Vehicular Channel Characterization

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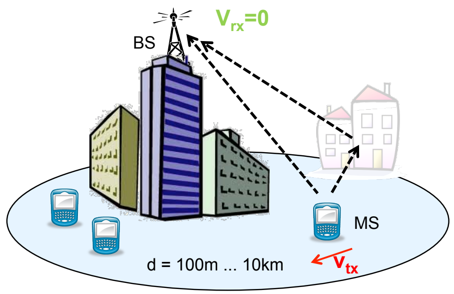
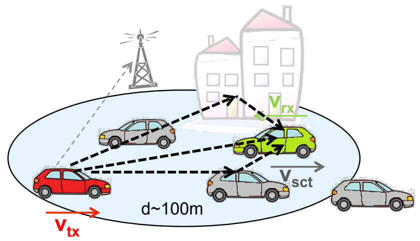
Communication Scenarios

Cellular



- mobile stations (MS) are moving, base station (BS) is fixed
- time-variant multi-path propagation
- interference

Vehicular

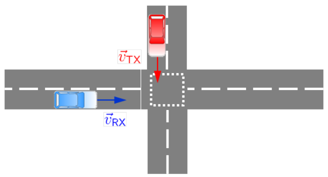


- transmitter and receiver are mobile
- safety critical scenarios

Safety Critical Scenarios (I)

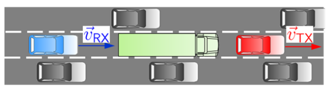
- **Road crossing**

  Emergency vehicle warning, intersection collision warning, pre-crash sensing warning.



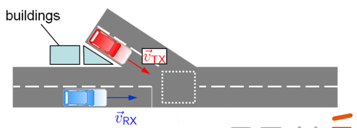
- **General LOS obstructions**

  Hazardous location notification



- **Merging lanes**

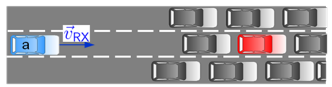
  Wrong way driving warning, co-operative merging assistance



Safety Critical Scenarios (II)

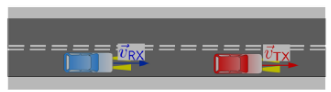
- **Traffic congestion**

  Traffic condition warning



- **In-tunnel**

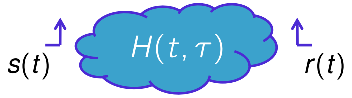
  Emergency electronic brake lights, slow vehicle warning, lane change assistance, co-operative forward collision warning



Channel Measurement

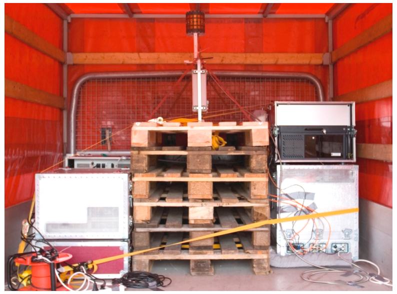
- Principle of channel sounding

$$r(t) = \int_0^\infty H(t,\tau)s(t-\tau)\mathrm{d}\tau + n(t)$$



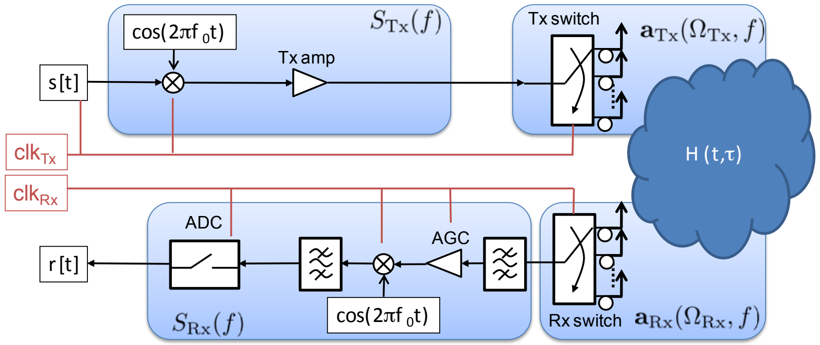
Setup

- **Lund 2007** - two transporters



- **DRIVEWAY 2009** – two station wagon with realistic antennas

Channel Sounder (1)



- Needs a joint clock!
- Phase and frequency synchronization
- Every part of the system has its own impulse response!
- “End-to-end” calibration of the equipment
- Antenna calibration for directional estimation

Channel Sounder (2)

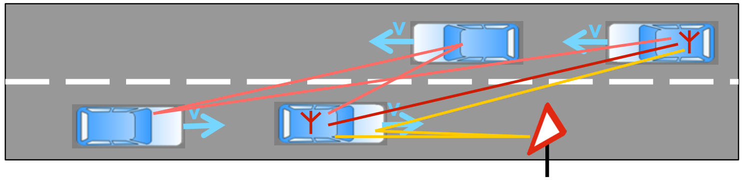
- Transmit signal design criterion
  - Broadband signal
  - Low peak-to-average power ratio (PAPR) for optimal Tx amplifier usage
  - Flat spectrum preferrable
- Solutions
  - OFDM based training sequence
  - **“Engineered” chirp** → pre-amplifying of cable losses, flat spectrum, low PAPR (as used by RUSK MEDAV sounders)

Channel Sounder (3)

- Fast AGC and signal sampling
  - For high bandwidths, ADCs have only low resolution (typically 8 bits)
  - Sampling the received signal over a wide dynamic range → fast AGC
- Phase synchronization of Tx and Rx
  - Rubidium (^{87}Rb) clock
  - Phase drift is small (though it may become significant over longer time!)
  - Phase noise is some times problematic

Vehicular Channel Sounding

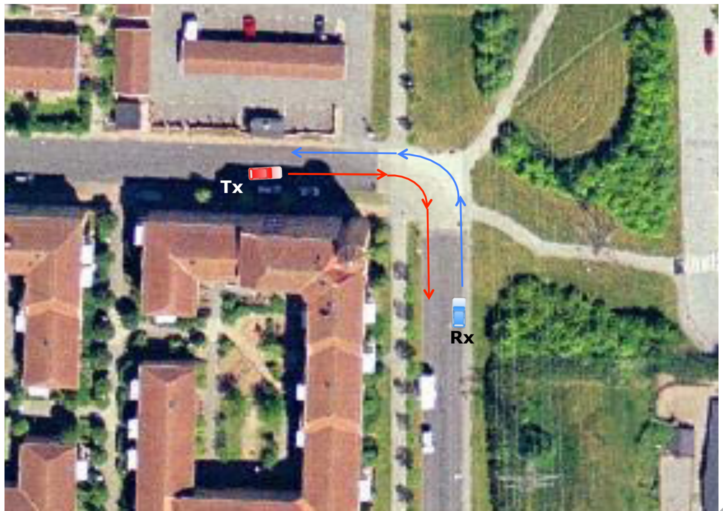
- Vehicles are moving at high relative velocities
- Large Doppler shifts due to multiple reflections



- **Key parameters of interest:**
  - **Power delay profile** – multipath propagation
  - **Doppler power spectral density** – time-variance

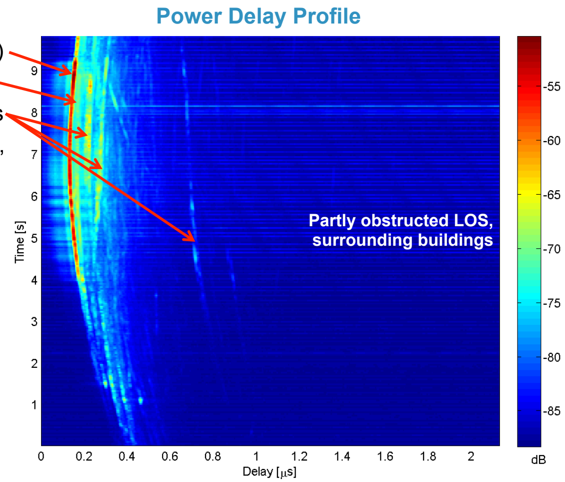
Scenario 2: Road Crossing

Scenario 2.2 – Obstructed LOS, otherwise open surroundings (suburban)



Power Delay Profile

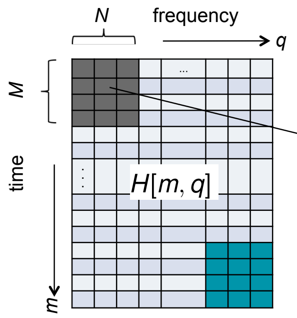
- Strong line of sight (LOS)
- Weak tail following LOS
- Multiple reflecting objects
- Delays change over time, as well as Doppler shifts
- Non-stationary fading process - can be assumed wide-sense stationary for a limited time interval (stationarity time) only



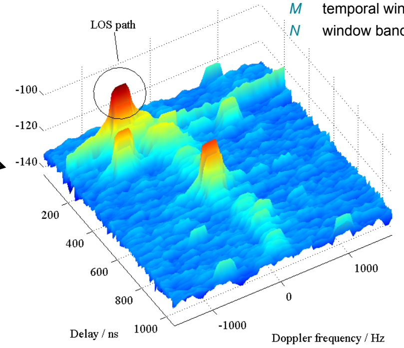
Local Scattering Function (LSF)

- Sampled time-variant frequency response $H[m, q]$
- Local scattering function [Matz 2005]

m	discrete time index
q	discrete frequency index
n	discrete delay index
p	discrete Doppler index
M	temporal window length
N	window bandwidth



2D-sliding window in time and frequency



Local multi taper estimate of the scattering function $\hat{C}[m, q; n, p]$

Video

Local Scattering Function (II)

m	discrete time index
q	discrete frequency index
n	discrete delay index
p	discrete Doppler index
M	temporal window length
N	window bandwidth

- Local scattering function [Matz 2005]

$$\hat{C}[m, q; n, p] = c_1 \sum_{k=0}^{K-1} \left| \mathcal{H}^{(G_k)}[m, q; n, p] \right|^2$$

$$\mathcal{H}^{(G_k)}[m, q; n, p] = \sum_{m'=-\frac{M}{2}}^{\frac{M}{2}-1} \sum_{q'=-\frac{N}{2}}^{\frac{N}{2}-1} H[m'-m, q'-q] G_k[m', q'] e^{j2\pi(pm'-nq')}$$

LSF is the multi-taper estimate of the local two-dimensional power spectral density

- Separable window function

$$G_k[m', q'] = u_i[m' + M/2] \tilde{u}_j[q' + N/2]$$

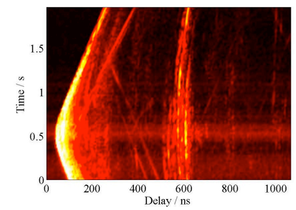
  - u_i, u_j ... discrete prolate spheroidal sequences [Slepian 1978]

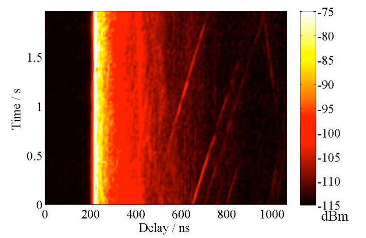
Stationarity Time

- **Two scenarios**
  - Highway, opposite direction, 90km/h
  - Urban, same direction, 30km/h
- **Stationarity region**
  - LSF vector: $\mathbf{c}[m] \leftarrow \hat{C}[m, q; n, p]$
  - Distance measure in Hilbert space

$$R_{\mathbf{c}}[m_1, m_2] = \frac{\mathbf{c}[m_1]^T \mathbf{c}[m_2]}{|\mathbf{c}[m_1]| |\mathbf{c}[m_2]|}$$

- **Mean stationarity time**
  - Highway, opposite direction: 23 ms
  - Rural, same direction: 1412ms

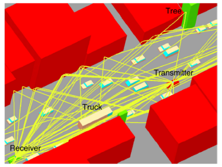




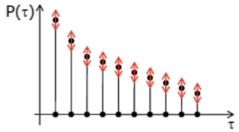
❖ Paier, Zemen, Bernadó, Matz, Karedal, Czink, Dumard, Tufvesson, Molisch, Mecklenbräuker, "Non-WSSUS vehicular channel characterization in highway and urban scenarios at 5.2 GHz using the local scattering function," *Workshop on Smart Antennas*, 2008.

Vehicular Channel Models

- **Ray-based models**
  - Detailed modelling of all objects affecting wave propagation
  - High computational complexity is required



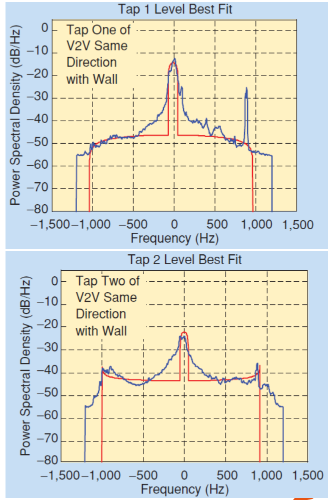
- **Tap-delay line models**
  - Average power decays exponentially
  - Each tap fades independently and has individual Doppler shape



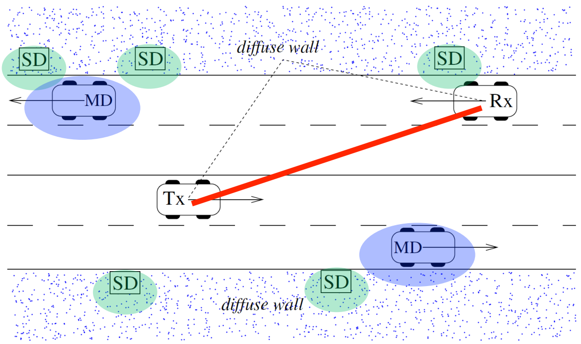
Tap-Delay Line Model [Acosta/Ingram]

- Six tap-delay line models:
  - Up to 8 taps
  - Up to 12 paths in total

Scenario	*Distance Between Tx and Rx (m)*	*No. of Takes Used in Model*	*Average per Result (%)*
V2V—Expressway Oncoming	300–400	4	5.6
V2V—Urban Canyon Oncoming	100	2	4.4
RTV—Suburban Street	100	10	3.0
RTV—Expressway	300–400	8	2.7
V2V—Expressway Same Direction with Wall	300–400	21	1.9
RTV—Urban Canyon	100	4	0.8



Geometry Based Stochastic Model

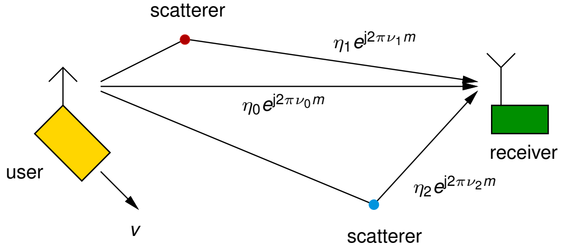


- line of sight
- static discrete scatterers (SD)
- mobile discrete scatterers (MD)
- diffuse scattering

- Important structures modelled by a given scatterers distribution
- Allows for modelling of non-stationary channels
- Good tradeoff between complexity and accuracy

❖ Karedal, Tufvesson, Czink, Paier, Dumard, Zemen, Mecklenbräuker, Molisch, "A geometry-based stochastic MIMO model for vehicle-to-vehicle communications," *IEEE Transaction Wireless Communications*, 2009.

Low-Complexity Implementation (I)



- v velocity
- P no. paths
- η_p path weight
- ν_p Doppler shift
- m discrete time
- p path index

Time-variant channel impulse response (sum of complex exponentials)

$$h[m] = \sum_{p=0}^{P-1} \eta_p e^{2\pi j \nu_p m}$$

- For realistic models P = 400 paths are needed
- Evaluation of $h[m]$ in real time is computationally expensive

Low-Complexity Implementation (II)

- Fading process is bandlimited

$$\mathcal{W} = (-\nu_{\text{Dmax}}, \nu_{\text{Dmax}}) \text{ with } \nu_{\text{Dmax}} = \frac{r v_{\text{max}} f_{\text{C}}}{c_0} T_{\text{S}}$$

v_{max}	maximum velocity
f_{C}	carrier frequency
c_0	speed of light
T_{S}	sampling time
r	number of reflections

- Snapshots of $h[m]$ are time limited to

$$m \in \mathcal{I}_M = \{0, M-1\}$$

spanning a subspace with

$$D = \lceil |\mathcal{W}| M \rceil + 1 \ll M$$

essential dimensions.

- Discrete prolate spheroidal (DPS) sequences $u_d[m]$ [Slepian 1978] span the same subspace

$$h[m] \approx \sum_{p=0}^{P-1} \sum_{d=0}^{D-1} \gamma_d(\nu_p) u_d[m] \quad \text{with} \quad \sum_{n=0}^{M-1} \frac{\sin 2\pi \nu_{\text{Dmax}}(m-n)}{\pi(n-m)} u_d[m] = \lambda_d u_d[m]$$

Low-Complexity Implementation (III)

- Challenge: compute

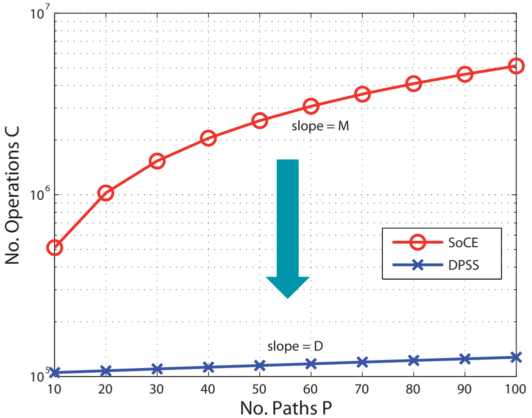
$$\gamma_d(\nu_p) = \sum_{m=0}^{M-1} u_d[m] e^{2\pi j \nu_p m}$$

- Low complexity solution
  - Exploiting special properties of DPS sequences and DPS wave functions,
  - we showed that $\gamma_d(\nu_p)$ can be approximated using scaled and shifted DPS sequence (table lookup)

$$\gamma_d(\nu_p) \approx \tilde{\gamma}_d(\nu_p) = f(M, \nu_p) u_d \left[\left\lfloor \left(1 + \frac{\nu_p}{\nu_{\text{Dmax}}} \right) \frac{M}{2} \right\rfloor \right]$$

❖ Kaltenberger, Zemen, Ueberhuber, "Low-complexity geometry-based MIMO channel simulation," *EURASIP Journal on Advances in Signal Processing*, 2007.

Complexity Reduction

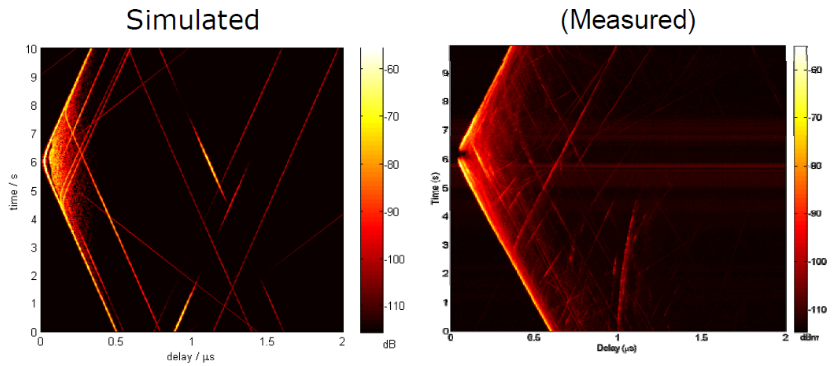


D=4 subspace dimension
M=2560 block length
ν_{Dmax}=4.82e-5 norm. Doppler bandw.

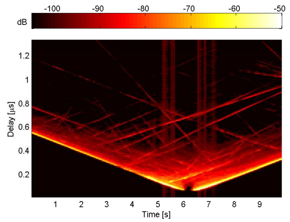
System parameters
- f_{C}=2 GHz
- v=100km/h
- $1/T_{\text{S}}$=3.84e6MHz
- 16 bit resolution
- UMTS frame

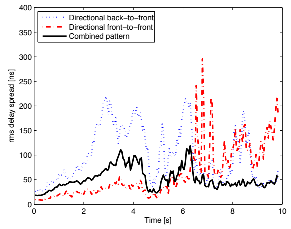
- SoCE ... sum of complex exponentials
- DPSS ... discrete prolate spheroidal sequences

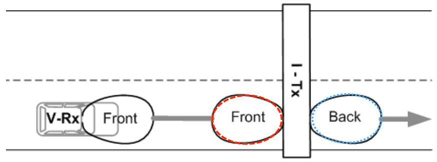
Geometry-Based Stochastic Model Evaluation



Delay Spread



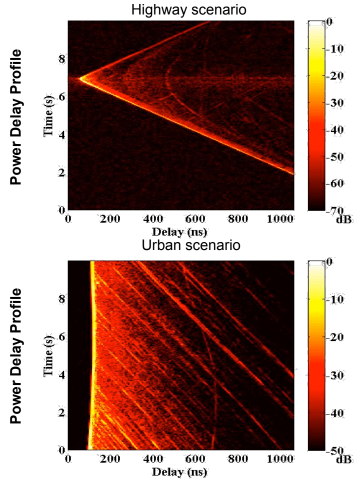


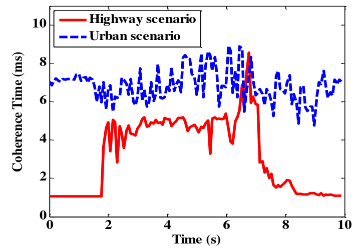


- Absence of line of sight (LOS) under the bridge
- Root mean square (rms) delay spread mean value: 52 ns

❖ Mecklenbräuker, Molisch, Karedal, Tufvesson, Paier, Bernadó, Zemen, Klemp, Czink, "Vehicular channel characterization and its implications for wireless system design and performance," Proceedings of IEEE, to be published.

Coherence Time





- coherence time: $T_c[m] = 1/\sqrt{\nu^2[m]}$
- rms Doppler spread $\nu^2[m]$, is second central moment of

$$S(m,p) = \sum_n \sum_q \hat{C}[m,q;n,p]$$

❖ Bernado, Zemen, Paier, Matz, Karedal, Czink, Dumard, Tufvesson, Hagenauer, Molisch, Mecklenbräuker "Non-WSSUS vehicular channel characterization at 5.2 GHz - spectral divergence and time-variant coherence parameters," *URSI*, 2008.

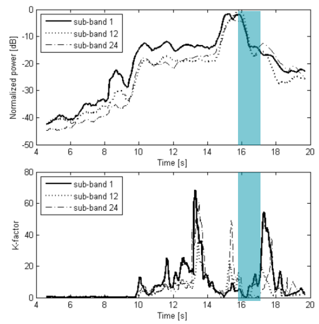
Fading Statistics

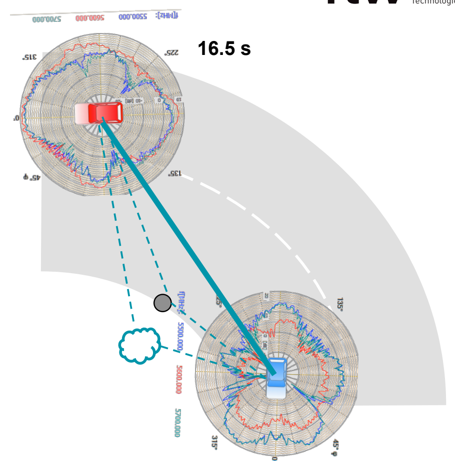
Ricean fading: Mixture of line of sight (LOS) and non-LOS components

$$h = \sqrt{\frac{K}{1+K}}\bar{h} + \sqrt{\frac{1}{1+K}}h_R, \quad \text{where } h_R \sim \mathcal{CN}(0,1)$$

- $\sqrt{\frac{K}{1+K}}\bar{h}$ is the deterministic LOS component
- $\sqrt{\frac{1}{1+K}}\bar{h}_R$ is the Rayleigh fading non-LOS component
- The *K*-factor is an indicator for the severity of fading

Time-Varying *K*-Factor





- Sub-band bandwidth: 10MHz
- The *K*-factor is influenced by:
  - Antenna radiation pattern
  - Trees and street lights

❖ Bernadó, Zemen, Karedal, Paier, Thiel, Klemp, Czink, Tufvesson, Molisch, Mecklenbräuker, "Multi-dimensional K-factor analysis for V2V radio channels in open sub-urban street crossings, " *IEEE PIMRC*, 2010.