An optimized GFDM software implementation for low-latency

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Who are we?

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Armin Dekorsy

Research Focus

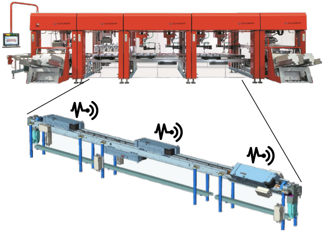
- (Wireless) Communications
- Digital Signal Processing
- Physical Layer
- Medium Access Layer

New wireless communication system for Industry 4.0

- State-of-the-Art technologies
  - high latency
  - low reliability
  - non-deterministic
  - FPGA or ASIC
- The future
  - high flexibility
  - software implementation
  - parameterizable

INDUSTRIAL RADIO.DE

- I4.0 closed-loop-control
  - latency $< 1\text{ms}$
  - reliability 10^{-9}
  - deterministic



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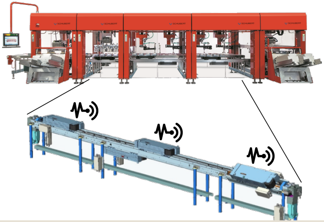


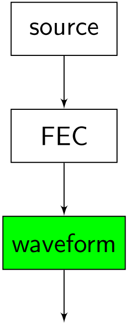
Goal

A new wireless communication system $\rightarrow$ HiFlecs

Outline

Outline

System model



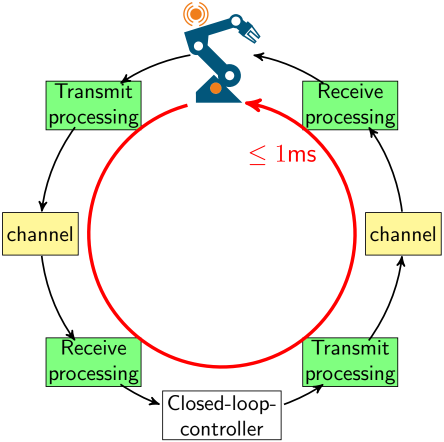
Multicarrier waveform

- flexible
- robust
- coexistence

Other components

- source
- error correction (FEC)
- etc.

Motivation



Channel

- control properties

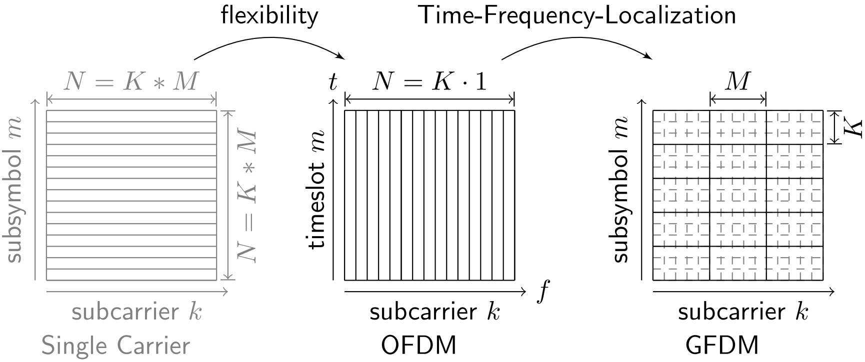
Processing

- SDR implementation
- measure latency

→ **can we achieve low latency?**

Outline

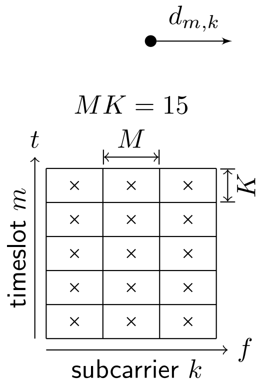
GFDM[1]



N complex symbols, K subcarriers, M timeslots

[1] N. Michailow et al. (2014), "Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks"

GFDM basics



- map $d_{m,k}$ onto $\boldsymbol{d} \in \mathbb{C}^{N\times 1}$, $N = MK$
  - elements in $\boldsymbol{d}$ correspond to lattice points
  - unused subcarriers are filled with 0
- modulate frame with $\boldsymbol{x} = \boldsymbol{A}\boldsymbol{d}$, $\boldsymbol{A} \in \mathbb{C}^{N\times N}$
  - $\boldsymbol{A}$ contains circularly shifted and modulated replicas of a prototype filter $\boldsymbol{g} \in \mathbb{C}^{N\times 1}$
  - non-rectangular filters $\boldsymbol{g}$ are used
- apply Cyclic Prefix (CP) to modulated frame
  - only one CP per frame
  - circular frame property for simple equalization

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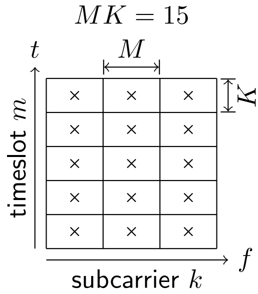

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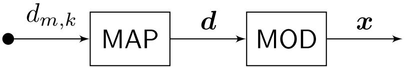

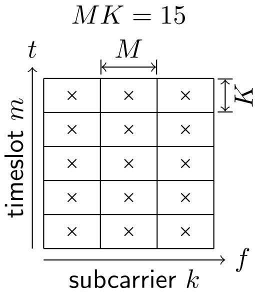

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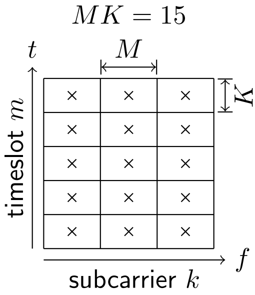

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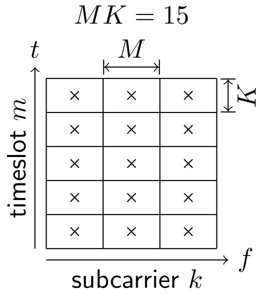

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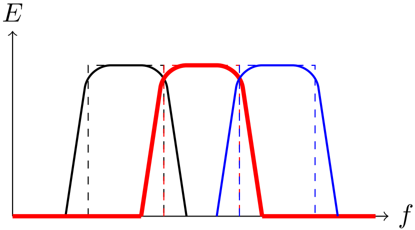
Challenge $\boldsymbol{x} = \boldsymbol{A}\boldsymbol{d}$ is inefficient

GFDM modulation[2]

Modulate $x = Ad$ in frequency domain

choose subcarrier filters G to be bandlimited



Advantages

G bandlimited, e.g. red

- fast FFT implementation

managed limited interference to neighboring subcarriers

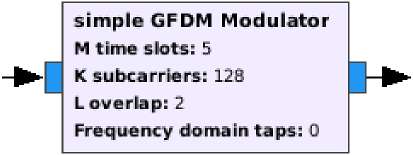
- robust against imperfections

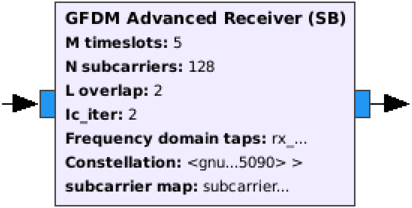
[2] I. Gaspar et al. (2013), "Low complexity GFDM receiver based on sparse frequency domain processing"

Outline

SDR implementation

GNU Radio module **gr-gfdm**[3] implements GFDM functionality





Components

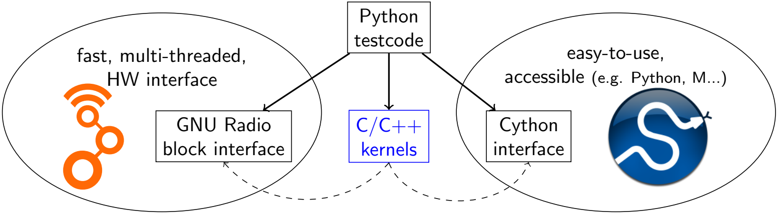
- Modulation & Demodulation
- Synchronization
- Lattice mapper & demapper

Contributions to gr-gfdm

- Heavy **code optimization**
- Implemented excessive **test code**

[3] https://github.com/kit-cel/gr-gfdm

Modular implementation



- use GNU Radio ecosystem
- flowgraph integration

- modularity
- optimized
- simple interface

- academic simulations
- simple playground

Benchmark setup

Assumptions

- perfect channel
  - no channel nor noise
- small packets 48 bit to 1024 bit
- small constellation, e.g. QPSK

Parameters

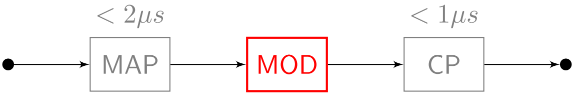
- $N = MK$ block size
- J Interference Cancellation iterations

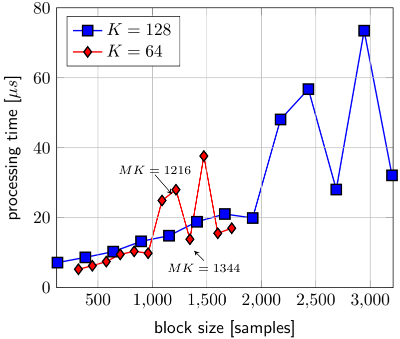
Objective

→ identify critical processing steps

→ identify high-impact parameters

Transmit Signal Processing Latencies

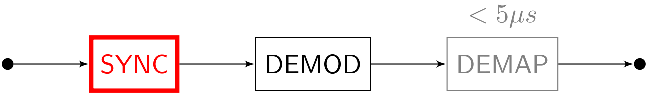


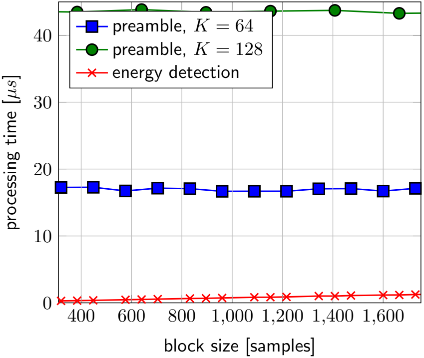


Results

- Modulation dominates latency
- Almost linear latency increase
  - Avoid outliers
- FFTW causes outliers because of large prime factors, e.g.
  - $MK = 1216 = 2^6 \cdot 19$
  - $MK = 1344 = 2^6 \cdot 3 \cdot 7$

Receive Signal Processing Latencies

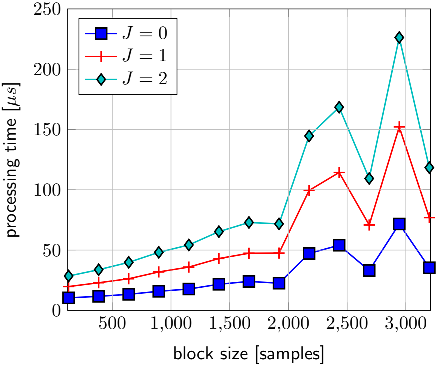




Synchronization

- 2-step synchronization
  1. rough frame-energy detection
  2. improved Schmidl&Cox preamble detection
- low-latency energy detection
- constant preamble detection latency due to window

Receive Signal Processing Latencies

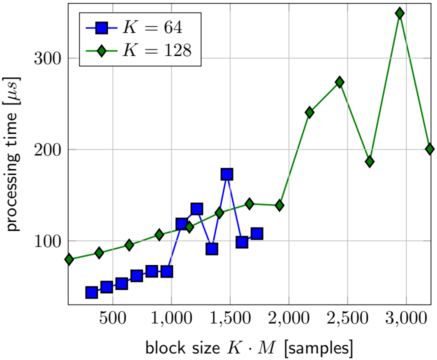


Demodulation

- FFTW-based frequency domain demodulation
- outliers due to prime factors, compare modulator
- Parallel Interference Cancellation
- interference cancellation iterations J increase latency

Outline

Overall latency budget



Example

- $M = 21$, $K = 64$, $MK = 1344$
- 20 MSps

\+ 74 µs air time

\+ 92 µs processing delay

→ 166 µs one-way latency

2× 332 µs round trip time

Result

Low-latency SDR GFDM implementation is feasible