Measurement-based Channel Characterization and Modelling of Vehicle-to-Vehicle Communications

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Outline

- **Lund University and Department of EIT (overview)**
- **Overview of intelligent transportation systems**
- **Properties of propagation channels**
  - Fundamentals
  - Radio channel research
  - V2V channels
- **V2V channel measurements**
  - Initial Lund'07 measurements
  - Follow up DRIVEWAY'09 measurements
  - Antenna placement and diversity measurements
- **Channel characterization and modeling**
- **Summary & Discussion**

A world-class university

- Founded in 1666
- 8 faculties
- 47 000 students
- Almost 3 000 research students
- 6 800 employees
- Around 650 professors
- 800 senior lecturers
- 1 200 lecturers and other research staff
- Turnover EUR 760 million – 1/3 education, 2/3 research

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Department of EIT

- Research labs at EIT
  - Broadband Communication
  - Electronics
  - Communication →
    - Information Theory
    - **Radio Systems**
    - Telecommunication Theory
  - Network and Security
  - Signal Processing
  - Electromagnetic theory

- Radio Systems
  - Channel measurements and modeling
  - Algorithm development for digital transmitter/receiver

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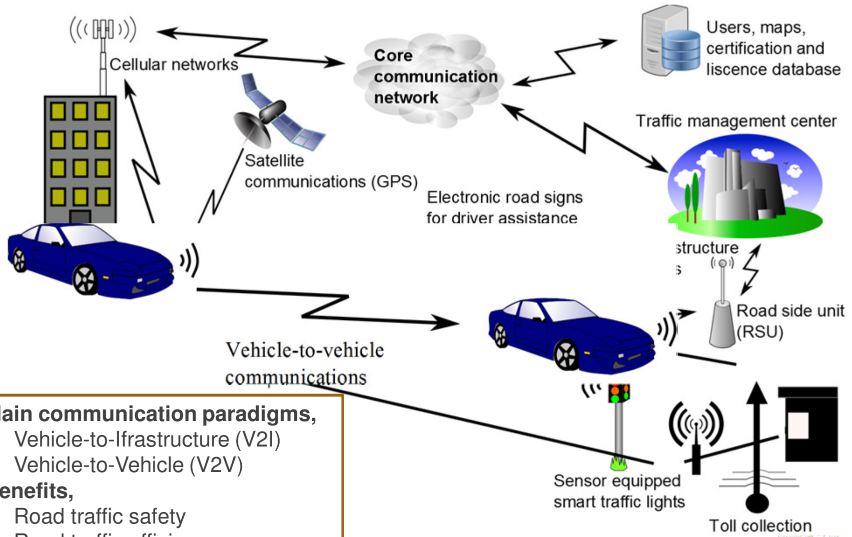
Outline

Current road traffic related problems

Fact:
Land transportation systems have become crucial components of modern world.

Problems:
- According to world health organization report in 2004, 1.2 million people die in road accidents per year.
- 50% of these are vulnerable road users,
  - 23% motorcyclists,
  - 22% pedestrains,
  - 4% cyclists.
- By 2020, road crashes will be third leading cause of disability/death worldwide.
- The ever increasing number of vehicles demands efficient use of available roads.

Intelligent Transportation Systems



Main communication paradigms,
- Vehicle-to-Ifrastructure (V2I)
- Vehicle-to-Vehicle (V2V)

Benefits,
- Road traffic safety
- Road traffic efficiency

Vehicle-to-vehicle communications

- Vehicle-to-vehicle (V2V) communication at 5.9 GHz frequency will mainly be used for safety related applications.
- The reliability of safety applications highly depends on the latency and the quality of the communication link.
- The quality of the communication link relies on the properties of the propagation channel.

In short...
It is the channel that determines the ultimate performance limits of any communication system.

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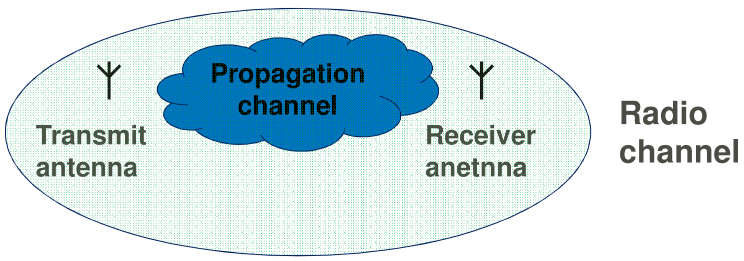
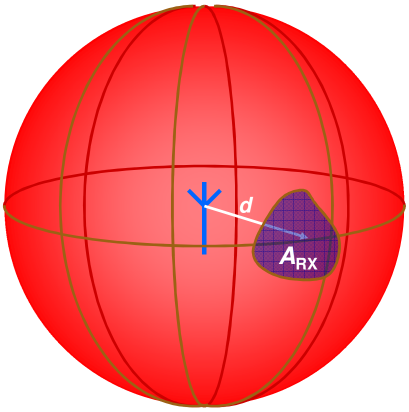
What is Channel?



- **Usually channel model is made of three constituents**
  - **Path-loss** determines the average (over local space and time) power received for a given TX-RX range
  - **Shadowing** is added to the path-loss to account for local large-scale effects (Obstruction, static multi-paths, etc.)
  - **Fading** represents the short-term variations of the received power and is caused by multipath propagation

Free-space loss



If we assume RX antenna to be isotropic:

$$P_{RX} = \left(\frac{\lambda}{4\pi d}\right)^2 P_{TX}$$

Attenuation between two isotropic antennas in free space is (free-space loss):

$$L_{free}(d) = \left(\frac{4\pi d}{\lambda}\right)^2$$

Free-space loss
Friis' law

Received power, with antenna gains G_{TX} and G_{RX}:

$$P_{RX}(d) = \frac{G_{RX} G_{TX}}{L_{free}(d)} P_{TX} = P_{TX} \left(\frac{\lambda}{4\pi d}\right)^2 G_{RX} G_{TX}$$

Valid in the far field only

$$P_{RX|dB}(d) = P_{TX|dB} + G_{TX|dB} - L_{free|dB}(d) + G_{RX|dB}$$

$$= P_{TX|dB} + G_{TX|dB} - 10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^2 + G_{RX|dB}$$

In free space, the received power decays with distance at a rate = 20 dB/decade

Free-space loss
What is far field?

The free-space loss calculations are only valid in the **far field** of the antennas.

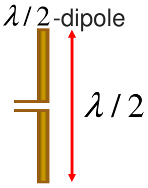
Far-field conditions are assumed "**far beyond**" the Rayleigh distance (also known as Fraunhofer distance):

$$d_R = \frac{2L_a^2}{\lambda}$$

where L_a is the largest dimesion of the antenna.

Another rule of thumb is:
"At least 10 wavelengths"

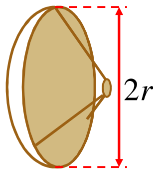
$\lambda/2$-dipole



$L_a = \lambda/2$

$d_R = \lambda/2$

Parabolic



$L_a = 2r$

$d_R = \frac{8r^2}{\lambda}$

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The reference distance d_0

- For path-loss propagation models, a close-in distance d_0 is selected such that it lies in the far-field region.

$$P_{RX}(d)dBm = 10log\left[\frac{P_{RX}(d_0)}{0.001W}\right] - 20\log(\frac{d}{d_0}) \qquad d \geq d_R$$

- For practical systems in the 1-2 GHz region, d_0 is typically chosen to be 1 m in indoor environments, and 100 m or 1 km for outdoor environments.

- For distances $d > d_{break}$, the above equation doesn't hold anymore.

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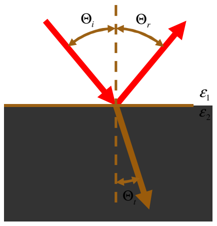
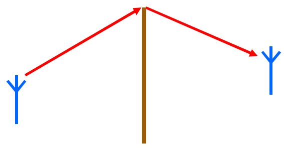
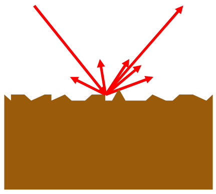
Propagation mechanisms



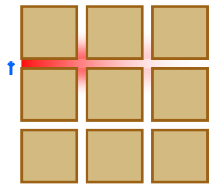
Reflection and transmission



Diffraction



Scattering



Waveguiding

The WSSUS model
Assumptions

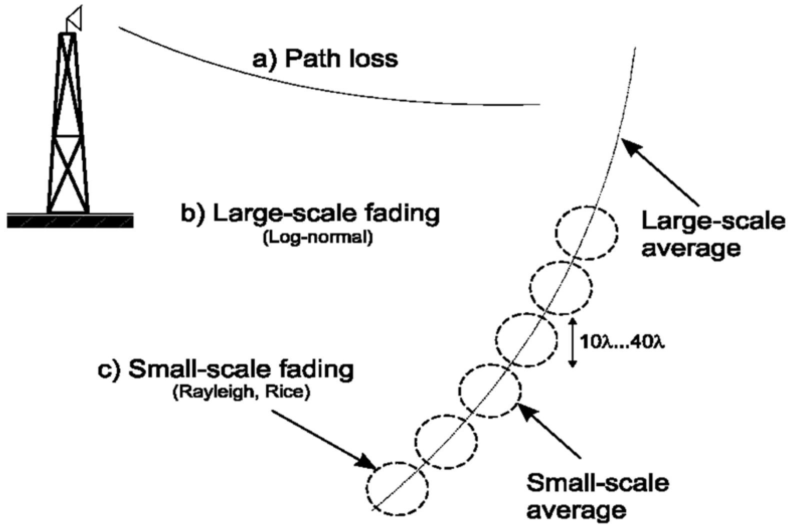
A very common wide-band channel model is the WSSUS-model. **Roughly speaking it means that the statistical properties remain the same over the considered time (or area)**

Recalling that the channel is composed of a number of different contributions (incoming waves), the following is assumed:

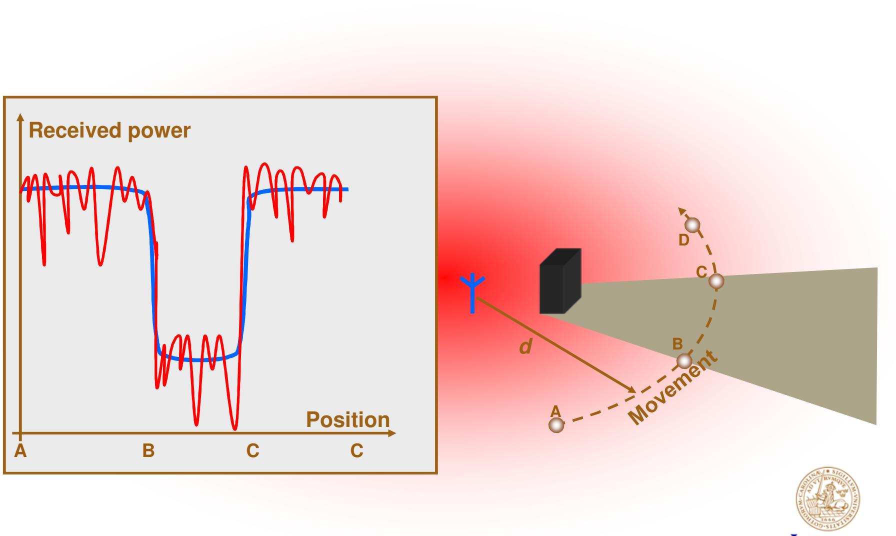
The channel is Wide-Sense Stationary (WSS), meaning that the time correlation of the channel is invariant over time.

The channel is built up by Uncorrelated Scatterers (US), meaning that contributions with different delays are uncorrelated.

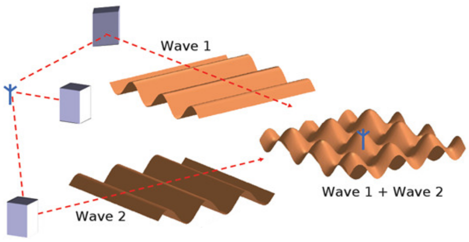
What is large scale and small scale?



Large-scale fading
Basic principle



Small-scale fading, two waves: *location-dependent, time-varying* fading



- If no movement is involved, Rx sees different signal strength (*location-dependent fading*)
- If Rx moves, Rx experiences *time-varying fading* (small-scale fading, short-term fading)

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Radio channel research

Main objective is to **understand the underlying mechanisms** behind the propagation of a signal from transmitter to receiver in order to **construct a mathematical model** for controlled synthesis of channels

- **Static Model**
  - Spectral-based, e.g., beamforming
  - Stochastic maximum likelihood
  - Deterministic maximum likelihood →
- **Dynamic Model**
  - Kalman filters, e.g., EKF, UKF
  - Sequential Monte Carlo, e.g., Particle filter

- **Measurement based**
  - SAGE, RIMAX
- **3D ray-optical based**
  - Ray tracing

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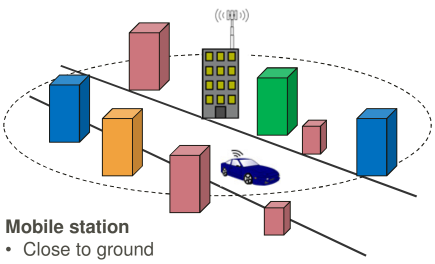
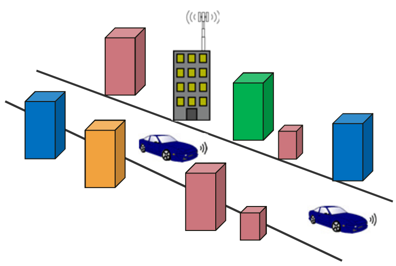
Cellular Channels vs. V2V Channels

Base station
- Elevated position
- Fewer scatters
- Static



Mobile station
- Close to ground
- Many scatterers in the surrounding
- Static or Dynamic



Vehicle-to-vehicle
- Both antennas are close to ground
- Many scatterers in the surrounding (moving/static)
- Highly dynamic
- Typically higher frequency compared to cellular systems.

The catch:
V2V channels are fundamentally different from cellular channels and are subject to faster fluctuations.

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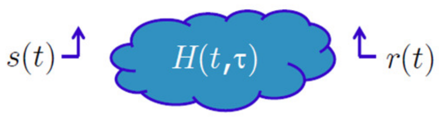
Channel measurements



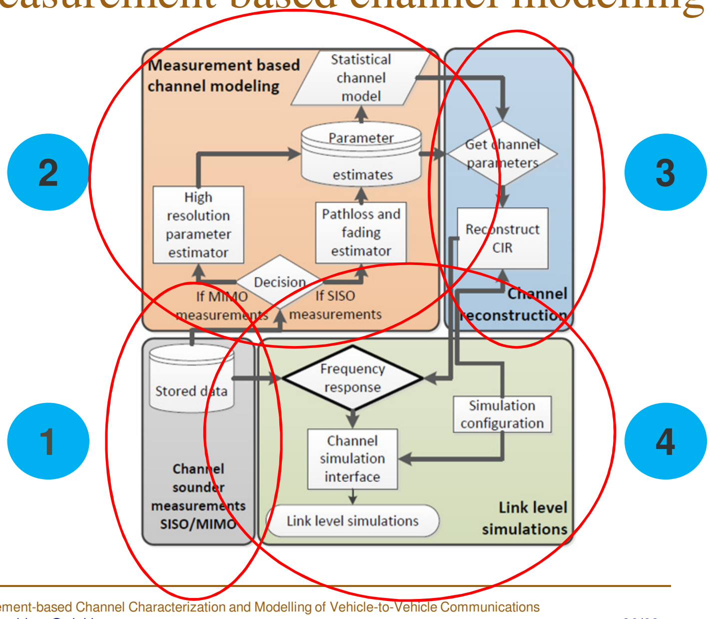
- **Principle of channel measurements**
  - Transmit a known signal $s(t)$
  - Estimate the channel $H(t,f)$ from the received signal $r(t)$

Commonly used channel measurement tools:
- **Vector network analyzer**
- **Channel sounder**

Channel Sounder

- Calibrated antenna elements for directional estimation

Measurement based channel modelling



V2V channel measurements objectives

- Obtain a **general understanding** of vehicle-to-vehicle propagation channels
  - Underlying mechanisms
  - System impact
  - Gain from multiple-antenna systems
  - Antenna/channel interaction
- Build **simulations models** for system evaluation
  - Vehicle-to-vehicle propagation channels are different from many other propagation channels

Next step:
Preparation for measurements

Measurement campaign step by step

Antenna calibration

↓

Channel sounder mounting

↓

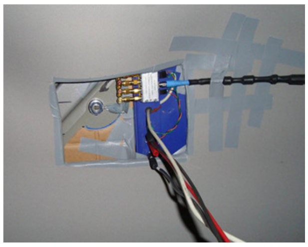
Conduction measure-ments

Measurement campaign step by step

Antenna calibration

Channel sounder mounting

Conduction measure-ments



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Measurement campaign step by step

Antenna calibration

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Measurement campaign step by step

Antenna calibration

↓

Channel sounder mounting

↓

Conduction measure-ments

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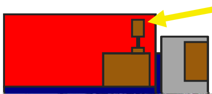
Initial Lund'07 V2V channel measurements

- TX/RX mounted on small trucks
- 4x4 M
  camp
- Meas
  same



Antenna elements

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Measured Traffic Scenarios

Highway Measurements:

- Two lane (each direction) highway
- Direction of travel was separated by 0.5m high wall
- TX/RX speed (80-90km/h)
- Many moving vehicles
- LOS and OLOS conditions
- Only *convoy* measurements

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Measured Traffic Scenarios

Urban Measurements Lund:

- Width 9-14 m
- Single lane
- Parked cars along street
- Some traffic

Urban Measurements Malmö:

- Width 14-40 m
- Two lanes and turn lanes
- Parked Cars along street
- Busy traffic

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Measured Traffic Scenarios

Rural Measurements:

- Single lane country road
- TX/RX speed (60-70km/h)
- No moving vehicles
- Always LOS conditions
- Measurements while driving in *Convoy* and in *Opposite* direction

Rural measurements can be treated as reference; where **no** or **very few** scatterers are around.

Conclusions from Initial '07 Masurements

We found that:

- Vehicle-to-vehicle propagation channels are fundamentally different from cellular propagation channels
- Vehicle-to-vehicle propagation channels are non-stationary
- A geometric-stochastic propagation channel model is suitable

…but also concluded that:

- Measurements with trucks are practical, but will influence the measured channel (antenna height)
- Measurement conduct (cars in convoy or opposite directions on highways etc.) is commonly used, but not representative for many vehicle-to-vehicle applications (e.g., intersection collision avoidance)

DRIVEWAY’09 measurements partners

ftw Creating Communication Technologies

TU WIEN TECHNISCHE UNIVERSITÄT WIEN Vienna University of Technology

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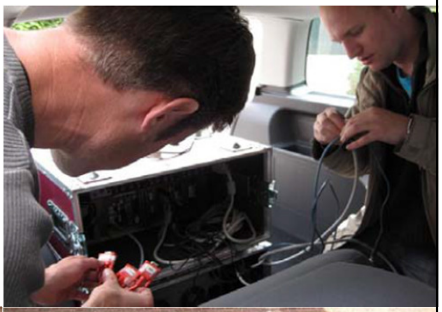
Lunds Tekniska Högskola

DELPHI

DRIVEWAY’09 measurements preparation

- Preparation time: **7 months**
- Time for channel measurements: **5 days**
- Time for antenna calibration: **8 days**
- Total milage: **3800km**
- Channel sounder IR: **120 GB**
- Audio/Video documentation: **14GB**
- Antenna calibration: **7GB**
- .xls notes: **600kB**



DRIVEWAY'09 measurements

Vehicle-to-vehicle measurements:

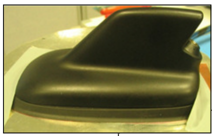
- Regular cars:

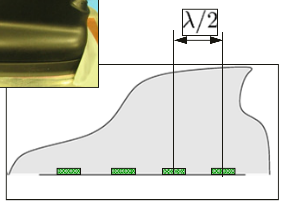
  standard hatchback style
- Realistic antenna design:

  4-element linear array of patch antennas integrated in rooftop radome
- I ment

Consequences:

- Shadowing by car roof inclination
- Shared space with other antennas (e.g., GPS)





Application specific measured scenarios

Identified scenarios where V2V comunications will be (particularly) useful, e.g.,

– collision avoidance,

– emergency vehicle warning,

– hazardous location notification,

– wrong-way driving warning,

– co-operative merging assistance,

– slow vehicle warning,

– lane change assistance

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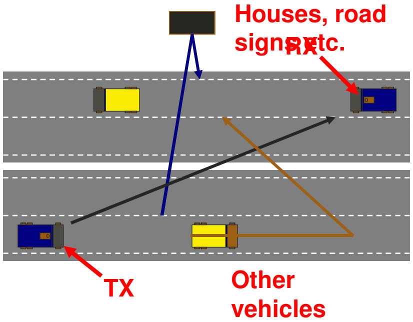
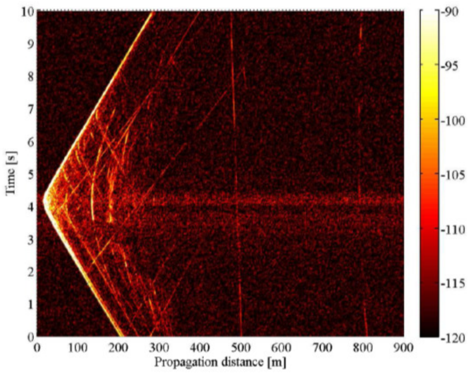
General Observations – Time/Delay

Time-delay characteristics:





- Rapidly varying channel
- Discrete components carry significant energy and change delay bin with time
- Diffuse components following LOS

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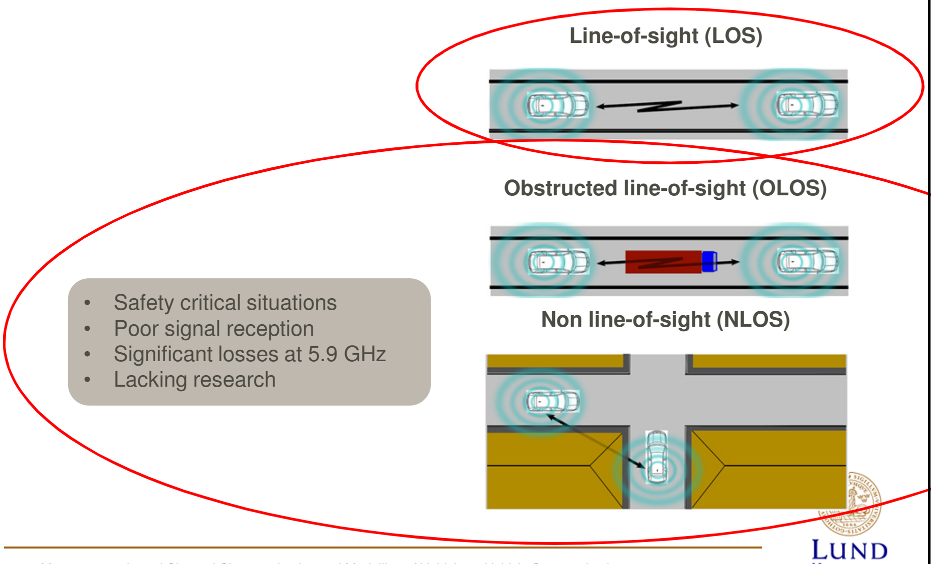
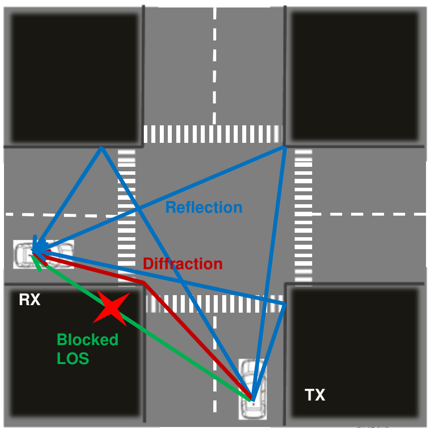
V2V communication link categorization



- Safety critical situations
- Poor signal reception
- Significant losses at 5.9 GHz
- Lacking research

Non Line-of-sight (NLOS) signal reception

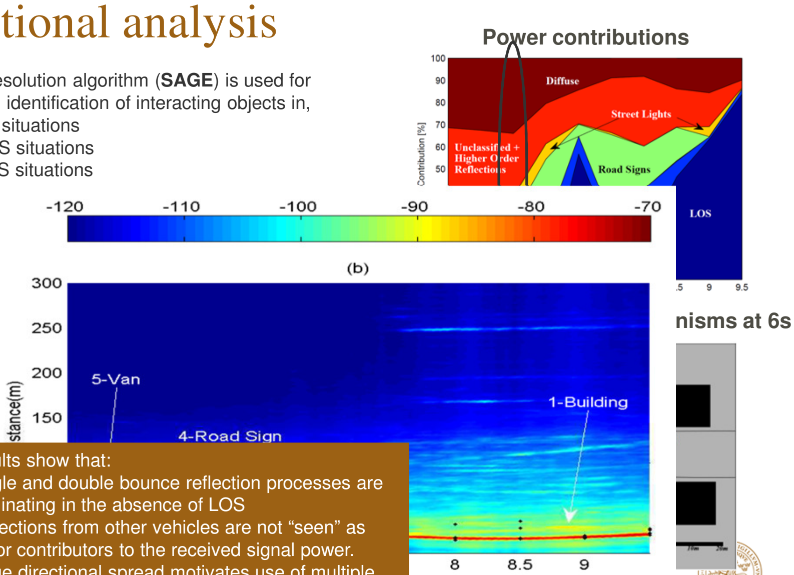
- NLOS signal reception is enabled due to scattering of radio waves, e.g.,
  - single or multiple bouce reflections,
  - diffraction.
- Factors that influence the NLOS-reception are:
  - Objects such as buildings, road-signs, light poles, parked and moving vehicles
  - Structure and material properties or these objects
  - Street width, distance of TX/RX vehicles from the intersection center



Directional analysis

A high-resolution algorithm (**SAGE**) is used for a refined identification of interacting objects in,

- LOS situations
- OLOS situations
- NLOS situations

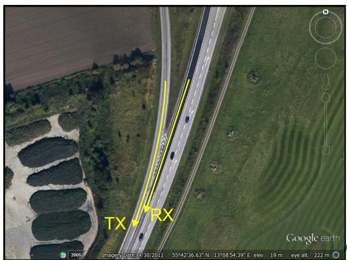


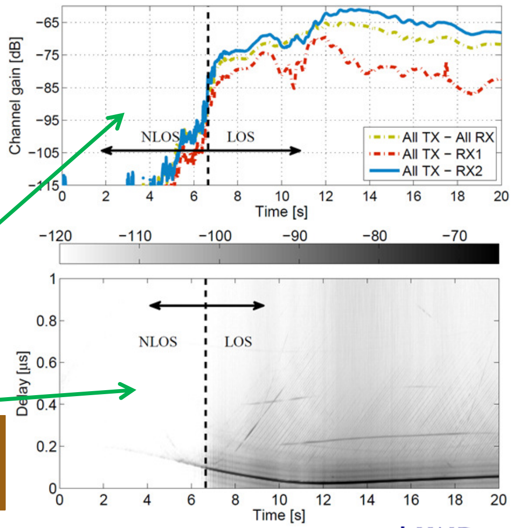
The results show that:

1. Single and double bounce reflection processes are dominating in the absence of LOS
2. Reflections from other vehicles are not "seen" as major contributors to the received signal power.
3. Large directional spread motivates use of multiple antennas to exploit diversity

Merging lanes vs. urban intersections

Merging lane scenario

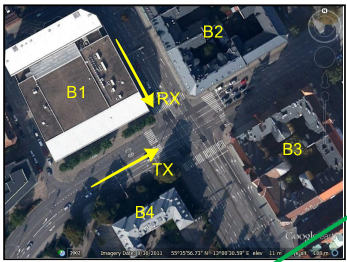


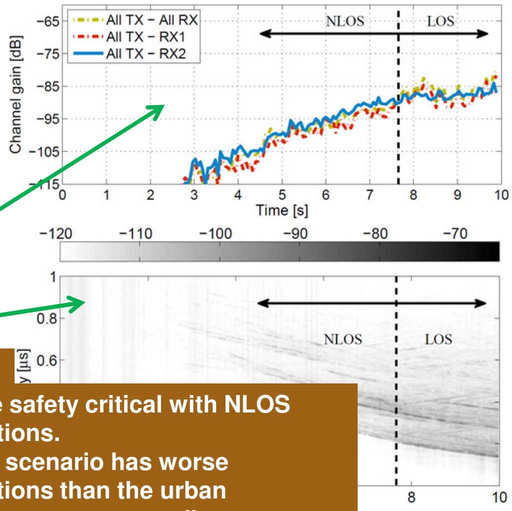


Received power is negligible in NLOS. Scatterers contributes only when there is LOS.

Merging lanes vs. urban intersections

Urban intersection scenario



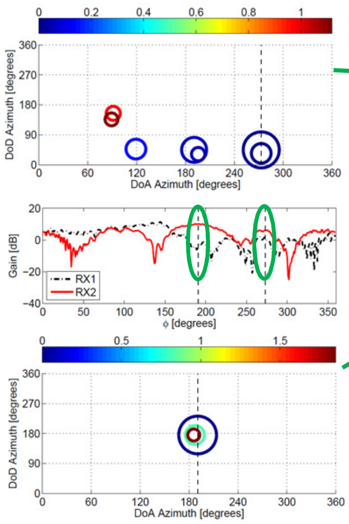


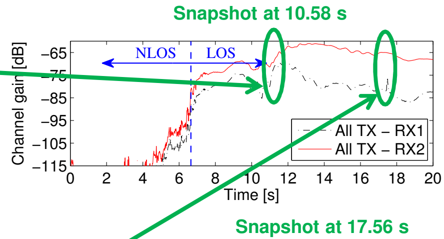
Relatively better NLOS reception than merging lan... multiple sca... at the corne...

- **Both scenarios are safety critical with NLOS propagation conditions.**
- **The merging lanes scenario has worse propagation conditions than the urban intersections due to open surroundings.**

Merging lanes vs. urban intersections

Estimation of direction-of-arrival and departure

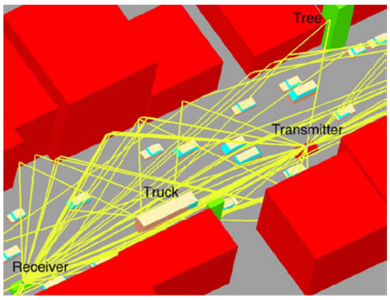




- Received power drops up to 20 dB depending upon the DOA and the differences in antenna gain of the RX elements.
- This motivates to use TX/RX antennas that has omni-directional pattern otherwise multiple antennas should be used.

Ray tracing

- Deterministic approach, can be very realistic
- Solve approximation to Maxwell's equation, using high-frequency approximation

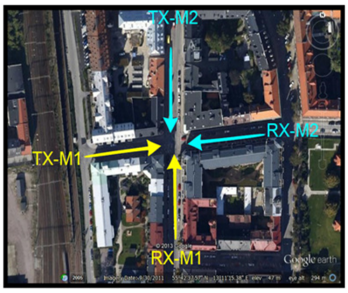


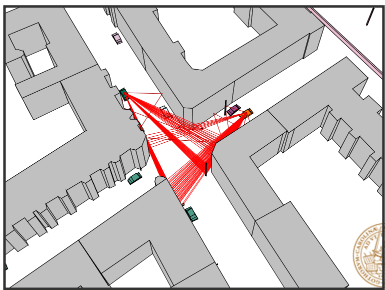
[Maurer et al. 2004]

Validation of ray-tracing based model

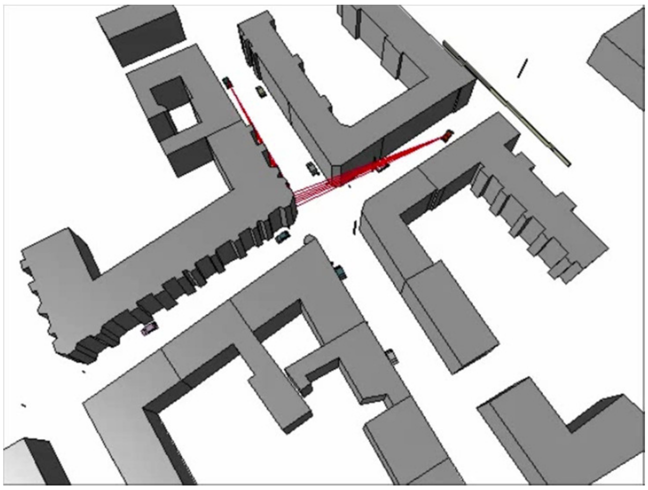
Goal: Comparison of ray-tracing channel simulator and channel **measurements**

- 3D virtual scenario is created which includes buildings, traffic signs, lamp posts as well as parked cars along roadside.
- Only the direct path, specular reflections (1st and 2nd order) and non-specular reflections (1st order) are considered to characterize the channel.
- Measured polarimetric antenna patterns are used.
- GPS coordinates of TX/RX, logged during measurement, are used for simulation.





Validation of ray-tracing based model



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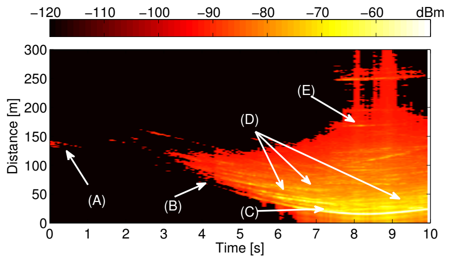
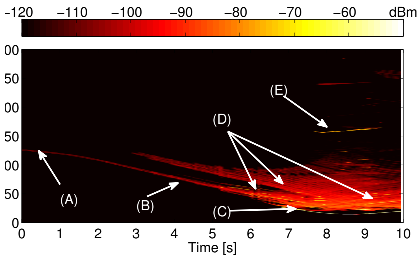
Validation of ray-tracing based model

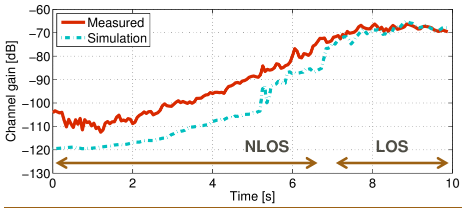
Measuremed PDP



Simulated PDP (Ray-tracing)



Channel gain



- Very good agreement in LOS and near LOS regions.
- In NLOS, the ray tracing model underestimates the channel gain.
- Gap can be reduced by increasing the order of reflection.
- Contribution of third and higher-order specular and non-specular reflections is missing in the simulator.

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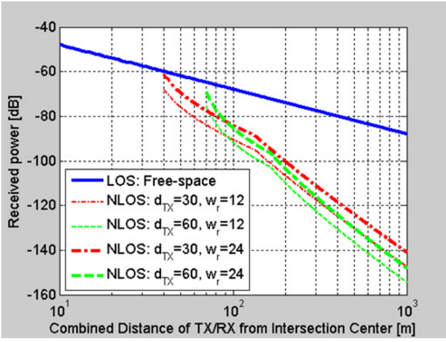
Validation of NLOS path loss model

Reference non-line-of-sight path loss model

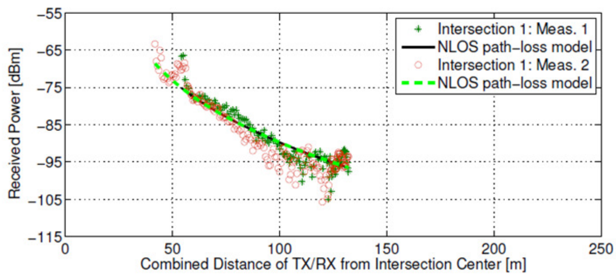
- Mangel et. al. in [1] has presented a NLOS path-loss model at 5.9 GHz named VirtualSource11p.
- The model is based on an extensive measurement campaign conducted in Munich, Germany.
- The NLOS path-loss model is claimed to be flexible and incorporated specific geometry aspects.
- Question: Is the model valid only in the intersections where the measurements were taken?

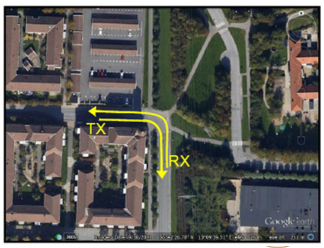


Validate the model with independent data?

[1] T. Mangel, O. Klemp, and H. Hartenstein, "5.9 GHz inter-vehicle communication at intersections: a validated non-line-of- sight path-loss and fading model," EURASIP Journal on Wireless Communications and Networking, vol. 2011, no. 1, p. 182, 2011.

Validation of NLOS path loss model

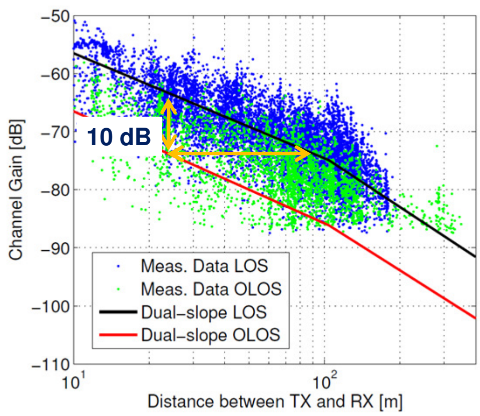




Validation of NLOS path loss model

The results in this study suggest to introduce **an intersection dependent gain parameter** in the reference NLOS model to cope with varying scattering. But otherwise the proposed model seems to be accurate.

Measured channel gain for urban scenario



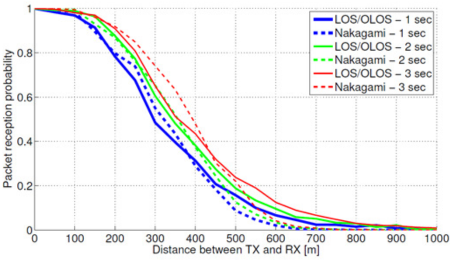
Scenario		n		PL_0	σ

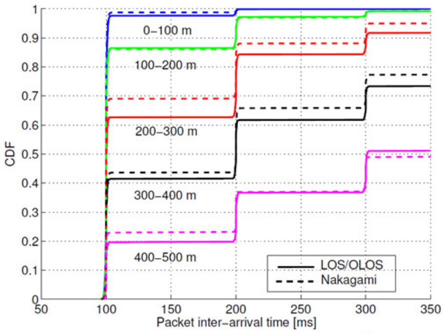
10 dB extra attenuation translates to a 3 time reduction of communication range, e.g. 100 m instead of 300 m.

Network simulations

Simulation scenario,

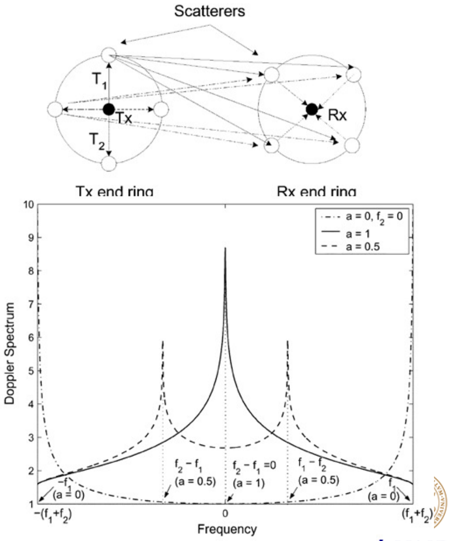
- 10 km long highway
- 4 lanes (2 on each side)
- 400 byte long CAM messages
- Channel access procedure is carrier sense multiple access (CSMA)
- Vehicle speeds independent Gaussian distributed with mean (23, 30) m/s per lane and standard deviation 1 m/s
- Vehicles Poisson distributed with inter-arrival rate of 1 s, 2 s, 3 s.
- Channel models comparison,
  - Nakagami dual slope
  - LOS/OLOS dual slope model





Two-ring model

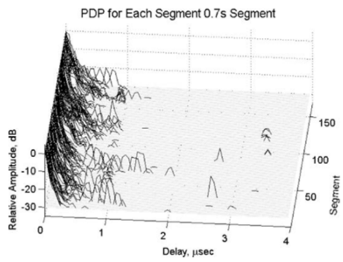
- Reflects key properties:
  - Scattering occurs around TX and RX
  - Both TX and RX are moving
- Closed-form equations for Doppler spectra



[Patel et al. 2005]

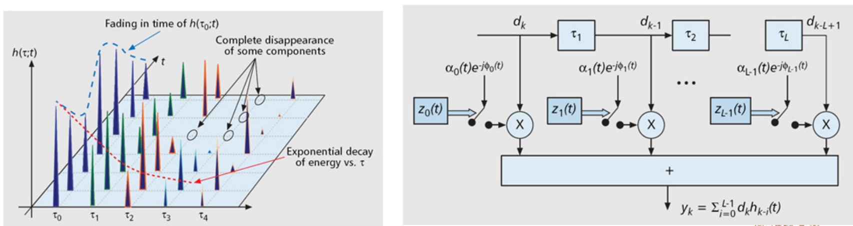
Tap-delay line model

- Segmented time-invariant tapped delay line



[Acosta and Ingram 2007]

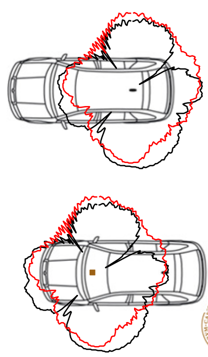
- Time-varying tapped delay line



[Matolak 2008]

Distributed antenna measurements

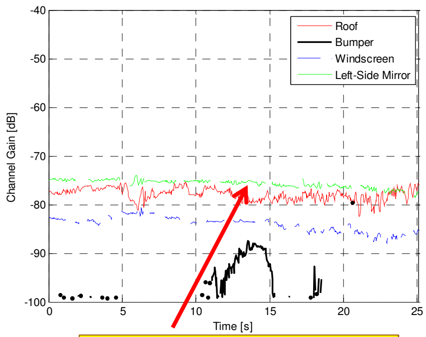
- Position of antenna is expected to have large impact
  - Both TX and RX antennas are at same height
  - Relatively close to ground level (1-2m above ground)
  - Shadowing effects are expected
- Measurements in the past have been conducted with same type of antenna arrangements
  - Usually **roof mounted** antenna
  - Single exception exists with antenna placed **Inside-windscreen**



DIVERSITY'11 measurement setup

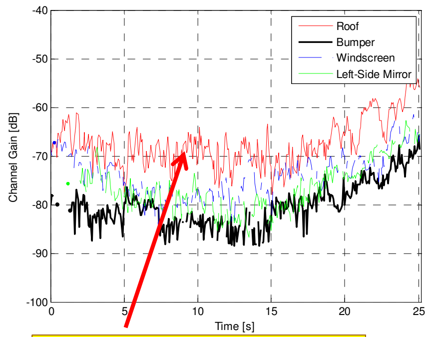
Impact of antenna placement

Rural - Convoy



Leftside-mirror antenna location has strongest channel gain

Urban - Convoy

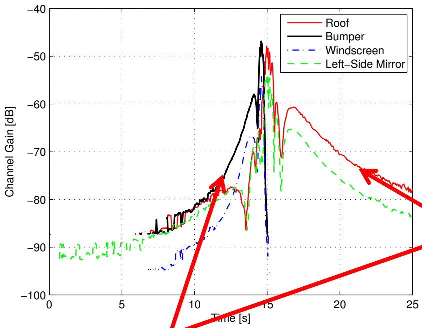


Roof antenna location has strongest channel gain

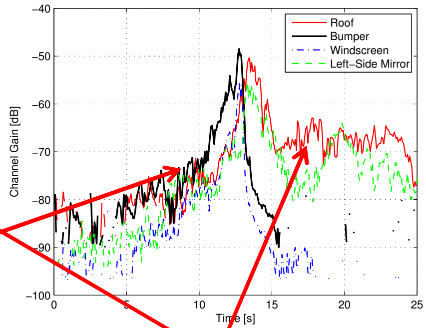
- **Leftside-mirror antenna is sensitive to the alignment of cars**

Impact of antenna placement

Rural - Opposite



Urban - Opposite



Diversity arrangements with complementary antennas seems to be the preferred solution, e.g., roof or left-side-mirror together with the bumper antenna.

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- A. Molisch, F. Tufvesson, J. Kåredal, C. F. Mecklenbräuker, "A Survey on Vehicle-to-Vehicle Propagation Channels," IEEE Wireless Communications, vol. 16, no. 6, pp. 12-22, 2009.
- J. Kåredal, F. Tufvesson, T. Abbas, O. Klemp, A. Paier, L. Bernadó, A. Molisch, "Radio channel measurements at street intersections for vehicle-to-vehicle applications," *Proc. IEEE Vehicular Technology Conference (VTC2010-spring)*, Taipei, Taiwan, pp. 1-5, May 16-19, 2010.
- A. Paier, L. Bernadó, J. Kåredal, O. Klemp, A. Kwoczek, "Overview of vehicle-to-vehicle radio channel measurements for collision avoidance applications," *Proc. IEEE Vehicular Technology Conference (VTC2010-spring)*, Taipei, Taiwan, pp. 1-5, May 16-19, 2010.
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- A. Paier, T. Zemen, L. Bernado, G. Matz, J. Kåredal, N. Czink, C. Dumard, F. Tufvesson, A. Molisch, C. Mecklenbräuker, "Non-WSSUS vehicular channel characterization in highway and urban scenarios at 5.2 GHz using the local scattering function," *Proc. International Workshop on Smart Antennas (WSA)*, pp. 9-15, 2008.
- L. Bernadó, T. Zemen, A. Paier, G. Matz, J. Kåredal, N. Czink, C. Dumard, F. Tufvesson, M. Hagenauer, A. Molisch, C. F. Mecklenbräuker, "Non-WSSUS Vehicular Channel Characterization at 5.2 GHz - Spectral Divergence and Time-Variant Coherence Parameters," *Proc. URSI General Assembly*, 2008.
- A. Paier, J. Kåredal, N. Czink, H. Hofstetter, C. Dumard, T. Zemen, F. Tufvesson, C. Mecklenbräuker, A. Molisch,
"First results from car-to-car and car-to-infrastructure radio channel measurements at 5.2GHz," *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Athens, Greece, pp. 1-5, Sept. 3-7, 2007.
- A. Paier, J. Kåredal, N. Czink, H. Hofstetter, C. Dumard, T. Zemen, F. Tufvesson, A. Molisch, C. Mecklenbräuker, "Car-to-car radio channel measurements at 5 GHz: Pathloss, power-delay profile, and delay-Doppler spectrum," *Proc. IEEE International Symposium on Wireless Communication Systems (ISWCS)*, Trondheim, Norway, pp. 224-228, Oct. 17-19, 2007.

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- T. Abbas, J. Karedal, F. Tufvesson, A. Paier, L. Bernadó, A. Molisch: Directional Analysis of Vehicle-to-Vehicle Propagation Channels, IEEE Vehicular Technology Conference, IEEE 73rd Vehicular Technology Conference 2011-spring, Budapest, Hungary, 2011-05-15/2011-05-18.
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- T. Abbas, L. Bernadó, A. Thiel, C. F. Mecklenbräuker, and F. Tufvesson: Radio Channel Properties for Vehicular Communication: Merging Lanes Versus Urban Intersections, IEEE Vehicular Technology Magazine, December, 2013 (Invited paper)
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- T. Abbas: Measurement Based Channel Characterization and Modeling for Vehicle-to-Vehicle Communications, Series of licentiate and doctoral dissertations, ISSN 1654-790X (No. 58), Department of Electrical and Information Technology, Lund University, Sweden, 2014.

- For details please visit: **Vehicle-to-vehicle channel modeling at EIT**

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Conclusions

- V2V channels differ significantly from standard cellular channels
  - do not expect satisfactory performance for standard WLAN equipment
- For network simulations – include shadowing effects
  - buildings, vehicles,
  - long correlation time for shadowing from other vehicles
- For link simulations – include non-stationarities and consider the double selective channel
  - high Doppler spread – short correlation time
  - high excess delay – small coherence bandwidth
- Multiple antenna arrangements might be required to get reliable links
  - Rx diversity
- Many challenges and opportunities still remain

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Thank you!

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