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TOMORROW TODAY

WIRELESS 6G FOR GREEN

ADV Sustainability 4.0

Thomas Zemen

October 7, 2021

RELIABLE WIRELESS COMMUNICATION SYSTEM RESEARCH @ AIT

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Application domains

Connected vehicles

Industry 4.0

Transport

UAV

Know How:
- 6G & 5G
- time sensitive applications
- distributed massive MIMO
- wireless channel measurements and modelling
- reflective intelligent surfaces
- mm-Wave communication systems
- UAV defense
- real-time digital twin
- joint communication and sensing

Team

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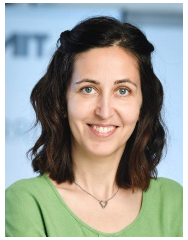

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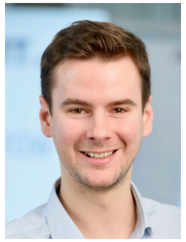

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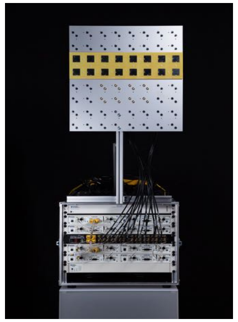
WIRELESS RESEARCH TOPICS AND TECHNOLOGIES

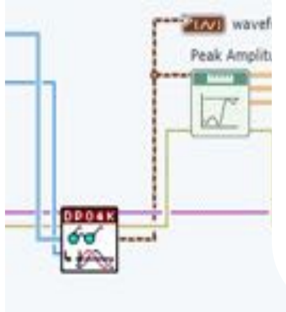
Distributed massive MIMO systems

- max. diversity
- min. frame error rate & latency
- SDR distributed massive MIMO



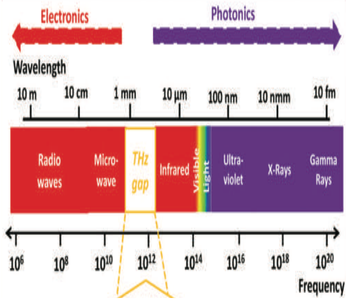
Software defined radio rapid prototyping

- multi channel processing
- phase coherency
- real-time implementation



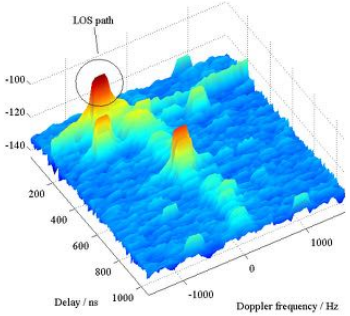
Optical / RF interface

- mmWave & THz
- antenna arrays
- remote radio heads
- quantum sensing



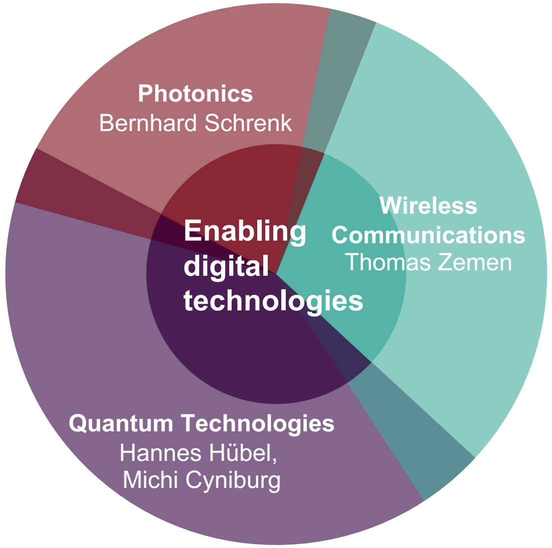
Wireless channel measurement characterization and modelling

- high mobility
- multi node
- massive MIMO
- mmWave
- ray tracing & GSCM

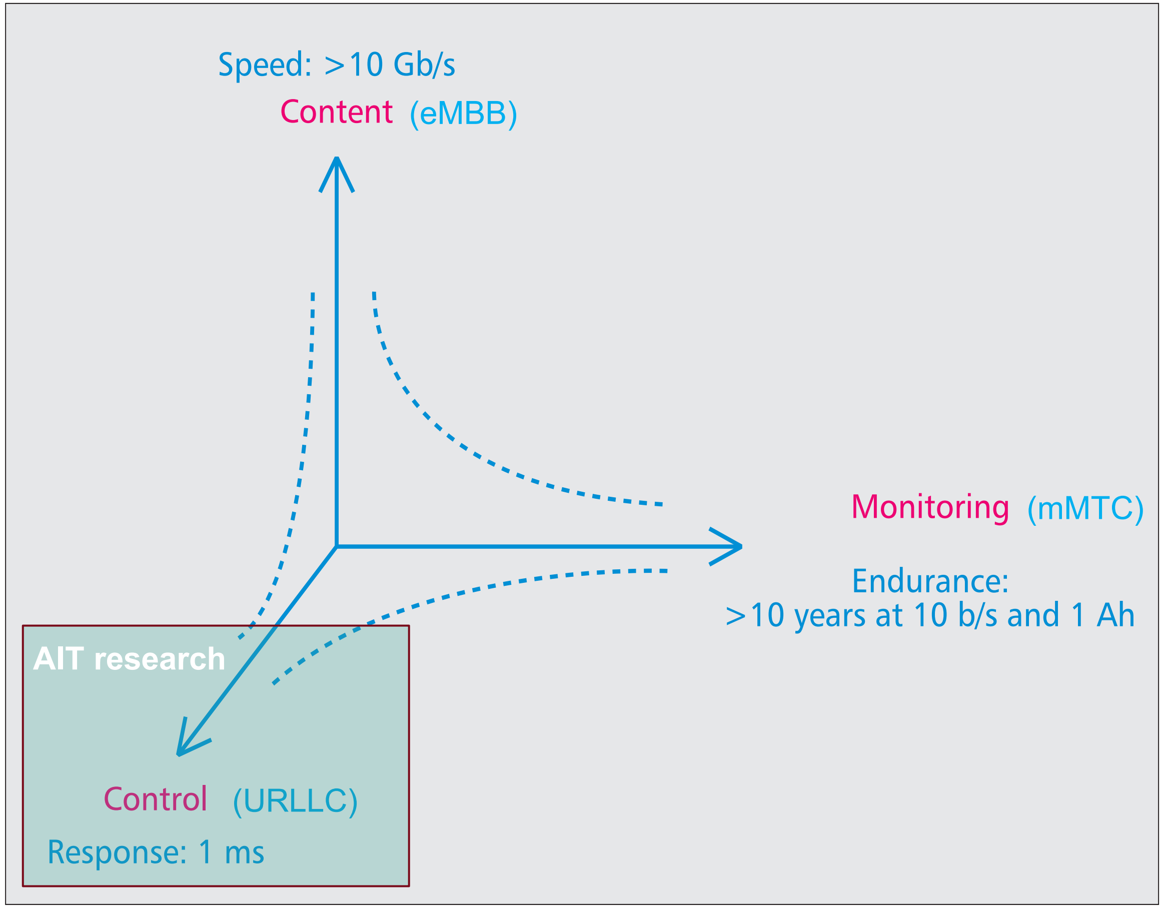


Real-time virtual test systems

- continuous delay
- continuous Doppler
- unlimited paths
- large area support
- system level test



5G – THREE SYSTEMS IN ONE



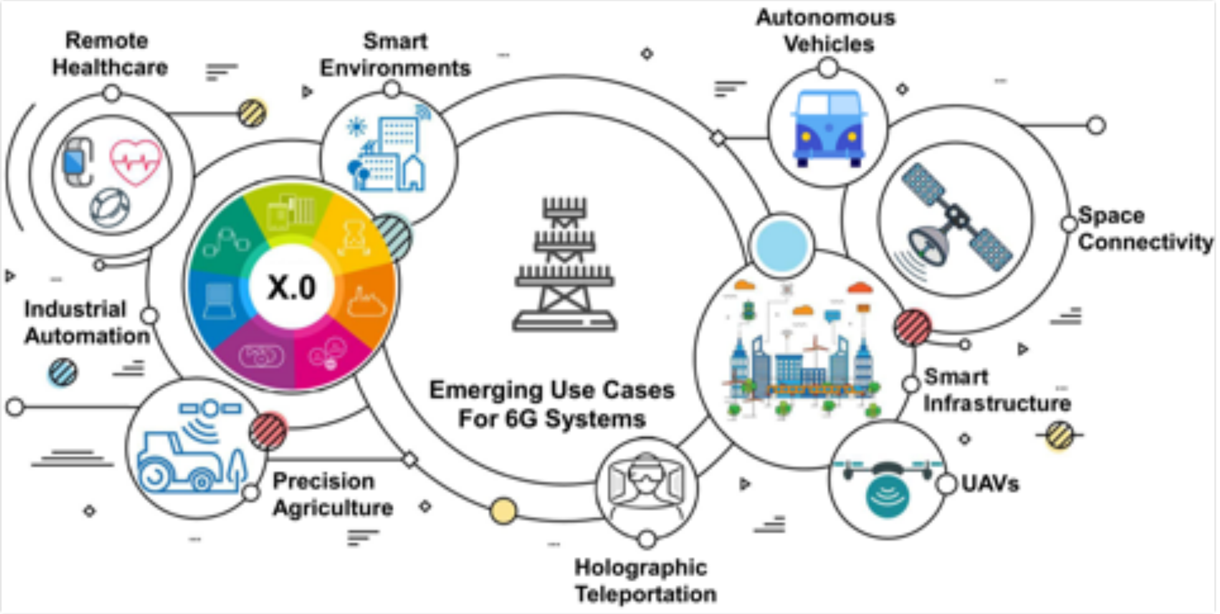
5G network slices

- eMBB, enhanced Mobile Broad band
- mMTC, massive machine type communication
- URLLC, ultra reliable low latency communication

❖ G. Fettweis, S. Alamouti, "5G: Personal mobile internet beyond what cellular did to telephony," IEEE Commun. Mag., Feb. 2014.

TIME SENSITIVE APPLICATIONS

- **Manufacturing processes**
  - human-robot interaction (1ms)
  - robot-robot interaction (100µs)
- **CO_2 efficient public transport**
  - Wireless railway safety systems (99,99999%)
  - Control links for urban air transport



➢ **Challenges: Low-latency and high reliability for mobile devices.**

❖ Akyildiz et al., "6G and beyond: The future of wireless communications systems," *IEEE Access*, July 2020.
❖ The Tactile Internet, ITU-T Technology Watch Report, August 2014.

5G NEW RADIO (NR) – VARIABLE LATENCY

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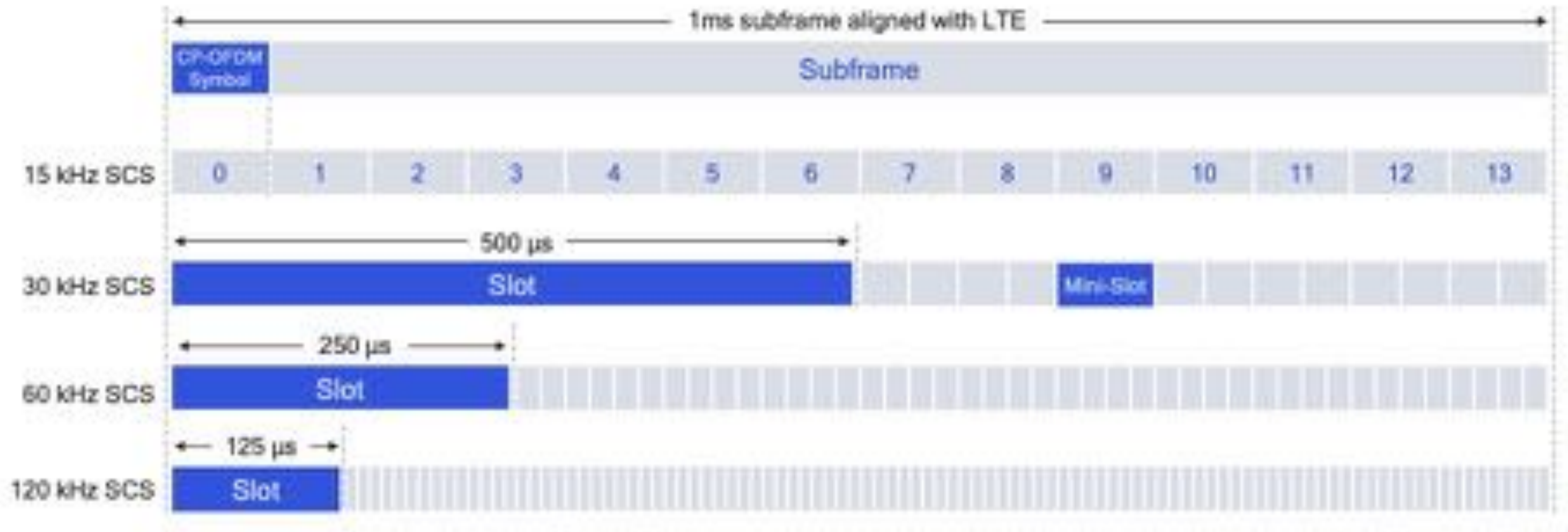
- 4G (LTE) – OFDM modulation with fixed parameters
- 5G – OFDM with flexible parametrization – adapted to bandwidth and latency requirements



Frequency band	Subcarrier spacing	Maximum bandwidth
0.45 GHz–6 GHz	15/30/60 kHz	50/100/200 MHz
24 GHz–52.6 GHz	60/120 kHz	200/400 MHz

TABLE 1. Subcarrier spacing for different frequency ranges.

- S. Parkvall, E. Dahlman, A. Furuskar, and M. Frenne, "NR: The new 5G radio access technology," IEEE Communications Standards Magazine, vol. 1, no. 4, pp. 24–30, 2017.
- Qualcomm, „Designing 5G NR", white paper, April 2018 .

MMWAVE – NEW SPECTRUM – 30 GHZ

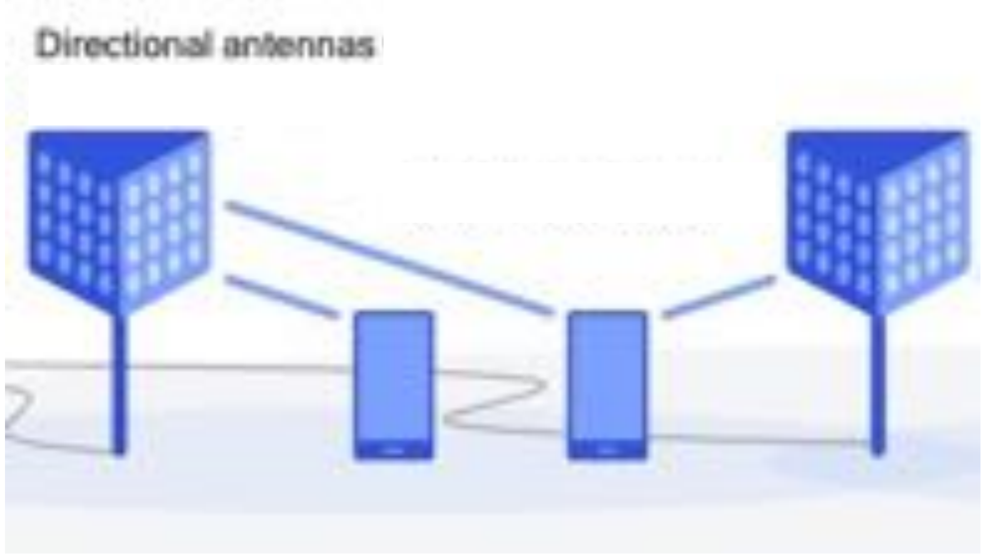
Received power (in free space)

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} G_{\mathrm{TX}} \frac{1}{4\pi d^2} A_{\mathrm{RX}}$$

Gain of receive antenna

$$G_{\mathrm{RX}} = \frac{4\pi}{\lambda^2} A_{\mathrm{RX}}$$

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{RX}} \left(\frac{\lambda}{4\pi d}\right)^2$$

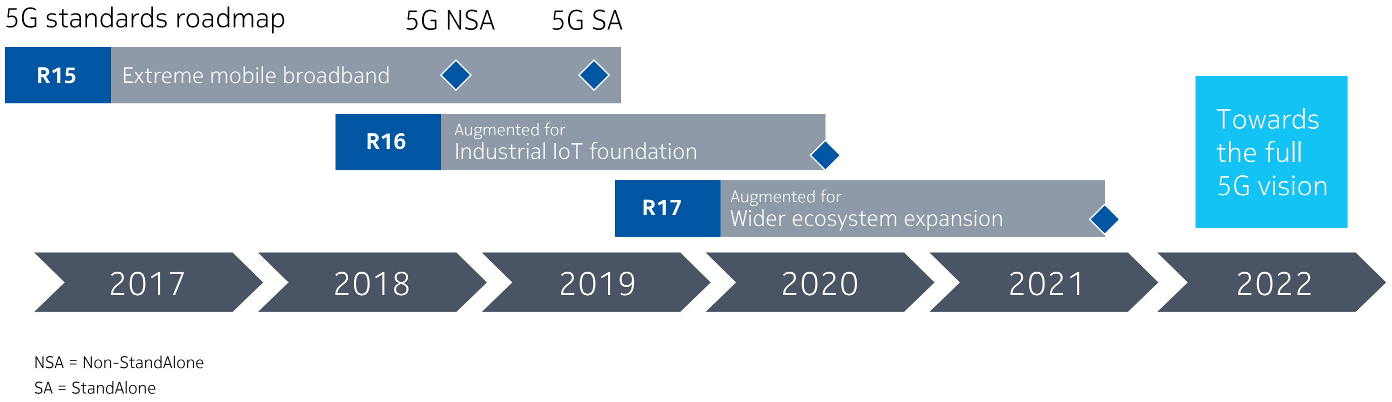


P_{TX} ... transmit power
d ... distance TX – RX
G_{TX} ... gain of transmit antenna (focused in a specific direction)
A_{RX} ... effective area of receive antenna
λ ... wave lengths, c_0/f

- ➢ **requires adaptive beamforming towards mobile users**
- ➢ **easy blocking by other objects in line of sight (no diffraction around corners)**

❖ A. Molisch, „Recent results in outdoor mm-wave and THz channels,“ keynote, 1st Post IRACON Workshop, 2020.
❖ Qualcomm, „Making 5G NR mmWave a commercial reality,“ white paper, 2018.

STATE OF THE ART



Generation	Latency	Reliability
3G	60 ms	80%
4G LTE	60 ms	99%
5G NR (plan)	1 ms	99,999%
5G NR (current)	5 ms	?
Goal for 6G	100 µs	99,99999%

- **5G Release (Rel.) 16 and Rel. 17**
  - focus on low-latency and high-reliability
  - vertical markets - automotive, railway, UAVs, I4.0
  - latency limit expected to be 5ms due to core network
- **Rel. 18 work started this year (5G Advanced, expected end 2024)**
  - enhanced mobility in dense cell deployments
  - resilient timing and positioning
  - energy efficiency

❖ G. Fettweis, S. Alamouti, "5G: Personal mobile internet beyond what cellular did to telephony," IEEE Commun. Mag., Feb. 2014.
❖ Nokia, „5G Releases 16 and 17 in 3GPP", white paper, 2020.
❖ https://www.nokia.com/blog/heres-our-first-real-glimpse-at-5g-advanced/

AIT 6G RESEARCH

DEDICATE DEPENDABLE WIRELESS 6G COMMUNICATION SYSTEMS

6G Use cases

- Holographic presence – 4 Tb/s data rate / user
- Connectivity of all Things – low energy consumption, backscattering
- Time sensitive applications – ultra low latency of 100µs and 99,99999% reliability

New Technology Goals/Needs

- Maximize reliability by exploiting diversity
- Reduce energy consumption

Funding framework: Principal scientist project, 2.5M€, runtime 2021-2025, 16 FTE.

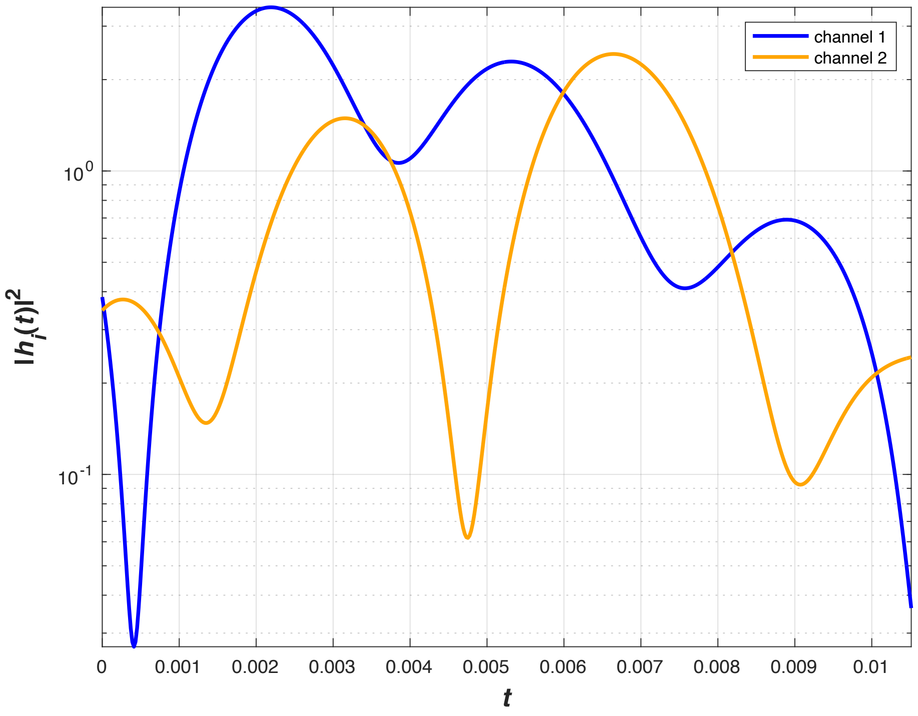
Web: https://dedicate.ait.ac.at

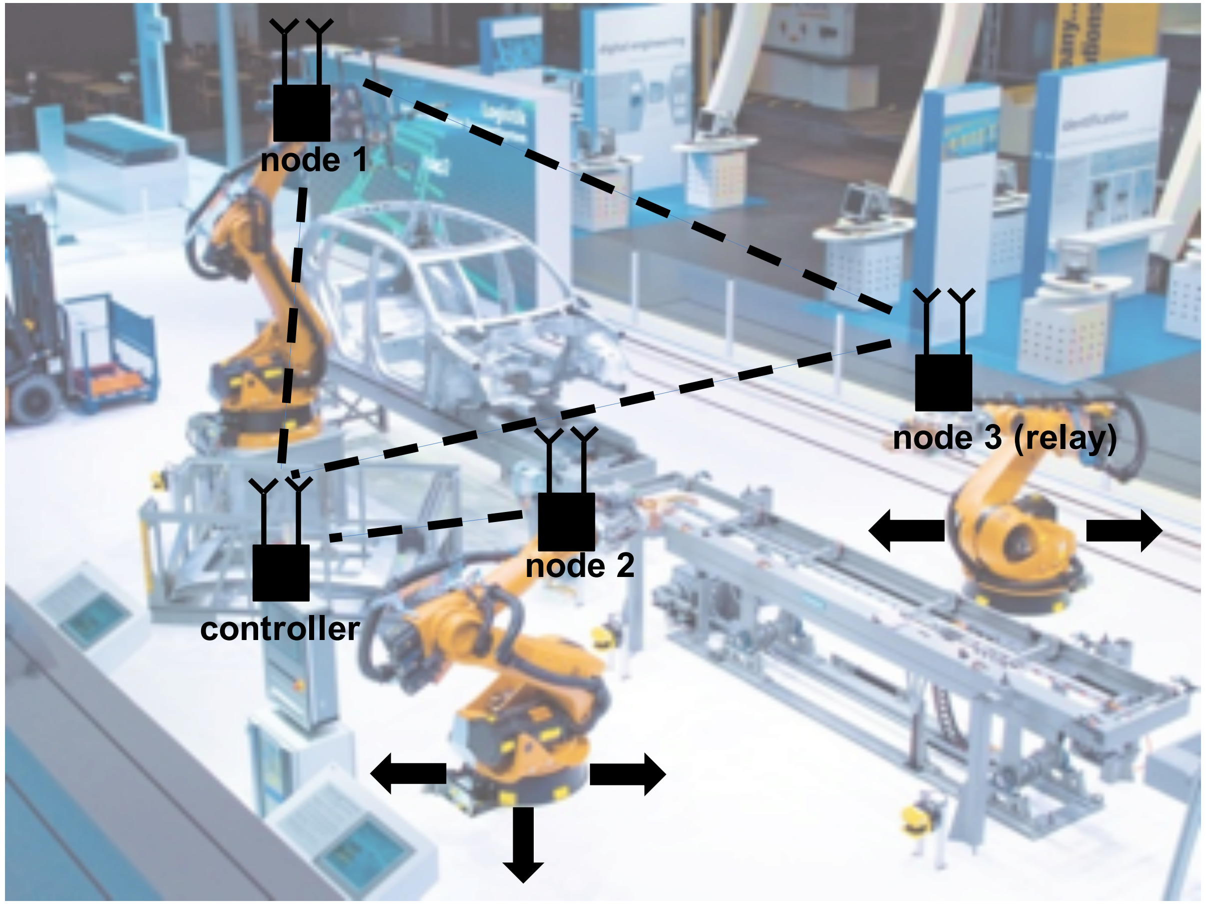
❖ H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, “6G wireless systems: Vision, requirements, challenges, insights, and opportunities,” arXiv preprint arXiv:2008.03213, 2020.

WIRELESS AUTOMATION AND CONTROL

- Reliability: 10^{-9} packet error rate (PER)
- Burst error < 3 packets

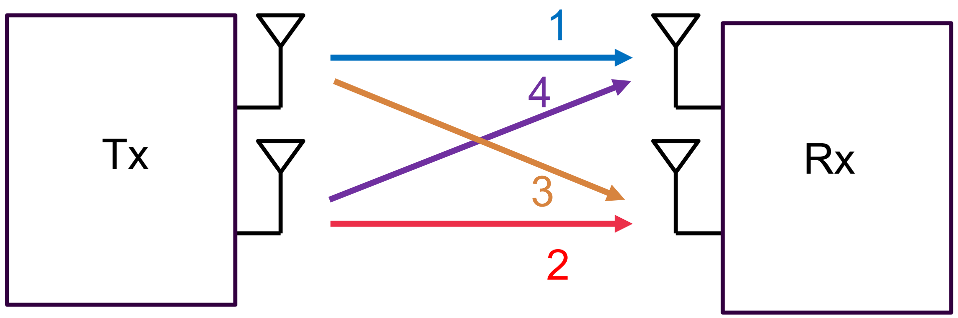
Wireless communication channels strength varies over time (fading)



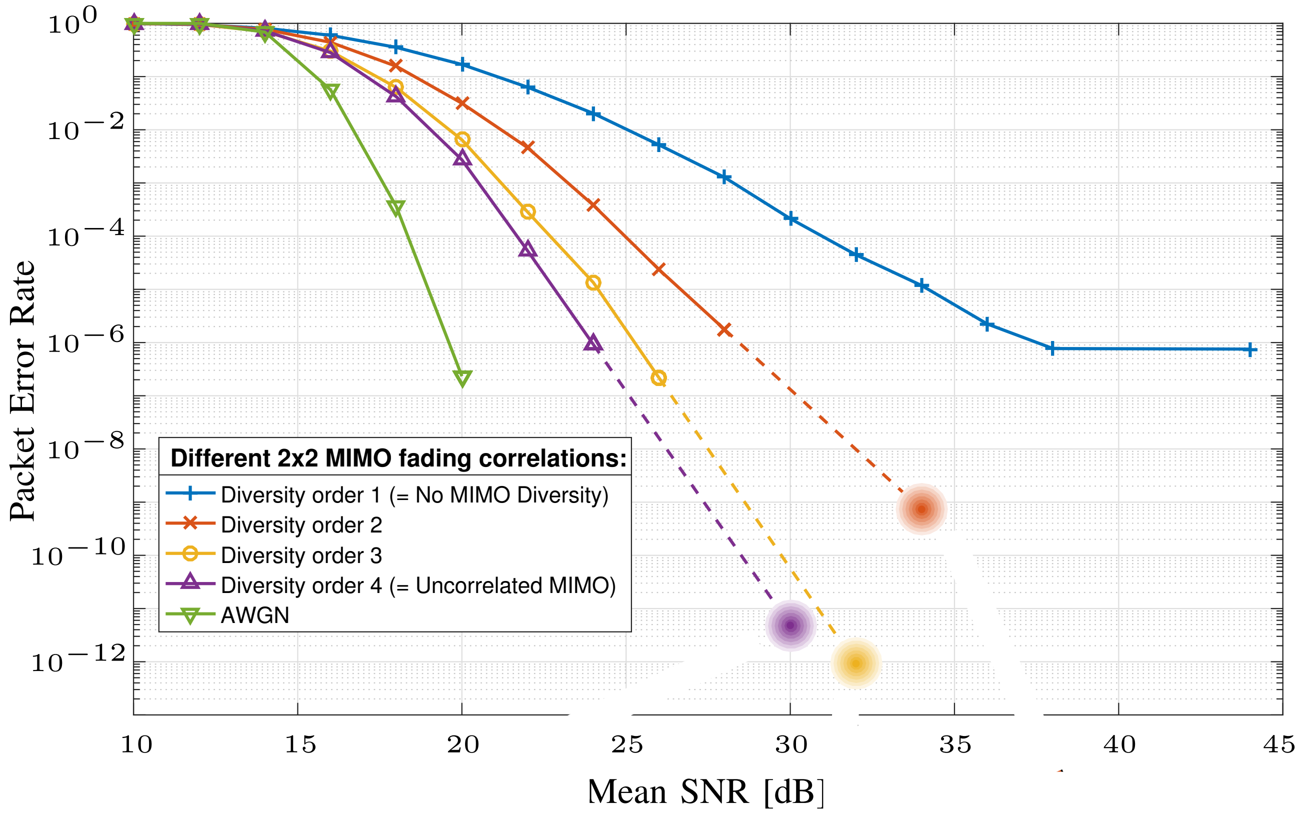


SPATIAL DIVERSITY TO IMPROVE RELIABILITY

Multiple input multiple output (MIMO) systems

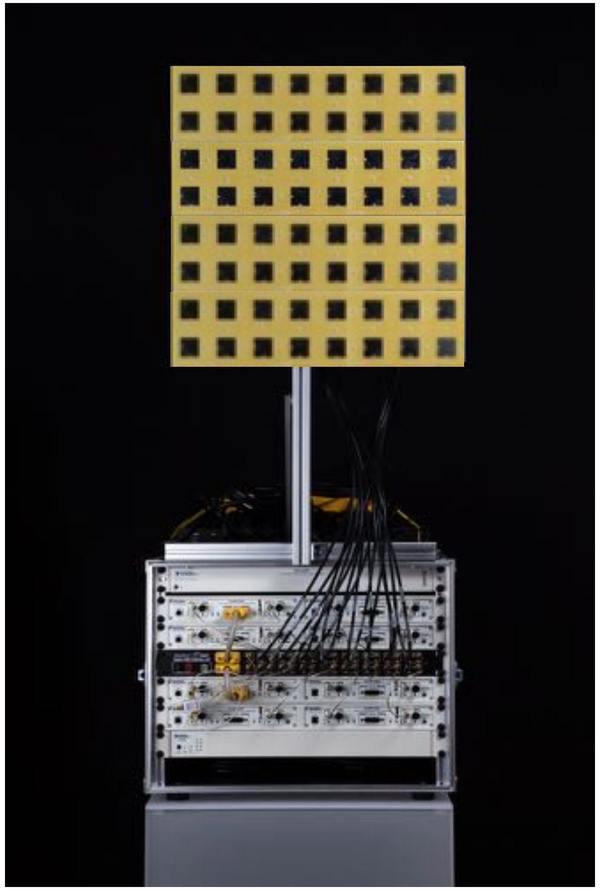


2 x 2 MIMO system can have diversity order 4



❖ G. Kail, H. Muhr, J. Gila, M. Schiefer, R. Hladik, M. Hofer, S. Zelenbaba, and T. Zemen, „A highly reliable ultralow-latency wireless solution for industrial control loops: Design and evaluation," in *Asilomar Conference on Signals, Systems, and Computers (ASILOMAR)*, hybrid conference, Pacific Grove (CA), USA, November 2021.

MASSIVE MIMO PRINCIPLE


(c) AIT, symbolic picture

- Many small low-power antenna elements
- Eliminates fading and enables reliable communication
- Sensitive to movement of mobile station

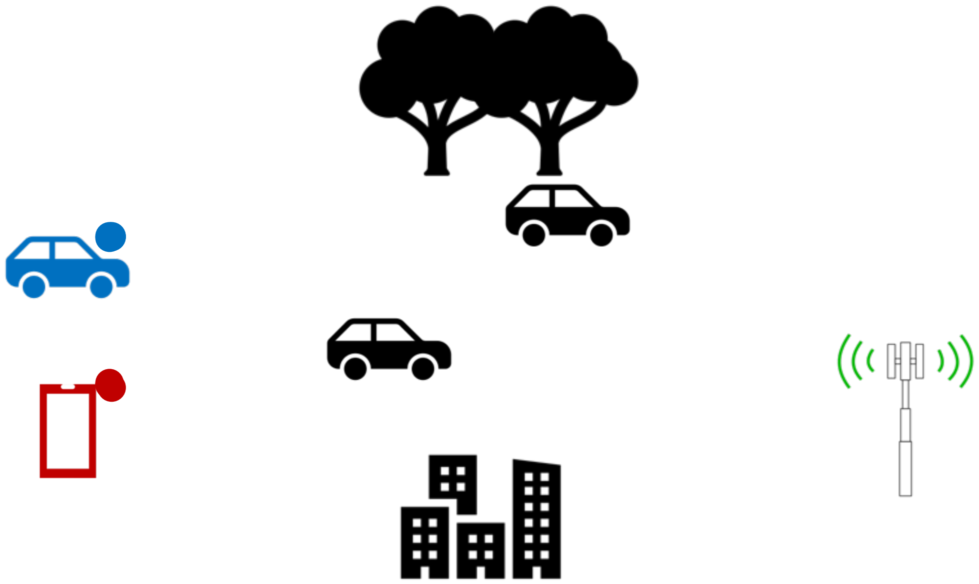
(c) Ove Edfors, Lund University

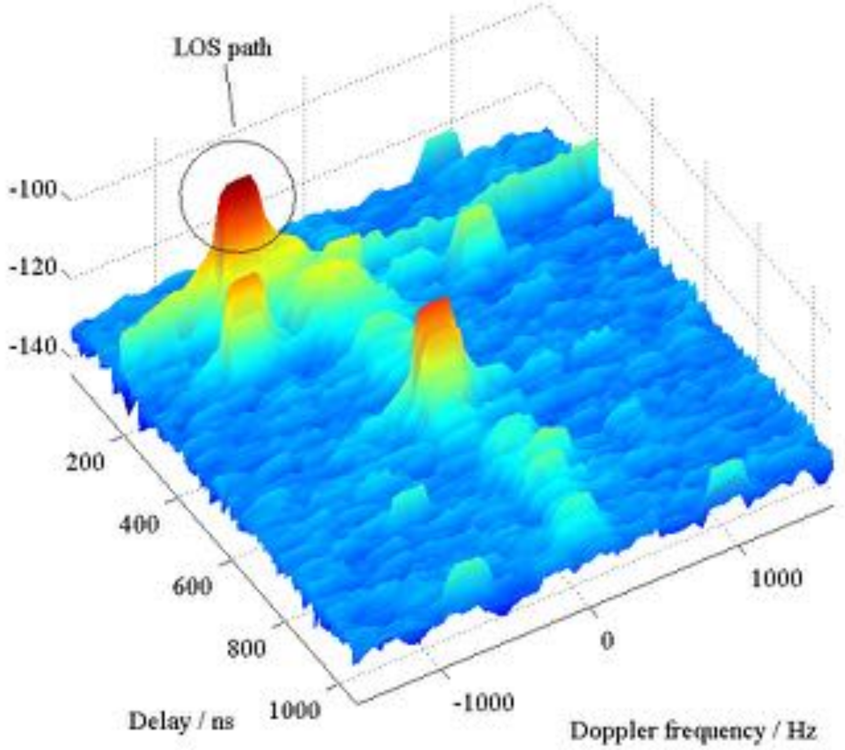
❖ D. Löschenbrand, M. Hofer, and T. Zemen, „Orthogonal precoding with channel prediction for high mobility massive MIMO," in IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), virtual conference, September 2020.

MOBILITY-AWARE MASSIVE MIMO

- Learn channel U1 + mobility
- Learn channel U2 + mobility
- Inverse + channel prediction and precoding

Enables **high-mobility use-cases** with **high reliability**

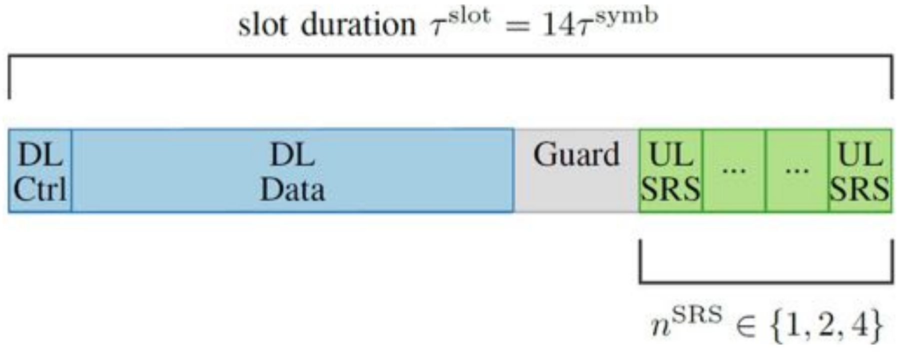




❖ D. Löschenbrand, M. Hofer, and T. Zemen, „Orthogonal precoding with channel prediction for high mobility massive MIMO," in IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), virtual conference, September 2020.

MASSIVE MIMO
PREDICTION AND PRECODING

- NR foresees flexible slot/symbol allocation
- Dedicated mode for massive MIMO
  - 4 UL sounding reference signals (SRS)
  - ➢ Timely channel data for beam forming



- **MARCONI approach**
  1. 2D orthogonal precoding
  2. Channel prediction

➢ **RESULT: 3 orders of magnitude gain in BER**

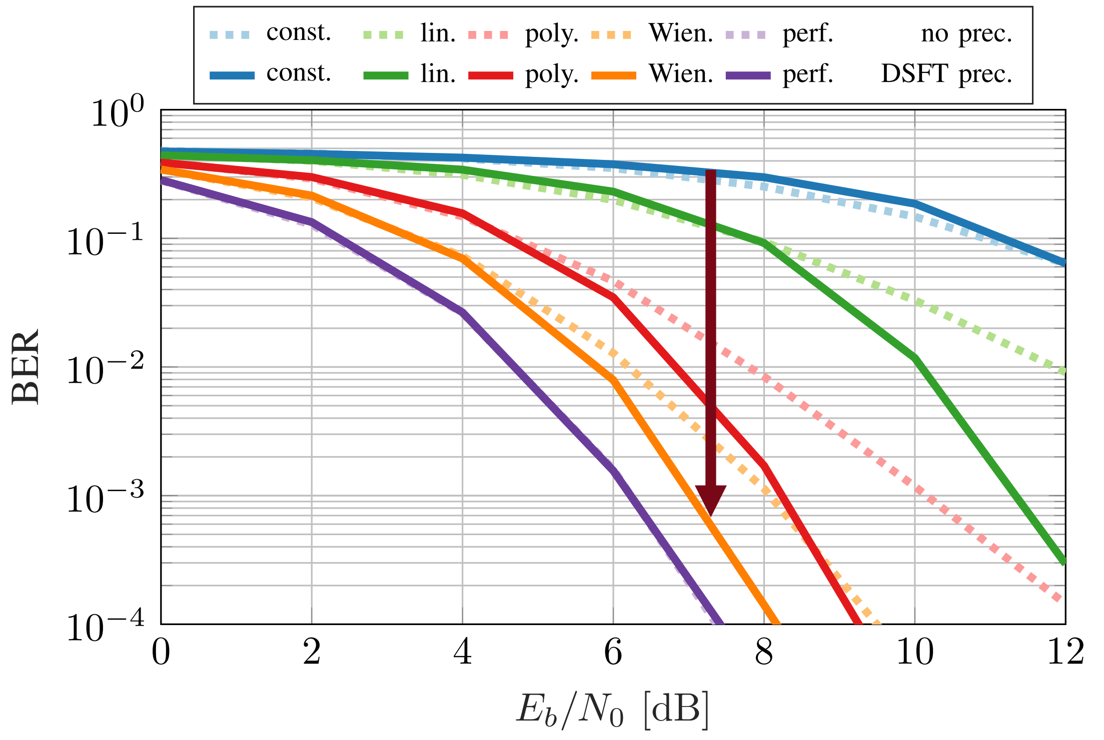
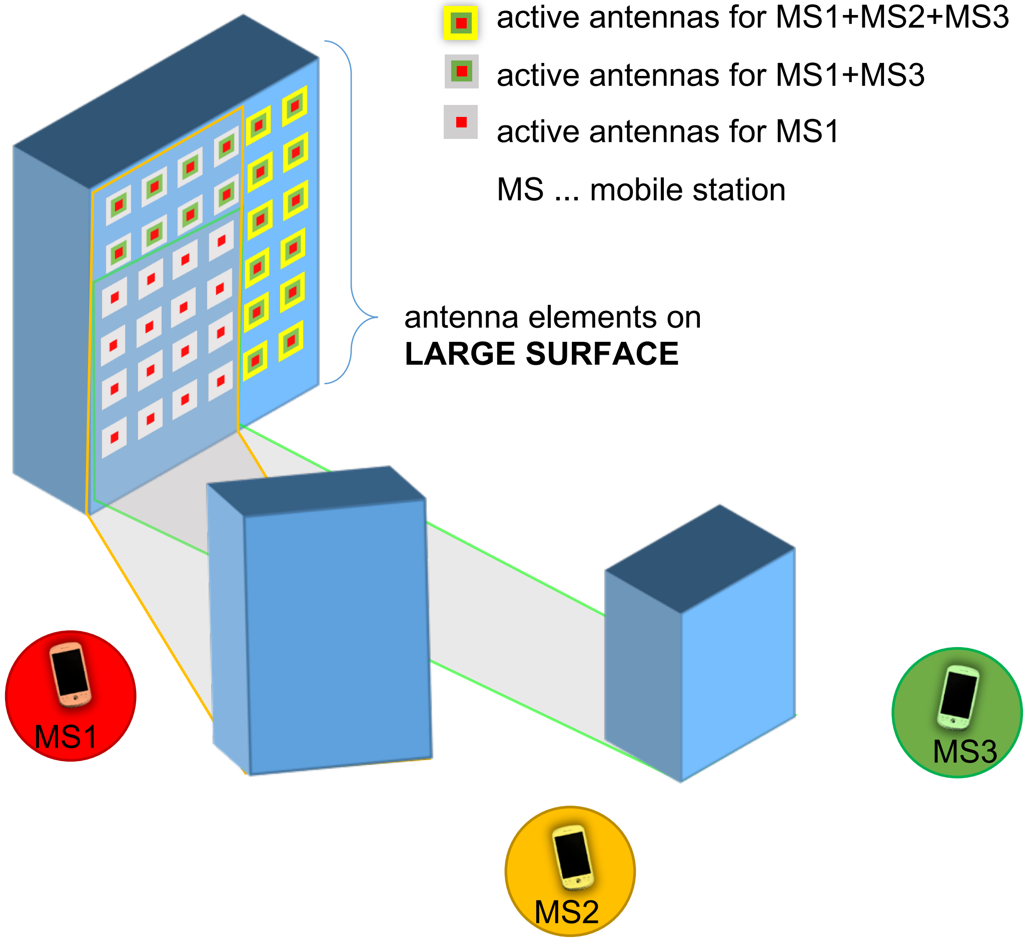


Fig. 5. Simulated BER for a massive MIMO system employing the considered prediction methods without precoding and with DSFT precoding. The prediction horizon is 0.8λ at a velocity of $160\,\text{km/h}$ and a frequency of $3.5\,\text{GHz}$, and the number of BS antennas $A = 64$. A significant performance gain is achieved through OP.

❖ D. Löschenbrand, M. Hofer, and T. Zemen, “Orthogonal precoding with channel prediction for high mobility massive MIMO,” in PIMRC, Sept. 2020.
❖ T. Zemen, D. Loeschenbrand, M. Hofer, C. Pacher, and B. Rainer, “Orthogonally precoded massive MIMO for high mobility scenarios,” IEEE Access, Dec. 2019.

6G WIDE APERTURE MASSIVE MIMO SYSTEM (3 GHZ)



First prototype on AIT building rooftop

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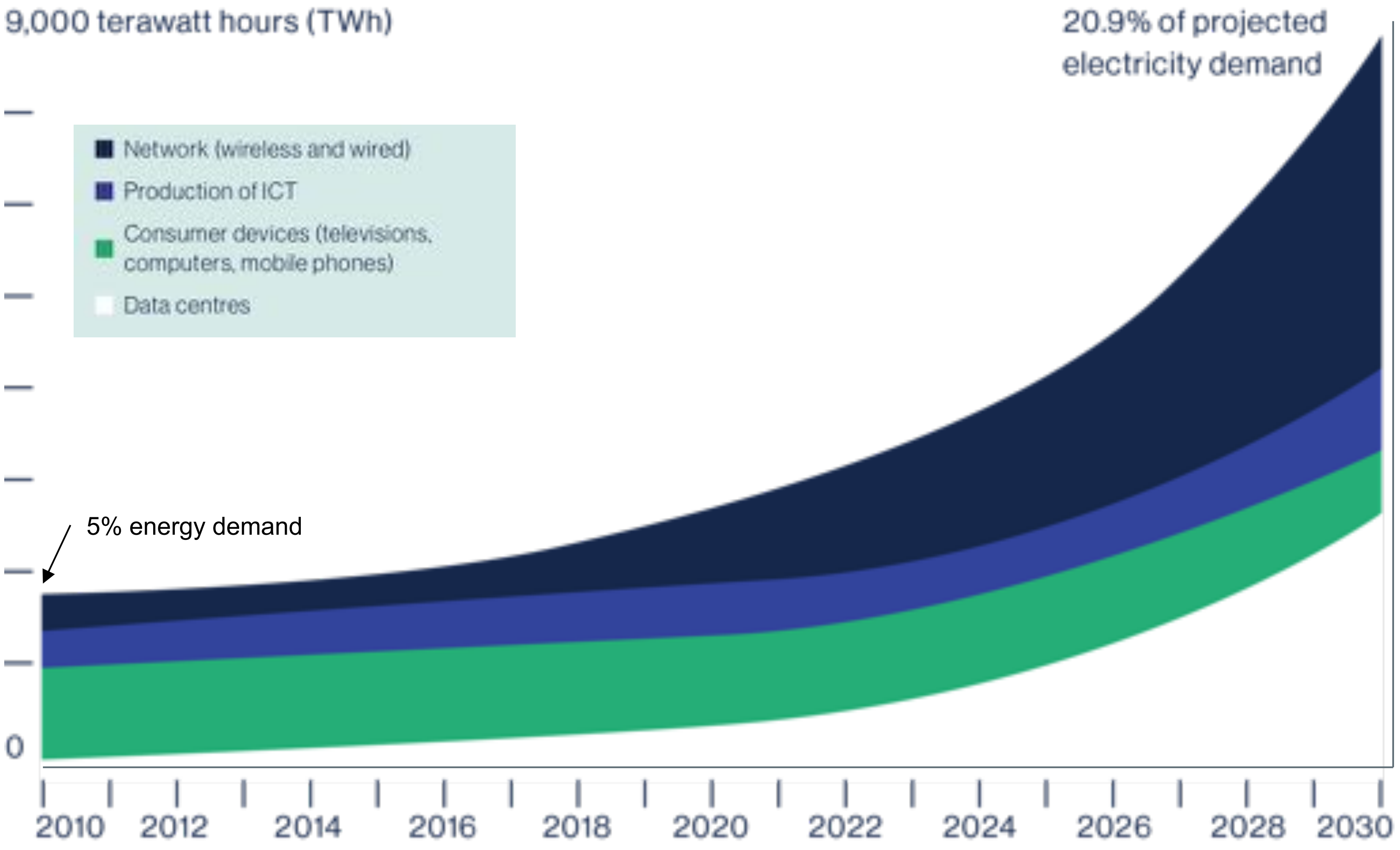
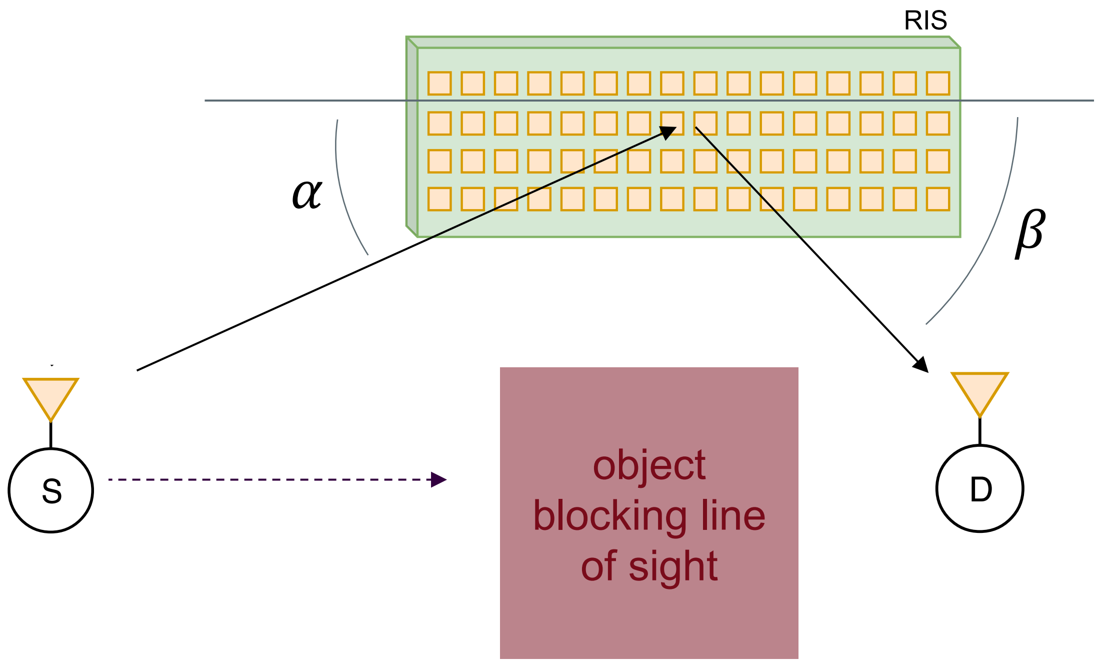
ICT ENERGY CONSUMPTION PREDICTION



❖ N. Jones, „The Information Factories,“ Nature, vol. 561, Sept. 2018.

REFLECTIVE INTELLIGENT SURFACE (30GHZ)



- mmWave signals blocked by objects
- reflective intelligent surface (RIS)
  - semi-passive operation
  - adjust β to establish path from source (S) to destination (D)

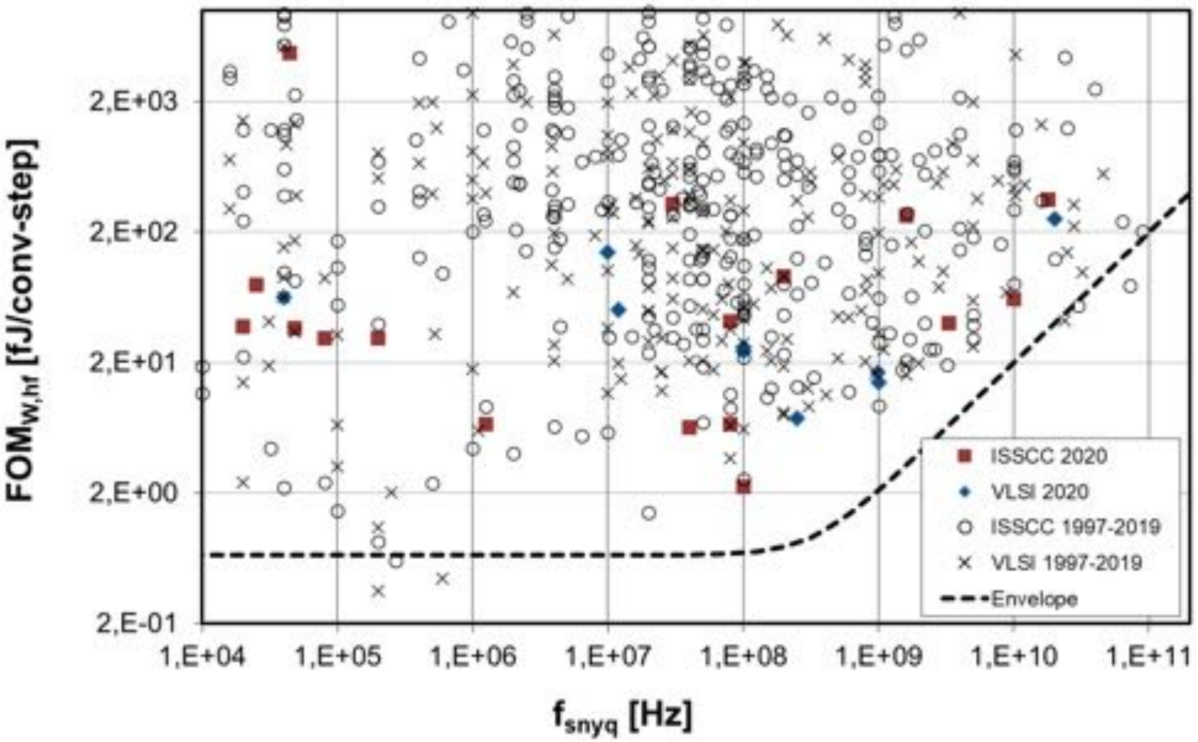
❖ E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, “Wireless communications through reconfigurable intelligent surfaces,” *IEEE Access*, vol. 7, pp. 116753–116773, 2019.

ANALOG TO DIGITAL CONVERSION (ADC)

- Multiple GHz bandwidth planned for 6G
- Anticipated resolution 12bit
- Walden figure of merit

$$FOM_W = \frac{P_{ADC}}{2^{ENOB} f_{snyq}}$$

P_{ADC} ... power consumption of ADC
ENOB ... effective number of bits
f_{snyq} ... sampling rate



10GHz sampling rate @ 12bit → 1 Watt

Strong increase in power consumption for f_{snyq}>500MHz

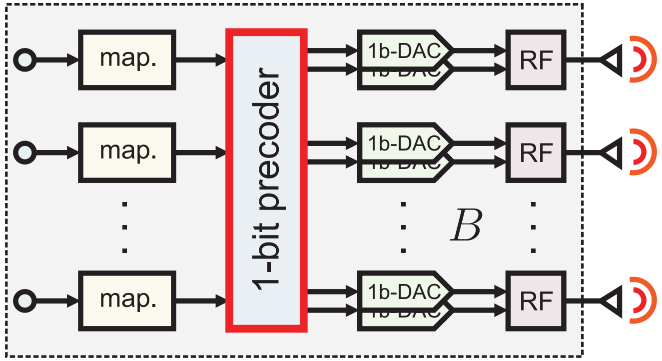
❖ Hexa-X, Deliverable D2.1 Towards Tbps Communications in 6G: Use Cases and Gap Analysis.
❖ B. Murmann, "ADC Performance Survey 1997-2020," [Online]. Available: http://web.stanford.edu/~murmann/adcsurvey.html.

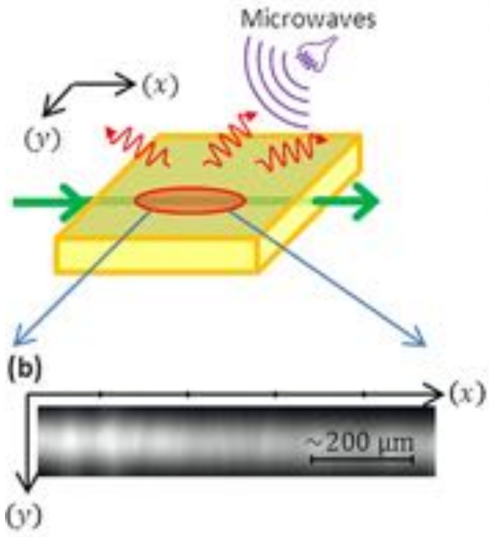
ENERGY EFFICIENT DETECTION

Energy consumption increases with resolution and sampling rate of analog-digital converter

- **1-bit quantization in time**
  - Orthogonal precoding for 1 bit quantization

- **1-bit quantization in frequency using quantum sensing**
  - Demodulating electromagnetic signals into the optical domain directly





❖ O. Castañeda, S. Jacobsson, G. Durisi, M. Coldrey, T. Goldstein, and C. Studer, "1-bit massive MU-MIMO precoding in VLSI," IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 7, no. 4, pp. 508–522, 2017.

❖ M. Chipaux, L. Toraille, C. Larat, L. Morvan, S. Pezzagna, J. Meijer, and T. Debuisschert, "Wide bandwidth instantaneous radio frequency spectrum analyzer based on nitrogen vacancy centers in diamond," Applied Physics Letters, vol. 107, p. 233502, December 2015.

CONCLUSION

6G - Wireless automation and control

- Improved latency and reliability goals over 5G
- New energy efficient technologies - AIT project DEDICATE
  - wide aperture massive MIMO arrays
  - reflective intelligent surfaces
  - quantum radio frequency sensing

Time-critical use cases

- Disruptive effects on established markets & creation of new markets
- Central component for CO_2 efficient transportation systems
  - safety systems for railway branch lines
  - urban air transport

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