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Compressive Sensing Multi-User Detection for Multi-Carrier Systems in Sporadic Machine Type Communication

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WORKSHOP ON 5G NEW AIR INTERFACE

Outline

I. Massive Machine Type Communication

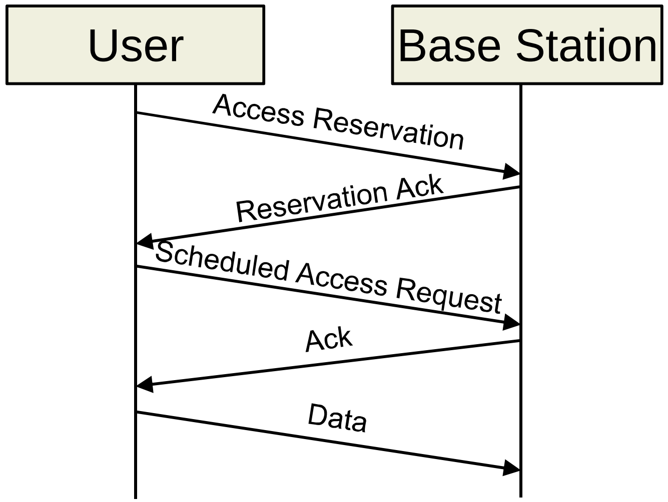
II. Multi-Carrier Compressive Sensing Multi-User Detection

III. Performance Evaluation

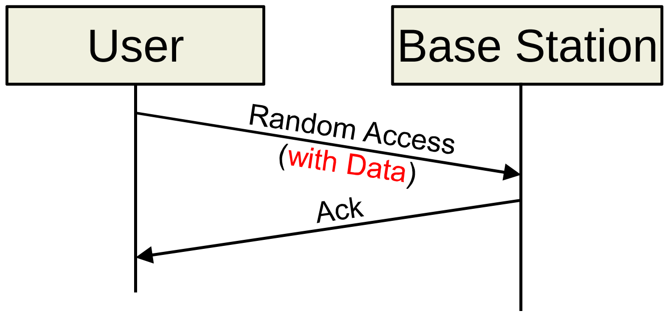
IV. Conclusion

Massive Machine Type Communication (MTC)

- Today's (cellular) systems (3G/4G):
  - Designed for high data rates / large packet sizes
  - Access reservation and scheduling
  - Control overhead is negligible vs. payload size
- 5G: Massive MTC
  - Massive number of nodes e.g. sensors
  - Typically low-data rates / small packet sizes
  - Access control overhead non-negligible
- Potential solution: Direct Random Access:
  - Reduced control signaling overhead
  - Random access by simply sending data
  - Challenge: Data collisions



Access Reservation

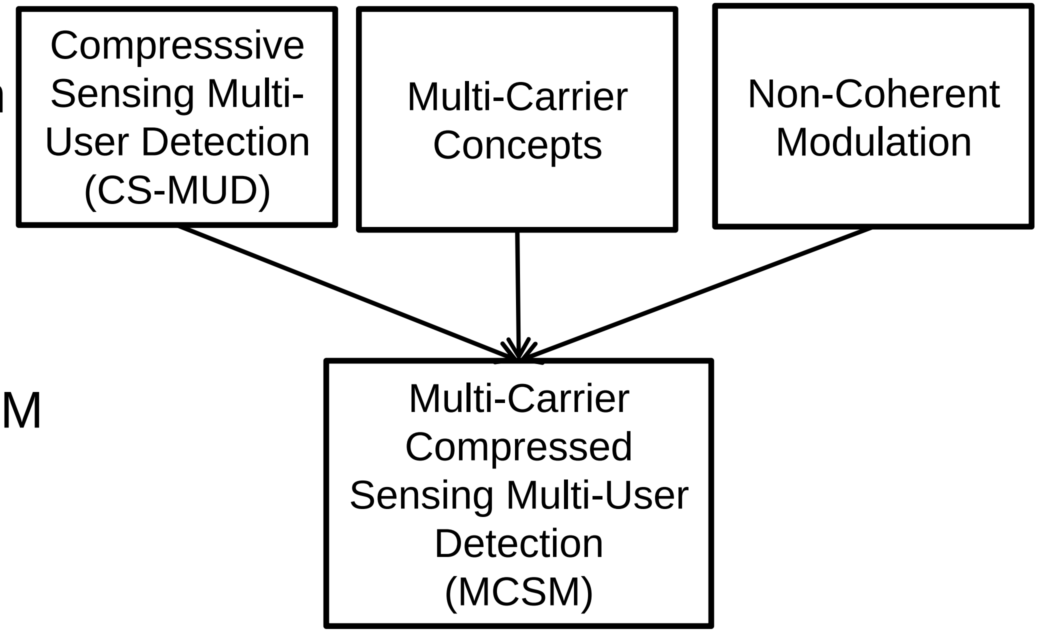


Direct Random Access

PHY-Technologies for Direct Random Access

1. Compressive Sensing Multi-User Detection (CS-MUD):

- Exploits sporadic access of nodes
- Facilitates joint activity and data detection
- Resolves collisions at the PHY layer



2. Multi-Carrier Concepts:

- Approaches: GFDM, UFMC, OQAM-OFDM
- Flexible resource allocation
- 5GNOW, METIS

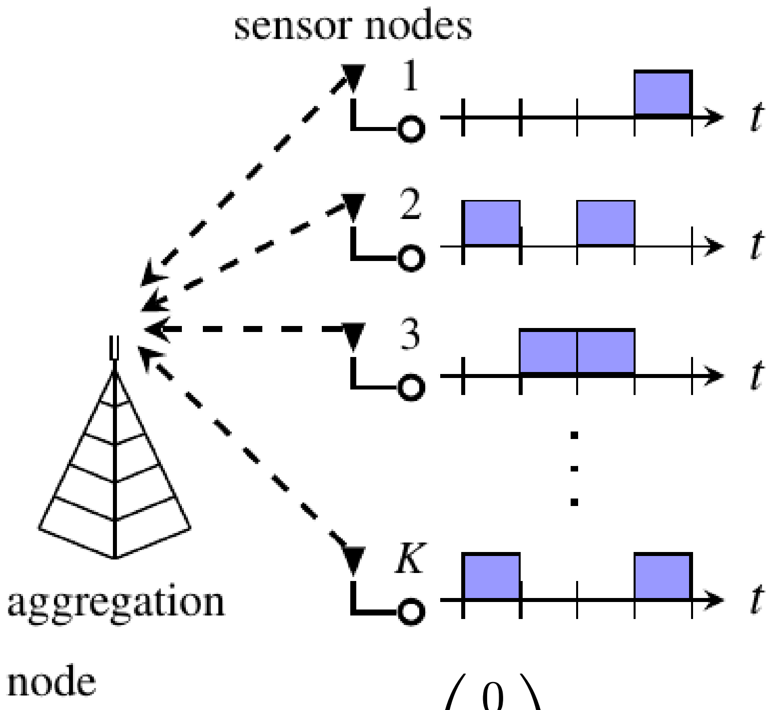
3. Non-coherent Modulation:

- No channel estimaton
- Robust against offsets

➢ Contribution of this talk MCSM

Review - Compressive Sensing MUD (CS-MUD)

- Scenario:
  - Machine to Machine uplink communication
  - Sporadic node access
  - Low activity probability $p_a \ll 1$
- Compressed Sensing:
  - Multi-User signal is sparse
  - Inactive nodes are modeled as transmitting zeros
  - Detection algorithm exploits sparse structure of Multi-User signal
  - Joint activity and data detection
- Bandwidth Efficient:
  - Detection in highly overloaded systems possible



$$\mathbf{x} = \begin{pmatrix} 0 \\ x_2 \\ 0 \\ x_k \end{pmatrix}$$

Review - Compressive Sensing MUD (CS-MUD)

- Recent Advances (part of METIS):
  - Transmission in single carrier setups with channel coding [1,2]
  - Solutions for asynchronous transmissions [3]
  - Techniques for channel estimation [4]

- Main Challenges for CS-MUD:
  - Massive access → Massive pilot overhead
  - Timing and frequency offsets

- Possible Solution (This talk):
  - Very low bandwidth
    - single tap channel
  - Non-Coherent modulation schemes
  - Multi-Carrier scheme → spreading over subcarriers to separate nodes

➢ Is the resulting data-rate still high enough?

Example: LTE Like Channel Parameters

- LTE Cyclic Prefix in downlink → Delay spread:

$$\tau_{\mathrm{CP}} = \{4.69, 16.67\}\mu\mathrm{s}$$

Min. coherence BW

$$B_c \approx \{50, 15\}\mathrm{kHz}$$

Put 20 subcarrier within the coherence BW for spreading

$$N_B = 20$$

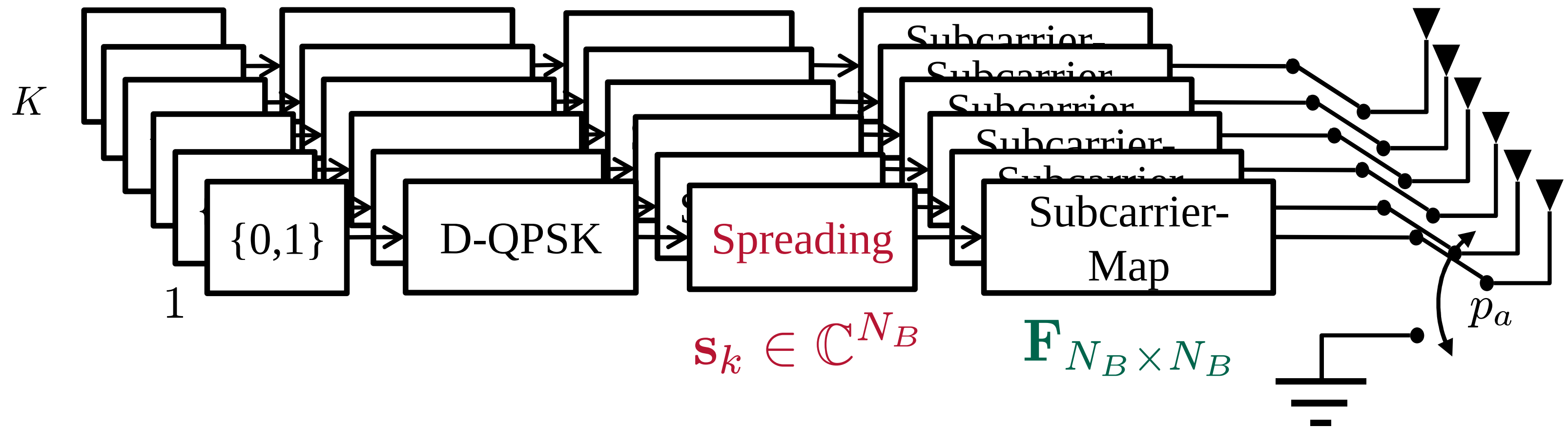
$$\Delta f = \frac{B_c}{N_B} = \{2.5, 0.75\}\mathrm{kHz}$$

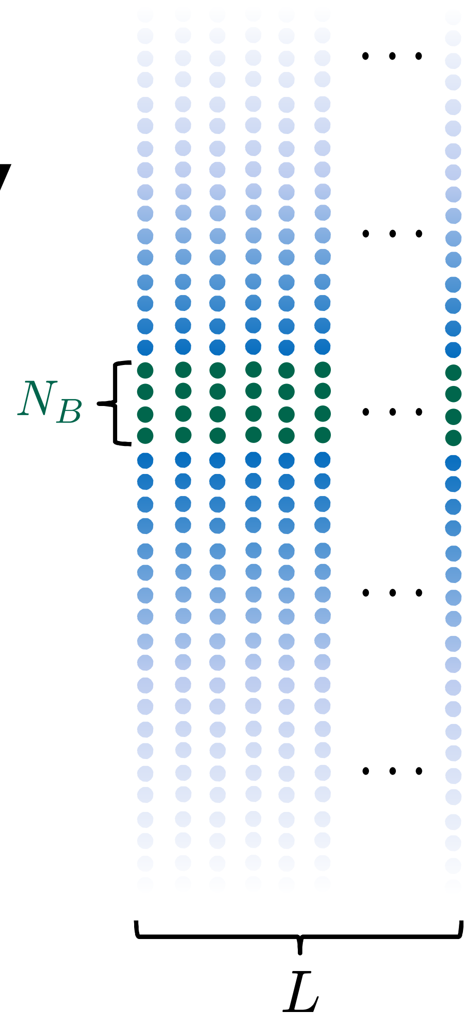
- Gross per node data rate with D-QPSK:

$$R_k = \frac{2\mathrm{Bit}}{\tau_{\mathrm{CP}}+1/\Delta f} \approx \{1.5, 5\}\mathrm{kBit/s}$$

➢ Suitable for low data-rate M2M applications

Multi-Carrier Compressive Sensing MUD (MCSM)





- MCSM Key Components:
  - Differential modulation → non-coherent reception
  - CS-MUD → allows to separate nodes at base-station
  - Subcarrier mapping → spreading sequence length equals subcarrier block size
- Massive Access:
  - $K \gg N_B$ → more nodes than subcarriers
  - Nodes are separated by unique spreading sequence $\mathbf{s}_k \in \mathbb{C}^{N_B}$
  - Spreading sequence length → much lower than number of nodes
  - MCSM system is highly overloaded

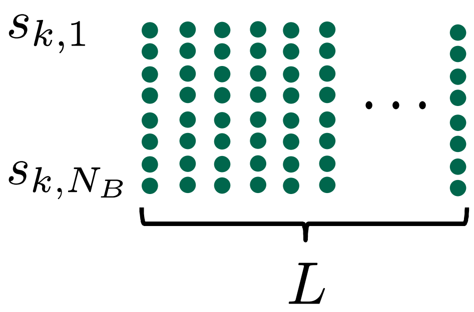
MCSM Detection Model

- Exemplary: OFDM as Multi-Carrier scheme:

$$\mathbf{Y} = \sum_{k=1}^{K} \mathbf{F}\mathbf{H}_k\mathbf{F}^H\mathbf{s}_k\mathbf{x}_k \;\Rightarrow \mathbf{Y} = \mathbf{S}\mathrm{diag}\{\mathbf{h}\}\mathbf{X}$$

- Transmit signal $\mathbf{x}_k \in \mathbb{C}^{1\times L}$
- Multi-User signal $\mathbf{X} \in \mathbb{C}^{K\times L}$ is a row-sparse matrix containing transmit frames
- Vector $\mathbf{h} = [h_1, h_2, ..., h_k]^T$ contains the channel taps of K nodes
- Single tap channel → non coherent reception possible

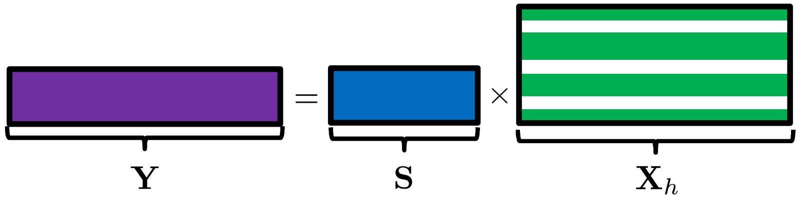
Here: 1 to 1 mapping from chips to subcarriers:



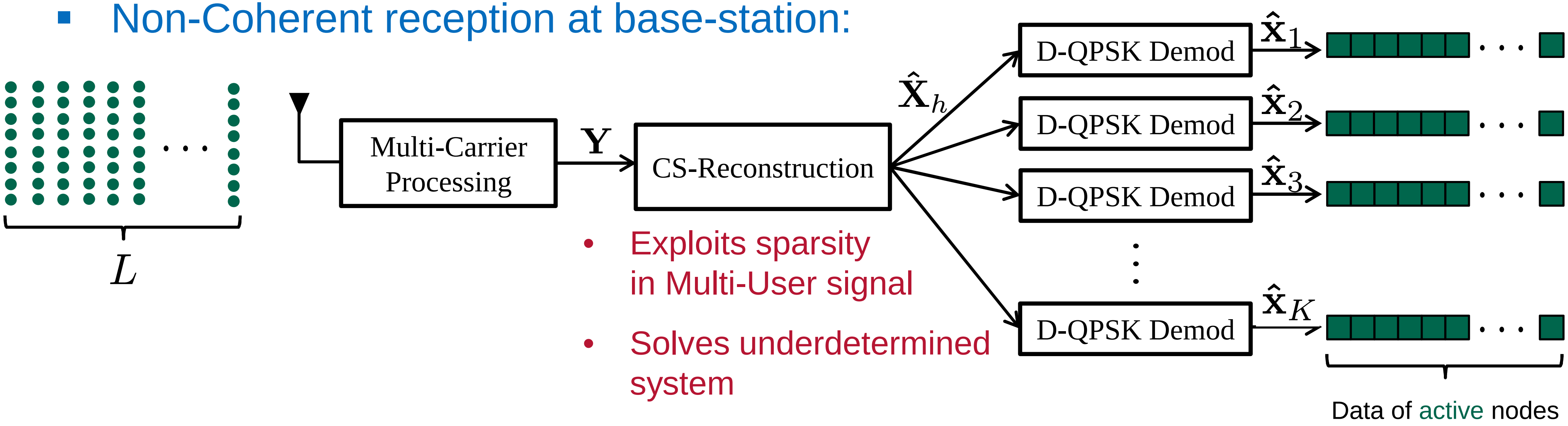
MCSM Base-Station Processing

- Compressed Sensing Problem for MCSM system:

$$\mathbf{Y} = \mathbf{S}\text{diag}\{\mathbf{h}\}\mathbf{X} + \mathbf{N} \quad \Rightarrow \mathbf{Y} = \mathbf{S}\mathbf{X}_h + \mathbf{N}$$

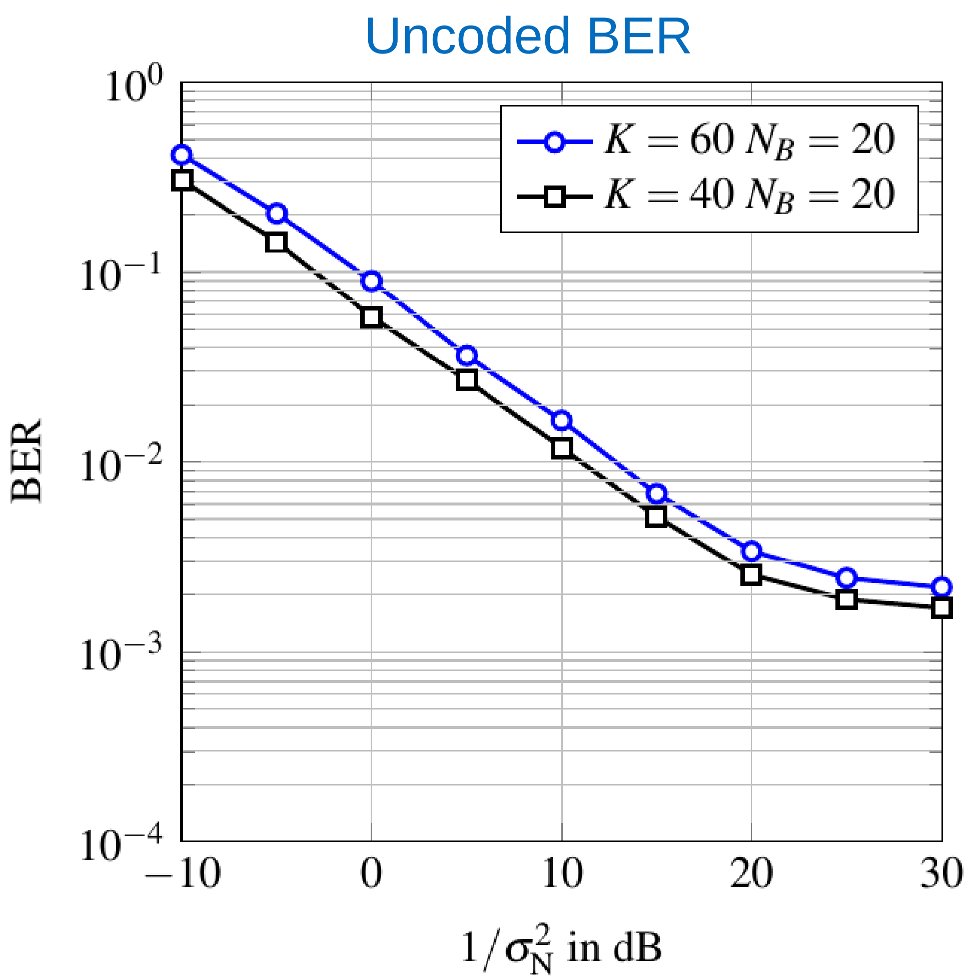


  - Matrix $\mathbf{S} \in \mathbb{C}^{N_B \times K}$ containins spreading sequences
  - Massive Access: $K \gg N_B$ system is under-determined
  - Matrix $\mathbf{X}_h$ is row-sparse containing frames of nodes
  - $\mathbf{N}$ is the additive white Gaussian noise
- Non-Coherent reception at base-station:



- Exploits sparsity in Multi-User signal
- Solves underdetermined system

First Results

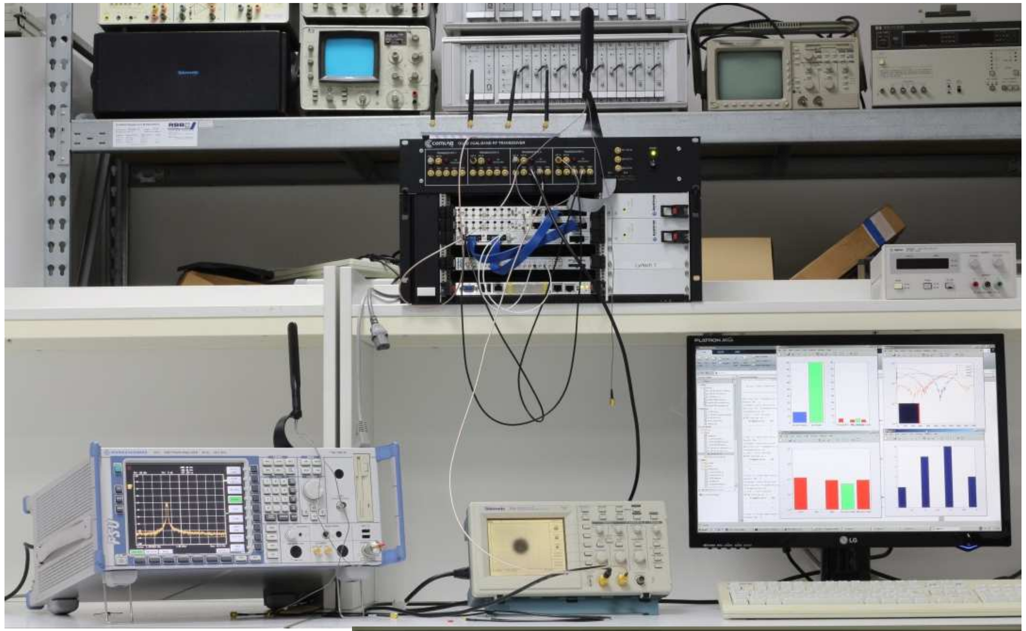


- Setup:
  - $K = \{40, 60\}$ nodes
  - Spreading N_B = 20
  - Factor 3 overloaded
  - Activity probability p_a = 0.2
  - Subcarrier spacing $\Delta f = 0.75\mathrm{kHz}$
- Observations:
  - Detection in massively overloaded systems possible
  - System exploits sparsity in multi-user signal

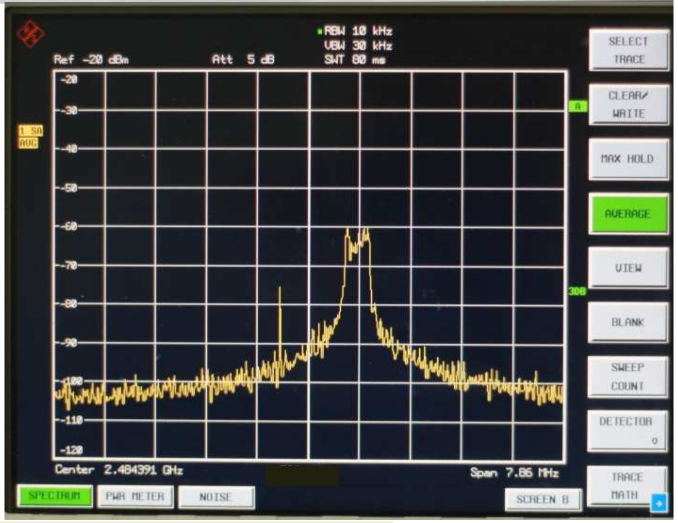
Laboratory hardware testbed

Tx

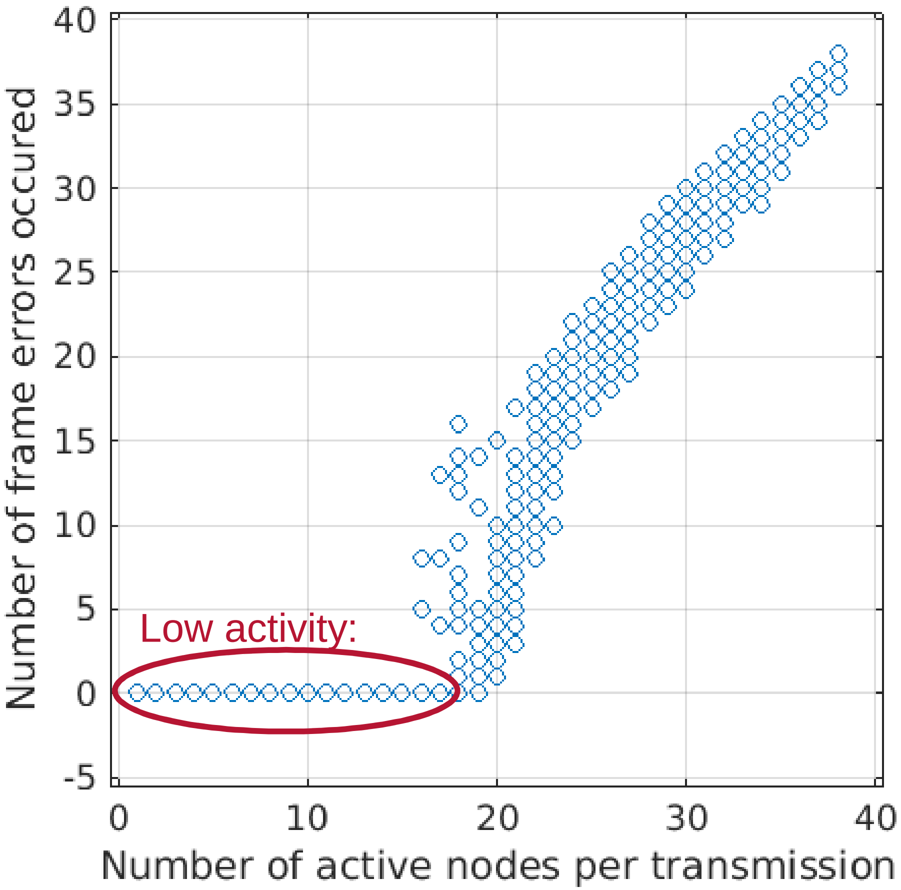
Rx



- N_k = 60 Nodes share 4 antennas
- N_B = 20 subcarrier
- $L = 120$ Bits
- Bandwidth $B = 50\text{kHz}$



First results from hardware setup



Setup:

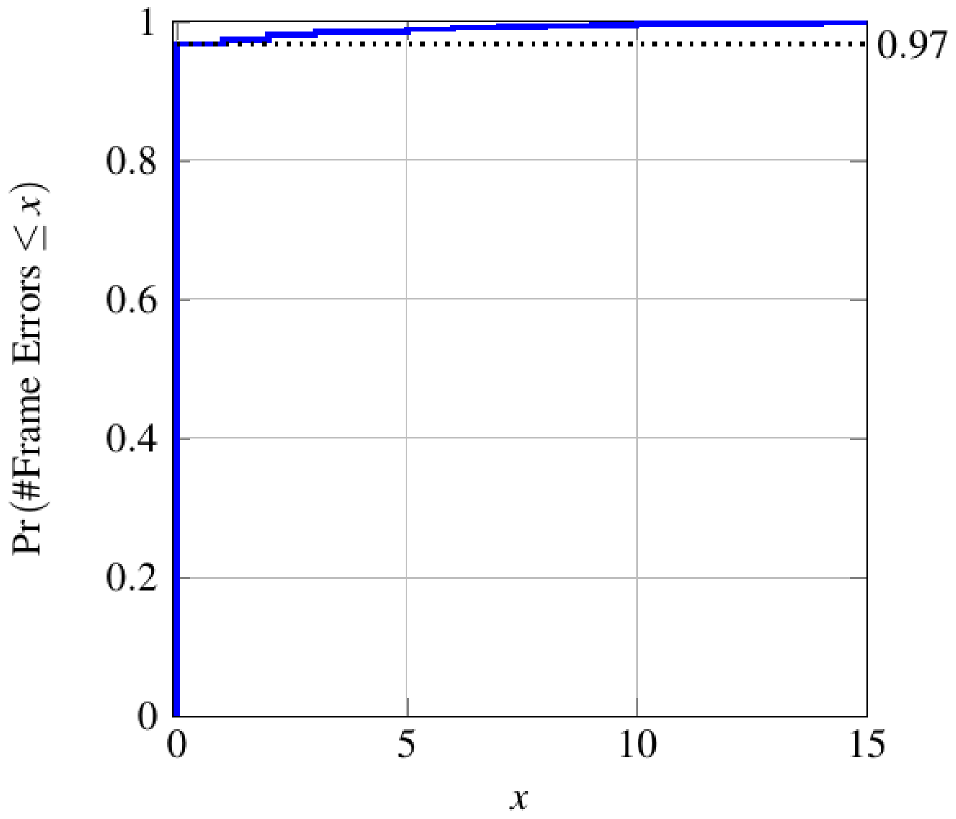
- K = 60 Nodes
- N_B = 20 spreading sequence length
- Factor 3 overloaded
- 2000 transmission in lab setup

Observations:

- Very reliable in low activity regime
- ➢ Suitable for low-activity MTC traffic

First results from hardware setup

CDF of measured Frame Errors



- Setup:
  - K = 60 nodes
  - N_B = 20 spreading sequence length
  - p_a = 0.2 activity probability
  - Low node activity scenario
- Observations:
  - Frame Error rate of $\approx 3 \times 10^{-3}$
  - Low Frame Error rate in low activity scenario

Conclusion

- Multi-Carrier Compressive Sensing Multi-User Detection

1. Compressed Sensing Algorithms:
   - Exploits sparse structure of MTC signal
   - Allows for overloading the system → Bandwidth efficiency

2. Multi-Carrier Scheme:
   - Signal is mapped to the coherence bandwidth of channel
   - 1 tap channel per node

3. Non-Coherent Reception:
   - No channel estimation
   - Robust against small offsets

➢ Successful verification in laboratory setup

➢ Potential candidate for 5G MTC (further evaluations are necessary)

References

[1]: Bockelmann, Carsten, Henning F. Schepker, and Armin Dekorsy. **"Compressive sensing based multi-user detection for machine-to-machine communication."** *Transactions on Emerging Telecommunications Technologies 24.4 (2013): 389-400.*

[2]: Bockelmann, Carsten, Henning F. Schepker, and Armin Dekorsy. "**Compressive sensing based multi-user detection for machine-to-machine communication."** *Transactions on Emerging Telecommunications Technologies* 24.4 (2013): 389-400.

[3]: Schepker, Henning F., Carsten Bockelmann, and Armin Dekorsy. **"Coping with CDMA asynchronicity in compressive sensing multi-user detection."** *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th. IEEE, 2013.*

[4]:Schepker, Henning F., Carsten Bockelmann, and Armin Dekorsy. ***"Exploiting sparsity in channel and data estimation for sporadic multi-user communication."*** *Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on. VDE, 2013.*