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IEEE Montréal Section and VTS/ComSoc/ITSoc/SPS Chapters – McGill U., Jan. 05, 2017, 4-5:30pm.

Self-Driving Vehicles: The Path Forward with LIDAR and V2x Technologies

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Acknowledgment

European Commission

MARIE CURIE ACTIONS

erc European Research Council

HIGHTS High precision positioning for Cooperative-ITS

SAFER VEHICLE AND TRAFFIC SAFETY CENTRE AT CHALMERS

VINNOVA

ERICSSON

Seminar Link: https://meetings.vtools.ieee.org/m/42757

Contents

Background

VLSI

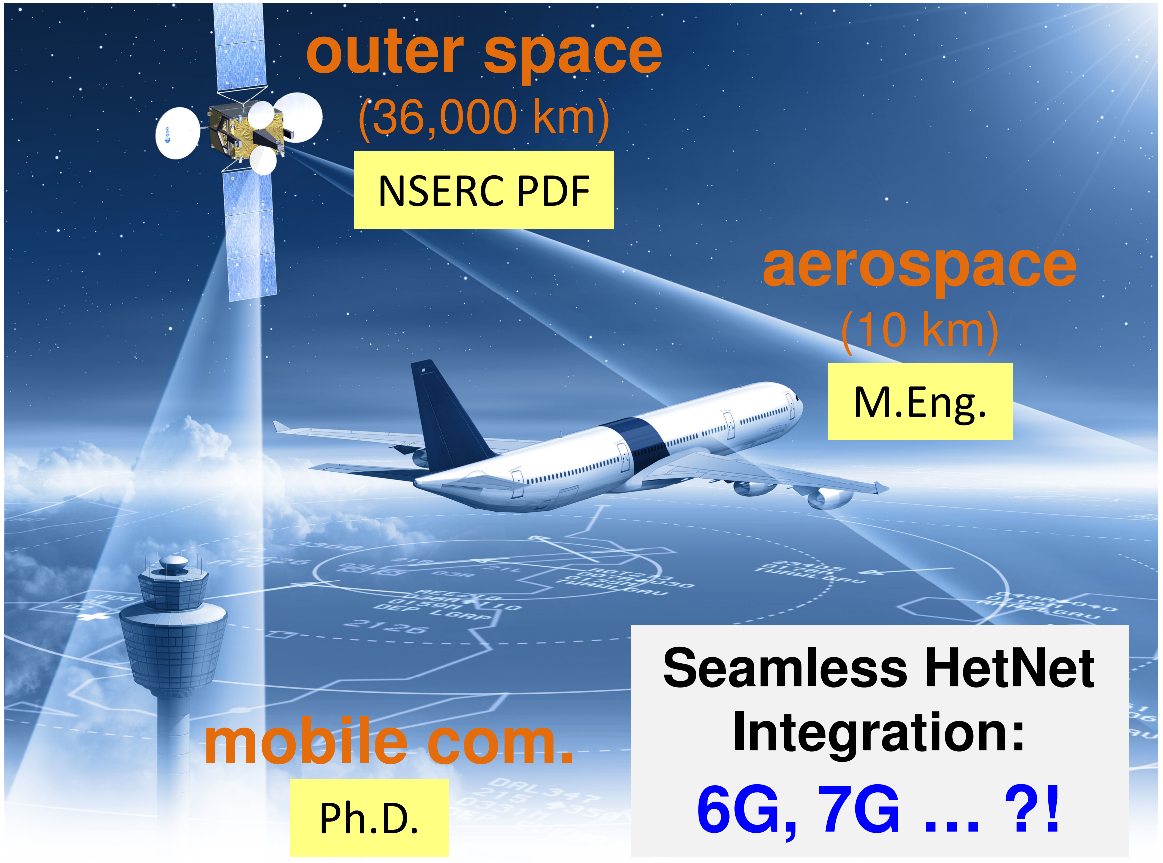
B.Eng.

IBM

industry

vehicular

Marie-Curie Fellowship



Sweden

"Sverige" or "Sweden"

- *Population = 10M*
- *3 major cities (Stockholm, Göteborg, Malmö)*
- *Europe's most innovative country!*

The Telegraph

How Sweden became the startup capital of Europe

Stockholm is the second most prolific tech hub in the world on a per capita basis, behind Silicon Valley. How did that happen and where does it go from here?

By Lauren Davidson, in Stockholm
10:26PM BST 28 Jun 2015
Follow 4,104 followers

Chalmers

"Göteborg" or "Gothenburg"

- *2nd largest city (like MTL!)*
- *Population = 500,000*
- *HQ of Volvo (founded in 1927)*
- *2 Universities*

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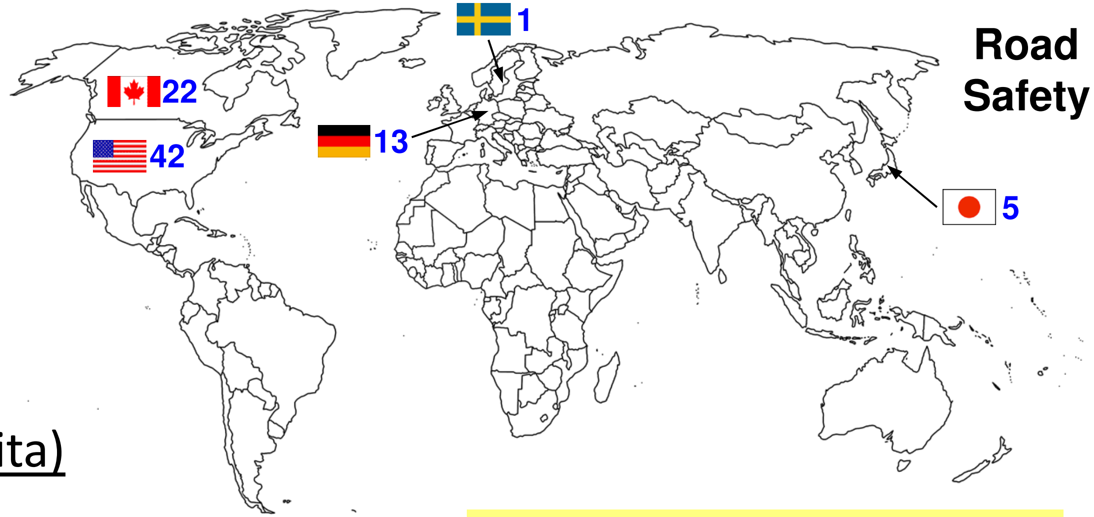
- *Chalmers (since 1829)*
- *"Sustainability"*
- *17 Dept. (Signals & Systems)*
- *ComSys (largest group in Sweden)*
- *Research Focus (Vehicular, Cellular, PA, Optical, Coding, IT)*

Motivation

World Health Organization

Oct. 2015

infrastructure, regulations and R&D



Road Safety

Road Traffic Fatalities (per capita)

 ~ 3,400 / day

 ~ 230 / day

 ~ 0.7 / day

Causes?

- careless driving
- speeding
- DUI (driving under the influence)

Europe:

- safest roads w.r.t. world
- target: ↓50% (2020)

Driverless Vehicles

- **Definition**: *vehicle that can by itself*
  - Accelerate
  - Break
  - Steer.

- **Synonyms**:
  - Self-Driving Car
  - Automated Car
  - Autonomous Vehicle
  - Robotic Vehicle
  - Robo Car
  - Etc.

Geometric awareness of the surrounding

Ford

LEXUS

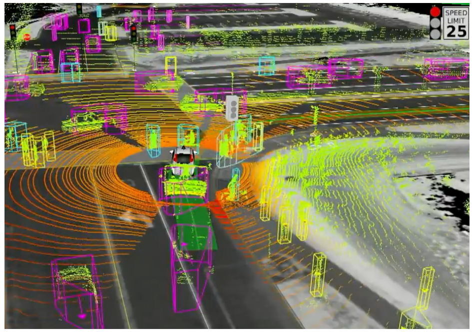
VOLVO

WAYMO

Driverless is Complicated

- **Map/Sensors:**
  - Only vehicles

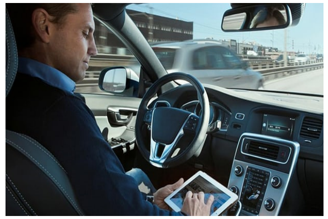
  - Pedestrians, Cyclist, Objects



  - Unexpected Mobility
  - Machine Learning
  - Prediction Capability
  - Complicated Computing
  - Big Data (~ 1GB data/s)

Type of Driverless Capability

- **Driver Assisted Vehicle**: (i.e. hands "**always**" on the wheel)
  - Offer support to a driver (augmented capability).
  - Keep a safe distance to nearby vehicles.
  - Keep car in the lane.
  - It's legal to use!
  - e.g. **Volvo XC-90: "Pilot Assist"**



Incremental Deployment

- **Semi-Autonomous Vehicle**: (i.e. hands "**sometimes**" on the wheel)
  - When activated, the car drives itself.
  - Driver is not responsible during "autonomous mode".
  - No legal framework yet! (special permit for testing: Gothenburg, CA, AZ,…)
  - e.g. **Volvo Drive Me XC-90: "IntelliSafe Autopilot"**

Technological Leap

- **Full-Autonomous Vehicle**: (i.e. there are "**no wheel/pedals**")
  - e.g. **Waymo** (a.k.a. "**Google Car**")

Volvo's "*Drive Me*" Project

- Biggest ever large-scale public trial of autonomous driving (alongside traditional vehicles).
- **<u>Ecosystem – Partnership with 5 Key Organizations</u>:**
  - **Swedish Transportation Agency**:
    - **Laws**
  - **Swedish Transport Administration**:
    - **Road Infrastructures**
  - **City of Gothenburg**:
    - **Sustainable Transportation**
  - **Lindholmen Science Park**:
    - **Vehicular R&D**
  - **Autoliv** (software):
    - **Advanced Driver Assistance Systems (ADAS)**
    - **Active Safety System**

TRANSPORT STYRELSEN

TRAFIKVERKET
SWEDISH TRANSPORT ADMINISTRATION

City of Göteborg

LINDHOLMEN SCIENCE PARK

ERICSSON

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Autoliv

BREAKING NEWS

Volvo (50%) & Autoliv (50%) merger for "autonomous driving" called "Zenuity" (Jan.2017)

Volvo's "*Drive Me*" Project …

- ~ 100 Self-driving Volvos in Gothenburg in 2017!

Video Link: www.youtube.com/watch?v=asKvI8ybJ5U

~ 70 km/hr

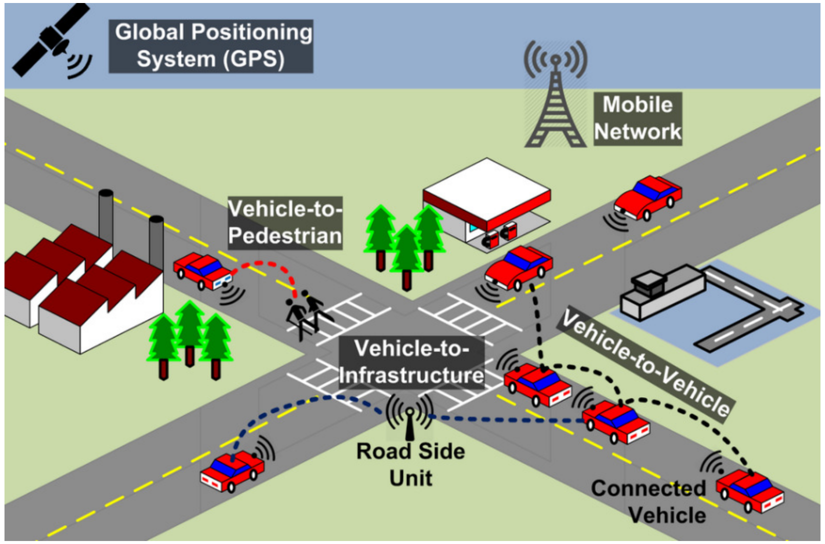
System Features:

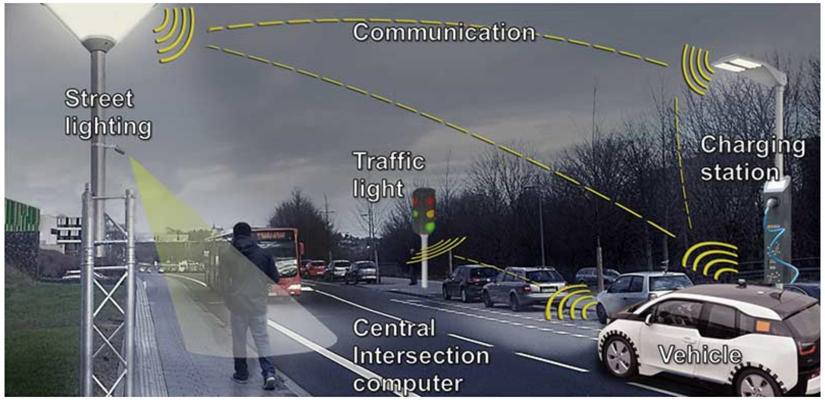
- 7 short/long range radars (60, 150m)
- 5 cameras
- frontal LIDAR (150m)
- 12 ultrasonic sensors
- network of powerful computers (brain!)
- high performance GPS
- 3D digital map (V2I: traffic authorities digital center)
- multiple system redundancies

What about V2x?

- LIDAR & V2x enhances:
  - Road-Safety
  - Traffic Efficiency
  - Energy Consumption

- Sharing critical information among:
  - Network & Road-side units (V2I)
  - Vehicles (V2V)
  - Pedestrians





V2x Enablers

- **Standard:** (interoperability = common language!)

Volvo

Google car

Ligier EZ-10

- **IEEE 802.11p** (DSRC: Direct Short Range Com.) **Ready!**
- **4G/LTE-A** (rel.14: D2D+)
- **5G** (~ 2023)

2008 European Commission

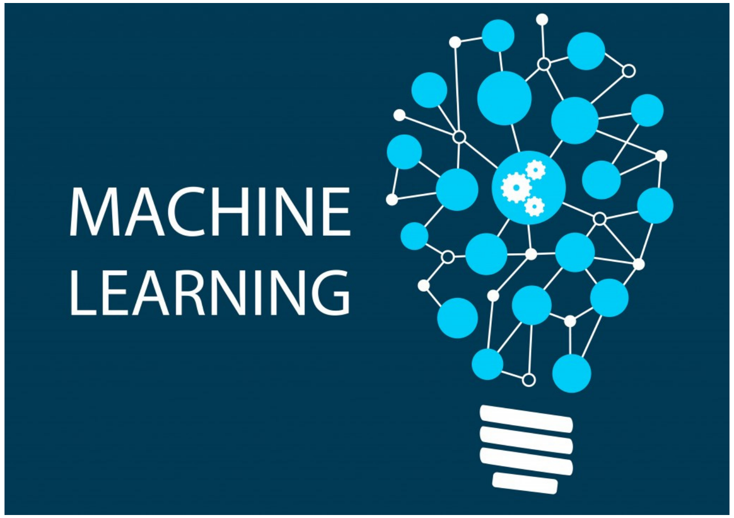
2015 DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

5.9GHz
(unlicensed)

My 2-cents

- **Short-term (2020-2030):**
  - 802.11p (**local**)
- **Long-term (2030-2050):**
  - 5G+ (**regional**)
    - Network
    - Base Station
    - Cloud
    - Internet

Slow, but it represents the future!!



Share the knowledge to all the kids in the region

5G Reliability Vision

Metrics	4G	5G	Change?
Data-Rate (peak)	up to 100 Mbps	up to 10 Gbps	**X100 fold**
Densification	1,000 / km^2	1 Million / km^2	**X1000 fold**
Power	P_0	$P_0/10$	**↓90%** (from 2010)
Latency	~25 ms	~5-10 ms	**↓60~80%**
Reliability	10^{-4}	10^{-5}	**X10 more reliable**

≤ 1/10,000

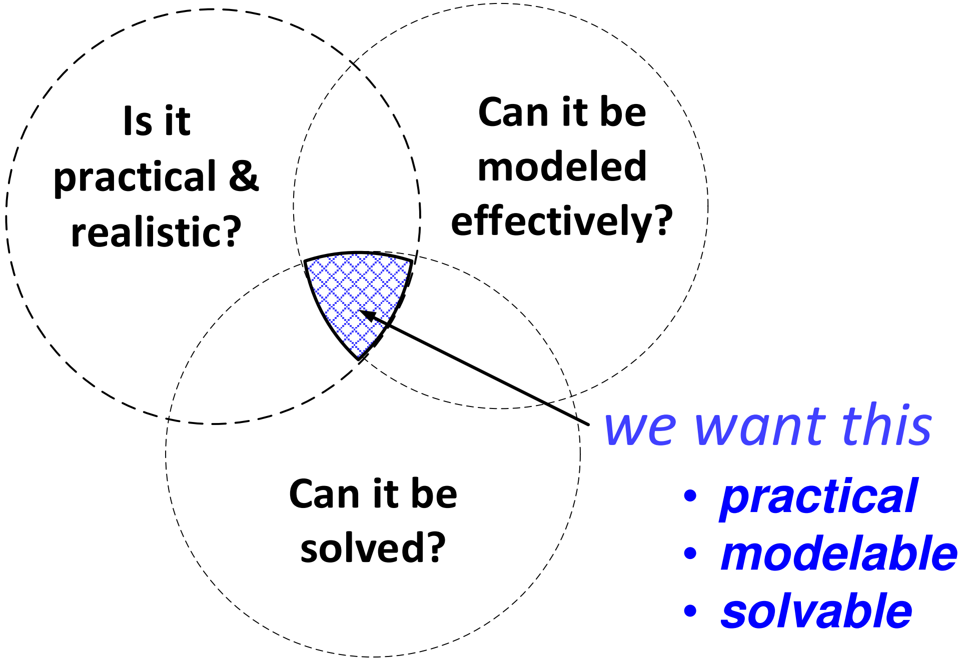
≤ 1/100,000
(**semi-autonomous**)

≤ 10^{-9}
(**full-autonomous**)

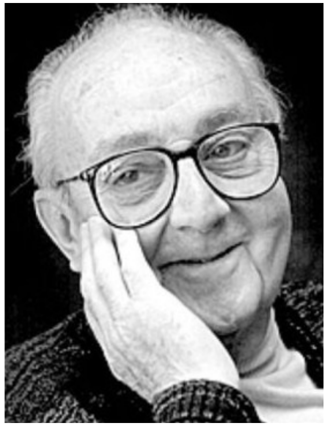
PHY/MAC $p_{out} \leq 10^{-x} \quad x < 5$ **Not Easy!** → **Design!** → **Modeling!**

Effective Modeling

"*Essentially, all models are wrong, but some are useful*."
– Prof. George E.P. Box (statistics, 1919-2013)



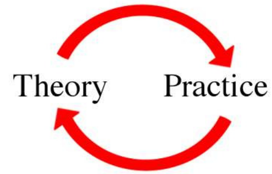
- ***practical***
- ***modelable***
- ***solvable***



Complicated!!

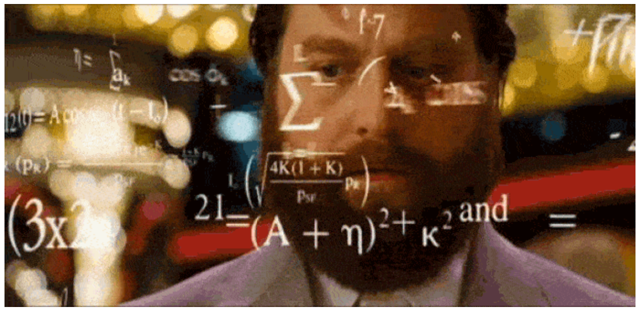
Effective Modeling …

“iterative”



Analysis:

Offer understanding of the basic fundamentals (all the nitty-gritty).



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“affordable”

“design”

Measurements:

Give a sense of realism to the research (data collection, etc).

LUND UNIVERSITY

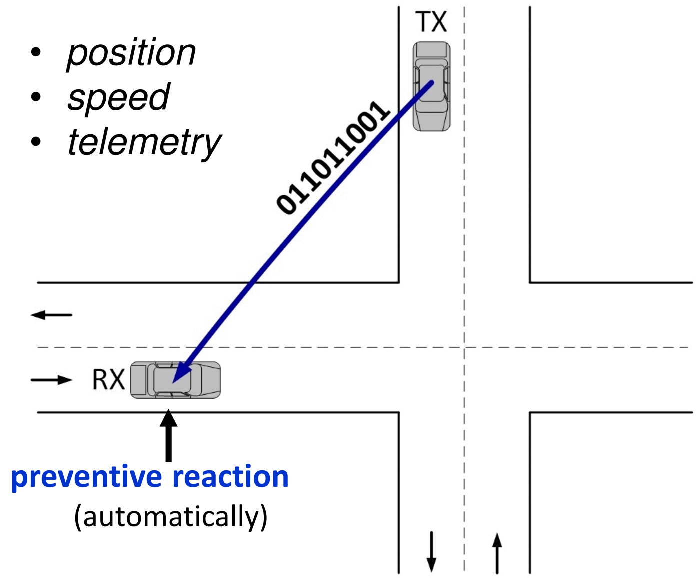
“time-consuming”

“compatibility”

Intersection Problem

~ 6,000,000 crashes/yr

~ **40%** at the intersection!

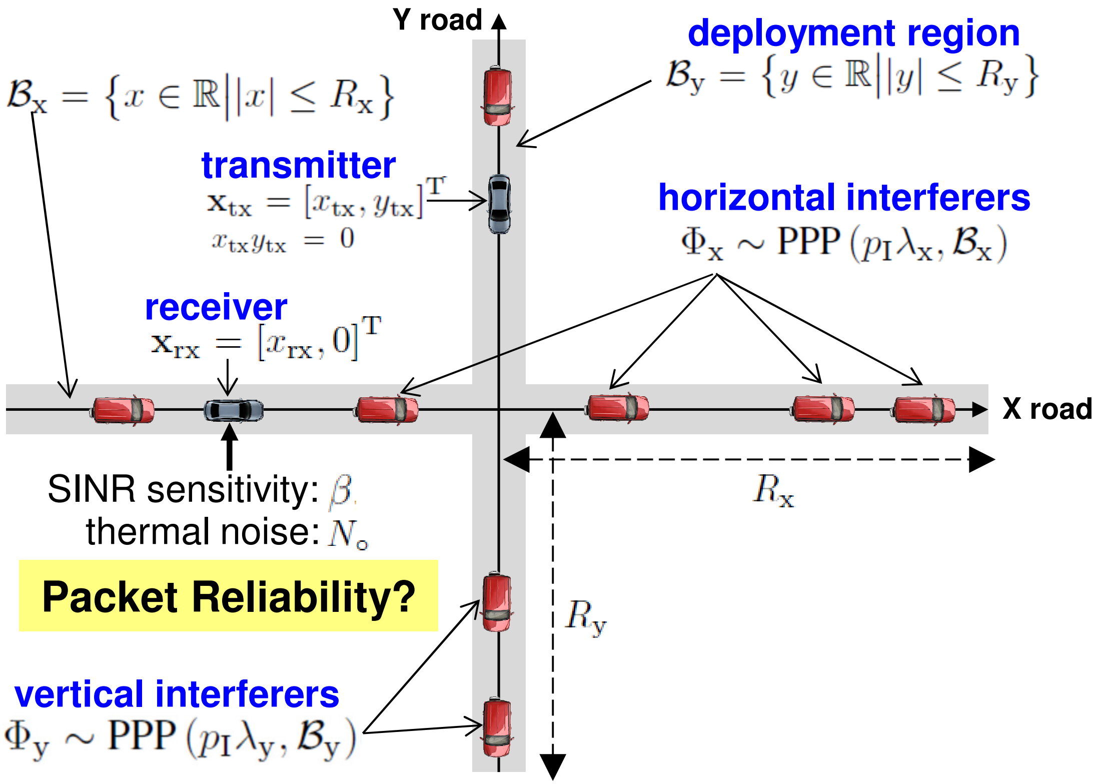


"Packet Reliability"

↓

Road Safety

Network Model



transmit power
$P_{\circ}$

Aloha transmit probability:
p_{I}

$$\boxed{\Phi = \{\mathbf{x}_i\}_{i=1,2,\ldots,n} \sim \mathrm{PPP}(\lambda, \mathcal{B})}$$

Poisson Point Process (PPP)

(1) region: $\mathcal{B} \subseteq \mathbb{R}^d$
(2) intensity: $\lambda\,[\#/\mathrm{m}^d]$
(3) no. points: $n \sim \mathrm{Pois}(\bar{n})\,;\ \bar{n} = \lambda\,|\mathcal{B}|$
(4) positions: $\mathrm{x}_i \sim \mathcal{U}(\mathrm{x} \in \mathcal{B})$

Channel Model

Link Budget:

fast fading (Rayleigh)

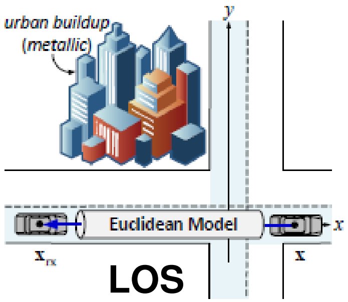
$L_{\mathrm{f}}(\mathbf{x}) \sim \mathrm{Exp}(1)$

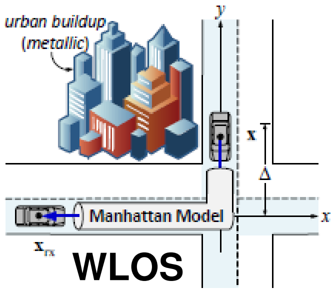
channel losses

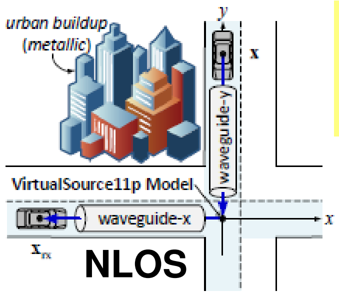
$$P_{\mathrm{rx}}(\mathbf{x}, \mathbf{x}_{\mathrm{rx}}) = P_{\circ} L_{\mathrm{ch}}(\mathbf{x}, \mathbf{x}_{\mathrm{rx}}) \simeq P_{\circ} \ell(\mathbf{x}, \mathbf{x}_{\mathrm{rx}}) L_{\mathrm{f}}(\mathbf{x})$$

power received power transmitted path loss

Path Loss for Urban Intersection:







measurement campaigns:
5.9 GHz

Accurate model!

$$\ell(\mathbf{x}, \mathbf{x}_{\mathrm{rx}}) = A_{\circ} \left\| \mathbf{x}_{\mathrm{rx}} - \mathbf{x} \right\|^{-\alpha}$$

inverse power law model

$$\ell(\mathbf{x}, \mathbf{x}_{\mathrm{rx}}) = A_{\circ} \left(\|\mathbf{x}\| + \|\mathbf{x}_{\mathrm{rx}}\| \right)^{-\alpha}$$

$\min\left(\|\mathbf{x}\|, \|\mathbf{x}_{\mathrm{rx}}\|\right) \leq \triangle$

$\triangle = 10 \sim 15\mathrm{m}$

Manhattan model

$$\ell(\mathbf{x}, \mathbf{x}_{\mathrm{rx}}) = A'_{\circ} \left(\|\mathbf{x}\| \, \|\mathbf{x}_{\mathrm{rx}}\| \right)^{-\alpha}$$

$\min\left(\|\mathbf{x}\|, \|\mathbf{x}_{\mathrm{rx}}\|\right) > \triangle$

$A'_{\circ} < A_{\circ} (\triangle/2)^{\alpha}$

VirtualSource11p model

Success Probability (SP)

observed at RX, threshold

$$\mathcal{P}_{\mathrm{c}}\left(\beta, \mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right) = \Pr\left(\mathsf{SINR} \geq \beta\right)$$

wanted link

$$\mathsf{SINR} = \frac{L_{\mathrm{f}}\, \ell\left(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right)}{I + N_{\circ}/P_{\circ}}$$

aggregate interference

normalized noise

isolate for fading from TX

$$\mathcal{P}_{\mathrm{c}}\left(\beta, \mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right) = \mathbb{E}_I\left\{\Pr\left(L_{\mathrm{f}} \geq \beta\left(\gamma_{\circ} + I\right)/\ell\left(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right)\right)\right\}$$

averaged over all PPP realizations

$$= \mathbb{E}_I\left\{\exp\left(-\beta\left(\gamma_{\circ} + I\right)/\ell\left(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right)\right)\right\}$$

CCDF of Rayleigh fading: "Exp(1)"

$$= \underbrace{\boxed{\exp\left(-\beta\gamma_{\circ}/\ell\left(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right)\right)}}_{\text{cap on SP}}\ \underbrace{\boxed{\mathbb{E}_I\left\{\exp\left(-\beta' I\right)\right\}}}_{\text{degradation to SP}}$$

$\mathcal{P}_{\mathrm{noint}}$
deterministic
(no interference)

random
(interference)

PPPs

$$\boxed{I = I_{\mathrm{x}} + I_{\mathrm{y}} = \sum_{\mathrm{x} \in \Phi_{\mathrm{x}} \cup \Phi_{\mathrm{y}}} L_{\mathrm{f}}\left(\mathbf{x}\right) \ell\left(\mathbf{x}, \mathbf{x}_{\mathrm{rx}}\right)}$$

Interference from other Vehicles

$$\boxed{\mathcal{P}_{\mathrm{c}}\left(\beta, \mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right) = \mathcal{P}_{\mathrm{noint}} \mathcal{P}_{\mathrm{x}} \mathcal{P}_{\mathrm{y}}}$$

interference

Horizontal Interferers:

$$\mathcal{P}_{\mathrm{x}} = \exp\left(-p_{\mathrm{I}} \lambda_{\mathrm{x}} \zeta \mathcal{X}\left(R_{\mathrm{x}}\right)\right)$$

$$\begin{aligned} \mathcal{X}\left(R_{\mathrm{x}}\right) = {} & g_{\circ}\left(\alpha, \frac{\left(R_{\mathrm{x}} + \|\mathbf{x}_{\mathrm{rx}}\|\right)}{\zeta}\right) \\ & + g_{\circ}\left(\alpha, \frac{\left(R_{\mathrm{x}} - \|\mathbf{x}_{\mathrm{rx}}\|\right)}{\zeta}\right) \mathbf{1}_{\|\mathbf{x}_{\mathrm{rx}}\| \leq R_{\mathrm{x}}} \\ & - g_{\circ}\left(\alpha, \frac{-\left(R_{\mathrm{x}} - \|\mathbf{x}_{\mathrm{rx}}\|\right)}{\zeta}\right) \mathbf{1}_{\|\mathbf{x}_{\mathrm{rx}}\| > R_{\mathrm{x}}} \end{aligned}$$

road segment

$$g_{\circ}\left(\alpha, \vartheta\right) \triangleq \vartheta \, {}_2F_1\left(1, \frac{1}{\alpha}; \left(1 + \frac{1}{\alpha}\right); -\vartheta^{\alpha}\right)$$

path loss exponent

Gauss's hypergeometric

e.g.

$$\boxed{g_{\circ}\left(2, \vartheta\right) = \arctan\left(\vartheta\right)}$$

urban intersection

$$\boxed{1 < \alpha < 2}$$

Vertical Interferers:

$$\mathcal{P}_{\mathrm{y}} = \exp\left(-2 p_{\mathrm{I}} \lambda_{\mathrm{y}} \zeta \mathcal{Y}\left(R_{\mathrm{y}}\right)\right)$$

$$\begin{aligned} \mathcal{Y}\left(R_{\mathrm{y}}\right) = {} & -g_{\circ}\left(\alpha, \frac{\|\mathbf{x}_{\mathrm{rx}}\|}{\zeta}\right) \\ & + g_{\circ}\left(\alpha, \frac{\left(R_{\mathrm{y}} + \|\mathbf{x}_{\mathrm{rx}}\|\right)}{\zeta}\right) \mathbf{1}_{\|\mathbf{x}_{\mathrm{rx}}\| \leq \triangle} \\ & + g_{\circ}\left(\alpha, \frac{\left(\triangle + \|\mathbf{x}_{\mathrm{rx}}\|\right)}{\zeta}\right) \mathbf{1}_{\|\mathbf{x}_{\mathrm{rx}}\| > \triangle} \\ & + \frac{1}{\kappa}\left(g_{\circ}\left(\alpha, \frac{\kappa R_{\mathrm{y}}}{\zeta}\right) - g_{\circ}\left(\alpha, \frac{\kappa \triangle}{\zeta}\right)\right) \mathbf{1}_{\|\mathbf{x}_{\mathrm{rx}}\| > \triangle} \end{aligned}$$

road segment

$$\zeta = \left(A_{\circ} \beta / \ell\left(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right)\right)^{1/\alpha}$$

$$\kappa = \left(A_{\circ} / A_{\circ}'\right)^{1/\alpha} \|\mathbf{x}_{\mathrm{rx}}\|$$

Design & Analysis

V2V reliability metric

$$\boxed{\mathcal{P}_{\mathrm{c}}\left(\beta, \mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right) = \mathcal{P}_{\mathrm{noint}} \mathcal{P}_{\mathrm{x}} \mathcal{P}_{\mathrm{y}}}$$

system parameters	
transmit probability	p_{I}
transmit power	$P_{\circ}$
AWGN floor	$N_{\circ}$
RX sensitivity	β

propagation parameters	
operating frequency	$f_{\circ}$
reference distance	$d_{\circ}$
break-point distance	$\triangle$
path loss (PL) exponent	α
PL coefficient for LOS/WLOS	$A_{\circ}$
PL coefficient for NLOS	$A'_{\circ}$

TX/RX Geometry	
TX position	$\mathbf{x}_{\mathrm{tx}}$
RX position	$\mathbf{x}_{\mathrm{rx}}$

dimensions and traffic	
road dimensions	$R_{\mathrm{x}}, R_{\mathrm{y}}$
vehicular traffic	$\lambda_{\mathrm{x}}, \lambda_{\mathrm{y}}$

design parameters

(R, p_{I})

<u>Requirement:</u> $\mathcal{P}_{\mathrm{noint}} \mathcal{P}_{\mathrm{x}} \mathcal{P}_{\mathrm{y}} \geq \mathcal{P}_{\mathrm{target}}$

target reliability
(worst-case scenario)

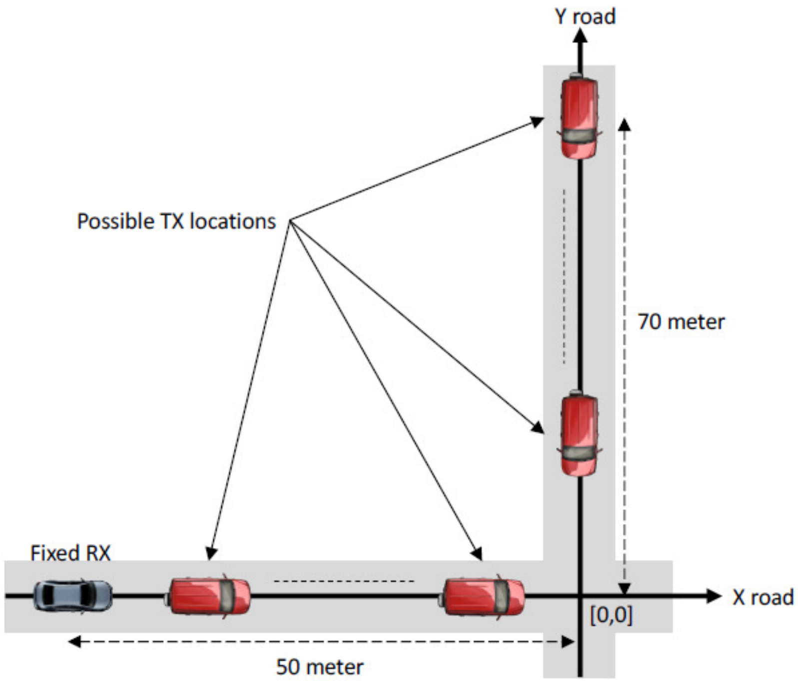
(Q1) Can any "target" of choice be selected? NO $\mathcal{P}_{\mathrm{target}} < \mathcal{P}_{\mathrm{noint}}$

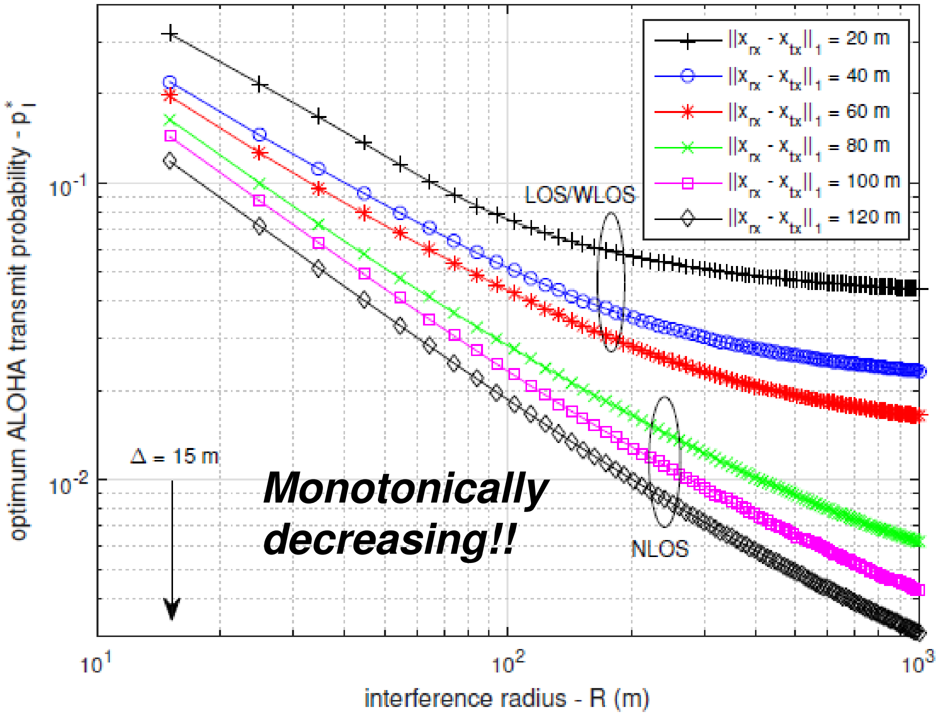
(Q2) How are the design parameters related?

$$p_{\mathrm{I}} \leq p_{\mathrm{I}}^{*}(R)$$

$$\boxed{p_{\mathrm{I}}^{*}(R) = \frac{-\beta N_{\circ} / \left(P_{\circ} \ell\left(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}\right)\right) - \ln\left(\mathcal{P}_{\mathrm{target}}\right)}{\zeta \lambda\left(\mathcal{X}(R) + 2\mathcal{Y}(R)\right)}}$$

Numerical Evaluation



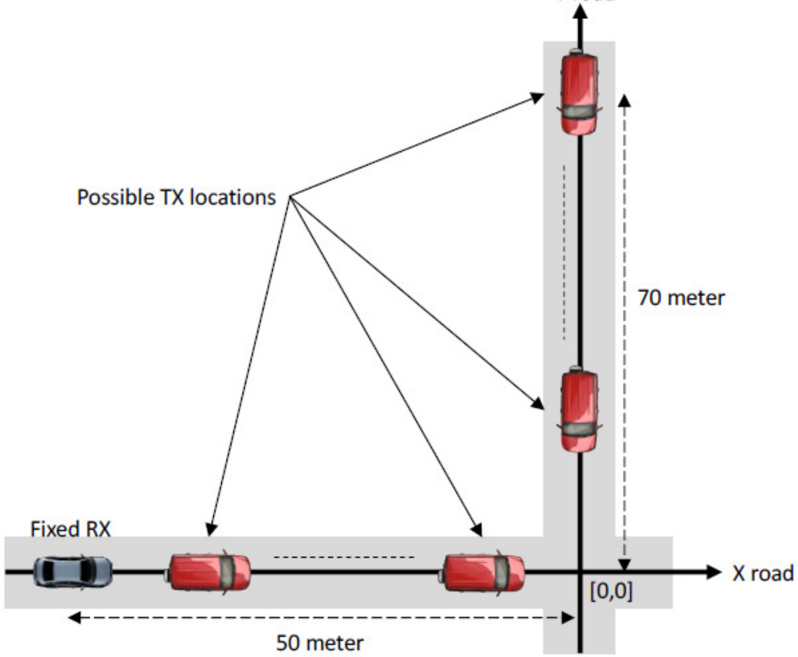


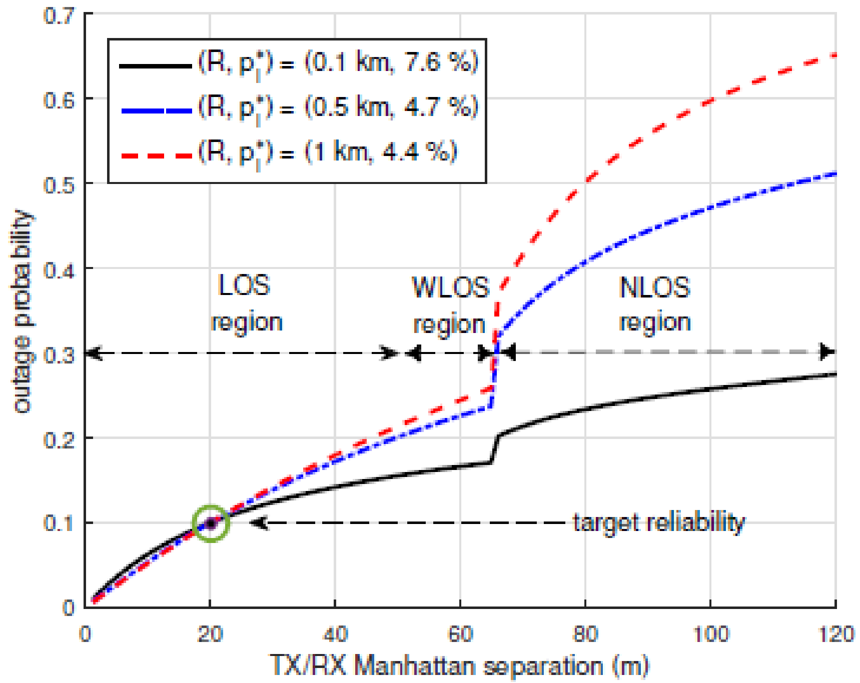
RX: Fixed
TX: Movable
Interference Radius: $R \in [\triangle, R_{\max}]$

$\mathcal{P}_{\text{target}} < \mathcal{P}_{\text{noint}} = 0.966$

$\mathcal{P}_{\text{target}} = 0.9$

Numerical Evaluation



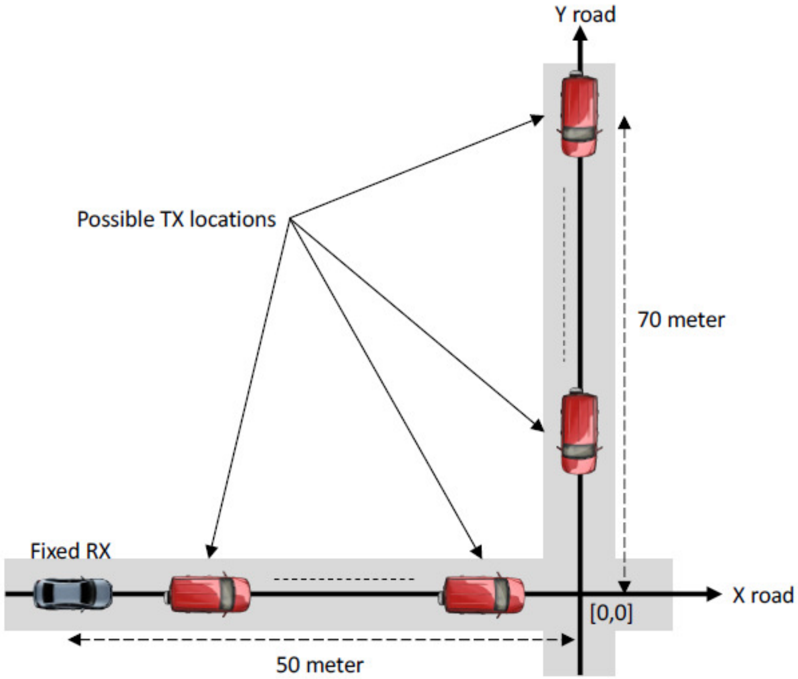


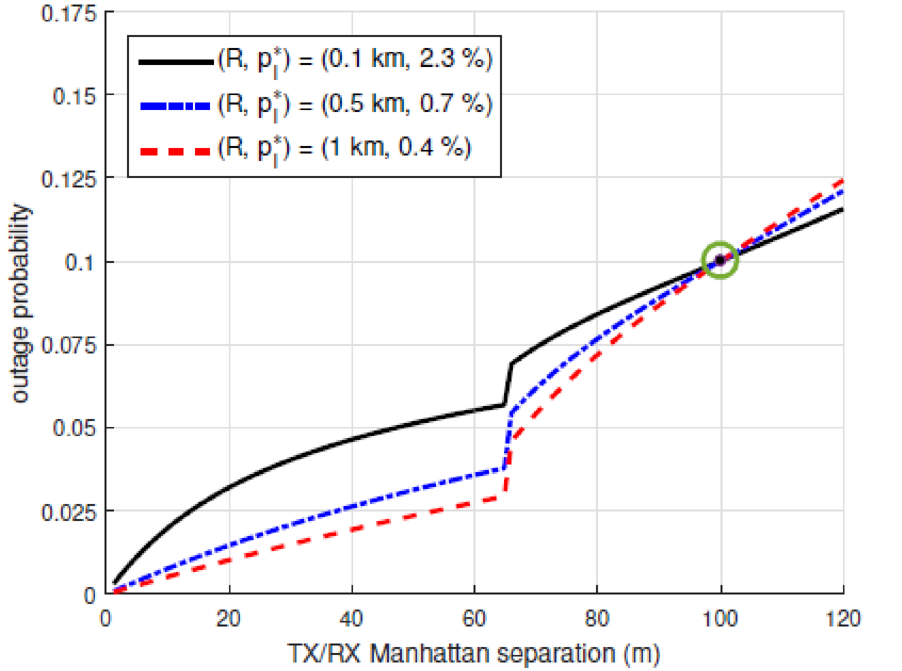
(a) $p_{\mathrm{I}}^*(R)$ designed for $\|\mathbf{x}_{\mathrm{rx}} - \tilde{\mathbf{x}}_{\mathrm{tx}}\|_1 \leq 20$

RX: Fixed
TX: Movable
Interference Radius: $R \in [\triangle, R_{\max}]$

Meet the target for: LOS

Numerical Evaluation





(e) $p_{\mathrm{I}}^{*}\,(R)$ designed for $\|\mathbf{x}_{\mathrm{rx}} - \tilde{\mathbf{x}}_{\mathrm{tx}}\|_1 \leq 100$

RX: Fixed
TX: Movable
Interference Radius: $R \in [\triangle, R_{\max}]$

Meet the target for: LOS, WLOS, NLOS

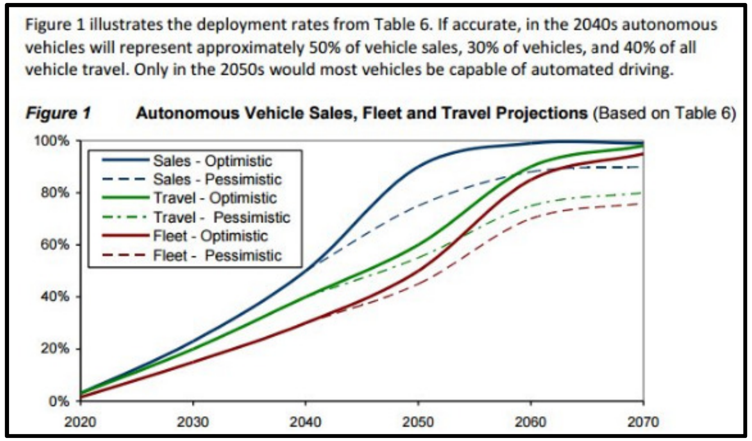
Observation

- Beneficial to limit interference to a **small spatial region**; while allowing **more simultaneous transmitters**.

- We also evaluated the SP over different:
  - Environments: Suburban vs. Urban
  - Interference: Finite vs. Infinite interferes.
  - Traffic: Random vs. Deterministic (predictable, for driverless!)

Source: M. Abdulla, E. Steinmetz, and H. Wymeersch, "Vehicle-to-Vehicle Communications with Urban Intersection Path Loss Models," In *Proc. of IEEE Global Communications Conference (GLOBECOM'16)*, pp. 1-6, Washington DC, USA, Dec. 4-8, 2016. http://publications.lib.chalmers.se/publication/245087

Conclusion



- Humans are terrible drivers.
- Driverless vehicle is the future.
- Full autonomy by all vehicles requires both
  - Sensors/LIDAR (ready!)
  - V2x communications (in the making!)
- 5G-V2x standard/deployment/business model is yet to be realized.
- A lot of research work is ought to be done: traffic/control, proof-of-concept, analysis, simulators, channel models, measurements campaigns, …
- High performance & low latency is Critical:
  - Spatial Diversity (multi-antenna)
  - Smart Resource Allocation (controller, combinatorial optimization techniques)
  - Low-latency HARQ retransmission (≤ 3 retransmissions)
  - High Performance MAC Protocol

Captivate the Imagination: Full Autonomy

Video Link: www.youtube.com/watch?v=WmYsWYDQxuI