Perspectives of Cooperative PCL (CPCL) in Next Generation Mobile Radio

R. Thomä, C. Andrich, G. Del Galdo, M. Döbereiner, M. Hein, M. Käske, G. Schäfer, S. Schieler, C. Schneider, A. Schwind, P. Wendland

reiner.thomae@tu-ilmenau.de

THÜRINGER INNOVATIONSZENTRUM MOBILITÄT

Fraunhofer IIS

TECHNISCHE UNIVERSITÄT ILMENAU

Supported by the Freistaat Thüringen and the European Social Fund

ESF EUROPA FÜR THÜRINGEN EUROPÄISCHER SOZIALFONDS

EUROPÄISCHE UNION Europäischer Sozialfonds

Content

- 5G mobile radio
- 5G and ITS-G5 perspective for cooperative driving
- Limitations of conventional car radar sensing
- Basic idea of CPCL
- Features of ITS-G5 and LTE-V2X radio access as relevant for CPCL
- CPCL signal processing within the LTE-framework
- Perspectives of high resolution parameter estimation in sparse radio resource grids
- Future 5G network perspectives for CPCL

5G: Next Generation Mobile Radio – What can we expect?

- High data rates (100 fold)
- Low latency (down to 1 ms)
- Resource efficiency (bandwidth, energy, infrastructure)
- High connectivity
- High scalability
- High security

New business opportunities for Network Service Providers (NSP)

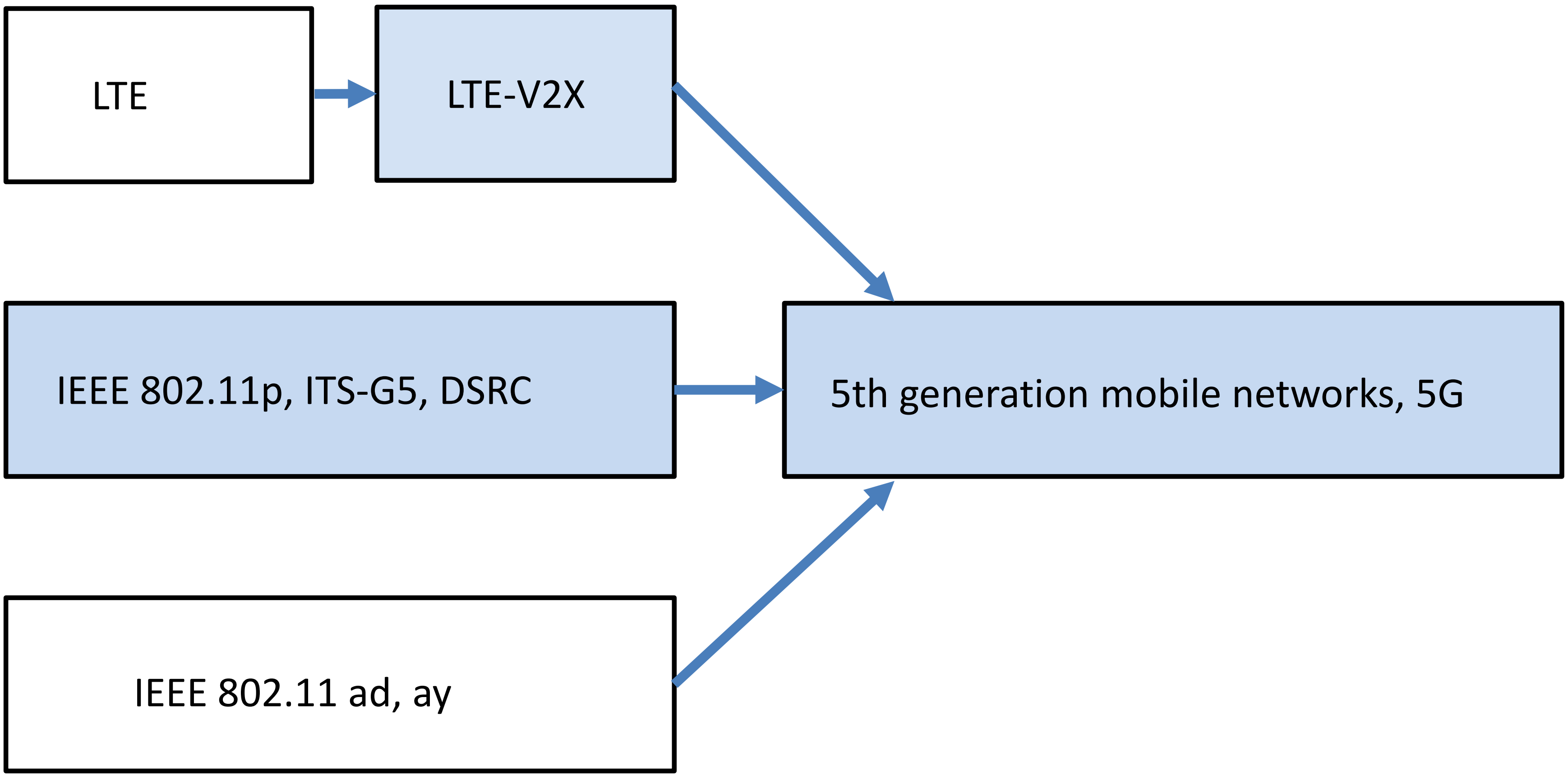
- *Vertical sectors* beyond pure telecom industry
  - Factory of the future
  - Healthcare
  - Energy
  - Media and entertainment
  - Security
  - *Automotive and mobility*

5G Air Interface and Network Architecture

- Wider range of spectrum bands (500 MHz…6 GHz, ca. 40 GHz, ca. 60 GHz)
- Spectral sharing, spectral aggregation, channel bonding
- Flexible air interface
- Network slicing
- New waveforms (**OFDMA**, **SC-FDMA**, FBMC, UFMC, GFDM)
- Full duplex air interface
- Massive MIMO (MU, full dimension, mmWave)
- Direct device-to-device communication (D2D, M2M, V2V)
- **Mobile Edge Cloud (MEC)** offers real-time computational facilities

Evolutionary Steps from LTE and ITS towards 5G V2X

the Standardization Perspective (3GPP, IEEE, ETSI)



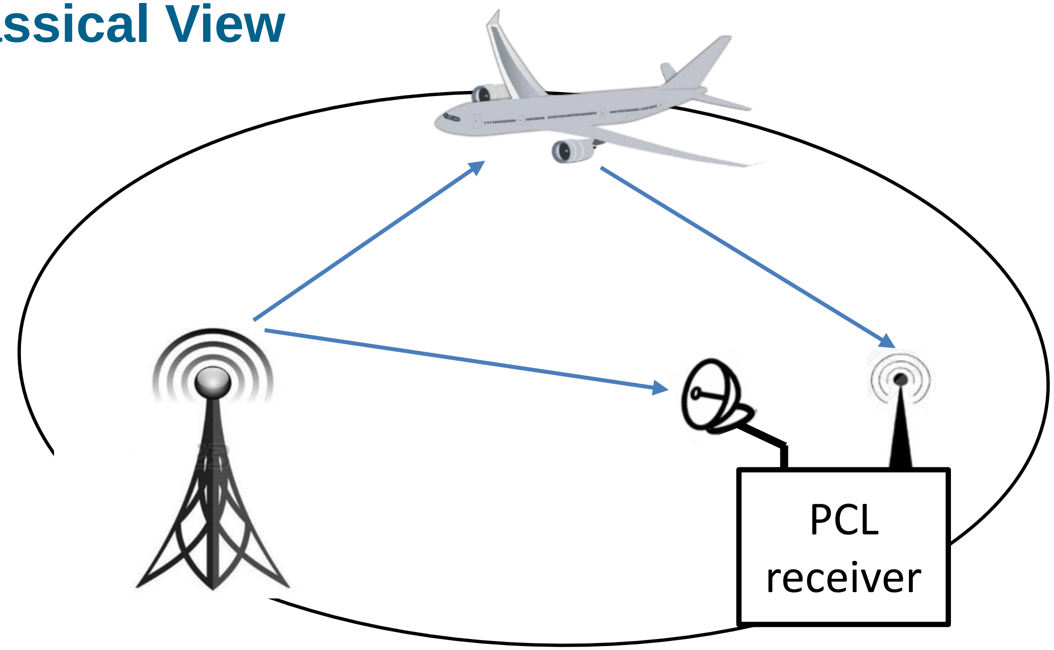
State of the Art in Car Radar Sensing

- Radar based Automatic Cruise Control (ACC) at 24/26 GHz and 76-81 GHz is already well established
- Penetration rate is still low (mostly high-end cars and trucks)
- Radar sensing data are used only locally (“ego-car-centric”, monostatic)
- Radar data fusion (cooperative sensing) is not yet used (no V2X communication)
- Cooperative and autonomous driving will lead to a huge increase in Radar sensor density (number of cars and increased field of view)
- Interoperability and interference issues will be increasing
- FMCW not well suited for interference mitigation
- Radar MAC and adaptive Radar resource scheduling not yet available

On the other hand - in mobile radio many of the problems that car-Radar will have in the future are already solved!

Bandwidth efficient access, frequency reuse, MAC, inherent synchronization, adaptive resource allocation, scheduling, Tx predistortion, spatial filtering rsp. beamforming, Radar data networking

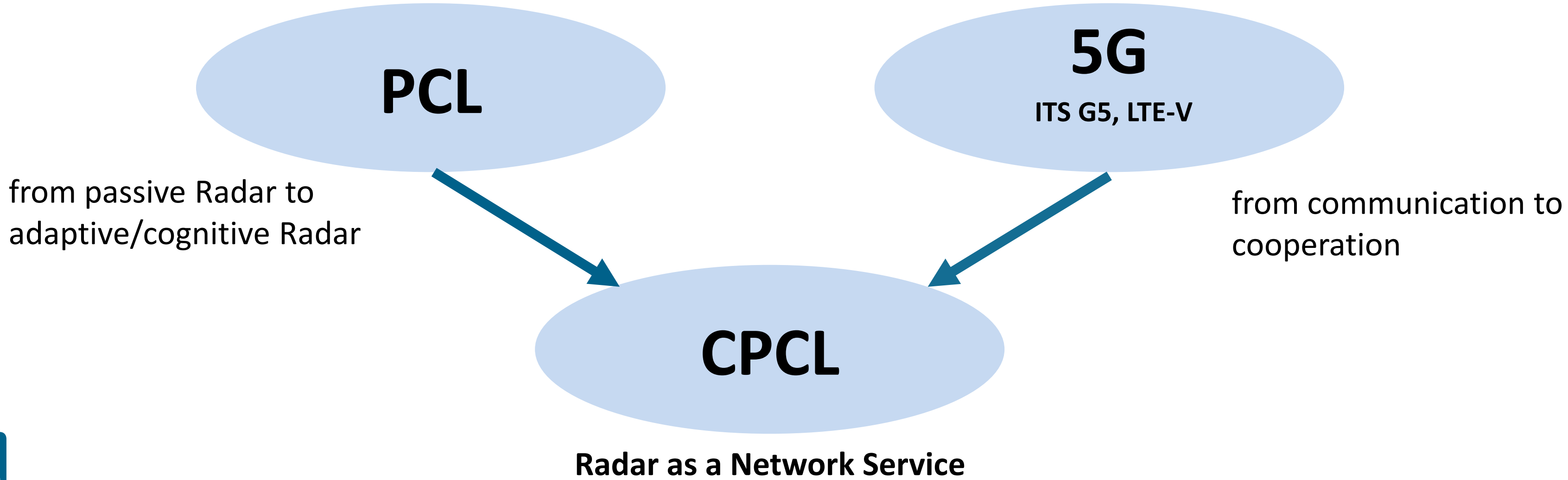
Passive Radar – The Classical View



- PCL: Passive Coherent Location
- Uses transmitter of opportunity: FM Radio, DVB-T, DAB, GSM, LTE, WiFi
  - Broadcast: FM Radio, DVB-T, DAB
  - Communication: GSM, LTE, WiFi
- Advantage: covert operation, bistatic view, resource efficient
- No cooperation between observer and transmitter
- Also in discussion: cognitive sharing of frequency bands for Radar and radio

CPCL: Cooperative Passive Coherent Location

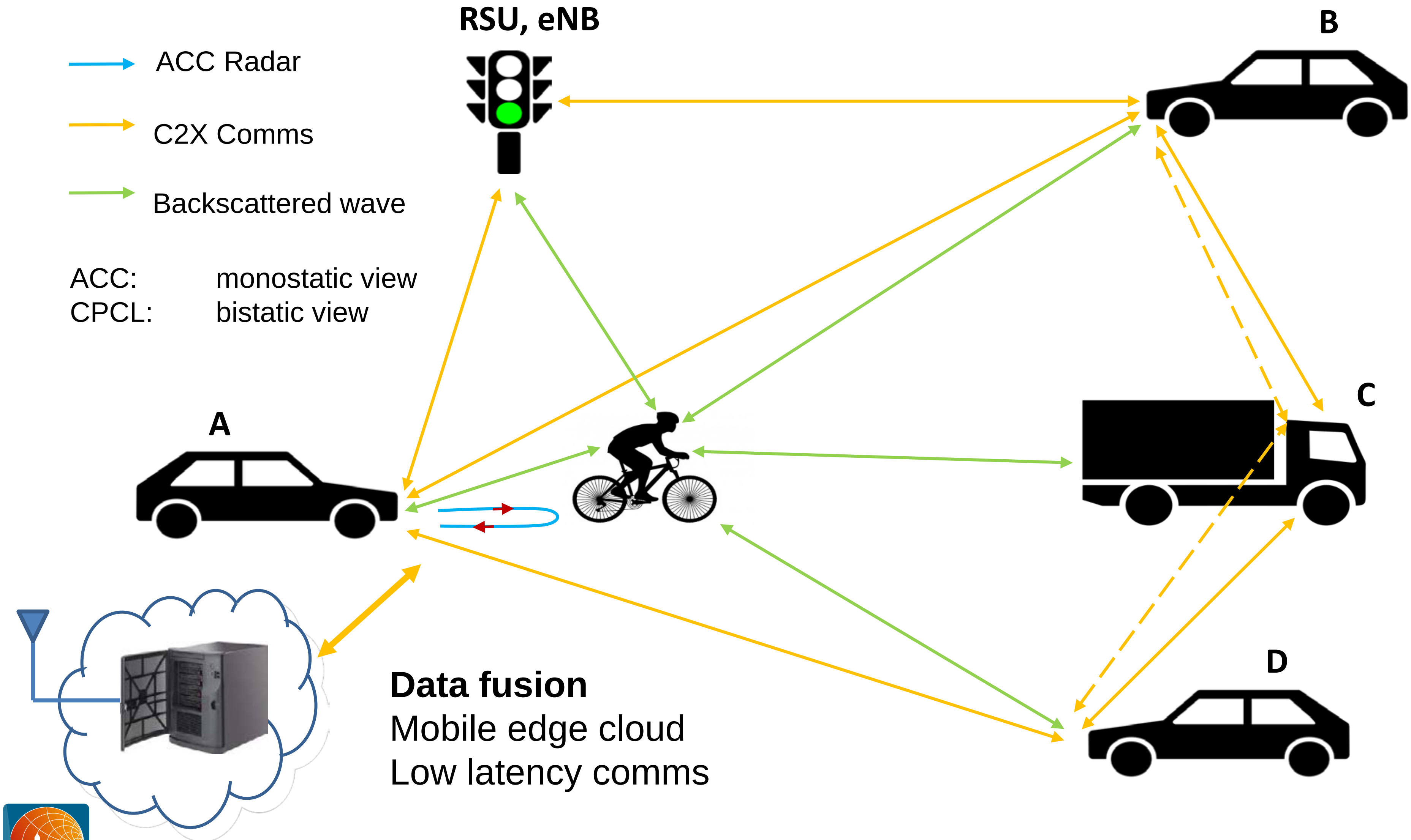
- From PCL to CPCL – a groundbreaking innovation?
- Integrates communication and passive coherent location (joint communication and Radar)
- CPCL uses radio communication nodes **of the same network** acting as distributed bistatic Radar illuminators
- Takes advantage of mobile radio signaling procedures (OFDM, MAC)
- Joint communication/Radar resource allocation
- Allows situation aware Radar resource scheduling
- Exploits mobile network resources for data fusion (mobile edge cloud)



CPCL – the Road Traffic Scenario

ACC Radar
C2X Comms
Backscattered wave

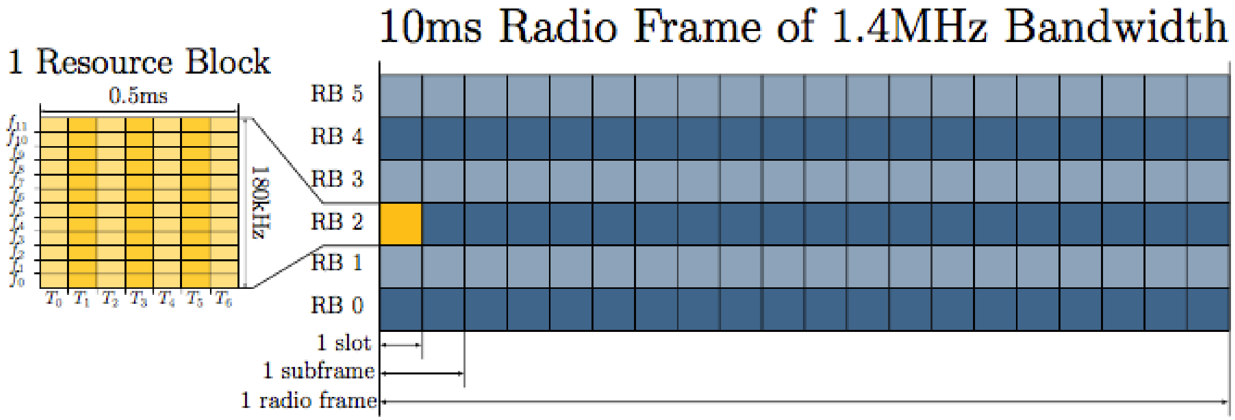
ACC: monostatic view
CPCL: bistatic view



Data fusion
Mobile edge cloud
Low latency comms

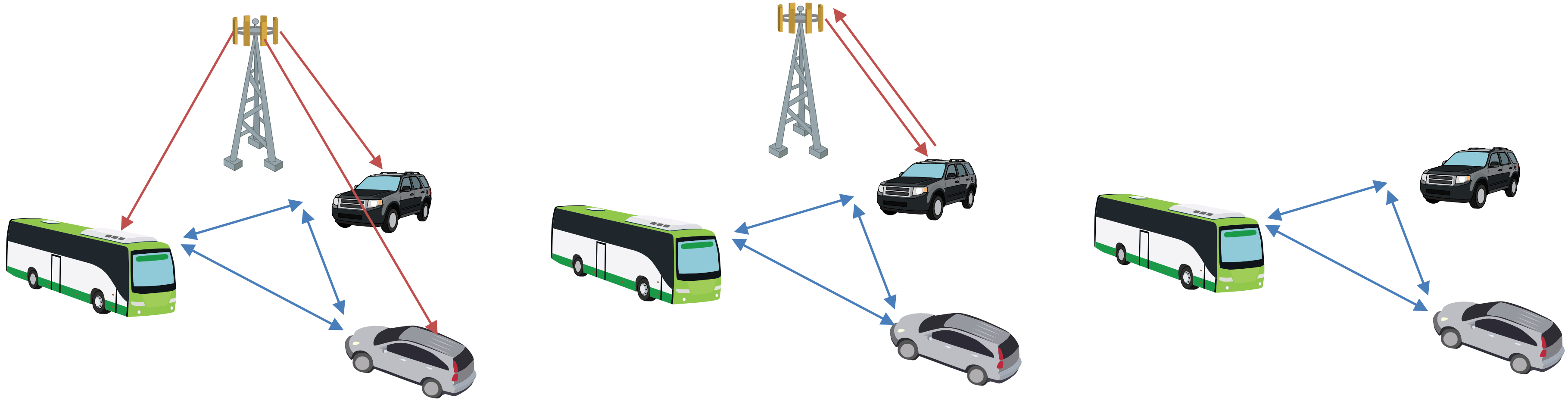
Synchronous DL/UL Radio Resource Allocation LTE

- Downlink: OFDMA, Uplink: SC-FDMA
- Multi-user version of OFDM, realized by assigning subsets of subcarriers to different users
- FDMA and TDMA Physical Resource Blocks (PRBs) assigned
- Timing advance synchronization allows time alignment of UL PRBs at eNB
- PRBs grouped in case of wider BW
- Scheduling according to time-frequency fading, network demands etc.
- $12 \cdot 7 = 84$ (#carriers $*$ #symbols) resource elements in case of normal cyclic prefix
- Minimum granularity: 2 PRBs (one subframe)
- 1.4 MHz: 6 PRBs … 20 MHz: 100 PRBs
- DL: equal power loading for all users, potentially spatial pre-distortion
- UL: user specific power loading



LTE-V2X Side-Link Channel

- Scenarios:



in coverage　　partial coverage　　out of coverage

- **In coverage of base station:**
  - eNB assigns resource pools (RPs)
  - scheduled access, predictable access times, less congestion problems
- **Partial coverage and out of coverage:**
  - Preconfigured resource and semi-persistent resource scheduling to reduce high scheduling overhead imposed by repeated broadcasts of small packets

Mobile illuminator network with largely synchronized multiple transmitters (synchronized MIMO Radar network)

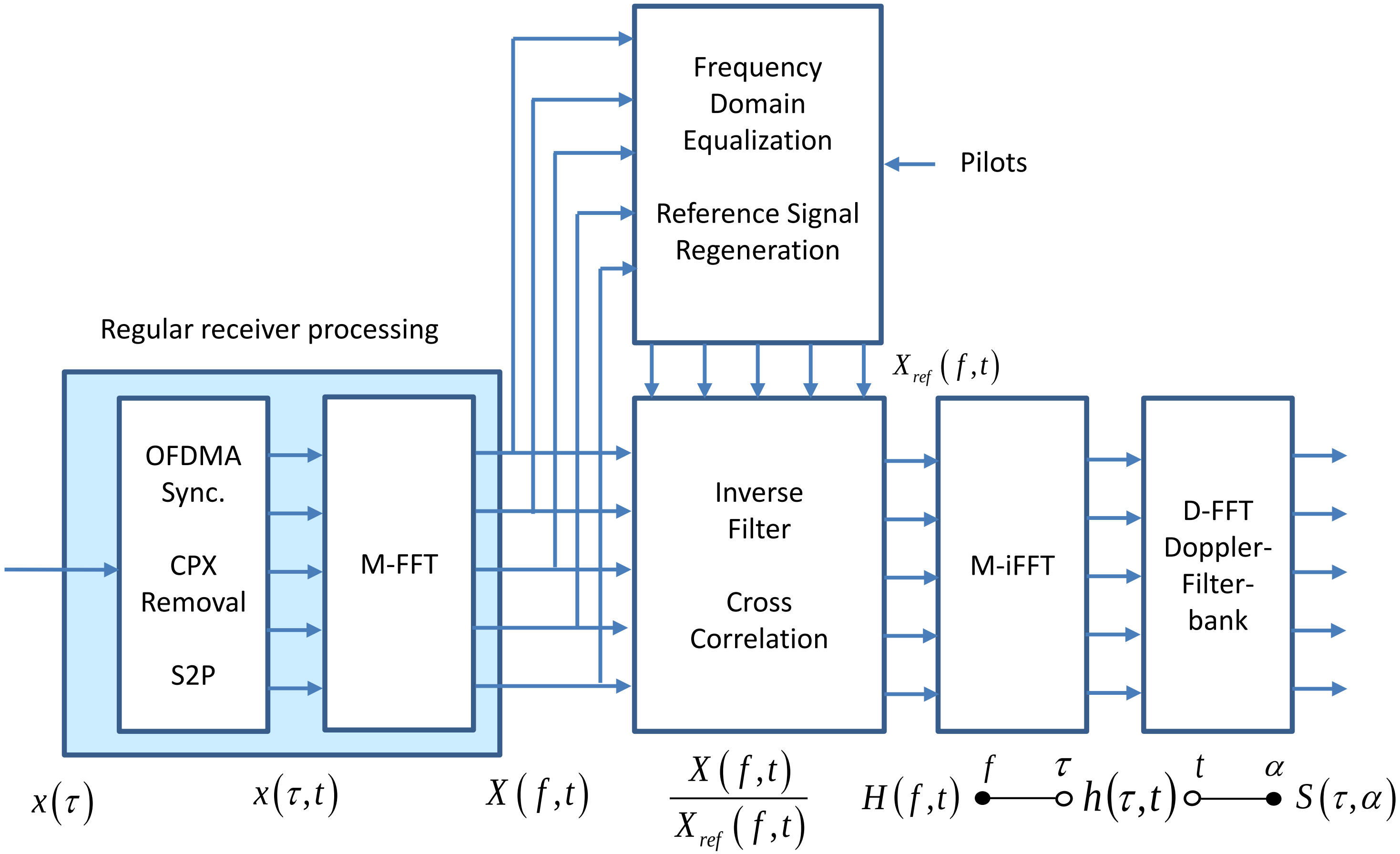
CPCL in LTE Down-Link

- eNB illuminates, multiple UE observe: **distributed SIMO-Radar**
- PRBs are allocated to serve multiple users
- Dedicated receiver (Radar-UE, RUE) logged in as UE
- **Synchronization and cyclic prefix removal reduces estimation variance (no leakage variance)**
- RUE receives full BW OFDM-symbol and uses it for Radar localization on the waveform level: Basically, any RUE can use the full OFDMA-symbol for Radar!
- OFDM-communication automatically includes reference signal regeneration
- Full band frequency domain equalization (FDE) desirable
- Reference signal inverse filtering simultaneously performs correlation processing
- Tx beamforming enhances/suppresses certain propagation directions. This has influence to CPCL performance (reference signal reconstruction target illumination). Pro or con?
- Tx spatial multiplexing (MIMO) causes self-interference if not properly decoded at the receiver. So, only RUEs can use the received MIMO transmit signal for Radar that perform full MIMO decoding
- Rx beamforming (if available) may enhance reference signal extraction

CPCL in LTE Up-Link

- PRBs are distributed to multiple users
- Tx power adjusted for equal received power
- Multiple UEs act as multiple synchronous Radar-illuminators **(distributed MISO)**
- Received signal PRBs are time aligned (synchronized) at eNB receiver
- Received PRBs can be processed as one single OFDM/SC-FDMA symbol (ensures multiple illuminator orthogonality, minimizes estimation variance!)
  - **Hint: never possible with an external PCL-observer (only with logged-in Tx/Rx!)**
- PRB waveforms associated to resp. Tx, isolated, individually equalized and regenerated
- Reference signal inverse filtering simultaneously performs correlation processing
- *But: Resulting radar return spectrum will be sparse in frequency domain and time domain according to uplink resource scheduling*
- *But: beamforming (if available) enhances reference signal extraction but has also influence to target illumination – Pro or Con?*

OFDMA based Receiver Signal Processing for CPCL

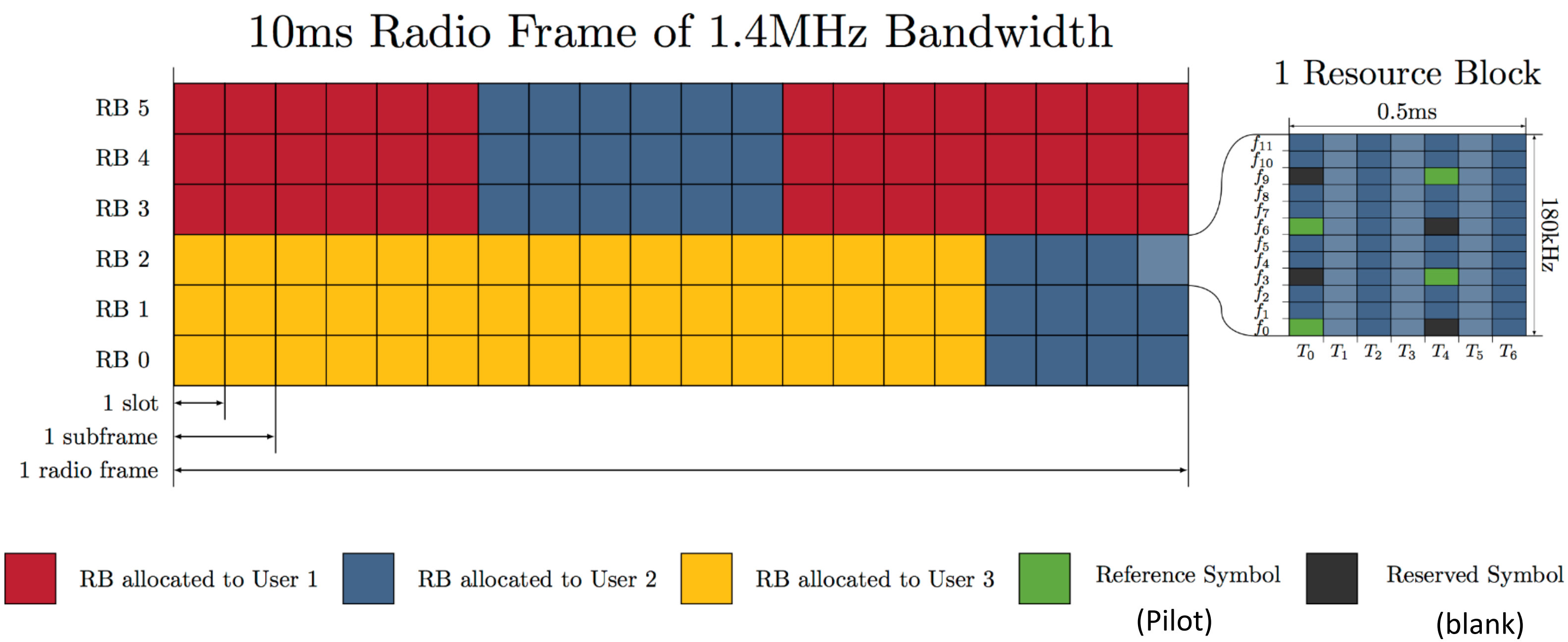


CPX : Cyclic Prefix
S2P : Serial to parallel

t : Slow time
τ : Fast time
α : Doppler frequency

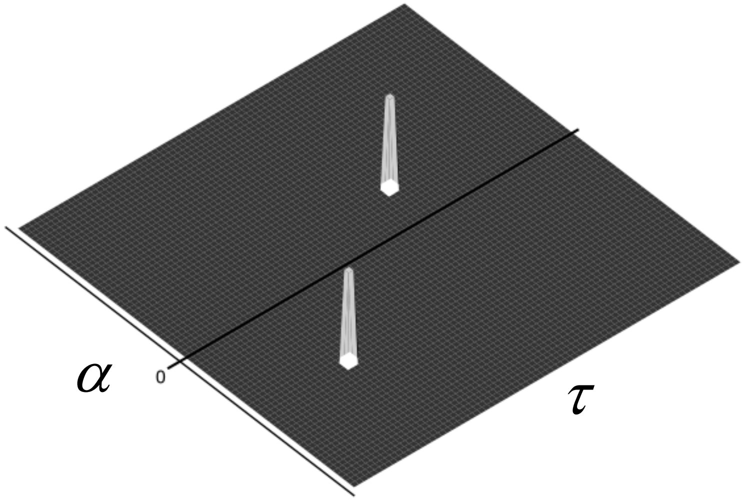
$X_{ref}(f,t)$: transmitted signal (correlation reference)
$x(\tau)$: received input signal
$H(f,t)$: Frequenz response (time variant)
$h(\tau,t)$: Impulse response (time variant)
$S(\tau,\alpha)$: Delay-Doppler-Spreading function

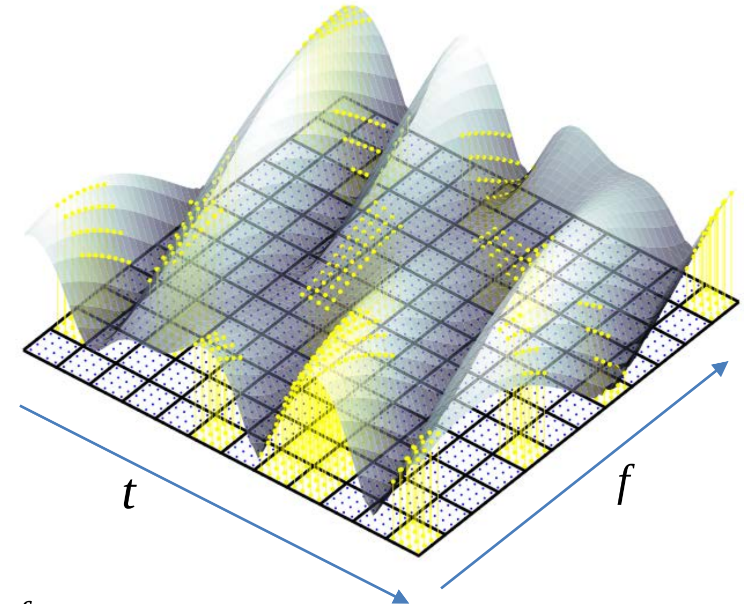
Sparse Ressource Grid in Time and Frequency



- UL: According to UE resource scheduling the resource grid in time and frequency belonging to one UE (one illuminator position) will be sparse
- DL: The resource grid can be kept more homogeneous by appropriate resource scheduling,
- Sparsity may also arise because of downlink beamforming (pro/con?)
- DL: Blank PRBs should be filled with dummy data

Two Path Example





$$S(\alpha,\tau) = \sum_{p=1}^{2} \gamma_p \delta(\tau - \tau_p)\,\delta(\alpha - \alpha_p)$$

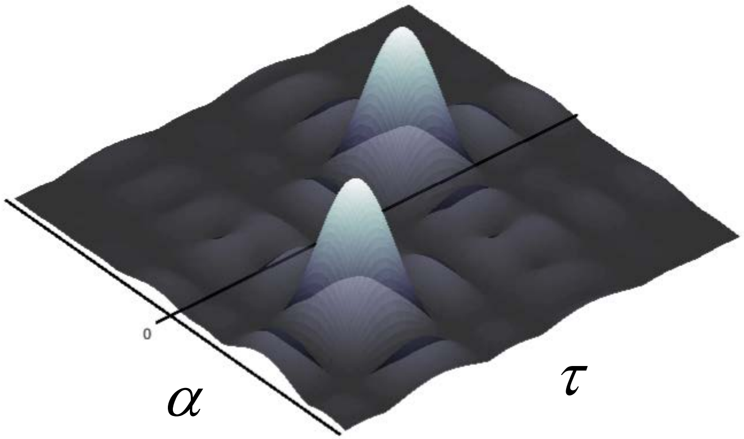
τ ●—○ f

α ●—○ t

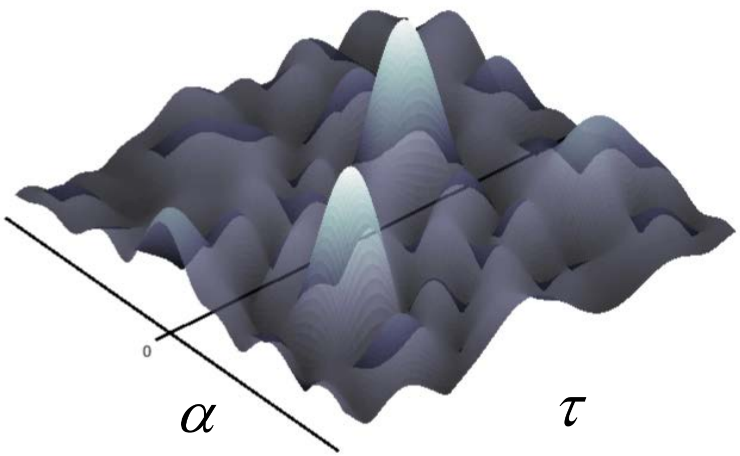
$$H(t, f) = \sum_{p=1}^{2} \gamma_p \, e^{-j2\pi f \tau_p} \, e^{-j2\pi\alpha_p t}$$

- Delay-Doppler domain (spreading/scatting function) transforms to slow time-frequency domain
- Limited observation aperture (in frequency and slow time) will limit resolution in Delay-Doppler domain
- Sparse sampling in slow time-frequency domain (according to time-frequency resource grid) may distort scattering function estimates

Two Path Example: Influence of Sparse Frequency Grid Occupation

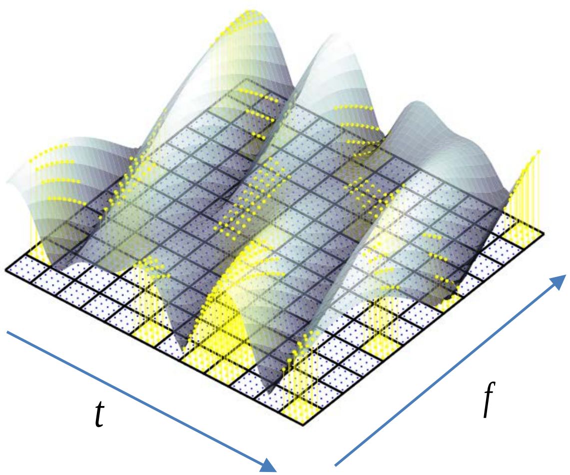


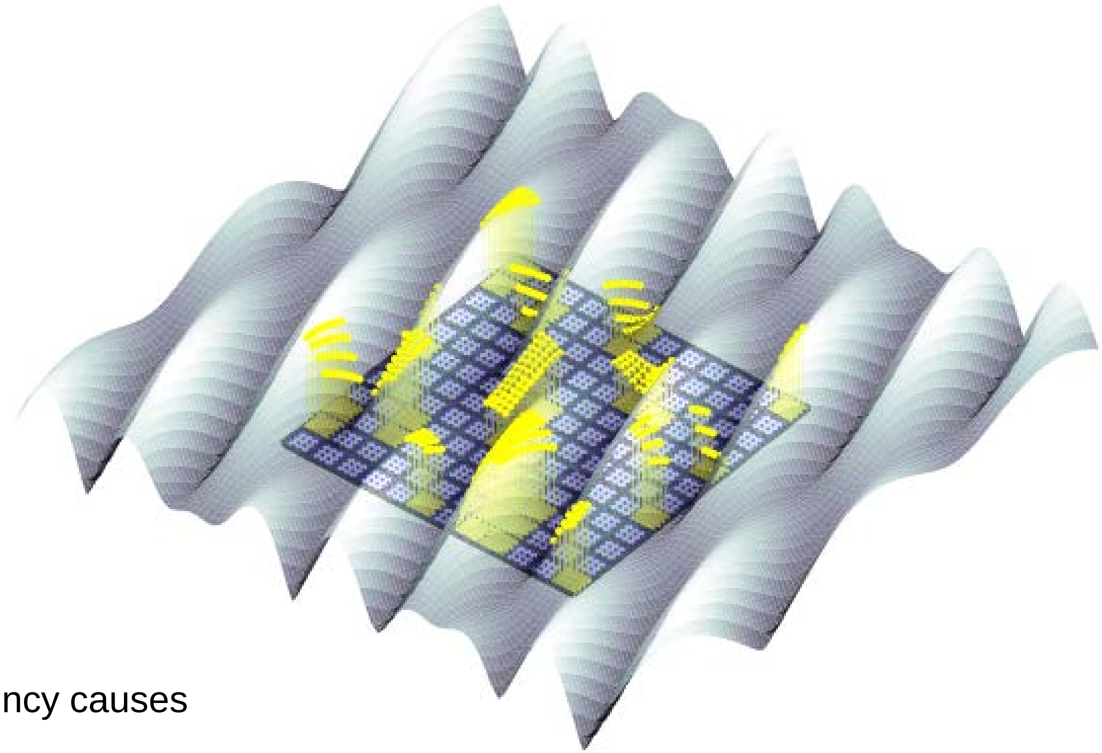
Fully occupied resource grid



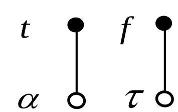
Sparse resource grid

High Resolution Parameter Estimation (HRPE)





- Limited aperture in (slow) time and frequency causes point spread in Doppler and delay, resp.
- Model assumption and model parameter estimation allows interpolation and extrapolation
- Interpolation may mitigate sparse resource grid sampling
- Extrapolation increases α, τ- resolution beyond Rayleigh (high resolution)



$$H(t, f) = \sum_{p=1}^{P} \gamma_p \, e^{-j2\pi f \tau_p} \, e^{-j2\pi \alpha_p t}$$

$$S(\alpha, \tau) = \sum_{p=1}^{P} \gamma_p \delta(\tau - \tau_p) \, \delta(\alpha - \alpha_p)$$

Maximum Likelihood HRPE

$\boldsymbol{\theta} = \left\{ \gamma_p, \alpha_p, \tau_p, \psi_{R_p}, \vartheta_{R_p}, \psi_{T_p}, \vartheta_{T_p} \right\}$: parameter vector

path weight, Doppler, delay, azimuth, elevation (Rx, Tx resp.)

$\hat{\boldsymbol{\theta}}$: estimated model parameters

P : model order

$\mathbf{x}$: measured data

$\mathbf{s}$: reconstructed data (considering transmit signal spectrum and antenna radiation pattern)

$$pdf\left(\mathbf{x}\middle|\boldsymbol{\theta}\right) = \frac{1}{\left(\pi \cdot \sigma^2\right)^M} e^{-\frac{1}{\sigma^2}\left(\mathbf{x}-\mathbf{s}(\boldsymbol{\theta})\right)^H \cdot \left(\mathbf{x}-\mathbf{s}(\boldsymbol{\theta})\right)}$$

$$\hat{\boldsymbol{\theta}} = \arg\min_{\hat{\boldsymbol{\theta}}} \sum_{\forall f,t} \left| \mathbf{x}(f,t) - \mathbf{s}(\boldsymbol{\theta}; f,t) \right|^2$$

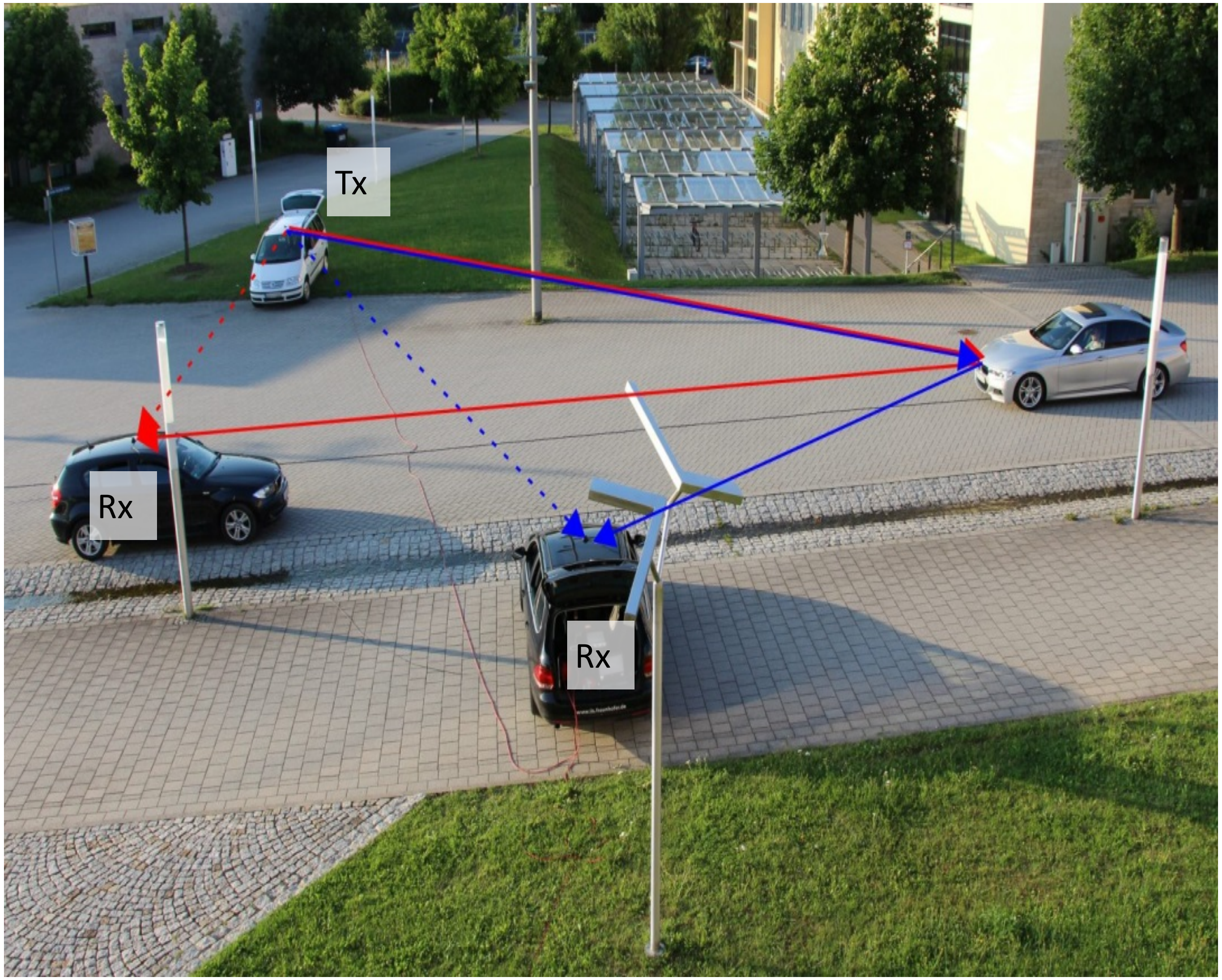
$$\mathrm{L}'\left(\mathbf{x};\boldsymbol{\theta}\right) = 2 \cdot \Re\left\{\mathbf{x}^H \cdot \mathbf{s}(\boldsymbol{\theta})\right\} - \mathbf{s}^H(\boldsymbol{\theta}) \cdot \mathbf{s}(\boldsymbol{\theta})$$

$$\hat{\boldsymbol{\theta}} = \arg\max_{\boldsymbol{\theta}} \left\{ L'\left(\mathbf{x};\boldsymbol{\theta}\right) \right\}$$

- ML reduces to MMSE
- Multidimensional search procedure is of crucial importance (SAGE, gradient, Kalman)
- Successive interference cancellation is necessary to achieve high resolution

First Field Trials

- Tx: USRP X310 with additional PA
- Rx: USRP X310 (dual channel)
- Tx-Rx Synchronization with GPSDO
- Tx signal: OFDM
  - 5.2 GHz
  - 33 dBm
  - 80 MHz
- Ground truth: Laser



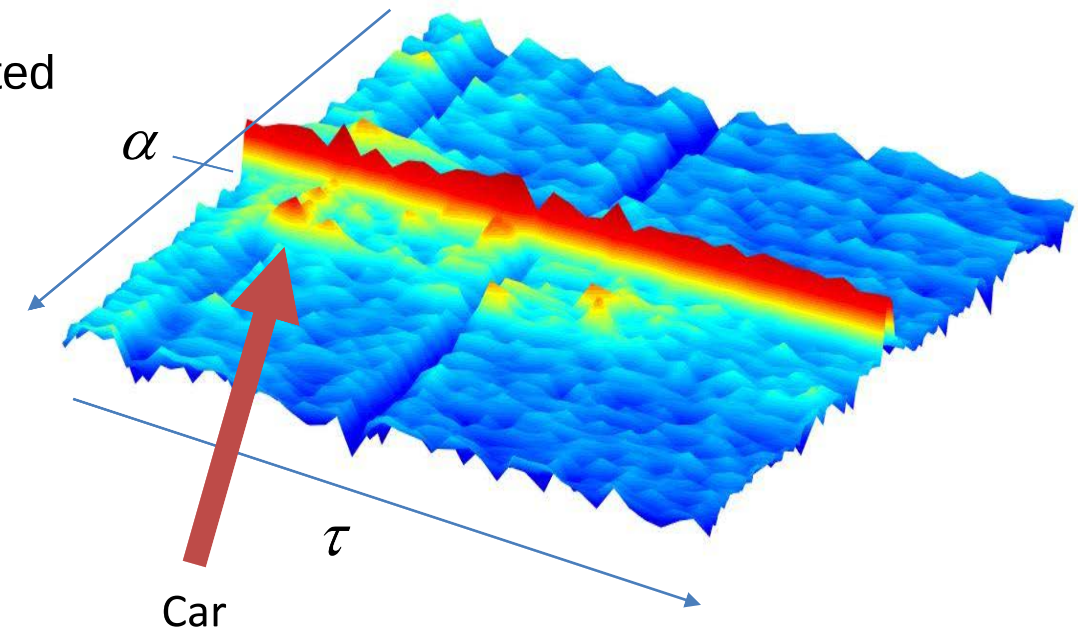
First Delay-Doppler Estimation Results: Car

- Frequency period: 80 MHz
- Delay grid/resolution: 12.5 ns
- Doppler-FFT length: 50 ms
- Doppler resolution: 20 Hz
- Doppler bandwidth: 2500Hz

- Strong static paths subtracted (estimated by HRPE)
  - 58.2 ns (LOS)
  - 86.2 ns

- Hann window for slow time

magnitue squared delay-Doppler plane (scattering function)



CPCL Dynamic Radio Resource Management (RRM)

- Radio resources: bandwidth, power control, allocation PRBs in frequency and time, spatial precoding, adaptive coding and modulation
- Radio resources are scheduled by eNB according to traffic volume, QoS requirement, and radio channel conditions
- Depends on anticipated service and operator policy
- Channel state identification feedback via CQI (Channel quality indicator)

CPCL challenges:

- Which channel state identification feedback is necessary to control CPCL performance?
- Are Radar resource requirements so much different from those of communications?
- Which competition about radio resources may arise between communication and Radar service?
- Which scheduling policies can be defined by the operator to accommodate CPL?

Mobile Edge Computing, MEC

- Principle: *Bringing computational resources closer to mobile users*
  - *Lower latency, scalability, situation awareness*
- Support multi-Radio Access Technology (RAT) and Network Function Virtualization (NFV)
- Fully compliant to 3GPP, supported and standardized by ETSI
- MEC paves the road to 5G
- MEC offers resources for computation offloading
- MEC is a key enabler for mission critical vertical solutions
- MEC supports real-time interaction between distributed applications
- MEC offers network-aided data processing

CPCL challenges:

- MEC can be used as CPCL real-time data fusion center for local radar networks
- MEC offers resources for situation aware Radar resource management
- MEC offers access to higher layers of road traffic control and cooperative driving

CPCL - Advantages and Challenges

- CPCL can be a part of part of a public cellular as well as of proprietary WLAN network
- CPCL reuses V2X comms frequencies and does not require dedicated radar frequencies (no waste of radio resources, no license effort, no need for new frequencies) > **"green Radar"**
- CPCL largely relies on existing radio interfaces
- CPCL (as compared to monostatic reuse of V2X) does not require Tx/Rx duplex
- CPCL inherently mitigates expected radar interference limits (as it already includes MAC)
- Multiple UE-illumination: synchronous/orthogonal MISO radar network
- Multiple eNB-illumination: multi-channel orthogonal MIMO radar network (frequency diversity)
- CPCL inherently takes advantage of network resources (for small scale and large scale cooperation and background information)
- CPCL includes centralized data fusion resources and high level vehicle cooperation (mobile edge cloud, large scale Internet access)
- CPCL is inherently multi-static (enhances target visibility)
- CPCL in road traffic can give better overview awareness (360° picture) as mm-wave car radar but probably less resolution

Future Perspective: 5G

- 5G offers required features for CPCL
  - ✓ 5G will inherently include both cellular and D2D/C2C communication
  - ✓ 5G will inherently deliver full network support from small scale to large scale
  - ✓ 5G will offer low latency services for real-time control applications
  - ✓ 5G will include edge computing facilities for real-time mobile computing
  - ✓ 5G will offer several frequency bands from below 1Ghz up to mmWave – hence frequency diversity, scalable bandwidth (resolution), and coverage
  - ✓ 5G will address massive MIMO (big arrays)
  - ✓ 5G addresses business models for vertical industries

- Which influence to 5G standardization is necessary?
- Which scheduling polices are appropriate?
- CPCL as a value-added service in 5G?
- **Operator Business model for CPCL?**
- There are many other applications besides road traffic!

CPCL Radar as an inherent feature of 5G mobile radio!