23. VDE/ITG Fachtagung Mobilkommunikation

Hochschule Osnabrück

NEW DIRECTIONS IN WIRELESS COMMUNICATION RESEARCH AND WHAT THEY WILL ENABLE

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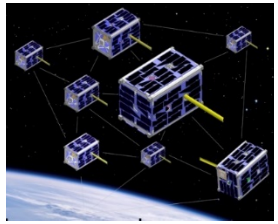
Future Wireless Networks

Dept. of Communications Engineering

- Ubiquitous communication among people and devices to serve huge amount of very divers future applications



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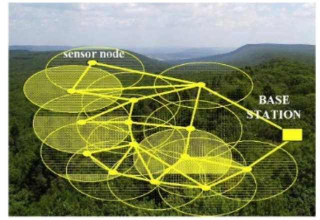
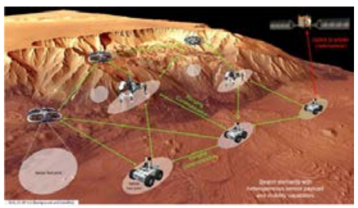


source: Universita Padova

source: EBIZBY Design



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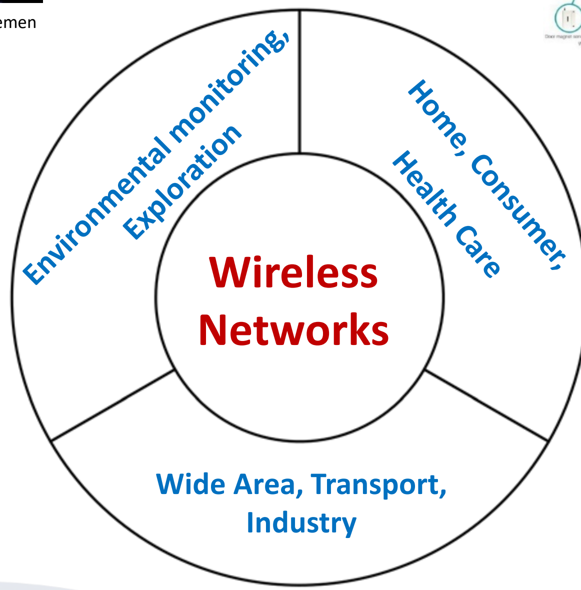

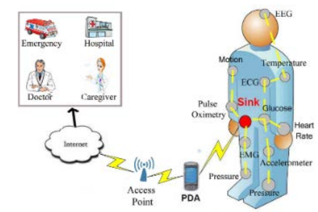

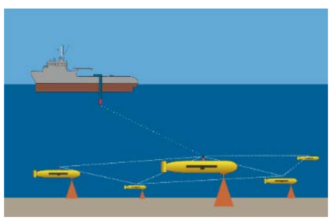

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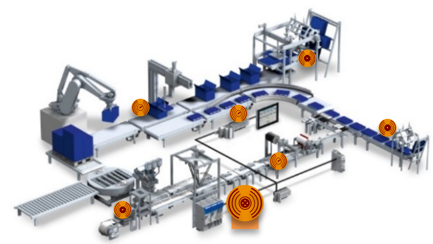

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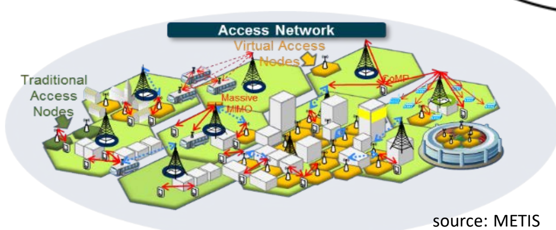

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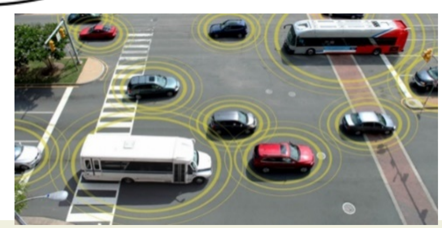
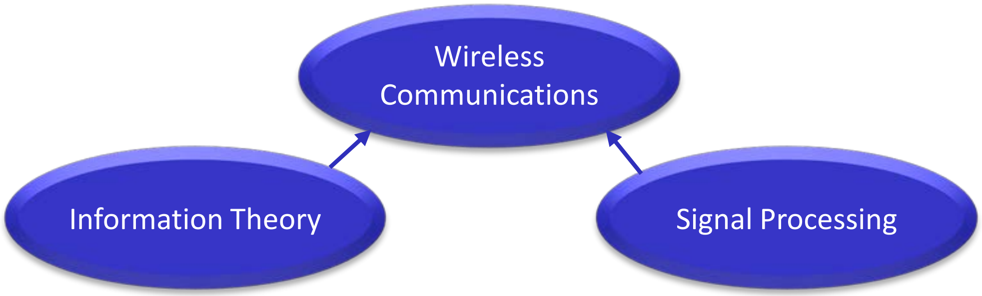


source: UBI telematics

Future Wireless Networks

- Key challenges:
  - Massive amount of connections
  - Massive amount of data
  - Huge variety of data rates and latencies
  - Huge variety of reliable requirements
  - …

- Key enabling/driving technologies
  - Wireless communication technologies (e.g. massive MIMO, mmWave, cooperative communications, relaying)
  - Signal and data processing approaches (e.g. compressive sensing, in-network processing, relevant information processing, graph-based processing, machine learning)
  - Information theoretical approaches (e.g. Information Bottleneck Framework)



COMPRESSIVE SENSING

- Signal Structure Processing-

C. Bockelmann, F. Monsees, H. Schepker. E. Beck, T. Schnier, A. Dekorsy

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The Compressive Sensing Problem in a Nutshell

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- Donoho/Candes 2006: Signal $\mathbf{z} \in \mathbb{R}^{1\times N}$ is compressible in some basis $\mathbf{\Phi} \in \mathbb{R}^{N\times N}$

$$\mathbf{z} = \mathbf{\Phi}\mathbf{x} \quad \text{with} \quad \mathbf{x} \in \mathbb{R}^{1\times N}$$

- Compressible:

$\mathbf{x}$ is k-sparse

$$\begin{pmatrix} 0 \\ 0 \\ 1.4 \\ 0 \\ 0 \\ 0 \\ 0 \\ 2 \end{pmatrix}$$

only a few non-zeros
2-sparse vector

→

Positions and values of non-zeros
represent signal!

- Observe $\mathbf{z}$ by measurement matrix $\mathbf{\Psi} \in \mathbb{R}^{M\times N}$ with $M < N$ noisy observations

$$\begin{aligned} \mathbf{y} &= \mathbf{\Psi}\mathbf{z} + \mathbf{n} \\ &= \mathbf{\Psi}\mathbf{\Phi}\mathbf{x} + \mathbf{n} = \mathbf{A}\mathbf{x} + \mathbf{n} \end{aligned}$$

(underdetermined linear system)

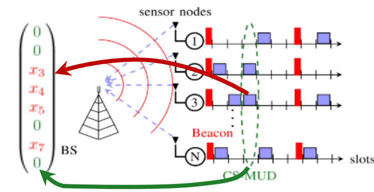
with noise $\mathbf{n} \in \mathbb{R}^{M}$ and $\mathbf{A} = \mathbf{\Phi}\mathbf{\Psi} \in \mathbb{R}^{M\times N}$

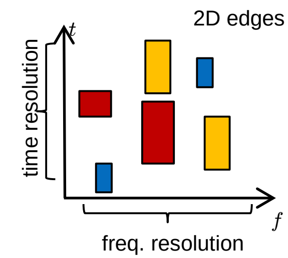
- Task: Recover $\mathbf{x} \in \mathbb{R}^{N}$ using $M < N$ measurements in vector $\mathbf{y}$ by exploiting the signal structure that $\mathbf{x}$ is sparse → $l1/l2$-optimization problems

$$\hat{\mathbf{x}} = \underset{\mathbf{x}\in\mathbb{R}^N}{\operatorname{argmin}} \|\mathbf{x}\|_1 \ \text{ s.t. } \ \|\mathbf{y} - \mathbf{A}\mathbf{x}\|_2^2 < \epsilon$$

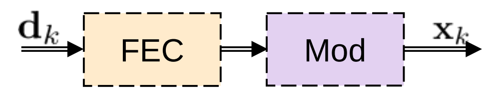
CS in Communications

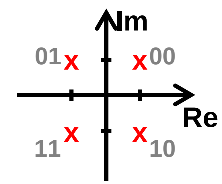
- Applications
  - Channel Estimation
    - Most impulse responses of wireless channels are sparse in sample clock
  - Sporadic Communication
    - Machine type traffic leads to sparse detection problems
  - Spectrum Sensing
    - Cognitive radio idea: Spectrum or edges of spectrum are sparse





- Key differences to standard CS problems
  - Forward Error Correction: non-zero elements in $\mathbf{x}$ are part of a codeword
    - Additional structure that can be exploited, e.g. by iterative decoding
  - Modulation: non-zero elements in $\mathbf{x}$ are not continuous
    - Discrete symbol alphabets → requires adapted CS-algorithms → Digital CS

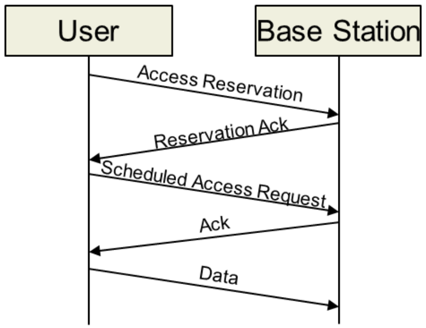




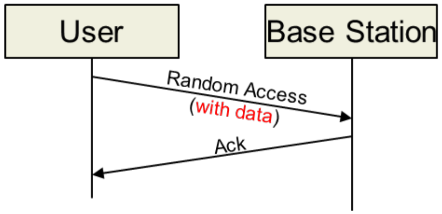
„Digital CS“

Compressive Sensing Multi-User Detection (CS-MUD)

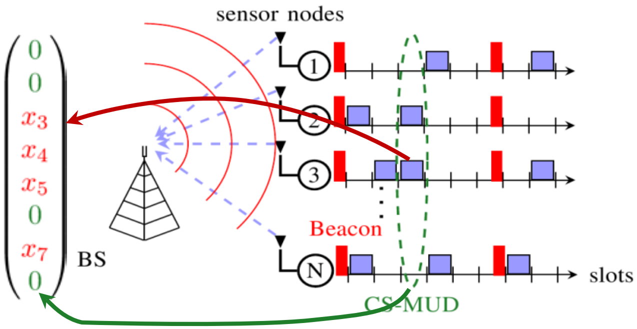
- IoT/5G challenge: Massive Machine type Communication (MMC)
  - MMC is usually of low power, low rate and intermittent activity
  - New PHY/MAC are needed to handle massive access with very low control signaling overhead



Access Reservation



Direct Random Access

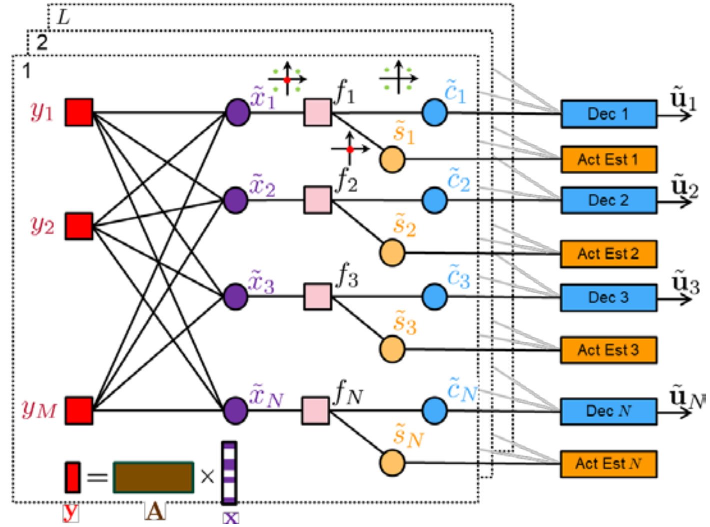


sporadic activity → sparse multi-user signal

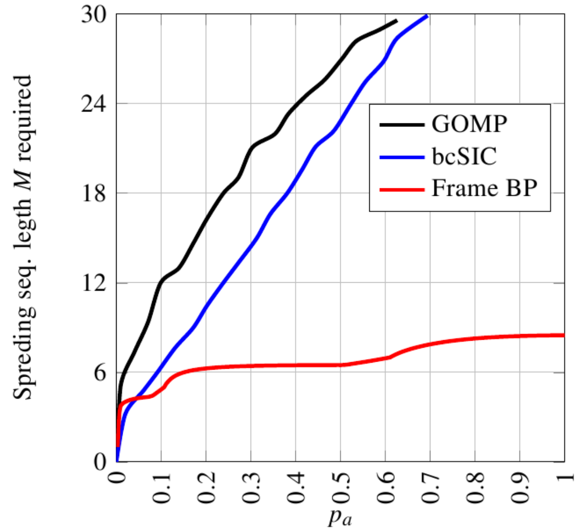
- Task: Design sparsity exploiting multi-user receivers (linear and non-linear) for activity, data and channel estimation

CS-MUD: Graph-based detection

- Research task: Message Passing for CS-MUD
  - Graph-based CS-MUD detector
  - Exchange of soft information (PDFs)
  - Spreading based transmission
- Key challenge:
  - Joint soft activity and data detection



- Key results:
  - Plot: spreading sequence length M required for a FER$<10^{-3}$
  - $M < N \rightarrow$ overloaded system
  - Frame Belief Propagation (Frame BP): slight increase in M for high p_a
  - Frame BP outperforms state-of-the art algorithms such as GOMP and bcSIC

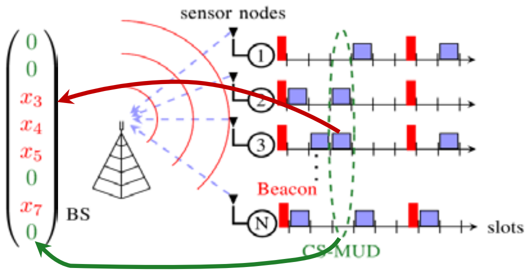


N=30 Nodes, Frame Length L=30 code-symbols

Repetition code R=5

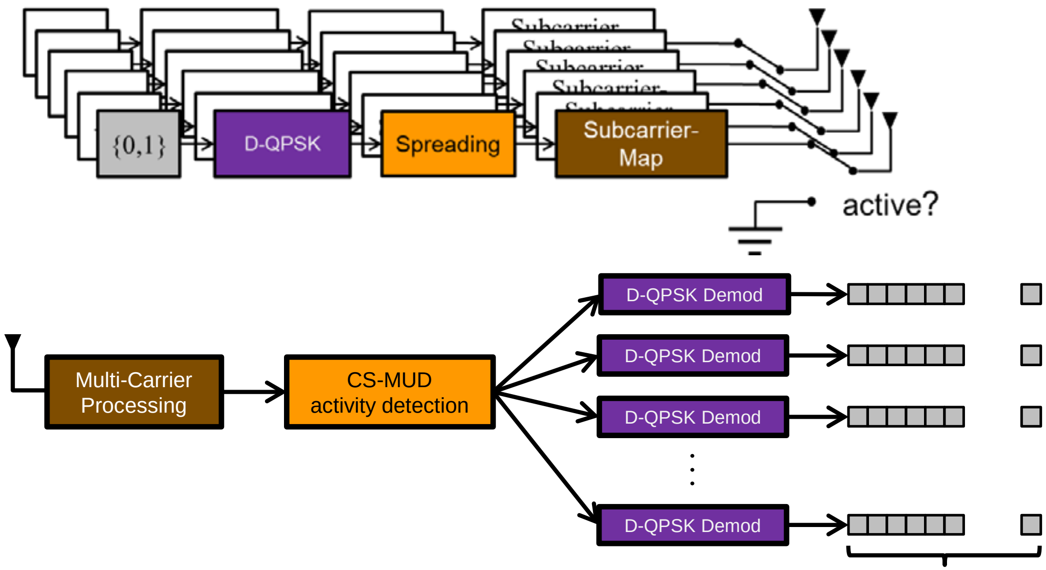
CS-Theory

MMC: Massive Machine type Communications



design process

MCSM concept



Data of **active** users

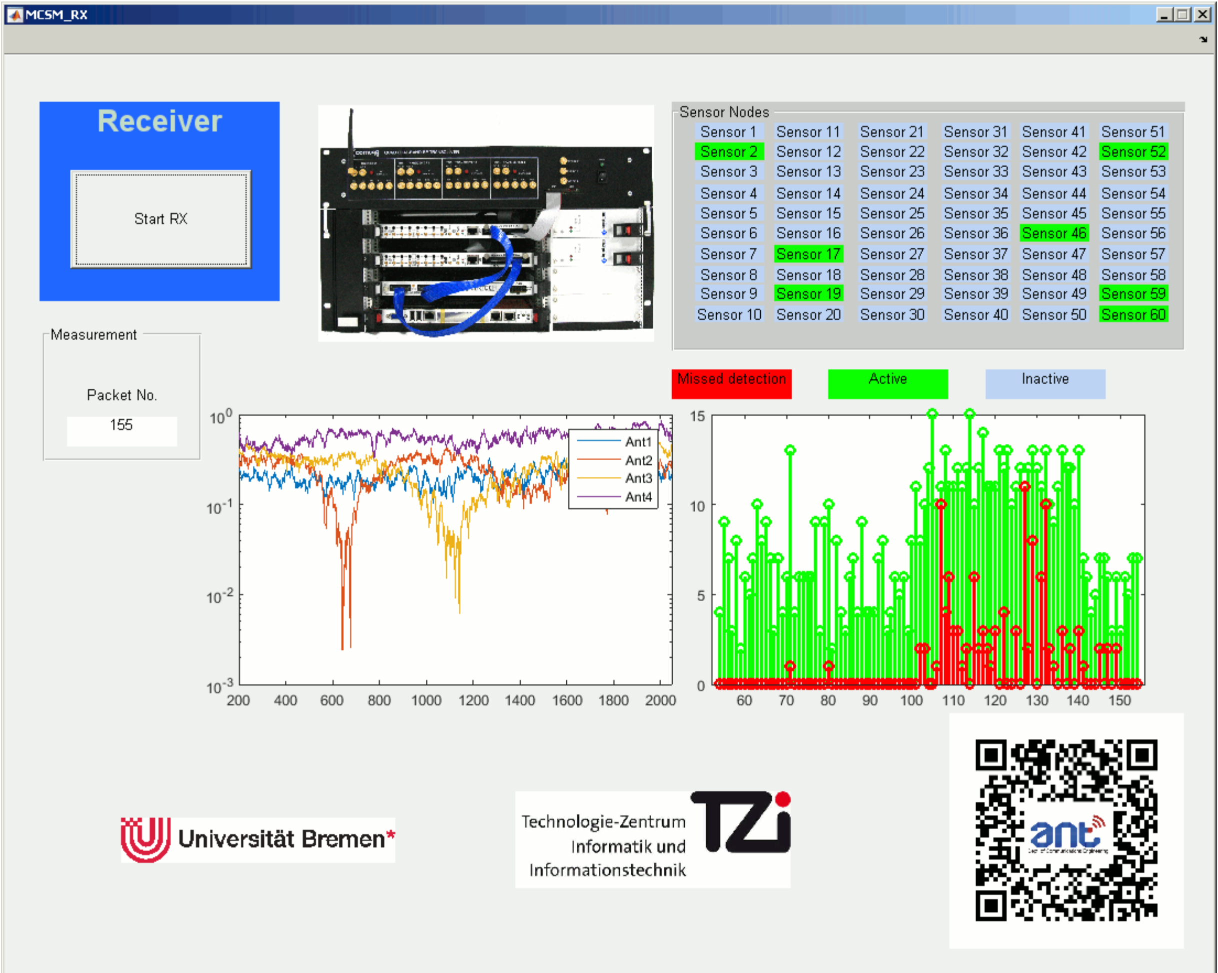
industry, standards

proof of concept

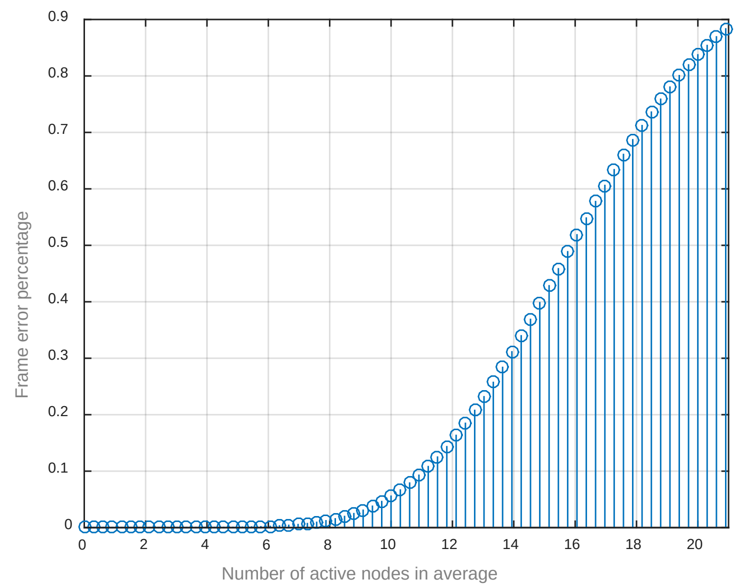
Demos:

SCC17, Wireless Automation 2017

MCSM Testbed



- **MCSM Receiver GUI**
  - Live recording of sporadic transmission of 60 nodes
  - Packet 1-100 with $p_a = 0.1$
  - Packet 101-140 with $p_a = 0.25$
  - FER performance: Graceful degradation with higher activity



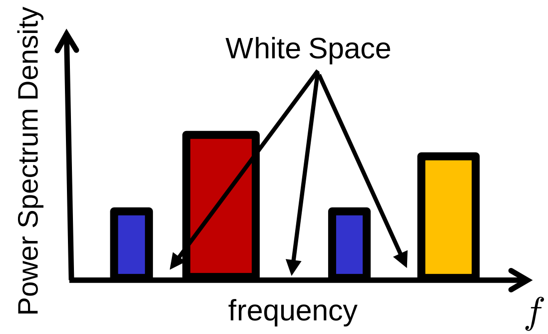
Compressive Edge Spectrum Sensing (CESS)

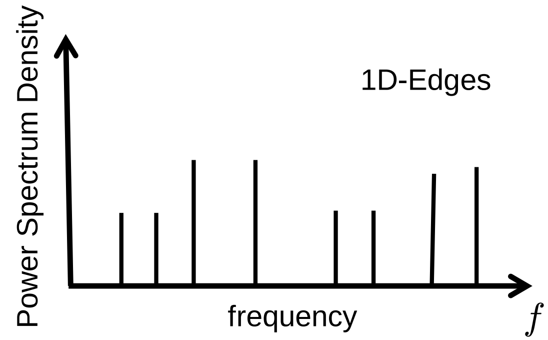
- Research task: Design of CS-spectrum sensing algorithms (input for coexistence management)

- SotA: Sensing approaches using Nyquist sampled signals → wide-band sensing → high sampling rate →costly hardware

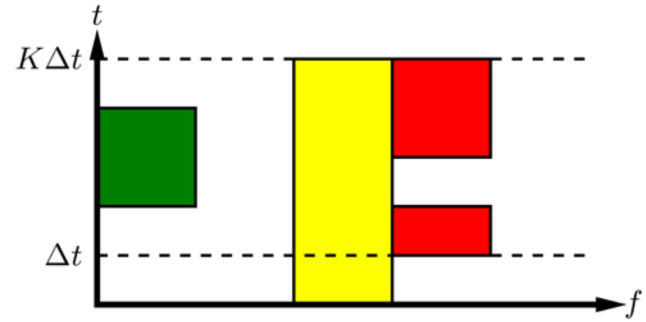
- Approach:
  - Exploit sparsity in spectral domain → go for undersampling with CS using autocorrelation properties
  - Edge detection → even more sparse signals
  - Sporadic activity → 2D edge sensing (f and t) by minimizing total variation

- Key challenges:
  - Reconstruct edges in 1D or 2D





2D-occupation in WLAN scheme

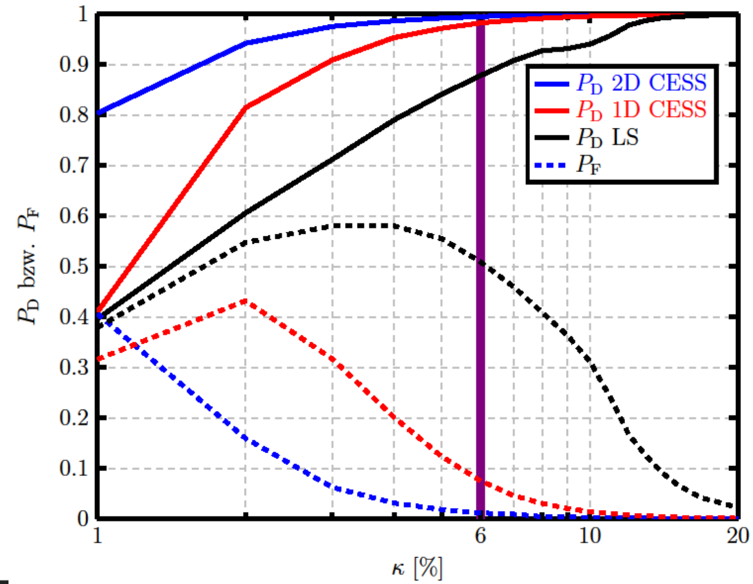


Compressive Edge Spectrum Sensing (CESS)

- Key results:
  - 1D and 2D outperforms classical LS sensing
  - 100% detection at 6% of Nyquist rate

Sporadic access with 40% mean occupation

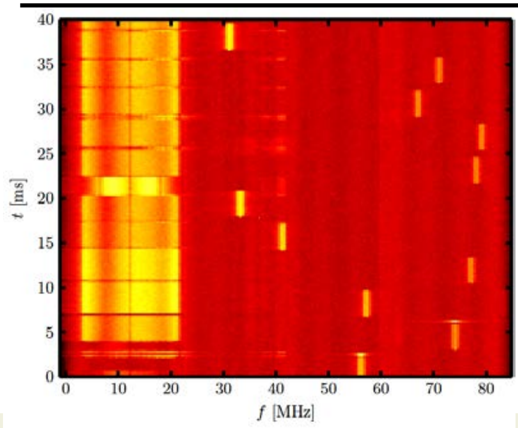
bandwidth 100 MHz, blocks of 20 MHz,1D: OMP, 2D: l1/l2-optimization



- Proof-of-Concept: WLAN and Bluetooth
  - WLAN: 15% of Nyquist rate works
  - Bluetooth (narrrow band) more sensitive

Bluetooth, WLAN

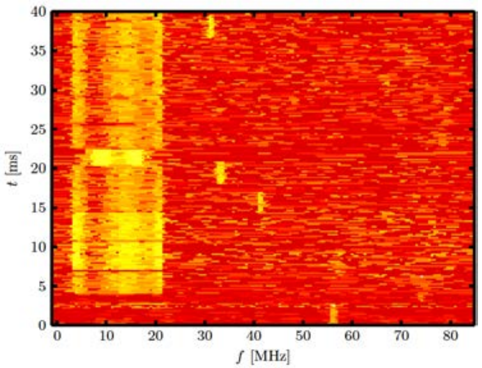
original



Wideband Sensing

80 MHz band, 2.4 GHz ISM-Band

1D, OMP reconstruction



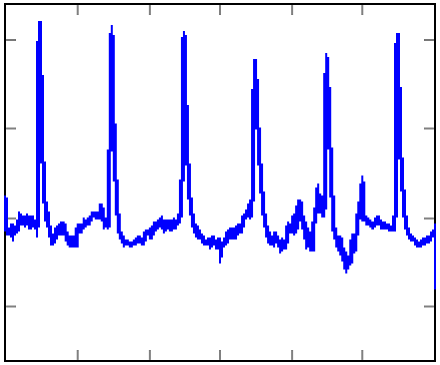
8% of Nyquist rate

CS-Signal Aquisition and Reconstruction of Neuronal Signals

Dept. of Communications Engineering

- **Research task:** Reduction of data rate for neural data acquisition
  - Utilize sporadic nature of spikes
  - Design of reconstruction algorithms

source:*www.extremetech.com/extreme*

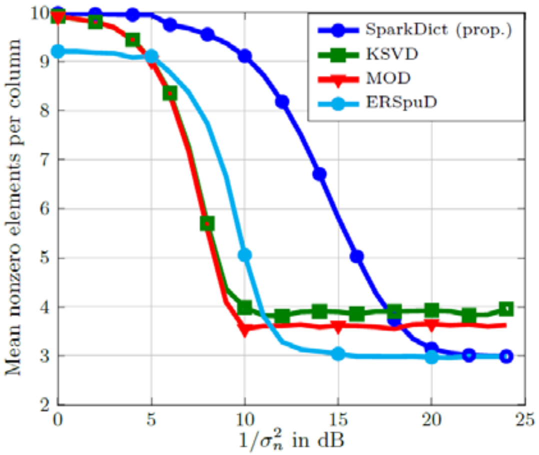


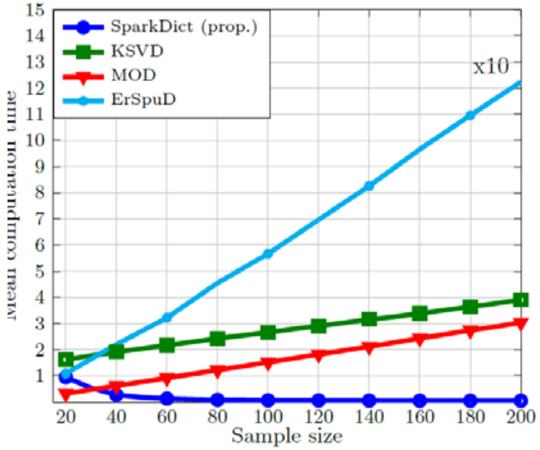
Typical neural spike shape

- **Key challenges:**
  - Strict circuit area and power constraint
  - Multiple correlated electrodes
    → joint reconstruction of correlated signals
  - Sparsity domain unknown
    → dictionary learning (machine learning)

- **Key results:**
  - SparkDict: CS reconstruction algorithm for joint reconstruction w/ dictionary learning

Sparsity $k = 3$





[KSVD] M. Aharon, M. Elad, and A. Bruckstein, k-SVD: An Algorithm for Designing Overcomplete Dictionaries for Sparse Representation", IEEE Transactions on Signal Processing
[MOD] K. Engan, S. O. Aase, and J. H. Husoy (Editors), Method of optimal directions for frame design, 1999, ISBN 0780350413
[ErSpuD] D. A. Spielman, H. Wang, and J. Wright, Exact recovery of sparsely used dictionaries", arXiv preprint arXiv:1206.5882, 2012.

IN-NETWORK-PROCESSING

Distributed Signal Processing

H. Paul, G. Xu, S. Wang, M. Röper, B. Shin, A. Dekorsy
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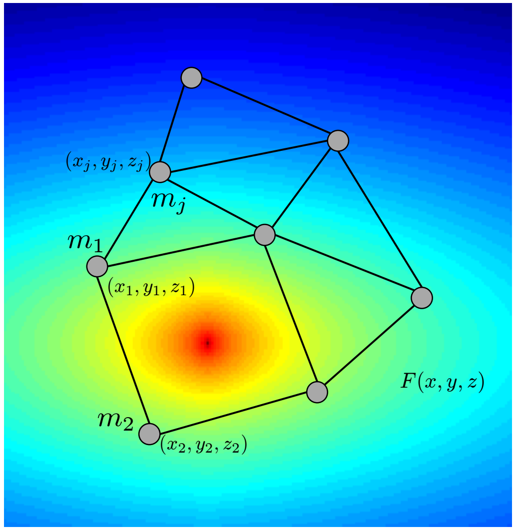
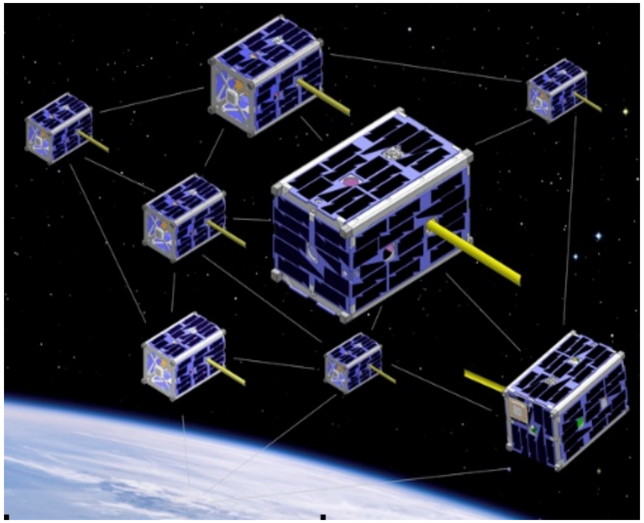
Distributed Processing / In-Network Processing

- Network of nodes perform noisy measurements of same physical quantity, e.g. temperature
- Measurements are processed within multi-agent system/network (In-Network Processing) to perform distributed estimation of physical entity
- Examples:



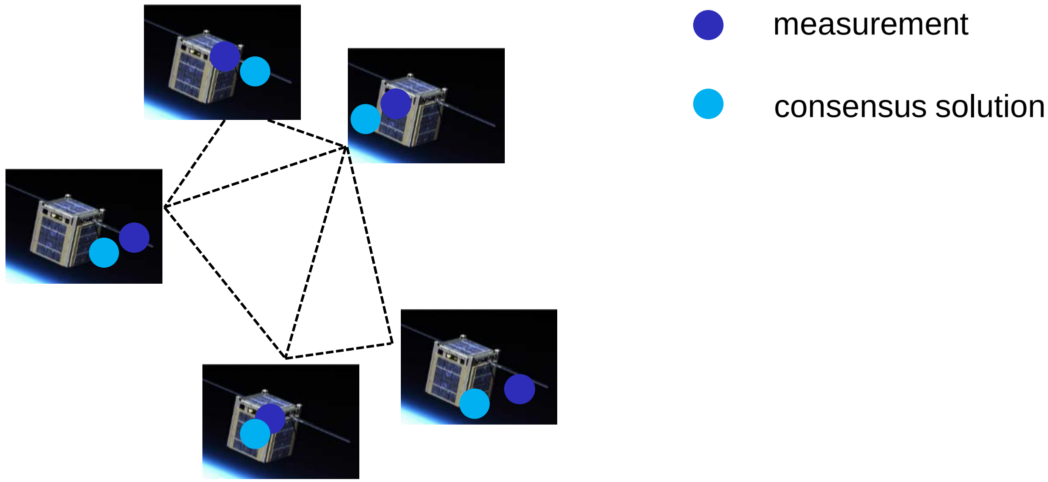
Environmental monitoring



CubeSat swarms e.g. for earth obervations

Distributed Processing / In-Network Processing

- Idea: Calculate a function within a network, e.g. averaging, MMSE/LS, Kalman filtering
- Consensus based: Algorithm converges to identical solution at all nodes, e.g. central solution



- Advantages: No single point of failure/trust, data processing in local network (no cloud), communication robustness, more secure (e.g. attacks)
- Challenges: Design of algorithms converging to central (optimum solution) with less communication overhead, facilitating tight integration of wireless communication

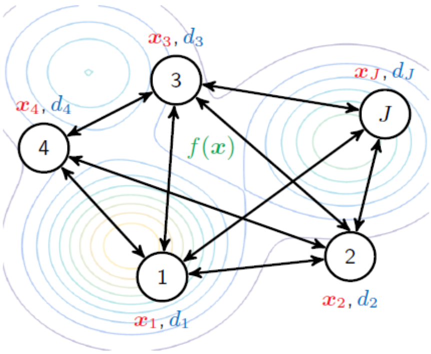
Distributed kernel-based regression

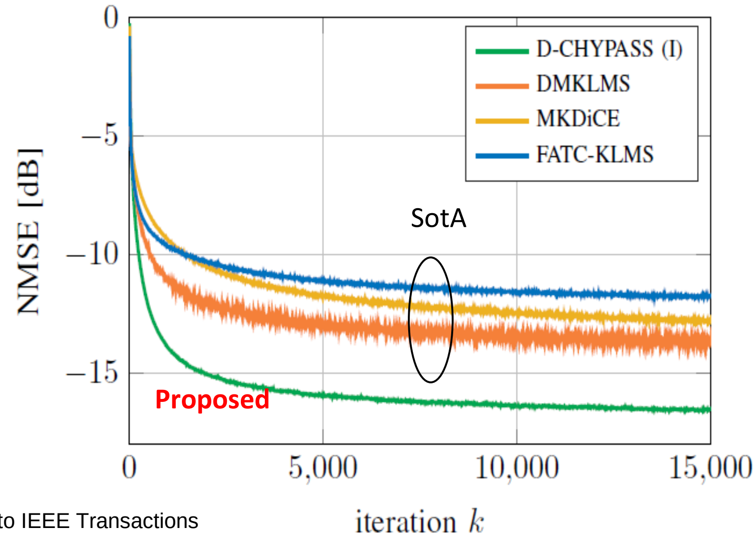
- Research task: Distributed nonlinear regression of any function $f(x)$
- Application: Predict diffusion field $f(x)$ at positions x using sensor measurements d
- Key challenges:
  - Nonlinear $f(x)$, convergence, communication overhead
- Mathematical approach:
  - Transform all sensor positions x_i by nonlinear kernel function $k(.,x_i)$ into reproducing kernel Hilbert space (RKHS)
  - Unknown nonlinear function f is modeled in linear form

$$f(.) = \sum_i w_i k(.,x_i)$$

    as element of RKHS

  - Estimate coefficients w_i by expanding set-theoretic learning to a distributed setting → faster convergence and improved estimation accuracy (NMSE)
- Key results:
  - Distributed kernel-based adaptive learning (D-CHYPASS)





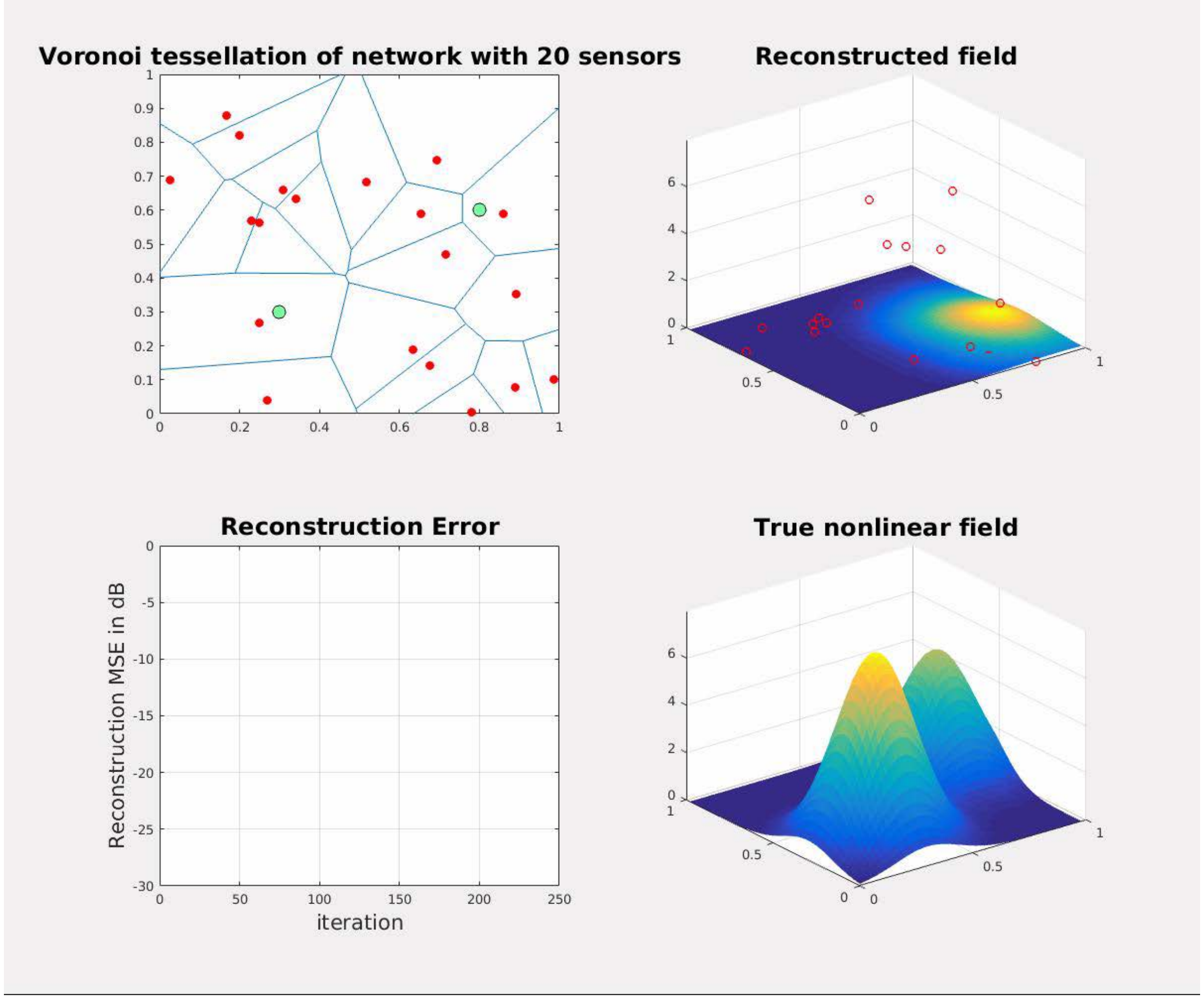
[DMKLMS] Shin, Yukawa, Cavalcante, Dekorsy, “Distributed adaptive learning with multiple kernels in diffusion networks”, submitted to IEEE Transactions on Signal Processing, 2018

[MKDiCE] Shin, Paul, Yukawa, Dekorsy, “Distributed nonlinear regression using in-network processing with multiple Gaussian kernels”, IEEE SPAWC 2017

[FATC-KLMS] Gao, Chen, Richard, Huang, “Diffusion adaptation over networks with kernel least-mean-square”, IEEE CAMSAP 2015

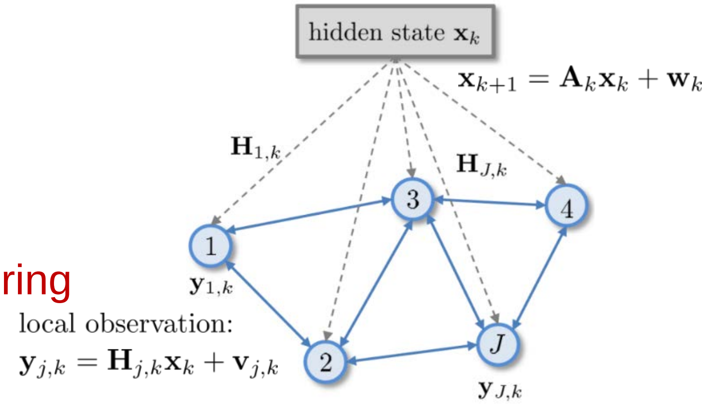
Distributed kernel-based regression

- Demo of mobile sensor network with distributed kernel least squares (KDiCE) algorithm
  - Mobile sensor network with 20 nodes (red)
  - Nonlinear field $f(x)$ with two diffusive sources (green)
  - Sensor moves to centroid of Voronoi cell of reconstructed field



- Research task: Distributed state estimation for dynamic systems

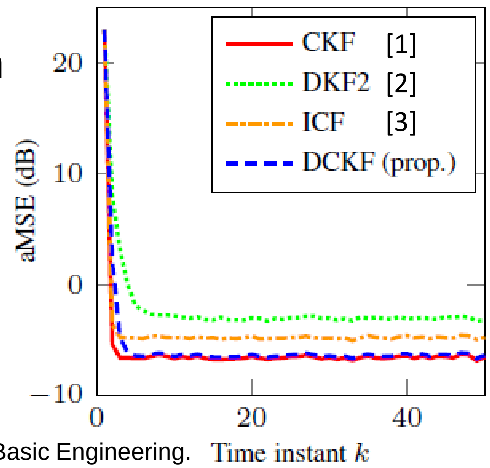
- Application: Distributed control, e.g. control of a swarm of unmaned autonomous vehicles (UAVs)

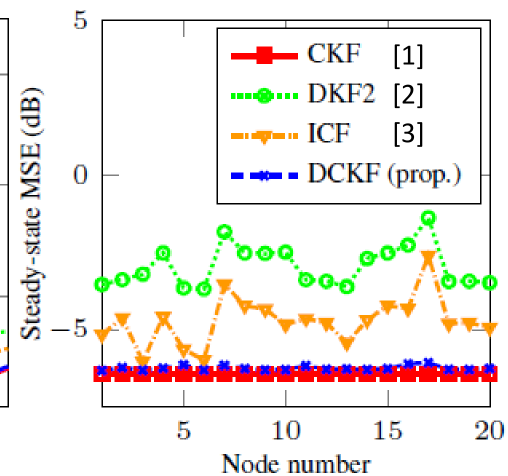


- Key challenge: Joint design of control and communication
  - Distributely estimate hidden states of system to be controlled by using local observation of states → Distributed Kalman Filtering

- Mathematical approach:
  - Exploit equivalence of KF and MAP estimation in Gaussian setting

- Key results: DCKF algorithm
  - Convergence to central solution proofed
  - DCKF ensures consensus on estimates





[1]. R. E. Kalman, "A new approach to linear filtering and prediction problems," Journal of Basic Engineering.

[2]. R. Olfati-Saber, "Distributed Kalman filtering for sensor networks," in Proc. of the 46th IEEE Conf. on Decision and Control, 2007.

[3]. A. T. Kamal, J. A. Farrell, and A. K. Roy-Chowdhury, "Information weighted consensus," in Proc. of the 51st IEEE Conf. on Decision and Control,2012.

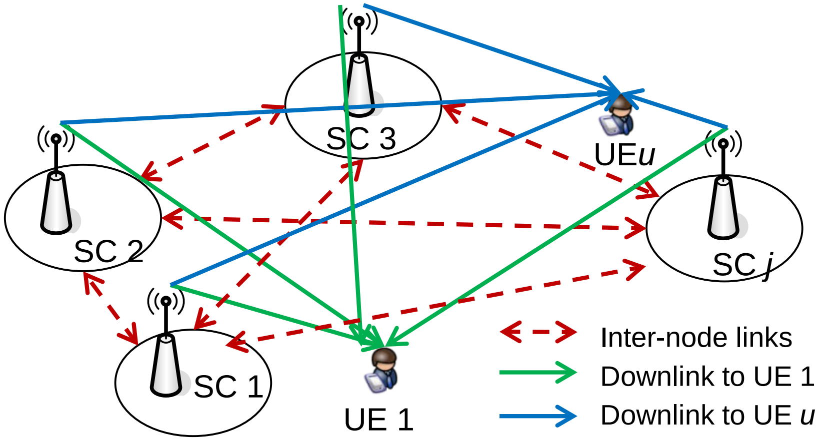
Distributed Precoding

- Research task: Investigations on algorithms for distributed precoder/beamformer design
- Application: Distributed RAN (5G) - Downlink
- Key challenges:
  - Computational efficient / low latency
  - Low communication overhead

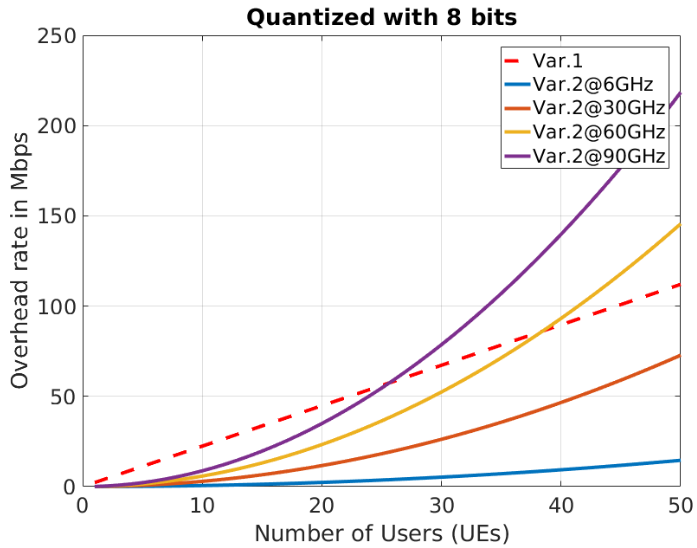
$\mathbf{x}_j = \mathbf{G}_j \mathbf{s}; \quad \dim(\mathbf{G}_j) = \#\,\text{transmit antennas} \times \#\,\text{UEs}$

data: $\mathbf{s}$ multiuser vector

receive signal: $\mathbf{y}_u = \sum_{j=1}^{N_{SC}} \mathbf{x}_j + \mathbf{n}$; superposition of all SCs



- Key results:
  - Distributed MMSE (e.g., Richardson (PR) iteration)
  - Var.1: Communicate transmitted signals ∝ # UEs
  - Var.2: Communicate precoding matrices ∝ $(\#\,\text{UEs})^2$
  - Var.2: The faster the channel the more often we have to update the matrix → overhead increases
  - Trade-off between Var1 and Var2



Distributed consensus-based estimation

- Research task: Design an analysis of distributed estimation algorithms
- Application: Distributed RAN (5G) – Uplink → Small Cells share information to jointly estimate received user signals → distributed multi-user detection

central LS problem

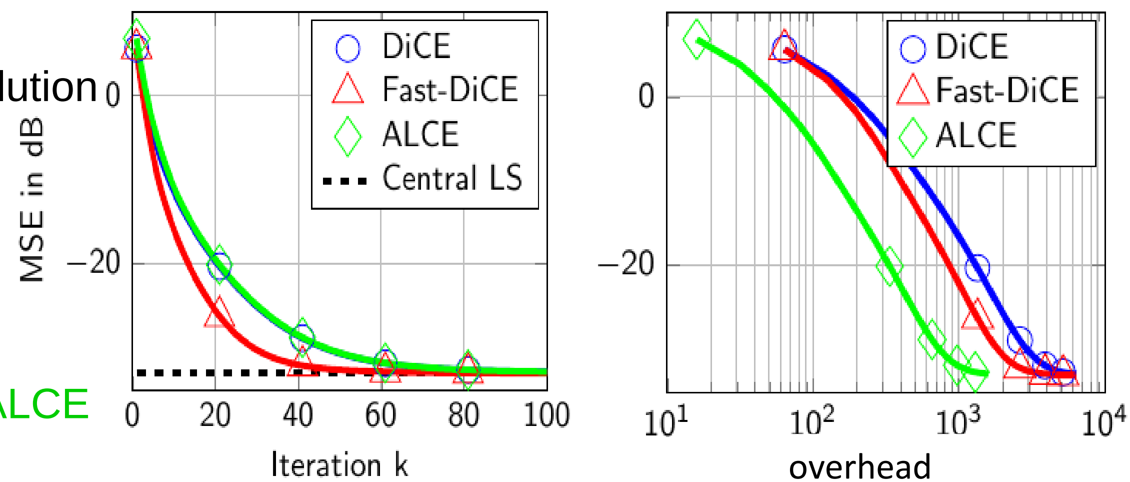
$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}} \sum_{j=1}^{J} ||\mathbf{x}_j - \mathbf{H}_j \mathbf{s}||^2 \equiv$$

Distributed consensus-based LS problem

$$\{\hat{\mathbf{s}}_j | j \in \mathcal{J}\} = \arg \min_{\{\mathbf{s}_j | j \in \mathcal{J}\}} \sum_{j=1}^{J} ||\mathbf{x}_j - \mathbf{H}_j \mathbf{s}_j||^2$$
$$\text{s.t.} \quad \mathbf{s}_j = \mathbf{s}_i \quad \forall \quad j \in \mathcal{J}, \quad i \in \mathcal{N}_j$$

$\mathcal{J}$: set of nodes
$\mathcal{N}_j$: set of neighbor nodes of node j

- Key challenges:
  - Guarantee convergence to central solution
  - Ensure high convergence rate and/or low communication overhead
- Key results:
  - Several algorithms DiCE/Fast-DiCE/ALCE



INFORMATION BOTTLENECK

Relevant Information Processing

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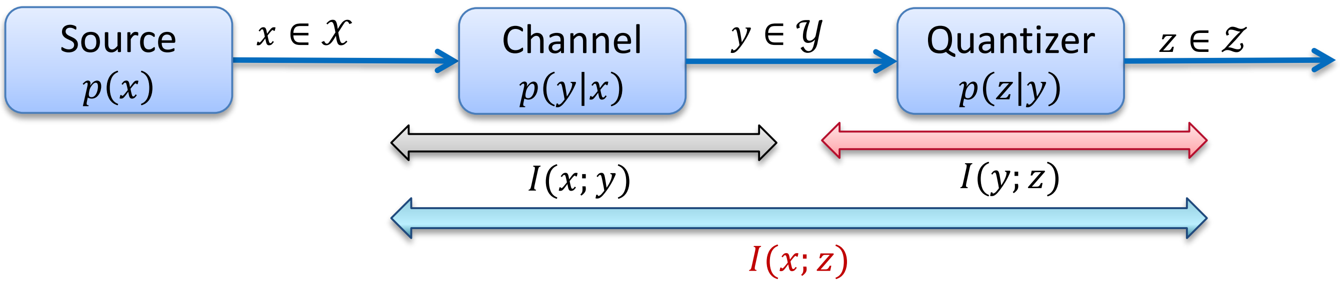
Department of Communications Engineering
University of Bremen

Information Bottleneck Method



Markov chain: $\mathrm{x} \rightarrow \mathrm{y} \rightarrow \mathrm{z}$

$p(x,z|y) = p(x|y) \cdot p(z|y)$

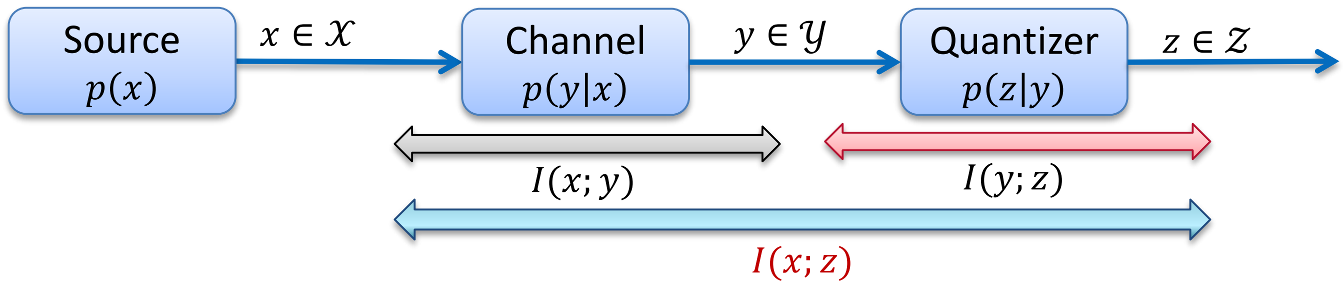
- Mutual Information $I(x;y)$: amount of information one random variable contains about the other

- Conventional quantization – information in signal x is not specifically considered, just by means of received signal y
  - Minimization of MSE $d(y,z) = \mathbb{E}\{|y-z|^2\}$ → Lloyd-Max/LBG algorithm
  - Rate-Distortion Theory: Minimization of compression rate $I(y;z)$, i.e. number of bits, for given maximum distortion $d(r,q) \leq D$ → Blahut-Arimoto algorithm

- Information Bottleneck Method (IBM)
  - Relevant information processing: interest is on information of source signal x
  - Trade-off between compression rate and relevant information

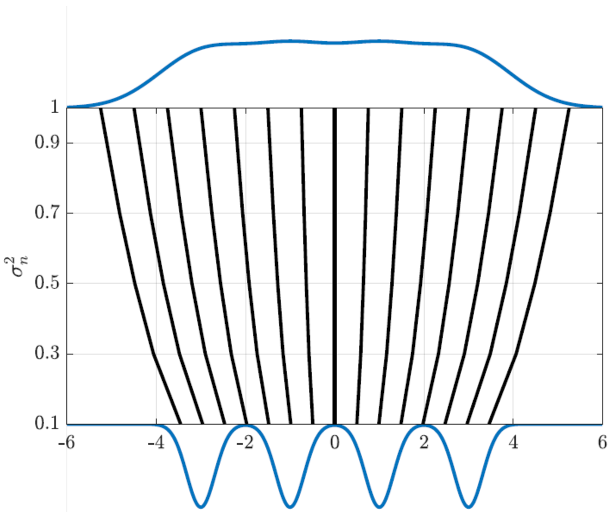
$$p^{\star}(z|y) = \arg\min_{p(z|y)} \big(I(y;z) - \beta I(x;z) \big) \quad \text{with} \quad |Z| \leq N$$

Information Bottleneck Method



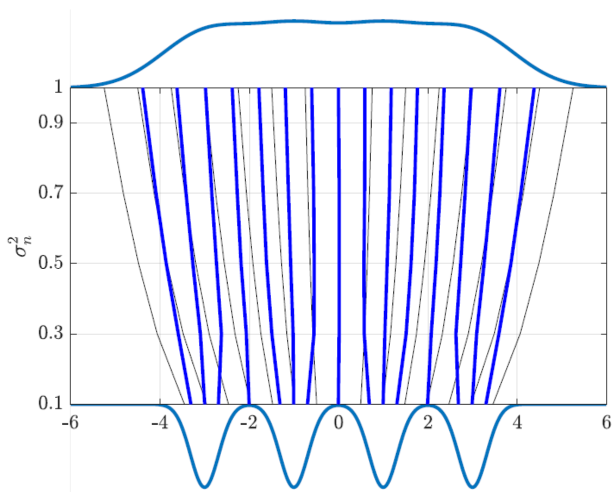
Quantization boundaries: 4-ASK over AWGN, noise variance σ_n^2, quantized to $N_z = 16$

Uniform Quantizer (UQ)



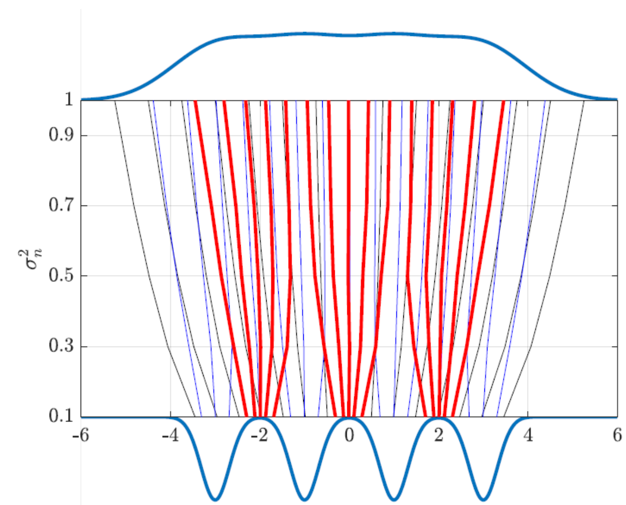
equidistant quantization

Lloyd-Max Quantizer (LM)



concentrates quantization levels around expected signals $(\pm 1, \pm 3)$

KL-Means-IB Algorithm



considers quantization levels around the middle values $(\pm 2, 0)$

Information Bottleneck Method

- Research task: Design and analyze IBM algorithms

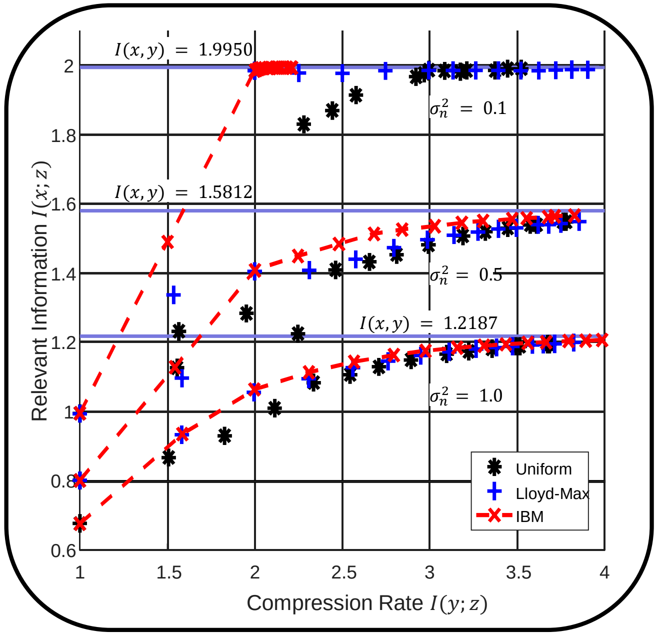
$$p^{\star}(z|y) = \arg\min_{p(z|y)} \big(I(y;z) - \beta I(x;z)\big) \text{ with } |Z| \leq N$$

$0 < \beta < \infty$ neither convex nor concave stochastic quantizer $0 \leq p(z|y) \leq 1$

$\beta \to \infty$ concave optimization with optimal deterministic solution $p(z|y) \in \{0,1\}$

- Key challenges:
  - Quantizer design is a non-convex optimization problem

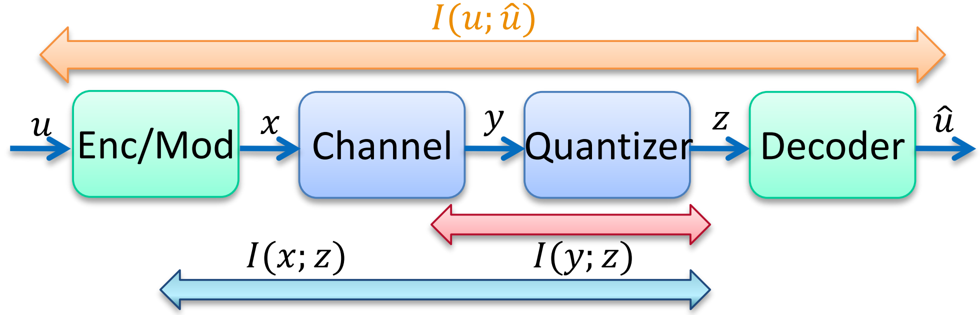
- Key results:
  - Proving equivalence among bunch of algorithmic approaches
  - SotA IBM algorithms:
    output z is a random variable, i.e. its values are indices
    $\rightarrow$ new pre-processing is required, e.g. new APP estimator
  - Affinity propagation based IBM quantizer ($\beta \rightarrow \infty$)
    output z representes a signal value $\rightarrow$ we can keep conventional pre-processing
  - Keeping more relevant information with lower compression rate



Information Bottleneck Method - Receiver

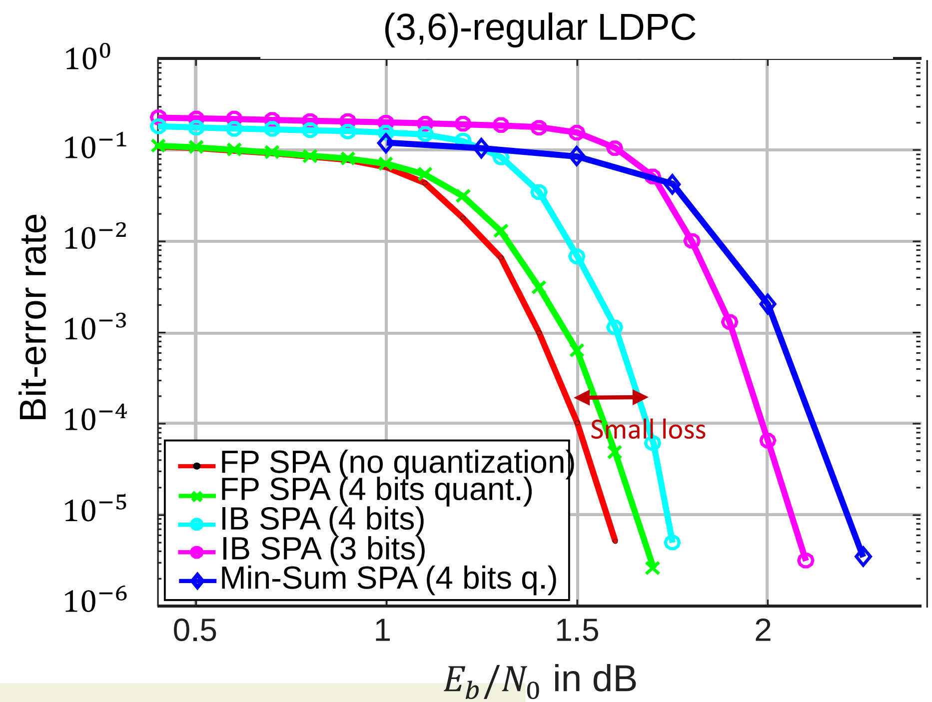
Dept. of Communications Engineering

- Research task: Analysis of Information Bottleneck based receivers
  - LDPC decoder: Information Bottleneck → discrete sum-product algorithm (IBM-SPA)



- Key challenges:
  - Trade-off between compression rate $I(y;z)$ and end-to-end information $I(u;\hat{u})$
  - Information Bottleneck based SPA (IBM-SPA) → instead of complex floating point operations discrete implementation by using LUTs

- Key results:
  - Trade-off between complexity and performance
  - IBM-SPA with 4-bit shows small loss compared to floating point SPA w/ quantization



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LOW LATENCY, SHORT PACKAGES

HiFlecs

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University of Bremen

Dept. of Communications Engineering

HiFlecs 4.0

Hochperformante, sichere Funktechnologien
und deren Systemintegration in zukünftige industrielle
Closed-Loop Automatisierungslösungen

Coordination: Prof. Dr. Armin Dekorsy, University of Bremen

ifak IMST inIT GÖTTING NXP PHOENIX CONTACT Lenze
SCHUBERT SIEMENS TECHNISCHE UNIVERSITÄT KAISERSLAUTERN Universität Bremen*

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Project Goal

Design
of
an industrial radio system

- Extremely low latency (< 1ms)
- Extremely high availability and reliability (PER < 10^{-9})

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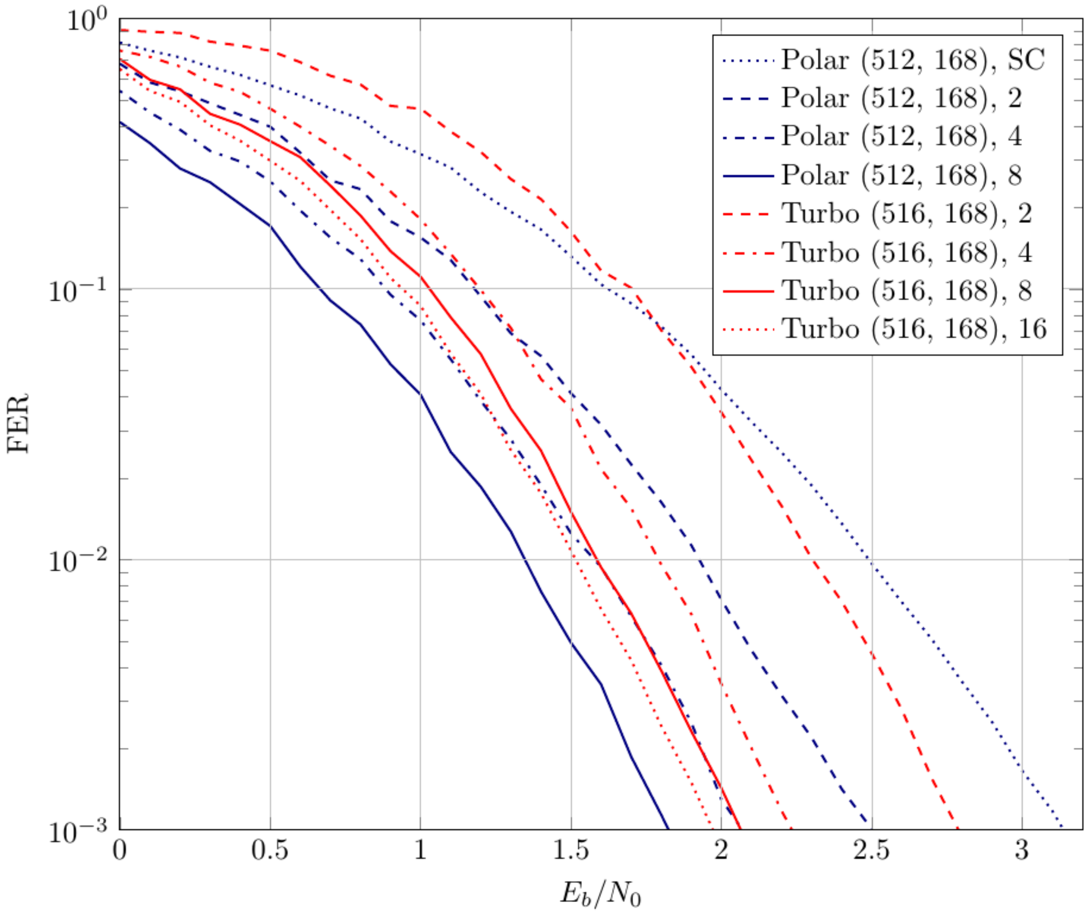
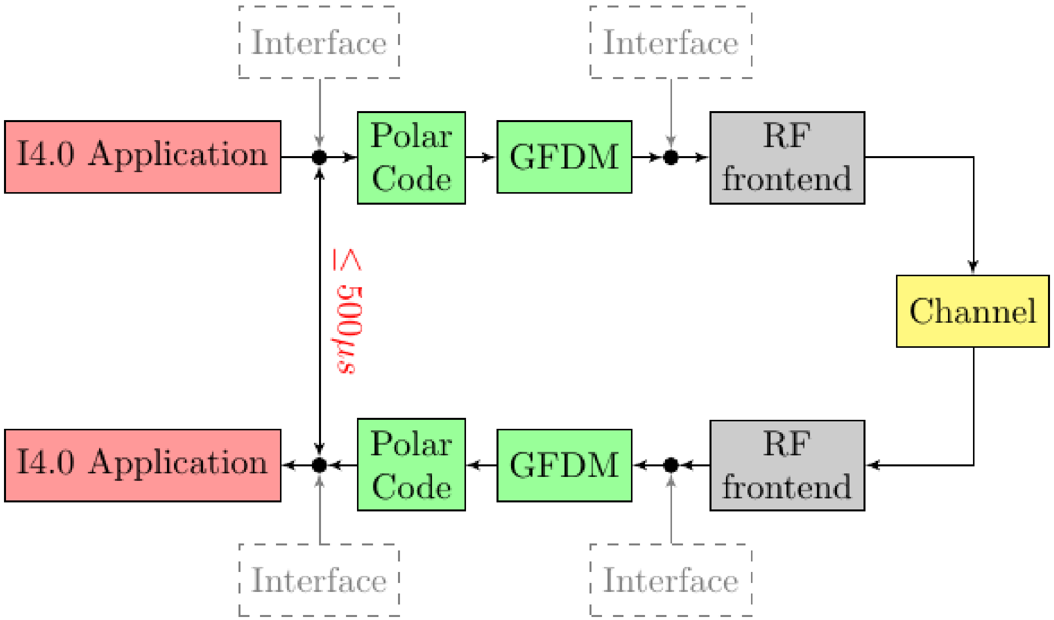
PHY – Channel coding for short packages

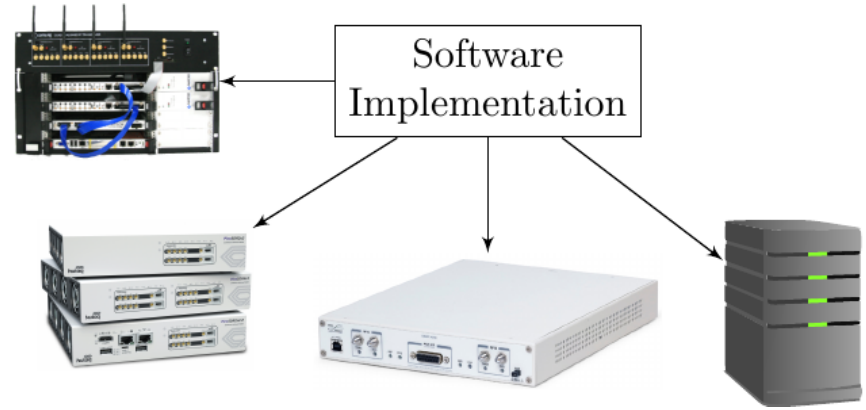
- Polar Codes with CRC vs. Turbo-Codes (e.g. used in LTE)
- Decoder: List-Decoder for Polar Codes
- Example: Packet length of 168 info bits



Polar Codes outperform Turbo Codes

PHY - Latency optimized SDR Baseband Implementation





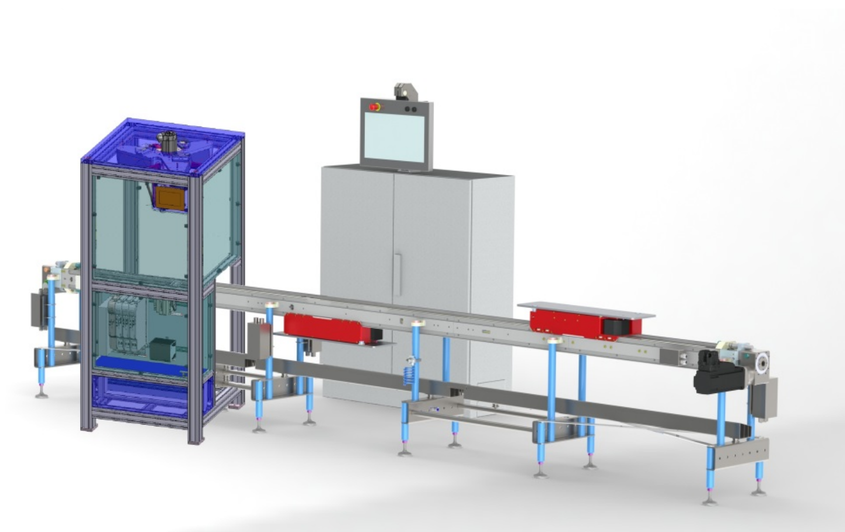
- **GFDM scheme:** low latency implementation
- **Polar Codes:** State-of-the-Art high throughput implementation

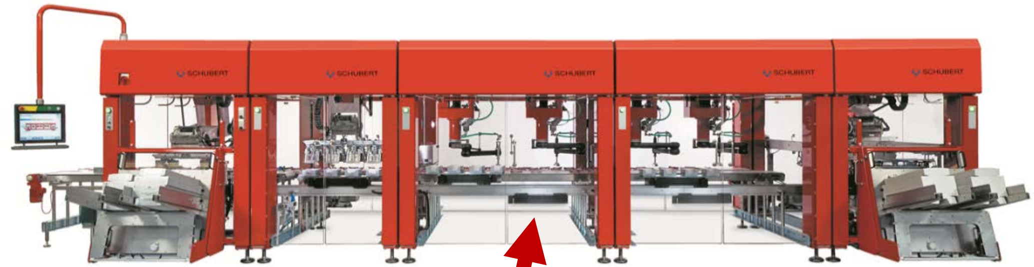
- Phy processing latency less than 1ms per link for typical block sizes used in control loop applications

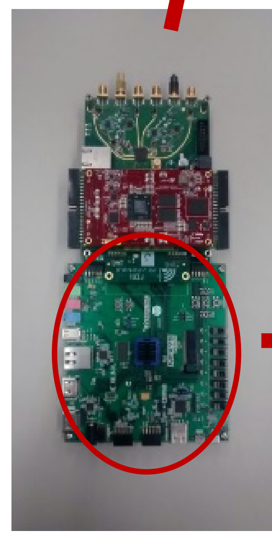
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

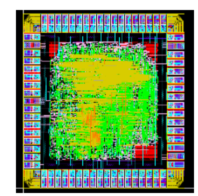
Demonstrator: Transmodul line of a packing machine

- Wireless data transmission between control module (SPS) and transport modules by HiFlecs
- Synchronization with delta-robot and linear measurement system via HiFlecs (cycle time 1ms)









Grafiken: Gerhard Schubert GmbH

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    Joint channel, activity and data estimation [ISWCS13], PHY/MAC integration [Globe14, ICC17]
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Thank you for your attention!