Machine learning methods for the identification of humans and devices from received 5G/B5G signals

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Brno University of Technology

Oldest university in Brno, 120 years history

Faculties

- Faculty of Civil Engineering
- Faculty of Mechanical Engineering
- Faculty of Electrical Engineering and Communication
- Faculty of Architecture
- Faculty of Chemistry
- Faculty of Business and Management
- Faculty of Fine Arts
- Faculty of Information Technology

University Institutes

- Centre of Sports Activities
- Central European Institute of Technology (CEITEC)
- Institute of Forensic Engineering

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Main areas of work

- Wireless transceivers for SatCom and UAV communications
  - to increase the power efficiency of the transmitter
- Classification of wireless transmitters
  - additional PHY layer security
- Joint communication and Sensing
  - New PHYsical layer waveforms
  - Channel measurements
  - Sensing of environment, e.g. crowd monitoring and activities detection

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Wireless transceivers for SatCom and UAV communications

This work has been supported by ESA-ARTES project AO/1-8873/17/NL/NR) - Compact Bidirectional Amplifier for Remotely Piloted Aeronautical Vehicles, and 4000124030/18/UK/ND - Fully Adaptive RF Linearizer

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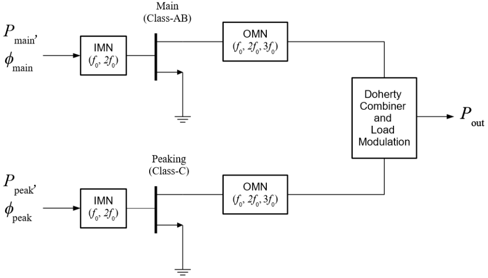
Dual Input Digital Doherty Power Amplifier in L-band (1-2 GHz)



- Main/Peaking PA power distribution
- Main/Peaking PA phase shift

Selected application:

- L-band INMARSAT, up to 64-QAM
- data rates of up to 1Mb/s, 200 kHz channel spacing
- PAPR of 6 dB, 42 dBm nominal power
- Qorvo T2G6003028-FL for Main and Peaking PA
- Doherty PA designed by Honeywell

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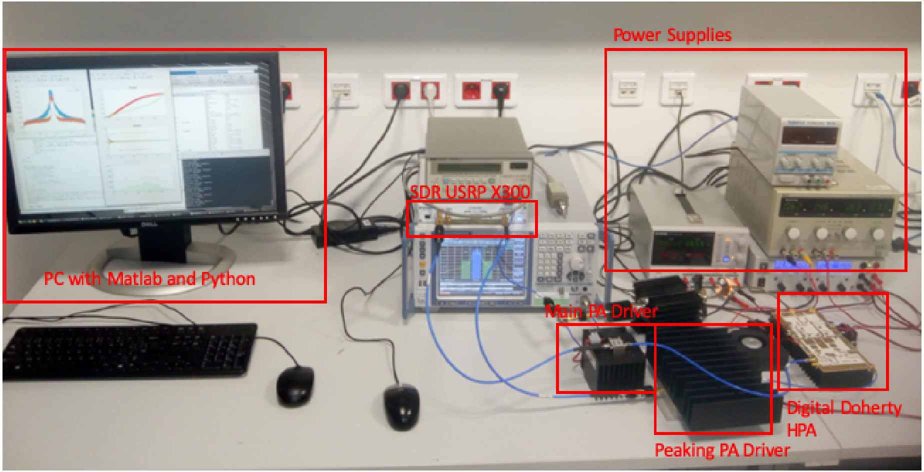
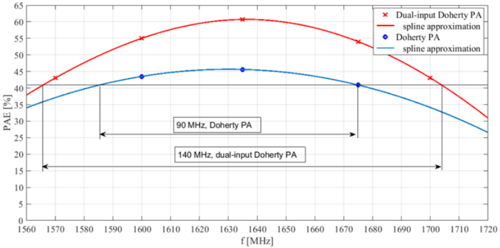
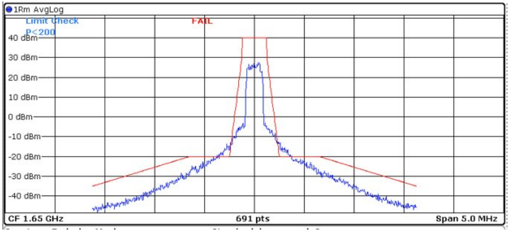
Dual Input Digital Doherty - Test-bed



Dual input digital Doherty - Efficiency / Spectral mask





- PAE improvement due digital Doherty optimization
- For 41% target PAE, 50% band extension

- tight INMARSAT mask, especially in corners
- cannot be met at nominal power
- Combination with Predistortion

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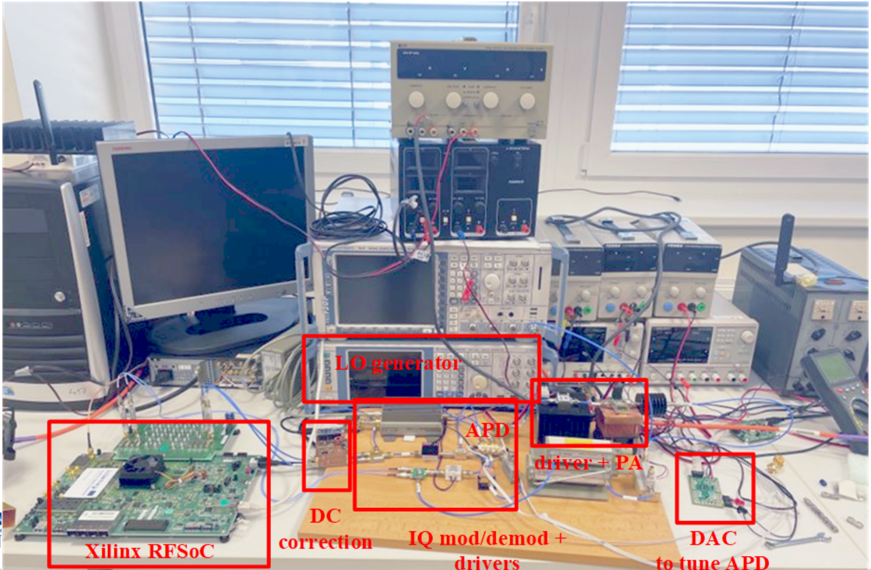
X-band SatCom test-bed (7-11 GHz)



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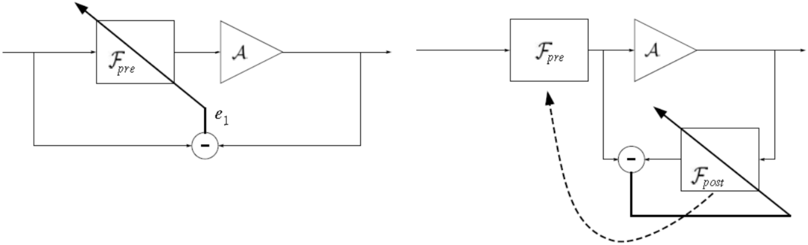
Digital Predistortion Architectures

- Direct vs Indirect Learning Architecture



- Feedback receiver needed
- Complexity increase
  - DPD algorithm estimation - Least Squares: $b = (U_x^H U_x)^{-1} U_x^H y$
  - Additional observation receiver with ADC's (BW increase by factor of 3)
  - BW increase in the forward path

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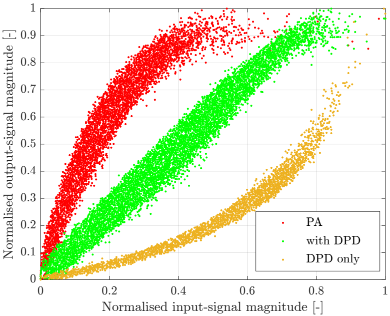
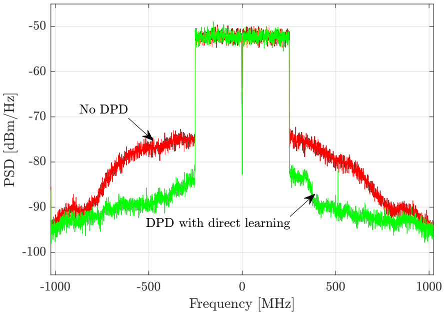
Wideband digital predistortion





- Testing predistortion limits
- 4096-subc. OFDM, DFT precoding,
- 64-QAM on subcarriers
- PAPR of 9.5 dB

- DLA DPD, damped Newton method
- 35 dBm power
- 10 dB ACPR improvement
- EVM improvement from 8.3 % to 5%

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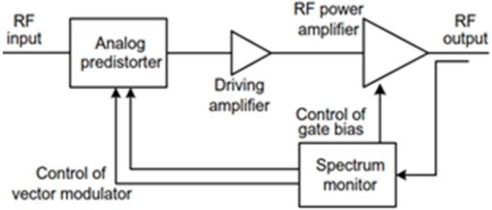
Analog predistortion - tuning

- APD tuning, selectable criteria (ACPR, ...)
- AM/AM and AM/PM APD tuning voltages, ATT prior/between/after APD



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Classification of wireless transmitters

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Classification of wireless transmitters

- Classification of user terminals
- Identification of fake base 4G/5G stations from the received signals

This work is funded by Ministry of Interior of the Czech Republic project VJ03030044 Robust 5G networks

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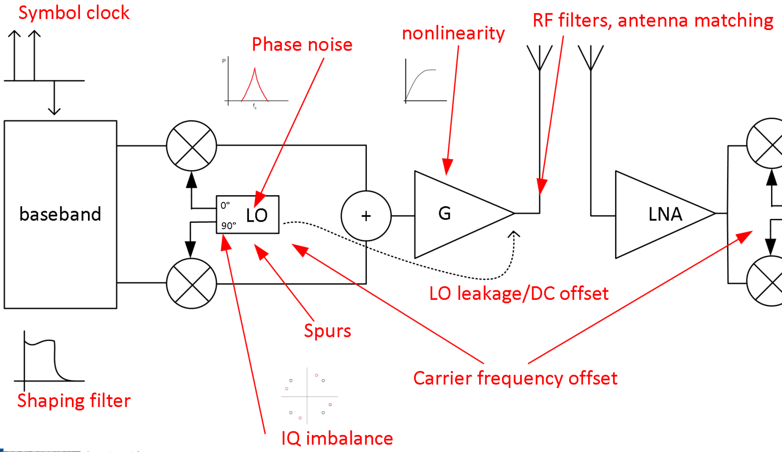
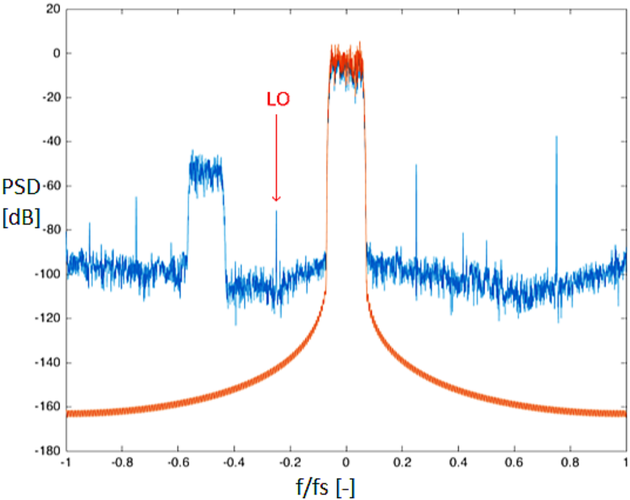
Radio Frequency (RF) transceiver imperfections

The quality of a signal influenced by imperfections of RF components.



How real transmitted signal looks like?



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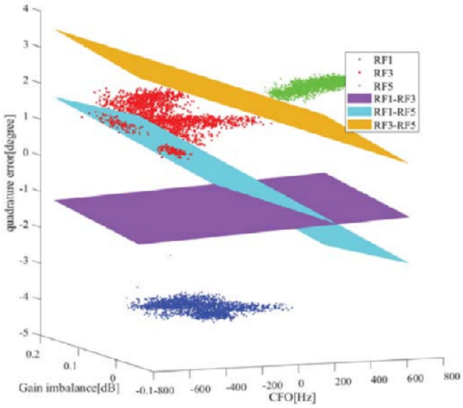
Classification example - feature space

- Experiment with 9 wireless transmitters
- The same manufacturer, same type
- Simple Support Vector Machine classifier
- Possibility to use raw data



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Joint communications and sensing: application to crowd monitoring and human activity classification

Why we are interested in

- Wireless devices are everywhere
- Passive solution to monitor persons with privacy by design
- Flow of crowd, evacuations, detection of emergency events, ...

Two scenarios we investigate

- Detection of human activity
- Counting persons in the crowd

Cooperation partners:

- Silicon Austria Labs, Linz, Austria
- TU Wien, Austria

This work is funded by Ministry of Interior of the Czech Republic project VJ01030008 Passive crowd monitoring system with privacy by design
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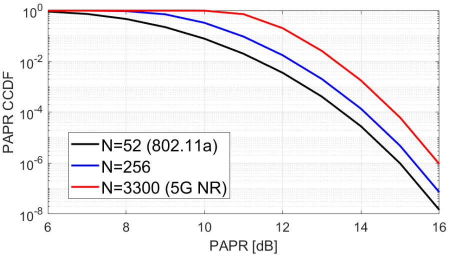
Waveforms and Bandwidths

Peak to Average Power Ratio (PAPR)

Modulation	$\beta = 0.1$	$\beta = 0.3$	$\beta = 0.5$
16-QAM	7.2 dB	6.3 dB	5.7 dB
16-APSK	5.7 dB	4.8 dB	4.2 dB

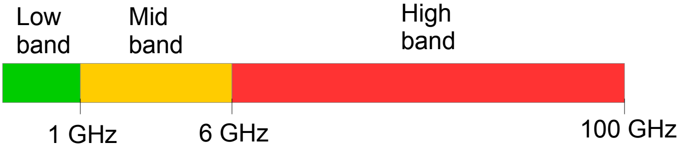
Baldi, M., Chiaraluce, F., Angelis, A.d. et al. A comparison between APSK and QAM in wireless tactical scenarios for land mobile systems. J Wireless Com Network 2012, 317 (2012).

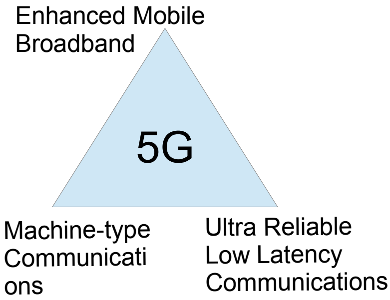


System	LTE	5G NR FR1	5G NR FR2	SAT X-band	IEEE 802.11ad
Bandwidth	20 MHz	100 MHz	400 MHz	400 MHz	1830 MHz

- **High bandwidth make us easier to monitor the environment (radar)**

Motivation for mm-waves: bandwidth



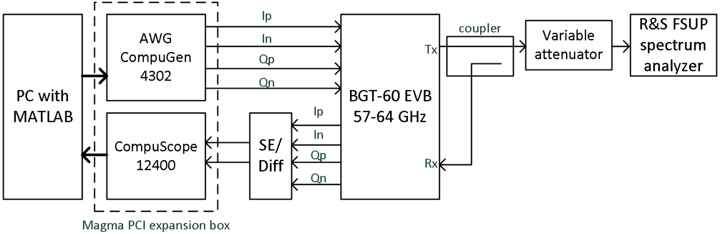


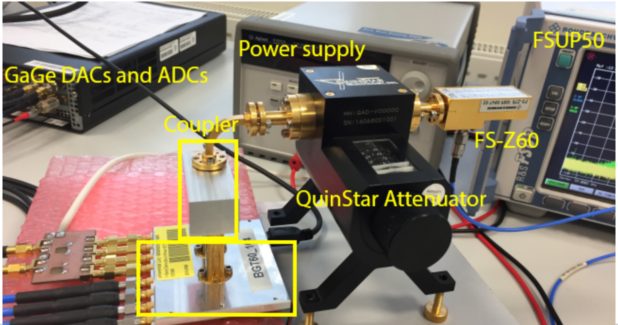
Licensed access in mm-waves
27.5-28.35 GHz
37.6-38.6 GHz
38.6-40 GHz

Shared/Unlicensed access
37-37.6 GHz
64-71 GHz

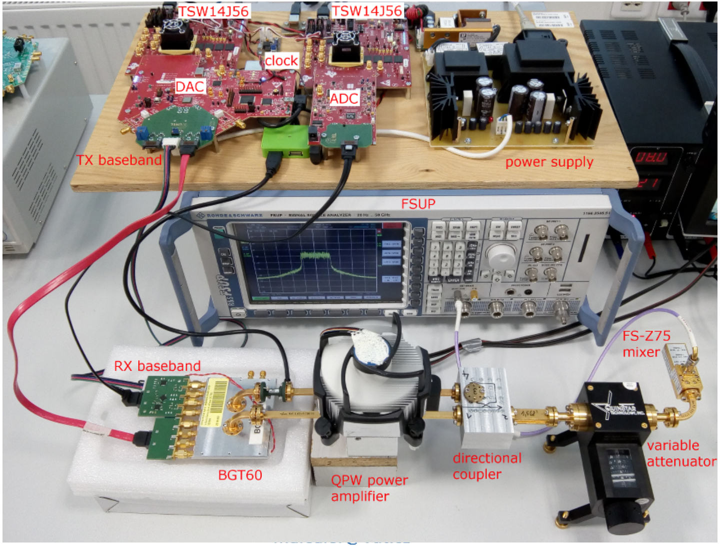
Total ~ 11 GHz !

1^{st} 60 GHz test-bed, version 1





1^{st} 60 GHz test-bed, version 2



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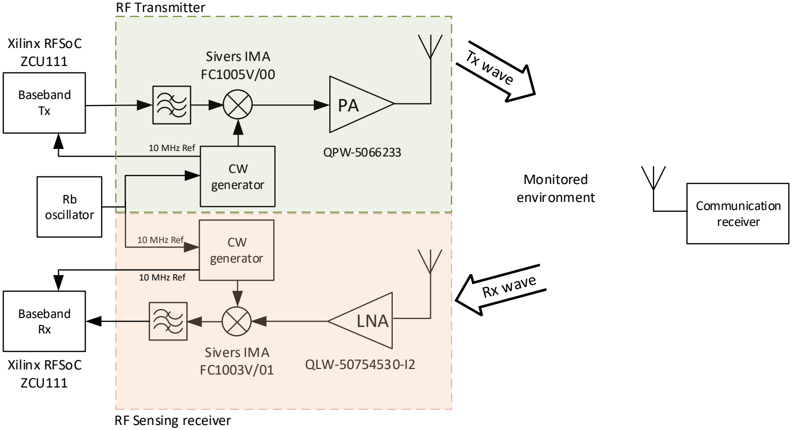
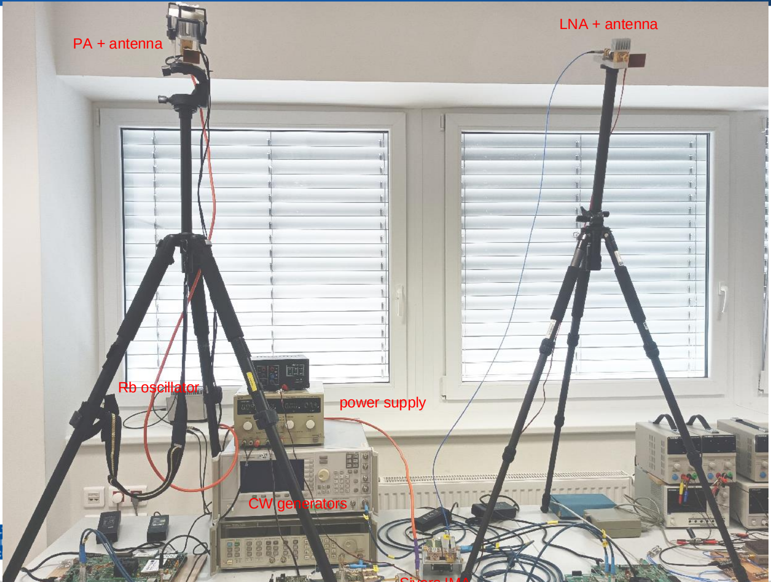
2^{nd} 60 GHz Test-bed used for experiment with person monitoring

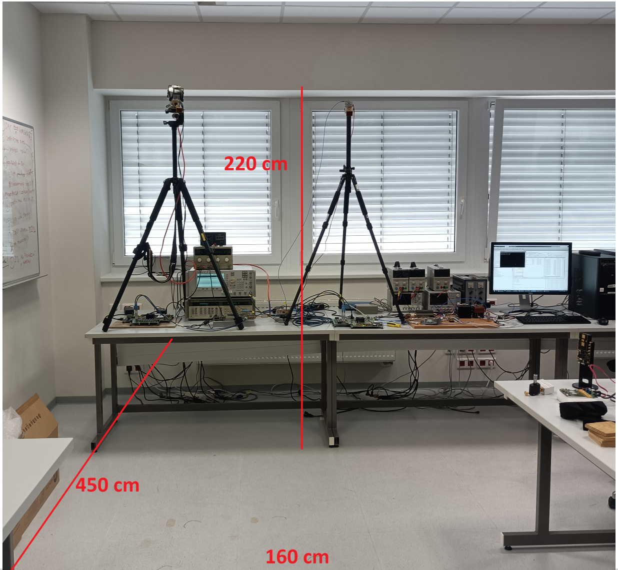


- 60 GHz band, up to 2 GHz bandwidth
- Xilinx RFSoC with 4 GSa/s ADC/DAC's
- Current investigation from point of view of person monitoring

Test-bed photo



Experimental scenario I



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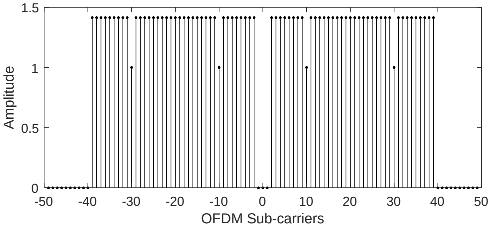
Person activity monitoring from 60 GHz OFDM transmission

- OFDM according IEEE 802.11a 60 GHz WLAN, limited to 400 MHZ BW
- subcarrier spacing of 5MHz
- 4 pilot carriers, equidistant, zero DC carrier
- 4 QAM payload



Person activity monitoring - processing, activities

- Activities distinguished by typical Doppler shifts variations over time
- Long FFT over N OFDM symbols used to get higher frequency resolution

$$X(n) = \sum_{k=1}^{N-1} X(k) \cdot e^{i \cdot 2 \cdot \pi \cdot n \cdot k / N}, \tag{1}$$

Activities:

- gait
- run at constant speed
- run with acceleration/deceleration passive/waving hands
- dancing

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Doppler spectrograms

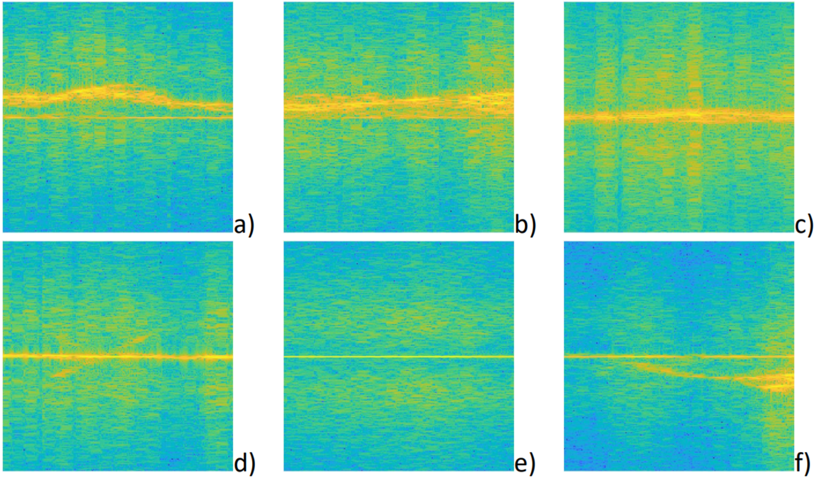
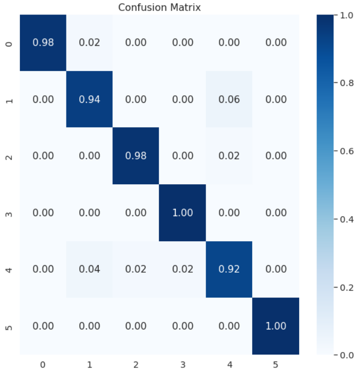


Fig. 7. Doppler patterns for all activity a) run b) gait c) random movement d) hand waving e) static f) deceleration

Classification

ARCHITECTURE OF THE CNN MODEL

Layers	Output dimensions
Conv2D	224x224x32
MaxPooling2D	112x112x32
Conv2D	112x112x32
MaxPooling2D	56x56x32
Conv2d	56x56x64
MaxPooling2D	28x28x64
Dropout	28x28x64
Flatten	50176
Dense	128
Dense (Softmax)	6
Trainable parameters	6 452 070



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Counting number of persons in the area

- Goal: Identify how many humans are in the monitored area?
- Requirement 1: Passive system, persons do not need to be connected
- Requirement 2: There are some wireless signals in place
- Similar to Vera/Tamara radar systems
- OFDM used in WiFi, 4G, 5G, DVB-T
- Which waveform will be used in 6G ?
- Orthogonal Time Frequency Space (OTFS) is one of the candidates
- **Note that the concepts of delay-Doppler processing can also be applied to different waveforms**

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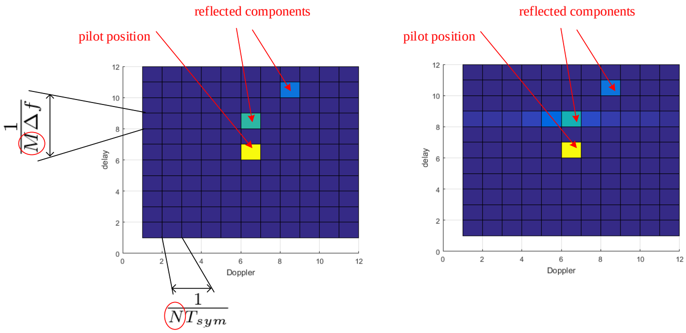
delay-Doppler grid

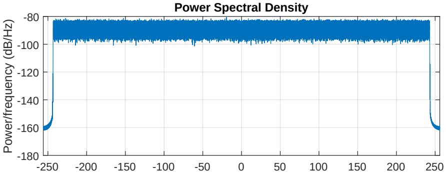
- Reflections from humans with some delay and Doppler shift



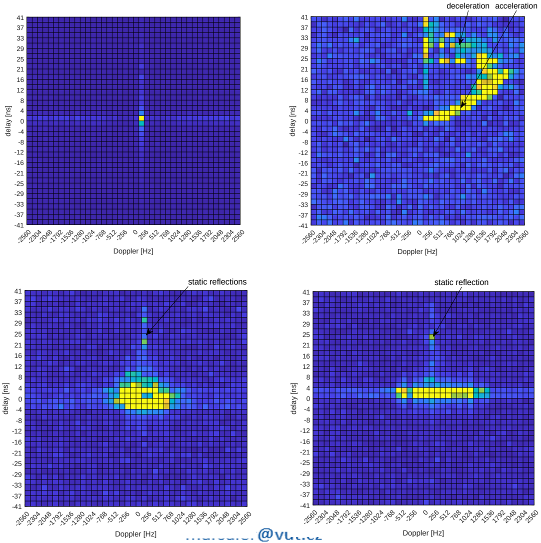
- delay and Doppler domain granularity: $\frac{1}{M\Delta f}$ and $\frac{1}{NT_{sym}}$

Signal parameters

M, number of subcarriers [-]	1900
M_0, number of zero subcarriers [-]	100
N, number of symbols in OTFS slot [-]	2000
Δ_d, delay resolution	2.1 ns
Δ_D, Doppler resolution	128 Hz
Number of pilot guards in delay domain [-]	48
Number of pilot guards in Doppler domain [-]	48
Sampling frequency	512 MHz
Signal bandwidth	$\approx$ 490 MHz
Data symbols	4-QAM, uncoded
Communication data rate	$\approx$ 920 Mbit/s



Max-hold plots



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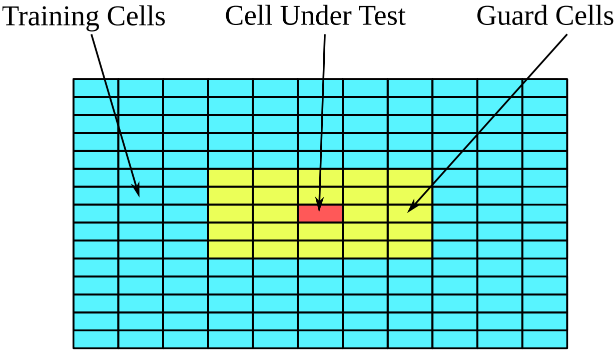
Constant False Alarm Rate (CFAR) detector

- The energy of Cell Under Test (CUT) is compared with the noise background
- noise estimated from training cells



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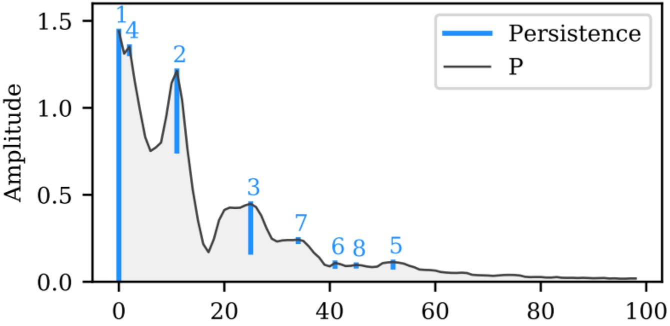
Persistent homology I

- Tool from mathematical topology
- Detection of Peaks
- Similarity to watershed transform from image processing



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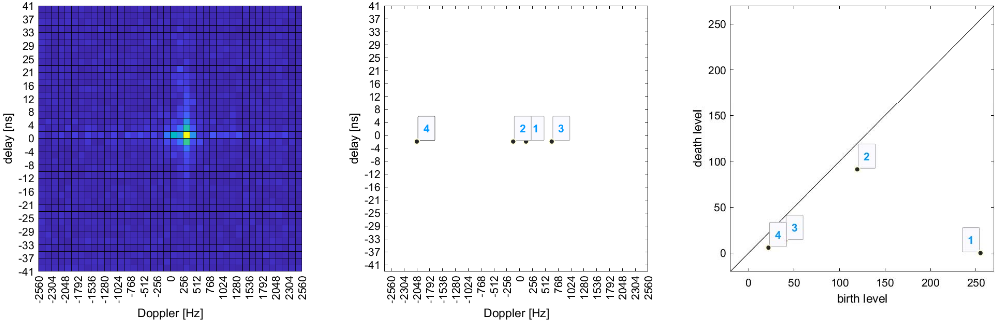
Huber, S. (2021). Persistent Homology in Data Science. In: Haber, P., Lampoltshammer, T., Mayr, M., Plankensteiner, K. (eds) Data Science – Analytics and Applications. Springer Vieweg, Wiesbaden. https://doi.org/10.1007/978-3-658-32182-6$_1$3

Persistent homology II

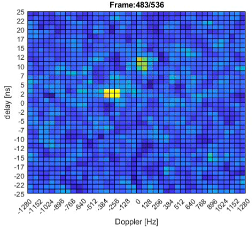
- Example from real measurement, one snapshot of dancing person
- delay-Doppler image, potential targets, death-birth diagram:



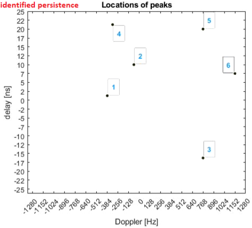
- Targets are classified according to their persistence
- Normalized z-score used to set the threshold for target (outlier) acceptance/rejection

Persistent homology + MultiTarget Tracker

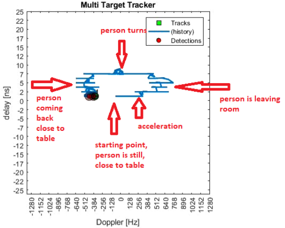
1. Plot in delay-Doppler domain for actual frame, you can see the received peaks caused by reflections



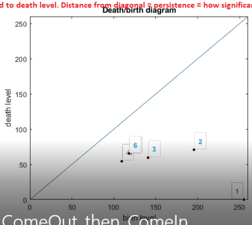
3. ouput of persistent homology: locations of identified peaks, 1 with highest persistence (see death/birth diagram), here 6 with the lowest identified persistence



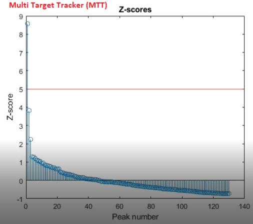
5. MTT output, to see the evolution of the position of identified peak. MTT also filters-out the detected peaks that are not confirmed in following frames



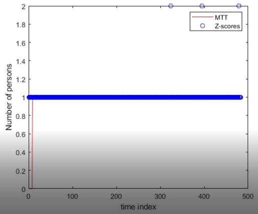
2. Output of Persistent homology. Maximal level of signal is 255. The threshold is starting at 255 and goes down. Once it crosses the peak in delay-Doppler domain, the peak "is born", when it vanishes, this correspond to death level. Distance from diagonal = persistence = how significant is the peak



4. Z-scores to of persistence of identified peaks, to check their significance. If above threshold (red line) then peak is input to the Multi Target Tracker (MTT)



6. Identified number of persons with the use of MTT and without (just based on Z-scores)



OnePerson_ComeOut_then_ComeIn

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Neural network classifier

- Classifies number of persons (1,2,3) in the area
- Uses ConvNet+LSTM, sequences of 61x91 images
- Does not track nor provide info on person distance/speed
- 7138 sample sequences, 80%/20% training/testing

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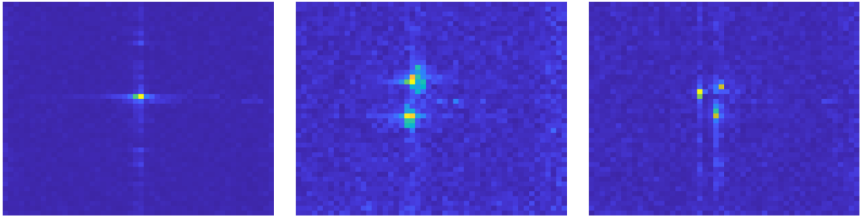
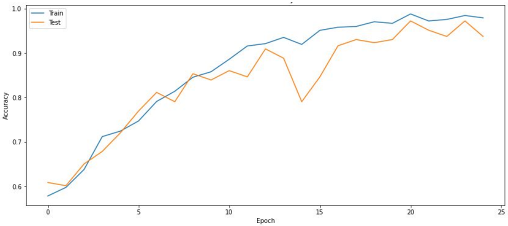
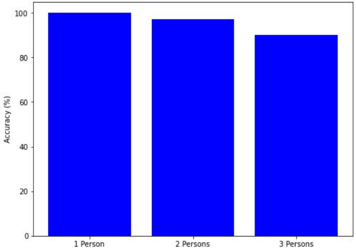
Neural network classifier II

- Example of clean images:



- Accuracy of classification





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Future work in this domain

- Investigate the methods in various environments (factory, garage, outside, ...)
- Extend to a higher number of persons (at least estimate)
- Differentiate humans and moving objects (forklift, crane, cyclist ...)
- To fuse data from various standards and bands
- Exploit the use of commercial devices

Thank you !

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