

Connected Cars

Falko Dressler
University of Paderborn, Germany

✧ Inter-Vehicular Communication

- ✧ Communication paradigms
- ✧ Applications

✧ Protocols and Standards

- ✧ Where do we got from
- ✧ DSRC/WAVE

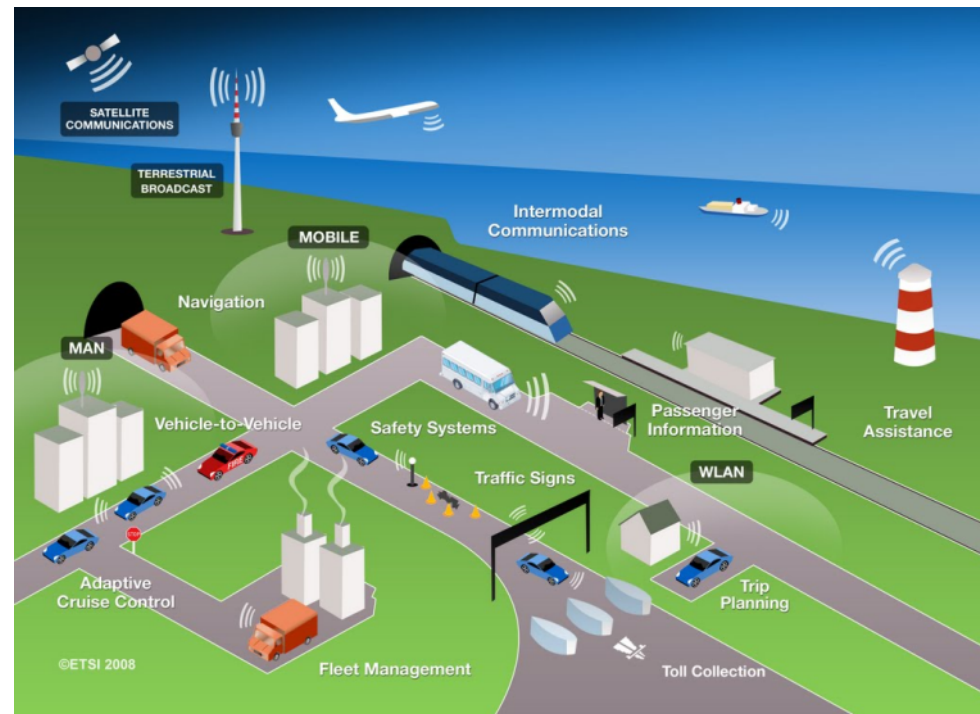
✧ New Challenges

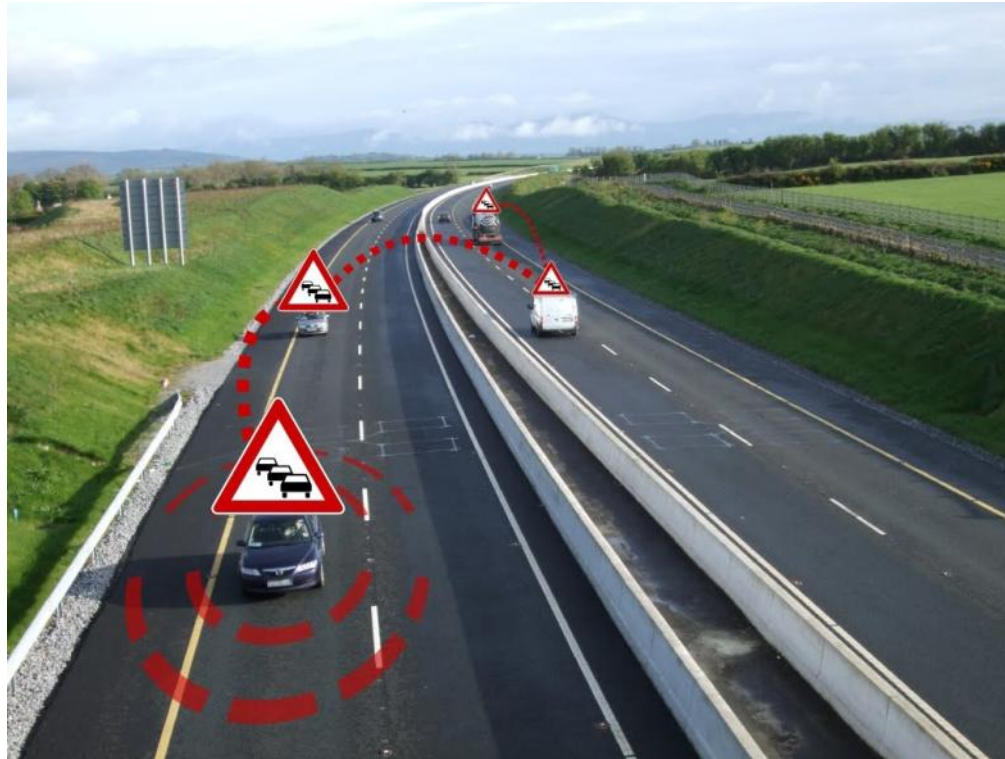
- ✧ Platooning

✧ Performance Evaluation

- ✧ Simulation using Veins

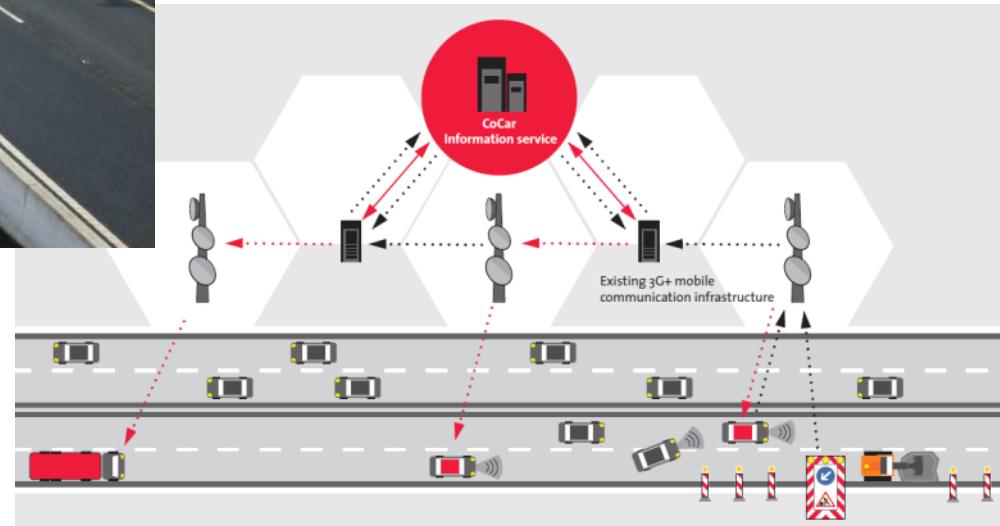
✧ Conclusions



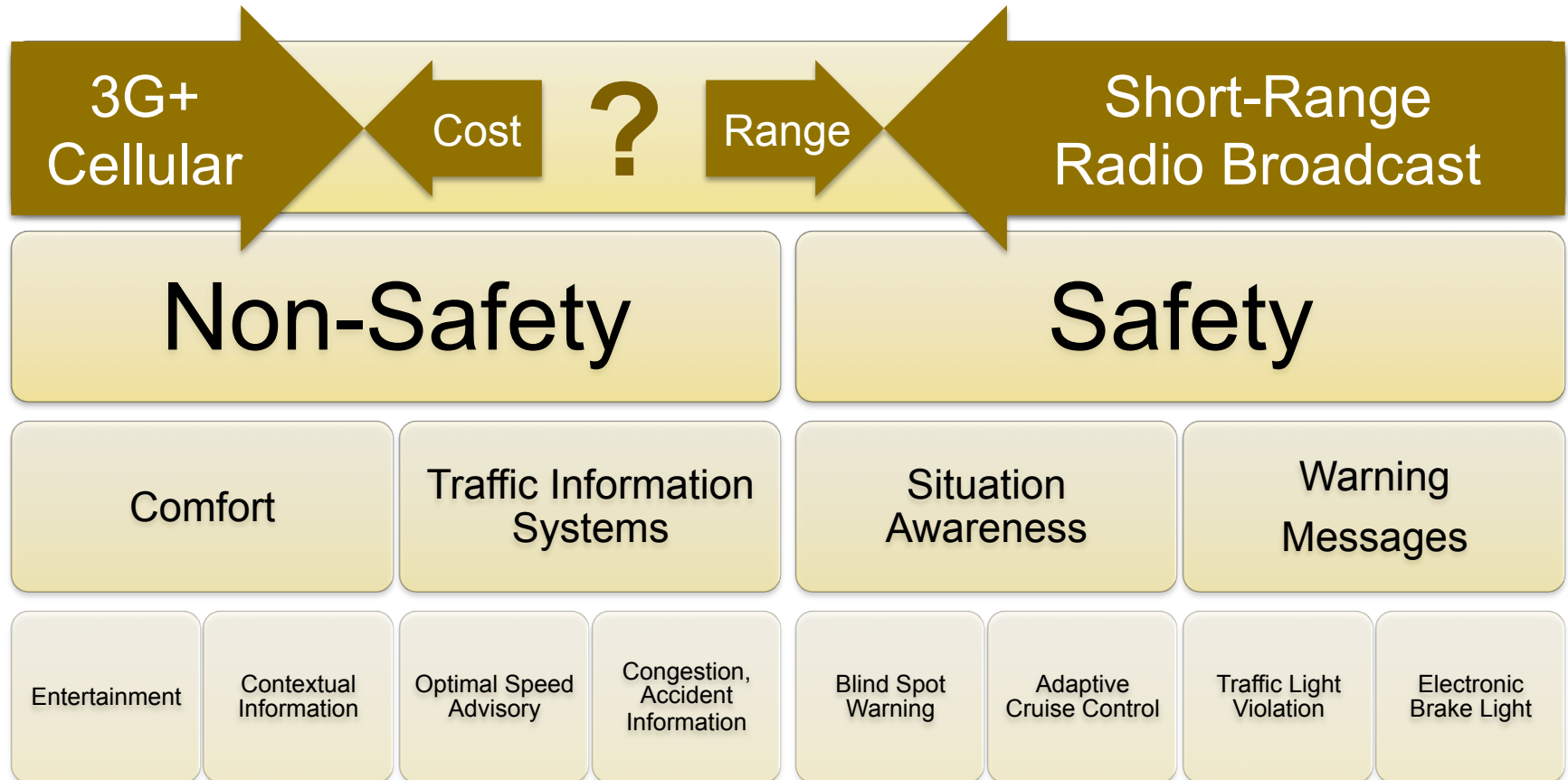


Ad Hoc Multihop Broadcasting

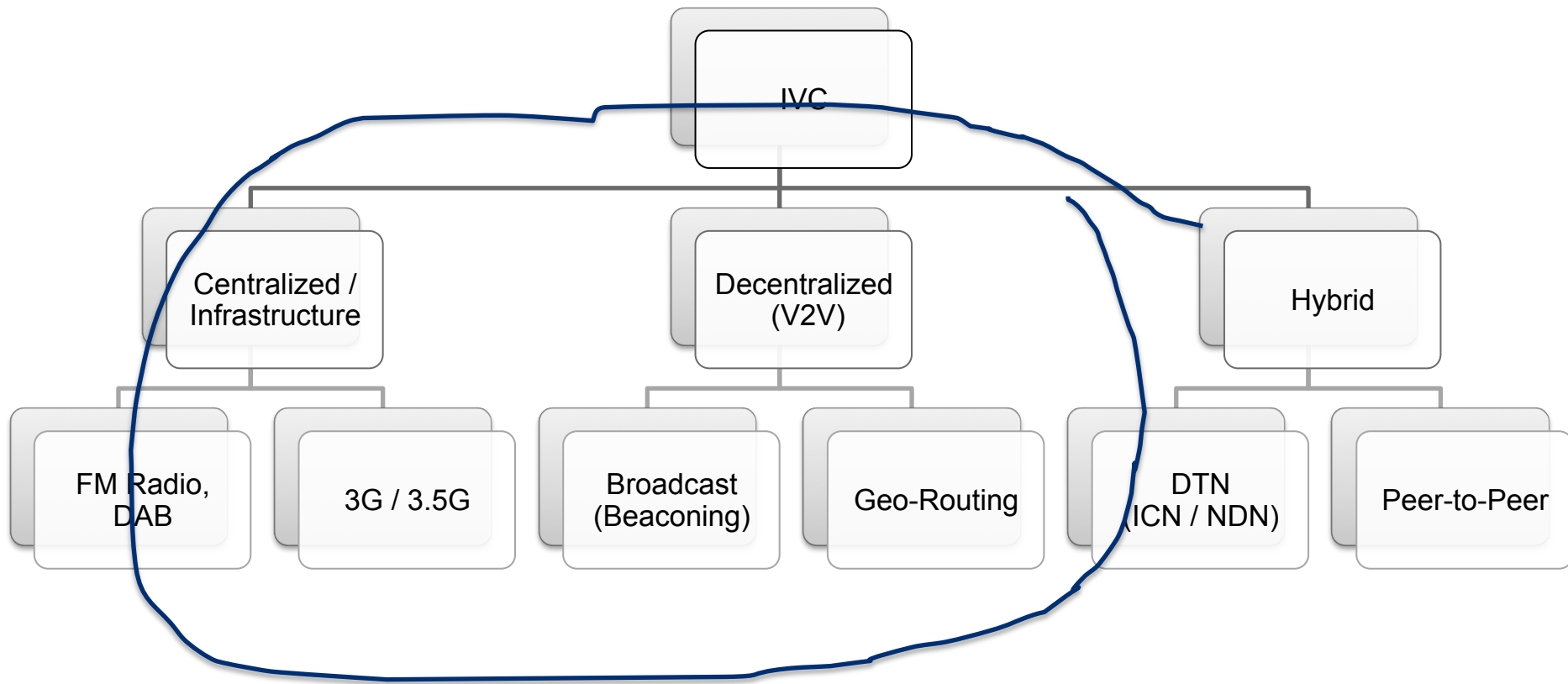
Infrastructure-assisted Data Exchange



✧ Wealth of applications [T. L. Willke 2009]



[1] G. T. L. Willke, P. Tientrakool, and N. F. Maxemchuk, "A Survey of Inter-Vehicle Communication Protocols and Their Applications," IEEE Communications Surveys and Tutorials, vol. 11 (2), pp. 3-20, 2009



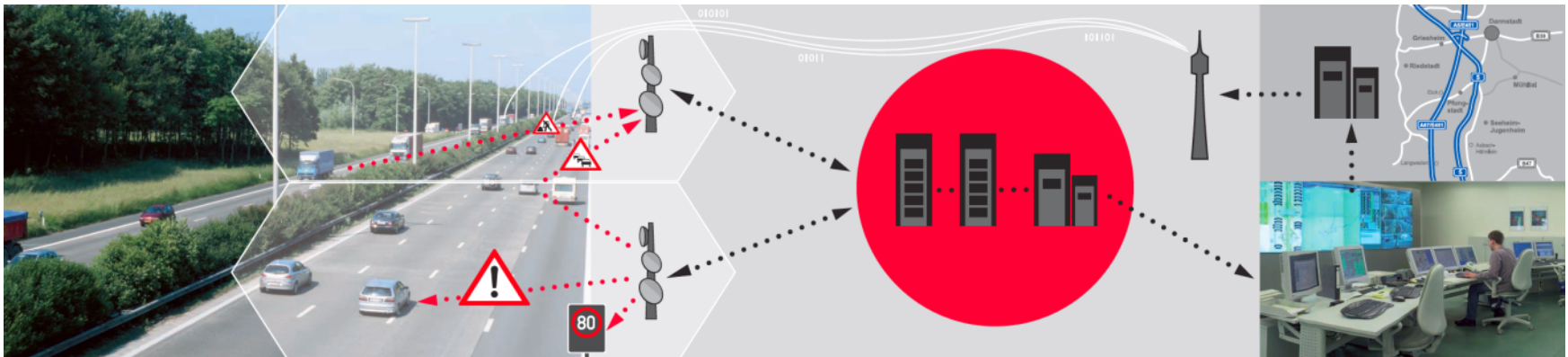
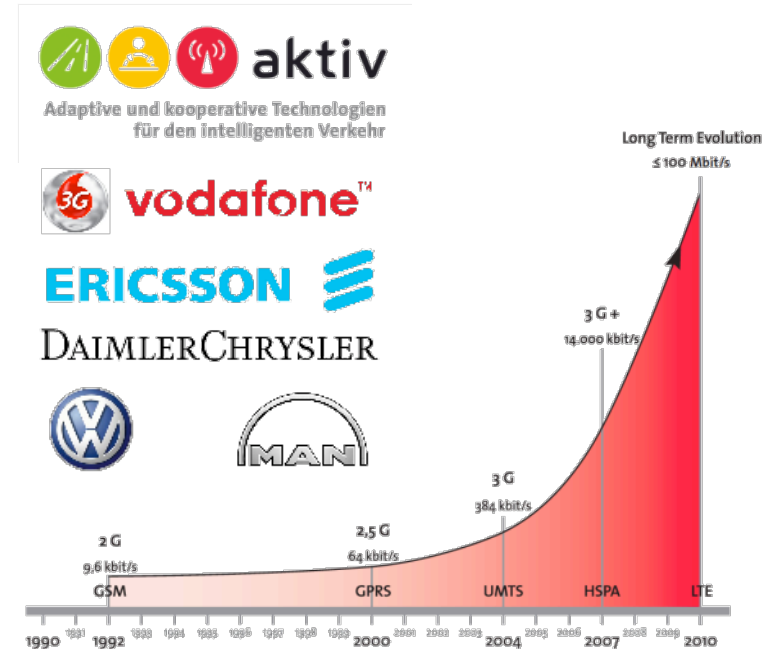
✧ aktiv CoCar

✧ Goals

- Investigate feasibility of Car-to-X over 3G/3.5G networks
- Establish business case

✧ Cooperation of

- Telcos, OEMs
- Car manufacturers
- Government, automobile association



✧ Hierarchy of (logical) function blocks

✧ Reflector

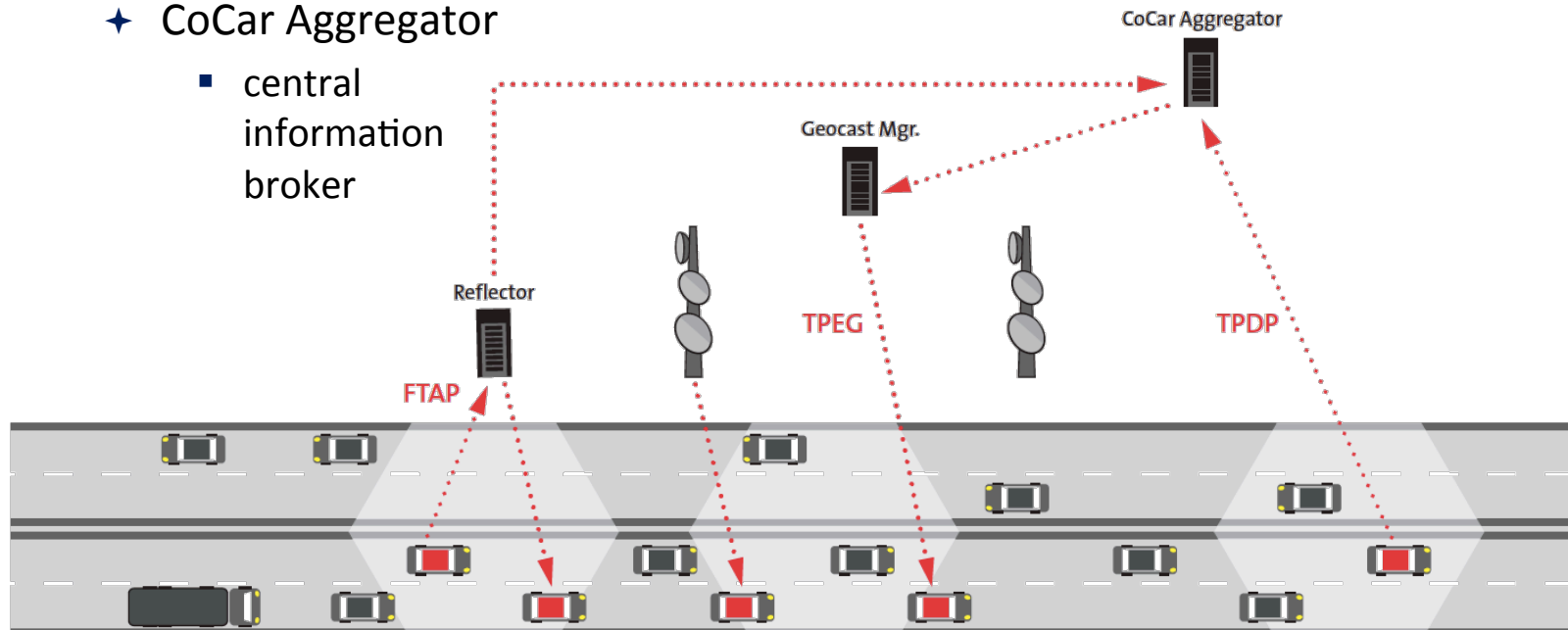
- blind re-broadcast of received data, copy sent upstream to CoCar Aggregator
- envisioned to be deployed close to roads, e.g. in base stations

✧ Geocast Manager

- autonomous wide-area dissemination of messages received from upstream

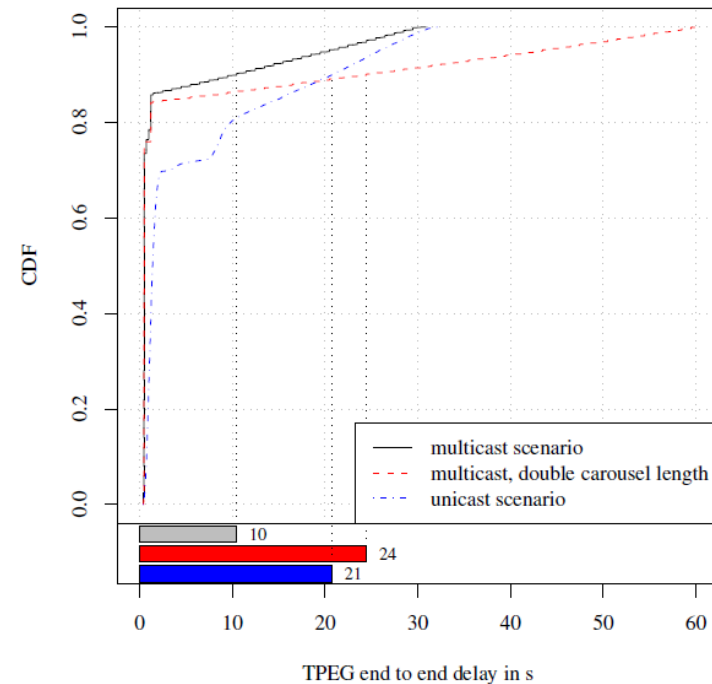
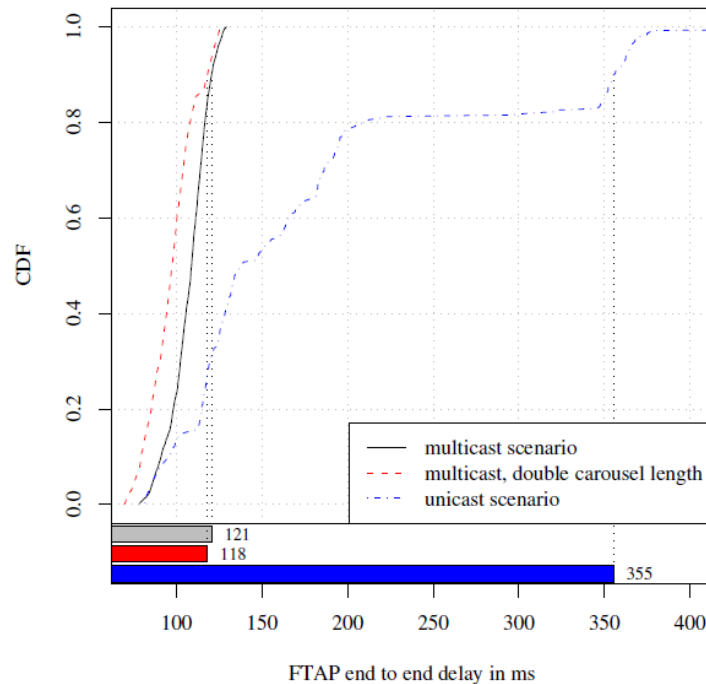
✧ CoCar Aggregator

- central information broker



✧ Selected performance measures

- ✧ Using MBMS (multicast service), emergency messages can be handled well using the FTAP (~120 ms end-to-end delay)



- [1] C. Sommer, A. Schmidt, R. German, W. Koch, and F. Dressler, "Simulative Evaluation of a UMTS-based Car-to-Infrastructure Traffic Information System," Proceedings of IEEE Global Telecommunications Conference (GLOBECOM 2008), 3rd IEEE Workshop on Automotive Networking and Applications (AutoNet 2008), New Orleans, LA, December 2008
- [2] C. Sommer, A. Schmidt, Y. Chen, R. German, W. Koch, and F. Dressler, "On the Feasibility of UMTS-based Traffic Information Systems," Elsevier Ad Hoc Networks, Special Issue on Vehicular Networks, vol. 8 (5), pp. 506-517, July 2010

Going Ad Hoc: New Challenges

- Centralized TIS + Ad Hoc Routing?
- Georouting?
- Routing at all?

Wireless Communication

- Error ratio
- Interference
- Collisions

Ad Hoc Networking

- Multihop forwarding
- Uni-directional links
- Multi-radio / multi-network

Mobility

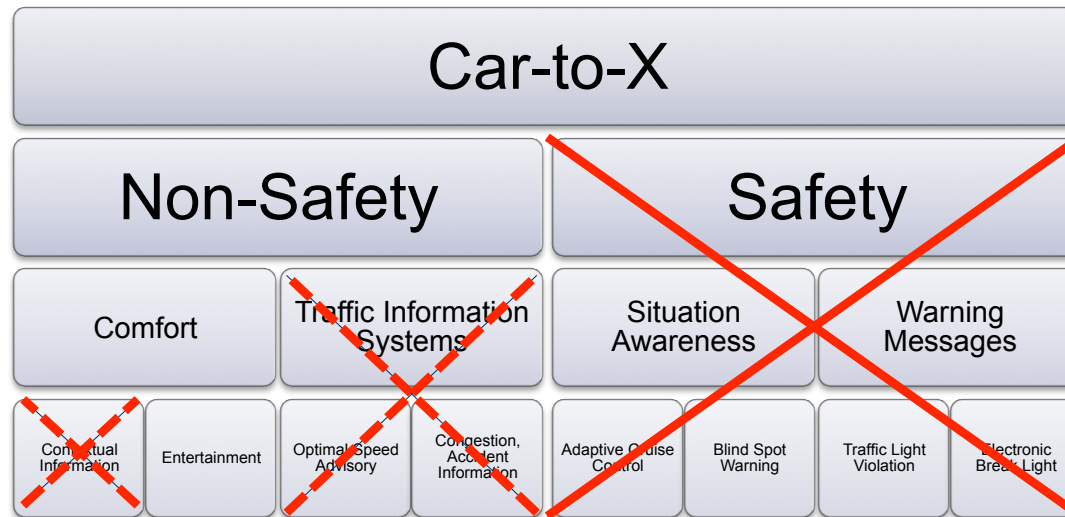
- Dynamic topologies
- Urban vs. highway
- Car following models

Privacy and Security

- Secure information exchange
- Privacy drama
- No permanent Internet connectivity

✧ Reflection on classical routing approaches

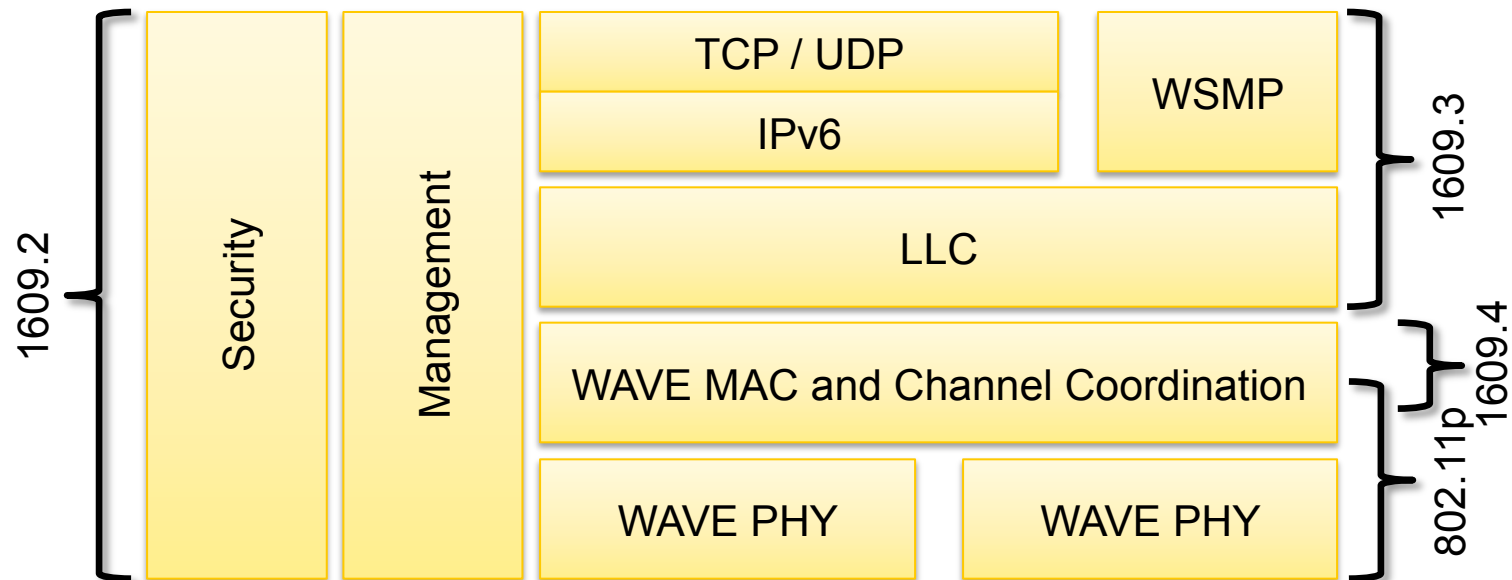
- ✧ Q: Can (classical) routing work in VANETs?
- ✧ A: Only in some cases.
- ✧ Commonly need multicast communication, low load, low delay
- ✧ Additional challenges and opportunities:
network partitioning, dynamic topology, complex mobility, ...



[1] Toor, Yasser and Mühlethaler, Paul and Laouiti, Anis and Fortelle, Arnaud de La, "Vehicle Ad Hoc Networks: Applications and Related Technical Issues," IEEE Communications Surveys and Tutorials, vol. 10 (3), pp. 74-88, 2008

✧ WAVE

- ✧ IEEE 1609.1: “Core System” ➡ IEEE 1609.3: Network Services
- ✧ IEEE 1609.2: Security ➡ IEEE 1609.4: Channel Management

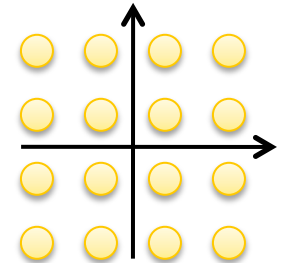


[1] Jiang, D. and Delgrossi, L., "**IEEE 802.11p: Towards an international standard for wireless access in vehicular environments**," Proceedings of 67th IEEE Vehicular Technology Conference (VTC2008-Spring), Marina Bay, Singapore, May 2008

[2] Uzcátegui, Roberto A. and Acosta-Marum, Guillermo, "**WAVE: A Tutorial**," IEEE Communications Magazine, vol. 47 (5), pp. 126-133, May 2009

✧ PHY layer almost identical to IEEE 802.11a

- ✧ OFDM using 16 QAM
- ✧ Reduced inter symbol interference (multipath effects and Doppler shift)
 - Doubled timing parameters
 - Channel bandwidth (10 MHz instead of 20 MHz)
 - Reduced throughput (3 ... 27 Mbit/s instead of 6 ... 54 Mbit/s)
 - Communication range of up to 1000 m
 - Vehicles' velocity up to 200 km/h



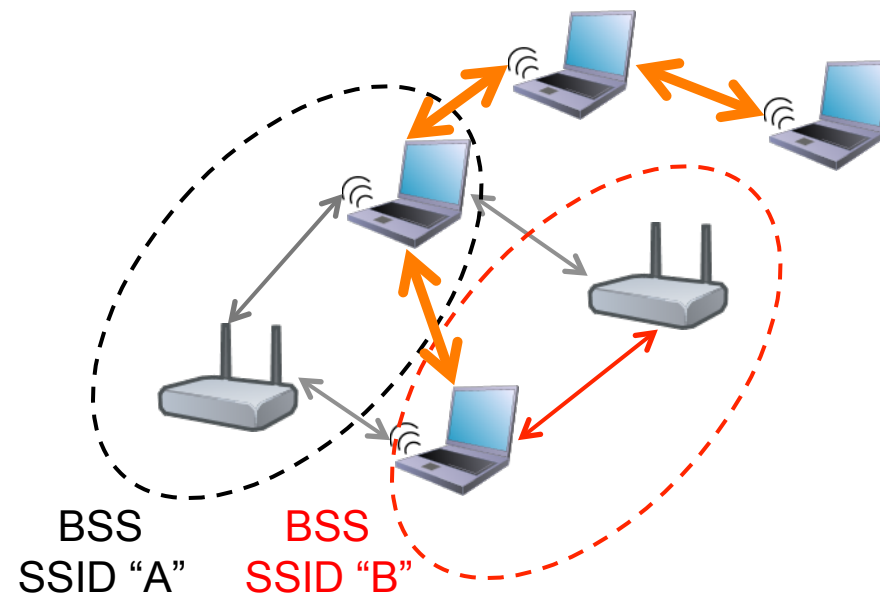
✧ MAC layer with extensions to IEEE 802.11a

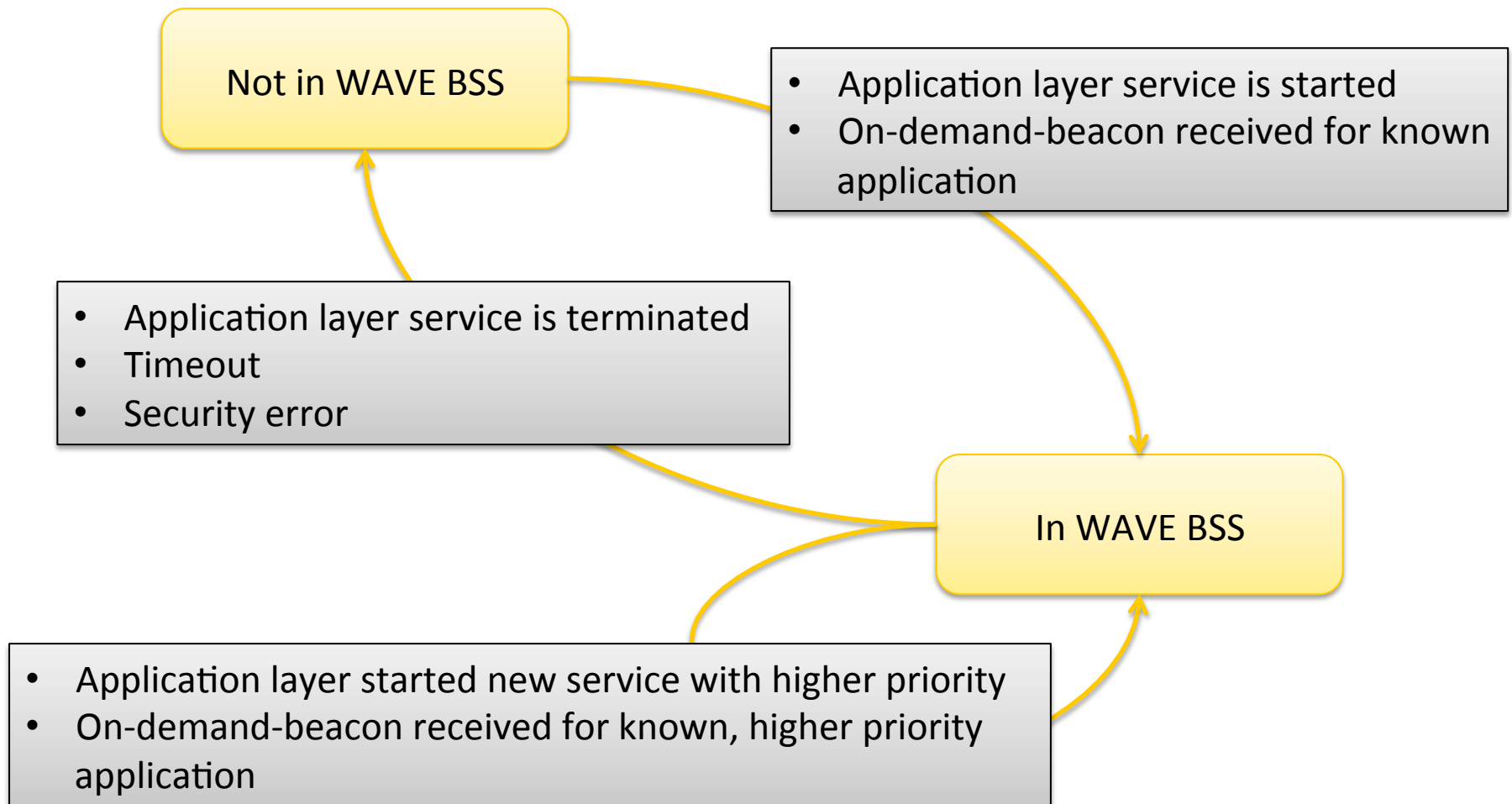
- ✧ Randomized MAC address
- ✧ QoS (Priorities, see IEEE 802.11e, ...)
- ✧ Support for multi channel and multi radio
- ✧ New ad hoc mode



✧ New: 802.11 WAVE-mode

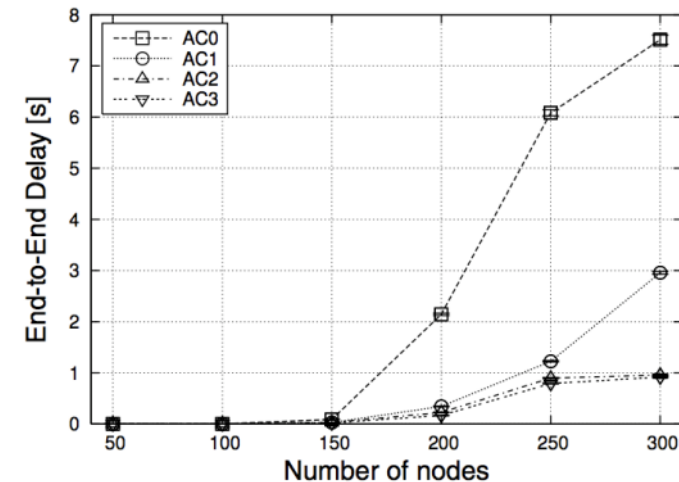
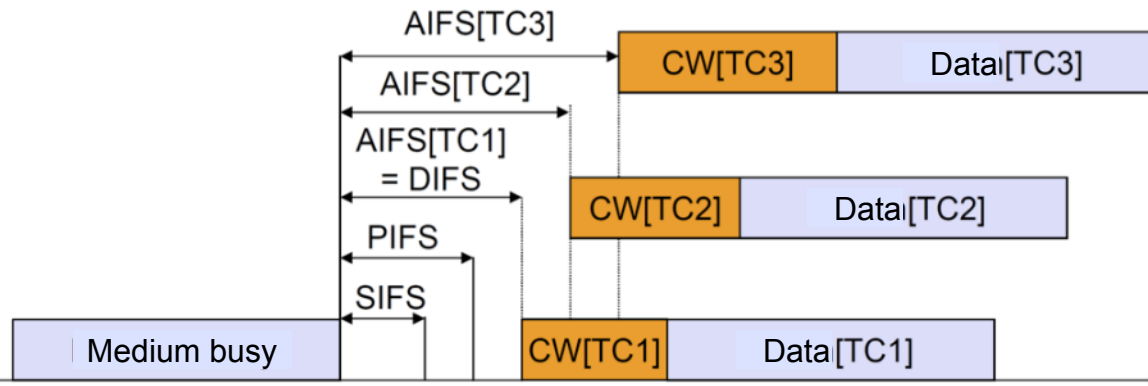
- ✧ Main mode for all WAVE nodes
- ✧ Suggests the use of “Wildcard-BSS” in transmitted packets
- ✧ Every node is required to receive all packets using a wildcard BSS
- ✧ Inherently allows simultaneous transmission from and to a BSS
- ✧ Membership management just by using a BSS





[1] IEEE Vehicular Technology Society, "IEEE 1609.3 (Networking Services)," IEEE Std, April, 2007

- ✧ Use of EDCA equivalent to IEEE 802.11e EDCA
- ✧ DCF -> EDCA (Enhanced Distributed Channel Access)
- ✧ Definition of four Access Categories (AC)
 - ✦ AC0 (lowest) to AC3 (highest priority)
- ✧ Introduction of AIFS (Arbitration Inter-Frame Space)



- ✧ ACs define...
 - ✦ CW_{min} , CW_{max} , AIFS, TXOP-Limit (max. continuous channel use)
- ✧ Management data are transmitted using DIFS instead of an AIFS

- ✧ WAVE uses a dedicated frequency range in the 5.9 GHz band
 - ✦ Exclusive for V2V and V2I communication
 - ✦ Strictly regulated but no license costs
 - ✦ In the US, FCC reserved 7 channels a 10 MHz („U.S. DSRC“)

...	Critical Safety of Life	SCH	SCH	Control Channel (CCH)	SCH	SCH	Hi-Power Public Safety	...
	ch 172 5.860GHz	ch 174 5.870GHz	ch 176 5.880GHz	ch 178 5.890GHz	ch 180 5.900GHz	ch 182 5.910GHz	ch 184 5.920GHz	

- 1 control and 4 service channels to be used by applications

- ✦ In Europa, ETSI reserved 5 channels a 10 MHz

SCH	SCH	SCH	SCH	CCH
ch 172 5.860GHz	ch 174 5.870GHz	ch 176 5.880GHz	ch 178 5.890GHz	ch 180 5.900GHz

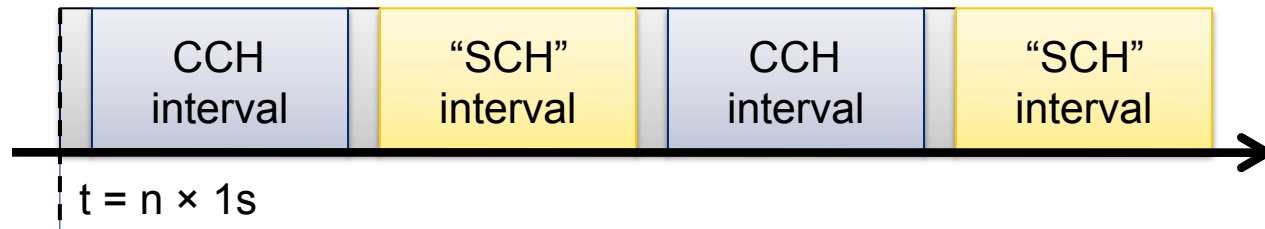
[1] **ETSI** ES 202 663 V1.1.0 (2010-01) : Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band

✧ Channel Management

- ✦ Management and safety information on the Control Channel (CCH)
 - single radios have to switch to the CCH at known times
- ✦ Two-way communication on the Service Channel (SCH)

✧ Slot management

- ✦ Synchronization using GPS
- ✦ Standard: 100ms sync interval including 50ms on the CCH
- ✦ Slots start with a guard interval

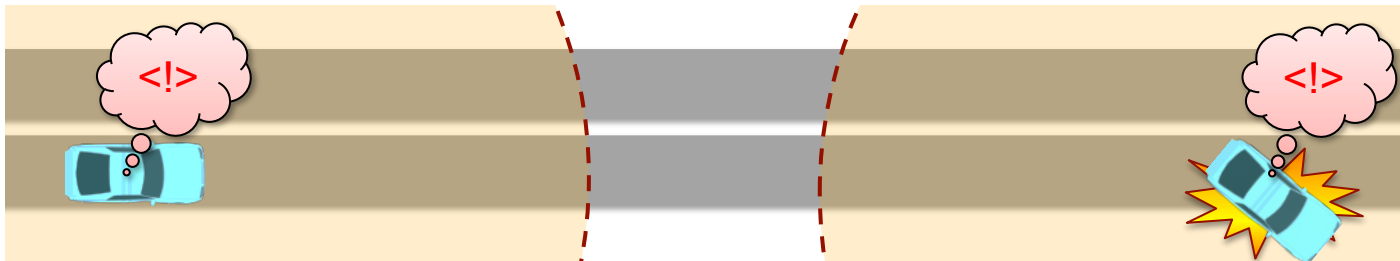


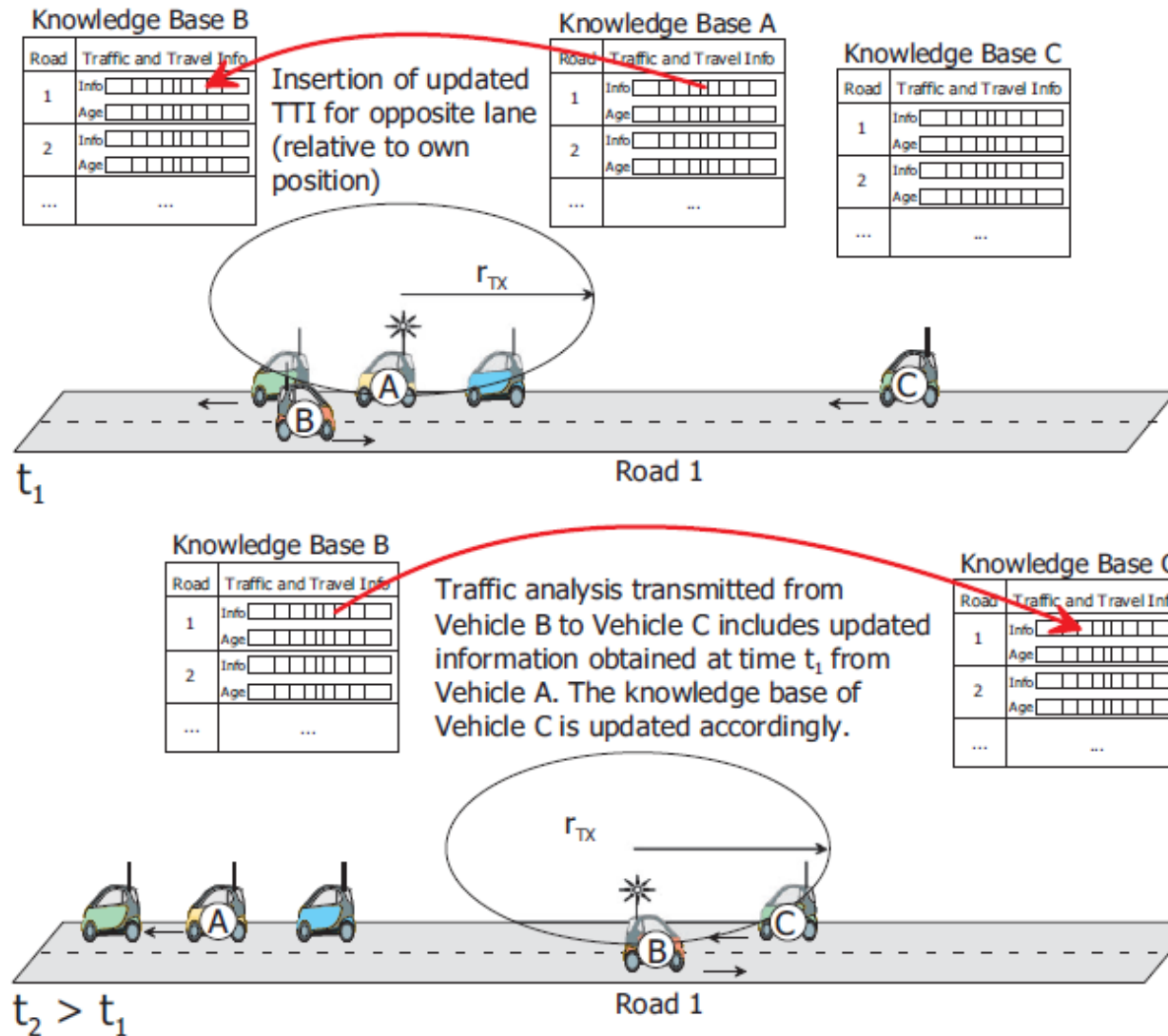
[1] IEEE Vehicular Technology Society, "IEEE 1609.4 (Multi-channel Operation)," IEEE Std, November, 2006

- ✧ Car-2-Car Communication Consortium & ETSI TC ITS
 - ✦ Not defined by DSRC/WAVE
 - but frame formats are provided (e.g., WAVE Short Messages)

- ✧ First application: Cooperative Awareness Messages (CAM)
 - ✦ Periodic beacons containing
 - Time
 - Speed
 - Position
 - Heading
 - ...
 - ✦ Period fix in the interval of 1 to 10 Hz

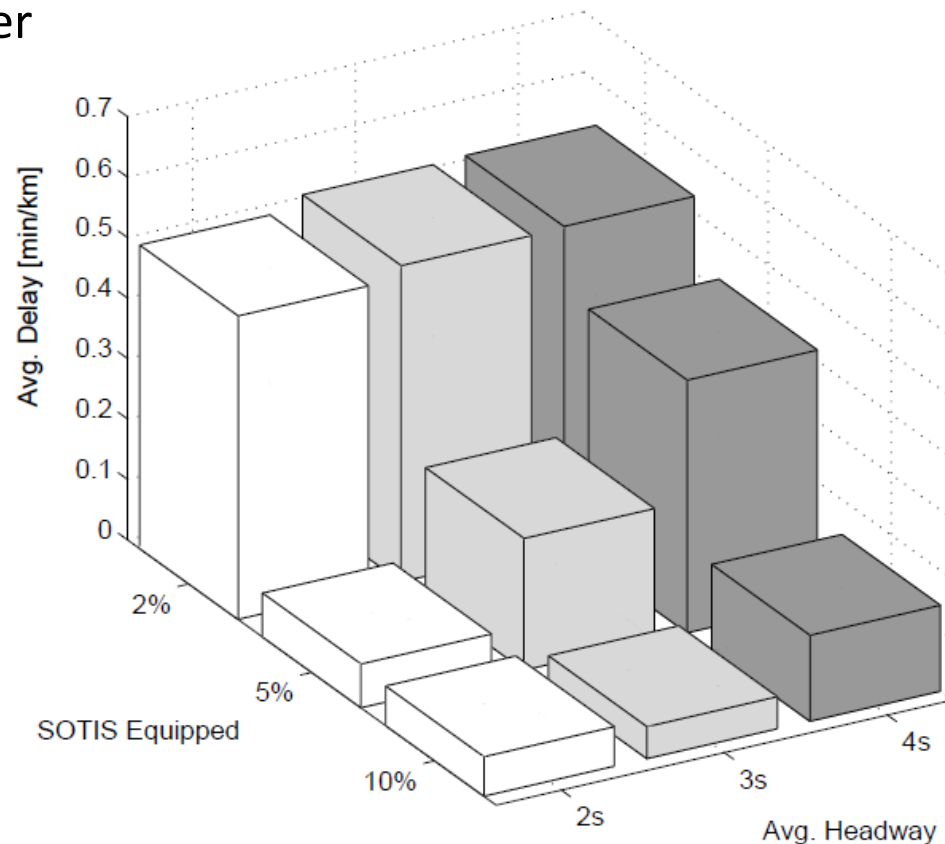
- ✧ Fully distributed approach
 - ✦ No communication infrastructure needed
 - ✦ No data loss in fragmented networks
 - ✦ No unique node identifiers mandated
 - ✦ No network topology assumed, created, or maintained
- ✧ SOTIS: local knowledge bases + beaconing
 - ✦ Aggregate all sensed data + received data
 - ✦ Periodic broadcast of entries (beaconing)
 - Ex.: one beacon every five seconds
 - ✦ No congestion control in the wireless network





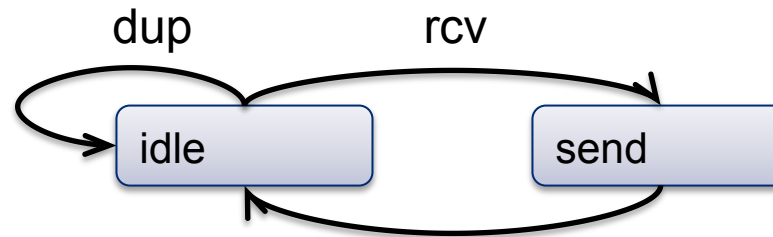
✧ Selected performance measures

- ✧ Depending on the node density (headway) and the penetration ratio, it takes ~6-30 seconds to send an information entry over one kilometer



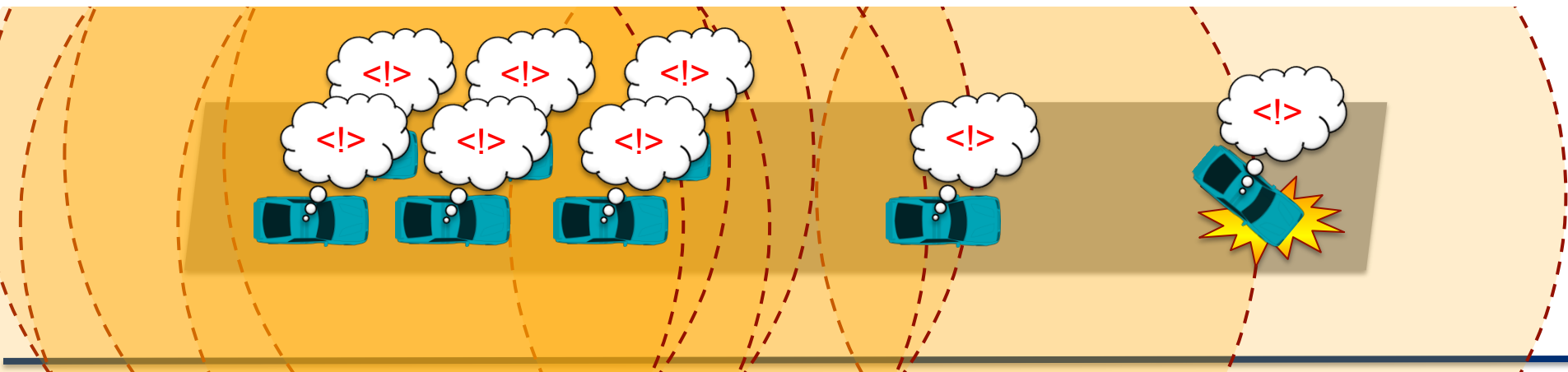
✧ Flooding (Multi-Hop Broadcast)

- ✧ Simplest protocol: „Smart Flooding“:



✧ Problem: Broadcast Storm

- Superfluous re-broadcasts overload channel



✧ Broadcast Suppression

★ Estimate distance to sender as $0 \leq \rho_{ij} \leq 1$

★ GPS based

$$\rho_{ij} = \begin{cases} 0 & \text{if } D_{ij} < 0 \\ \frac{D_{ij}}{R} & \text{if } 0 \leq D_{ij} < R \text{ (approx. transmission radius)} \\ 1 & \text{otherwise} \end{cases}$$

★ RSS based

$$\rho_{ij} = \begin{cases} 0 & \text{if } RSS_x < RSS_{min} \\ \frac{RSS_{max} - RSS_x}{RSS_{max} - RSS_{min}} & \text{if } RSS_{min} \leq RSS_x < RSS_{max} \\ 1 & \text{otherwise} \end{cases}$$

[1] Wisitpongphan, Nawaporn and Tonguz, Ozan K. and Parikh, J. S. and Mudalige, Priyantha and Bai, Fan and Sadekar, Varsha, "Broadcast Storm Mitigation Techniques in Vehicular Ad Hoc Networks," IEEE Wireless Communications, vol. 14 (6), pp. 84-94, December 2007

- ✧ Open issues
 - ✦ Infrastructure-less operation: needs high marked penetration
 - ✦ Required/tolerable beacon interval highly dependent on scenario
 - ✦ Design needs dedicated channel capacity

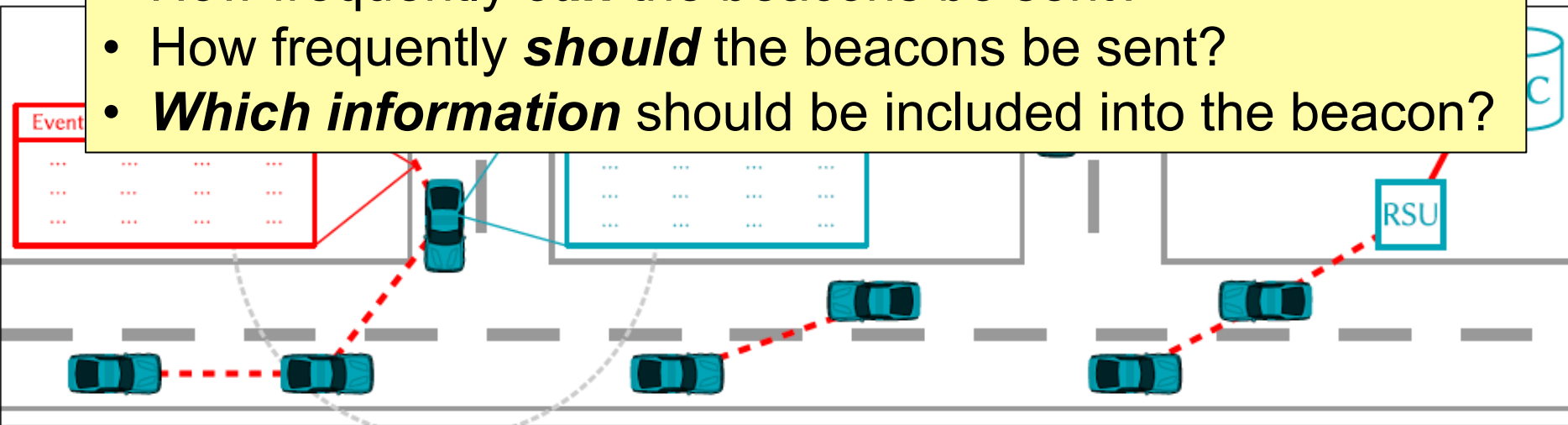
- ✧ Real networks are heterogeneous
 - ✦ Roadside infrastructure present vs. absent
 - ✦ Freeway scenario vs. inner city
 - ✦ Own protocol $\Leftrightarrow$ other, future, and legacy protocols

- ✧ How to do better?
 - ✦ Dynamically incorporate optional infrastructure
 - ✦ Dynamically adapt beacon interval
 - ✦ Dynamically use all free(!) channel capacity

- ✧ **Beacon interval**: measure of channel quality and message priorities
- ✧ **Infrastructure elements**: RSUs of different capabilities can be included
 - ✧ Lightweight SSUs (service support unit)

Challenging questions

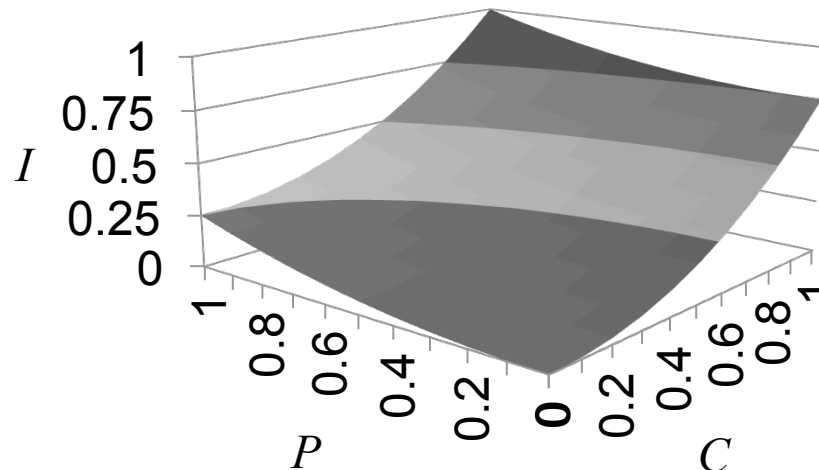
- How frequently **can** the beacons be sent?
- How frequently **should** the beacons be sent?
- **Which information** should be included into the beacon?



- [1] Christoph Sommer, Ozan K. Tonguz and Falko Dressler, "Traffic Information Systems: Efficient Message Dissemination via Adaptive Beaconing," *IEEE Communications Magazine*, vol. 49 (5), pp. 173-179, May 2011
- [2] Christoph Sommer, Ozan K. Tonguz and Falko Dressler, "Adaptive Beaconing for Delay-Sensitive and Congestion-Aware Traffic Information Systems," Proceedings of 2nd IEEE Vehicular Networking Conference (VNC 2010), Jersey City, NJ, December 2010, pp. 1-8
- [3] C. Sommer, R. German, and F. Dressler, "Decentralized Traffic Information Systems and Adaptive Rerouting in Urban Scenarios," Proceedings of 29th IEEE Conference on Computer Communications (INFOCOM 2010), Demo Session, San Diego, CA, March 2010

- ✧ Adaptive selection of beacon interval ΔI
 - ✦ Consider message utility P
 - ✦ Consider channel quality C

- ✧ Choose interval from range $I_{\min}$ to $I_{\max}$
 - ✦ Use factor w_I to increase weight of C (ex. $w_I=0.75$)
 - ✦ $\Delta I = ((1 - w_I) \times P^2 + (w_I \times C^2)) \times (I_{\max} - I_{\min}) + I_{\min}$

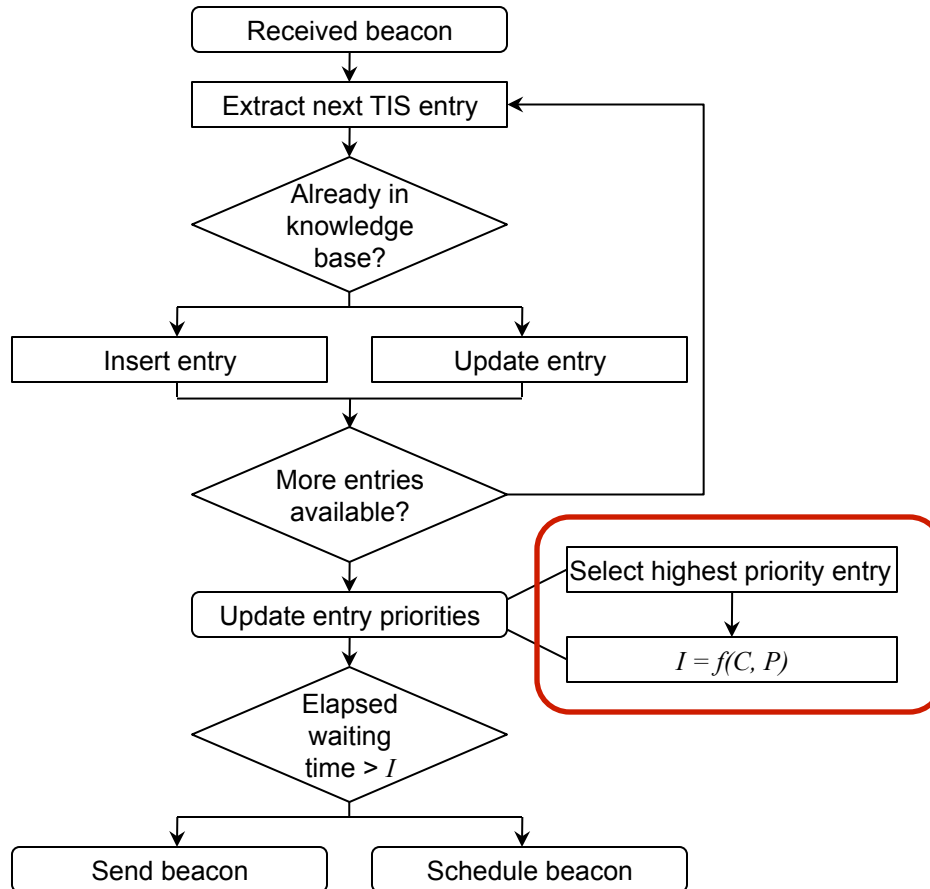


✧ Adaptive selection of beacon interval ΔI

- ✧ Calculation of message utility P based on metrics of (ex.)
 - A : age of information
 - D_e : distance to source of information
 - D_r : distance to closest Road Side Unit (RSU)
 - B : ratio of beacon contents received from Road Side Unit (RSU)

- ✧ Calculation of channel quality C based on metrics of (ex.)
 - N : (estimated) number of neighbors ($\rightarrow$ *future*)
 - S : (observed) signal-to-noise ratio ($\rightarrow$ *present*)
 - K : (measured) collisions on channel ($\rightarrow$ *past*)

$$P = \frac{A + D_e + D_r}{3} \times B \qquad C = \frac{N + w_C(S + K) / 2}{1 + w_C}$$

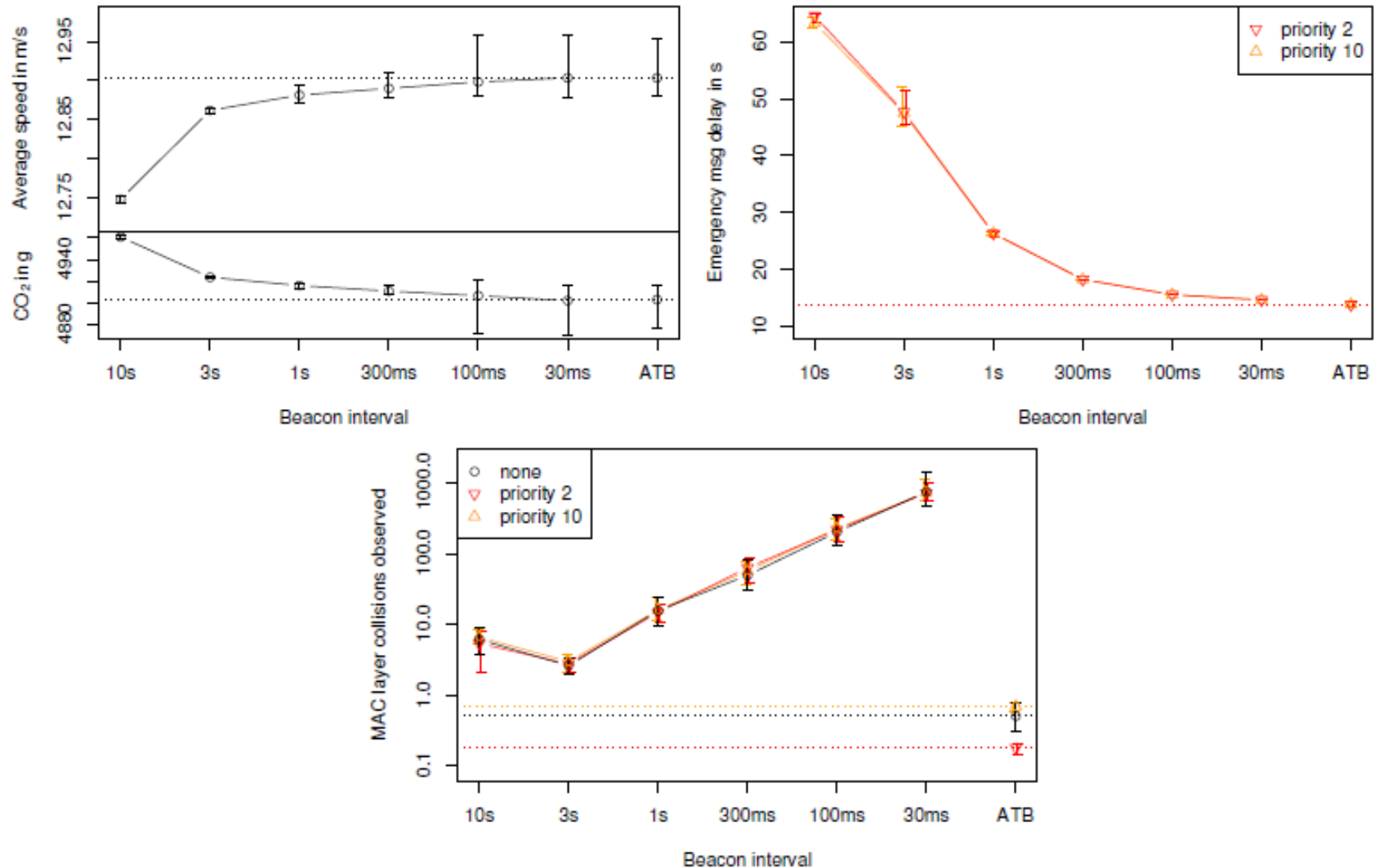


✧ Message store handling

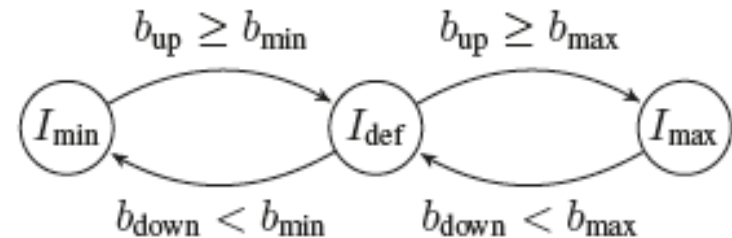
- ✧ Sorted list of all available traffic information

✧ Criteria

- ✧ Age of entry ↓
- ✧ Distance to event ↑
- ✧ Distance to RSU ↓

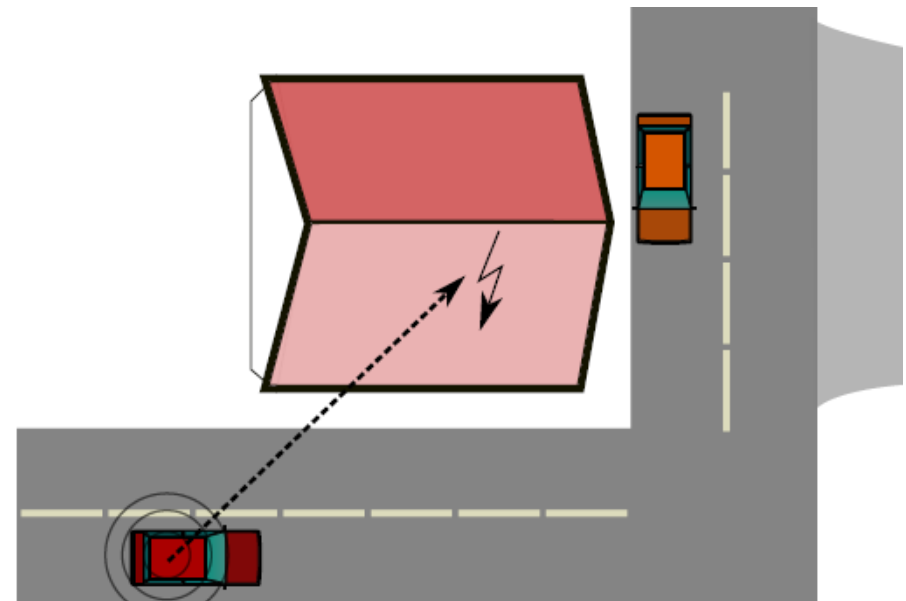
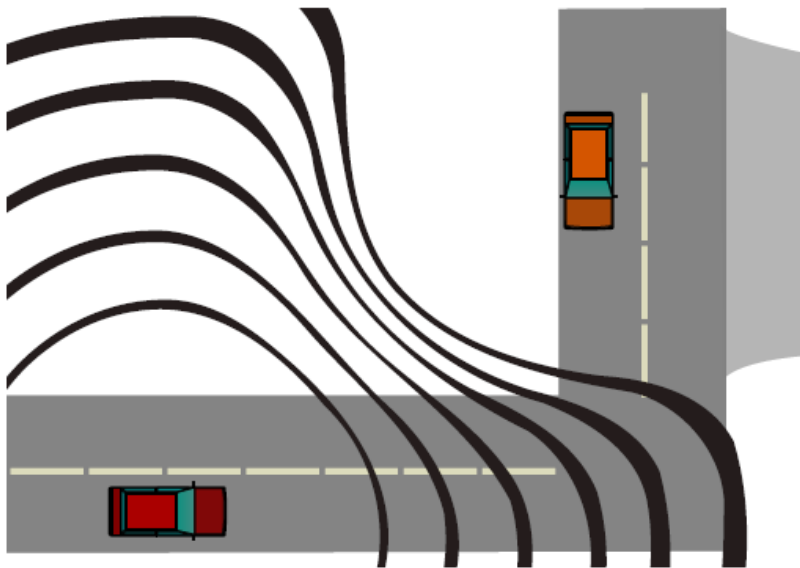


- ✧ Scenario independence
 - ✦ self-organization – no topology detection or maintenance
- ✧ Infrastructure independence
 - ✦ incorporates RSUs on demand
- ✧ Coexistence
 - ✦ makes liberal use of all unused channel capacity, leaves channel “virtually unloaded” for high-priority messages
- ✧ These concepts also went into standardization
 - ✦ ETSI ITS-G5 developed DCC (Decentralized Congestion Control) with TRC (Transmit Rate Control)
 - ✦ b_t is the “busy ratio” of the channel
 - ✦ Coarse grained measurement intervals



[1] Werner, Marc and Lupoie, Radu and Subramanian, Sundar and Jose, Jubin, "MAC Layer Performance of ITS G5 - Optimized DCC and Advanced Transmitter Coordination," Proceedings of 4th ETSI TC ITS Workshop, Doha, Qatar, February 2012

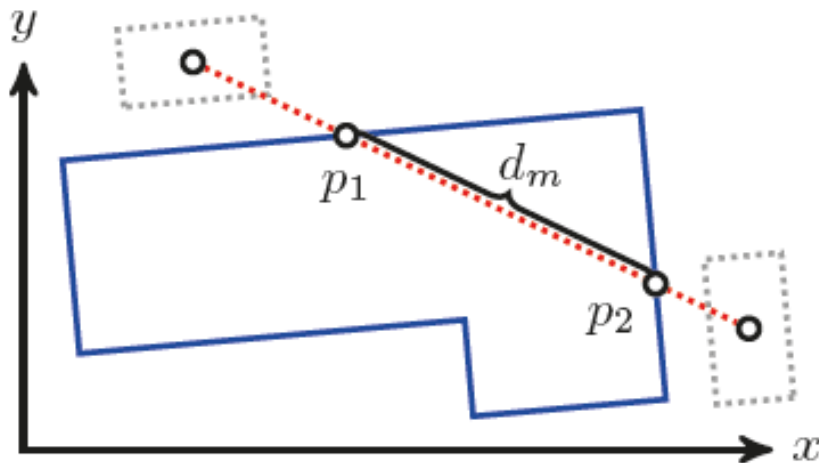
- ✧ Maybe we all overlooked some issues!
- ✧ Antenna characteristics
- ✧ Radio signal shadowing



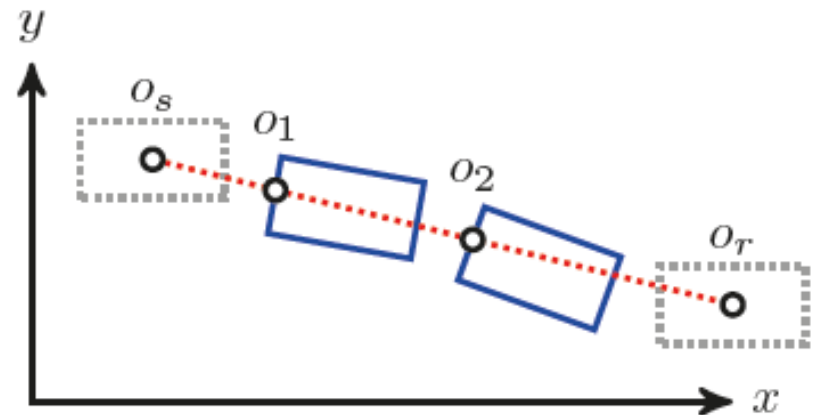


- [1] Christoph Sommer, David Eckhoff, Reinhard German and Falko Dressler, "A Computationally Inexpensive Empirical Model of IEEE 802.11p Radio Shadowing in Urban Environments," Proceedings of 8th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2011), Bardonecchia, Italy, January 2011, pp. 84-90
- [2] David Eckhoff, Christoph Sommer, Reinhard German and Falko Dressler, "Cooperative Awareness At Low Vehicle Densities: How Parked Cars Can Help See Through Buildings," Proceedings of IEEE Global Telecommunications Conference (GLOBECOM 2011), Houston, TX, December 2011

- ✧ Models allow taking into consideration
 - (a) static and
 - (b) moving obstacles
- ✧ **Research question: What is their impact on beaconing?**



(a) static obstacles



(b) moving obstacles

✧ DynB – Dynamic Beaconsing

- ✧ Considering all the radio shadowing effects to adapt very quickly to the current channel quality
- ✧ Main idea: continuously observe the load of the wireless channel to calculate the current beacon interval

$$\text{✧ } I = I_{des} + r (I_{max} - I_{des})$$

with $I_{max} = (N+1) I_{des}$ (N is the number of neighbors)
 and $r = (b_t / b_{des}) - 1$ clipped in $[0, 1]$

[1] Christoph Sommer, Stefan Joerer, Michele Segata, Ozan K. Tonguz, Renato Lo Cigno and Falko Dressler, "How Shadowing Hurts Vehicular Communications and How Dynamic Beaconsing Can Help," Proceedings of 32nd IEEE Conference on Computer Communications (INFOCOM 2013), Mini-Conference, Turin, Italy, April 2013

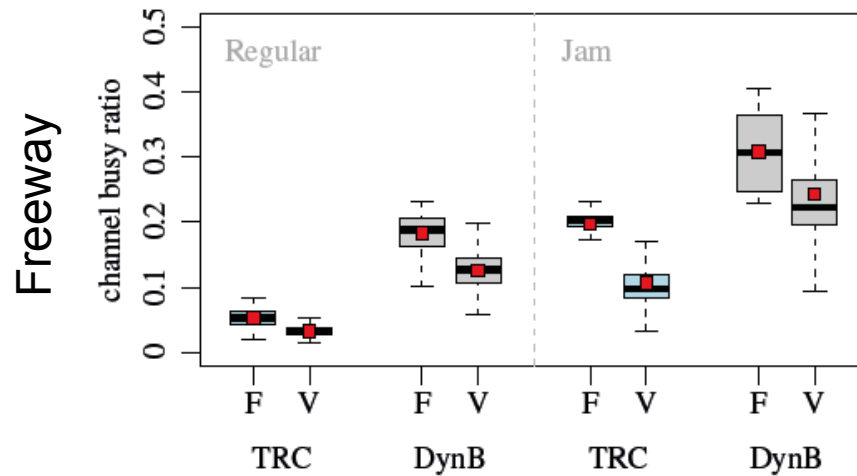
- ✧ Assuming a payload of $l = 512$ bit (at 18 Mbit/s), we obtain

$$t_{busy} = T_{preamble} + T_{signal} + T_{sym} [(16 + l + 6) / N_{DBPS}] = 104 \mu s$$

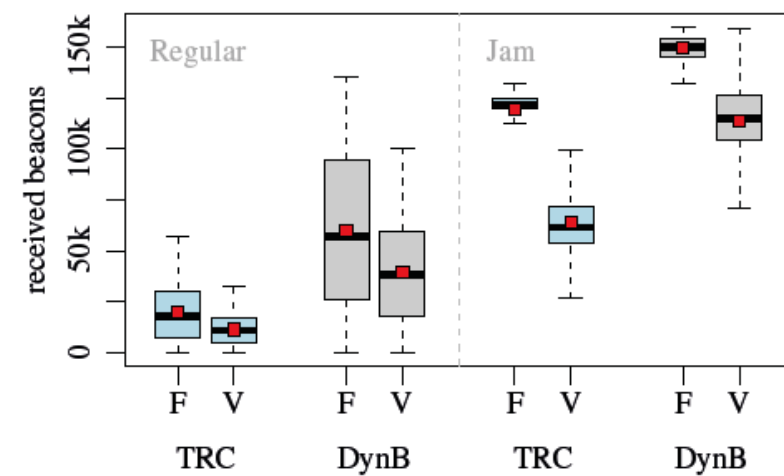
Using a minimum AIFS and an average initial backoff counter, we get a maximum b_t

$$b_t = t_{busy} / (t_{busy} + t_{aifs} + t_{idle}) = 0.64$$

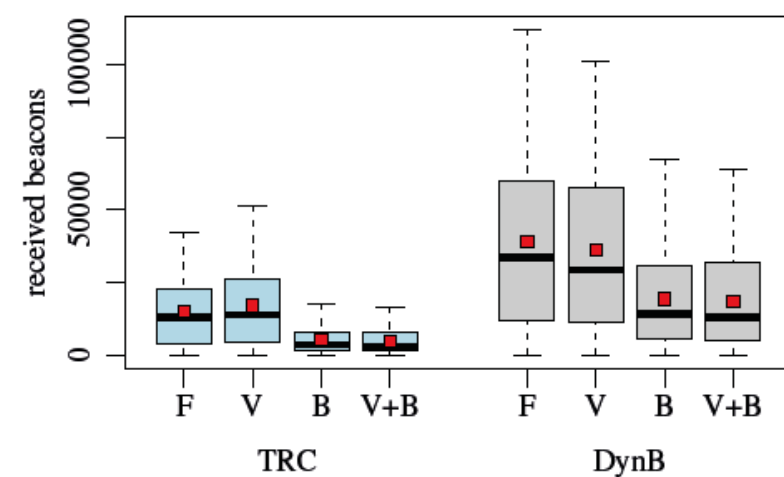
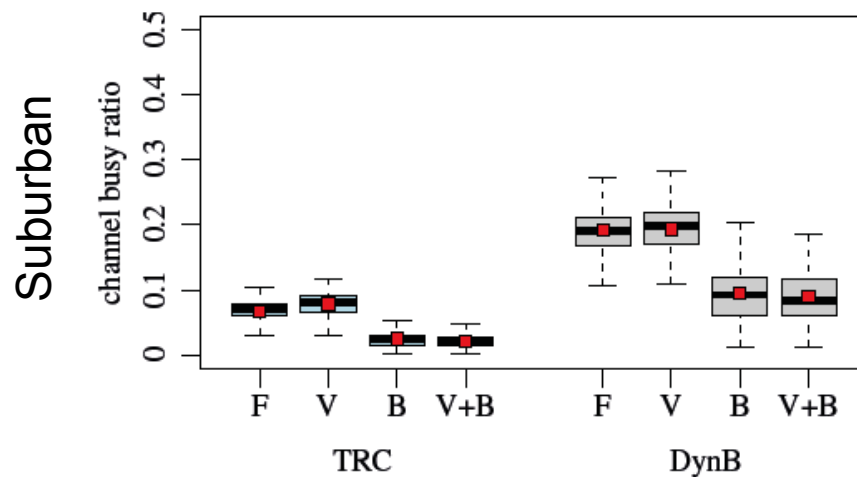
Comparing DynB to TRC



Channel busy ratio

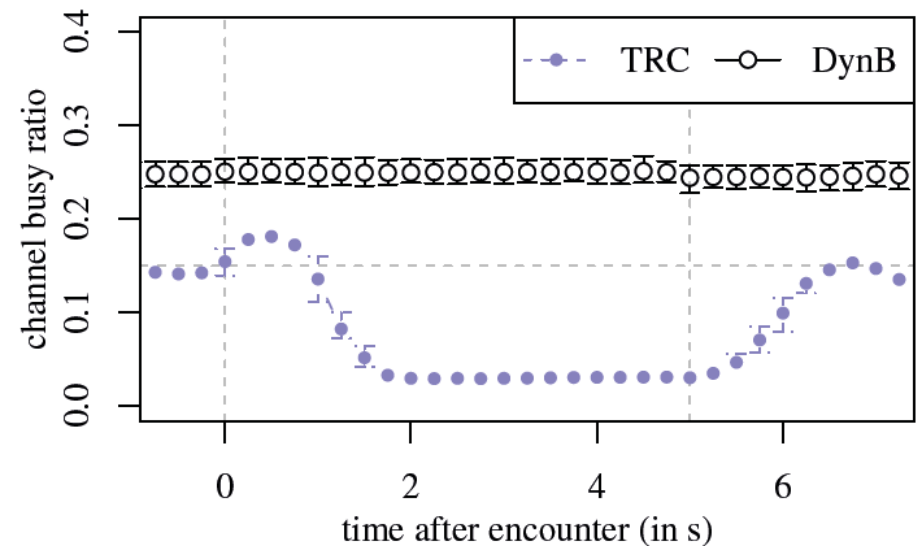
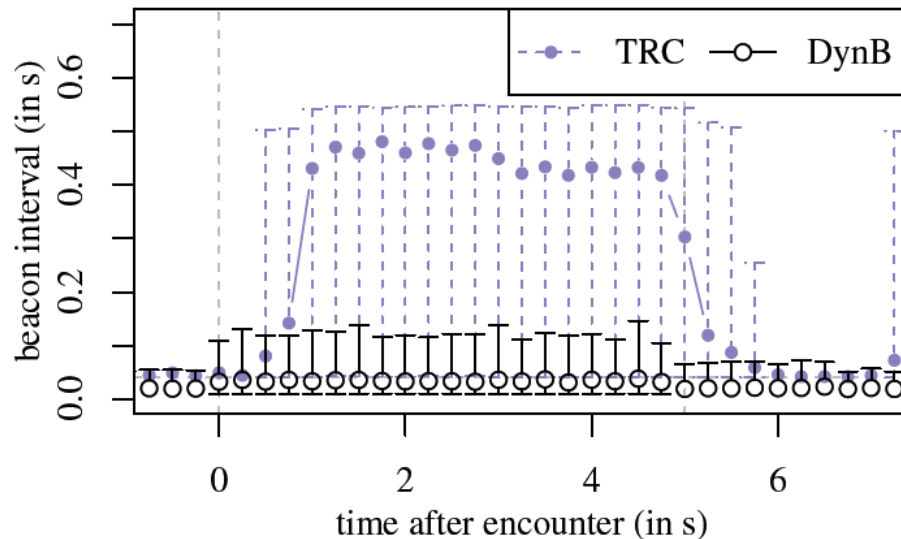


Received beacons



$$b_{\text{des}}=0.25, l_{\text{des}}=0.01$$

- ✧ Assuming two larger clusters of vehicles meeting spontaneously (e.g., at intersections in suburban or when two big trucks leave the freeway)



✧ A specific application: platooning

- ✦ solve traffic congestion problems
- ✦ decrease pollution
- ✦ increase safety
- ✦ decrease severe injuries/deaths
- ✦ Avoid wasting driving time

✧ Research questions

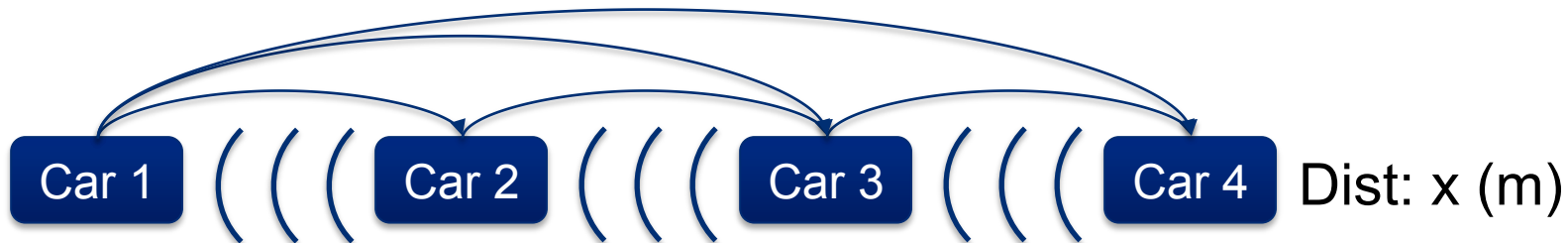
- ✦ Impact of platooning on network (and vice versa)
- ✦ Develop protocols to better support platooning



✧ ACC – Radar based



✧ CACC(s) – Radar + IVC



- ✧ Cooperative Adaptive Cruise Control (CACC)
 - ✦ maintains a fixed distance independent from current speed
 - ✦ can follow really closely
 - ✦ obtains leader and front vehicle data via wireless communication
- ✧ Communications based on IEEE 802.11p
 - ✦ Platooning requires frequent updates (> 10 Hz)
 - ✦ Concerns regarding network congestion

$$\ddot{x}_{i_des} = \alpha_1 \ddot{x}_{i-1} + \alpha_2 \ddot{x}_0 + \alpha_3 \dot{\varepsilon}_i + \alpha_4 (\dot{x}_i - \dot{x}_0) + \alpha_5 (\varepsilon_i + \text{gap}_{des})$$

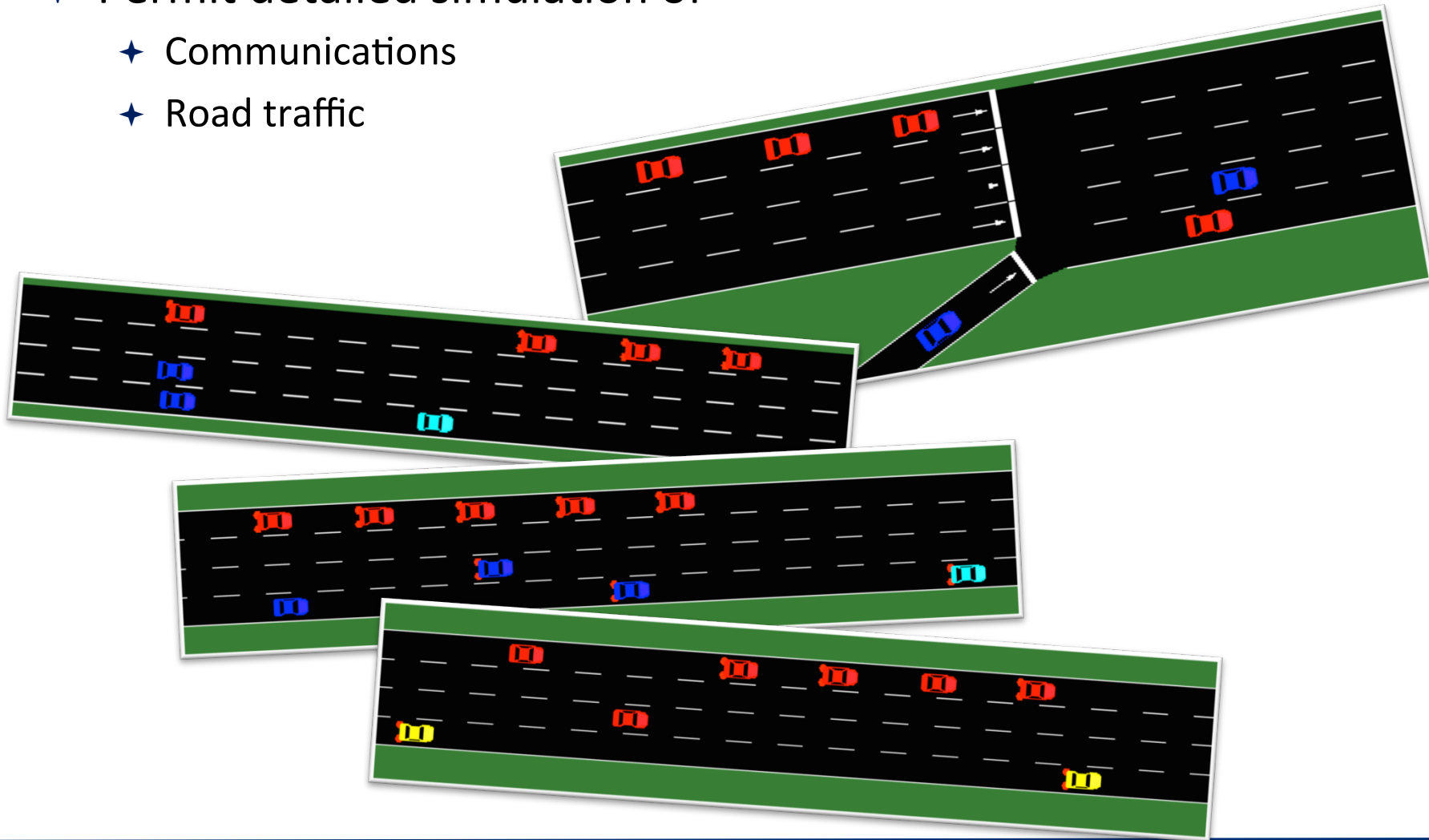
$\ddot{x}_{i-1}$, $\ddot{x}_0$, $\dot{\varepsilon}_i$, $\dot{x}_i$, $\dot{x}_0$: obtained through wireless communication

- ✧ Communications based on IEEE 802.11p
- ✧ Platooning (might) require frequent updates (> 10 Hz)
- ✧ Concerns regarding network congestion

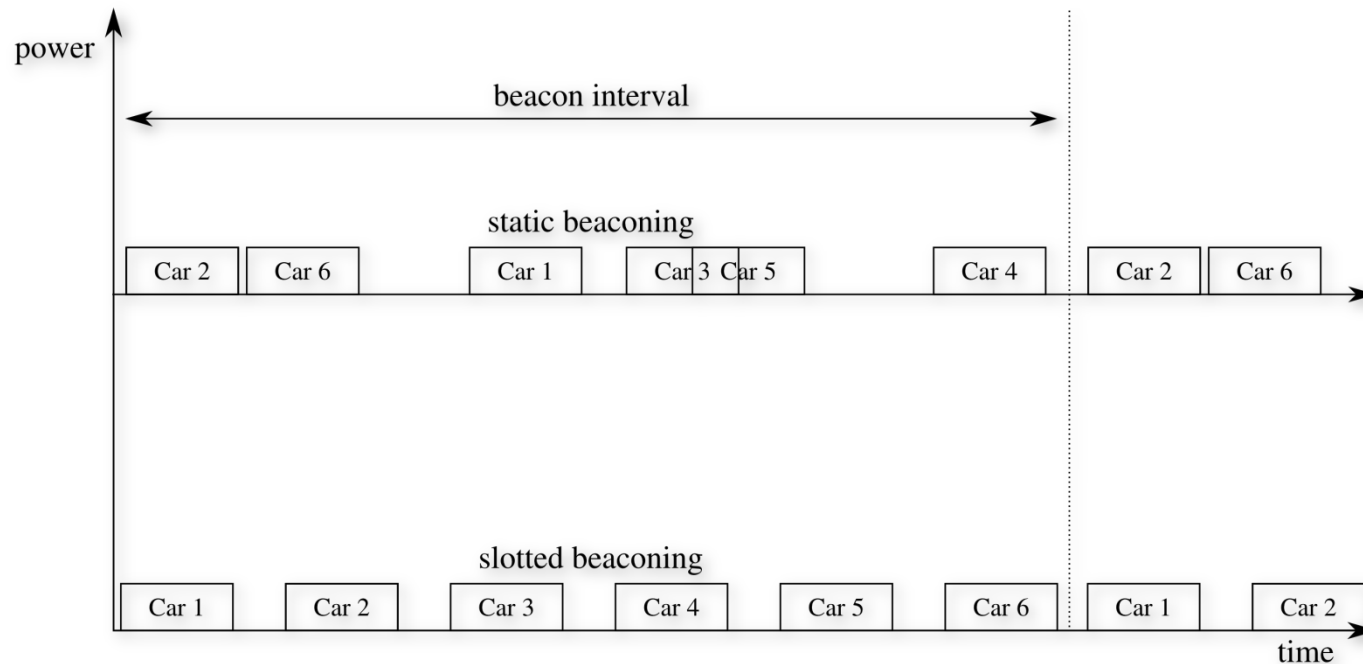
- ✧ Research Needed on
 - ✦ Impact of platooning on network (and vice versa)
 - ✦ Protocols to better support platooning

- ✧ Contributions
 - ✦ Large scale analysis
 - ✦ Beacons solution that is adaptive in time and space

- ✧ Permit detailed simulation of
 - ✦ Communications
 - ✦ Road traffic

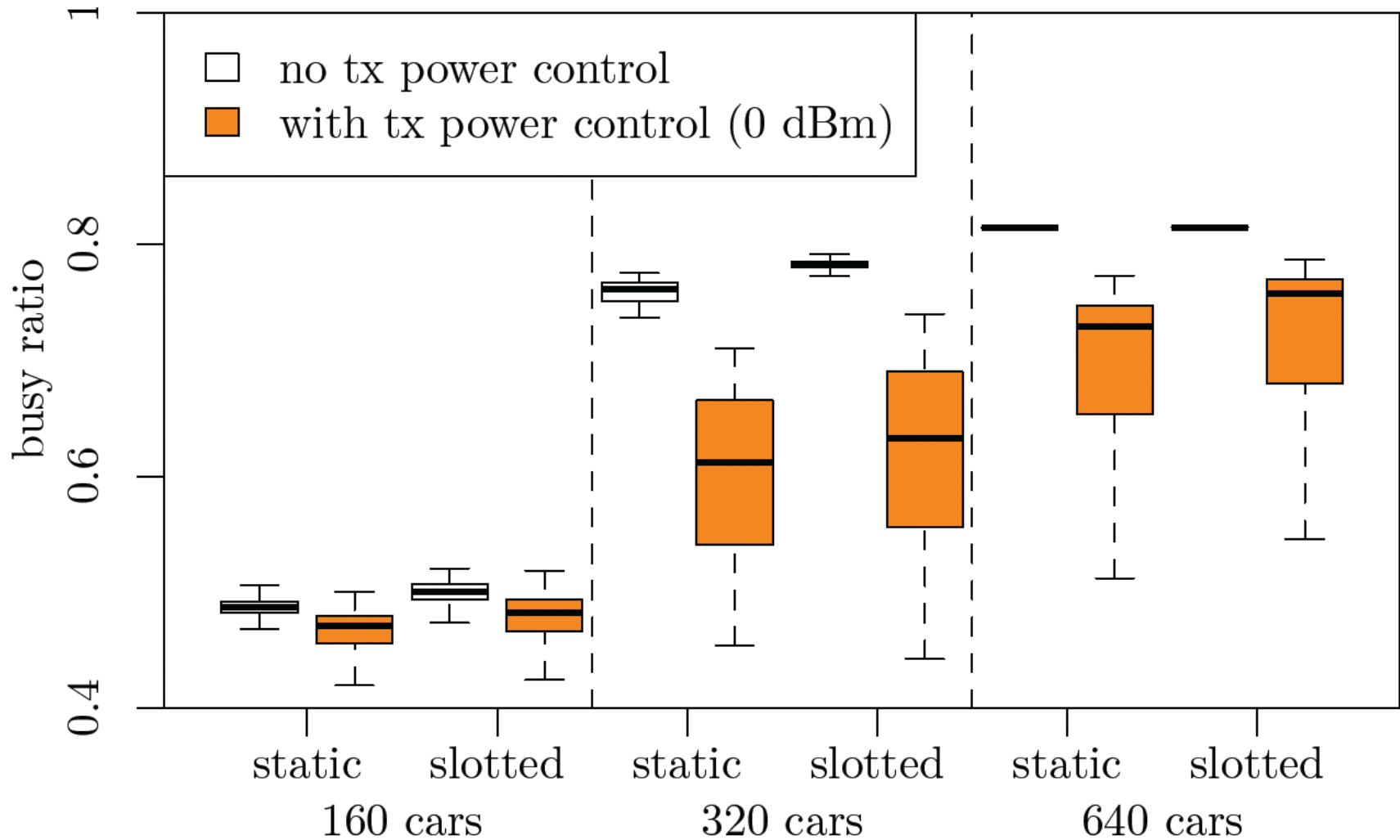


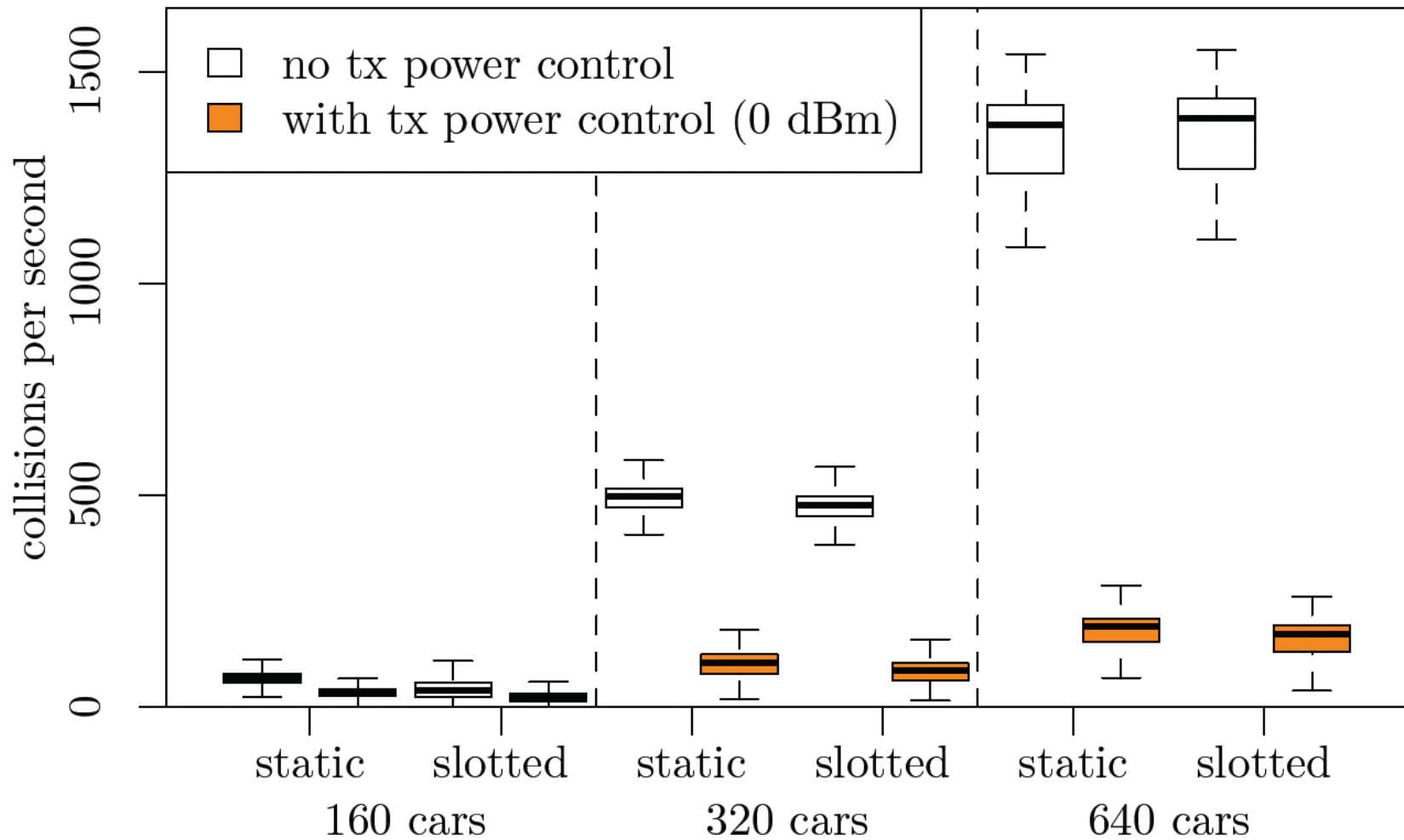
- ✧ Develop and test 4 different protocols
 - ✦ Random transmission (static beaconing)
 - ✦ Synchronized transmission (slotted beaconing)
 - ✦ Both w/ and w/o transmission power control

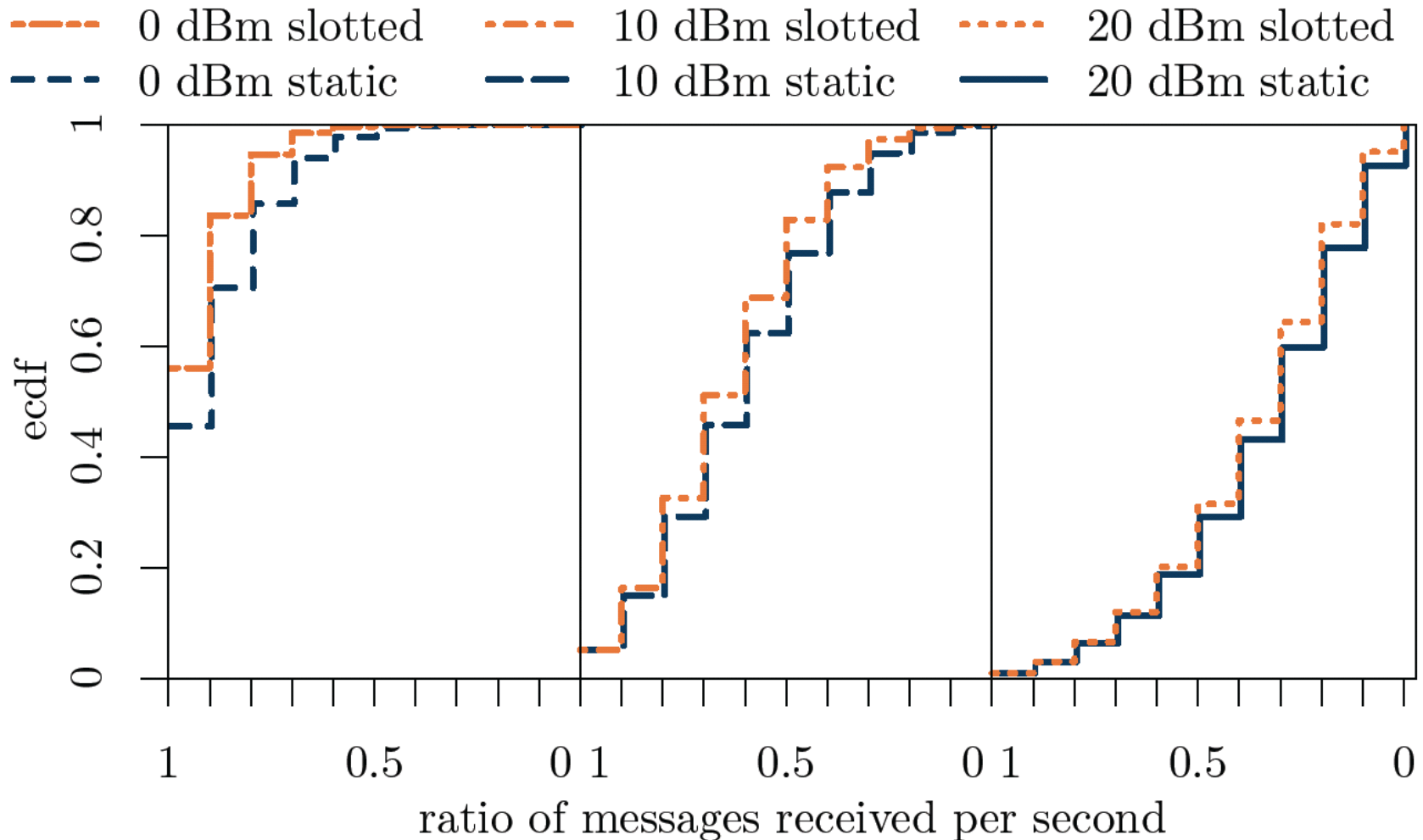


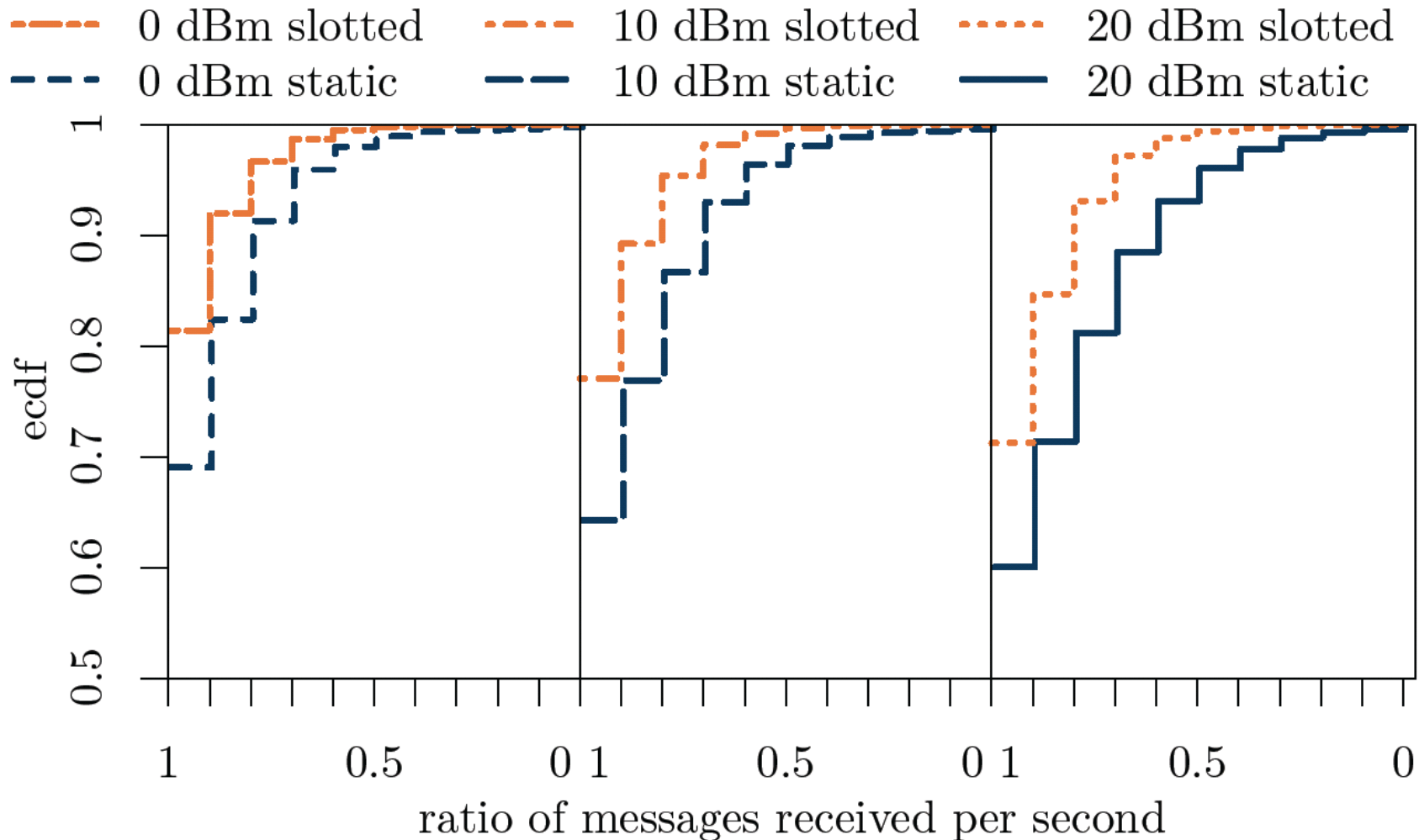
- ✧ Simulation of a highway:
 - ✦ Different number of cars (160, 320, 640)
 - ✦ 4 lanes
 - ✦ 20 cars per platoon
 - ✦ Use the 4 different protocols

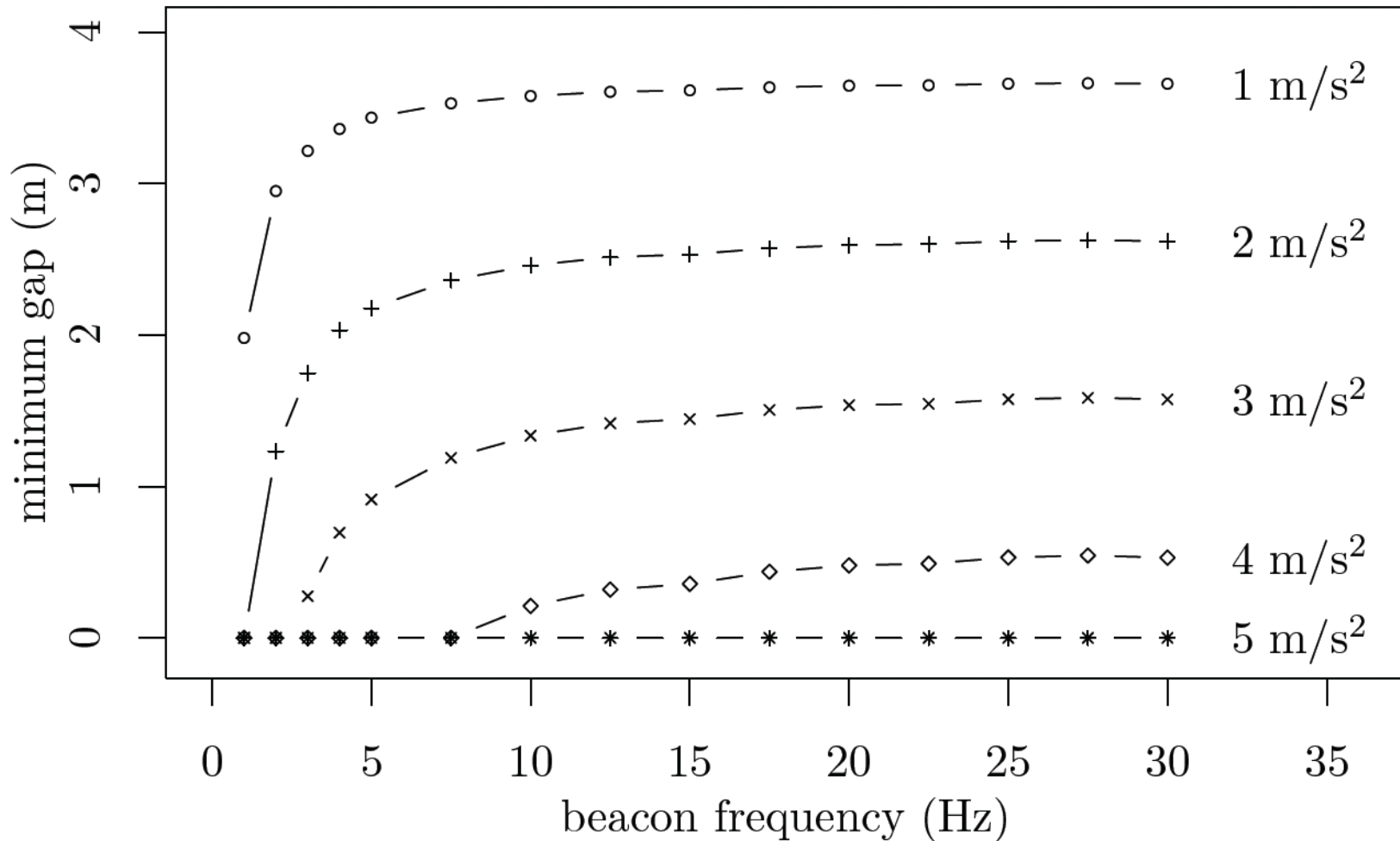












Performance Evaluation of Inter-Vehicle Communication

- ✧ Real-world experiments
 - ✦ Outline only limited information about the feasibility and the performance
 - experiments with roughly 400 cars are planned in a German project
 - ✦ Performance evaluation for 2%, 10%, 50%,... penetration?
- ✧ Simulation
 - ✦ Usually using standard network simulation methods
 - ns2/ns3, OMNeT++, GloMoSim, OPNET, ...
 - ✦ Detailed network layers, simple “support” modules
 - ✦ ***Appropriate for VANETs?***
- ✧ Research challenge: appropriate mobility modeling

✧ Early approaches

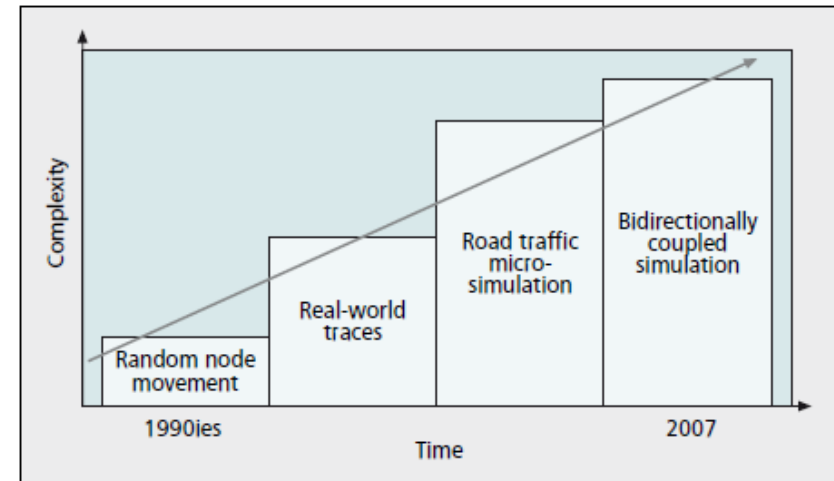
- ✦ Random Waypoint
- ✦ Manhattan Grid
- ✦ Traces

✧ Road traffic microsimulation

- ✦ Simulation of individual cars
- ✦ Exact modeling of streets, speed limits, etc.

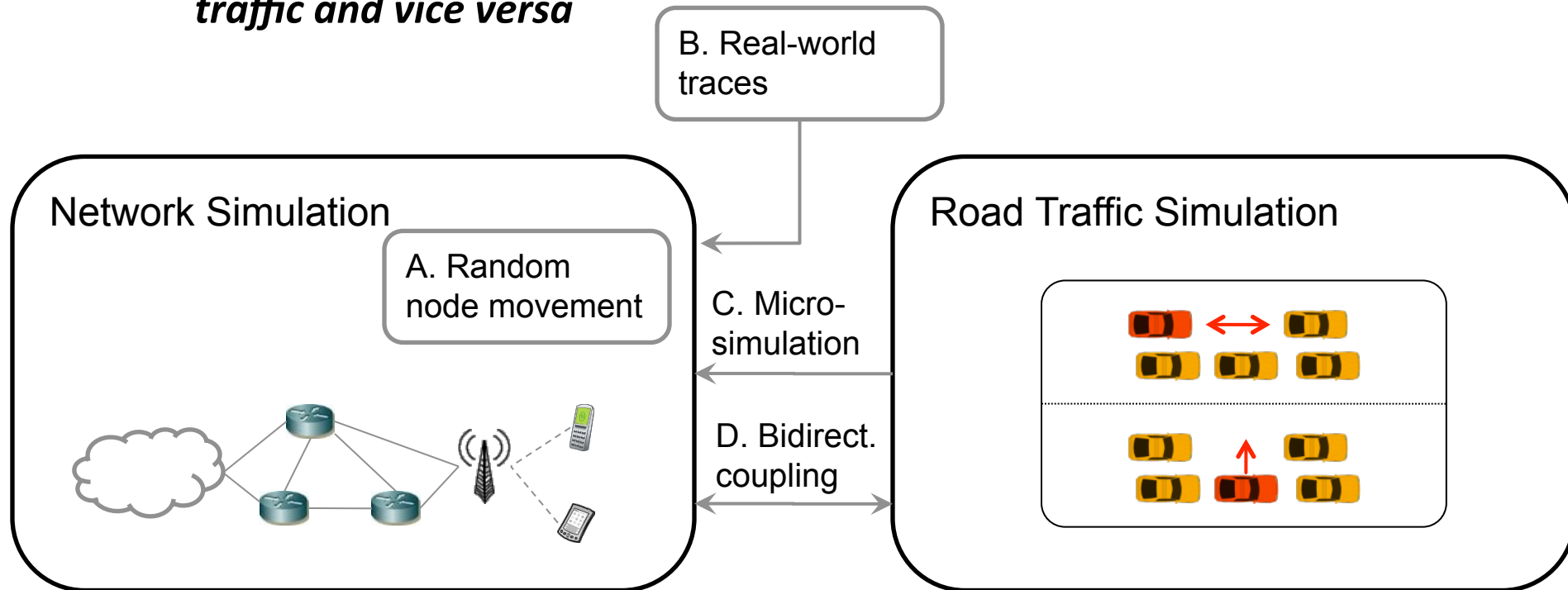
✧ Coupling with network simulation

- ✦ Pre-computation (or on-demand simulation) of road traffic
- ✦ Incorporation of computed traces into network simulators (can be used for real-world traces as well)

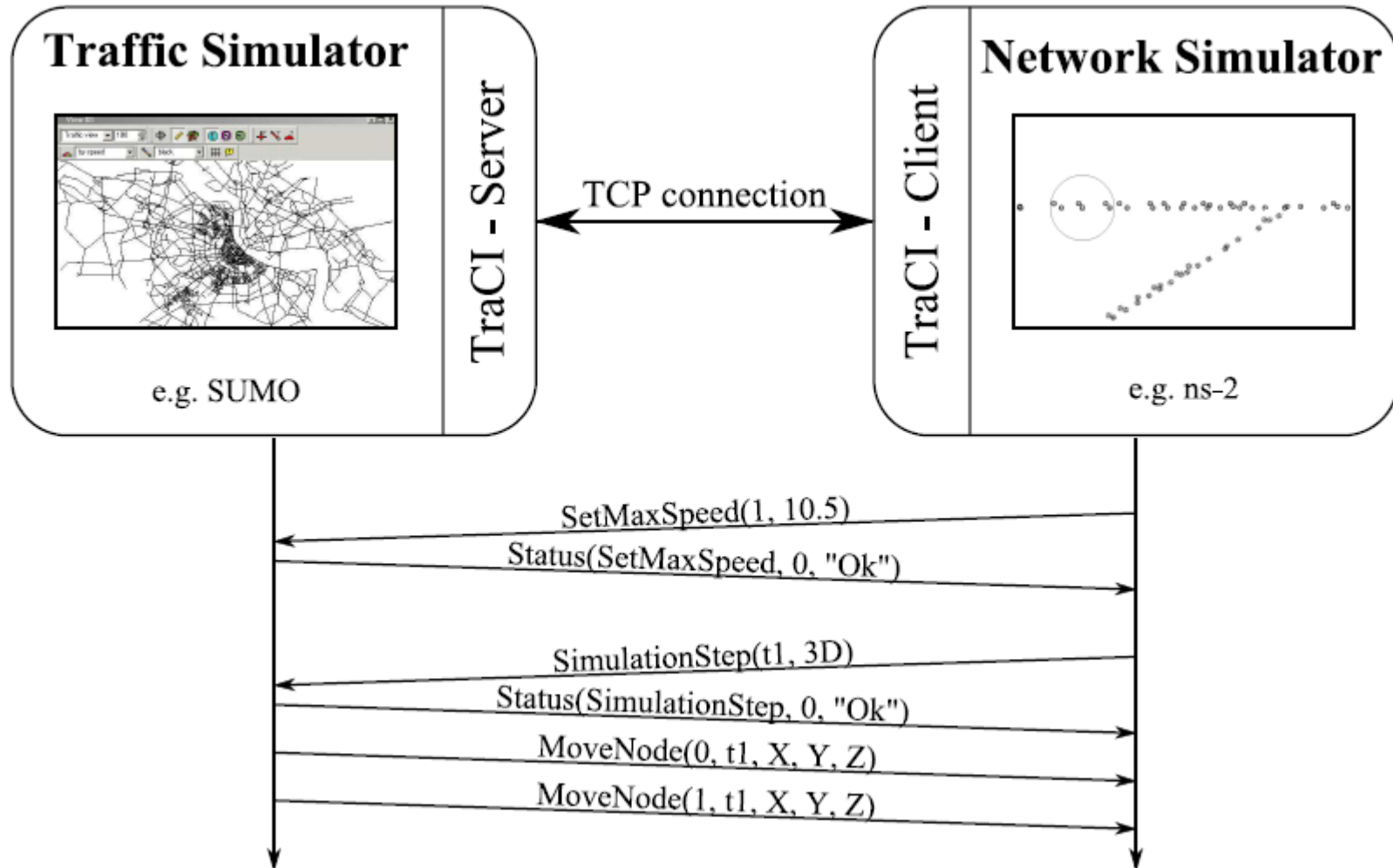


- [1] C. Sommer and F. Dressler, "Progressing Towards Realistic Mobility Models in VANET Simulations," IEEE Communications Magazine, vol. 46 (11), pp. 132-137, November 2008
- [2] J. Yoon, M. Liu, and B. Noble, "Random waypoint considered harmful," Proceedings of 22nd IEEE Conference on Computer Communications (IEEE INFOCOM 2003), vol. 2, San Francisco, CA, March 2003, pp. 1312-1321
- [3] V. Naumov, R. Baumann, and T. Gross, "An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces," Proceedings of 7th ACM International Symposium on Mobile Ad Hoc Networking and Computing (ACM Mobihoc 2006), Florence, Italy, March 2006, pp. 108-119
- [4] M. Fiore, J. Härrä, F. Filali, and C. Bonnet, "Vehicular Mobility Simulation for VANETs," Proceedings of 40th Annual Simulation Symposium (ANSS 2007), March 2007, pp. 301-309

- ✧ Unidirectional coupling: models road traffic without any optimization through TIS information
- ✧ ***Bidirectional coupling is important to analyze effects of IVC on road traffic and vice versa***



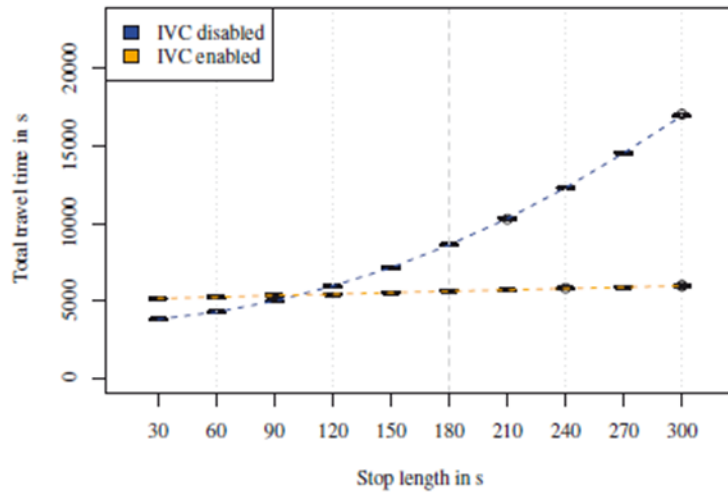
- [1] Christoph Sommer, Reinhard German and Falko Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," IEEE Transactions on Mobile Computing, vol. 10 (1), pp. 3-15, January 2011
- [2] B. Raney, A. Voellmy, N. Cetin, M. Vrtic, and K. Nagel, "Towards a Microscopic Traffic Simulation of All of Switzerland," Proceedings of International Conference on Computational Science (ICCS 2002), Amsterdam, The Netherlands, April 2002, pp. 371-380
- [3] M. Treiber, A. Hennecke, and D. Helbing, "Congested Traffic States in Empirical Observations and Microscopic Simulations," Physical Review E, vol. 62, pp. 1805, 2000



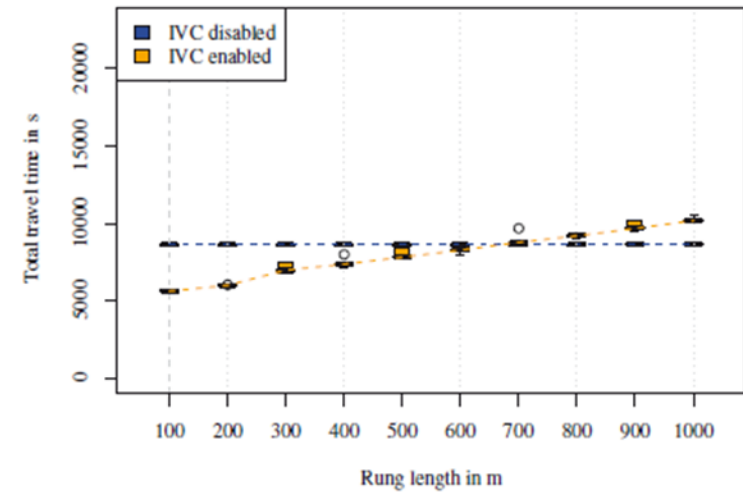
- ✧ Evaluation metrics: traveling time vs. CO₂ emission
 - ✦ Quite accurate gas consumption / emission models available
 - ✦ E.g., EMIT

factor		value	unit
v	vehicle speed		m s^{-1}
a	vehicle acceleration		m s^{-2}
A	rolling resistance	0.1326	$\text{kW m}^{-1} \text{s}$
B	speed-correction to rolling resistance	2.7384×10^{-3}	$\text{kW m}^{-2} \text{s}^2$
C	air drag resistance	1.0843×10^{-3}	$\text{kW m}^{-3} \text{s}^3$
M	vehicle mass	1.3250×10^3	kg
g	gravitational constant	9.81	m s^{-2}
ϑ	road grade	0	degrees
α		1.1100	g s^{-1}
β		0.0134	g m^{-1}
δ		1.9800×10^{-6}	$\text{g m}^{-3} \text{s}^2$
ζ		0.2410	$\text{g m}^{-2} \text{s}^2$
α'		0.9730	g s^{-1}

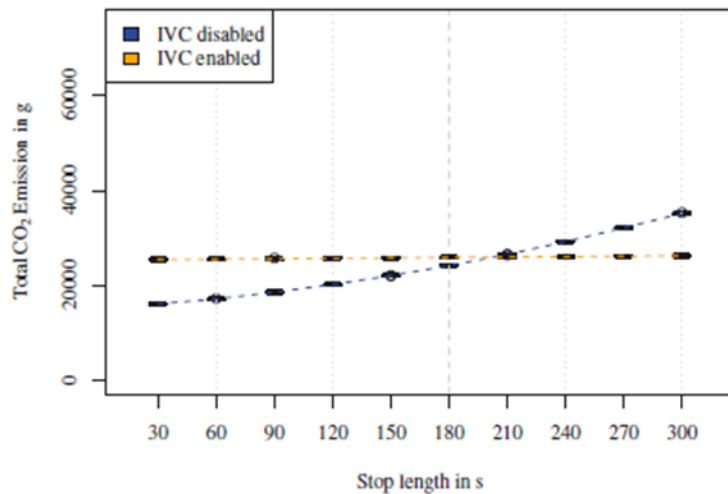
- [1] A. Cappiello, I. Chabini, E. Nam, A. Lue, and M. Abou Zeid, "A statistical model of vehicle emissions and fuel consumption," 5th IEEE International Conference on Intelligent Transportation Systems (IEEE ITSC), pp. 801–809, 2002
- [2] C. Sommer, R. Krul, R. German, and F. Dressler, "Emissions vs. Travel Time: Simulative Evaluation of the Environmental Impact of ITS," Proceedings of 71st IEEE Vehicular Technology Conference (VTC2010-Spring), Taipei, Taiwan, May 2010



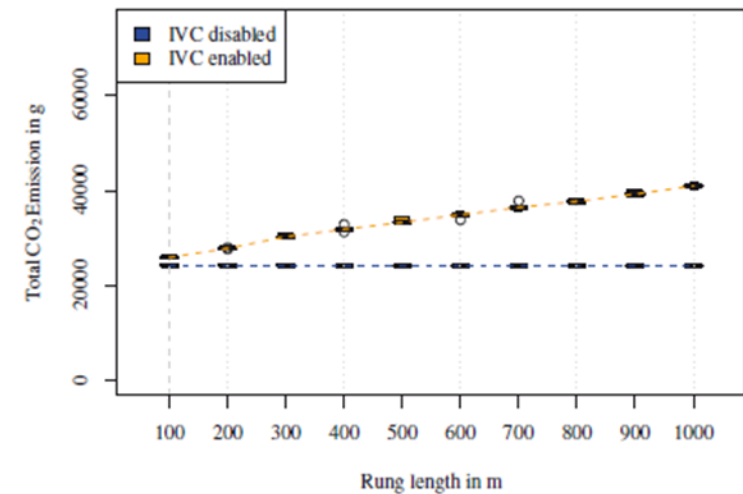
(a) influence of stop length on travel time; 100 m rungs



(b) influence of rung length on travel time; 180 s stops

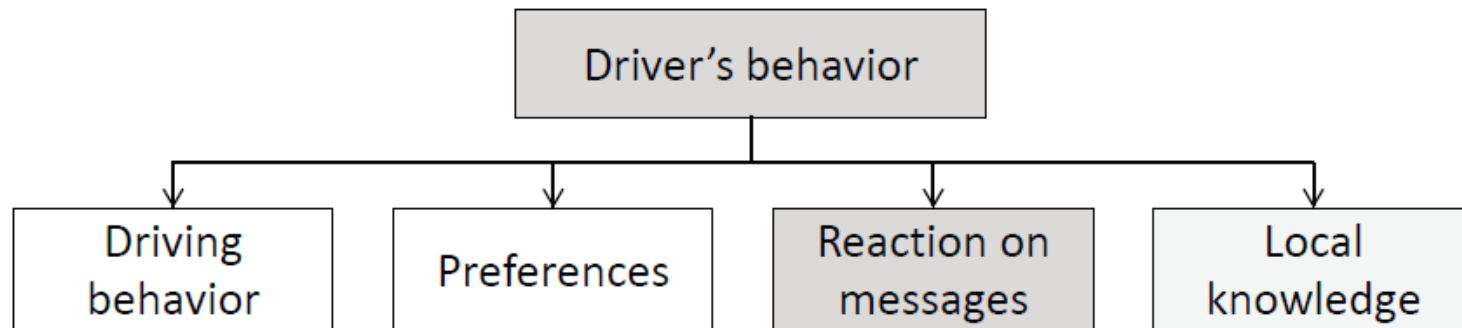


(c) influence of stop length on emissions; 100 m rungs



(d) influence of rung length on emissions; 180 s stops

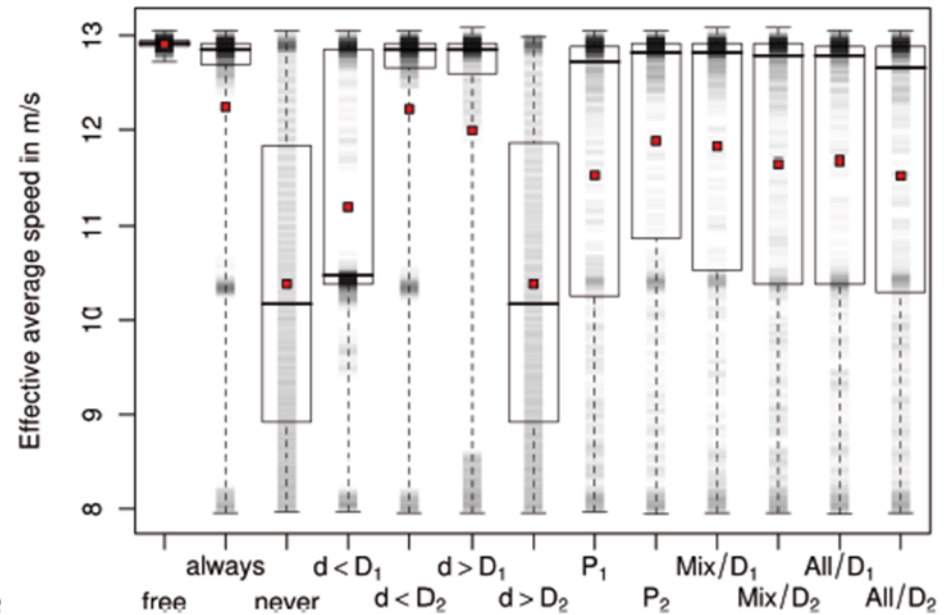
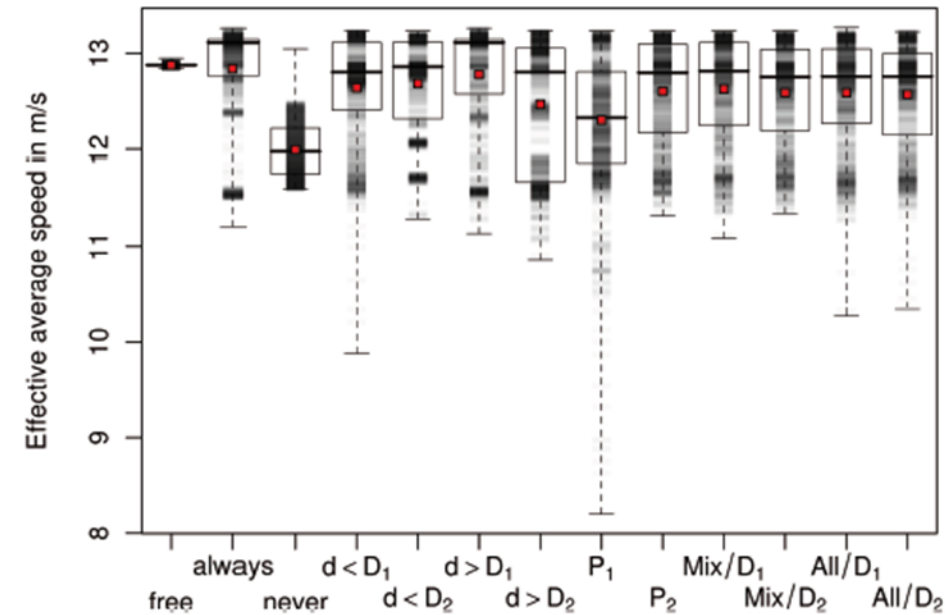
- ✧ Accuracy of technically optimal solutions and imperfect driver behavior



- [1] R. König, A. Saffran, and H. Breckle, "**Modelling of drivers' behaviour**," in Vehicle Navigation and Information Systems Conference, Yokohamashi, Japan, August/September 1994, pp. 371–376.
- [2] W. Barfield, M. Haselkorn, J. Spyridakis, and L. Conquest, "**Commuter Behavior and Decision-Making: Designing Motorist. Information Systems**," in 33rd Human Factors and Ergonomics Society Annual Meeting, Santa Monica, CA, 1989, pp. 611–614.
- [3] P. C. Cacciabue, Ed., **Modelling Driver Behaviour in Automotive Environments: Critical Issues in Driver Interactions with Intelligent Transport Systems**. Springer, 2007.
- [4] F. Dressler and C. Sommer, "**On the Impact of Human Driver Behavior on Intelligent Transportation Systems**," Proceedings of 71st IEEE Vehicular Technology Conference (VTC2010-Spring), Taipei, Taiwan, May 2010

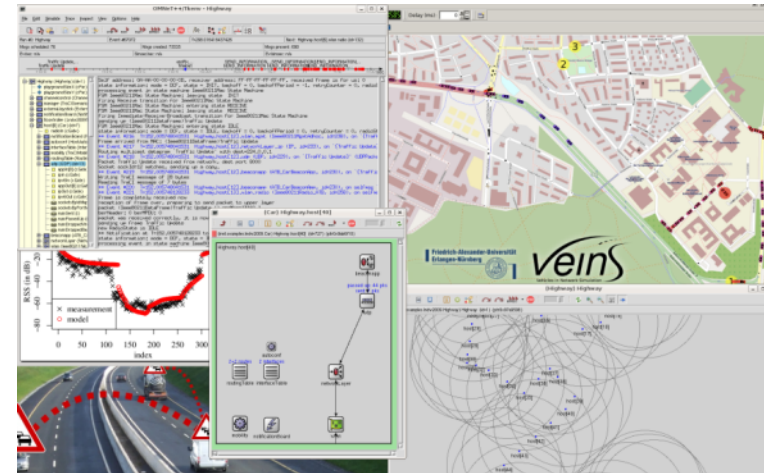
- ✧ Route changers – drivers who are willing to change both time and route of the tour depending on traffic information
- ✧ Non-changers – people who are absolutely unwilling to change the route
- ✧ Pre-trip changers – drivers who are willing to change the route before leaving the house
- ✧ In-trip changers – those who are only willing to change just before entering a possibly congested highway

Class	Description	Mix	All
Always	route selection according TIS recommendations	40.1 %	20 %
Never	drivers unwilling to change the route	23.4 %	20 %
$d < D$	route changes only if the distance to the congestion is less than D	20.6 %	20 %
$d > D$	route changes only if the distance to the congestion is larger than D	15.9 %	20 %
P	probabilistic decision whether to fall into class <i>always</i> or <i>never</i>	0 %	20 %



[1] F. Dressler and C. Sommer, "On the Impact of Human Driver Behavior on Intelligent Transportation Systems," Proceedings of 71st IEEE Vehicular Technology Conference (VTC2010-Spring), Taipei, Taiwan, May 2010

- ✧ Veins – Vehicles in Network Simulation
 - ✦ <http://veins.car2x.org/>
- ✧ Based on tools that are well-accepted in their respective communities
 - ✦ OMNeT++ for network simulation
 - ✦ SUMO for road traffic microsimulation



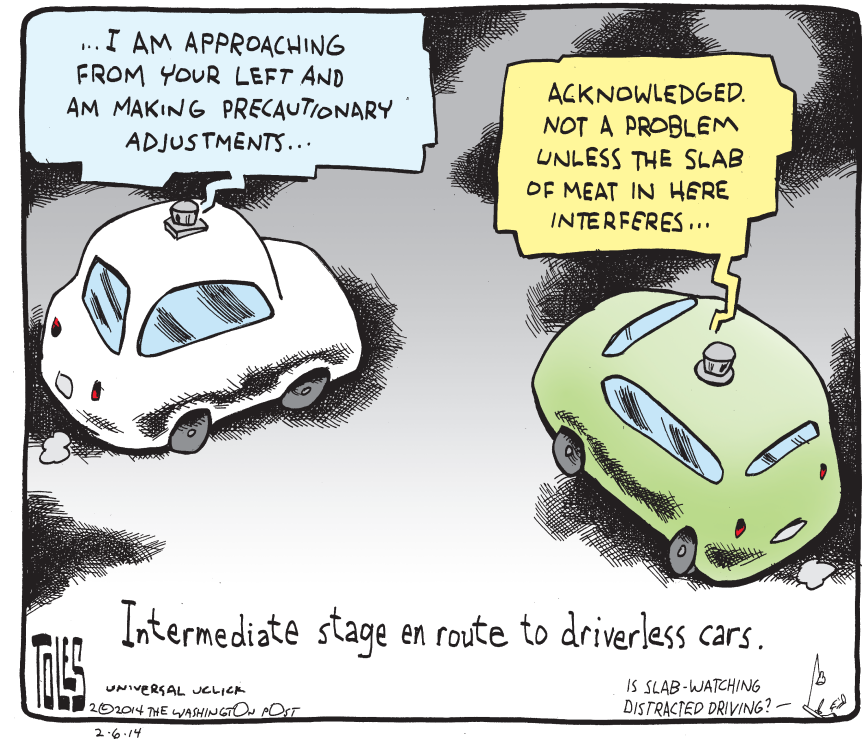
- ✧ Objectives
 - ✦ Bidirectionally-coupled simulation of VANETs
 - ✦ Incorporation of real-world street maps
 - ✦ Flexible and fast(!) simulation



- [1] Christoph Sommer, Reinhard German and Falko Dressler, "**Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis**," IEEE Transactions on Mobile Computing, vol. 10 (1), pp. 3-15, January 2011
- [2] C. Sommer, I. Dietrich, and F. Dressler, "**Realistic Simulation of Network Protocols in VANET Scenarios**," Proceedings of 26th IEEE Conference on Computer Communications (INFOCOM 2007): IEEE Workshop on Mobile Networking for Vehicular Environments (MOVE 2007), Poster Session, Anchorage, AK, May 2007, pp. 139-143

✧ Dagstuhl 2013 (Inter-Vehicle Communication – Quo Vadis)

- ✧ Scientific foundations
- ✧ Best practices from field operational tests
- ✧ IVC applications
- ✧ Heterogeneous vehicular networks



[1] Dressler, Falko and Hartenstein, Hannes and Altintas, Onur and Tonguz, Ozan K., "Inter-Vehicle Communication - Quo Vadis," *IEEE Communications Magazine*, vol. 52 (6), pp. 170-177, June 2014

In this lecture, we studied

- ✧ Inter-Vehicle Communication: Methods and Protocols
 - ✦ Centralized vs. Distributed
 - ✦ Beacons to the extreme
 - ✦ Simulation tools

- ✧ Not discussed: security and privacy concerns
 - ✦ Strong debate about privacy vs. security

... as can be seen, there are many open challenges and research issues for another decade of V2V research 😊