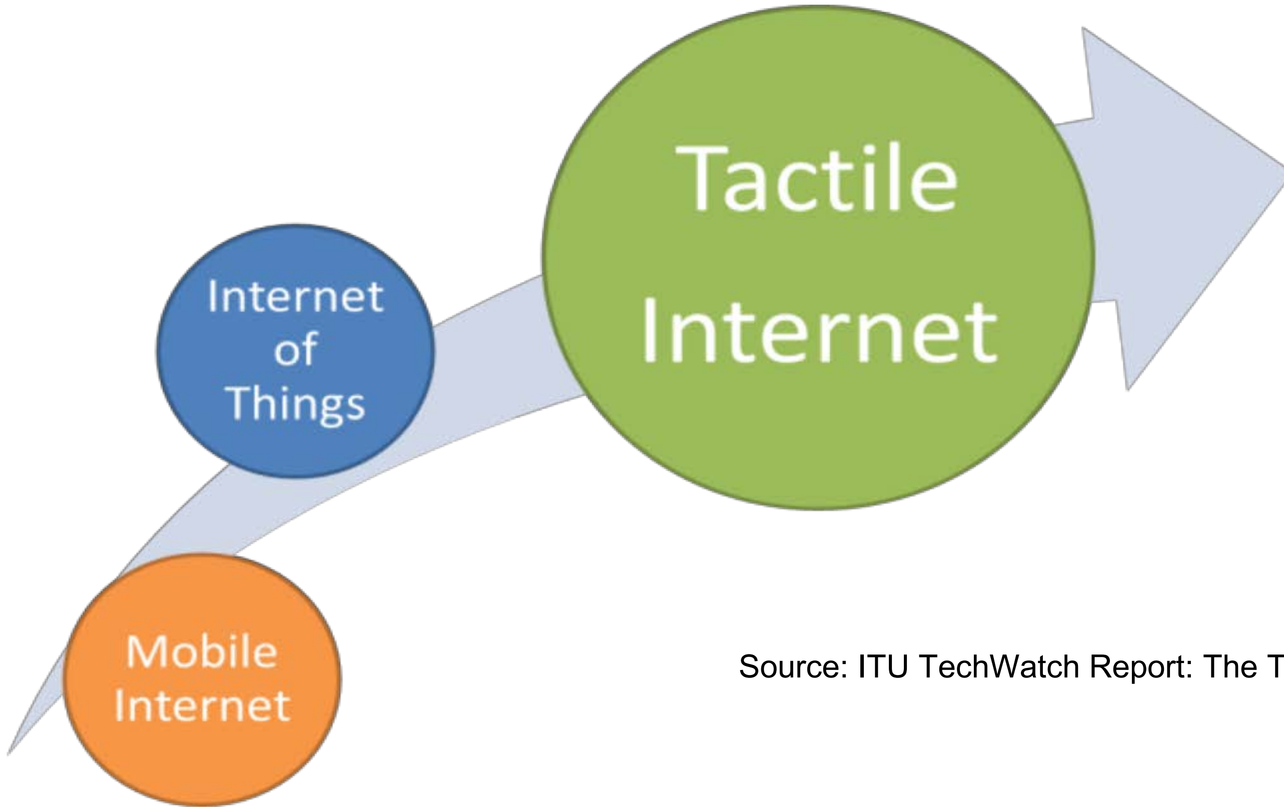
Evolution: everything IP based+ higher data rates

- **4G** • IP based (voice, email, web, audio/video streaming)

Evolution & Revolution (Integration of vertical industry)

- **5G** • Control & Management (IoT, Tactile Internet, **ML/AI**)

Revolutionary Leap of Tactile Internet



Source: ITU TechWatch Report: The Tactile Internet

Connecting machines into control loops at humanoid reaction times of milliseconds and less

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TACTILE INTERNET: Paradigm Shift from Transmititing Information for Humans to Networked Control

Source: www.domeoproducts.com

Source: http://blogs.voanews.com/

TACTILE INTERNET: New KPIs:
Interaction Speed and Functional Safety & Security

source: kuka-robotics.com *www.youtube.com/watch?v=tIIJME8-au8*

source: www.prismagroup.it

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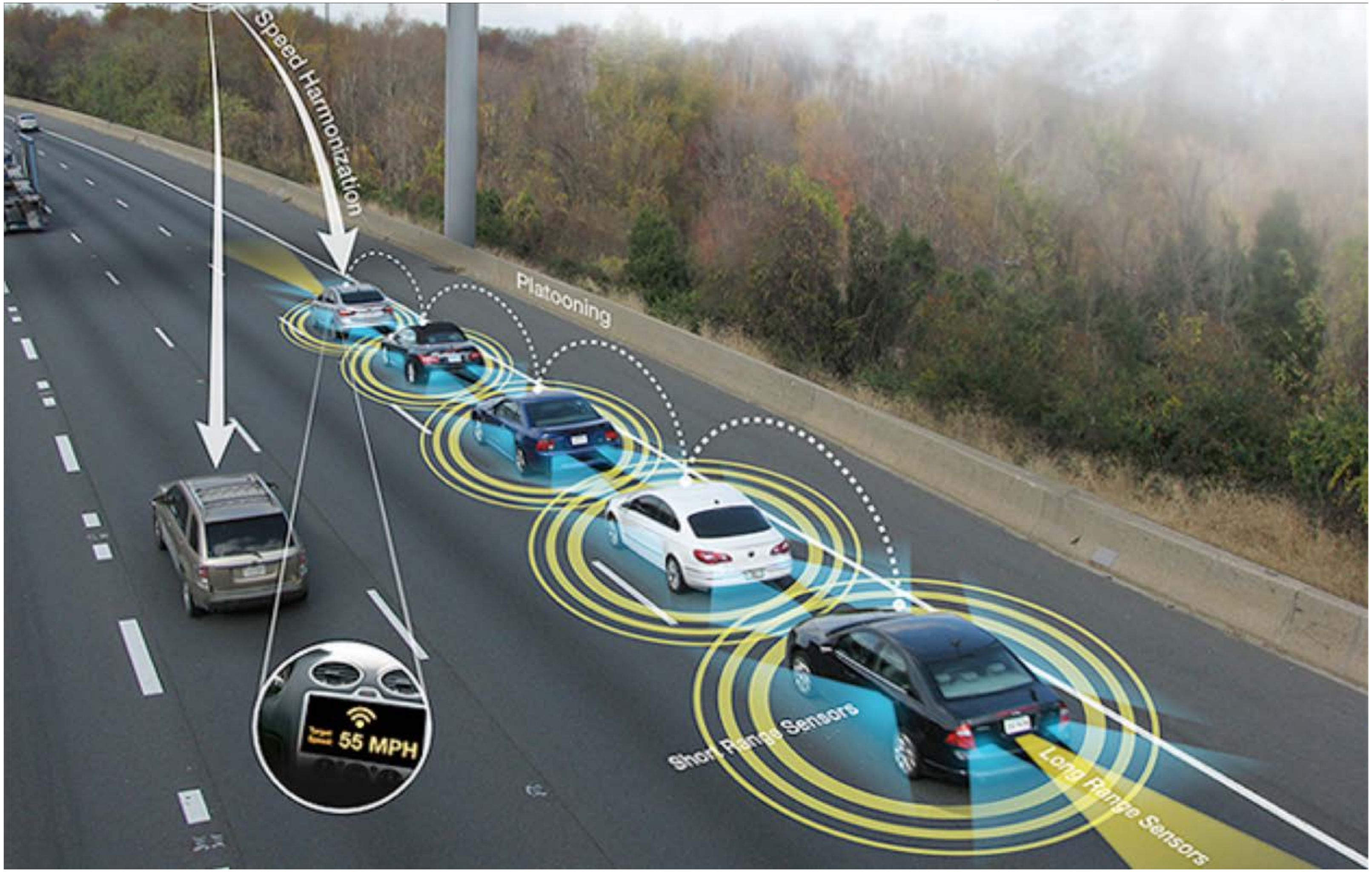
Tactile Internet for Production and Logistics

5G for Industry 4.0

- Reliable remote machine operation
- Predictive maintenance
- High precision positioning
- Industrial edge cloud
- Truck-to-X Communication
- Augmented worker/workspace
- Machine and process monitoring
- Secure remote access

TACTILE INTERNET: New KPIs:
Interaction Speed and Functional Safety & Security



Source: courtecy of the US Department of Transportation

Collaborative Driving

Source: ITU TechWatch Report: The Tactile Internet

Driver assistance with AR of potentially dangerous objects and situations

Tactile Networked Mobility

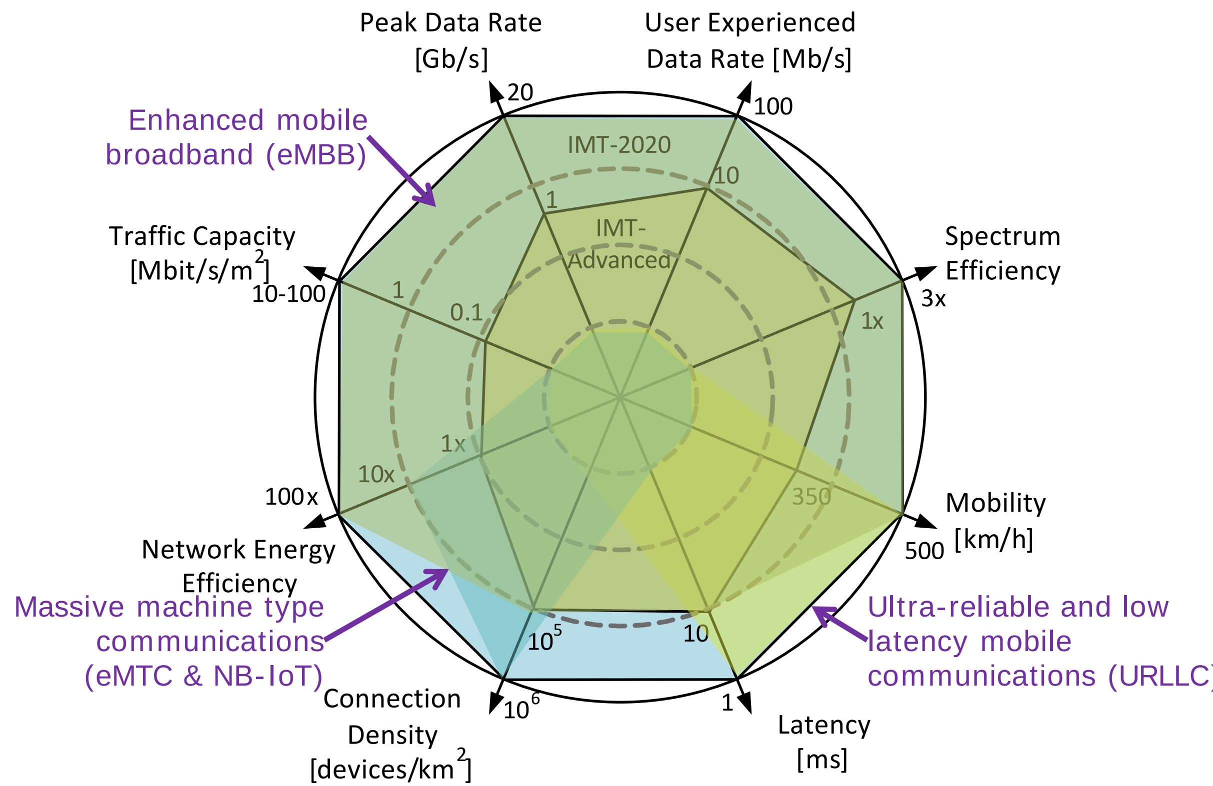
5G in Networked Driving

- Platooning
- Crossing traffic
- Collaborative driving
- Remote driving
- AR-based driver assistance
- Complete street perception
- Analysis of vehicle & driver conditions

Source: ITU TechWatch Report: The Tactile Internet

Source: The US Department of Transportation

4G and 5G compared



NB: Downlink metrics shown

Strong interdependencies between different requirements

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Industrial Communication Requirements

	Diagnoses & Maintenance		Discrete Manufacturing		Warehouses & Logistic			Process Automation	Augmented Reality	Safety
	Generally	Condition Monitoring	Generally	Motion Control	Generally	AGV	Cranes & Hoists			
Latency (Sensor → Controller → Actuator)	> 20ms	100 ms	1ms – 12ms	250µs – 1ms	>50ms	15ms – 20ms	15ms – 20ms	50ms – Xs	10ms	10ms
Reliability (wrt. to „successful transmission within latency bound)	$1-10^{-4}$	$1-10^{-5}$	$1-10^{-9}$	$1-10^{-9}$	$>1-10^{-2}$	$>1-10^{-6}$	$>1-10^{-6}$	$1-10^{-5}$	$1-10^{-5}$	$1-10^{-9}$
Data rate	kbit/s – Mbit/s	kbit/s	kbit/s – Mbit/s	kbit/s – Mbit/s	kbit/s – Mbit/s	kbit/s – Mbit/s	kbit/s – Mbit/s	kbit/s	Mbit/s – Gbit/s	kbit/s
Packet size	> 200 Byte	1 – 50 Byte	20 – 50 Byte	20 – 50 Byte	<300 Byte	< 300 Byte	< 300 Byte	< 80 Byte	> 200 Byte	<20 Byte
Distance (between comm. devices)	<100m	100m – 1km	< 100m	<50m	<200m	~ 2m	< 100m	100m – 1km	<100m	<30m
Motion speed	0 m/s	<10 m/s	<10 m/s	<10 m/s	<40 m/s	< 10 m/s	< 5m/s	Generally none, else < 10m/s	< 3m/s	<10 m/s
Latency critical mobility support	no	no	no	no	no	yes	no	No	n	yes
Device density	0.33 – 3 m^{-2}	10 – 20m^{-2}	0.33 – 3m^{-2}	< 5 m^{-2}	~0.1 m^{-2}	~0.1 m^{-2}	~0.1 m^{-2}	10000 / Factory	> 0.03 – 0.02m^{-2}	> 0.03 – 0.02m^{-2}
Energy efficiency	n/a	10 years	n/a	n/a	n/a	<8h	n/a	10 years	1 day	n/a
Localization accuracy	<50cm	<50cm	n/a	n/a	<1cm	[illegible]	<10cm	<50cm	n/a	<50cm

KOORDINIERTE INDUSTRIEKOMMUNIKATION

[2] VDE Positionspapier "Funktechnologien für Industrie 4.0"

Focus of KOI

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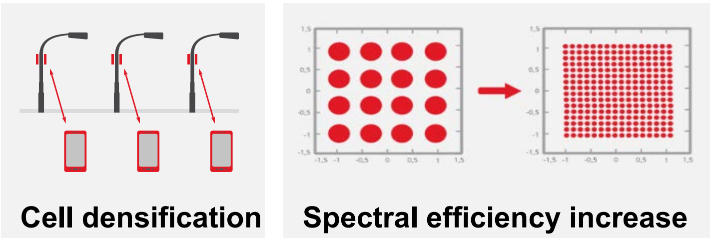
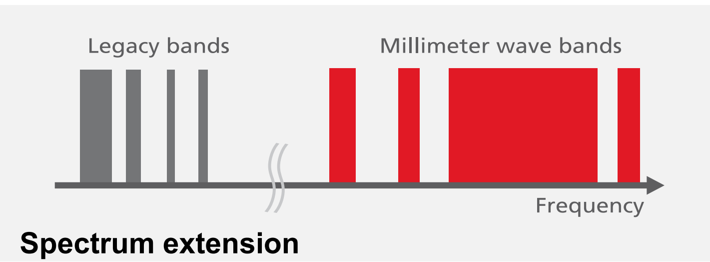
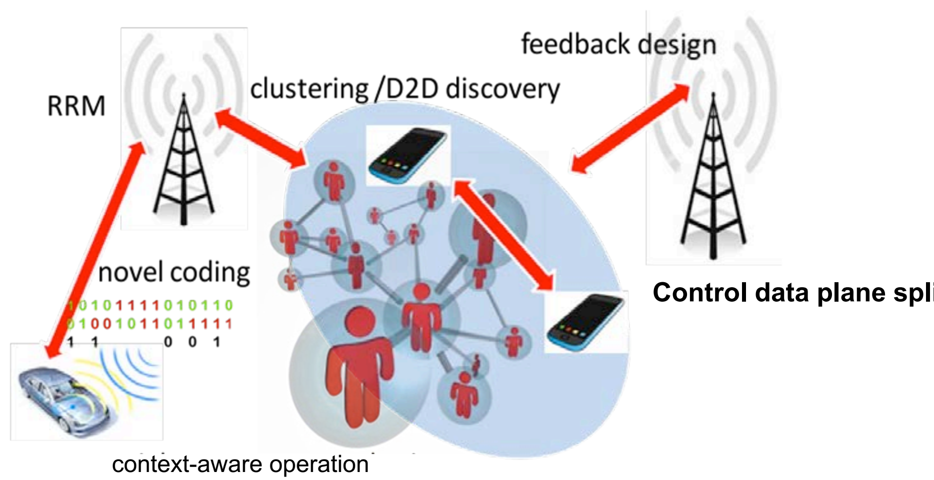
5G Enablers





New architectures for the mobile digital infrastructure

- Increase of network density
  ➔ New small-cell architectures
- Increase of spectral efficiency
  ➔ Massive MIMO (massive number of antennas)
- Increase of the available bandwidth
  ➔ Millimeter-Wave Technology



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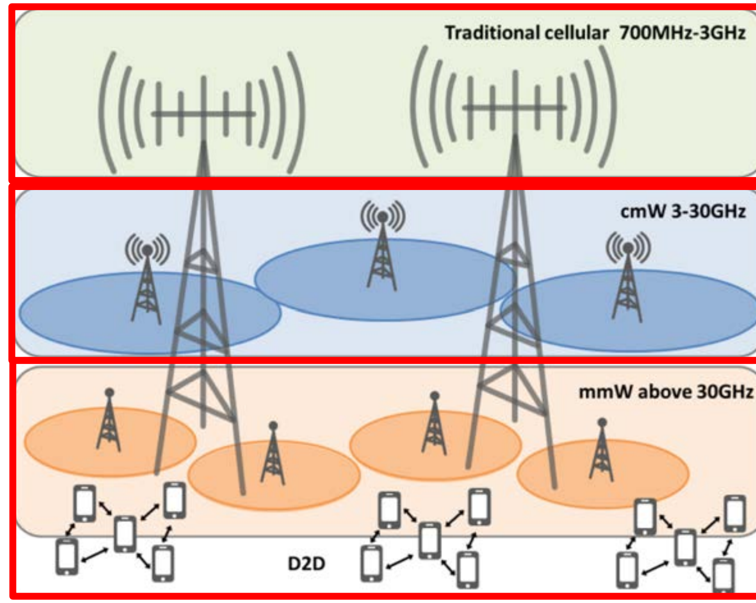
Network Densification

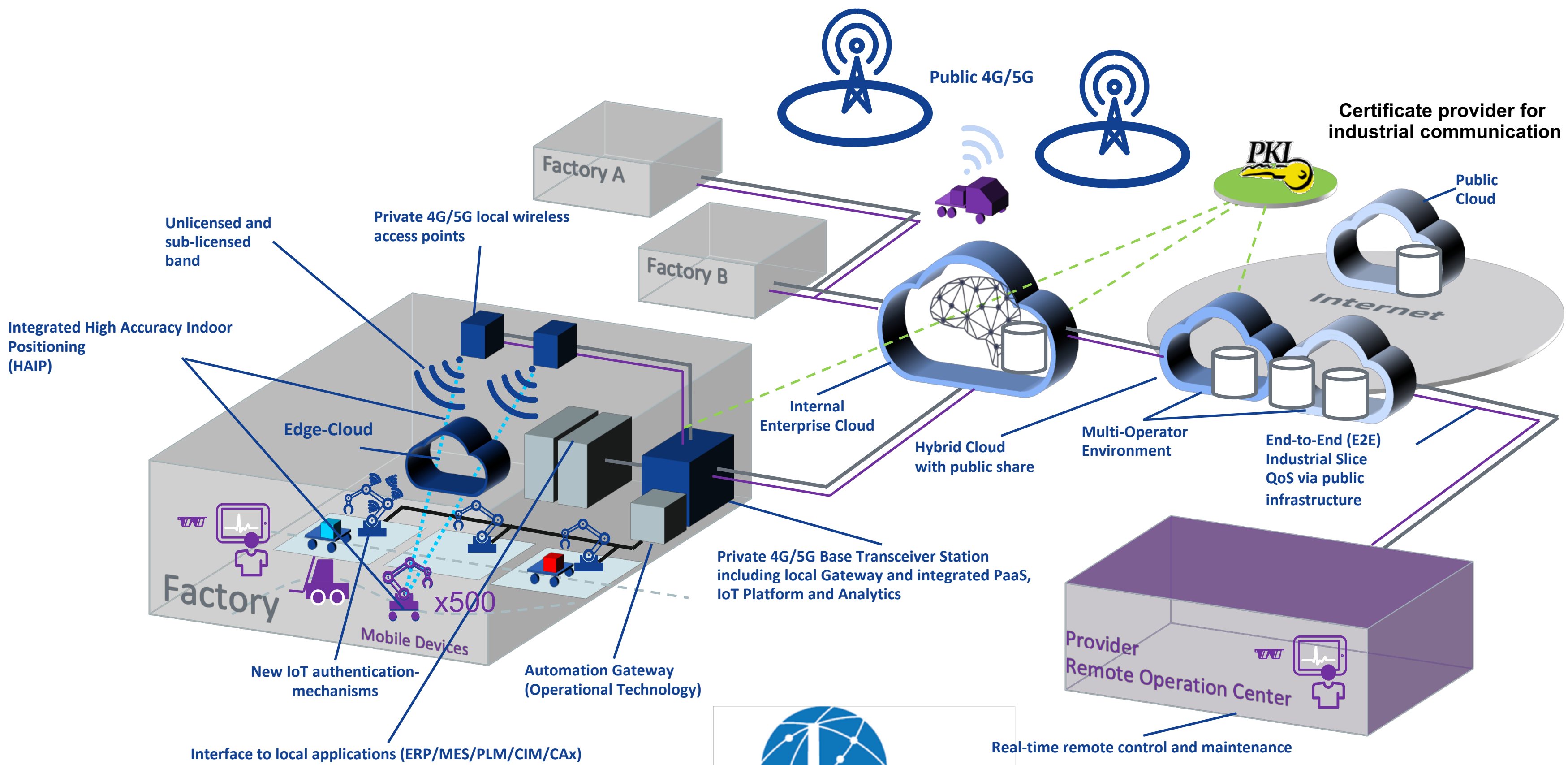
Multi-Layer Mobile Networks with Small Cell Deployments

- Multiple nested layers
- Top: Macro cells
  - Coverage, connectivity and mobility
  - Control, management and interoperability
- Downwards: smaller cells
  - Higher energy efficiency
  - Higher frequencies
- Bottom:
  - D2D communication
  - IoT



Massively increased complexity

Future Mobile Architecture for Industrial Communication



IC4F

PLATTFORM INDUSTRIE 4.0

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

PAiCE

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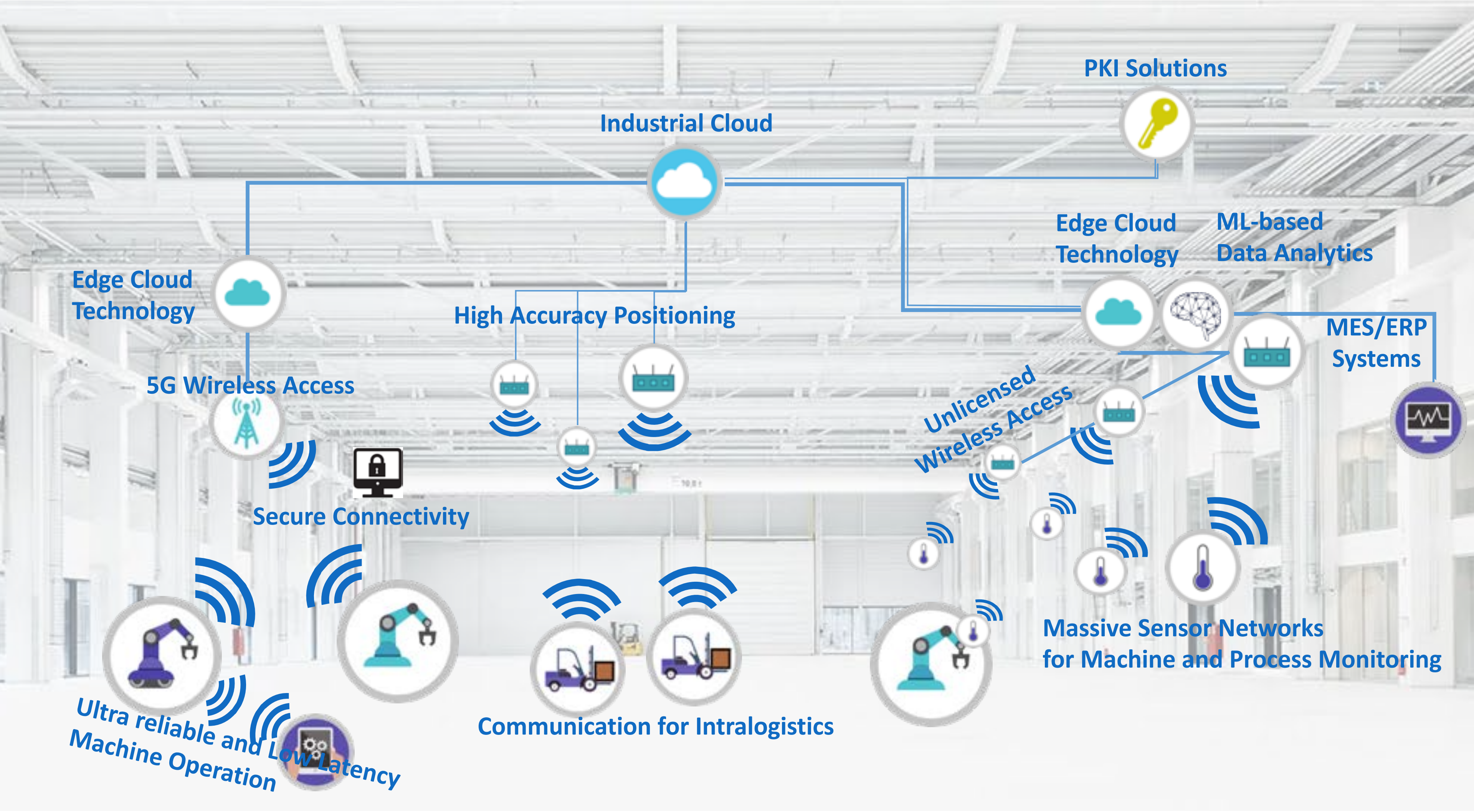

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The largest data records are not generated by companies in the Internet industry such as Google and Facebook, but by production technology systems. McKinsey

Measuring systems in the industry require

- new rules for secure and reliable data acquisition, processing and transmission
- new measuring methods with huge amounts of data and traceable data processing

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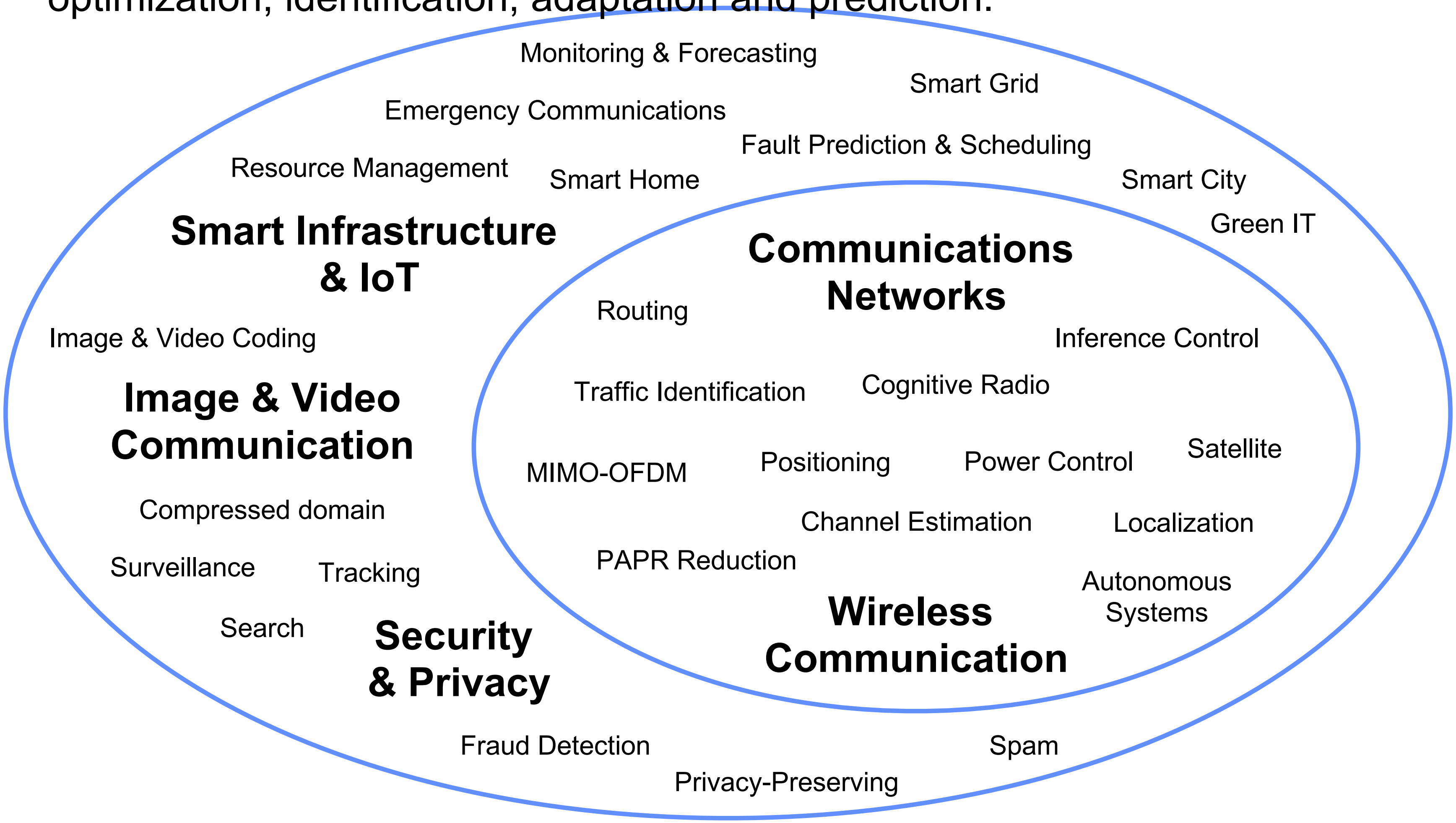
Machine Learning in Communications

These methods are widely used in traditional communications for optimization, identification, adaptation and prediction.

ML methods are also used in many other applications.



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Potential Benefits of ML for 5G

- to enable us to cope with a massively increased complexity
  → diminish mismatch between model and reality

- to reduce # measurements and facilitate robust decisions
  → enabling massive connectivity, MIMO and mmWave

- to facilitate self-organizing networks
  → cognitive network management

- to provide robust predictions
  → QoS prediction, anticipatory networking

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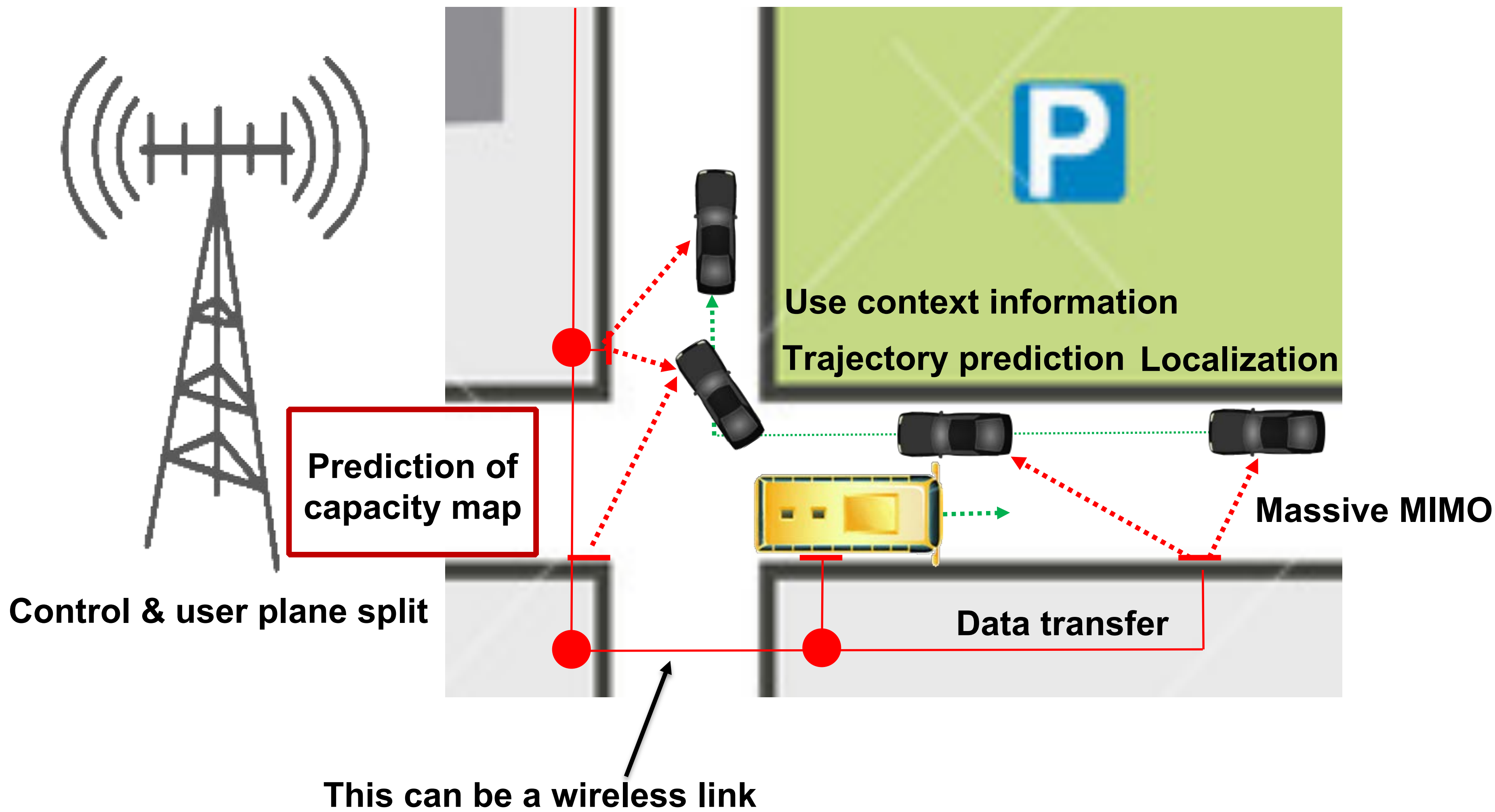
A potential future scenario



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Demands on ML for 5G

- Robust online ML with good tracking capabilities
  ➔ ML with **small (uncertain) data sets** and
- Exploit **domain knowledge** (e.g. models, correlations, AoA)
  ➔ Hybrid-driven ML approaches
  ➔ Learn features that change slowly over frequency, time...
- **Distributed learning** for efficient usage of scarce resources
  ➔ New functional architectures for Big Data analytics
- Low-complexity, **low-latency implementation**
  ➔ New algorithms, massive parallelization

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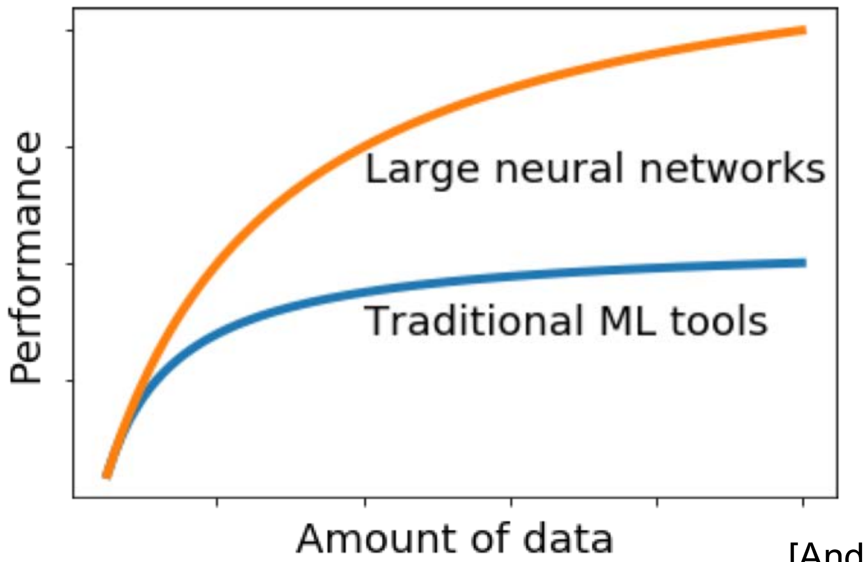
Current View of ML tools

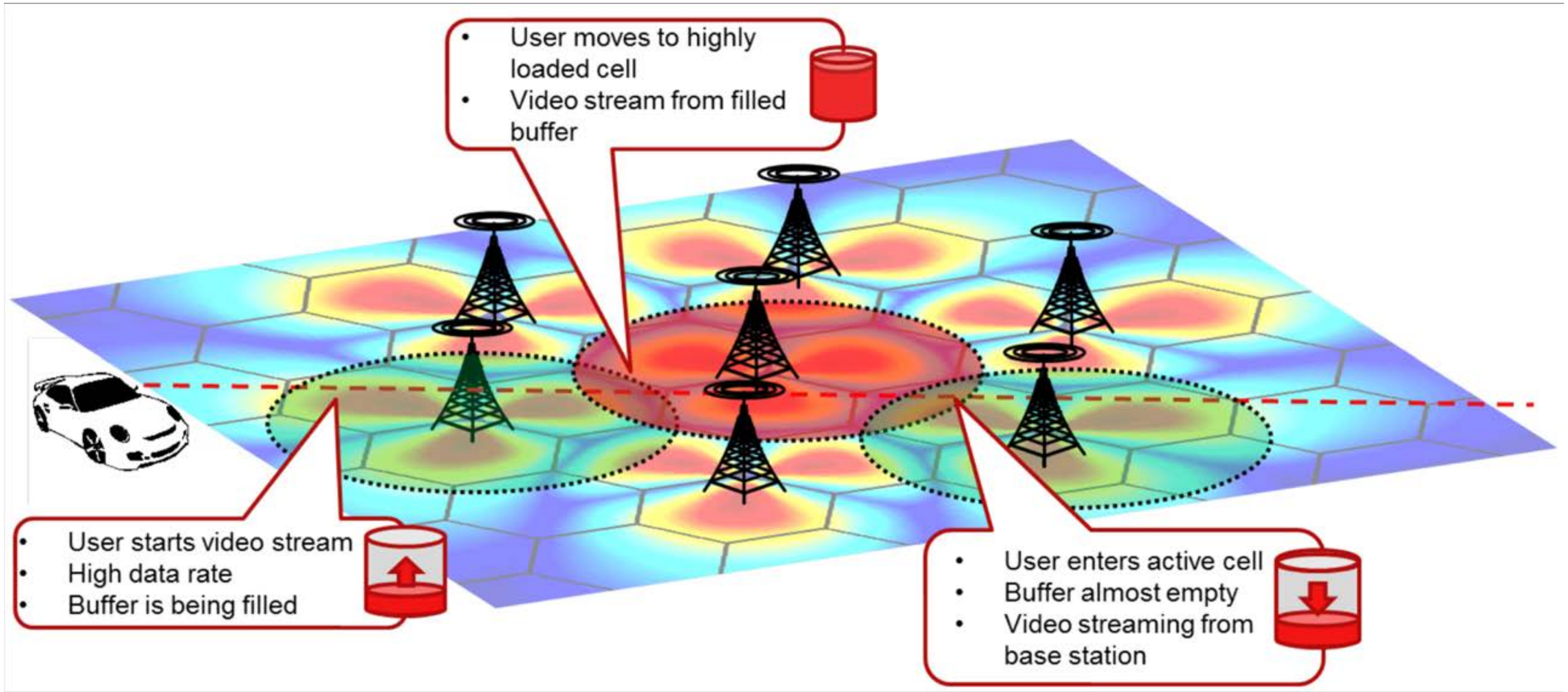


[Andrew Ng]

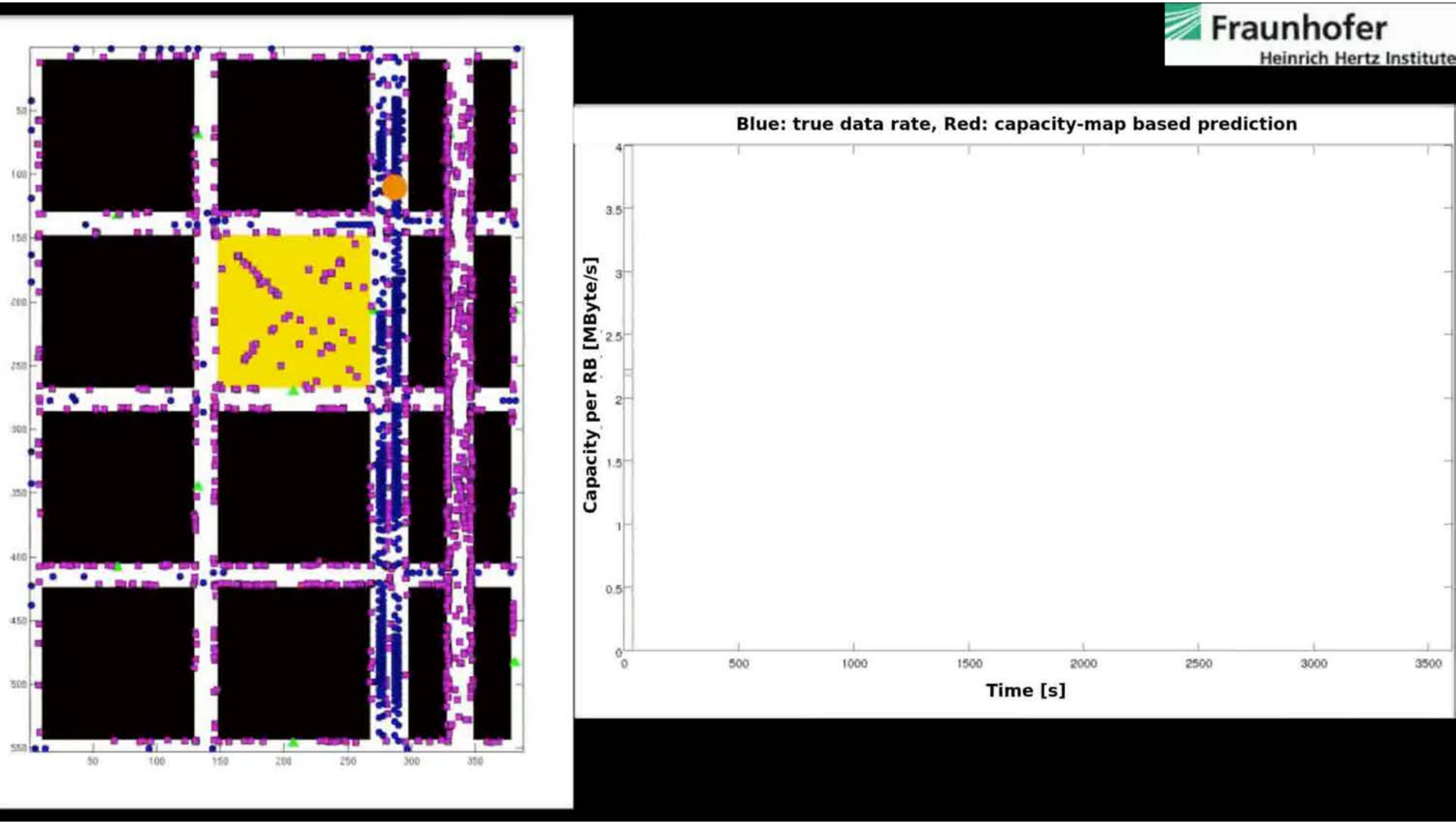
- The collection of training data may be limited by ***physical properties of the wireless environment***

ML for Reconstruction of Capacity Maps

- Adaptive learning of long-term capacity maps



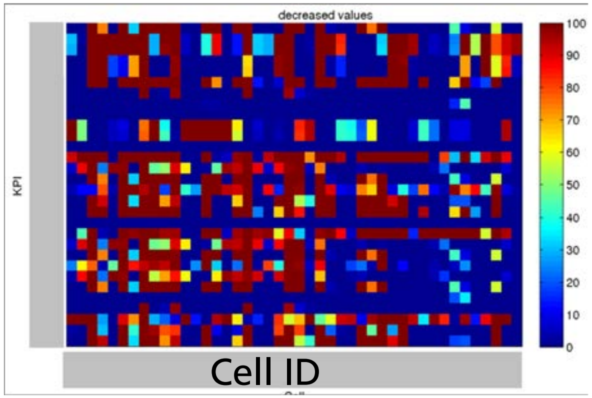
Madrid Scenario: Learning of Capacity Maps



Other Applications of ML for 5G

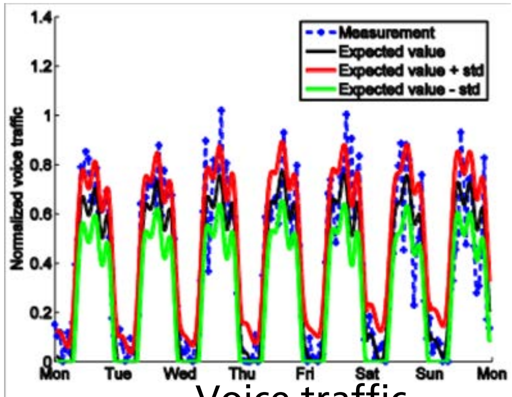
Prediction of significant changes

Key performance indicator

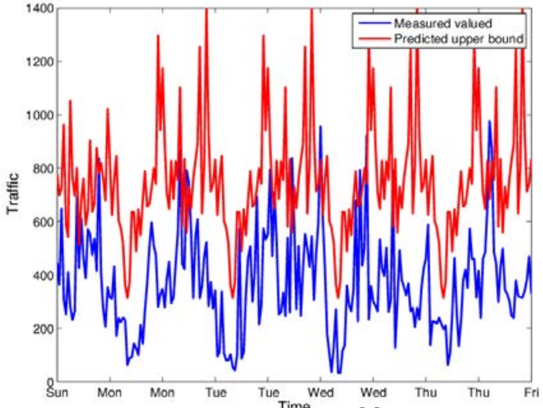


Cell ID

Traffic forecasts

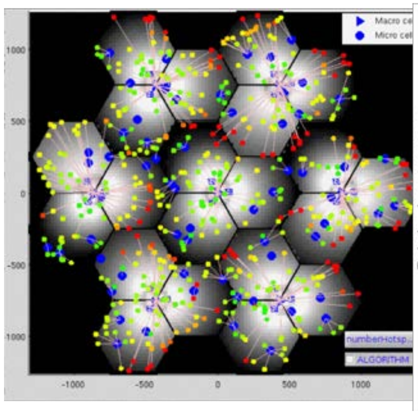


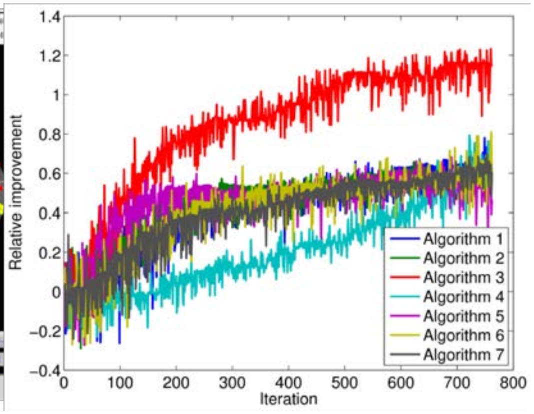
Voice traffic



Data traffic

Automatic network configuration





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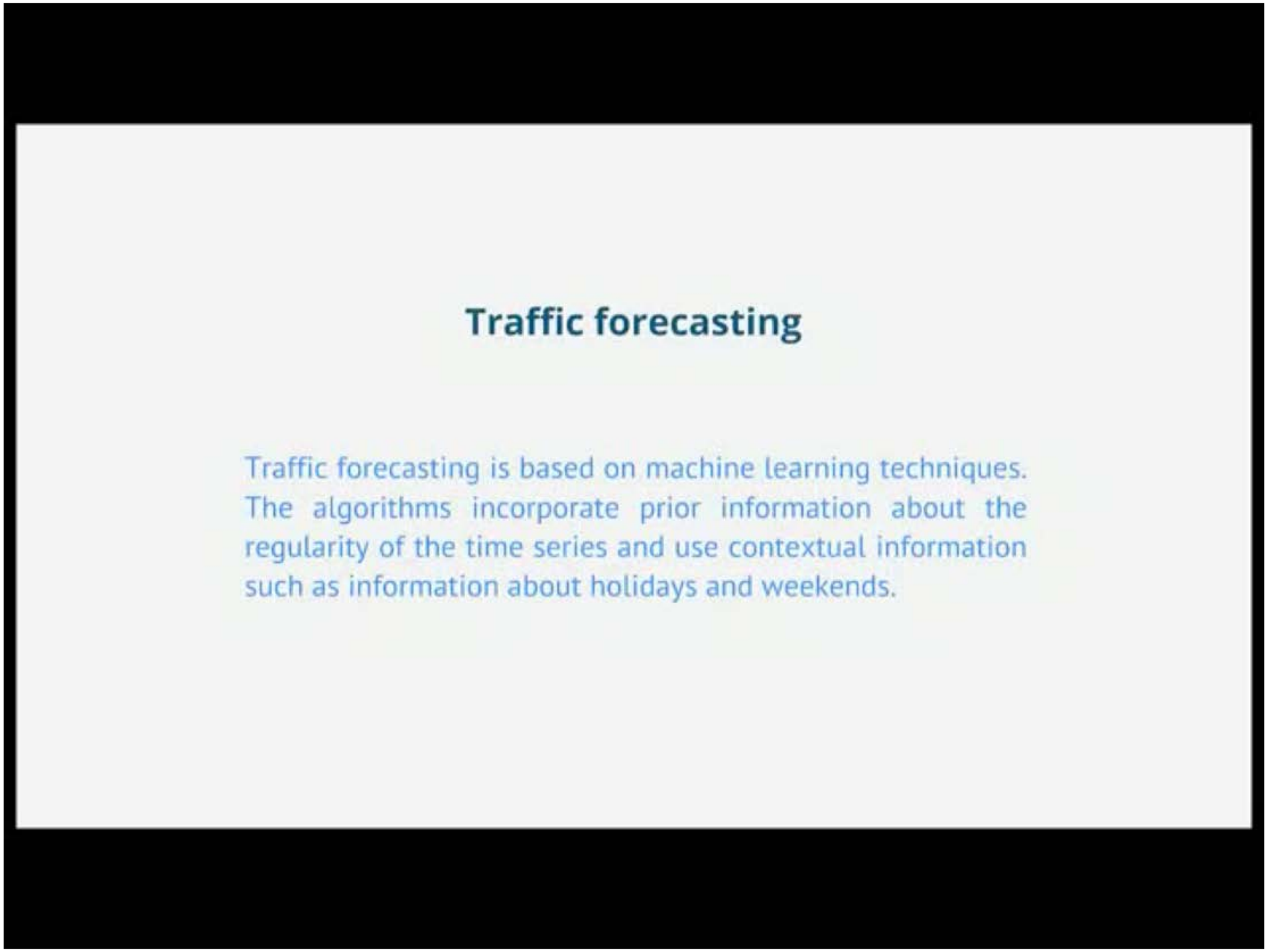
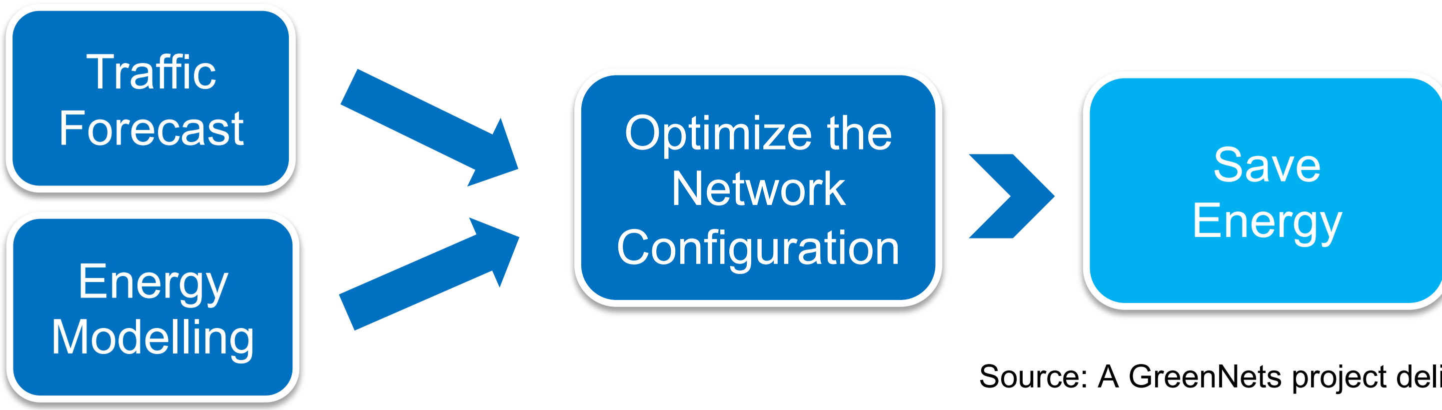
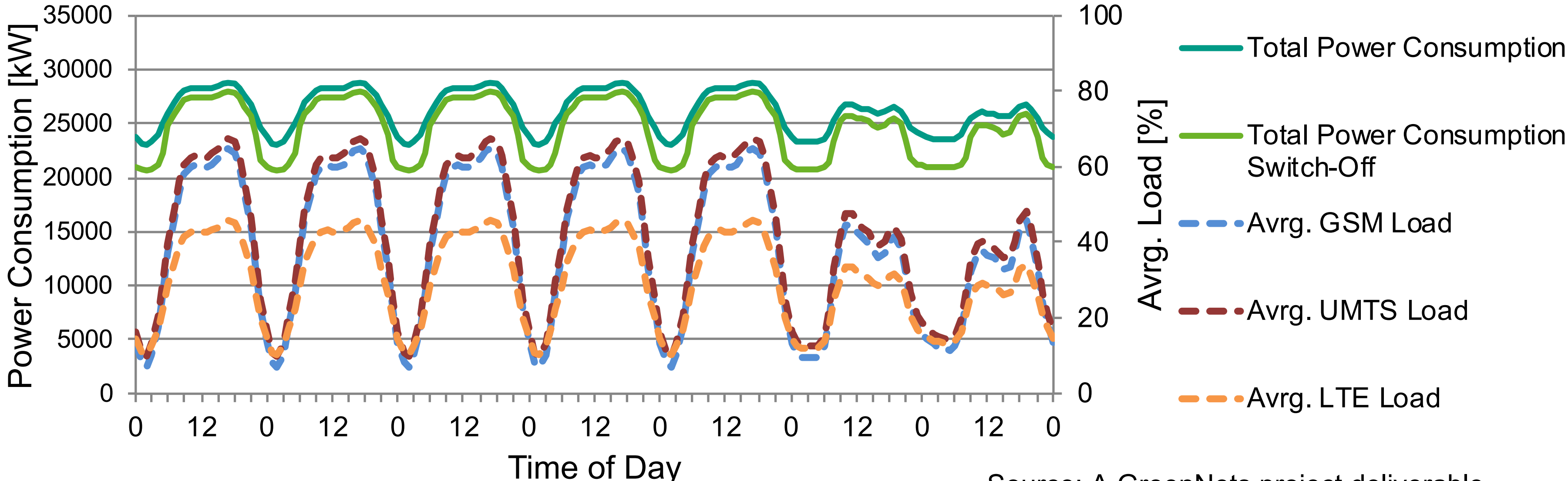
Real Network: Learning Data Traffic



Energy-Saving Optimization



Source: A GreenNets project deliverable



Source: A GreenNets project deliverable

Energy-Saving Optimization

- Simulation area: 20 km x 20 km
- Number of iterations in our algorithm: 10
- Single-RAT optimization (LTE)
- Using CPLEX in the iteration of the algorithm
- Conventional laptop (Core i7 with 4GB of ram)

Source: www.communicate-green.de

# Cells	# test points	Considered cells per test point	# opt var	Time [s]	Memory usage [%]	#active cells after optimization
900	20.000	900	1.5 mio	276	70-80	440
900	20.000	10	0.19 mio	41	30-40	440
900	20.000	5	0.09 mio	29	30-40	516

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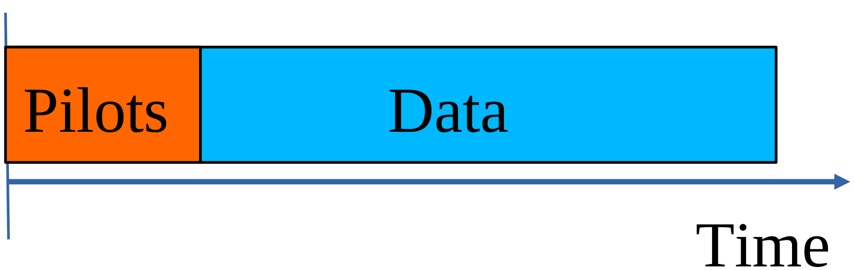
Machine Learning in the Physical Layer / Short-Term Learning

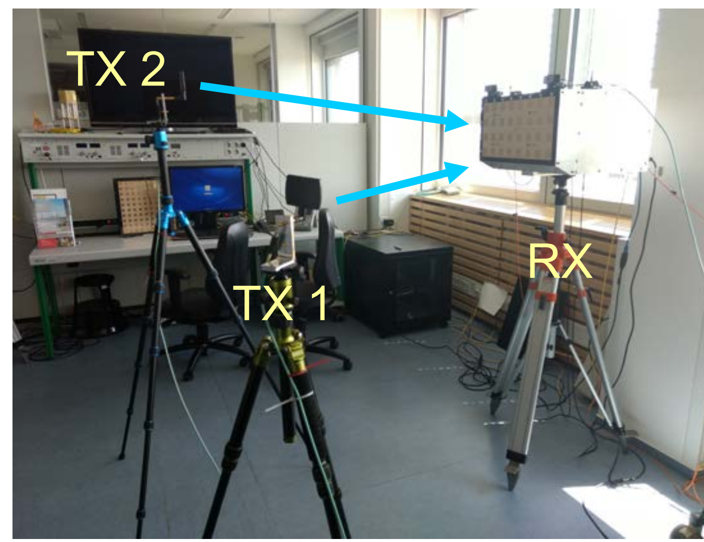
Example: 5G NOMA

- Conventional approach:
  - (1) Send pilots
  - (2) Estimate channels and other system parameters
  - (3) Construct, for example, a linear filter (receiver)
  - (4) Detect the symbols with the filter in step (3)

(one filter for each user)

$$f : \mathbb{C}^M \to \mathbb{C}$$



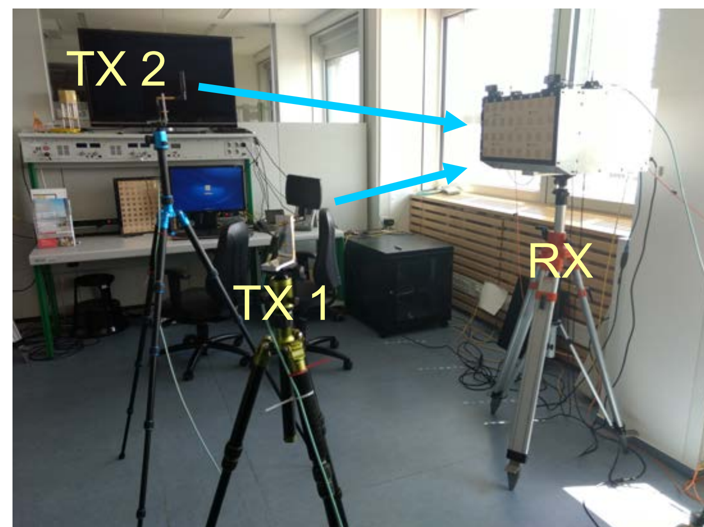


Example: 5G NOMA

- An ML approach:
  - (1) Send pilots
  - ~~(2) Estimate channels and other system parameters~~
  - (2) Use the pilots to train an ML tool to detect the symbols directly (no need to obtain channel state information, for example)
  - (3) Detect the symbols with the ML tool

(one nonlinear filter for each user)

$$f_{\mathrm{ML}} : \mathbb{C}^M \to \mathbb{C}$$

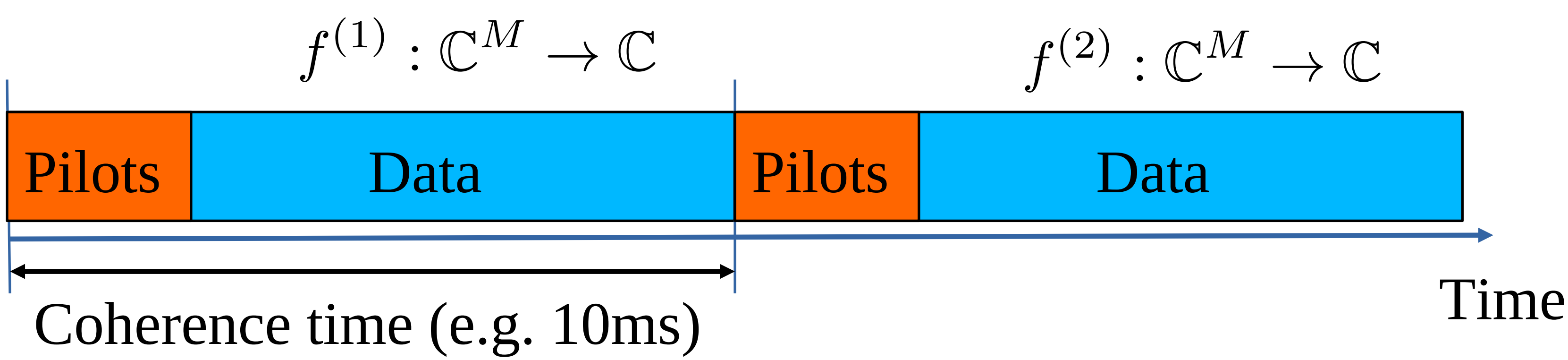


A Fundamental Challenge

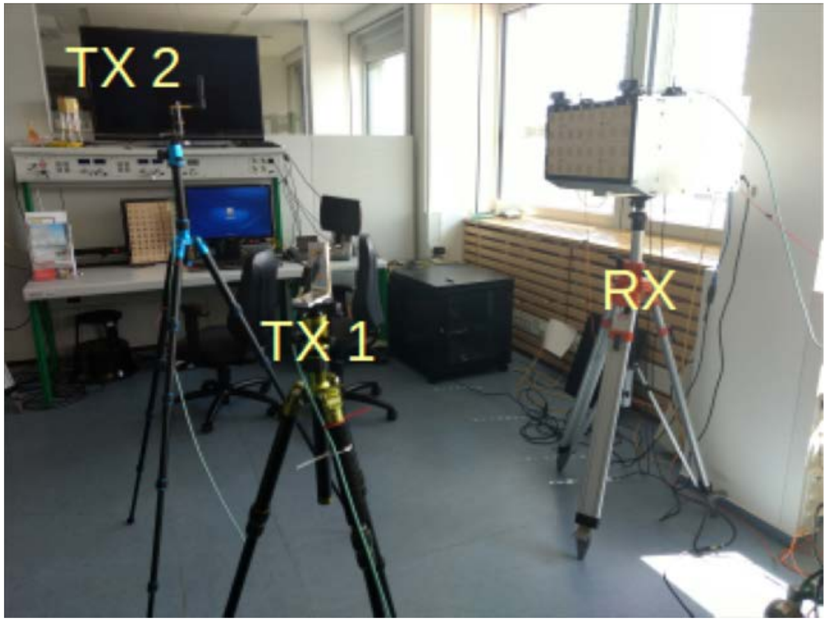
- **Many unknowns**: fast-time varying channels, varying number of users (inter- and intra-cell interference), changing modulation and power, etc.

- **Consequences:**

1. Training samples are highly limited (hundreds). Deep neural networks often require hundreds of thousands or more samples
2. Training and detection have to be performed within the coherence time, or ML tools have to learn (or be given) time-invariant features



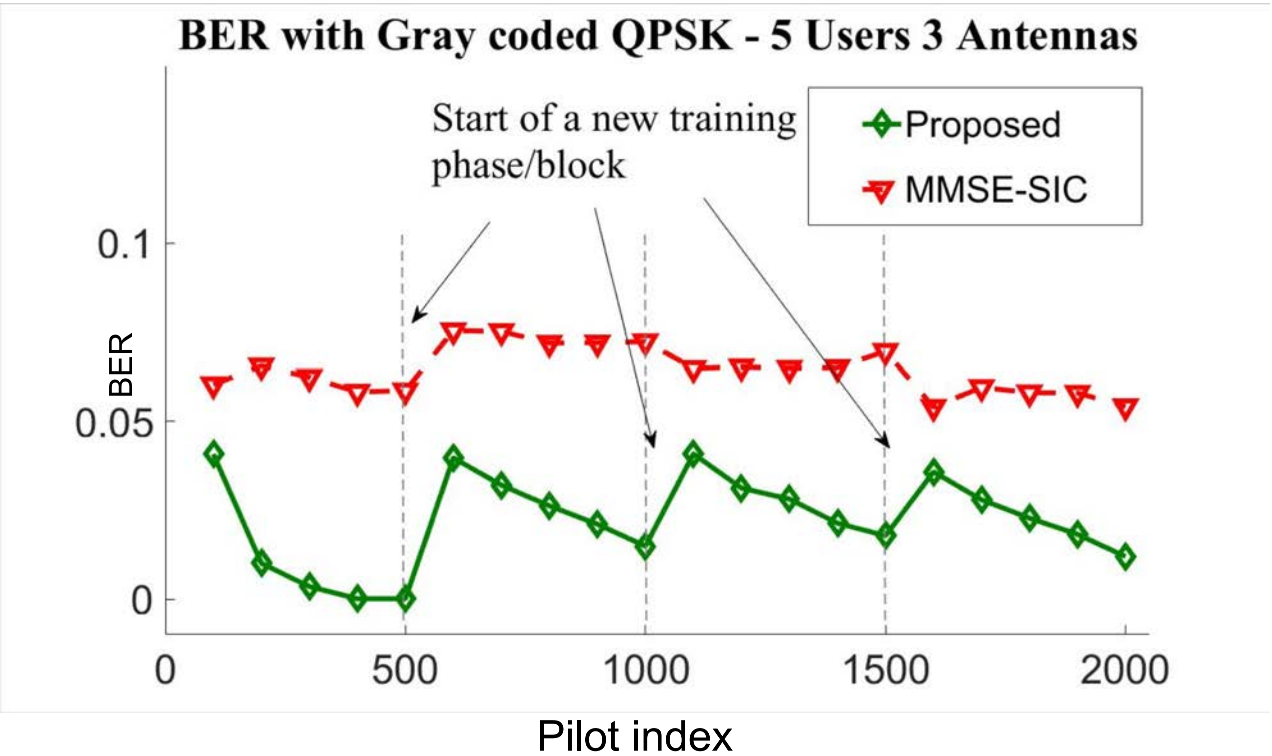
Example: Detection for 5G NOMA



- **Goal**: Use pilots to learn the receiver structure directly
- **Approach**: Online adaptive filter in the sum space of linear and Gaussian reproducing kernel Hilbert spaces

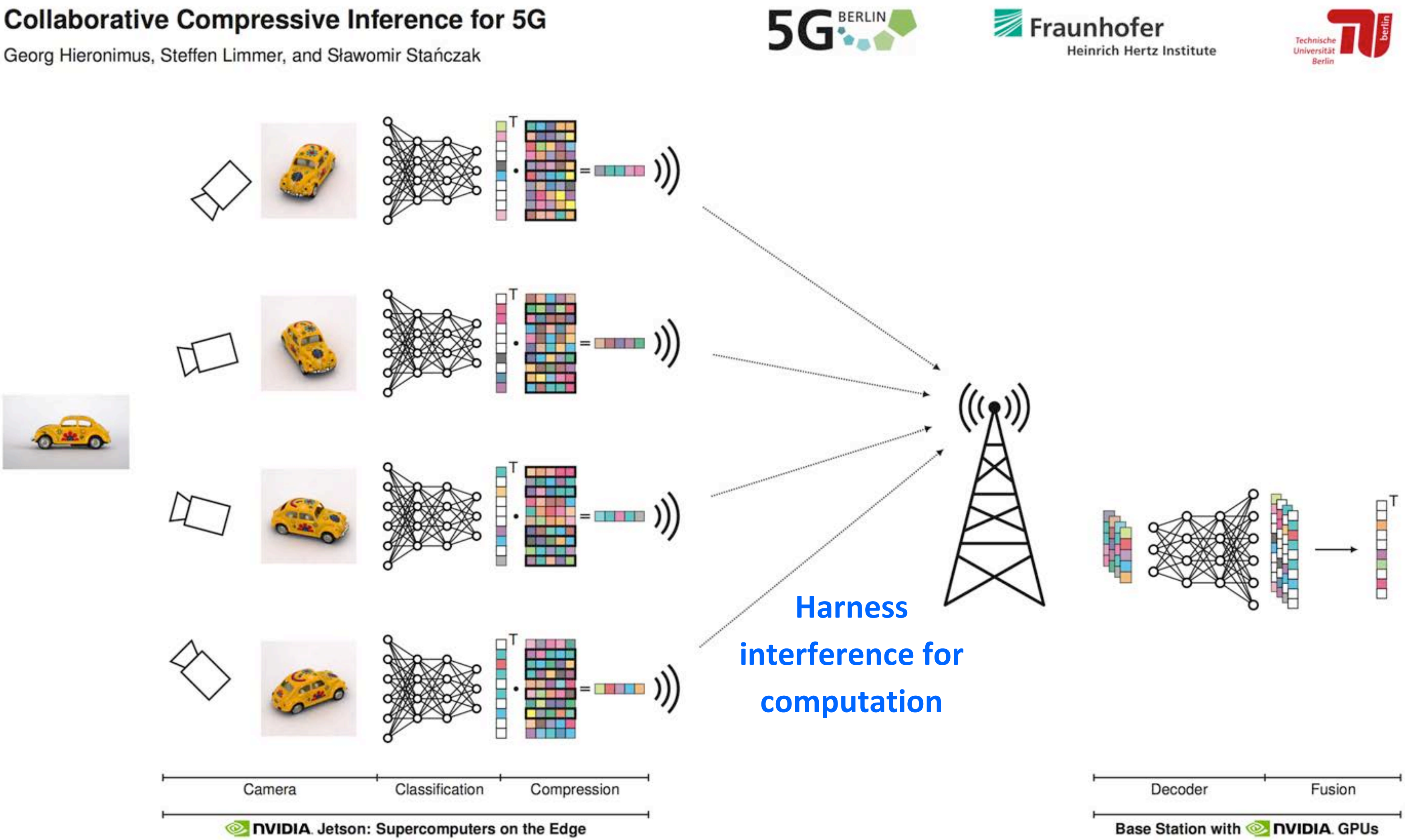
ML-based Solution for 5G NOMA

- Initial fast convergence and low complexity
- Easy to exploit side information and convergence guarantees



D. A. Awan, R. L. G. Cavalcante, M. Yukawa, and S. Stańczak, "Detection for 5G-NOMA: An Online Adaptive Machine Learning Approach," in Proc. IEEE International Conference on Communications (ICC), May 2018

Cooperative Deep Learning



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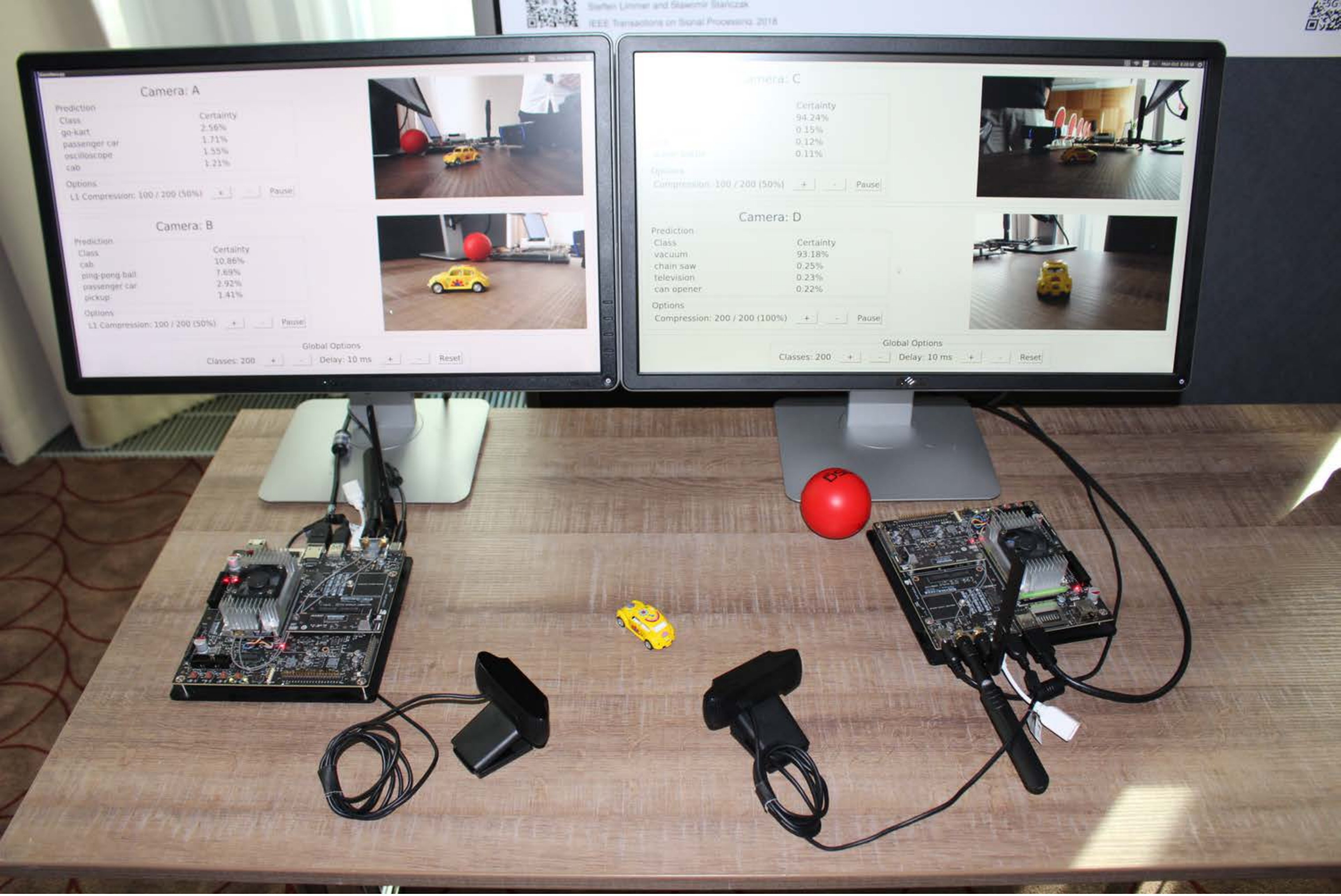

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Take-away Message

- ML will help to cope with the increasing complexity of 5G
- But there is a strong need for robust online ML methods
  → Exploit domain knowledge: Hybrid-driven distributed ML
  → Learn feature insensitive to frequency bands, phases …
- Projection methods for CFP allow massive parallelization
  → Low-latency implementations using GPUs possible
- No time and data for extensive training of DNN
  → Design good NN architectures for a given task

ITU-T Focus Group on Machine Learning for Future Networks including 5G (FG-ML5G)

Established by ITU-T SG13 in November 2017 to:

Identify relevant standardization gaps in order to improve interoperability, reliability and modularity of Machine Learning (ML) for 5G

Draft technical reports & specifications for ML for future networks, including interfaces, network architectures, protocols, algorithms and data formats

Analyse the impact of the adaption of ML for future networks (e.g. autonomic network control and management)

http://news.itu.int/itu-launches-new-focus-group-study-machine-learning-5g-systems/

First meeting: 30 January – 2 February 2018 (Geneva); preceded by a workshop on *ML for 5G and beyond*, on 29 January 2018

Remote participation will be provided

Chairman:

- Slawomir STANCZAK (Fraunhofer HHI, Germany)

Vice-chairmen:

- Charles Chike ASADU (University of Nigeria)
- Seongbok BAIK (KT, Republic of Korea)
- Viliam SARIAN (NIIR, Russian Federation)
- Mingjun SUN (CAICT, People's Republic of China)

"Machine learning and artificial intelligence are finding promising applications in communications networking," says the Focus Group's Chairman, Slawomir Stanczak of Germany's Fraunhofer Heinrich-Hertz-Institut. *"This Focus Group will establish a basis for ITU standards experts to capitalize on machine learning in their preparations for the 5G era."*

FG ML5G: Deliverables

Three working groups:

- WG1: Use cases, services & requirements
  - Deliverables
    - Use cases
    - Ecosystem, terminology and services.
    - Requirements and standardization gap
- WG2: Data formats & Machine Learning technologies
  - Deliverables
    - ML algorithms in communication networks: categorization, terminology & implications
    - Data formats including privacy and security aspects for ML in communication networks
    - Standardization and technology gaps
- WG3: Machine Learning-aware network architecture
  - Deliverables
    - Analysis of communication network architectures from the viewpoint of ML
    - Description of ML-related functions, interfaces and resources for communication network architectures
    - Standardization and technology gaps

How to participate: Website, Collaboration site

- FG ML5G website

  Participation in FG-ML5G is free of charge and open to all.

- Access to FG-ML5G Collaboration Site

  to see meeting documents, agendas, reports, etc.

  How to access:

  1. A TIES or Guest account is required to access FG documents and subscribe to the FG-ML5G mailing lists. Sign up here

  2. Alternatively, sign in to MyWorkspace and use the "Mailing lists" feature for one-click subscription (search for "fgml5g")

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