



Vehicular Networks [C2X]

Introduction Seminar for Nomadic Communications

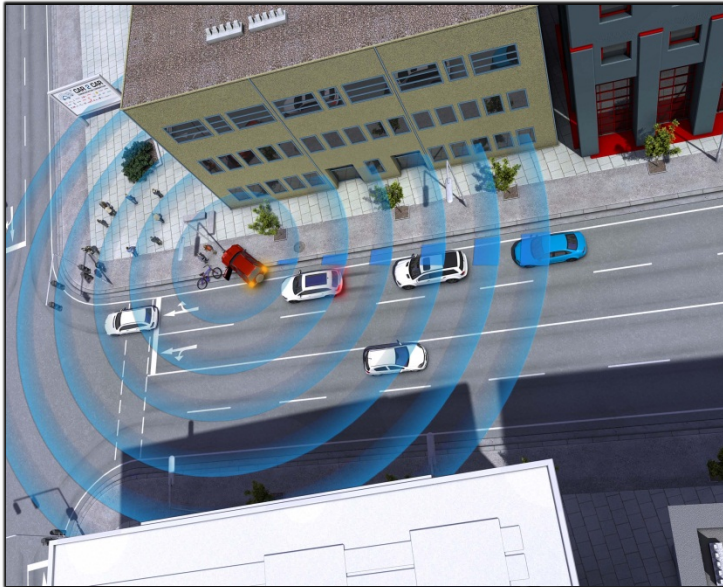
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with special thanks to

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Stefan Joerer, MED-EL Innsbruck

David Eckhoff, TUM CREATE Singapore



Illustrations: C2C-CC

Illustration: AKTIV

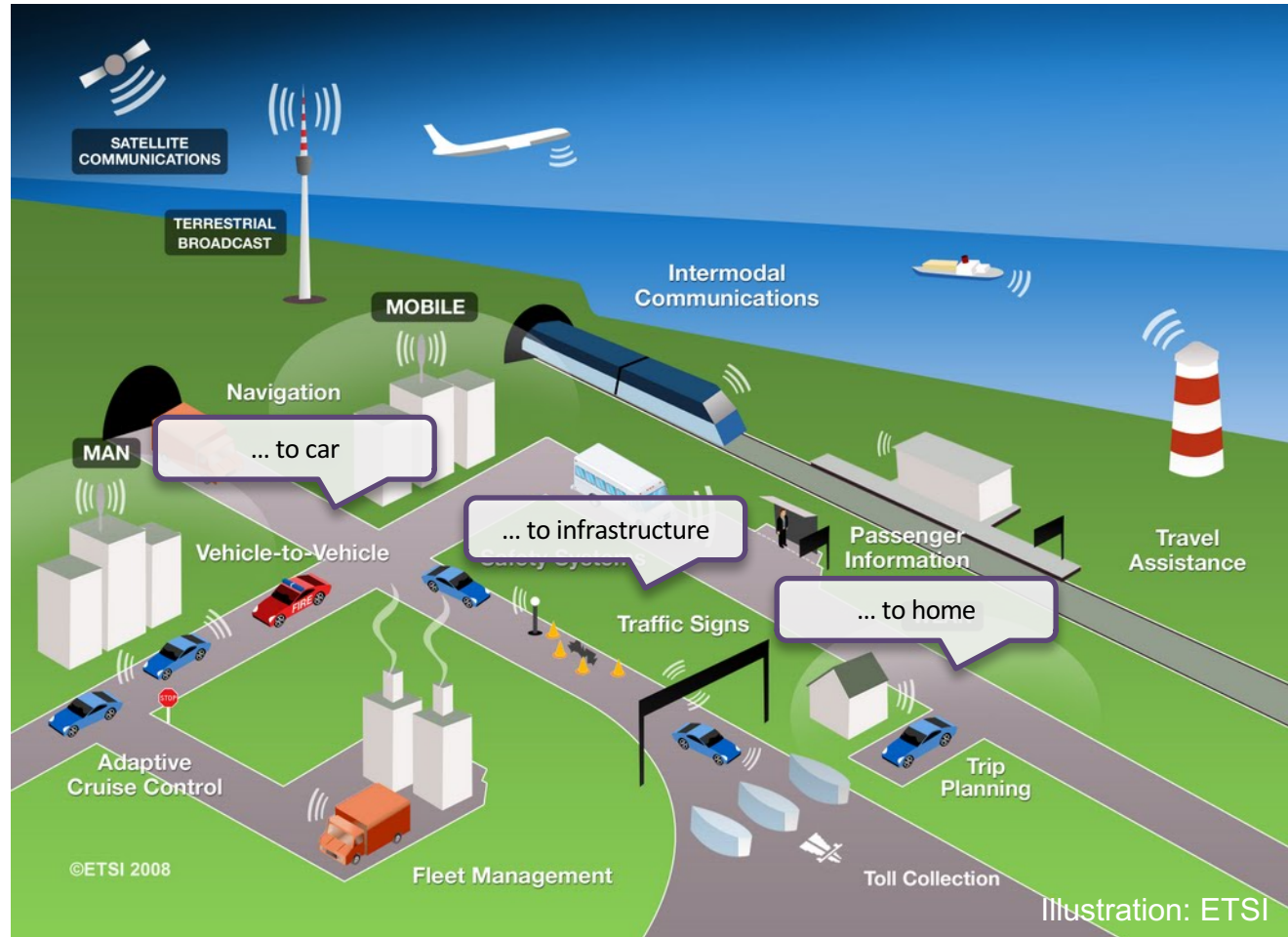
- Car-to-X (C2X) communication patterns

Vehicle-to-X (V2X),

Inter-Vehicle Communication (IVC),

Vehicular ad-hoc network (VANET),

...

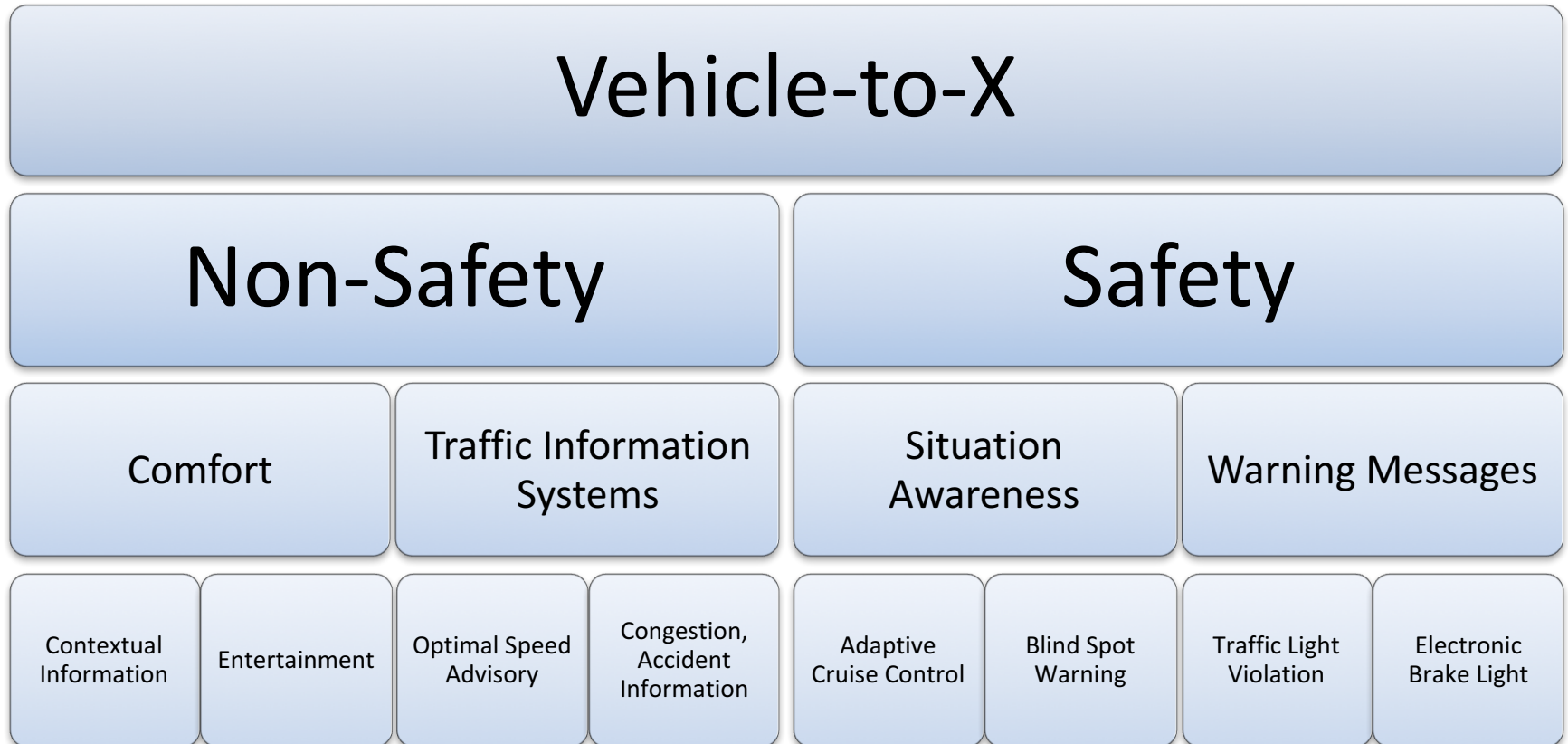




Time for a Video!

AUDI TRAVOLUTION

- Taxonomy of Use Cases



- Taxonomy of Use Cases

Vehicle-to-X

Non-Safety

- Many messages
- High data rate
- Low latency demands
- Low reliability demands
- Long range

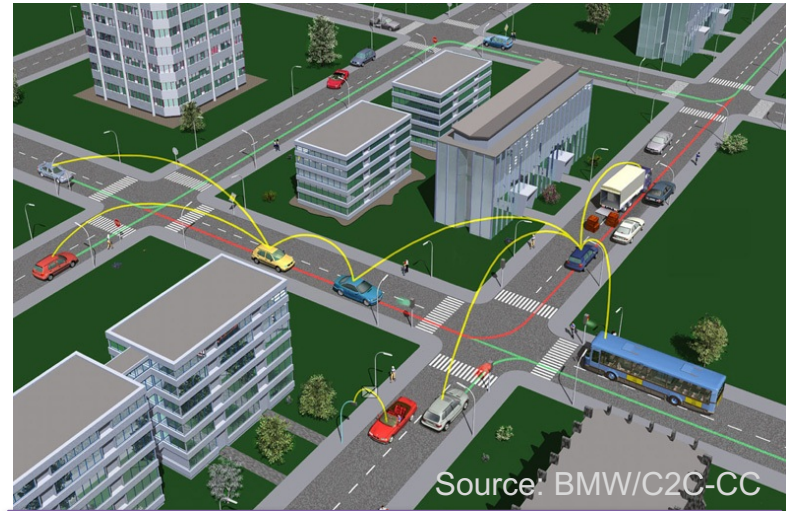
Safety

- Few messages
- Small packet size
- High latency demands
- High reliability demands
- Short range

- Freeway \Leftrightarrow Urban

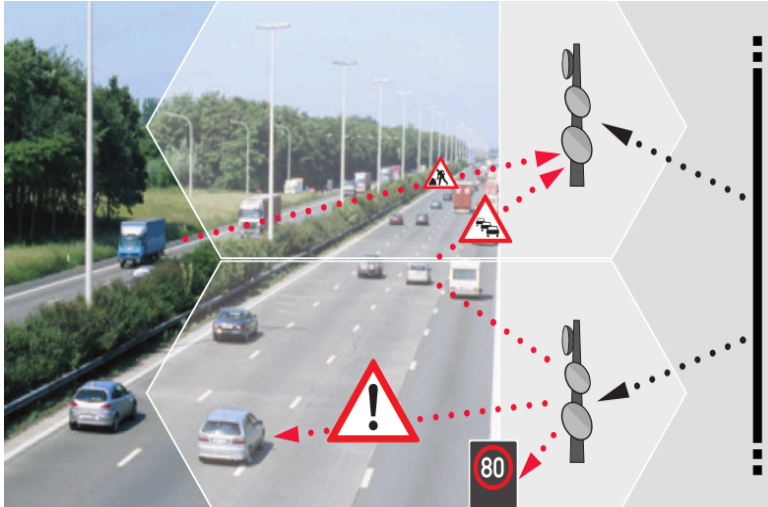


- 1D mobility
- Bimodal connectivity
 - Stable connection ($\rightarrow\rightarrow$)
 - \wedge Unstable connection ($\leftarrow\leftarrow$)
- High speed
- ...

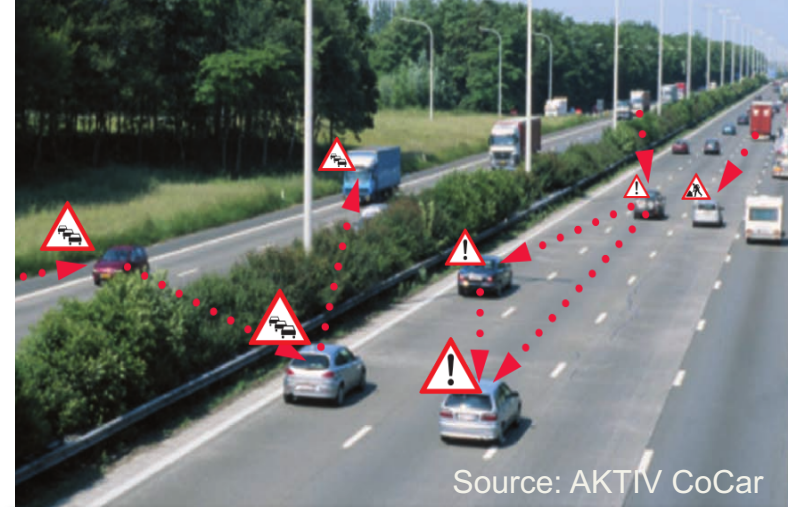


- 2D mobility
- Bipolar connectivity
 - Many neighbors (standing)
 - \vee Few neighbors (driving)
- Obstacles
- ...

- Infrastructure \Leftrightarrow No Infrastructure



- Central coordination
 - Resource management
 - Security
- High latency
- High load on core network
- ...



- Self organizing system
 - Channel access
 - Authentication
- Low latency
- Low data rate
- ...

- Challenges of C2X communication

Communication

- Highly varying channel conditions
- High congestion, contention, interference
- Tightly limited channel capacity

Networking

- Multi-Radio / Multi-Network
- Heterogeneous equipment

Mobility

- Highly dynamic topology
- But: predictable mobility
- Heterogeneous environment

Security

- No (or no reliable) uplink to central infrastructure
- Ensuring privacy



COMMUNICATION TECHNOLOGIES

- Communication paradigms and media

Wireless Communication Technologies

Infrastructure-based

Infrastructureless

Broadcast

Cellular

Short Range

Medium Range

FM Radio,
DAB/DVB,
...

GSM
2G Cellular

UMTS
3G
Cellular

LTE /
WiMAX
4G Cell.

Millimeter,
Infrared,
Visible

802.15.1
Bluetooth

802.15.4
ZigBee

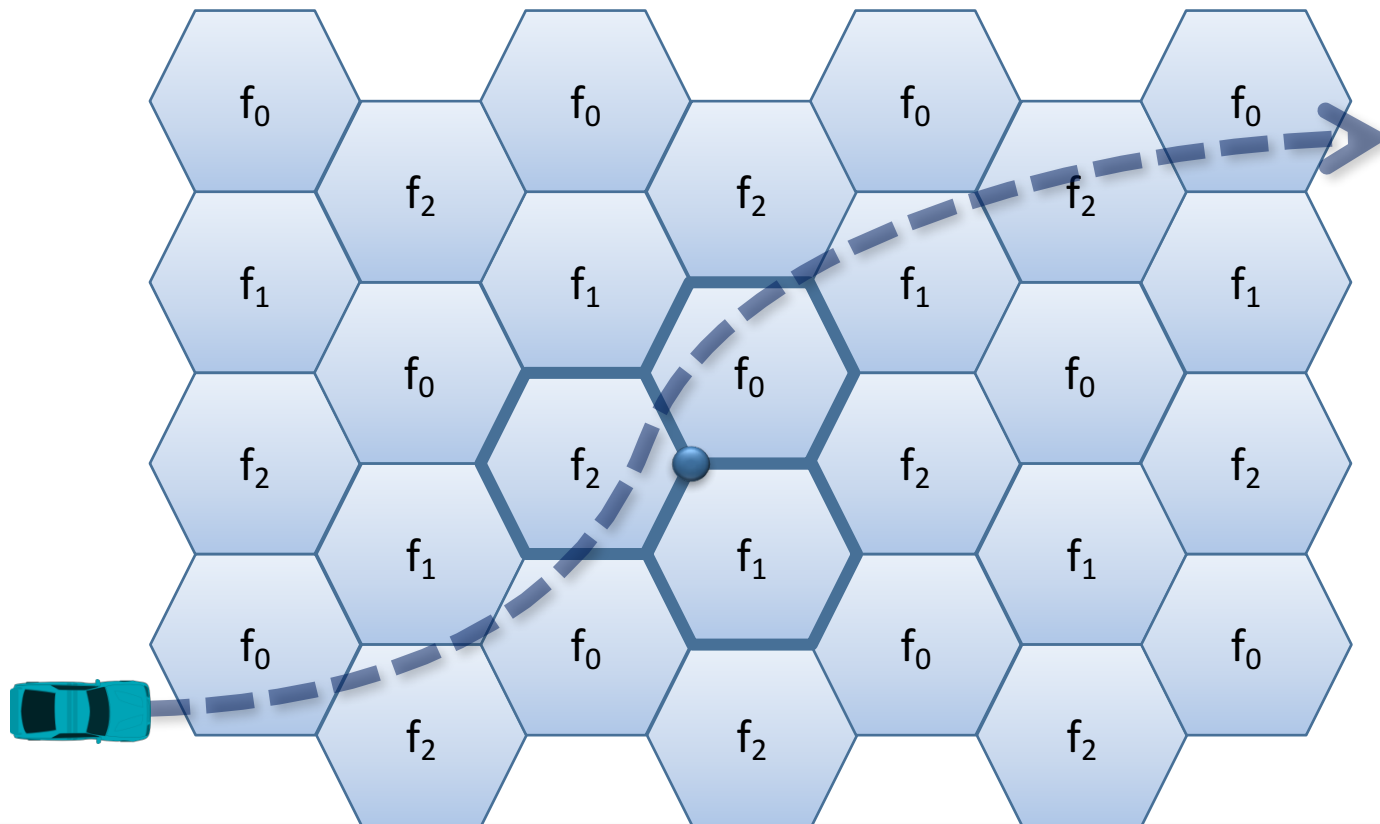
802.11
Wi-Fi

DSRC /
WAVE

[1] Dar, K. and Bakhouya, M. and Gaber, J. and Wack, M. and Lorenz, P., "Wireless Communication Technologies for ITS Applications," IEEE Communications Magazine, vol. 48 (5), pp. 156-162, May 2010

- Concept

- Divide world into cells, each served by base station
- Allows, e.g., frequency reuse in FDMA



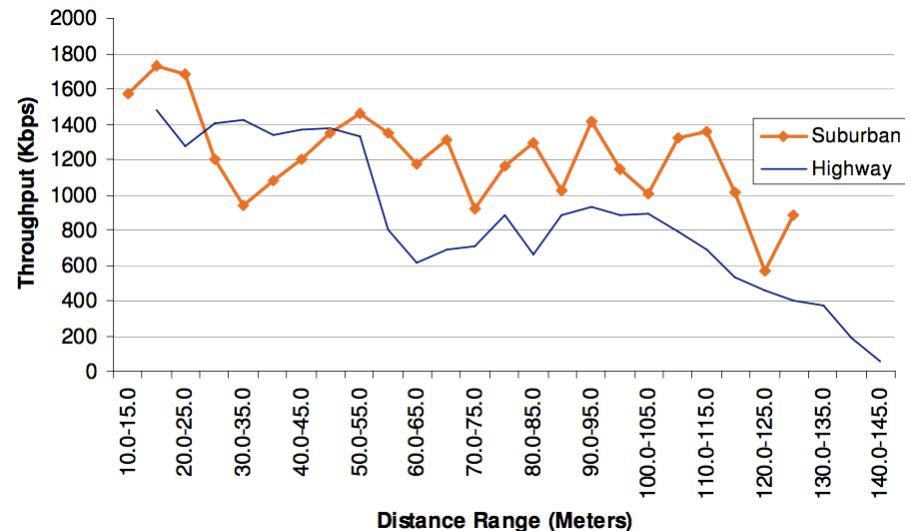


- Can UMTS support Car-to-X communication?
 - Ex: UTRA FDD Release 99 (W-CDMA)
 - Speed of vehicles not a limiting factor
 - Field operational tests at 290 km/h show signal drops only after sudden braking (⇒ handover prediction failures)
 - Open questions
 - Delay
 - Capacity
- Channels in UMTS
 - Shared channels
 - E.g. Random Access Channel (RACH), uplink and Forward Access Channel (FACH), downlink
 - Dedicated channels
 - E.g. Dedicated Transport Channel (DCH), up-/downlink



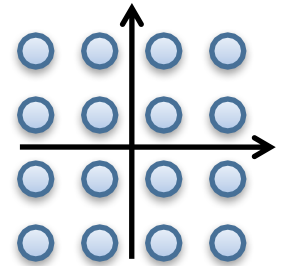
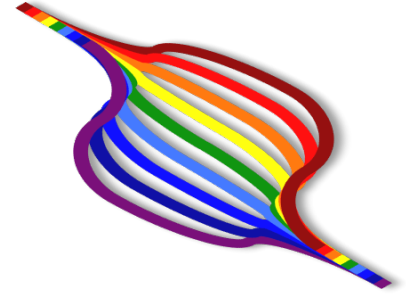
- So: can UMTS support Car-to-X communication?
 - At low market penetration: yes
 - Eventually:
 - Need to invest in much smaller cells (e.g., along freeways)
 - Need to implement multicast functionality (MBMS)
 - Main use case for UMTS: centralized services
 - Ex.: Google Maps Traffic
 - Collect information from UMTS devices
 - Storage of data on central server
 - Dissemination via Internet (⇒ ideal for cellular networks)

- IEEE 802.11{a,b,g,n} for Car-to-X communication?
 - Can't be in infrastructure mode and ad hoc mode at the same time
 - Switching time consuming
 - Association time consuming
 - (Massively) shared spectrum (⇒ ISM)
 - Multi-path effects reduce range and speed



[1] Fay Hui, Prasant Mohapatra. „Experimental Characterization of Multihop Communications in Vehicular Ad Hoc Network“. In Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks, 2005

- IEEE 802.11p
 - PHY layer mostly identical to IEEE 802.11a
 - OFDM based
 - Reduction of inter symbol interference because of multi-path effects
 - Double timing parameters
 - Channel bandwidth down to 10 MHz (from 20 MHz)
 - Throughput down to 3 ... 27 Mbit/s (from 6 ... 54 Mbit/s)
 - Range up to 1000 m, speed up to 200 km/h
 - MAC layer of IEEE 802.11a plus extensions
 - Random MAC Address
 - QoS (EDCA priority access, cf. IEEE 802.11e, ...)
 - Multi-Frequency and Multi-Radio capabilities
 - New Ad Hoc mode
 - ...



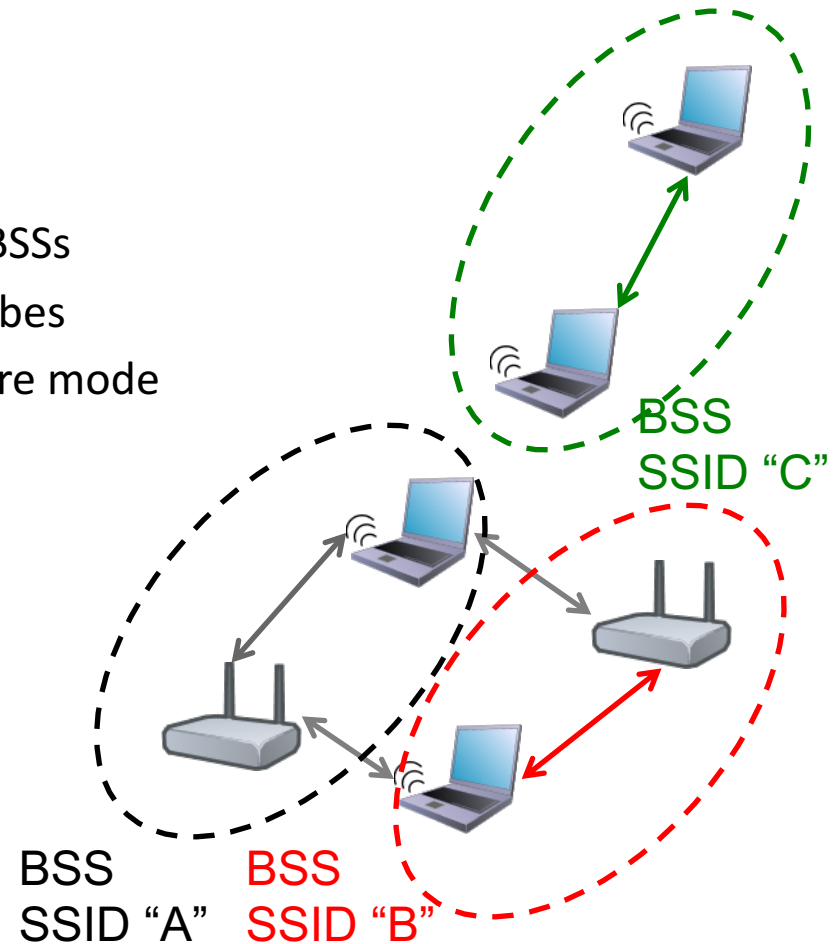
- Classic IEEE 802.11 Basic Service Set (BSS)

- Divides networks into logical units

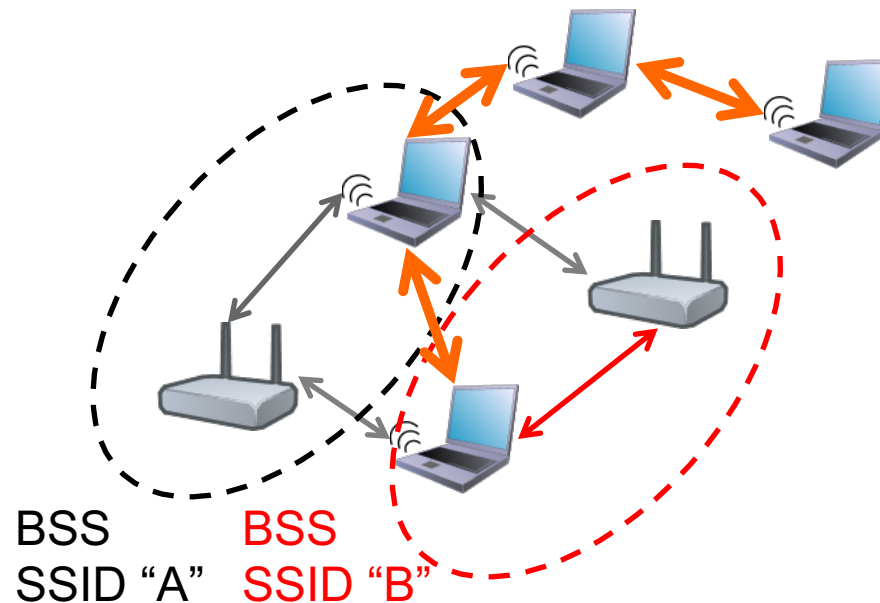
- Nodes belong to (exactly one) BSS
 - Packets contain BSSID
 - Nodes ignore packets from “foreign” BSSs
 - Exception: Wildcard-BSSID (-1) for probes
 - Ad hoc networks emulate infrastructure mode

- Joining a BSS

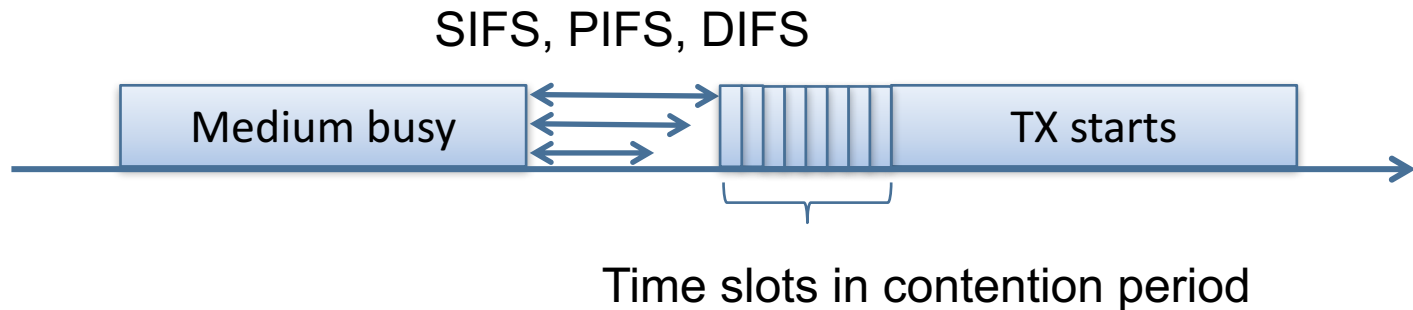
- Access Point sends beacon
 - Authentication dialogue
 - Association dialogue
 - Node has joined BSS



- New: 802.11 WAVE Mode
 - Default mode of nodes in WAVE
 - Nodes may always use Wildcard BSS in packets
 - Nodes will always receive Wildcard BSS packets
 - May join BSS and still use Wildcard BSS



- IEEE 802.11 Distributed Coordination Function (DCF)
 - aka “Contention Period”

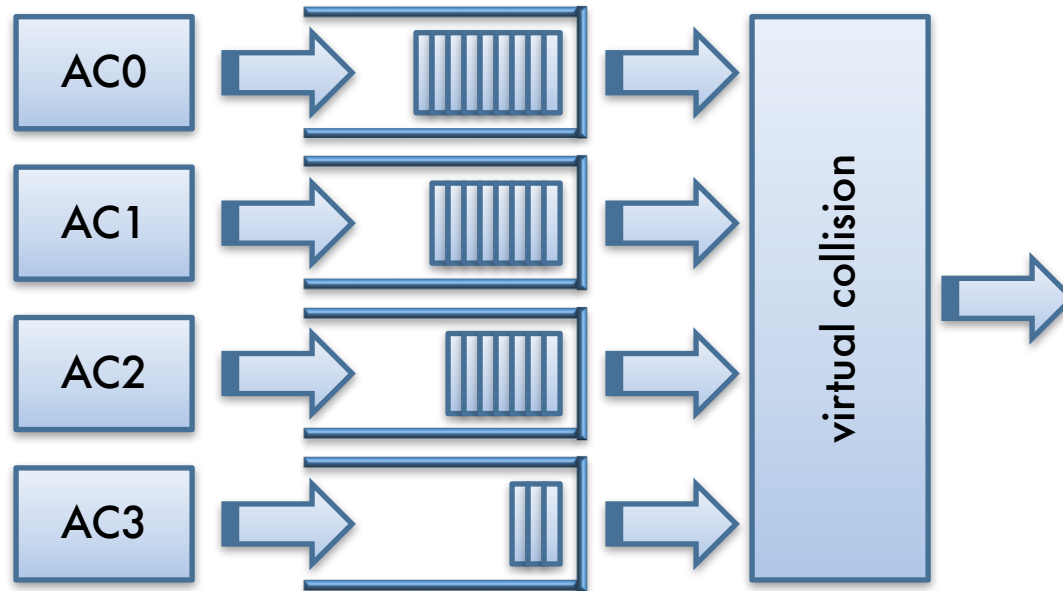


- Priority access via SIFS (ACK, CTS, ...) and DIFS (payload)
- Wait until medium has been free for duration of DIFS
- If medium busy, wait until idle, then wait DIFS plus random backoff time
- Cannot prioritize DATA frames



- QoS in 802.11p (HCF)
 - cf. IEEE 802.11e EDCA
 - DIFS \Rightarrow AIFS (Arbitration Inter-Frame Space)
 - DCF \Rightarrow EDCA (Enhanced Distributed Channel Access)
 - Classify user data into 4 ACs (Access Categories)
 - AC0 (lowest priority)
 - ...
 - AC3 (highest priority)
 - Each ACs has different...
 - CW_{\min} , CW_{\max} , AIFS, TXOP limit (max. continuous transmissions)
 - Management data uses DIFS (not AIFS)

- QoS in 802.11p (HCF)
 - Map 8 user priorities \Rightarrow 4 access categories \Rightarrow 4 queues
 - Queues compete independently for medium access



- QoS in 802.11p (HCF)
 - Parameterization

Parameter	Value
SlotTime	13 μ s
SIFS	32 μ s
CW_{min}	15
CW_{max}	1023
Bandwidth (PHY layer data rates)	10 MHz (3 .. 27 mbit/s)

- Sample queue configuration (from 802.11p standard)

Parameter	AC_BK	AC_BE	AC_VI	AC_VO
CW_{min}	CW_{min}	CW_{min}	$(CW_{min}+1)/2-1$	$(CW_{min}+1)/4-1$
CW_{max}	CW_{max}	CW_{max}	CW_{min}	$(CW_{min}+1)/2-1$
AIFSn	9	6	3	2



- QoS in WAVE

- mean waiting time for channel access, given sample configuration from IEEE 1609.4 2006

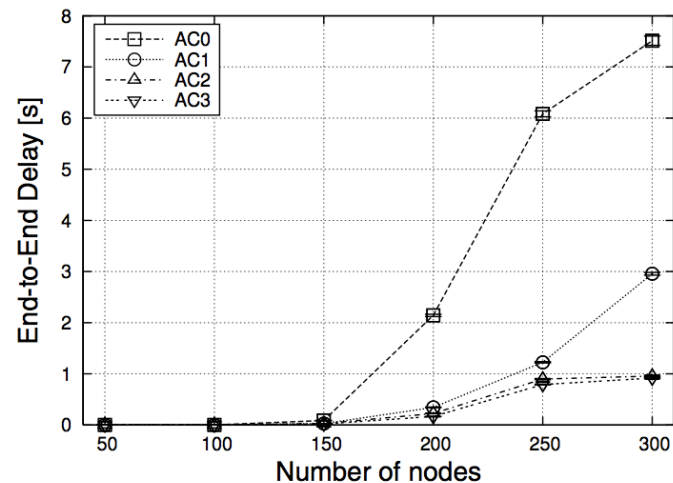
(and TXOP Limit=0

⇒ single packet)

- when channel idle:

- when channel busy:

AC	CW _{min}	CW _{max}	AIFS	TXOP	t _w (in μs)
0	15	1023	9	0	264
1	7	15	6	0	152
2	3	7	3	0	72
3	3	7	2	0	56



[1] Eichler, S., "Performance evaluation of the IEEE 802.11p WAVE communication standard," Proceedings of 66th IEEE Vehicular Technology Conference (VTC2007-Fall), Baltimore, USA, October 2007, pp. 2199-2203



- Pros of UMTS/LTE
 - + Easy provision of centralized services
 - + Quick dissemination of information in whole network
 - + Pre-deployed infrastructure
 - + Easy migration to (and integration into) smartphones
- Cons of UMTS/LTE
 - High short range latencies (might be too high for safety)
 - Network needs further upgrades (smaller cells, multicast service)
 - High dependence on network operator
 - High load in core network, even for local communication



- Pros of 802.11p/Ad hoc
 - + Smallest possible latency
 - + Can sustain operation without network operator / provider
 - + Network load highly localized
 - + Better privacy
- Cons of 802.11p/Ad hoc
 - Needs gateway for provision of central services (e.g., RSU)
 - No pre-deployed hardware, and hardware is still expensive
- The solution?
 - hybrid systems:
deploy both technologies to vehicles and road,
decide depending on application and infrastructure availability

- Channel management

- Dedicated frequency band at 5.9 GHz allocated to WAVE

- Exclusive for V2V und V2I communication
 - No license cost, but strict rules
 - 1999: FCC reserves 7 channels of 10 MHz (“U.S. DSRC”)

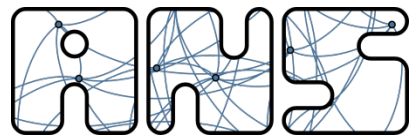
...	Critical Safety of Life	SCH	SCH	Control Channel (CCH)	SCH	SCH	Hi-Power Public Safety	...
	ch 172 5.860GHz	ch 174 5.870GHz	ch 176 5.880GHz	ch 178 5.890GHz	ch 180 5.900GHz	ch 182 5.910GHz	ch 184 5.920GHz	

- 2 reserved channels, 1+4 channels for applications

- ETSI Europe reserves 5 channels of 10 MHz

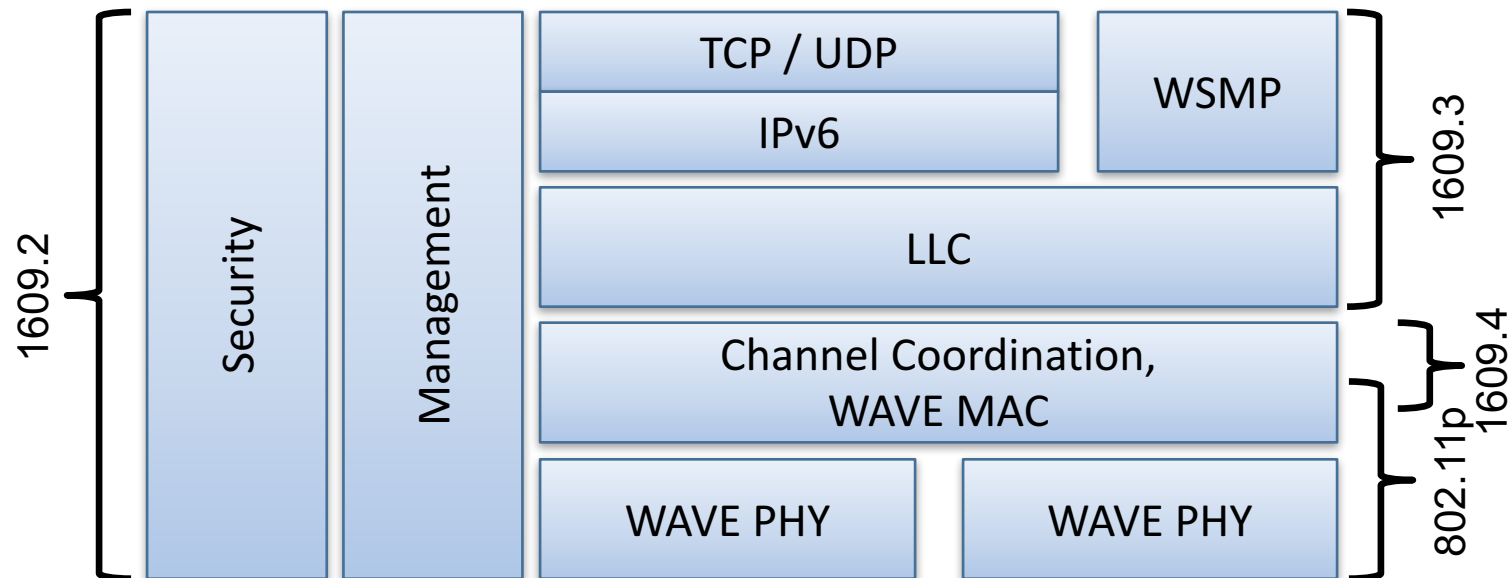
SCH	SCH	SCH	SCH	CCH
ch 172 5.860GHz	ch 174 5.870GHz	ch 176 5.880GHz	ch 178 5.890GHz	ch 180 5.900GHz

[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



- Need for higher layer standards
 - Unified message format
 - Unified interfaces to application layer
- U.S.
 - IEEE 1609.*
 - WAVE („Wireless Access in Vehicular Environments“)
- Europe
 - ETSI
 - ITS G5 (“Intelligent Transportation Systems”)

- IEEE 1609.* upper layers (building on IEEE 802.11p)
 - IEEE 1609.1: “Operating system”
 - IEEE 1609.2: Security
 - IEEE 1609.3: Network services
 - IEEE 1609.4: Channel mgmt.

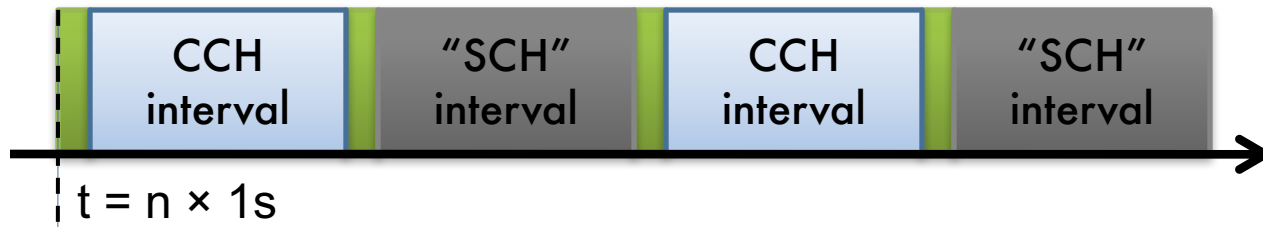


[1] Jiang, D. and Delgrossi, L., "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," Proceedings of 67th IEEE Vehicular Technology Conference (VTC2008-Spring), Marina Bay, Singapore, May 2008

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

- Channel management

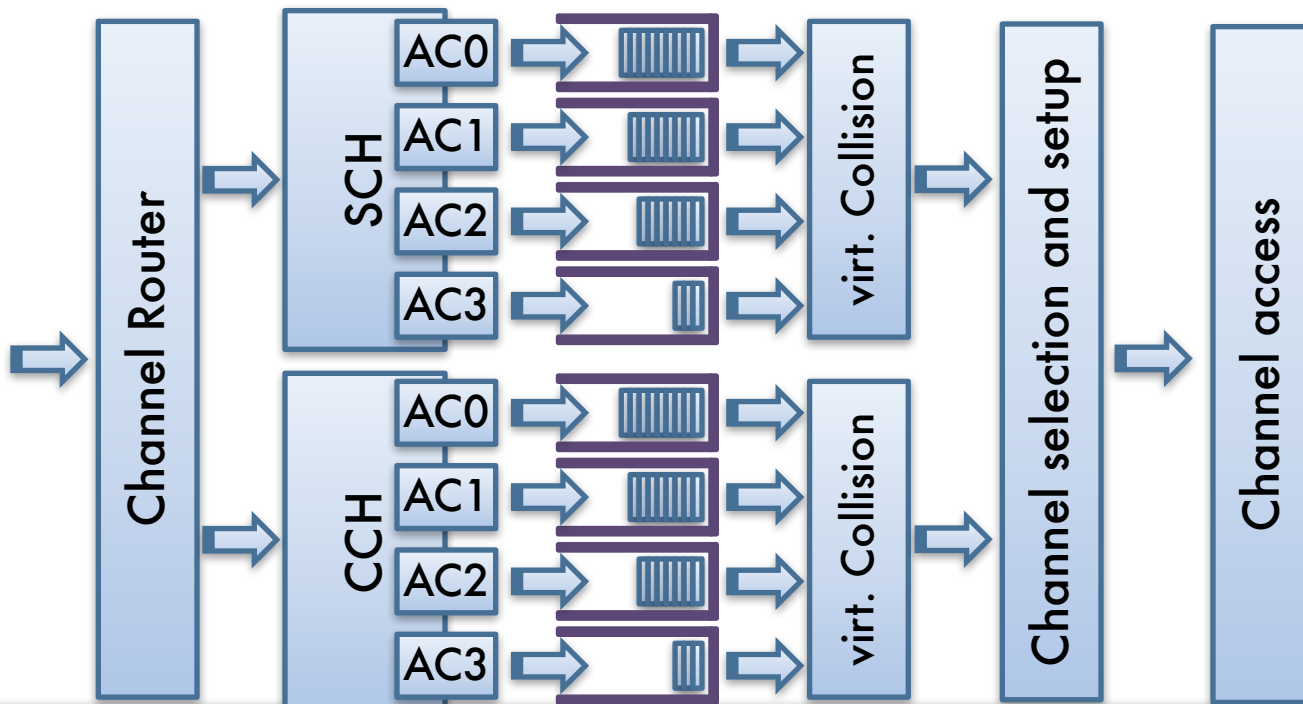
- WAVE allows for both single radio devices & multi radio devices
- Dedicated Control Channel (CCH) for mgmt and safety messages
 - ⇒ single radio devices need to periodically listen to CCH
- Time slots
 - Synchronization envisioned via GPS receiver clock
 - Standard value: 100ms sync interval (with 50ms on CCH)
 - Short guard interval at start of time slot
 - During guard, medium is considered busy (⇒ backoff)



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

- Packet transmission

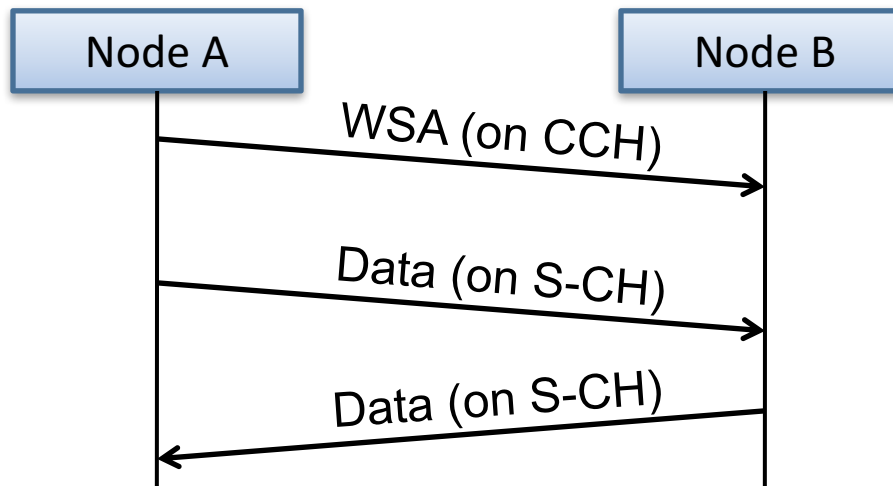
- Sort into AC queue, based on WSMP (or IPv6) EtherType field, destination channel, and user priority
- Switch to desired channel, setup PHY power and data rate
- Start medium access





- Channel management
 - Control Channel (CCH):
 - Default channel upon initialization
 - WAVE service advertisements (WSA),
WAVE short messages (WSM)
 - Service Channel (SCH):
 - Only after joining WAVE BSS
 - WAVE short messages (WSM),
IP data traffic (IPv6)

- WAVE service advertisement (WSA)
 - Broadcast on Control Channel (CCH)
 - Identifies WAVE BSSs on Service Channels (SCHs)
 - Can be sent at arbitrary times, by arbitrary nodes
 - Only possibility to make others aware of data being sent on SCHs





- WAVE service advertisement (WSA)
 - WAVE Version (= 0)
 - Provider Service Table (PST)
 - $n \times$ Provider Service Info
 - Provider Service Identifier (PSID, max. 0x7FFF FFFF)
 - Provider Service Context (PSC, max. 31 chars)
 - Application priority (max priority: 63)
 - (opt.: IPv6 address and port, if IP service)
 - (opt.: Source MAC address, if sender \neq data source)
 - Channel number (max. 200)
 - $1..n \times$ Channel Info (for each channel used in PST table)
 - Data rate (fixed or minimum value)
 - Transmission power (fixed or maximum value)
 - (opt.: WAVE Routing Announcement)

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



- WAVE service advertisement (WSA)
 - Provider Service Identifier (PSID) defined in IEEE Std 1609.3-2007

0x000 0000	system	0x000 000D	private
0x000 0001	automatic-fee-collection	0x000 000E	multi-purpose-payment
0x000 0002	freight-fleet-management	0x000 000F	dsrc-resource-manager
0x000 0003	public-transport	0x000 0010	after-theft-systems
0x000 0004	traffic-traveler-information	0x000 0011	cruise-assist-highway-system
0x000 0005	traffic-control	0x000 0012	multi-purpose-information system
0x000 0006	parking-management	0x000 0013	public-safety
0x000 0007	geographic-road-database	0x000 0014	vehicle-safety
0x000 0008	medium-range-preinformation	0x000 0015	general-purpose-internet-access
0x000 0009	man-machine-interface	0x000 0016	onboard diagnostics
0x000 000A	intersystem-interface	0x000 0017	security manager
0x000 000B	automatic-vehicle-identification	0x000 0018	signed WSA
0x000 000C	emergency-warning	0x000 0019	ACI

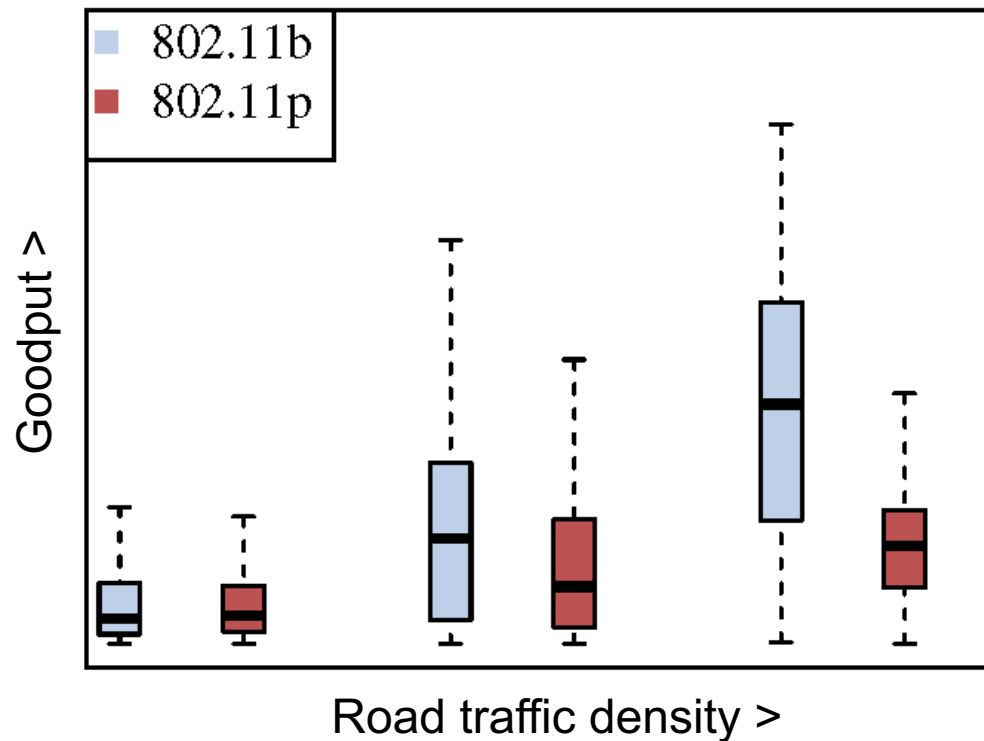


- WAVE Short Message (WSM)
 - Header (11 Byte)
 - Version (= 0)
 - Content type: plain, signed, encrypted
 - Channel number (max. 200)
 - Data rate
 - Transmission power
 - Provider Service Identifier (Service type, max. 0x7FFF FFFF)
 - Length (max. typ. 1400 Bytes)
 - Payload

- IP traffic (UDP/IPv6 or TCP/IPv6)
 - Header (40+n Byte)
 - Version
 - Traffic Class
 - Flow Label
 - Length
 - Next Header
 - Hop Limit
 - Source address, destination address
 - (opt.: Extension Headers)
 - Payload
 - No IPv6-Neighbor-Discovery (High overhead)
 - All OBUs listen to host multicast address, all RSUs listen to router multicast address

- 1) Goodput

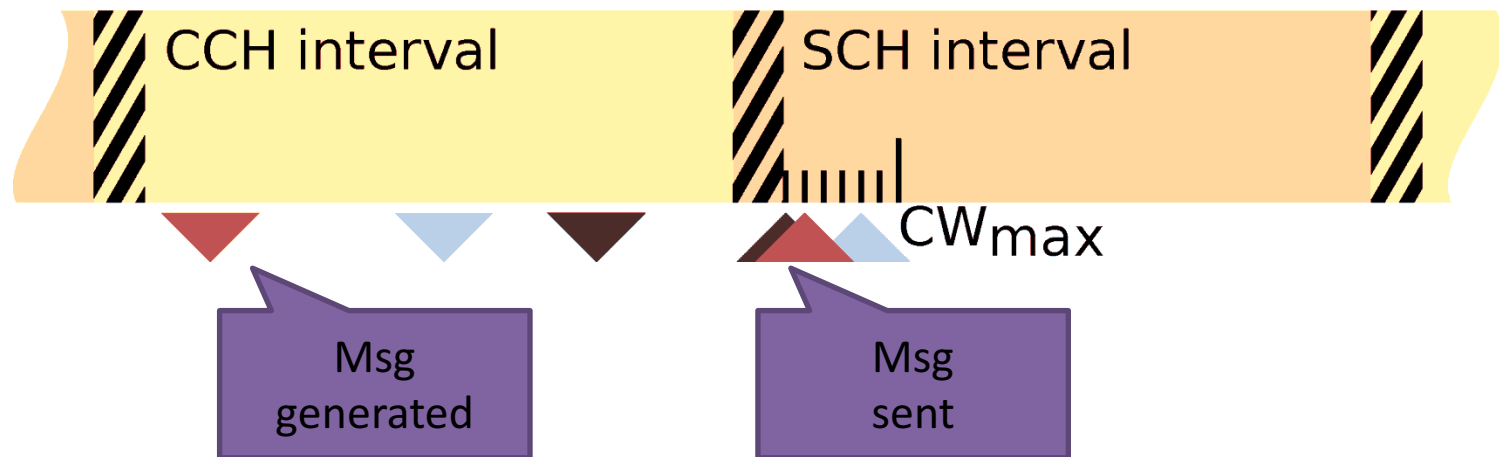
- User data must only be sent on SCH, i.e. during SCH interval
⇒ goodput cut in half



[1] David Eckhoff, Christoph Sommer and Falko Dressler, "On the Necessity of Accurate IEEE 802.11p Models for IVC Protocol Simulation," Proceedings of 75th IEEE Vehicular Technology Conference (VTC2012-Spring), Yokohama, Japan, May 2012.

- 2) Collisions

- Delay of data to next start of SCH interval
 - ⇒ increased frequency of channel accesses directly after switch
 - ⇒ increased collisions, packet loss



[1] David Eckhoff, Christoph Sommer and Falko Dressler, "On the Necessity of Accurate IEEE 802.11p Models for IVC Protocol Simulation," Proceedings of 75th IEEE Vehicular Technology Conference (VTC2012-Spring), Yokohama, Japan, May 2012.



PERFORMANCE EVALUATION

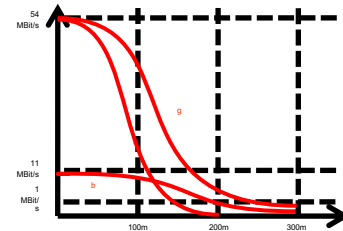
- Field Operational Tests

- + Highest degree of realism
- no in-depth investigations of network behavior
- Non-suppressible side effects
- Limited extrapolation from field operational tests



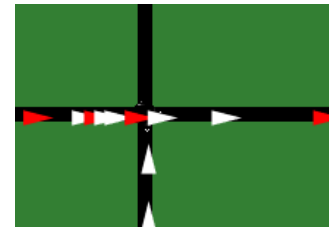
- Analytical evaluation

- + Closed-form description allows for far-reaching conclusions
- May need to oversimplify complex systems



- Simulation

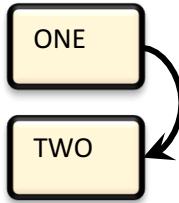
- Can serve as middle ground





- Models
 - Network protocol layers
 - Radio propagation
 - Node mobility
 - Model of approach to be investigated (e.g., flooding)
- Scenarios
 - Road geometry, traffic lights, meta information
 - Normal traffic pattern
 - Scenario of use case to be investigated (e.g., accident)
- Metrics
 - Network traffic metrics (delay, load, ...)
 - Road traffic metrics (travel time, stopping time, emissions, ...)
 - Metric of use case to be investigated (e.g., time until jam resolved)

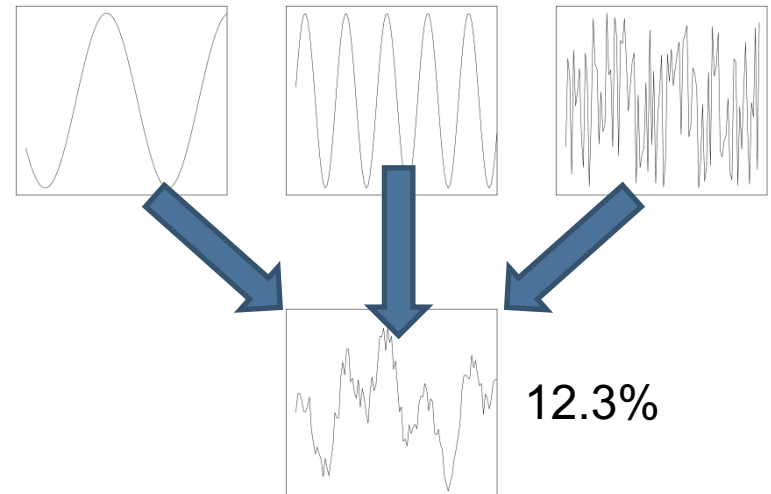
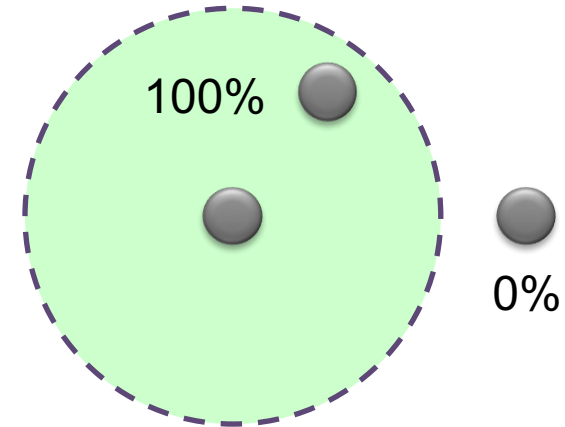
- Dedicated simulation tools
 - Discrete Event Simulation (DES) kernel
 - Manages queue of events (e.g., “an IP fragment was received”)
 - Delivers events to simulation models
- Model libraries
 - Simulate components’ reaction to events
 - E.g., HTTP server, TCP state machine, radio channel, human, ...
 - “when enough IP fragments received ⇨ tell TCP: packet received”



Engine	Language	Library	Language
OMNeT++	C++	MiXiM	C++
ns-2 / ns-3	C++	ns-2 / ns-3	Objective Tcl / Python
JiST	Java	SWANS	Java

- Simple model: unit disk
 - Fixed radio “range”
 - Node within range
⇔ packet received

- Enhanced models:
 - For each packet, consider
 - Signal strength
 - Interference (other radios)
 - Noise (e.g., thermal noise)
 - Calculate “signal to noise and interference ratio” (SNIR)
 - Derive packet error rate (PER)





- Signal attenuation
 - Received power depends on transmitted power, antenna gains, and path loss

$$P_r[\text{dBm}] = P_t[\text{dBm}] + G_t[\text{dB}] + G_r[\text{dB}] - \sum L_x[\text{dB}]$$

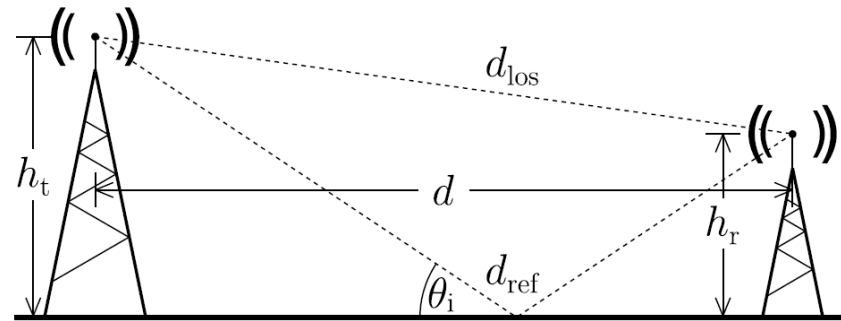
- Free space path loss

$$L_{\text{freespace}}[\text{dB}] = 20 \lg \left(4\pi \frac{d}{\lambda} \right)$$

- Empirical free space path loss

$$L_{\text{freespace,emp}}[\text{dB}] = 10 \lg \left(4\pi \frac{d}{\lambda} \right)^\alpha$$

- Two Ray Interference path loss



$$L_{\text{tri}}[\text{dB}] = 20 \lg \left(4\pi \frac{d}{\lambda} \left| 1 + \Gamma_{\perp} e^{i\varphi} \right|^{-1} \right), \text{ substituting}$$

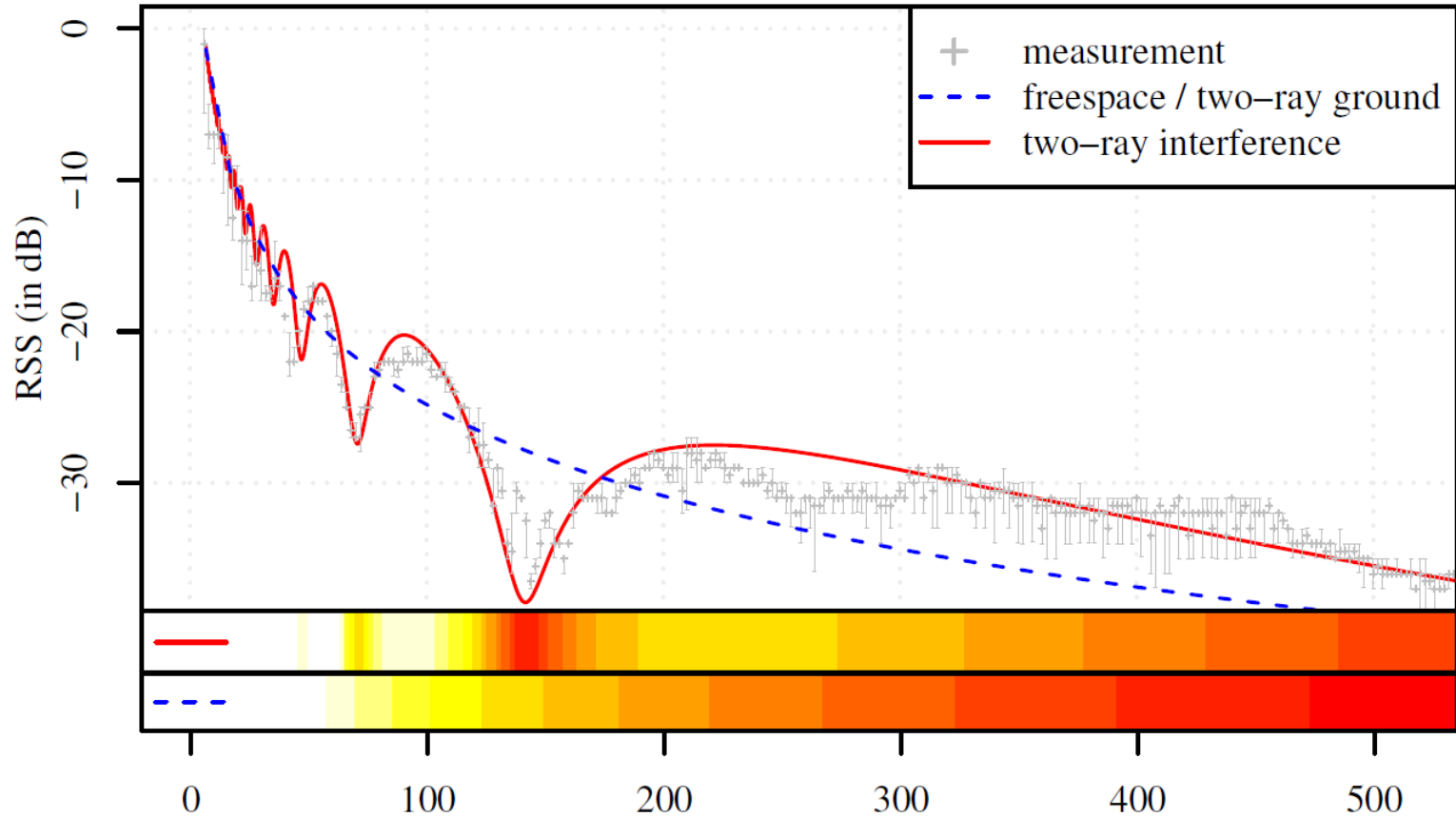
$$\varphi = 2\pi \frac{d_{\text{los}} - d_{\text{ref}}}{\lambda}, \quad \Gamma_{\perp} = \frac{\sin \theta_i - \sqrt{\epsilon_r - \cos^2 \theta_i}}{\sin \theta_i + \sqrt{\epsilon_r - \cos^2 \theta_i}},$$

$$d_{\text{los}} = \sqrt{d^2 + (h_t - h_r)^2}, \quad d_{\text{ref}} = \sqrt{d^2 + (h_t + h_r)^2},$$

$$\sin \theta_i = (h_t + h_r) / d_{\text{ref}}, \quad \cos \theta_i = d / d_{\text{ref}}.$$

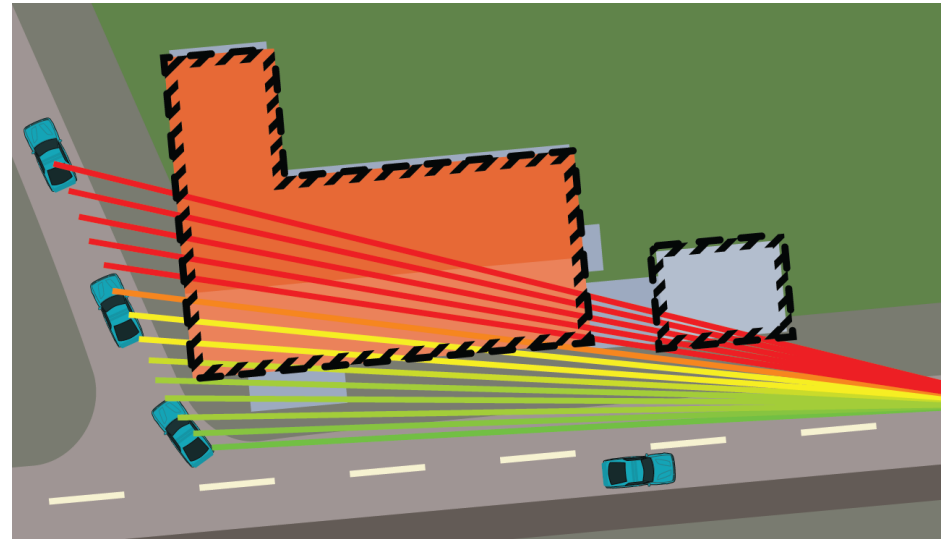


- Comparison: Two Ray Interference vs. Free Space

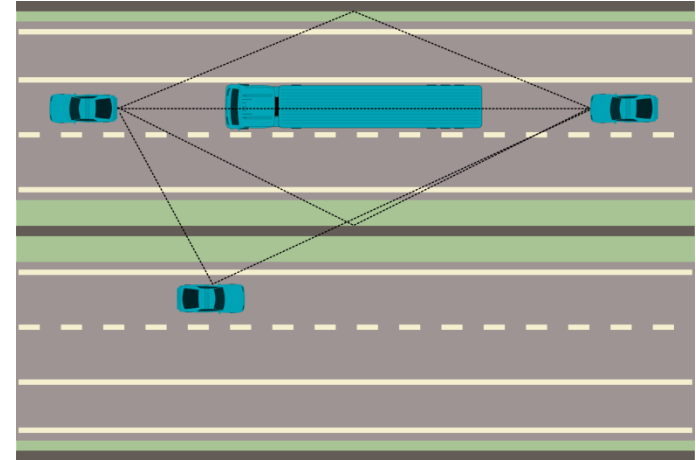


- Very(!) simple obstacle model
 - Take into account:
 - distance through matter,
 - number of walls

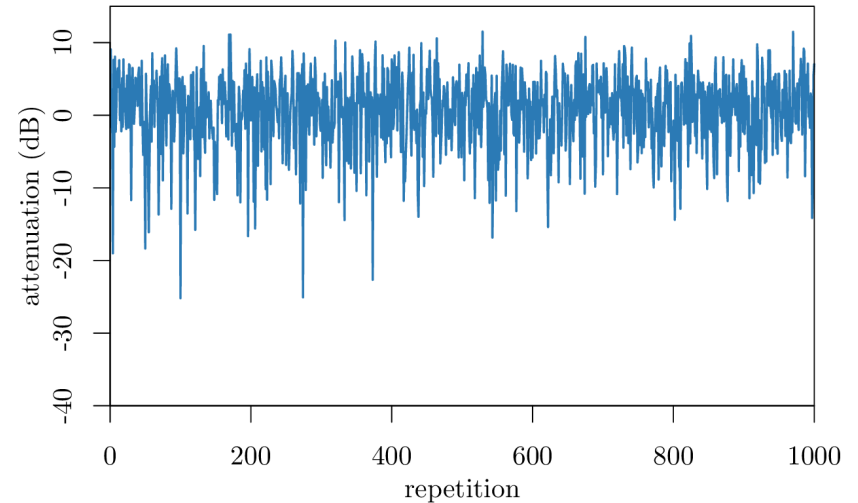
$$L_{\text{obs}}[\text{dB}] = \beta n + \gamma d_m$$



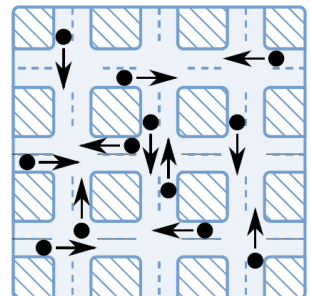
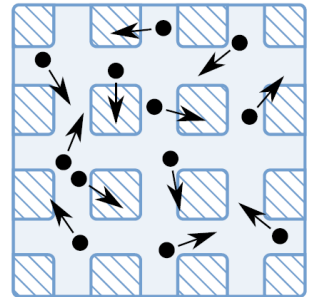
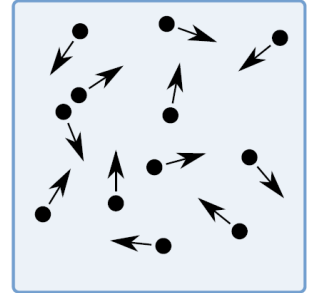
- Accounting for multi-path fading



- Example: Rayleigh samples



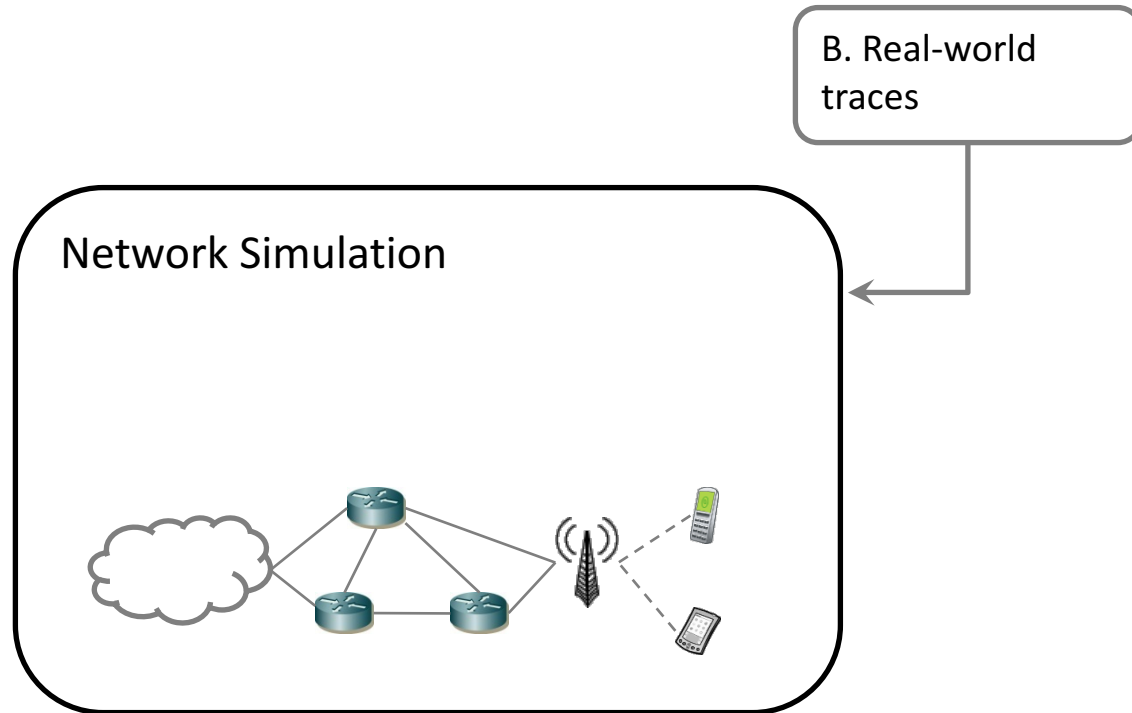
- Traditional approach in network simulation:
Random Waypoint (RWP)
 - „pick destination, move there, repeat“
- First adaptation to vehicular movement
 - Add mass, inertia
 - Add restriction to “roads”
 - Add angular restrictions
- Problem
 - Very unrealistic (longitudinal) mobility pattern



[1] 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

- First approach: Replay recorded trace data
 - Use GPS
 - Install in Taxi, Bus, ...
 - Highest degree of realism

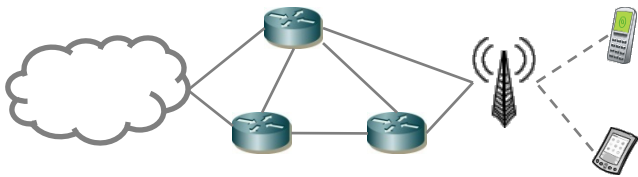
- Problems:
 - Invariant scenario
 - No extrapolation
 - To other vehicles (cars, trucks, ...)
 - To more vehicles
 - To fewer vehicles



- [1] 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
- [2] M. Fiore, J. Härri, F. Filali, and C. Bonnet, "Vehicular Mobility Simulation for VANETs," Proceedings of 40th Annual Simulation Symposium (ANSS 2007), March 2007, pp. 301-309
- [3] H-Y. Huang, P-E. Luo, M. Li, D. Li, X. Li, W. Shu, and M-Y. Wu, "Performance Evaluation of SUVnet With Real-Time Traffic Data," IEEE Transactions on Vehicular Technology, vol. 56 (6), pp. 3381-3396, November 2007

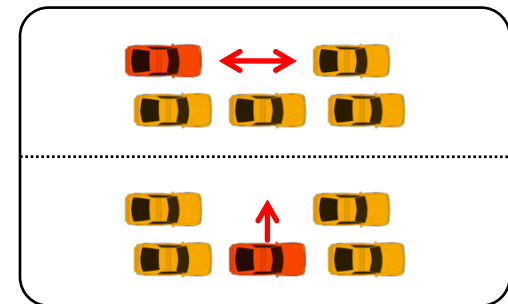
- Replay artificial trace data
 - Microsimulation of road traffic
 - Pre-computation or live simulation
 - Problem: how to investigate traffic information systems (TIS)?

Network Simulation



C. Micro-simulation

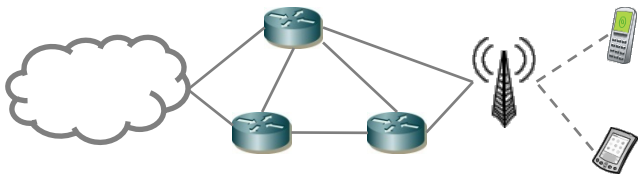
Road Traffic Simulation



- [1] 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
- [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

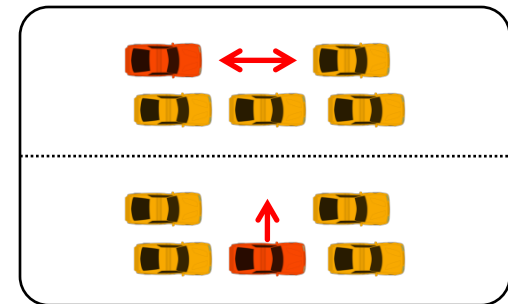
- Bidirectional coupling
 - Network traffic can influence road traffic

Network Simulation



D. Bidirect.
coupling

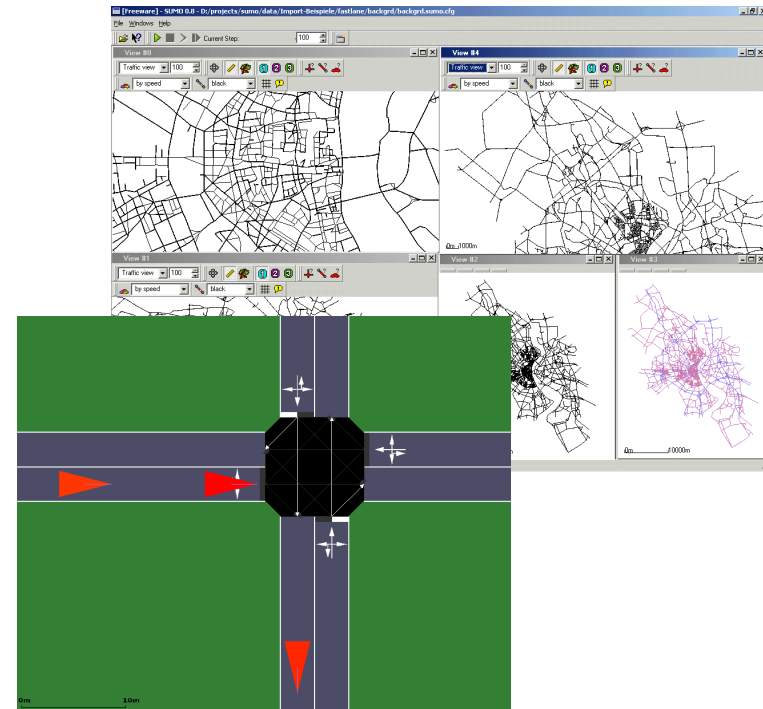
Road Traffic Simulation



[1] C. Sommer, Z. Yao, R. German, and F. Dressler, "On the Need for Bidirectional Coupling of Road Traffic Microsimulation and Network Simulation," Proceedings of 9th ACM International Symposium on Mobile Ad Hoc Networking and Computing (Mobihoc 2008): 1st ACM International Workshop on Mobility Models for Networking Research (MobilityModels 2008), Hong Kong, China, May 2008, pp. 41-48

[2] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," IEEE Transactions on Mobile Computing, 2010. (to appear)

- Road traffic microsimulation
 - Ex.: SUMO – Simulation of Urban Mobility
 - Time discrete microsimulation
 - Car following models (Krauss, IDM)
 - Lane change models
 - Road topology
 - Speed limits
 - Traffic lights
 - Access restrictions
 - Turn restrictions
 - ...



[1] D. Krajzewicz, G. Hertkorn, C. Rössel, and P. Wagner, "**SUMO (Simulation of Urban MOBility); An open-source traffic simulation,**" Proceedings of 4th Middle East Symposium on Simulation and Modelling (MESM2002), Sharjah, United Arab Emirates, September 2002, pp. 183-187



- Krauss car following model

- maximum velocity v_{\max} \Leftrightarrow safe gap g_{des} \Leftrightarrow dawdle factor epsilon

$$v_{\text{safe}} = v_l + \frac{g - g_{\text{des}}}{\tau_b + \tau}$$

$$v_{\text{des}} = \min \{ v_{\max}; v + a\Delta t; v_{\text{safe}} \}$$

$$v(t + \Delta t) = \max \{ 0; v_{\text{des}} - \eta \}$$

$$\eta = \text{rand} [0, \epsilon a]$$

- Intelligent Driver Model (IDM)

- Desired velocity v_0 \Leftrightarrow safe distance s^*

$$s^* = s_0 + s_1 \sqrt{\frac{v}{v_0}} + vT + \frac{v\Delta v}{2\sqrt{ab}}$$

$$\dot{v} = a \left(1 - \left(\frac{v}{v_0} \right)^\delta - \left(\frac{s^*}{s} \right)^2 \right)$$

[1] S. Krauss, P. Wagner, and C. Gawron, "Metastable states in a microscopic model of traffic flow," *Physical Review E*, vol. 55, pp. 5597–5602, May 1997.

[2] S. Krauss, "Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics," PhD Thesis, University of Cologne, 1998

[3] M. Treiber, A. Hennecke, and D. Helbing, "Congested Traffic States in Empirical Observations and Microscopic Simulations," *Physical Review E*, vol. 62, p. 1805, 2000



- Examples of coupled simulation frameworks
 - IDM/MOBIL \Rightarrow OMNeT++/INET [1]
 - VGSim: VISSIM traces \Rightarrow ns-2 [2]
- Examples of bidirectionally coupled frameworks
 - Veins: SUMO \Leftrightarrow OMNeT++/MiXiM [3]
 - TraNS: SUMO \Leftrightarrow ns-2 [4]
 - NCTUns (hand-made simulator) [5]
 - iTETRIS: SUMO \Leftrightarrow ns-3
 - VSimRTI: VISSIM \Leftrightarrow JiST/SWANS

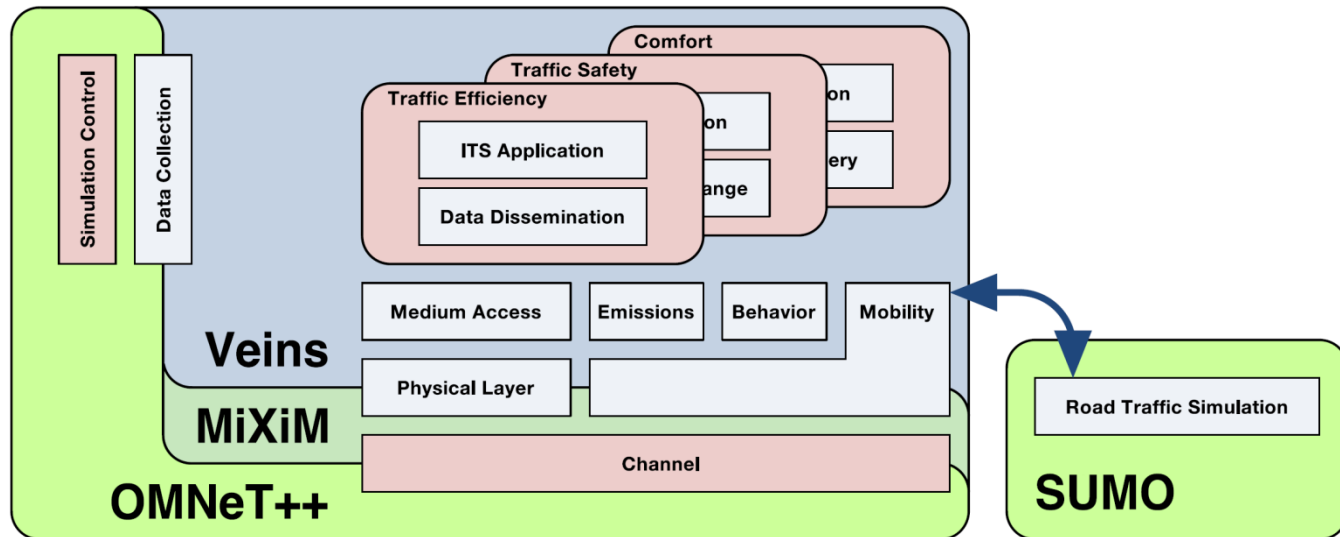
[1] C. Sommer, I. Dietrich, and F. Dressler, "**Realistic Simulation of Network Protocols in VANET Scenarios**," Proceedings of 26th IEEE Conference on Computer Communications (INFOCOM 2007): IEEE Workshop on Mobile Networking for Vehicular Environments (MOVE 2007), Poster Session, Anchorage, AK, May 2007, pp. 139-143

[2] B. Liu, B. Khorashadi, H. Du, D. Ghosal, C-N. Chuah, and M. Zhang, "**VGSim: An Integrated Networking and Microscopic Vehicular Mobility Simulation Platform**," IEEE Communications Magazine, vol. 47 (5), pp. 134-141, May 2009

[3] C. Sommer, R. German, and F. Dressler, "**Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis**," IEEE Transactions on Mobile Computing, 2010.

[4] M. Piorkowski, M. Raya, A. L. Lugo, P. Papadimitratos, M. Grossglauser, J.-P. Hubaux, "**TraNS: Joint Traffic and Network Simulator**," Proceedings of 13th ACM International Conference on Mobile Computing and Networking (ACM MobiCom 2007), Poster Session, Montreal, Canada, September 2007

[5] S. Y. Wang, C. L. Chou, Y. H. Chiu, Y. S. Tseng, M. S. Hsu, Y. W. Cheng, W. L. Liu, and T. W. Ho, "**NCTUns 4.0: An Integrated Simulation Platform for Vehicular Traffic, Communication, and Network Researches**," Proceedings of 1st IEEE International Symposium on Wireless Vehicular Communications (WiVec 2007), Baltimore, MD, October 2007



[1] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," IEEE Transactions on Mobile Computing, vol. 10, no. 1.

[2] C. Sommer, Z. Yao, R. German, and F. Dressler, "Simulating the Influence of IVC on Road Traffic using Bidirectionally Coupled Simulators," in 27th IEEE Conference on Computer Communications (INFOCOM 2008), Phoenix, AZ: IEEE, April 2008.

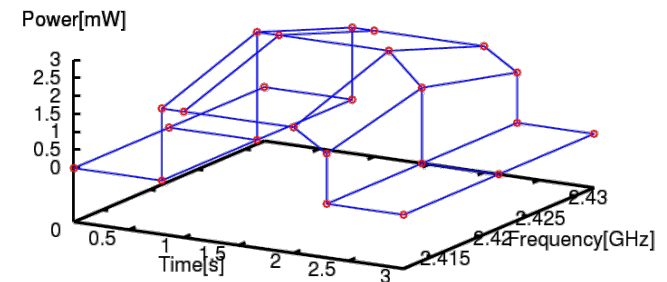
- OMNeT++

- Discrete-Event Simulation (DES) kernel
 - Simulate model's reaction to queue of events
- Main use case: network simulation
 - e.g., MANETs, Sensor nodes



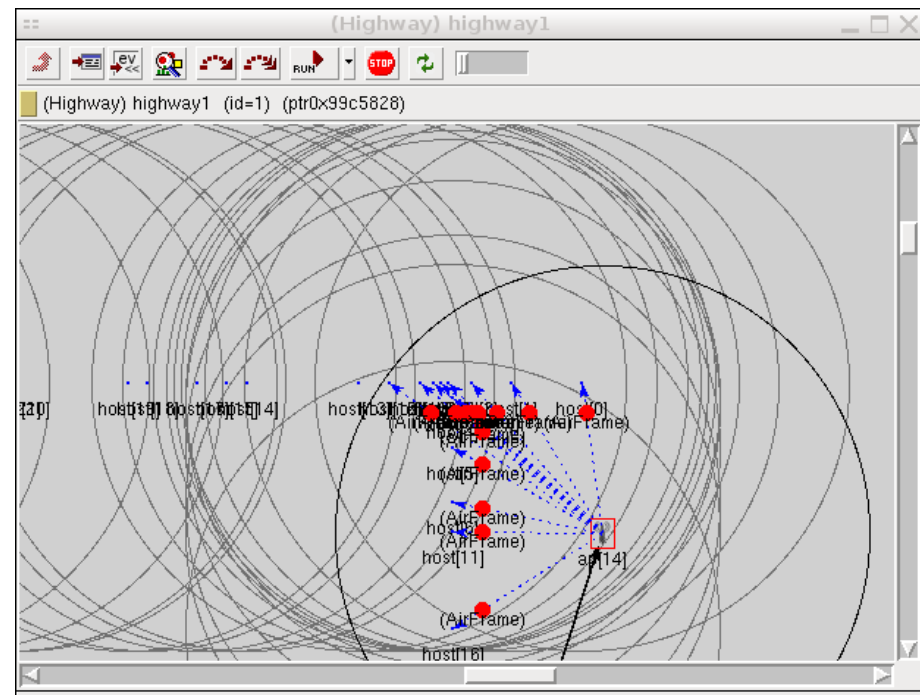
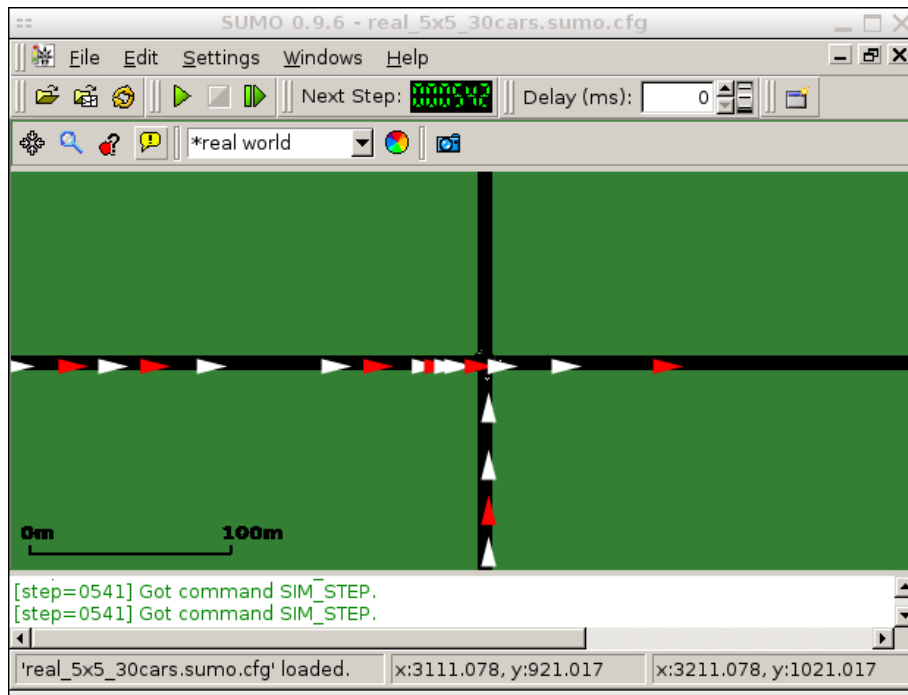
- MiXiM

- Model library for OMNeT++ for PHY layer and mobility support
- Event scheduling
- Signal propagation
- SINR / bit error calculation
- Radio switching
- ...

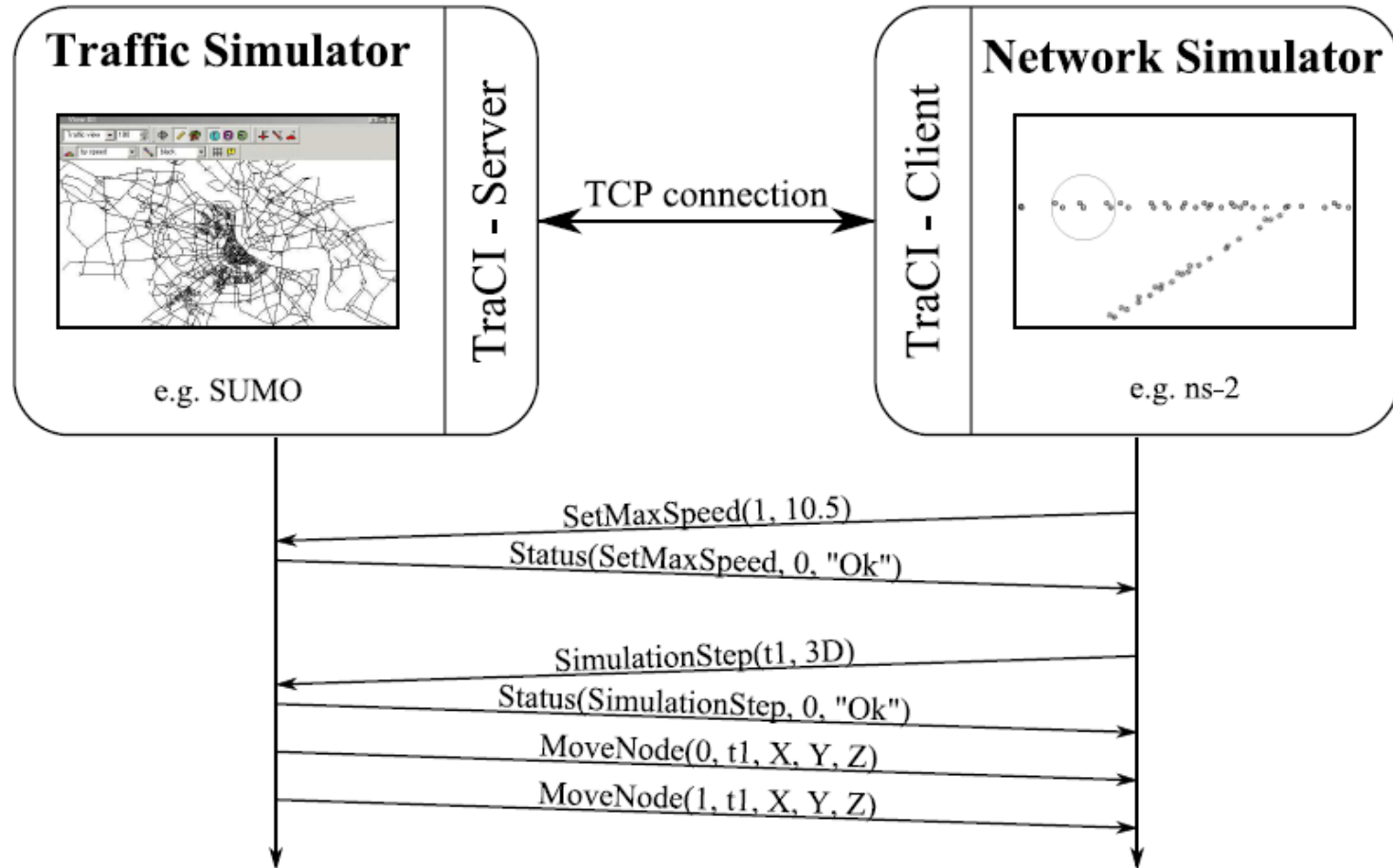


[1] A. Varga, "The OMNeT++ Discrete Event Simulation System," Proceedings of European Simulation Multiconference (ESM 2001), Prague, Czech Republic, June 2001

- Coupling OMNeT++ and SUMO
 - Synchronize time steps
 - Exchange commands and status information

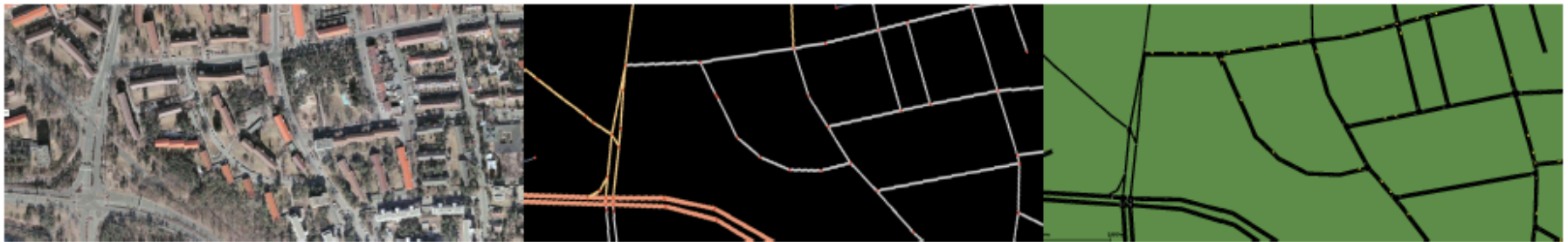
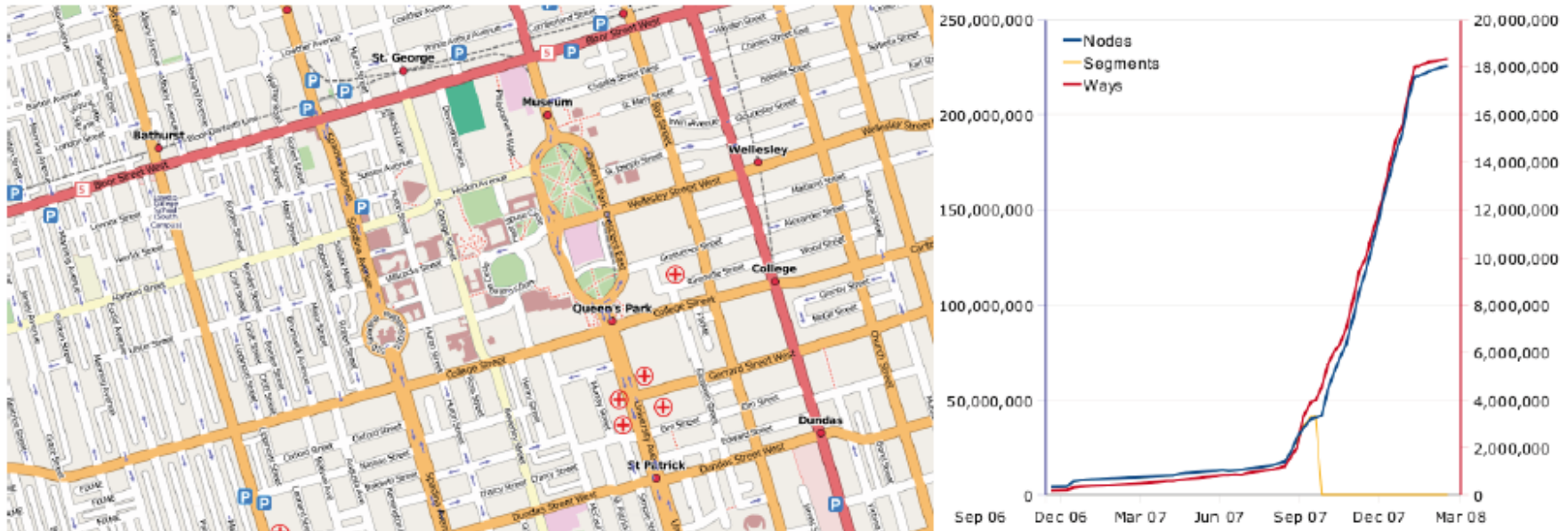


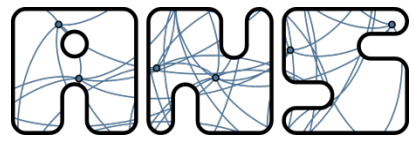
- TraCI: Message Sequence Chart





- Freely available road topology information
 - Geodatabase of OpenStreetMap project





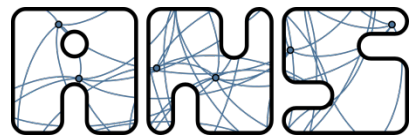
WHAT WE'RE WORKING ON



- Aims of platooning:
 - solve traffic congestion problems
 - decrease pollution
 - increase safety
 - decrease severe injuries/deaths
 - avoid wasting driving time



Illustrations: PATH and SARTRE projects

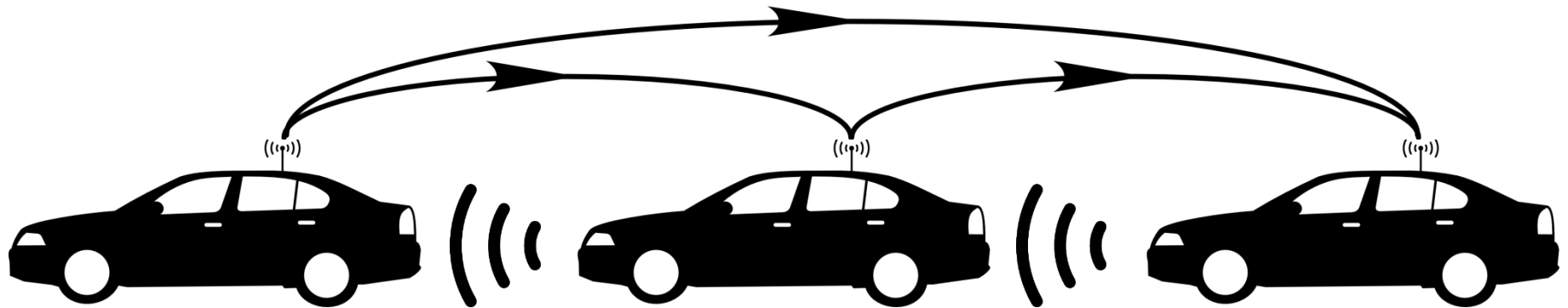


Time for another Video!
Volvo SARTRE Project

- ACC – Radar based: distance $d = T * v$ with $T > 1s$



- CACC – Radar + IVC: distance $d = d_{des}$ (fixed)





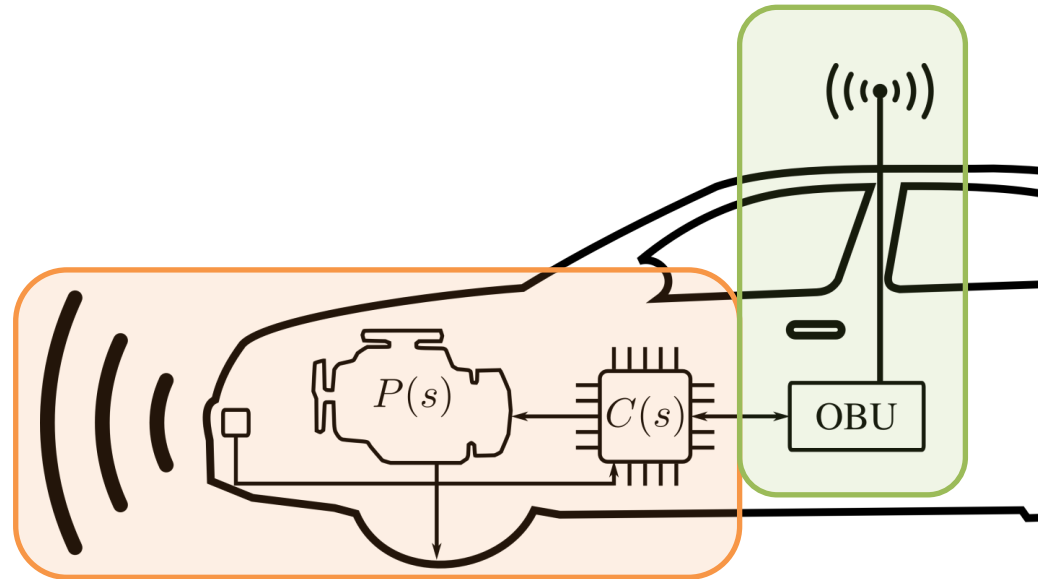
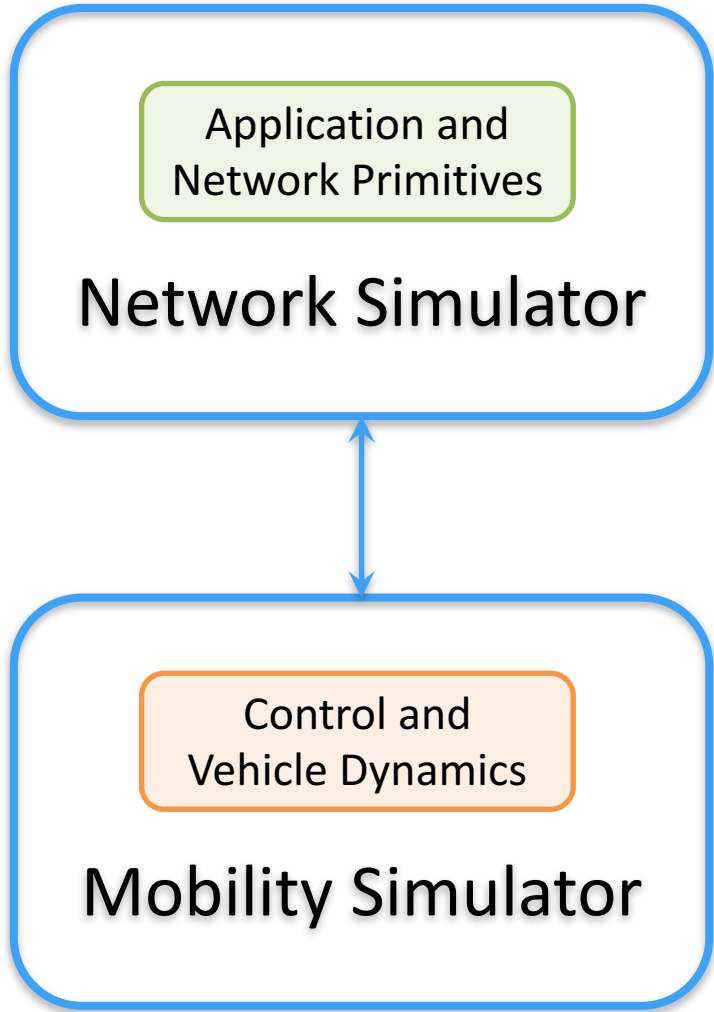
- What happens if... ?
 - can an 802.11p-based network support platooning?
 - can we design a communication protocol that can cope with such situations?





- Extends Veins (OMNeT++ and SUMO)
- Detailed 802.11p model + detailed controller/vehicle dynamics
 - Channel, PHY, and MAC models
 - Different CACCs available
 - Detailed engine model with torque modeling, gears, aerodynamics, ...
- Networking and control studies possible, easily extensible
- Co-existence of human-driven and automated vehicles
 - wait a few slides
- Open source, available for download at

<http://plexe.car2x.org>





Let's take a ride

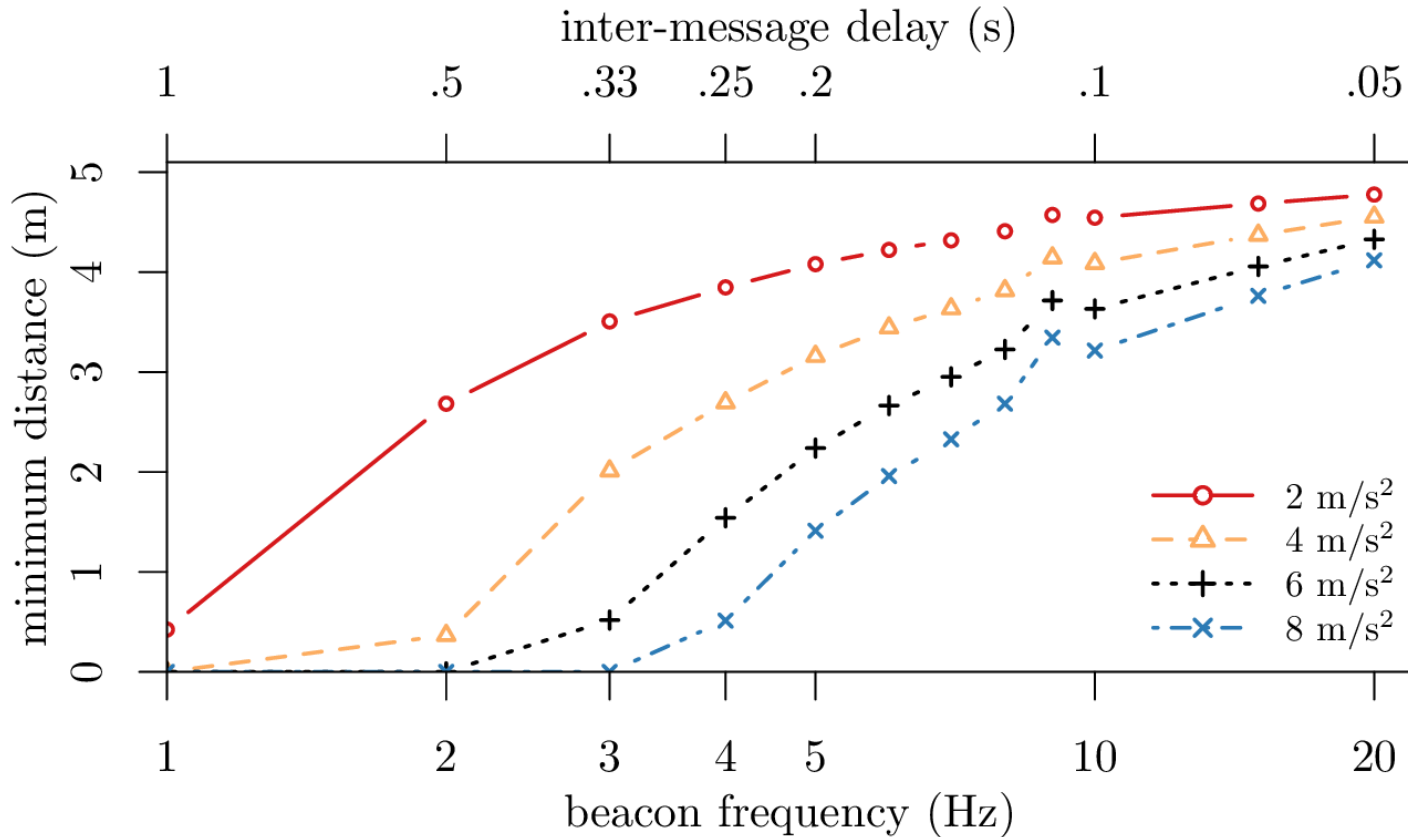
Plexe engine model in action



Demo: Join Maneuver

Demo video

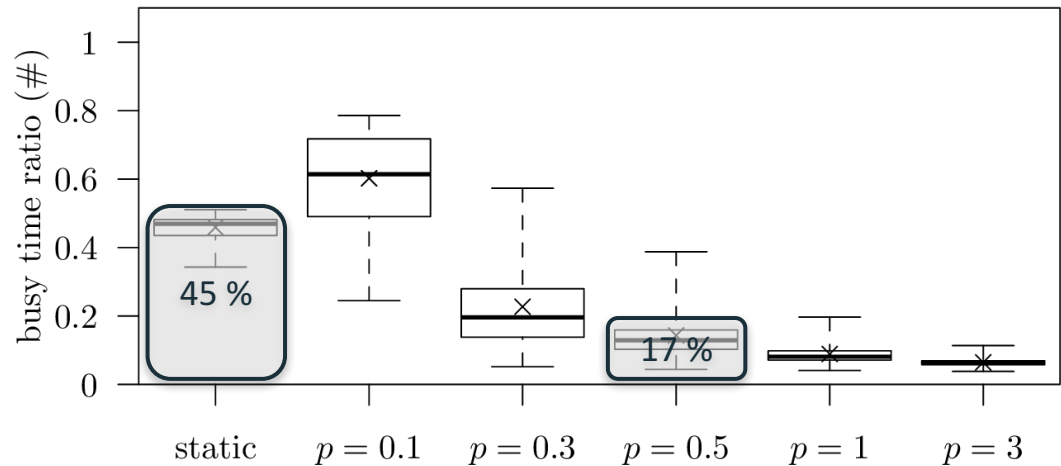
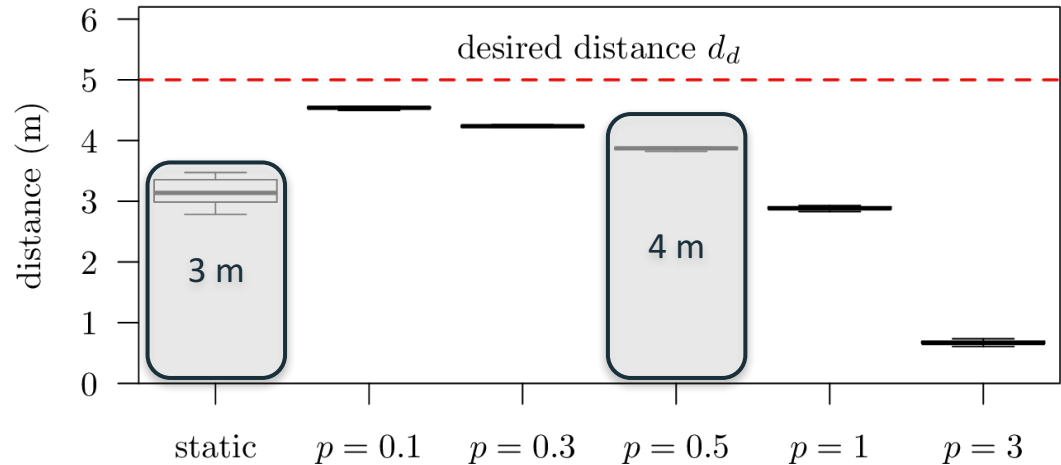
Join at middle maneuver





640 cars

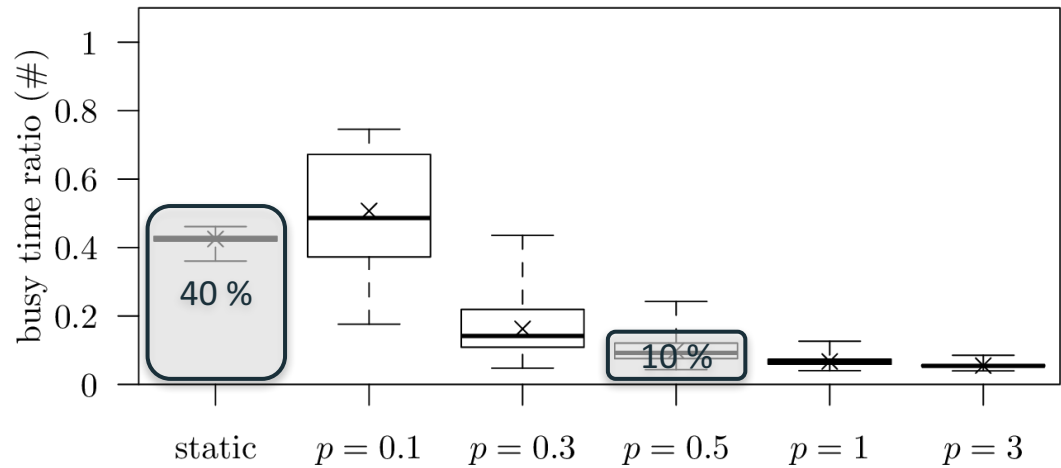
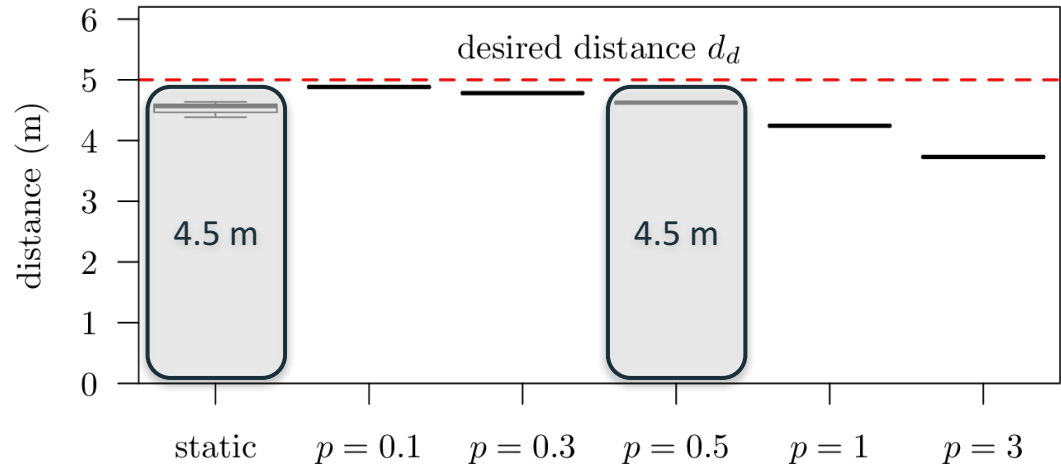
severe decelerations





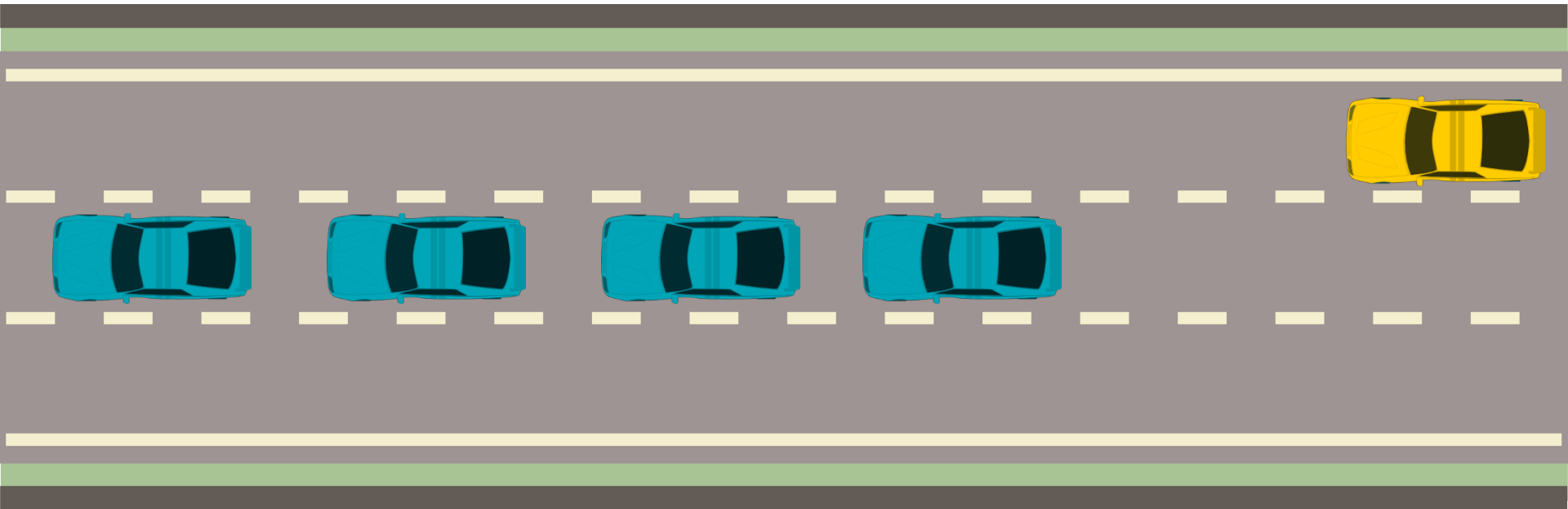
640 cars

mild decelerations



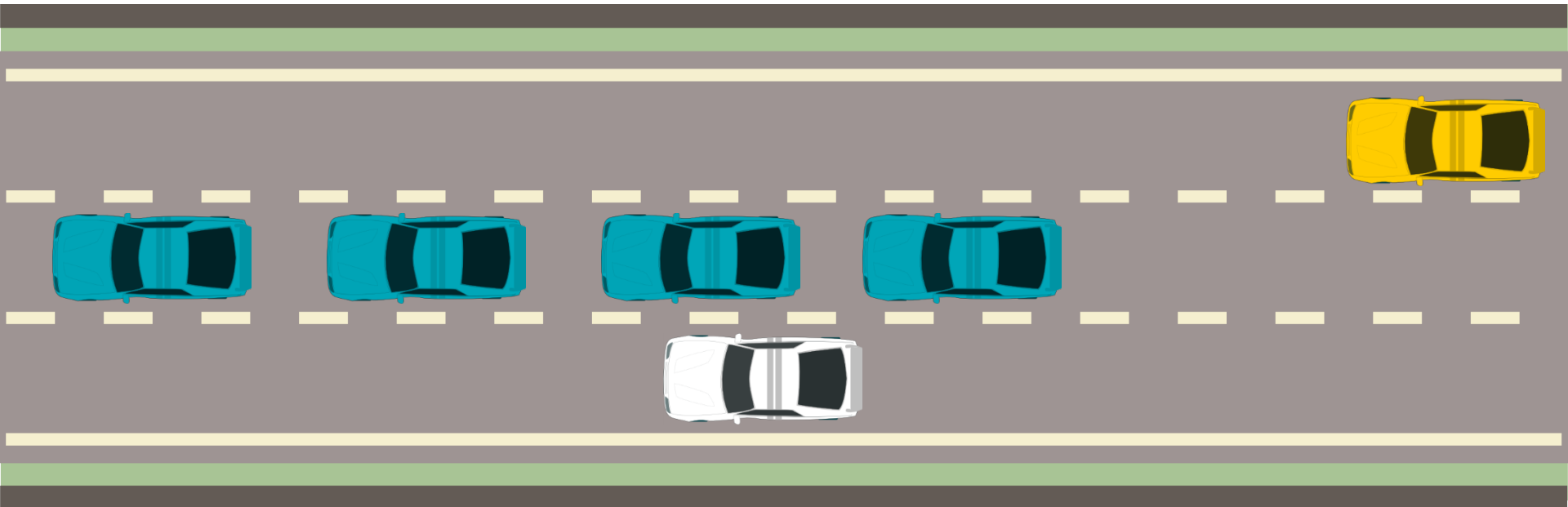


- Join-at-middle:

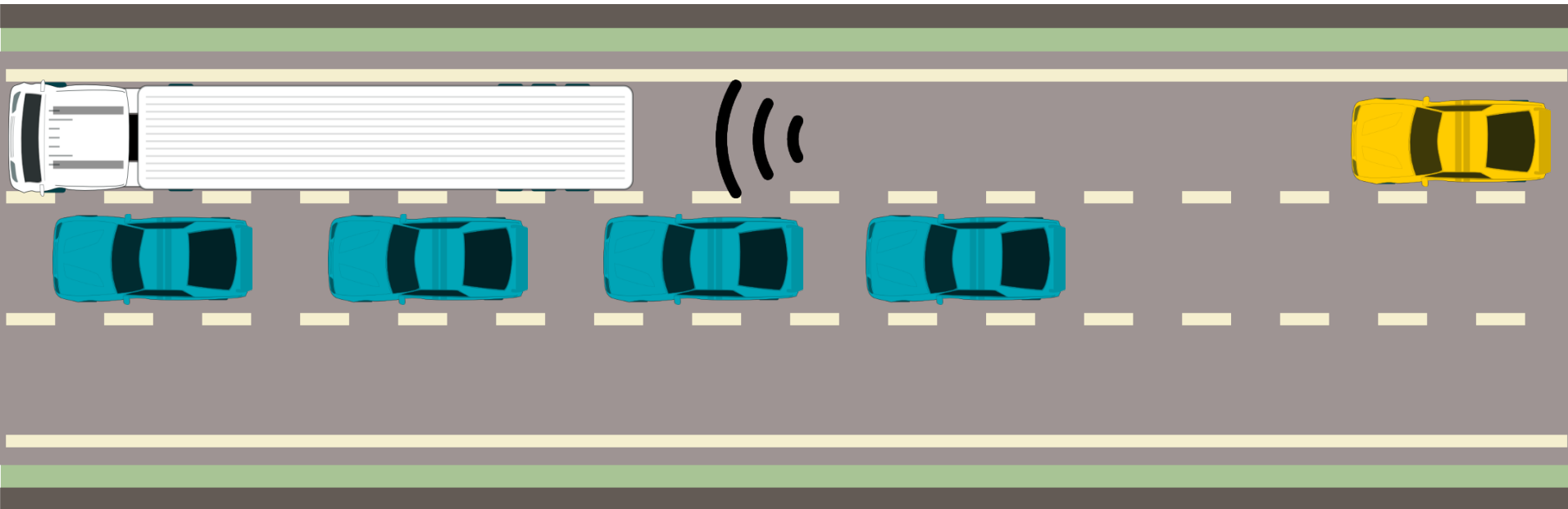




- Join-at-middle: human-driven car interference



- Join-at-middle: slow vehicle interference





MASTER THESIS

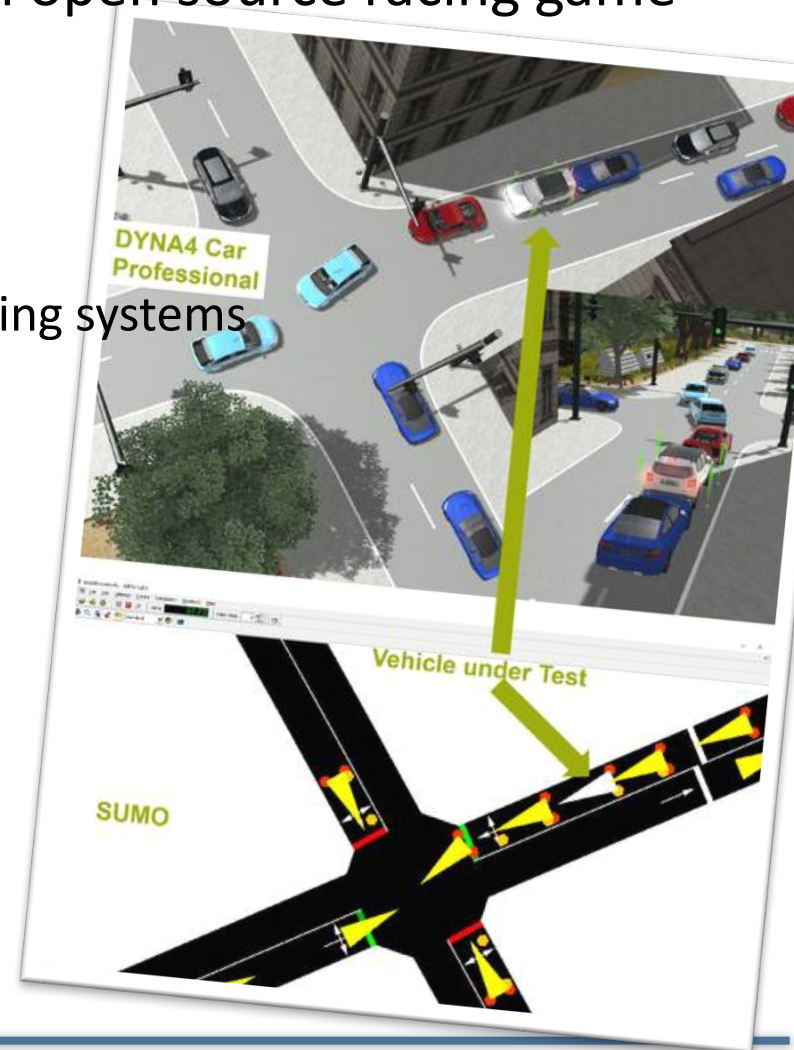
- Development of PHY models
 - speed-up network simulation by using a stochastic PHY model
 - use a “simplified” description of the NIC status
- MAC protocols for clustering-based vehicular applications
 - platooning is one particular application
 - development of a distributed EDCA bursting mechanism
 - reduce wasted overhead time
- Protocol development
 - maneuver management (see next)



- Development of organizational strategies
 - cooperation w/ University of Mannheim
 - Plexe communicates with an external unity (Fesas)
 - Fesas takes care of the organizational part of platooning
 - Plexe should “execute” the commands
- Emergency procedures
 - what to do if something goes wrong?
 - tightly correlated to protocol design
- Revenue schemes???
- related to first proposal
- Privacy???



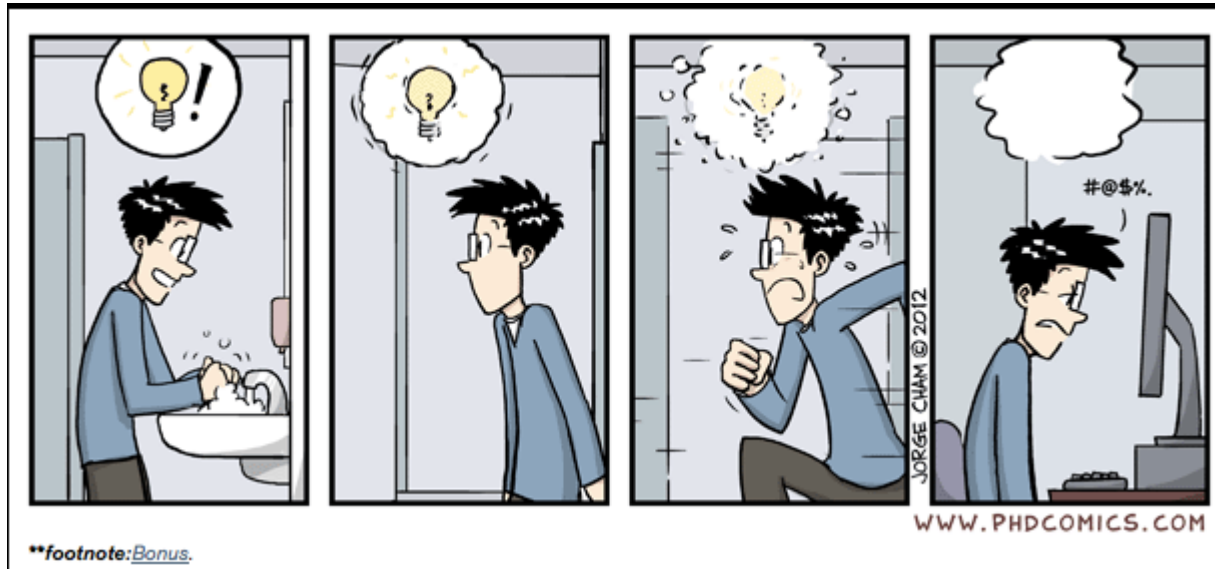
- Implementation of control algorithm in open source racing game
 - coupling with Plexe
 - use cases: training, HCI
- Implementation of drag aerodynamics
 - fundamental for the evaluation of platooning systems
 - estimating fuel savings
- Interface improvements





- Urban safety applications
 - safety of vulnerable road users
 - pedestrian
 - cyclists
 - intersection collision avoidance
 - more possible

- Your ideas are welcome!





Thank you
Any question?