Methods for distributed sensing using OFDM based signals for Joint Communications and Sensing

Fraunhofer Institute for
High Frequency Physics and
Radar Techniques FHR

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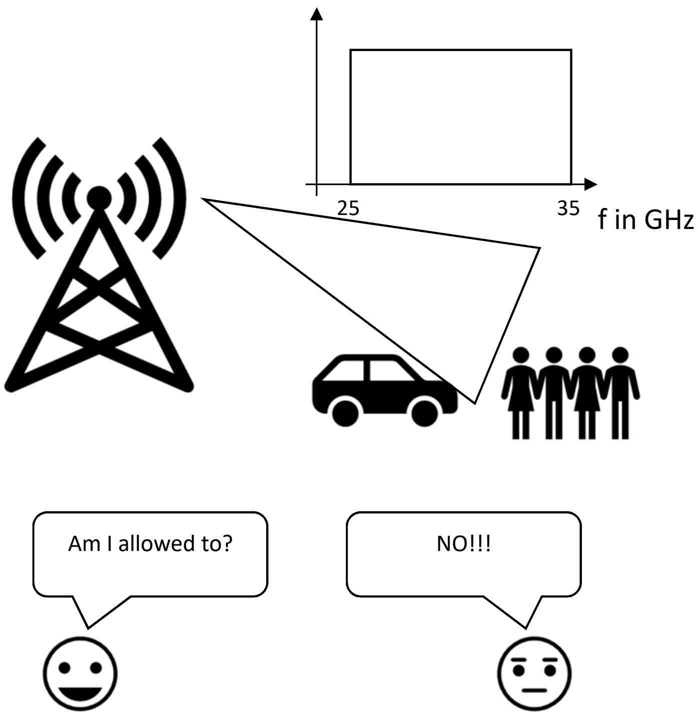
Motivation

- Conflicting objectives
  - Radar: Signals with high bandwidth for fine resolution
  - Communications: Signals with small bandwidth to save resources
- Issue with high-bandwidth signal
  - Information content of echo in fact limited and wasteful use of resources
  - Straightforward approach not feasible for a communication centric JCAS system



Is there a way to create a signal with a high bandwidth while keeping the occupied spectrum as limited as possible?

- Previously approach for high-resolution Radar based on gapped spectrum introduced in Guha et al. (2023)
- Transition of this idea to JCAS based on multi-carrier signals (here: OFDM)

S. Guha, A. Bathelt, M.H. Conde, J. Ender, IEEE Journal of Selected Topics in Signal Processing 17 (2023)

Agenda

1. Introduction
2. Compressed Sensing Methods on Non-Contiguous OFDM Signals
3. Consensus-Based Time Synchronization for Distributed Sensing
4. System and Antenna Requirements
5. Summary and Outlook

Introduction

Concepts form communications and radar

Let's address the elephant in the room: Spectrum is a scarce resource!

- Circumvent this problem by coexistence, Cognitive Radio, JCAS / ISAC approaches
- General problem: Resolution vs. available spectrum

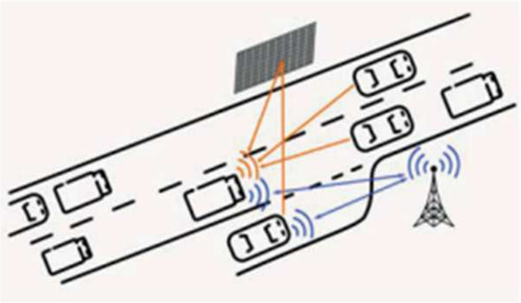


Figure 1: Car to car communication on a highway as an example for an JCS scenario.

Relevant concepts from communications and Radar

- From communications
  - Application of OFDM signals for sensing, e.g., Sturm et al. (2009)
  - (Communication centric) JCAS for additional sensing for a given communication signal, e.g., Zhang et al (2022)
- From Radar and Compressed Sensing
  - Approaches for high-resolution radar, e.g., Herman & Strohmer (2009)
  - Approaches for fusion of disjoint bands to form a wideband signal from narrow sub-band in Guha et al. (2022)

📖 S. Guha, A. Bathelt, M.H. Conde, J. Ender, IEEE Journal of Selected Topics in Signal Processing 17 (2023)
📖 C. Sturm et al., 2009 IEEE Radar Conference
📖 J. A. Zhang et al., IEEE Communication Surveys and Tutorials 24 (2022)
📖 M. A. Herman & T. Strohmer, IEEE Transaction on Signal Processing 57 (2009)
📖 G. vom Bögel, M. Weimer, R. Thill et al., WSA & SCC 2023

Signal Model I

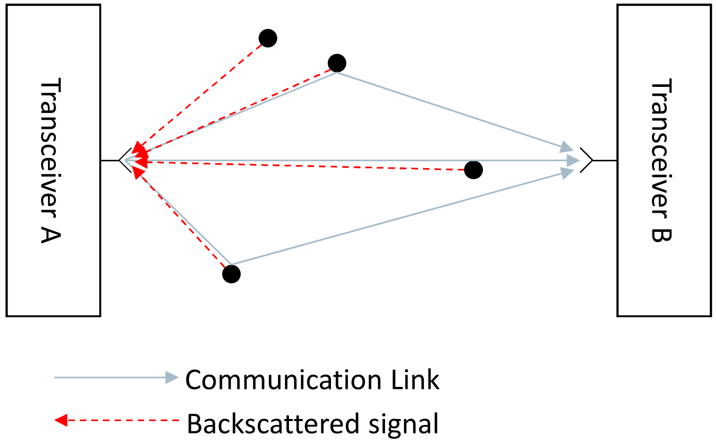
Preliminaries

Basic assumption on system structure

- Communication centric system design
- Mono-static sensing
- Multi-carrier system to facilitate spectrum allocation

Basic assumptions on signal

- Transceivers A and B use CP-OFDM for communication and sensing
  - Signal generation in the digital domain
  - DA conversion good signal reproduction assumed
  - Multipath AWGN channel
- Backscattered signal only contains a few strong scatterers (short to medium distance)
- ToF of backscattered signal is within the cyclic prefix of the OFDM-symbol
- SISO setup, so far only range measurements no angle information



Signal Model II

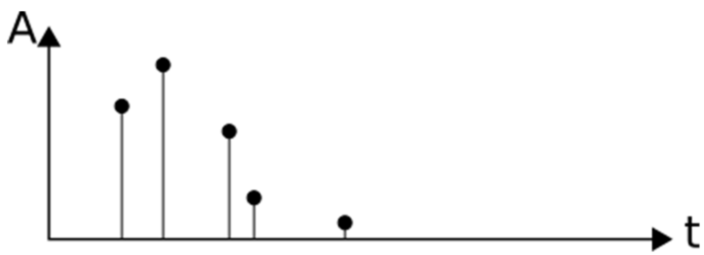
Structure of Sensing Matrix

- Rx-signal given convolution of range profile (modelled as weighted sum of time-shifted Dirac pulses) with Tx-signal
- Fourier representation of Rx-signal in base-band given by

$$\mathcal{F}[y_{Rx}^{b}](f) = \sum_{k=1}^{s} \rho_k \mathcal{F}[y_{Tx}^{b}] e^{-j2\pi f \tau_k} e^{-j2\pi f_{Tx} \tau_k}$$

where

- y_{Rx}^{b} is the received time domain base-band signal
- y_{Tx}^{b} is the transmitted time domain base-band signal
- ρ_k is the complex scattering coefficient (amplitude and phase)
- τ_k is the round-trip time delay of scatterer k ; $1 \leq k \leq s$
- f_{Tx} is the carrier frequency



📖 S. Guha, A. Bathelt, M.H. Conde, J. Ender, IEEE Journal of Selected Topics in Signal Processing 17 (2023)

Non-contiguous Spectrum Assignment I
Some Signal Properties

Spectrum properties of OFDM signal

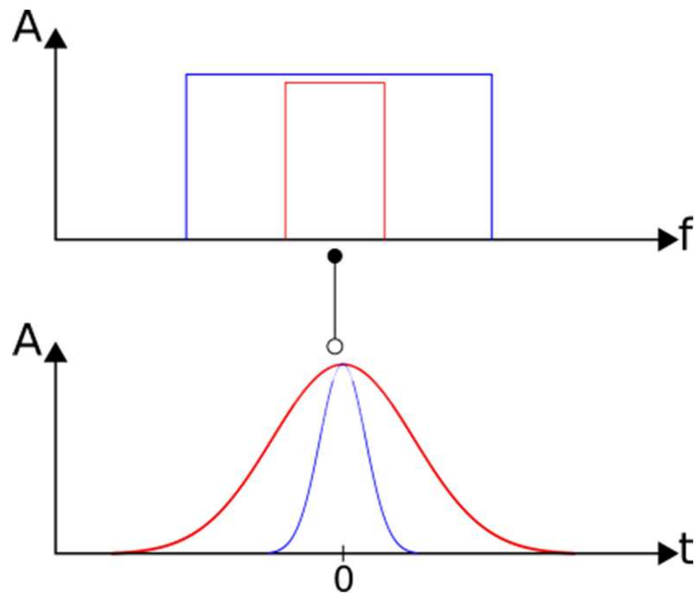
- Occupation of spectrum by carriers in contiguous way
- Narrow spectrum

Resolution properties

- Nominal range resolution given by $\Delta\tau \propto \frac{c}{2\beta}$
- Further decrease of resolution due to shape of ambiguity function

Compressed Sensing properties

- Depending on problem definition
  - Decrease of τ_r for fixed number of measurements m
  - Decrease of number of measurements m for fixed τ_r (e.g., random selection)
- Decrease of τ_r nevertheless impacted by increasing coherence



Matrix representation in frequency domain for arbitrary range grid:

$$y = A \cdot x$$

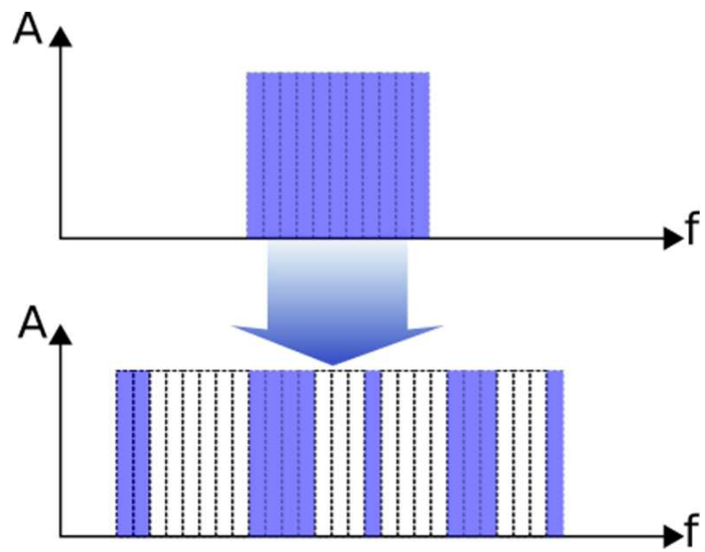
Solve for:

$$\min\|x\|_1 \text{ subject to } \|y - Ax\|_2 < \epsilon$$

Non-contiguous Spectrum Assignment II

Gapped Carrier Grid

- Option left: Increased bandwidth for decrease of τ_i
- Straightforward idea: Increase number of occupied carriers or increase sub-carrier bandwidth
  - Problem: Scarce spectrum even more congested, other users are denied from accessing the spectrum to communicate



Solution

- Random distribution of required sub-carriers along the usable spectrum
  - Only a minimal amount of the spectrum effectively used
  - Leaving gaps (big enough) for other users to communicate
- Choose M sub-carriers out of N total available sub-carriers along the available spectrum
  - f_{j_i} ; $i = 1, \ldots, M$ with $j_i \in \{1, \ldots, N\}$
- Yielding:
  - Effective communication bandwidth: $\beta_{\text{Comm,eff}} = M\Delta f$
  - Synthetic sensing bandwidth : $\beta_{\text{Sens,eff}} = f_{j_M} - f_{j_1}$

📖 A. Bathelt & R. Thill, 2023 EuRAD

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Simulations I
Setup

Signal Setup

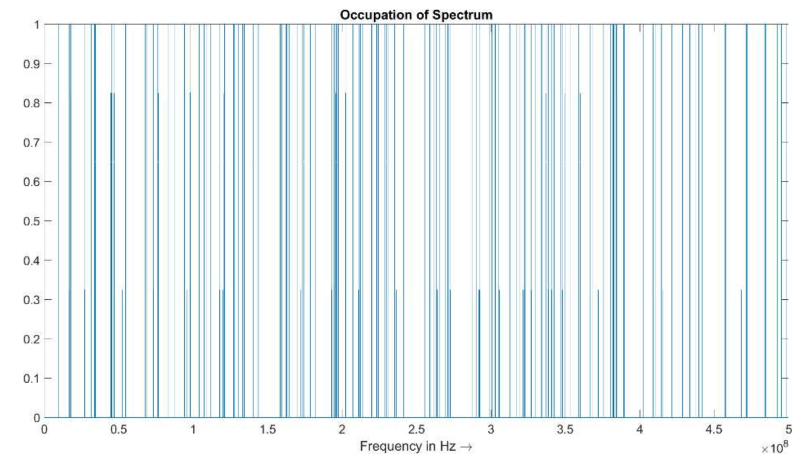
- Frequency range 2 of 5G, n257 (26.5 – 29.5 GHz) (exemplarily)
- QPSK modulation, amplitude 1
- 200 (100) carriers with $\Delta f = 15 \text{ kHz}$ out of $\left\lceil \frac{BW}{\Delta f} \right\rceil = 33334$ occupied
- y_{Tx}^{b} by FFT over whole BW and cyclic prefix
- y_{Rx} by convolution of y_{Tx} with range profile
- Noise with respect to energy of y_{Tx}

CS Setup

- Sensing matrix set according to randomly chosen carrier
- Range gate width of 0.3 m / 0.2997 m with a total of 1000 positions
- 7 objects >> sparsity (s) is 7
- Algorithms: OMP (needs a-priori specification of s), BLASSO

BW	f_{TX}	T	Tgi	SNR
500 MHz	28 GHz	$1/\Delta f$	$T/4$	0

N	M	Δf	ΔR	s
1000	200 / 100	15 kHz	0.3 m / 0.2997 m	7



A. Bathelt & R. Thill, 2023 EuRAD

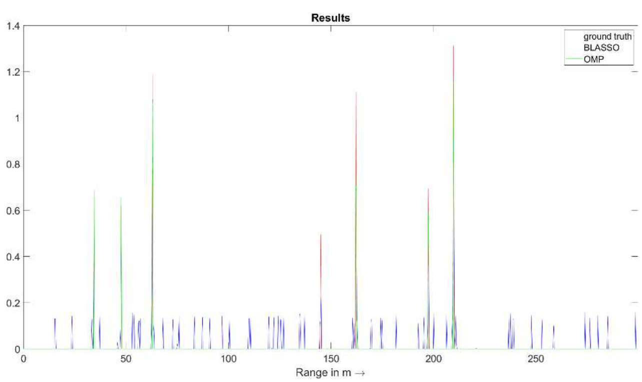
Simulations II

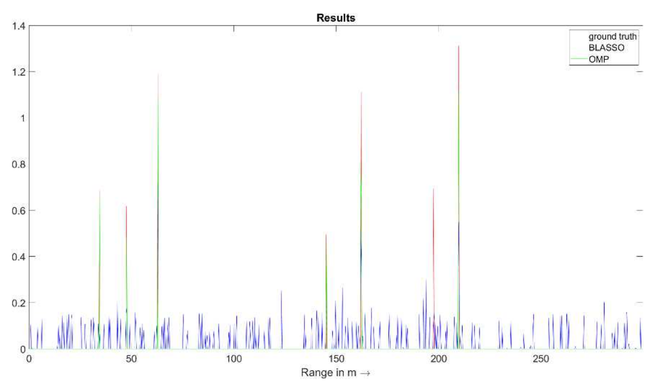
Results I – Basis Mismatch

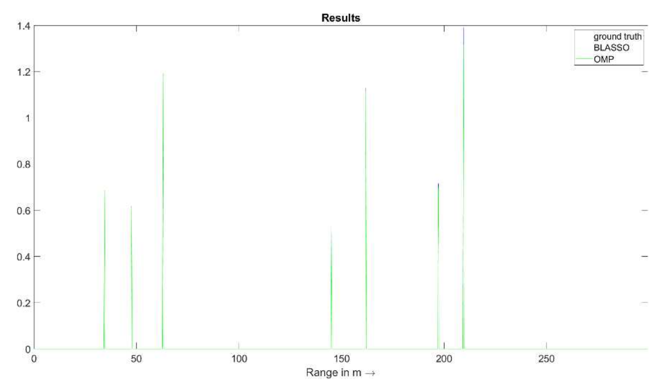
📖 A. Bathelt & R. Thill, 2023 EuRAD

- Object grid given by $\frac{[BW/\Delta f]c_0}{2} = 0.2997\ \mathrm{m}$
- Range gate width of $0.3\ \mathrm{m}$ not aligned with object grid
- Objects #4, #5 most severe impacted by deviation (left diagram)
- Ripple of BLASSO due to estimation of deviations of objects from grid not due to noise (cf. left diagram for $m = 200$ and $m = 100$)
- Estimation exact for aligned grid (only as theoretical reference)

	ground	0.3 m	0.2997 m
#1	34.764 m	115.88	116
#2	47.951 m	159.84	160
#3	63.236 m	210.79	211
#4	145.353 m	484.51	485
#5	162.435 m	541.45	542
#6	197.8 m	659.33	660
#7	210.087 m	700,29	701







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Consensus-based time synchronization I
Basic Algorithm

- For a JCS network individual sensors (=agents) need to be synchronized
  - Hardware solutions can be ruled out due to size restrictions
  - Agents need to agree on same time basis -> consensus problem
- Current CBTS algorithms assume local clocks to be time-invariant
  - In reality LOs always contain some kind of time variation, e.g. phase noise
- Idea: Use dynamic consensus on local clocks $\tau_i(t) = \alpha_i(t)t + \beta_i(t)$
- Create global, common clock: $\bar{\tau}(t) = \hat{\alpha}_i\tau_i(t) + \hat{\beta}_i$
  - with some compensation factors $\hat{\alpha}_i$ and $\hat{\beta}_i$
  - t_k: global time basis
  - Local estimation of common clock $\hat{\bar{\tau}}_i(t_k) = x_i^{[2]}(t_{k+1})$
  - Neighbour states: $x_j^{[l]}$
  - Local states: $x_j^{[l]}$
  - $a_{im} = \frac{1}{|\mathcal{N}_i|+1}$ if $x_m^{[l]}$ neighbor or local, else 0
  - $\Delta^{(n)}$: n^{th}-order difference of local clock τ_i

$$x_i^{[1]}(t_{k+1}) = \sum_{m=1}^{n} a_{im}x_m^{[1]}(t_k) + \left(\Delta^{(2)}\tau_i\right)(t_k)$$

$$x_i^{[2]}(t_{k+1}) = \sum_{m=1}^{n} a_{im}\, x_m^{[2]}(t_k) + x_i^{[1]}(t_{k+1})$$

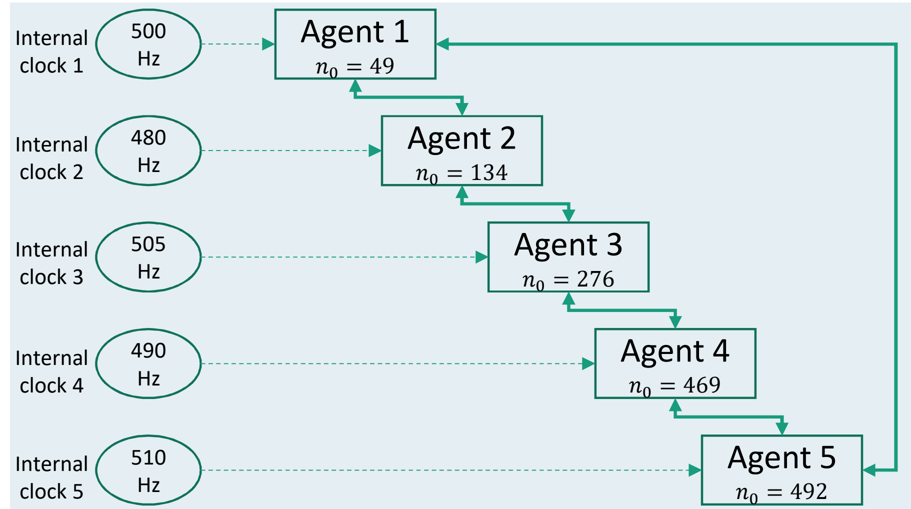
$$\hat{\alpha}_i(t_k^+) = \frac{x_i^{[1]}(t_{k+1})}{(\Delta^{(1)}\tau_i)(t_k)}$$

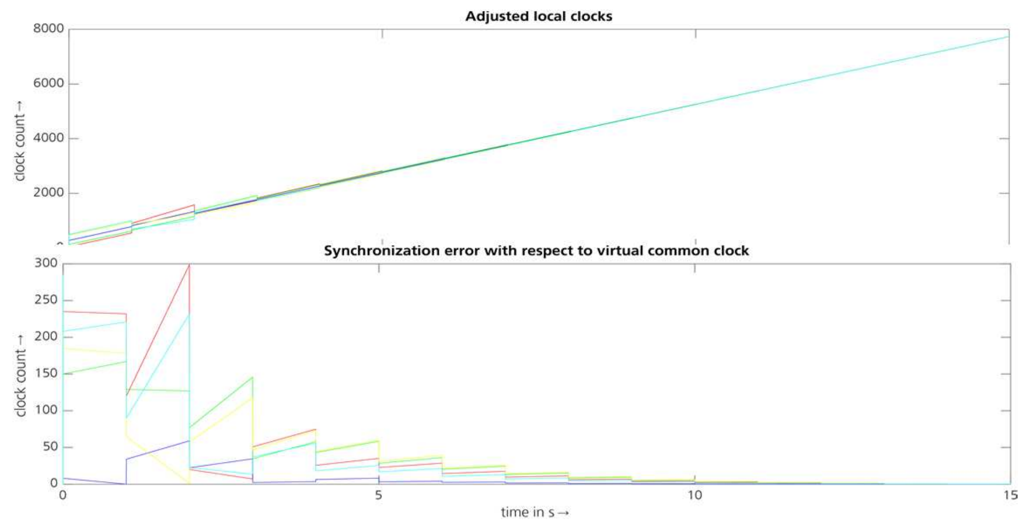
$$\hat{\beta}_i(t_k^+) = x_i^{[2]}(t_{k+1}) - \hat{\alpha}_i(t_k^+)\tau_i(t_k)$$

A. Bathelt, IEEE Control Systems Letters 7 (2023)

Consensus-based time synchronization II
Simulation

- For a JCS network individual sensors (=agents) need to be synchronized
  - Hardware solutions can be ruled out due to size restrictions
  - Agents need to agree on same time basis -> consensus problem
- Current CBTS algorithms assume local clocks to be time-invariant
  - In reality LOs always contain some kind of time variation, e.g. phase noise
- Idea: Use dynamic consensus on local clocks $\tau_i(t) = \alpha_i(t)t + \beta_i(t)$
- Create global, common clock: $\bar{\tau}(t) = \hat{\alpha}_i \tau_i(t) + \hat{\beta}_i$
  - with some compensation factors $\hat{\alpha}_i$ and $\hat{\beta}_i$
- Problem: Global timing by t_k
  - Not realistic in practice
  - Asynchronous operation more relevant
  - Consensurs not absoulte but relative





A. Bathelt, IEEE Control Systems Letters 7 (2023)

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System and Antenna Requirements

Antenna

- (Ultra-) massive MIMO
  - High directivity
  - Multi-beam possible
  - Should be applicable to high bandwidths
- Reconfigurable Intelligent Surfaces (RIS)
  - Controlled beam steering for distributed sensing
  - Metasurfaces
  - Reflect arrays with phase shifters

Components

- Highly integrated T/R modules
- Mixed-signal design
  - e.g. SiGe
  - CMOS compatible process
- Heterointegration
  - Graphene
  - Cheap thin-film process
  - Substrate independent process
- Increased computational load of FFT due to wider spectrum
- Multi-band reconfigurable filters

System

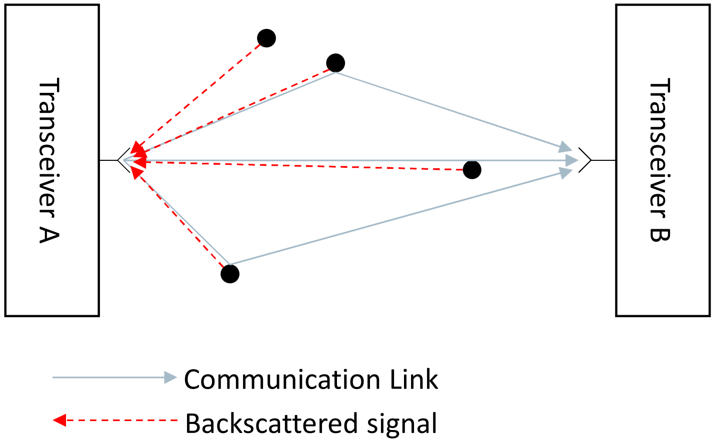
- System required to operate in full-duplex mode
  - Improved hardware for good Tx/Rx isolation
  - Cross-talk considered object at range 0
    -> removed in post processing or by filter
  - Implement self-interference cancellation methods
- Alternative: Co-located Rx that acts as sniffer

📖 I. F. Akyildiz et al., IEEE Access 8 (2020)
📖 G. vom Bögel, M. Weimer, R. Thill et al., WSA & SCC 2023
📖 Z. Wang et al., Adv. Electron. Mater. 7 (2021)

Summary & Outlook

Summary

- Problem: „Good“ resolution needs bandwidth, which is wasteful considering the amount of information
- Previous work showed feasibility of gapped spectrum for sensing
- Sub-carrier structure of OFDM facilitates gapped spectrum based on choice of carrier
- Random carrier selection yields CS problem based on random selection of rows of orthogonal basis matrix
- Effective bandwidth
  - Communication: $\beta_{Comm} = M\Delta f$
  - Sensing: $\beta_{Sens} = f_{j_m} - f_{j_1}$ with $f_{j_i}, i = 1, \ldots, M, j_i \in \{1, \ldots, N\}$



Future work

- Implementation of estimation using sparse FFT
- Implement asynchronous dynamic CBTS
- Development of reconfigurable hardware platform for JCS
- Integration of RIS with Graphene components and SiGe mixed-signal components

Thank you for your attention!

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