6G – Make It or Break It

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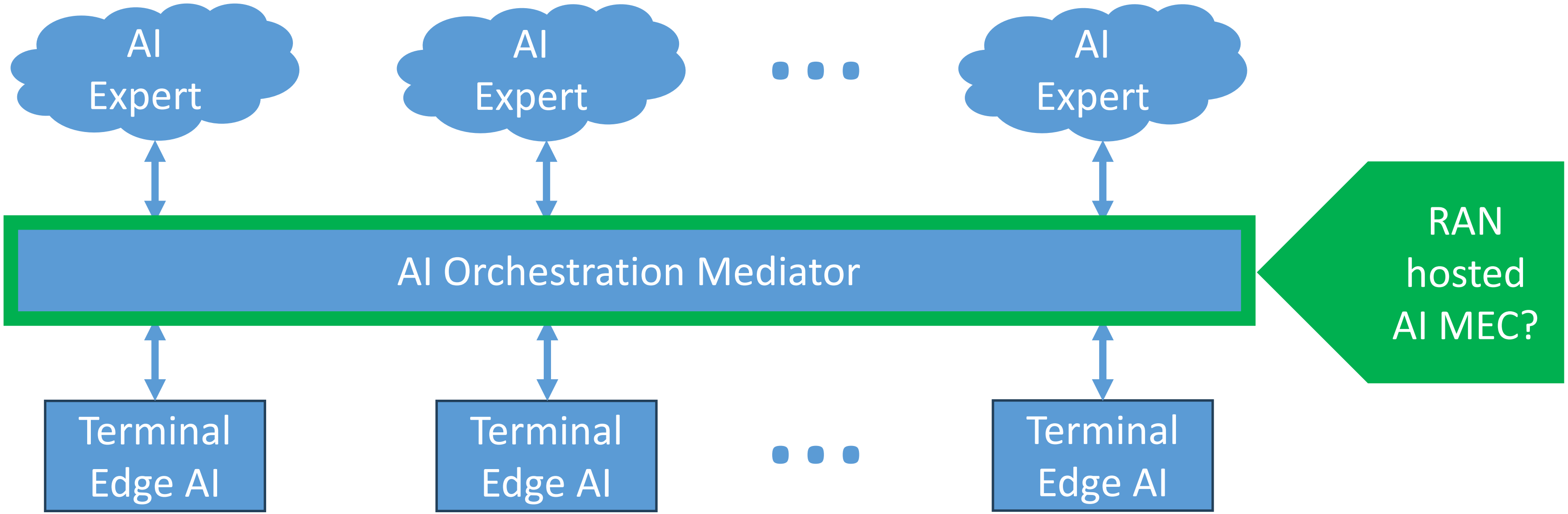
Member of

Fellow of IEEE, VDE/ITG, US NAI, EURASIP, DATE, WWRF

Centers:

New Revenue – AI

Possible AI Inference Architecture



The AI Prompting Data Wave Ahead

Cellular:

2G: SMS → 3G: Files → **4G: Video** → **5G: Motion**

AI prompting:

Text → Files → **Video** → **Interactive Motion**

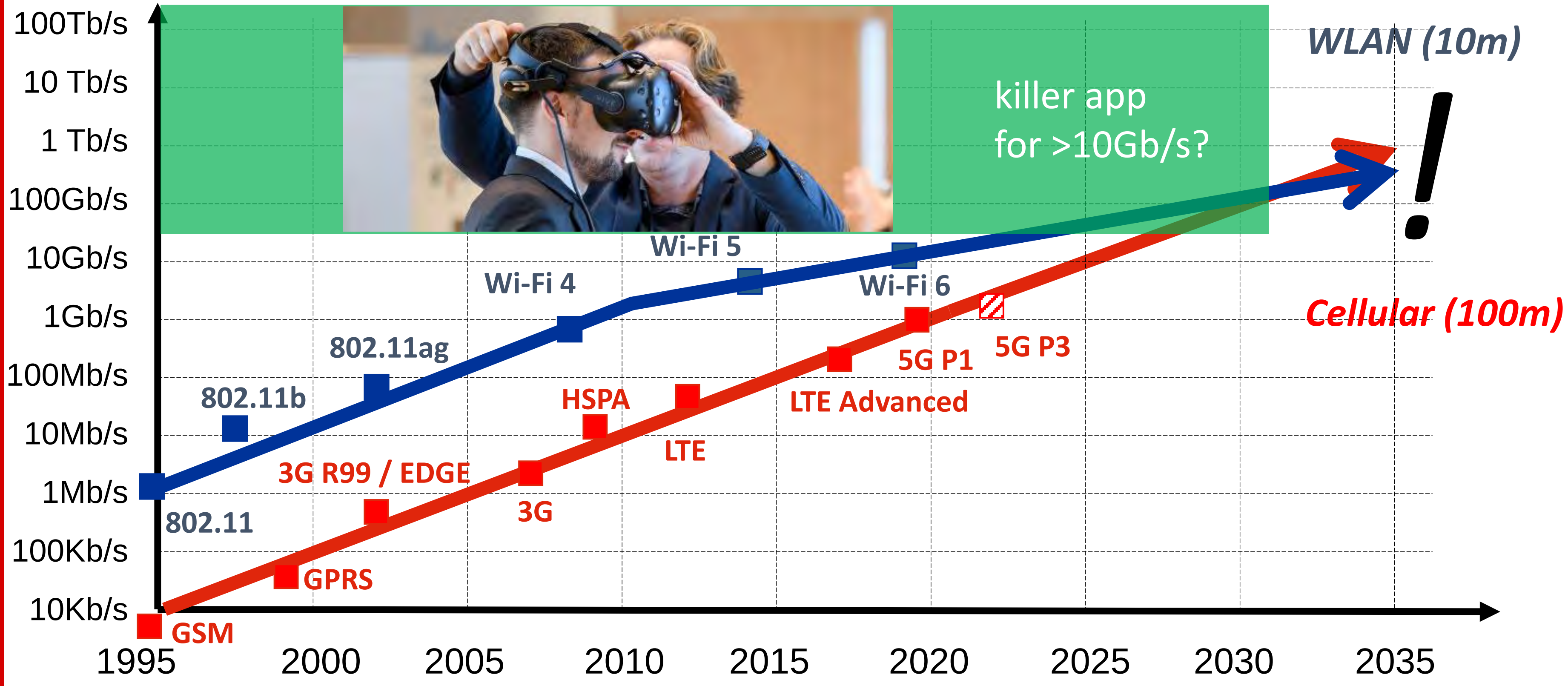
Network Traffic Load Will Explode Soon !!!

AI Orchestration: MNOs’ Revenue Opportunity

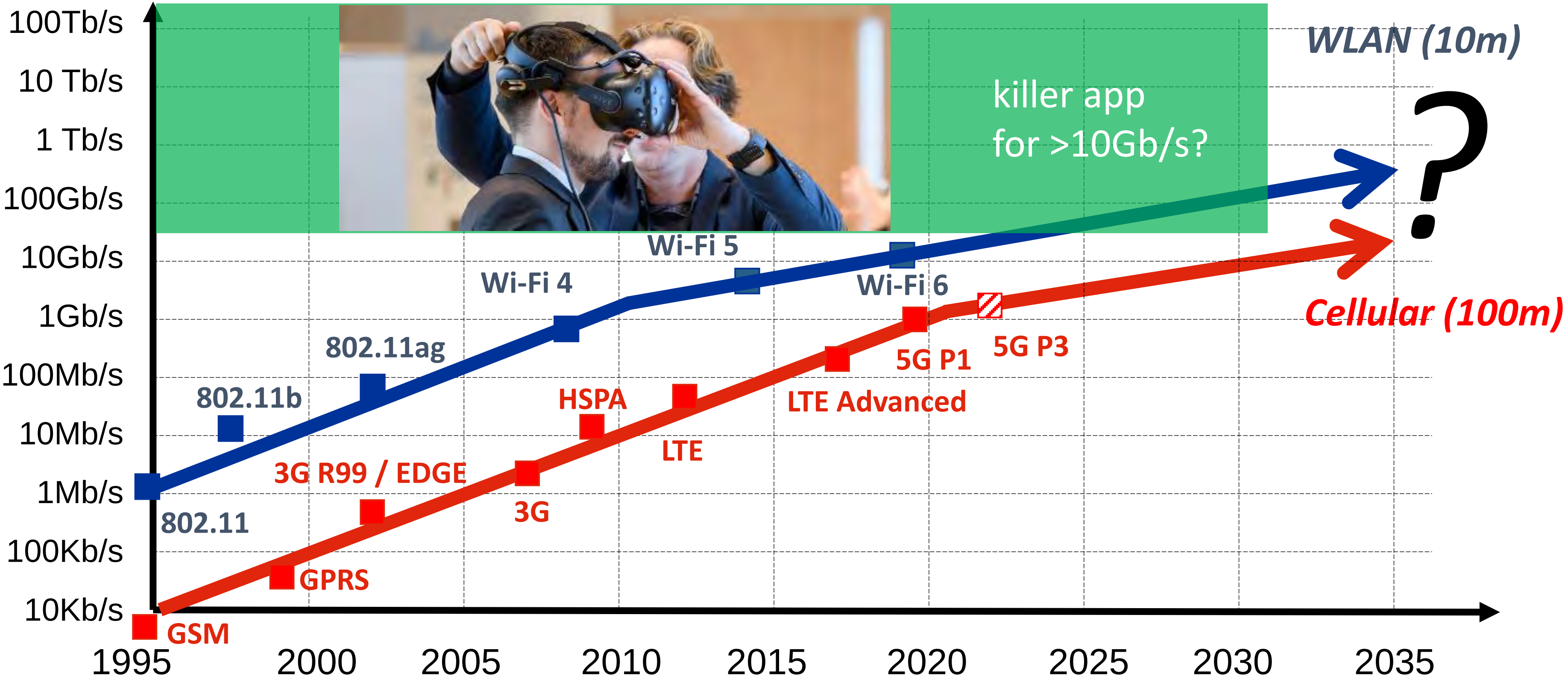
- ➔ **AI compute will be part of 6G RAN anyhow**
- ➔ **AI orchestration is a LARGE monetizable asset for MNOs !!!**

- ➔ **Future interactive AI will drive NETWORK LOAD**

The Wireless Roadmap

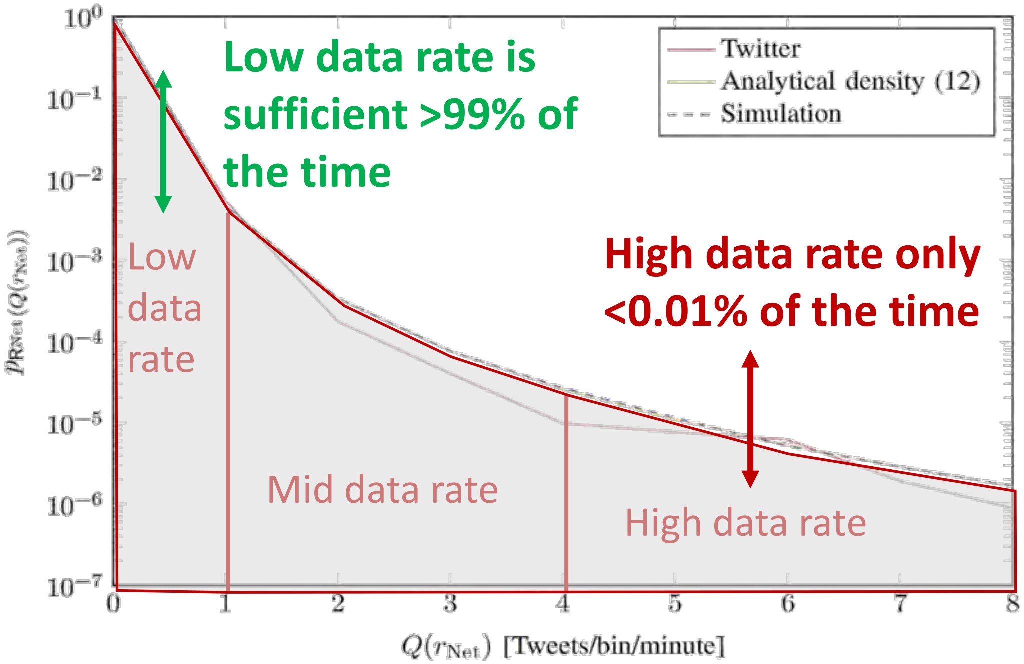


The Wireless Roadmap – Reaching the Energy Wall?

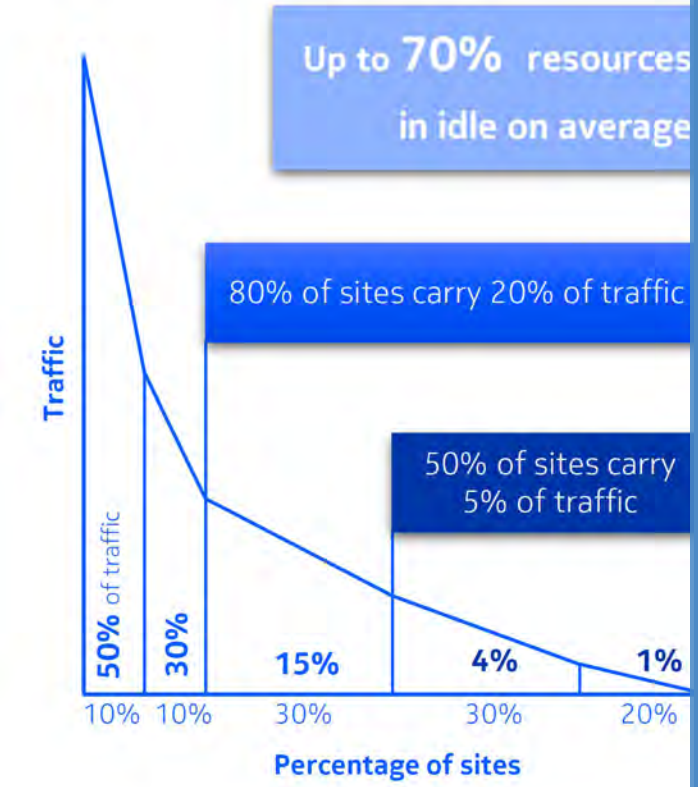


Energy Efficiency

Distribution of Data Rates



Distribution of data rates in a network [0,1]

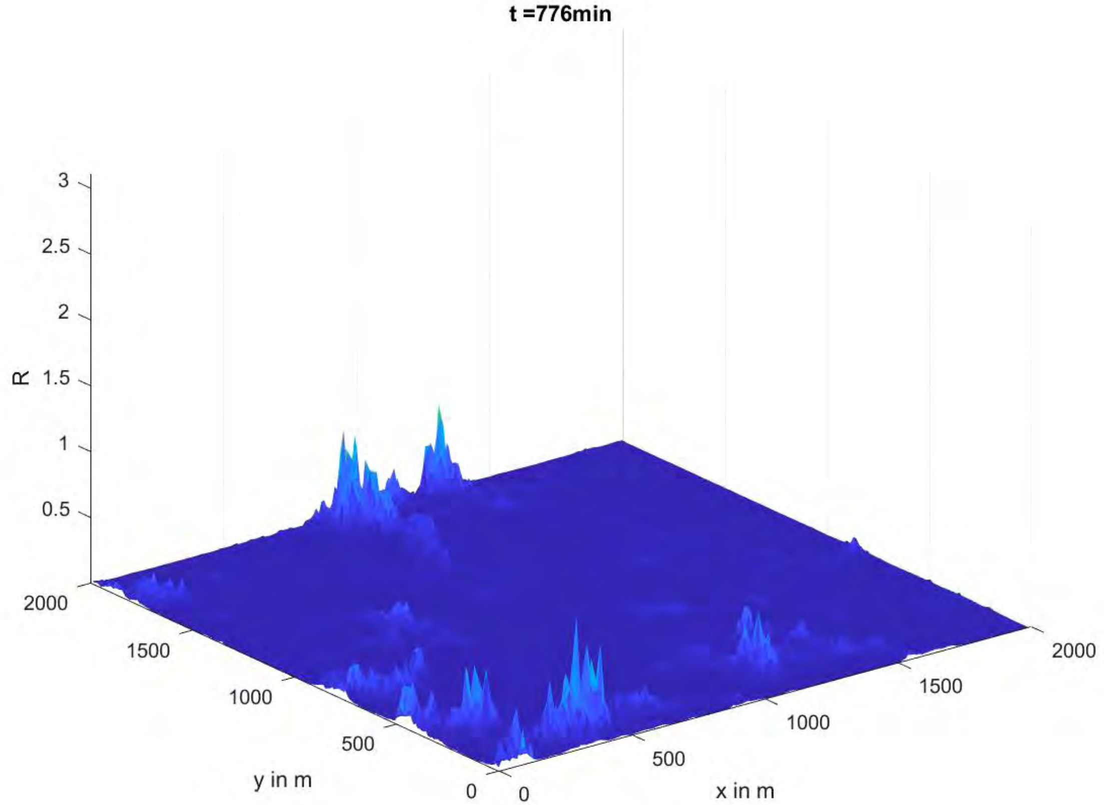


[Nokia Bell Labs – Stefan Wesemann Keynote @ WS

[0] G. P. Fettweis and H. Boche, “6G: The personal tactile internet—and open questions for information theory,” IEEE BITS Inf. Theory Mag., vol. 1, no. 1, pp. 71–82, 2021.
[1] F. Gast, M. Dörpinghaus, G. Fettweis, “A New Spatio-Temporal Model for Data Rate Distributions in a Cellular Network”, WSA 2024

70-80% Energy Consumption in RAN

How often do we need peak rate?



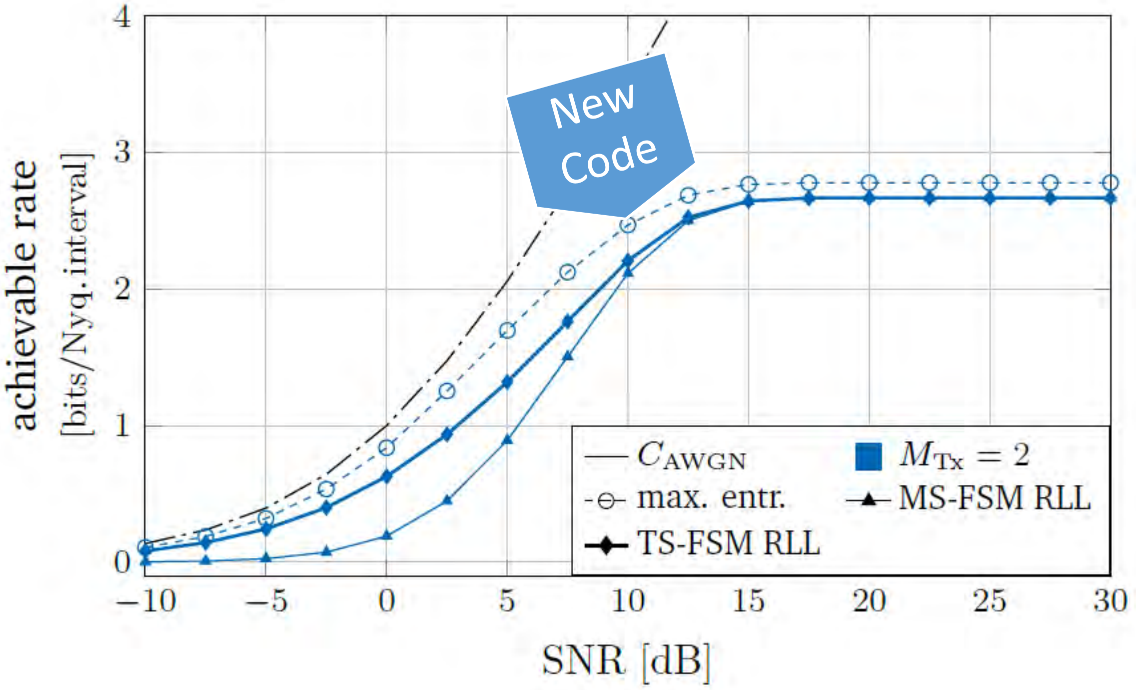
A Possible Gearbox-PHY: Optimizing for Energy

Idea:

Idea:	90% *P/100 ↔ P/100	10% *P/10 ↔ P/100	1% * 10P ↔ < P/10
Available Spectrum	High	Medium	Low
PHY/Gear	Impulse Radio	ZXM Zero-Xing-Modulation	OFDM (MIMO)
Energy Efficiency	Extreme	High	Medium

At least Power/10 over 5G *!!!*

New Run-Length Limited Codes for ZXM: 3dB Improvement of 2-state (TS) versus @ Mtx=2



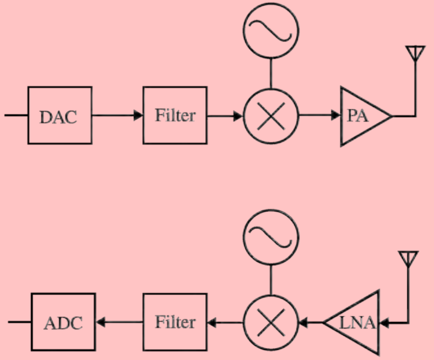
TS-FSM RLL **S. Zeitz, K. Kochs, M. Dörpinghaus and G. Fettweis**, "Improved Runlength-Limited Codes for Systems Employing Zero-Crossing Modulation," invited paper for PIMRC 2025, Sep 2025.

MS-FSM-RLL: **P. Neuhaus, D. M. V. Melo, L. T. N. Landau, R. C. de Lamare and G. Fettweis**, "Zero-Crossing Modulations for a Multi-User MIMO Downlink with 1-Bit Temporal Oversampling ADCs," in Proceedings of European Signal Processing Conference (EUSIPCO 2021), Virtual Conference, Aug 2021

Gearbox-PHY Example Gears

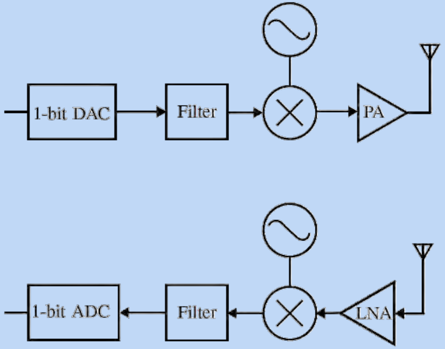
M - Quadrature Amplitude Modulation

- Representative for conventional modulation schemes
- Standard linear transceiver
- Minimal number of ADC/DAC bits, i.e, $\log_2(\sqrt{M})$



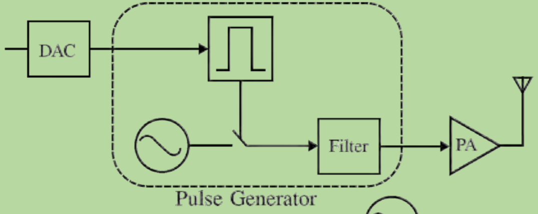
Zero-Crossing Modulation

- Modulation for energy-efficient receiver with 1-bit quantization
- **1-bit ADC and DAC**
- Faster-than-Nyquist signaling factor M_{Tx}

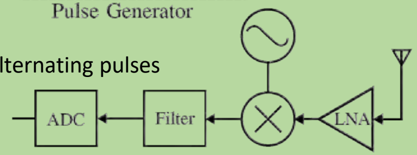


Impulse Radio

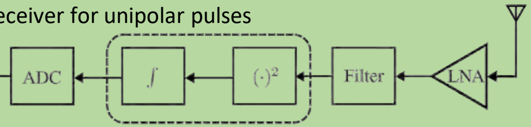
- Spiking Modulation scheme
- 2 thresholds for DAC and ADC



Receiver for alternating pulses



Receiver for unipolar pulses



F. Gast, F. Roth, M. Dörpinghaus, P- Sen, S. Zeitz, G. Fettweis, “Energy Optimization using Joint Modulation Scheme and Front End Adaptation - the Gearbox-PHY”- accepted at ISWCS 2024

Using a Gearbox-PHY to Optimize Energy Efficiency

We allow the Gearbox to control:

1. The active *gear*
2. The system bandwidth B
3. The transmit power P_T
4. The transmission duty cycle $\frac{T}{T_\mathrm{max}}$

Hardware Power consumption P_Tx and $P_{\mathrm{R}x}$

- **Conservative estimates** for front end components from literature or surveys for
- Digital-to-Analog Converter
- Local Oscillator
- Mixer
- Power Amplifier
- Low-Noise Amplifier
- Analog-to-Digital Converter

Mathematical Optimization

$$\min_{B,\gamma,P_\mathrm{T},\mathrm{gear}} \quad \mathcal{E}_\mathrm{bit} = \frac{(\gamma + \epsilon_\mathrm{Tx}(1-\gamma))P_\mathrm{Tx} + (\gamma + \epsilon_\mathrm{Rx}(1-\gamma))P_\mathrm{Rx}}{R_\mathrm{eff}} \tag{1a}$$

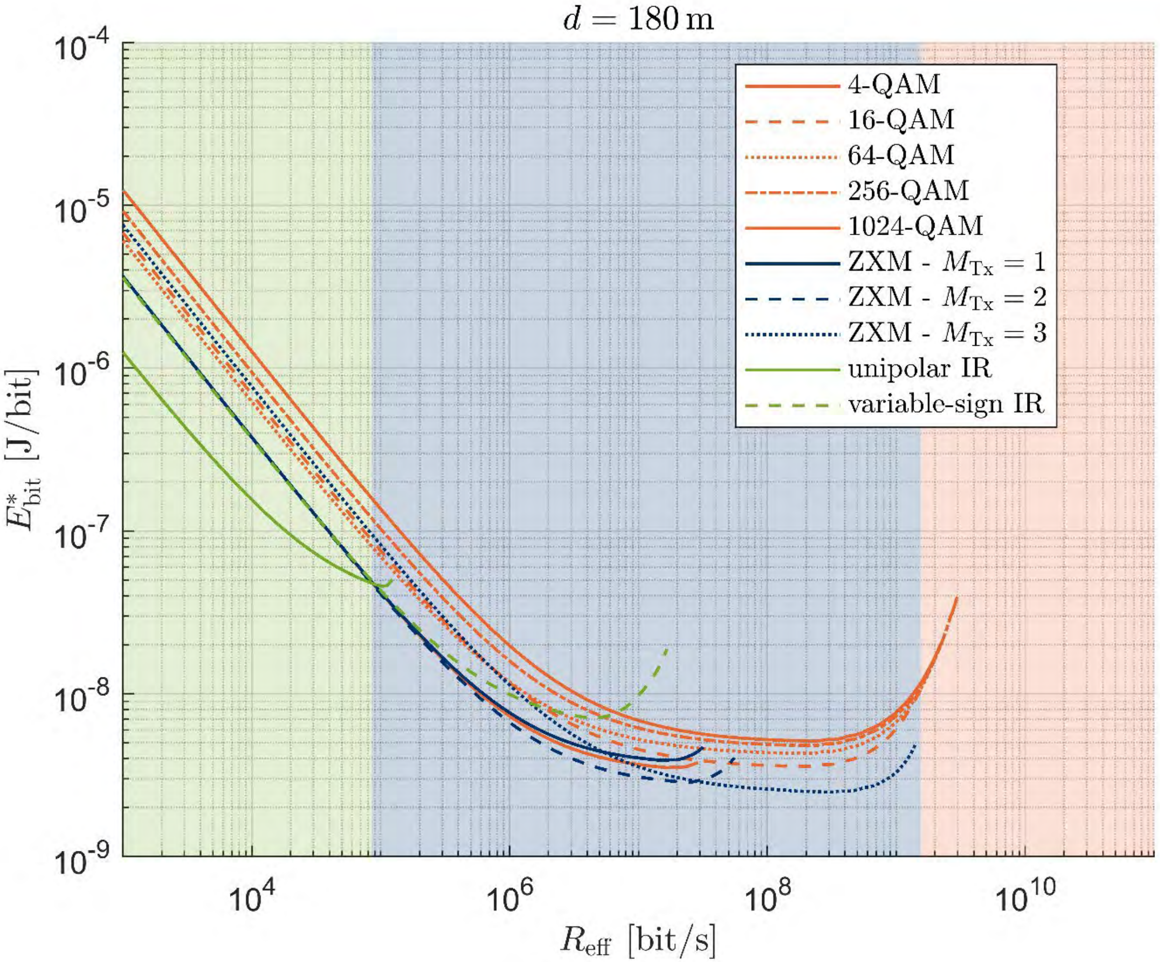
$$\text{s. t.} \quad R_\mathrm{eff} = \gamma\, B\, S \tag{1b}$$

$$0 \le P_\mathrm{T} \le P_\mathrm{max} \tag{1c}$$

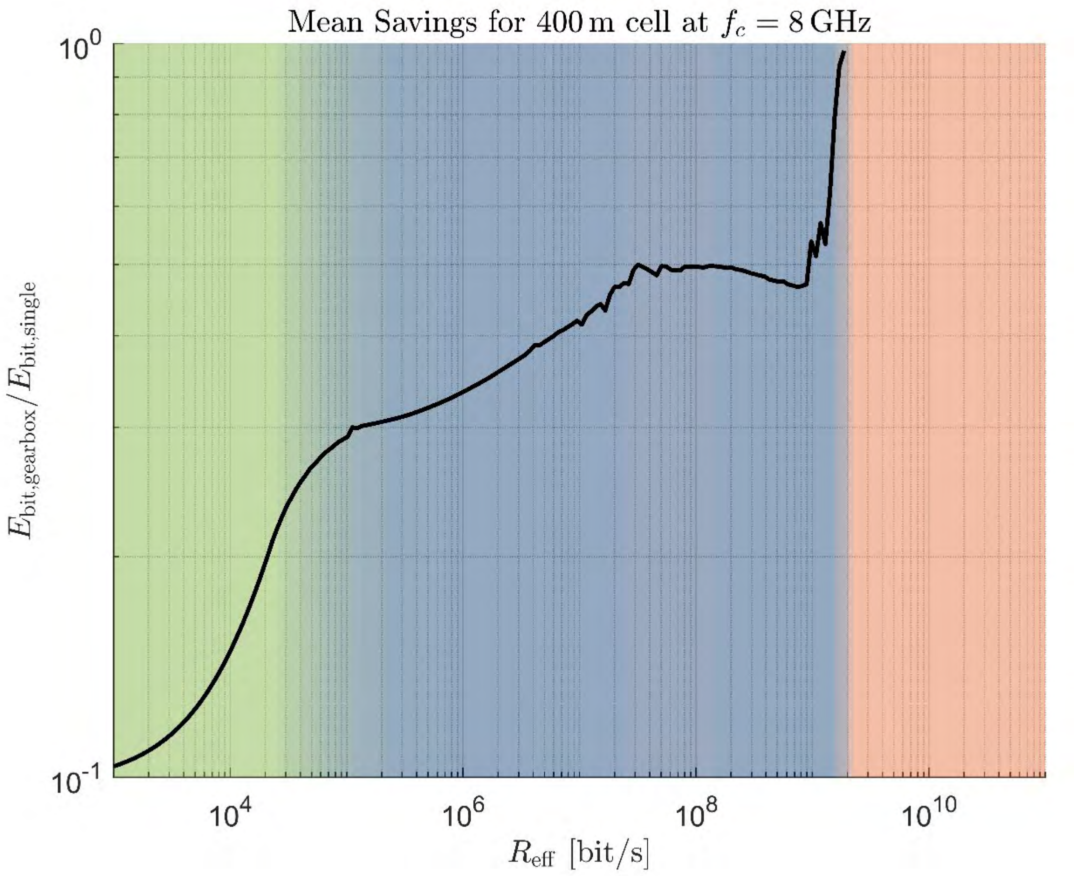
$$0 \le T \le T_\mathrm{max} \tag{1d}$$

$$0 \le B \le \eta f_c, \tag{1e}$$

Gears @ FR3


$d = 180\,\mathrm{m}$
4-QAM
16-QAM
64-QAM
256-QAM
1024-QAM
ZXM - $M_{\mathrm{Tx}} = 1$
ZXM - $M_{\mathrm{Tx}} = 2$
ZXM - $M_{\mathrm{Tx}} = 3$
unipolar IR
variable-sign IR
E^*_{bit} [J/bit]
R_{eff} [bit/s]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{4}
10^{6}
10^{8}
10^{10}

Savings @FR3 @avg



F. Gast, F. Roth, M. Dörpinghaus, P. Sen, S. Zeitz and G. Fettweis, "The Role of Oscillator Phase Noise in Maximizing Transceiver Energy Efficiency," WCNC, Mar 2025

Come to Our GLOBECOM Demo in Taipei: 12’2025

2-Gear demo @ FR3:

- 64-QAM OFDM
- 4-QAM single carrier

Selected further readings on GearboxPHY

2025

F. Gast, F. Roth, M. Dörpinghaus, P. Sen, S. Zeitz and G. Fettweis, "The Role of Oscillator Phase Noise in Maximizing Transceiver Energy Efficiency," in Proceedings of 2025 Wireless Communications and Networking Conference (WCNC 2025), Milan, Italy, Mar 2025.

F. Gast, K. Xu, M. Dörpinghaus and G. Fettweis, "Improving Power Amplifier Efficiency of Zero-Crossing Modulation at Sub-THz Frequencies," in GeMiC 2025

2024

G. Meller, F. Gast, F. Protze, J. Wagner, F. Ellinger and G. Fettweis, "Noise Analysis of a 434-MHz Wakeup Receiver Analog Frontend Core with 93-dBm Input Sensitivity and 65-pJ/Bit Efficiency Based on a Switched Injection-Triggered Oscillator With Surface Acoustic Wave Resonator," in IEEE Transactions on Microwave Theory and Techniques, *pp. 1-16,* Nov 2024. *DOI:10.1109/TMTT.2024.3482456.*

F. Roth, M. Dörpinghaus, S. Zeitz, F. Gast and G. Fettweis, "Why to Use the Phase in Time-Encoding Modulation and Its Effect on the Spectral Efficiency," in Proceedings of IEEE International Symposium On Personal, Indoor And Mobile Radio Communications (PIMRC 2024), Valencia, Spain, Sep 2024. *DOI:10.1109/PIMRC59610.2024.10817435.*

F. Gast, F. Roth, M. Dörpinghaus, P. Sen, S. Zeitz and G. Fettweis, "Energy Optimization using Joint Modulation Scheme and Front End Adaptation - the Gearbox-PHY," in Proceedings of International Symposium on Wireless Communication Systems (ISWCS 2024), Rio de Janeiro, Brazil, Jul 2024.

F. Gast, M. Dörpinghaus, P. Sen and G. Fettweis, "On the Energy-Saving Potential of Adaptive Wireless Transceiver Front Ends," in Proceedings of IEEE Communications Theory Workshop (CTW 2024), Banff, Alberta, Canada, May 2024.

F. Gast, M. Dörpinghaus, P. Sen, A. Nimr and G. Fettweis, "Hardware-Aware Energy Efficiency Optimization in Wireless Communications using a Gearbox-PHY," in IEEE Communications Letters, *pp. 1-1,* Apr 2024.

F. Gast, M. Dörpinghaus, F. Roth and G. Fettweis, "A New Spatio-Temporal Model for Data Rate Distributions in Mobile Networks," in Proceedings of 27th International Workshop on Smart Antennas (WSA 2024), Dresden, Germany, Mar 2024.

2021

G. Fettweis and H. Boche, "6G: The Personal Tactile Internet - And Open Questions for Information Theory," in IEEE BITS the Information Theory Magazin, vol. 1, no. 1, *pp. 71-82,* Aug 2021.

Vodafone Chair

We Must

- ➔ Not demand new spectrum for capacity, but **demand new spectrum to achieve ENERGY EFFICIENCY**

Fair Access for All

Connecting the Unconnected
Exploit GearboxPHY idea to add “extended range gear?

Assume

700MHz carrier

20dBi base station antenna gain

0dBi terminal antenna gain

pathloss exponent of 2.7

3 gears:

Coded Impulse Radio

Coded ZXM / Coded 4-FSK

Coded 4-QAM

Modulation	Receiver Sensitivity (dBm)	Range (km)
CIR	-110	147.9 km
ZXM / 4-FSK	-100	64.6 km
4-QAM	-90	27.0 km

barkhausen institut

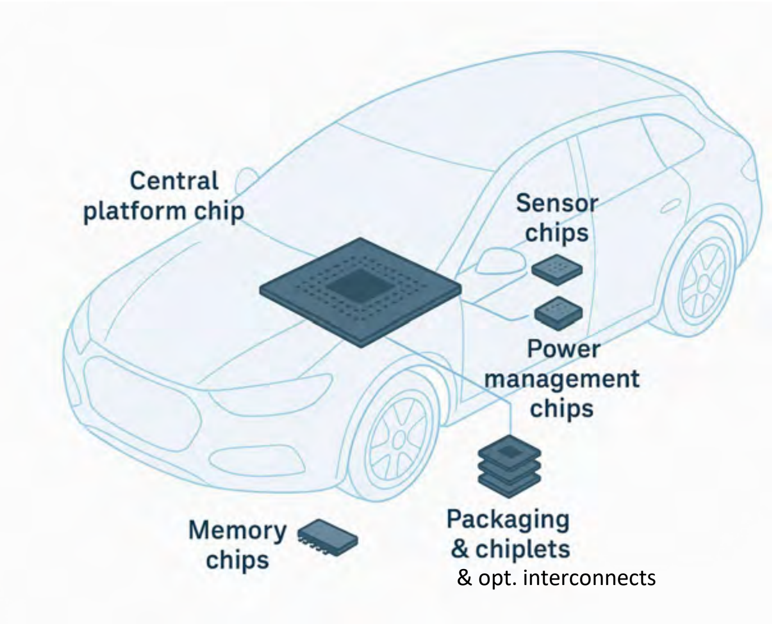
HermesPy - Heterogeneous Radio Mobile Simulator

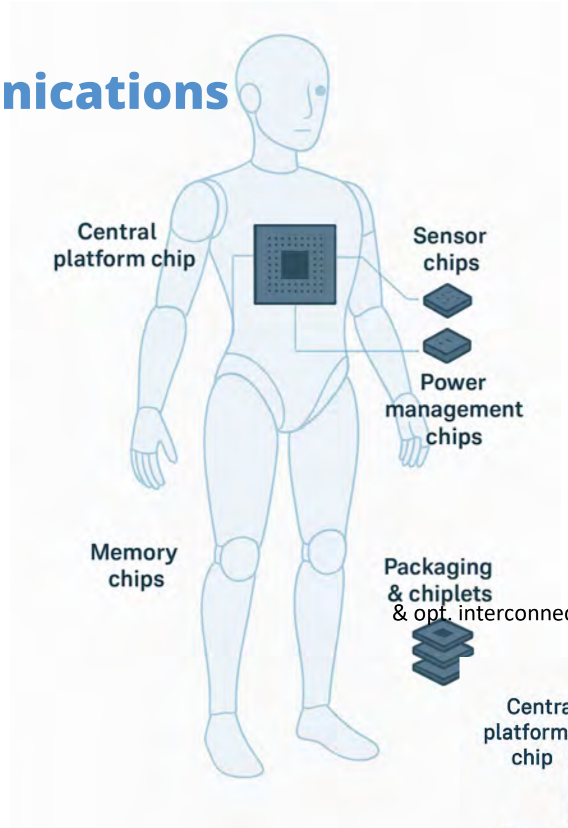
15.09.2025

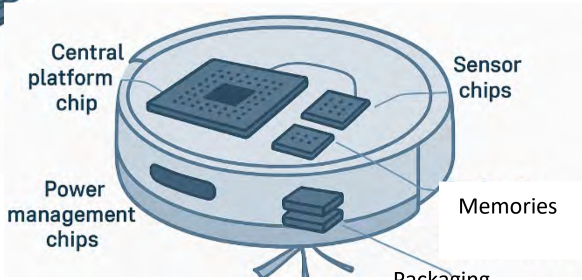
HermesPy – Heterogeneous Radio Mobile Simulator Python

… a unifying API for physical layer radar and communication R&D

Robots are Coming!
Require: Sensing & Communications







HermesPy Highlights

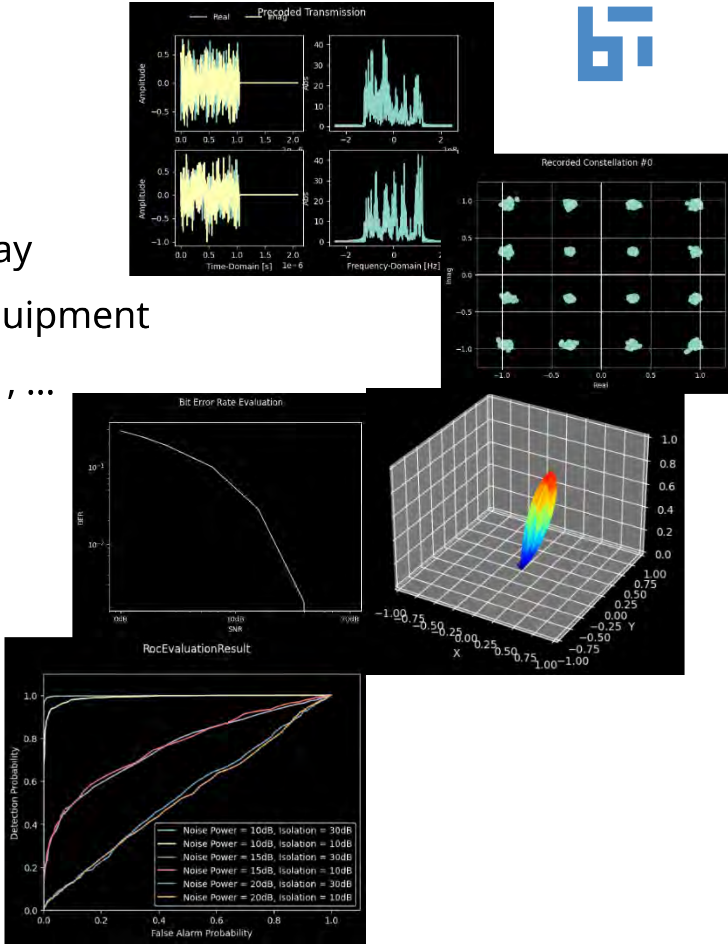
Simulation deployment to high performance clusters via Ray

Hardware in the loop evaluations with USRPs and audio equipment

Channel modeling via SionnaRT, Quadriga, 3GPP TR 38.901, …

Implementations of FMCW, OFDM, OTFS, OCDM, GFDM, …

Customizable RF front-end blocks (coming soon)



HermesPy in Numbers

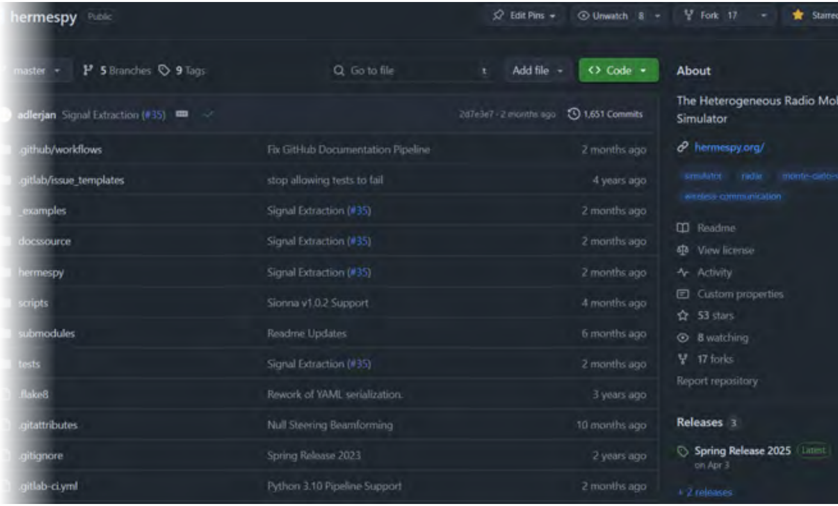
2 major open-source releases per year [1]

55.000 fully tested lines of Python / C++ code

More than 100 pages of documentation [2]

120 example scripts and code snippets

30.000 package downloads since 2022 [3]



[1] https://github.com/Barkhausen-Institut/hermespy
[2] https://hermespy.org/
[3] https://clickpy.clickhouse.com/dashboard/hermespy

A Huge Market Ahead

➔ **Consumer Robotics**

See also:
Zheyuan Yang, J. Casas, Andres Villamil, G. Fettweis, „Joint Resource Allocation and Controller Selection for Communication and Control Co-Design," ICCC 2025 (Shanghai)

6G Cellular Communications Poses a Need to Act

voice
Telephony

data
Internet

motion
Tactile Internet

business	consumer	business	consumer	business	consumer
1G 1980s	2G 1992+	3G 2002+	4G 2012+	5G 2020+	6G 2030+

…





entertainment
gardening
chores
mobility
tools
health
fitness
…

consumer
cordless

consumer
WiFi/laptop

consumer
home robots


New Revenue: ISAC

JC&S / ISAC: Integrated Sensing & Communications

Positioning
- Implicit / Explicit

Radar sensing
- Implicit / Explicit

Channel sensing
- Implicit / Explicit

Jammer/Anomaly Detection

IEEE ISAC Nov 2026 - Portugal

We Must Design for

➔ **airspace surveillance**

Vulnerable users
Hazards
Intrusion
…

➔ **airspace control**

Logistics
…

➔ **ground/air surveillance & control**

Selected further readings on JC&S

2025

A. Schösser, F. Burmeister, J. Bogner, Z. Li, P. Schulz, G. Fettweis and N. Franchi, "Pinpointing Radio Devices: Robust Fingerprint Localization in Industrial Environments," ASILOMAR 2025, Oct 2025.

F. Burmeister, R. Walstab, A. Schösser, M. Matthé, P. Schulz and G. Fettweis, "REM-Based Channel Awareness in Time-Varying Environments for CSI Feedback Reduction," ICC 2025, Jun 2025

2024

Z. Li, A. Nimr, P. Schröter, M. Stark, G. Jornod and G. Fettweis, "Two-way Ranging Evaluation in Realistic V2V Scenarios with SDR-based Experimental Platform," in Proc. of IEEE VTC Fall 2024, Oct.

Z. Li, A. Nimr, P. Schulz and G. Fettweis, "Enhanced Superresolution Path Delay Estimation for Channel Impulse Response Based Localization," in Proceedings of WS05 ICC 2024 3rd Workshop on Synergies of Communication, Localization, and Sensing towards 6G (WS05 ICC 2024 Workshop - SCLS6G 2024), Denver, USA, Jun 2024. *DOI:10.1109/ICCWorkshops59551.2024.10615315.*

Z. Li, A. Nimr, P. Schulz and G. Fettweis, "On Filtering and Complexity Reduction for Subspace-Based SuperresolutionPath Delay Estimation Algorithms," in Proc. 4th IEEE JC&S, 2024, *(p. 6),* Mar 2024.

2023

Z. Li, A. Nimr, P. Schröter, M. Stark and G. Fettweis, "Flexible SDR-based Experimental Platform for Realistic Ranging Evaluation in 5G and Beyond," in Proc. of IEEE VTC Fall 2023, Hong Kong, Oct

Z. Li, A. Nimr, P. Schulz and G. Fettweis, "A Flexible Matrix Structure for Superresolution Delay Estimation," in Proceedings of WS13 ICC 2023, Rome, Italy, Jun 2023.

Z. Li, A. Nimr, P. Schulz and G. Fettweis, "A Comparative Study of Subspace-based Superresolution Path Delay EstimationTechniques," in Proceedings of International ITG 26th Workshop on Smart Antennas and 13th Conference on Systems, Communications, and Coding (WSA&SCC 2023), Braunschweig, Germany, Feb 2023.

2022

F. Burmeister, Z. Li, N. Schwarzenberg, A. Traßl, R. Jacob and G. Fettweis, "Quantifying the Impact of Localization Error on Indoor Channel Prediction Using REMs," iGLOBECOM 2022, Brazil, 2022.

I. Bizon Franco de Almeida, Z. Li, A. Nimr, M. Chafii and G. Fettweis, "Experimental Performance of Blind Position Estimation Using Deep Learning," IEEE GLOBECOM 2022 SAC MLC 2022, Brazil.

Z. Li, A. Nimr, P. Schulz and G. Fettweis, "Superresolution Wireless Multipath Channel Path Delay Estimation for CIR-Based Localization," in Proceedings of IEEE WCNC 2022, Austin, USA, Apr 2022.

R. Bomfin, Z. Li, A. Nimr and G. Fettweis, "Experimental Validation of Superresolution Delay Estimation Algorithm Using a 26 GHz Radar Setup," in Proceedings of 2nd IEEE International Hybrid Symposium on Joint Communications & Sensing (JC&S 2022), Seefeld, Austria, Mar 2022. Get PDF. Show BibTeX.

Z. Li, A. Nimr, P. Schulz and G. Fettweis, "Multi-Band Superresolution Multipath Channel Path Delay Estimation for CIR-Based Localization," in Proceedings of 2nd IEEE International Hybrid Symposium on Joint Communications & Sensing (JC&S 2022), Seefeld, Austria, Mar 2022. *DOI:10.1109/JCS54387.2022.9743505*. Get PDF. Show BibTeX.

2021

Z. Li, R. Bomfin, I. Bizon Franco de Almeida, A. Nimr, N. Franchi and G. Fettweis, "Position-Driven Wireless Multipath Channel Simulator for Square-Shaped Environments," in Proceedings of 1st IEEE International Online Symposium on Joint Communications & Sensing (JC&S 2021), Virtual Conference, *(pp. 1-6),* Feb 2021. *DOI:10.1109/JCS52304.2021.9376345*. Get PDF. Show BibTeX.

2020

A. Nimr, Z. Li, M. Chafii and G. Fettweis, Chapter: "Generalized Frequency Division Multiplexing: Unified Multicarrier Framework," in Radio Access Network Slicing and Virtualization for 5G Vertical Industries, pp. 63--82, John Wiley & Sons, 2020. ISBN: 9781119652380.

M. Danneberg, R. Bomfin, A. Nimr, Z. Li and G. Fettweis, "USRP-Based Platform for 26/28 GHz mmWave Experimentation," in Proceedings of 2020 IEEE WCNC 2020, Seoul, South Korea, *(pp. 1-6),*

2019

Z. Li, A. Nimr and G. Fettweis, "Implementation and Performance Measurement of Flexible Radix-2 GFDM Modem," in Proceedings of IEEE 5G World Forum, Germany, *(pp. 130-134),* Sep 2019.

M. Danneberg, Z. Li, P. Kühne, A. Nimr, S. Ehsanfar, M. Chafii and G. Fettweis, "Real-Time Waveform Prototyping," in Proceedings of IEEE SPAWC 2019), Cannes, France, *(pp. 1-5),* Jul 2019

Operators Revenue Opportunity

➔ **Sensing data is a monetizable asset for MNOs !!!**

➔ **Sensing data acquisition a valuable service for governments !!!**

Pragmatic ISAC

FR2 could become a game changing revenue generator for MNOs

What We Need to Know from Radar

Managed radar would create huge SINR gains

→ But Radar is **not standardized**

→ For radar identification:
Manufacturers have proprietary “pilot signals”

Radar community proposed embedding communications in Radar for a coordinating MAC in 1994 already *)

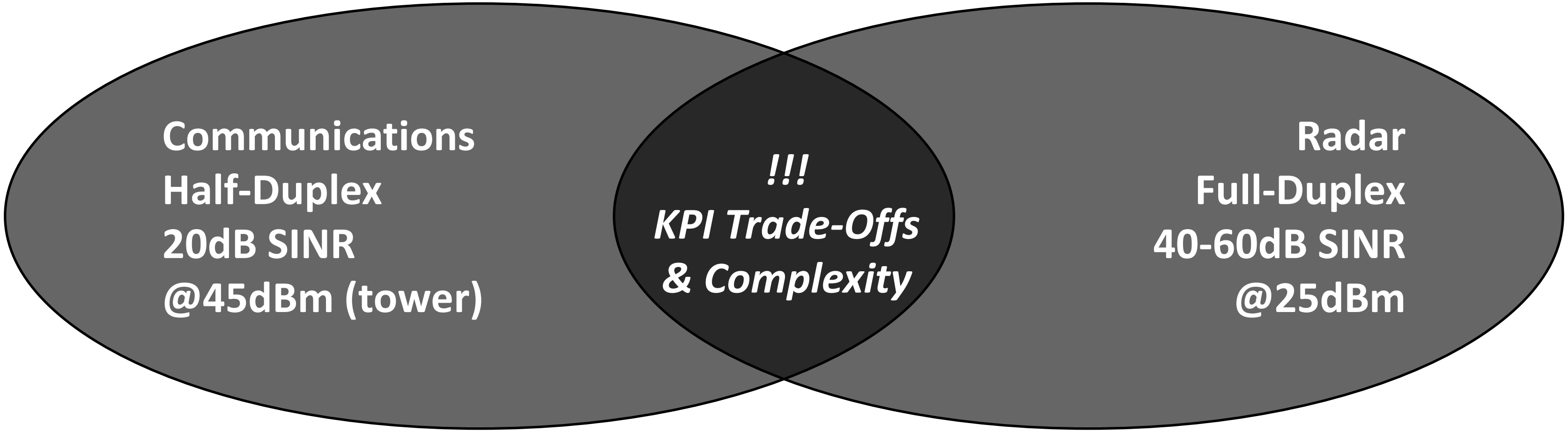
- **No results so far due to lack of standardization body**

*) M. Uchida, Y. Kagawa, and A. Okuno, “A vehicle-to-vehicle communication and ranging system based on spread spectrum techniques-SS communication radar,” in Vehicle Navigation and Information Systems Conference. Proceedings, Aug. 1994, pp. 169 –174

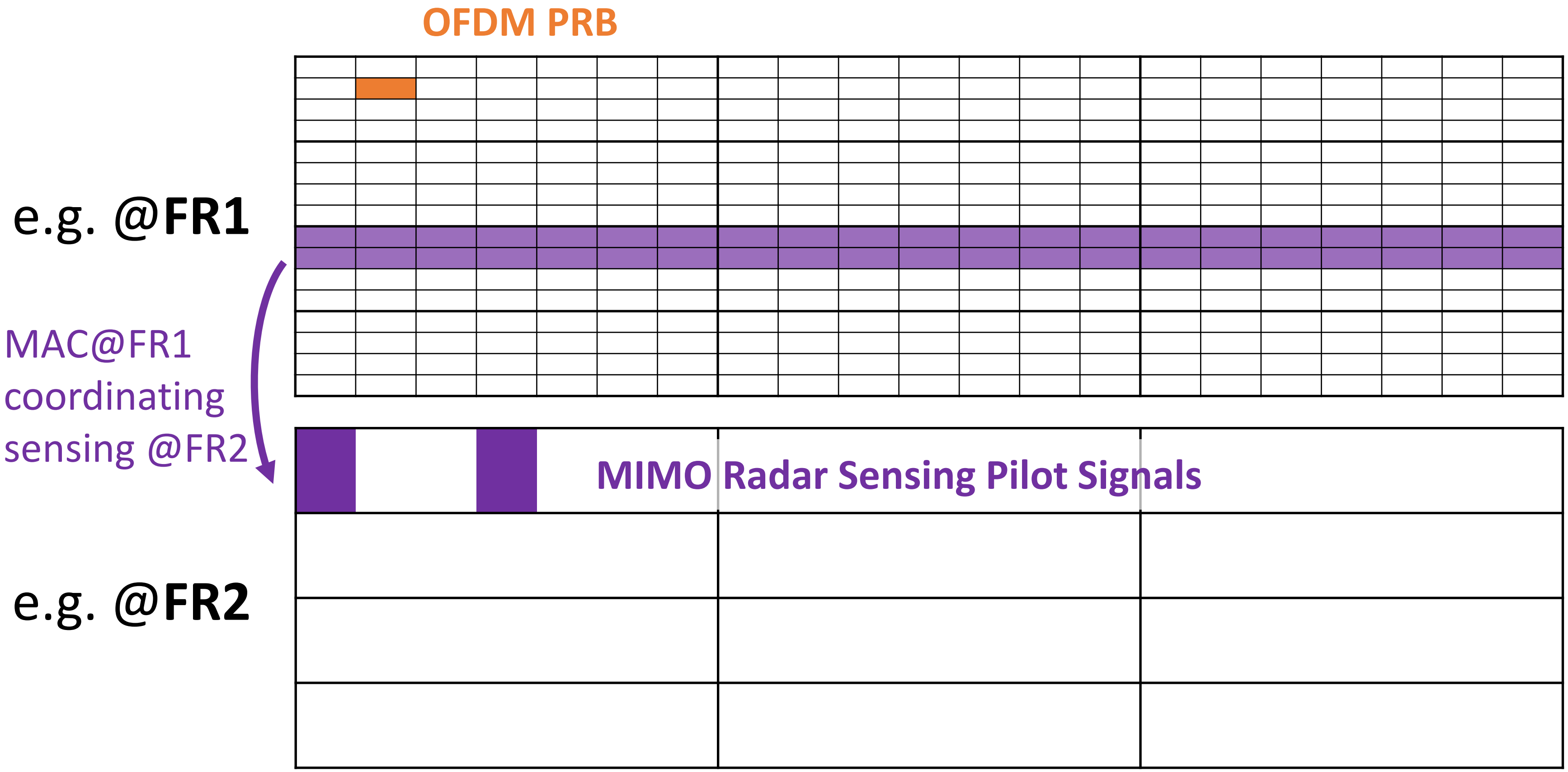
In-Band ISAC

Monostatic Radar Requirements

- ~40dB SINR for static objects
- ~60dB SINR for moving objects (velocity detection)



ISAC Within GearboxPHY Grid Resource Plane



Look At the Retail Cost of Radar

24GHz InnoSenT Module

77GHz InnoSenT Module

Comparing Radar Bands with FR2

Frequency Band	Range Class	Bandwidth (MHz)	Regulatory Notes
24 GHz ISM	Short-range radar (SRR)	~100 – 200 MHz	24.05–24.25 GHz; small bandwidth due to ISM interference w. others. Being phased out (EU)
	Mid-range radar (MRR)	~150 – 200 MHz	Sometimes used; overlap with SRR allocation.
	Long-range radar (LRR)	Not typical	Insufficient bandwidth and regulatory clearance for high-resolution long-range.
77 GHz	Short-range radar (SRR)	~1–2 GHz	Usually 78–81 GHz allocations for SRR, offering wide bandwidth, fine resolution.
	Mid-range radar (MRR)	~500 MHz – 1 GHz	Typically within 76–77 GHz or 77–78 GHz
	Long-range radar (LRR)	~200 – 500 MHz	76–77 GHz for highway/autonomous LRR. Resolution lower than SRR but higher range
FR2	Europe	800MHz /MNO	24.25–27.5 GHz for cellular
	North America	0.8–1GHz /MNO	24.25-27.5 GHz and 27.5-28.35GHz for cellular
	China	1GHz /MNO	24.75-27.5 GHz and 37-42.5 GHz for cellular
	India	800MHz /MNO	24.24-26.5 GHz

FR2: Operators Revenue Opportunity

- ➔ **Radar sensing data @ FR2 can be accumulated to REMs**
- ➔ **Data is a HUGE monetizable asset for MNOs !!!**

Conclusions

6G Opportunities

Top-Line:	Consumer Robotics “Pragmatic ISAC” collected data is monetizable asset for MNOs Connecting the Unconnected with GearboxPHY large cells AI @ RAN edge
Bottom-Line:	Energy Efficiency with GearboxPHY GearboxPHY & large cells
And:	Rethink spectrum need: **for good causes:** Connecting the unconnected & energy efficiency