Vehicular Networks [C2X]

Introduction Seminar for Nomadic Communications

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with special thanks to
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Stefan Joerer, University of Innsbruck
David Eckhoff, University of Erlangen

Motivation

Illustrations: C2C-CC

Illustration: AKTIV

Motivation

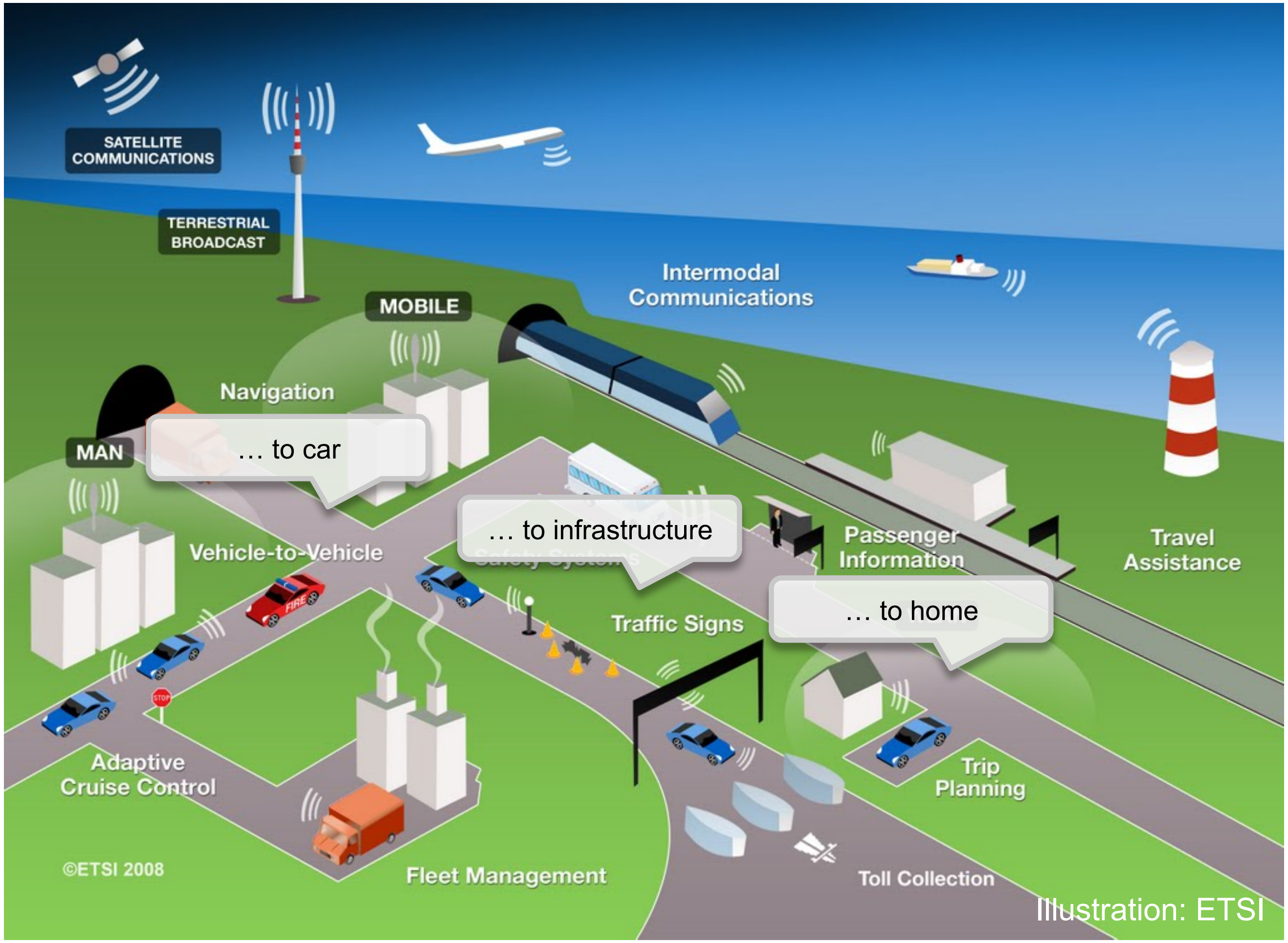
- Car-to-X (C2X) communication patterns

Vehicle-to-X (V2X),

Inter-Vehicle Communication (IVC),

Vehicular ad-hoc network (VANET),

…



Motivation

Time for a Video!

Audi Travolution

Motivation

- Taxonomy of Use Cases

- Vehicle-to-X
  - Non-Safety
    - Comfort
      - Contextual Information
      - Entertainment
    - Traffic Information Systems
      - Optimal Speed Advisory
      - Congestion, Accident Information
  - Safety
    - Situation Awareness
      - Adaptive Cruise Control
      - Blind Spot Warning
    - Warning Messages
      - Traffic Light Violation
      - Electronic Brake Light

Motivation

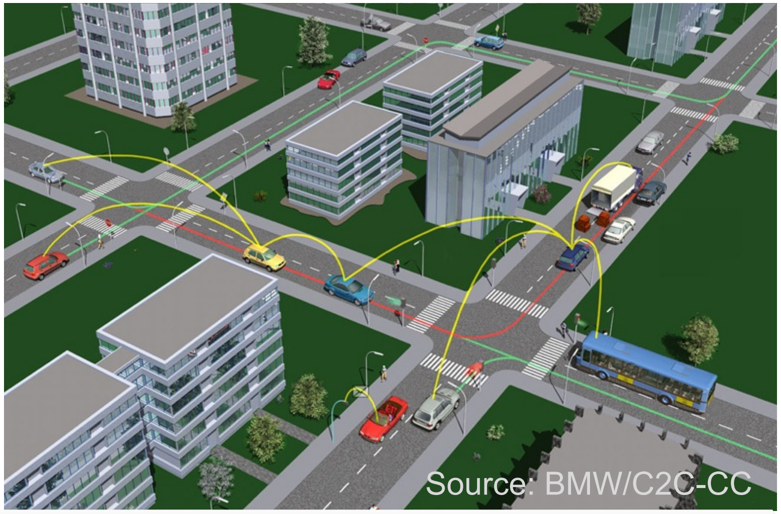
- Taxonomy of Use Cases

Vehicle-to-X	
Non-Safety	Safety
▪ Many messages ▪ High data rate ▪ Low latency demands ▪ Low reliability demands ▪ Long range	▪ Few messages ▪ Small packet size ▪ High latency demands ▪ High reliability demands ▪ Short range

Motivation

- Freeway ⇔ Urban

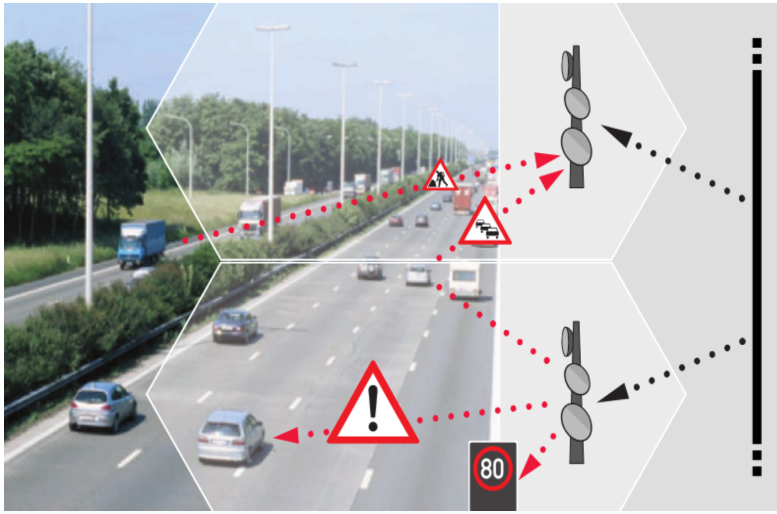
- 1D mobility
- Bimodal connectivity
  - Stable connection (➔➔)
  - ⋀ Unstable connection (🡠🡠)
- High speed
- …



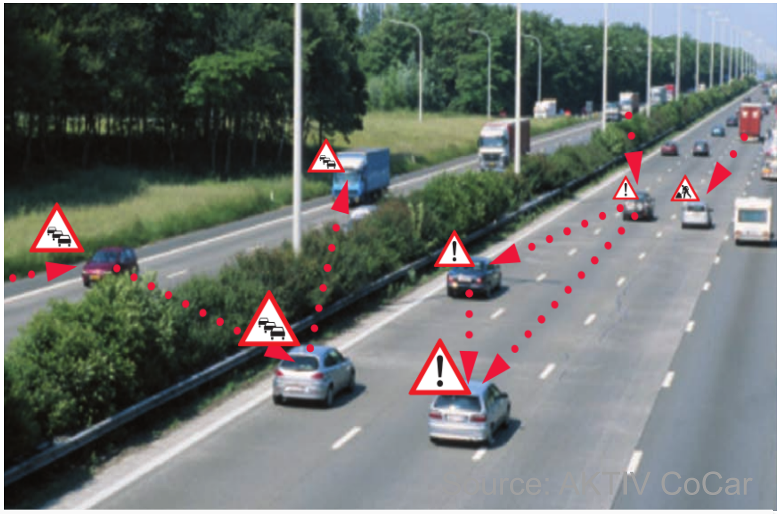
- 2D mobility
- Bipolar connectivity
  - Many neighbors (standing)
  - ⋁ Few neighbors (driving)
- Obstacles
- …

Motivation

- Infrastructure ⇔ 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
- …

Motivation

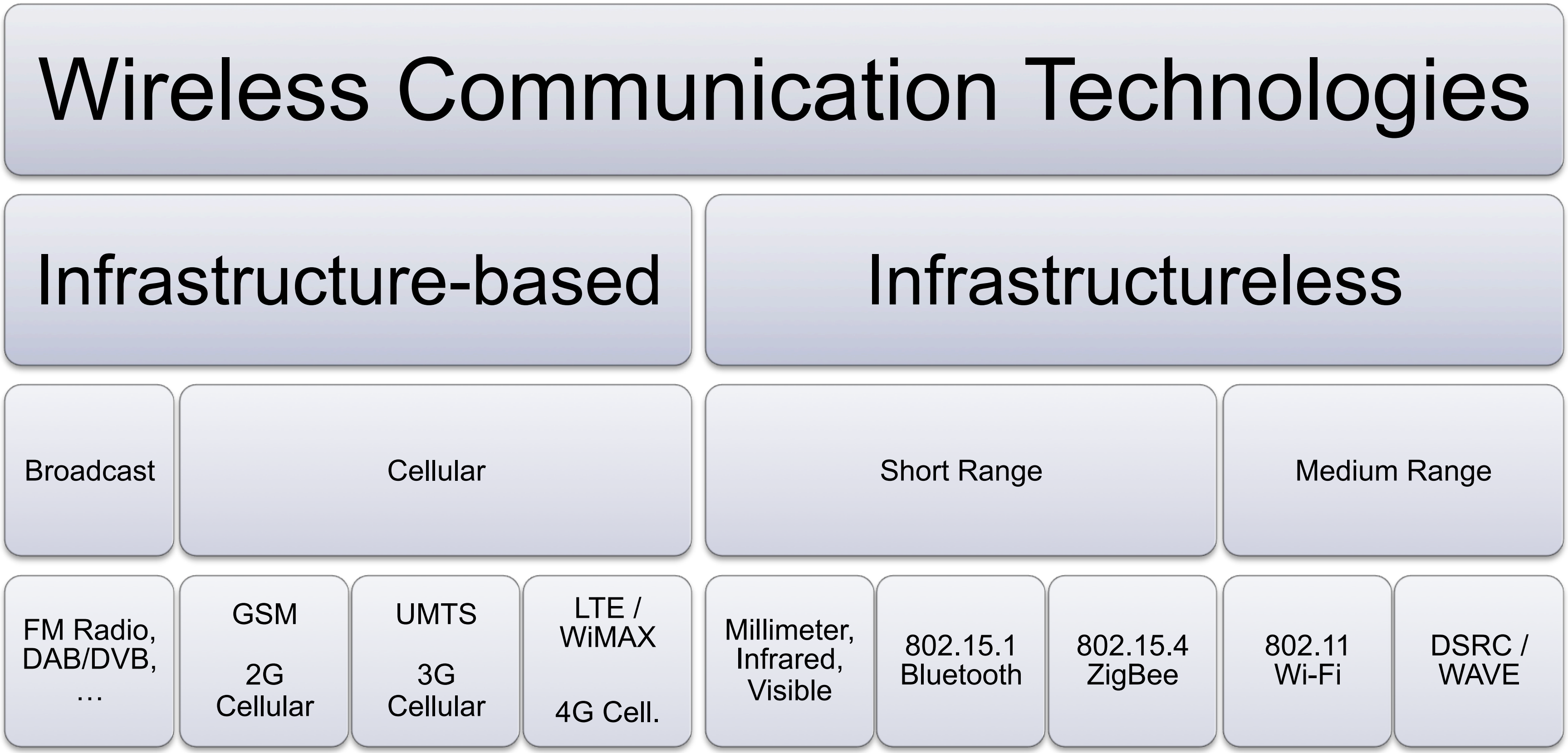
- Challenges of C2X communication

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

Technology

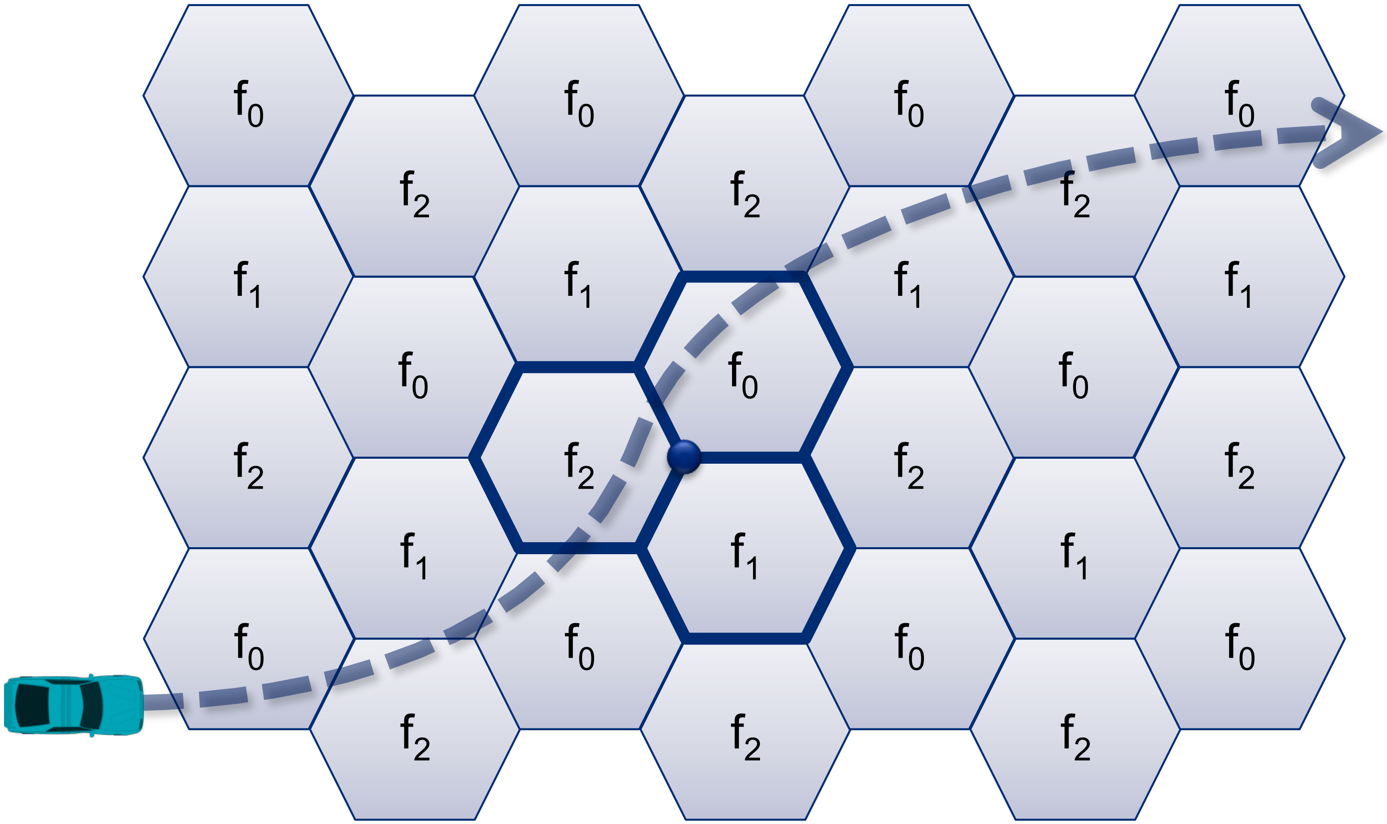
- Communication paradigms and media



[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

Cellular Networks

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



Cellular Networks

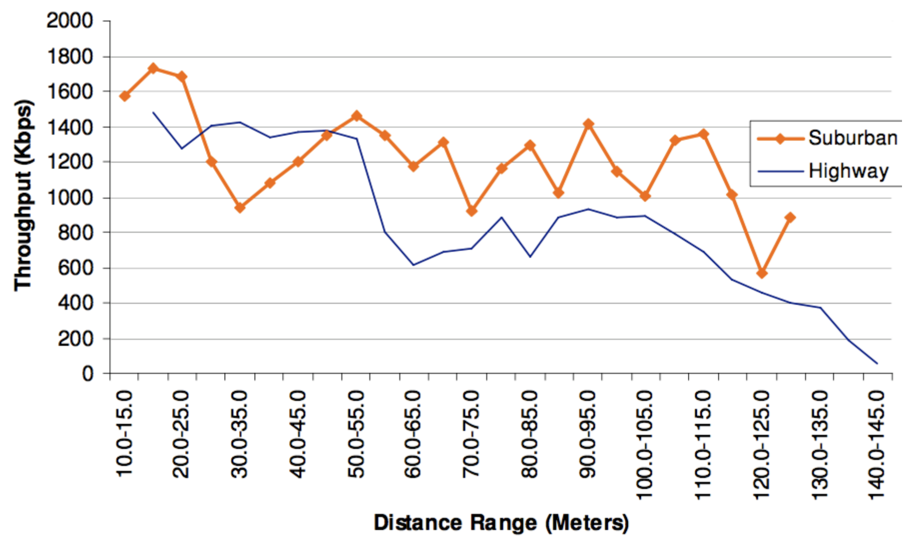
- Can UMTS support Car-to-X communication?
  - Ex: UTRA FDD Release 99 (W-CDMA)
  - Speed of vehicles not a limiting factor
    - Field operational tests at 290 km/h show signal drops only after sudden braking ($\Longrightarrow$ handover prediction failures)
  - Open questions
    - Delay
    - Capacity
- 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

Cellular Networks

- 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 ($\Longrightarrow$ ideal for cellular networks)

IEEE 802.11p

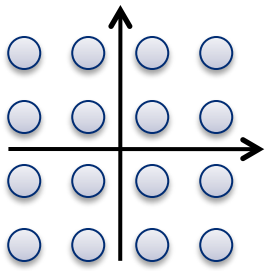
- IEEE 802.11{a,b,g,n} for Car-to-X communication?
  - Can't be in infrastructure mode and ad hoc mode at the same time
  - Switching time consuming
  - Association time consuming
  - (Massively) shared spectrum (⇒ ISM)
  - Multi-path effects reduce range and speed



[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

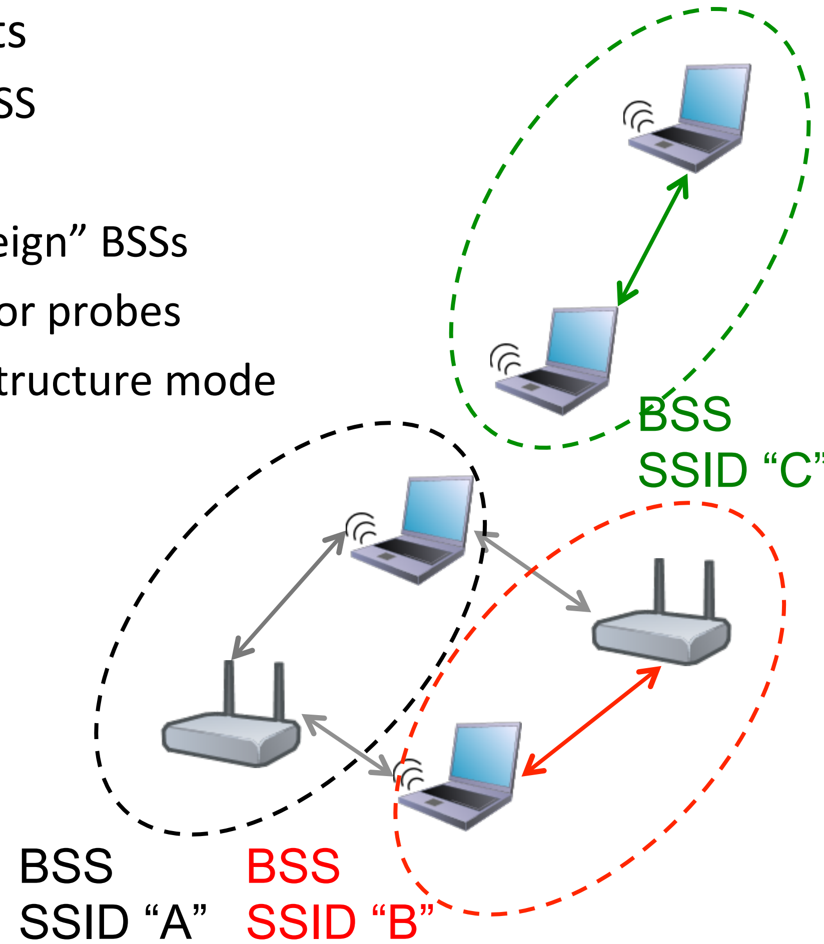
IEEE 802.11p

- 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
    - ...



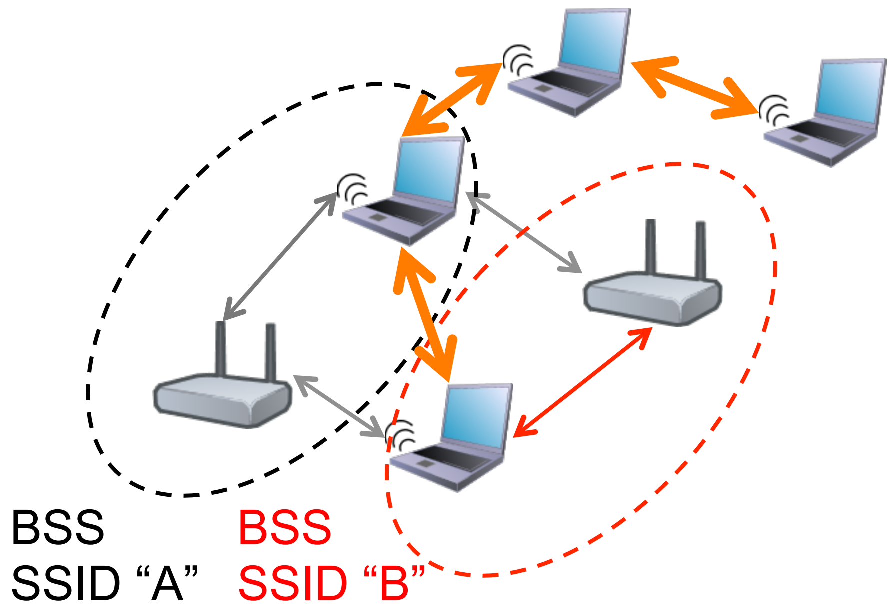
IEEE 802.11p

- 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



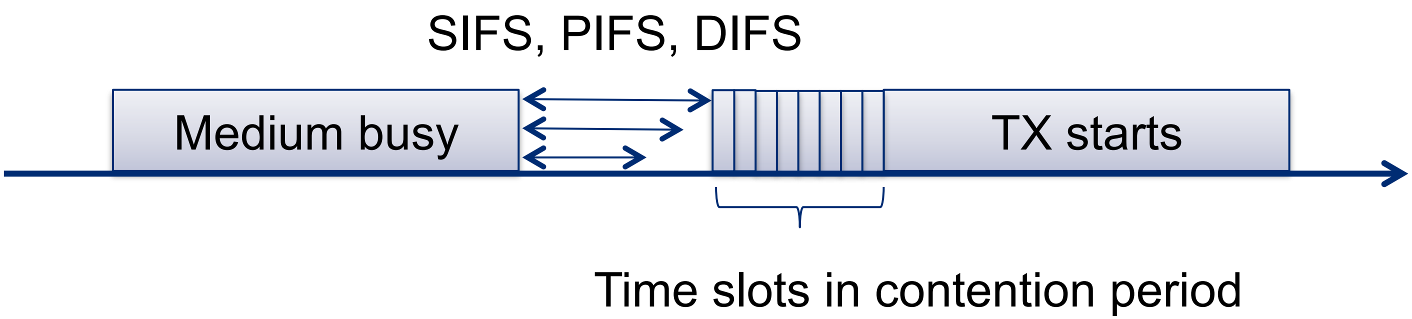
IEEE 802.11p

- 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 802.11p

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



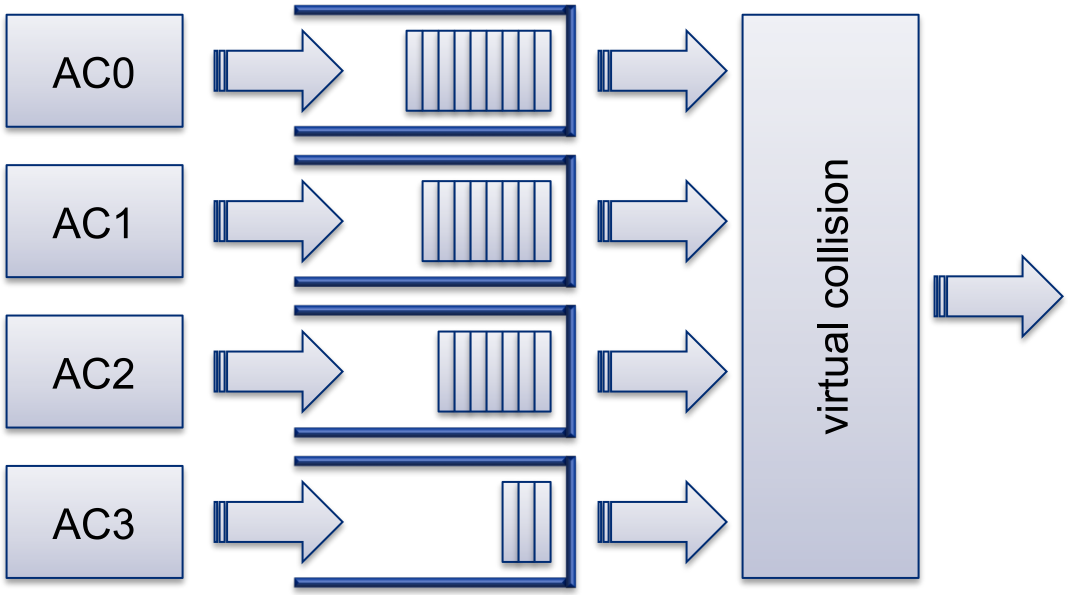
  - Priority access via SIFS (ACK, CTS, ...) and DIFS (payload)
  - Wait until medium has been free for duration of DIFS
  - If medium busy, wait until idle, then wait DIFS
    plus random backoff time
  - Cannot prioritize DATA frames

IEEE 802.11p

- QoS in 802.11p (HCF)
  - cf. IEEE 802.11e EDCA
  - DIFS ⟹ AIFS (Arbitration Inter-Frame Space)
    - DCF ⟹ 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)

IEEE 802.11p

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



IEEE 802.11p

- QoS in 802.11p (HCF)
  - Parameterization

Parameter	Value
SlotTime	13µs
SIFS	32µs
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

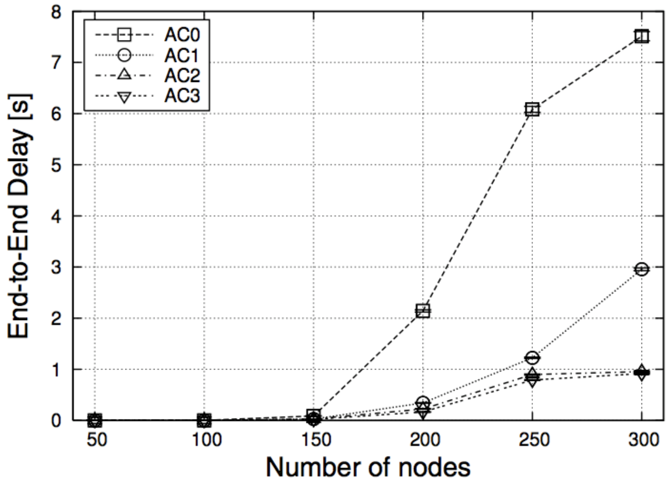
IEEE 802.11p

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

    (and TXOP Limit=0
    ⟹ single packet)

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

  - when channel idle:
  - when channel busy:



[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

UMTS/LTE vs. 802.11p

- 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

UMTS/LTE vs. IEEE 802.11p

- 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

Higher Layer Standards for IEEE 802.11p

- 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

Higher Layer Standards for IEEE 802.11p

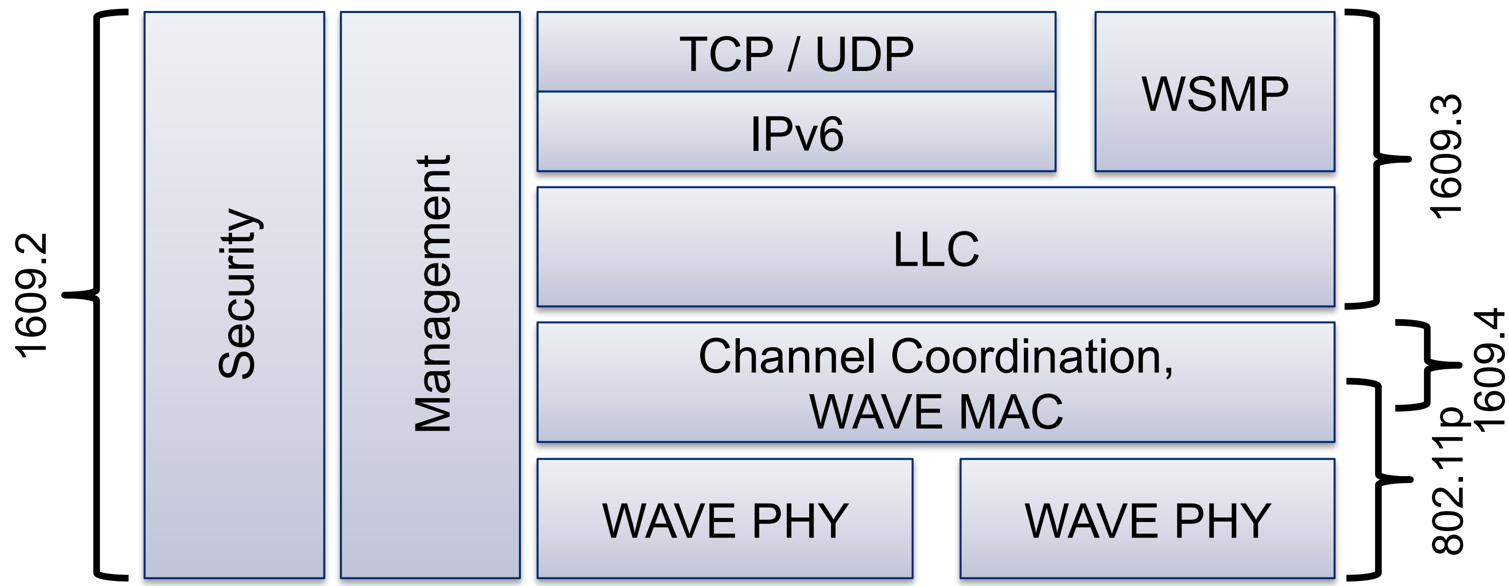
- Need for higher layer standards
  - Unified message format
  - Unified interfaces to application layer

- U.S.
  - IEEE 1609.*
  - WAVE („Wireless Access in Vehicular Environments“)

- Europe
  - ETSI
  - ITS G5 (“Intelligent Transportation Systems”)

IEEE 1609

- 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.

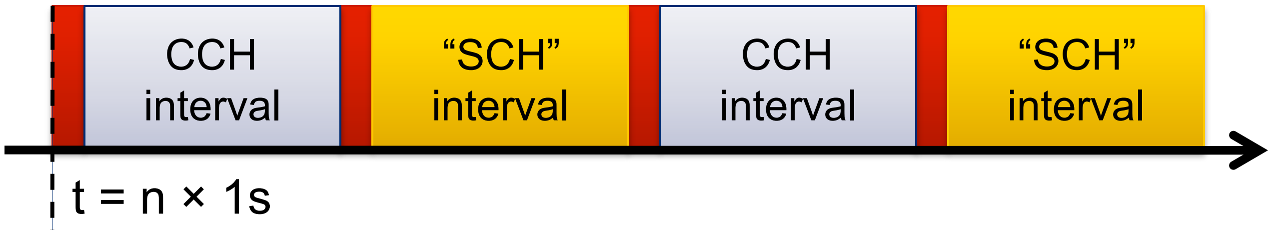


[1] Jiang, D. and Delgrossi, L., "**IEEE 802.11p: Towards an international standard for wireless access in vehicular environments**," Proceedings of 67th IEEE Vehicular Technology Conference (VTC2008-Spring), Marina Bay, Singapore, May 2008

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

IEEE 1609

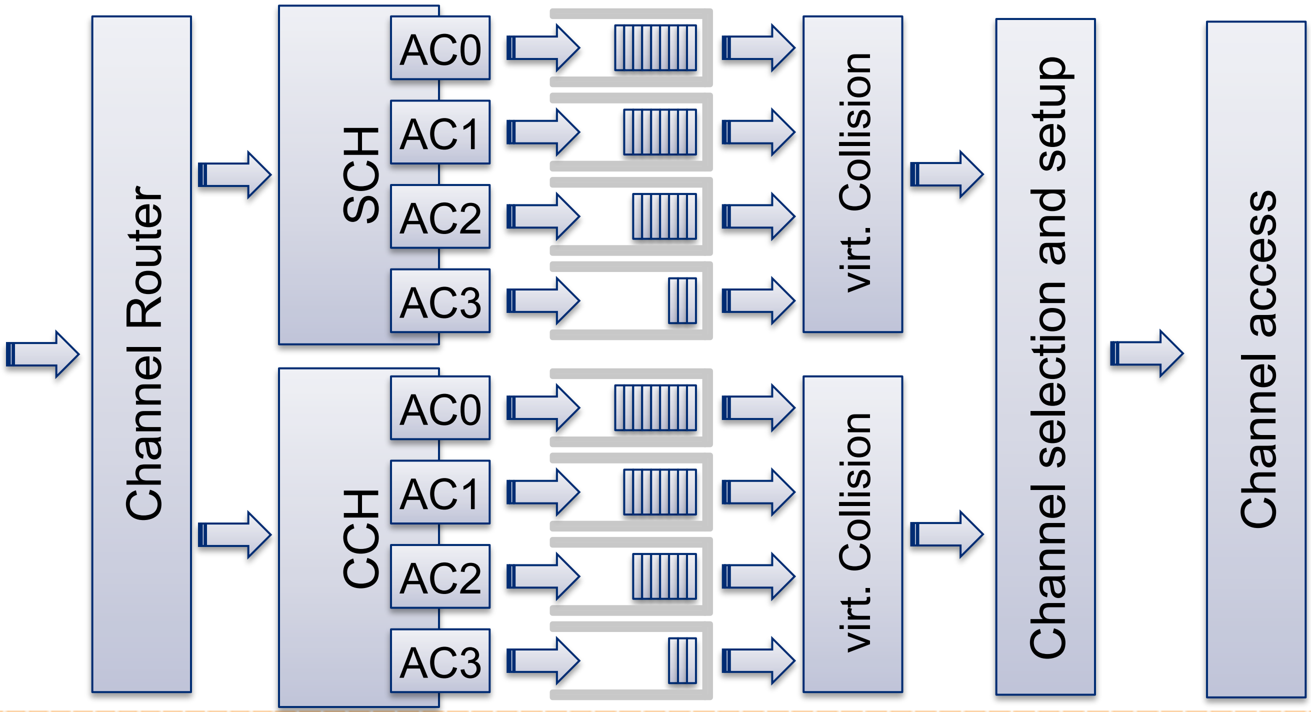
- Channel management
  - WAVE allows for both single radio devices & multi radio devices
  - Dedicated Control Channel (CCH) for mgmt and safety messages
    ⟹ single radio devices need to periodically listen to CCH
  - Time slots
    - Synchronization envisioned via GPS receiver clock
    - Standard 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

IEEE 1609

- 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

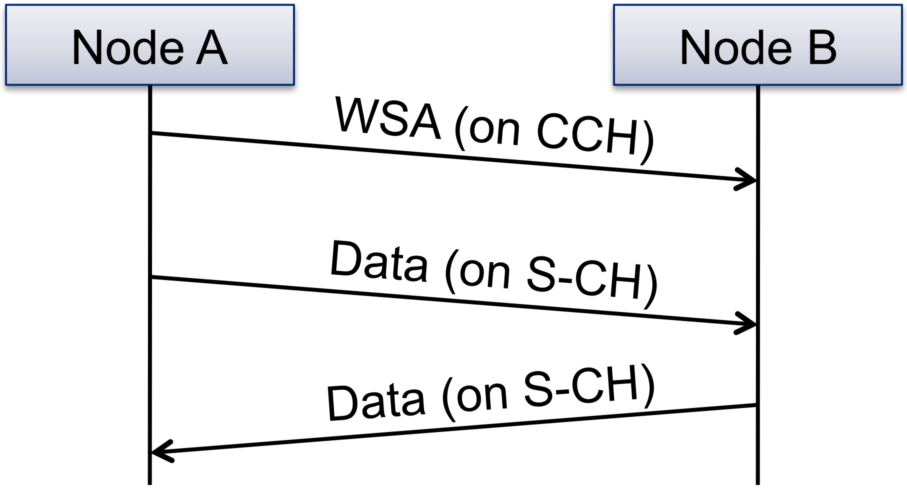


IEEE 1609

- 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)

IEEE 1609

- 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



IEEE 1609

- WAVE service advertisement (WSA)
  - WAVE Version (= 0)
  - Provider Service Table (PST)
    - n × 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 ≠ data source)
      - Channel number (max. 200)
    - 1..n × 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

IEEE 1609

- 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

IEEE 1609

- 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

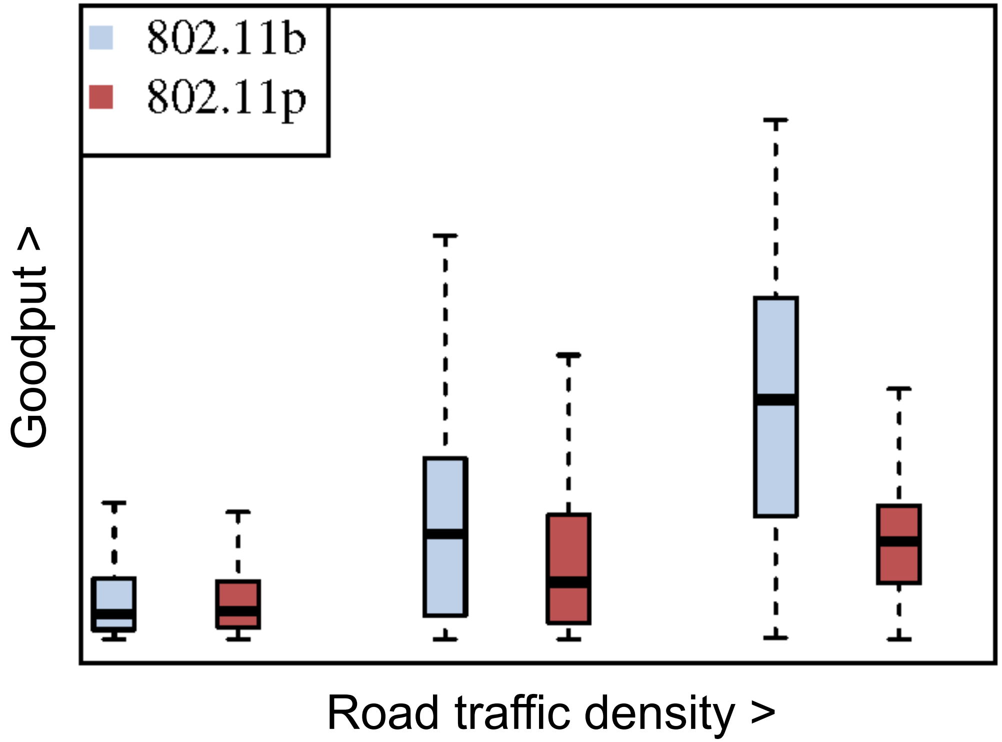
IEEE 1609

- 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

Drawbacks of Channel Switching

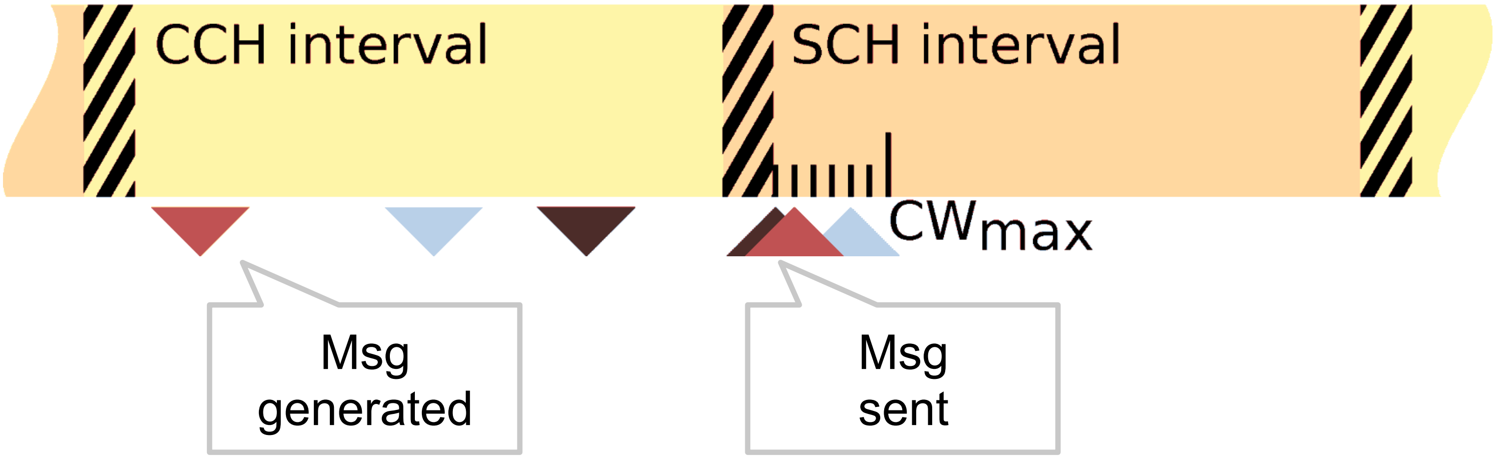
- 1) Goodput
  - User data must only be sent on SCH, i.e. during SCH interval ⟹ goodput cut in half



[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.

Drawbacks of Channel Switching

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



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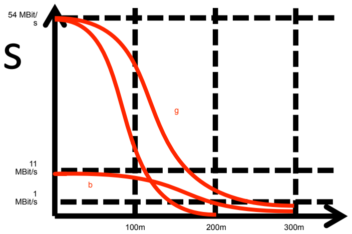
PERFORMANCE EVALUATION

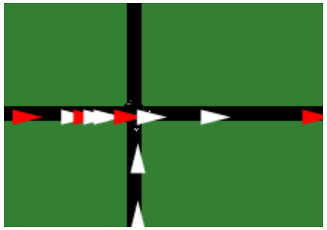
Approaches to Performance Evaluation

- 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

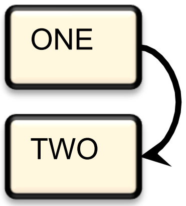


Requirements for Simulation

- 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)

Modeling Network Protocols

- Dedicated simulation tools
  - Discrete Event Simulation (DES) kernel
  - Manages queue of events (e.g., “an IP fragment was received”)
  - Delivers events to simulation models

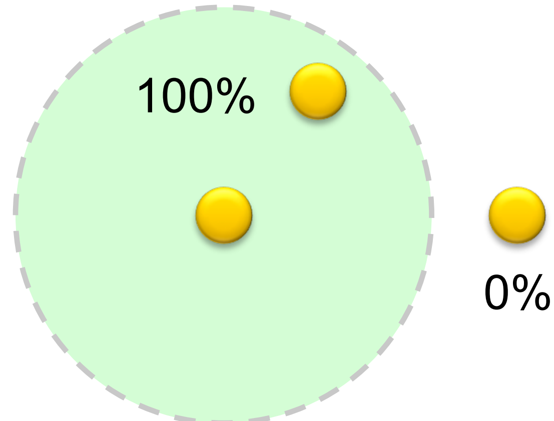


- Model libraries
  - Simulate components’ reaction to events
  - E.g., HTTP server, TCP state machine, radio channel, human, …
  - “when enough IP fragments received ⇒ tell TCP: packet received”

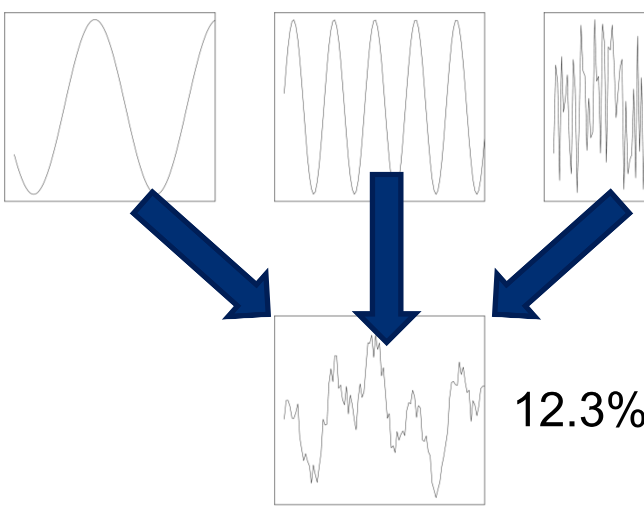
Engine	Language	Library	Language
OMNeT++	C++	MiXiM	C++
ns-2 / ns-3	C++	ns-2 / ns-3	Objective Tcl / Python
JiST	Java	SWANS	Java

Modeling Radio Channel

- 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)



Modeling Radio Propagation

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

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

- Free space path loss

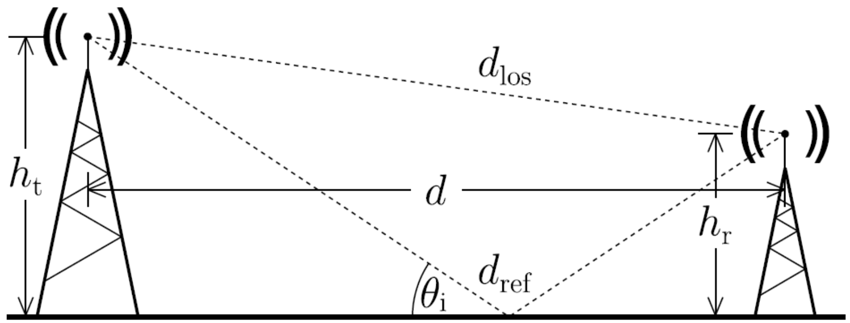
$$L_{\text{freespace}}[\text{dB}] = 20\,\text{lg}\left(4\pi\frac{d}{\lambda}\right)$$

- Empirical free space path loss

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

Modeling Radio Propagation

- Two Ray Interference path loss



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

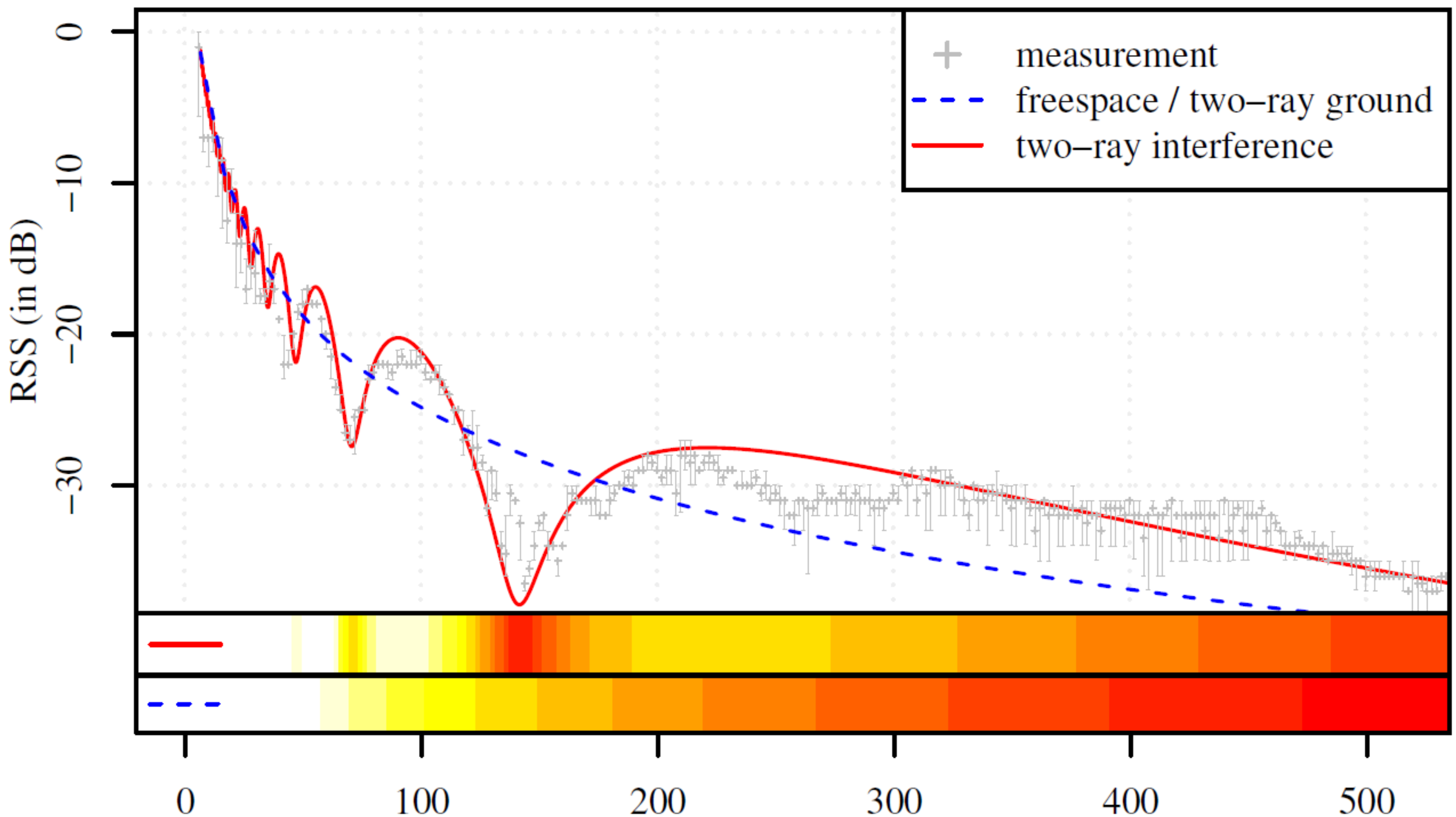
$$\varphi = 2\pi\frac{d_{\text{los}}-d_{\text{ref}}}{\lambda},\ \Gamma_{\perp} = \frac{\sin\theta_{\text{i}}-\sqrt{\epsilon_{\text{r}}-\cos^2\theta_{\text{i}}}}{\sin\theta_{\text{i}}+\sqrt{\epsilon_{\text{r}}-\cos^2\theta_{\text{i}}}},$$

$$d_{\text{los}} = \sqrt{d^2+(h_{\text{t}}-h_{\text{r}})^2},\ d_{\text{ref}} = \sqrt{d^2+(h_{\text{t}}+h_{\text{r}})^2},$$

$$\sin\theta_{\text{i}} = (h_{\text{t}}+h_{\text{r}})/d_{\text{ref}},\ \cos\theta_{\text{i}} = d/d_{\text{ref}}.$$

Modeling Radio Propagation

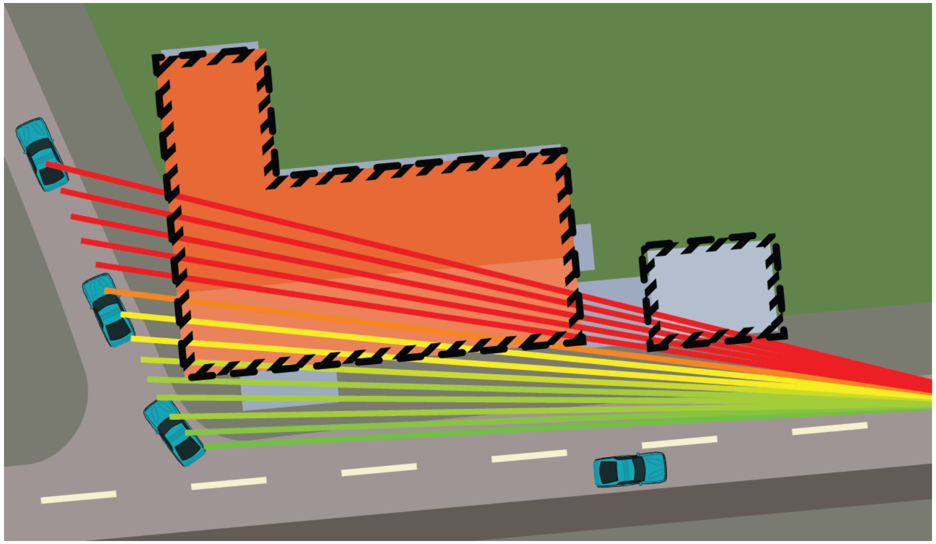
- Comparison: Two Ray Interference vs. Free Space



Modeling Radio Propagation

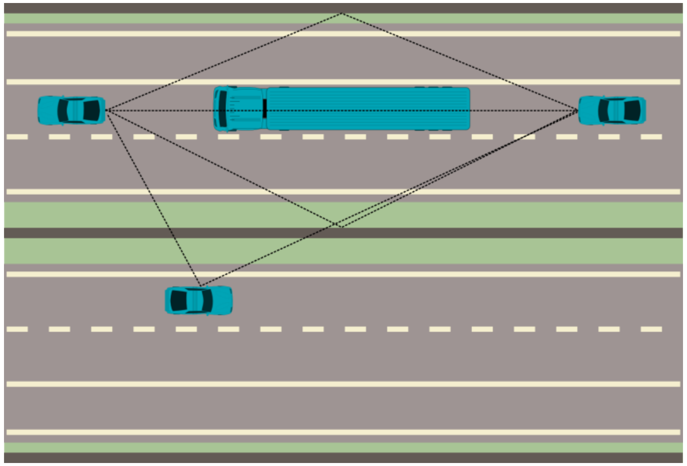
- Very(!) simple obstacle model
  - Take into account: distance through matter, number of walls

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

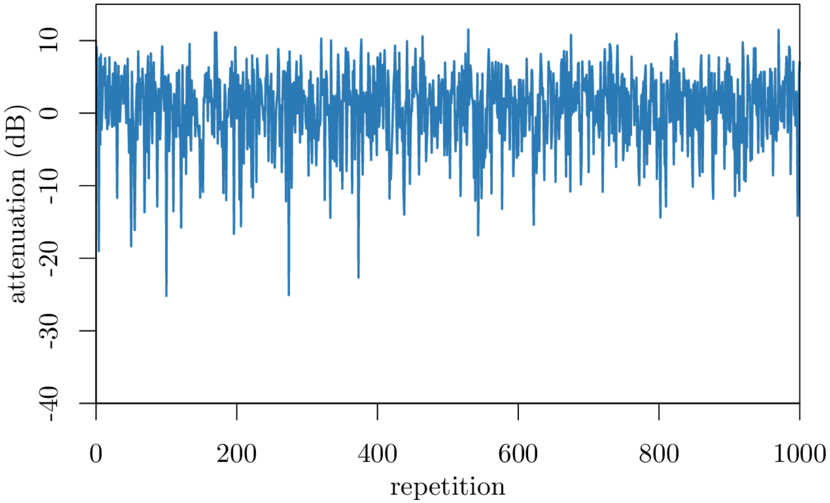


Modeling Radio Propagation

- Accounting for multi-path fading

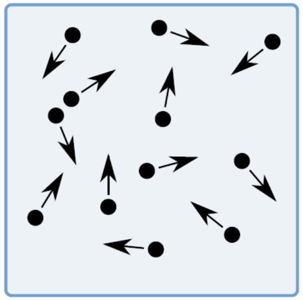


- Example: Rayleigh samples

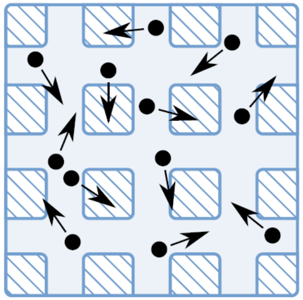


Modeling Mobility

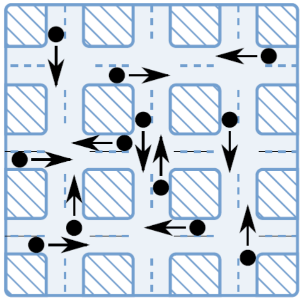
- Traditional approach in network simulation: Random Waypoint (RWP)
  - „pick destination, move there, repeat“



- First adaptation to vehicular movement
  - Add mass, inertia
  - Add restriction to “roads”
  - Add angular restrictions



- Problem
  - Very unrealistic (longitudinal) mobility pattern



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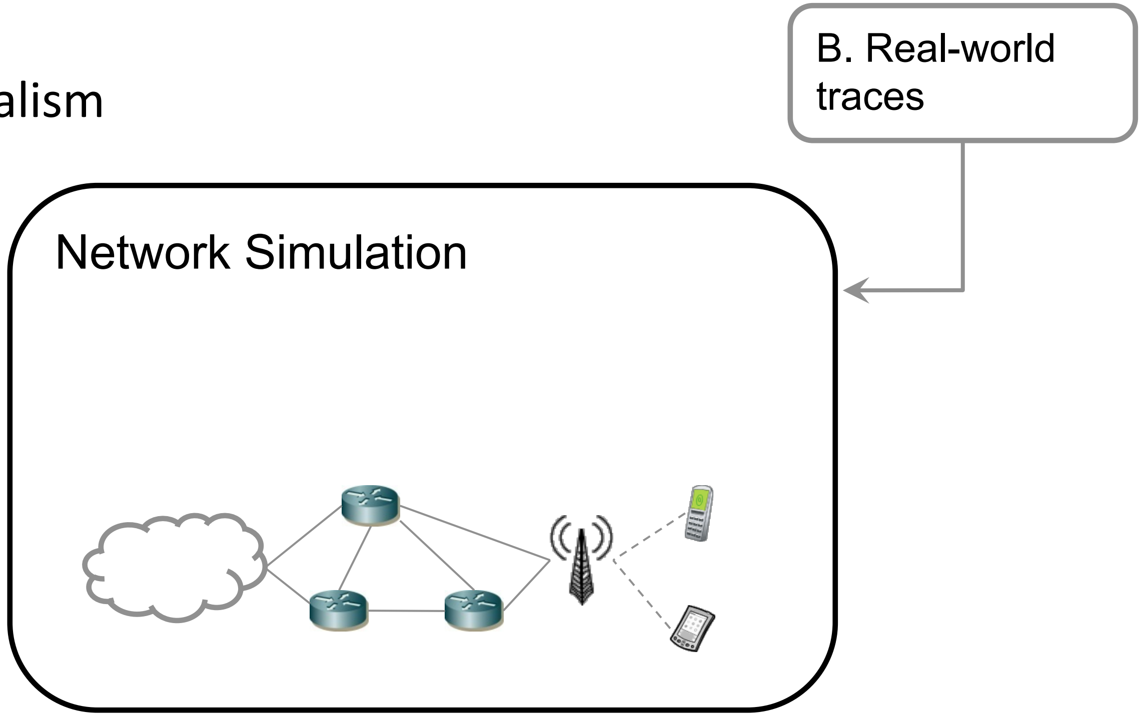
Modeling Mobility

- 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



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[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

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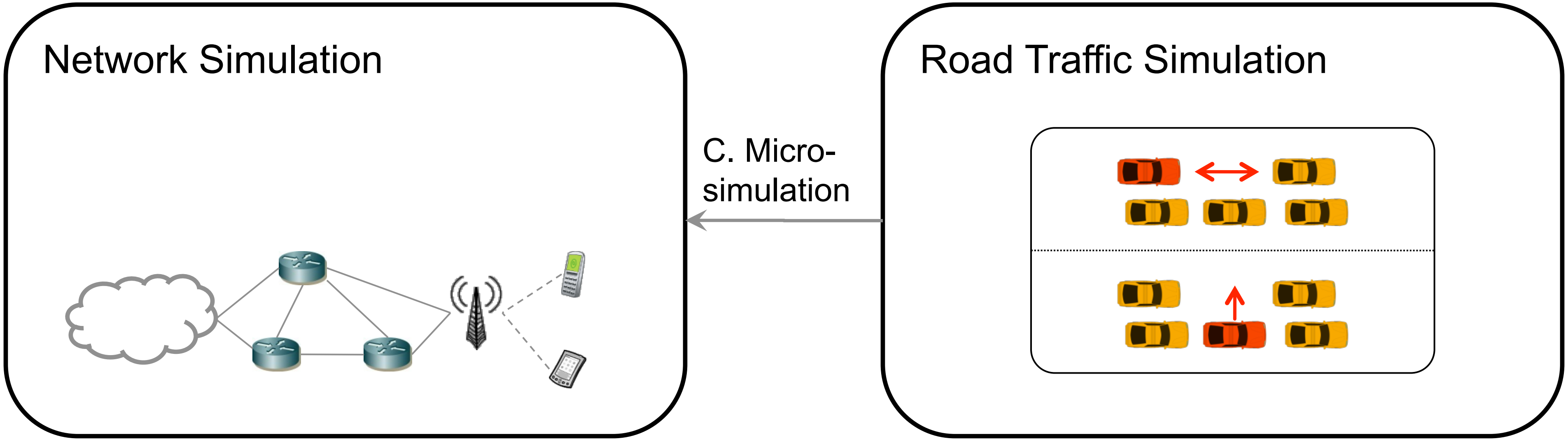
Modeling Mobility

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



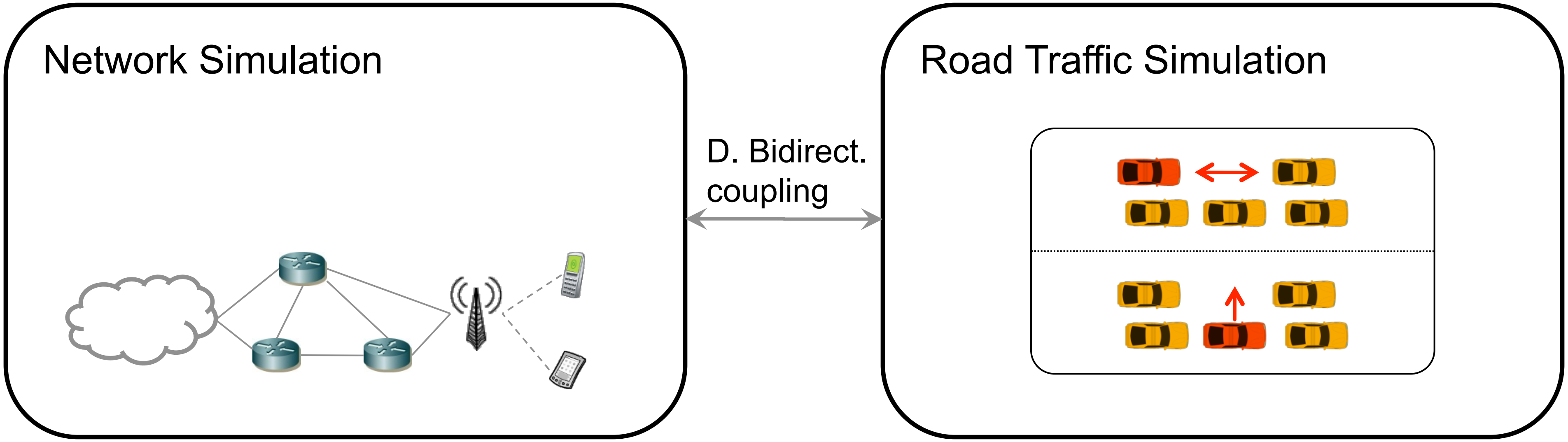
[1] C. Sommer, I. Dietrich, and F. Dressler, "**Realistic Simulation of Network Protocols in VANET Scenarios**," Proceedings of 26th IEEE Conference on Computer Communications (INFOCOM 2007): IEEE Workshop on Mobile Networking for Vehicular Environments (MOVE 2007), Poster Session, Anchorage, AK, May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

Modeling Mobility

- Bidirectional coupling
  - Network traffic can influence road traffic



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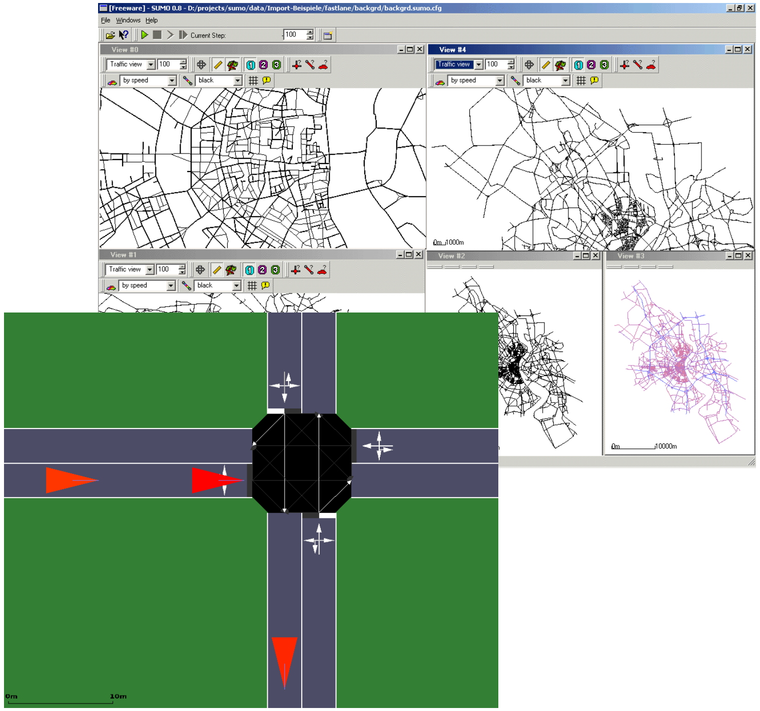
[2] C. Sommer, R. German, and F. Dressler, "**Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis**," IEEE Transactions on Mobile Computing, 2010. (to appear)

Modeling Road Traffic

- 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
    - ...



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Modeling Car Following

- Krauss car following model
  - Maximum velocity $v↓max$ ⇔ safe gap $g↓des$ ⇔ dawdle factor ϵ

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

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

$$v(t + \Delta t) = \max\{0;\ v_{\text{des}} - \eta\} \qquad \eta = \text{rand}[0,\ \epsilon a]$$

- Intelligent Driver Model (IDM)
  - Desired velocity $v↓0$ ⇔ safe distance $s↑*$

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

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

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[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

Simulation Frameworks

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

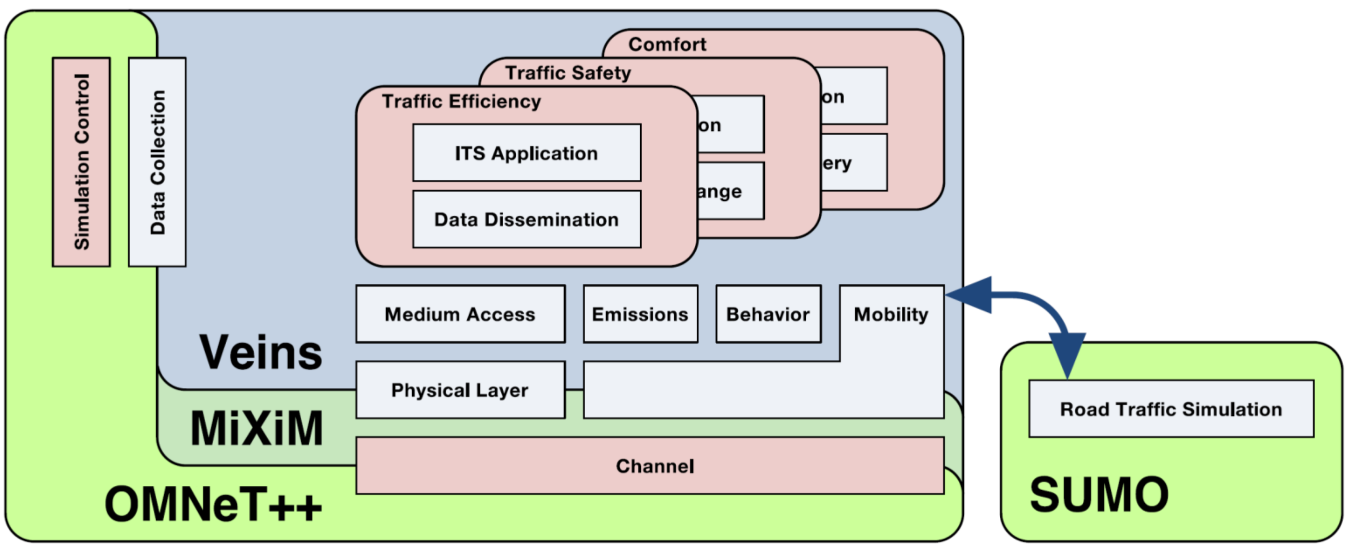
[3] C. Sommer, R. German, and F. Dressler, "**Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis**," IEEE Transactions on Mobile Computing, 2010.

[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

Veins

http://veins.car2x.org



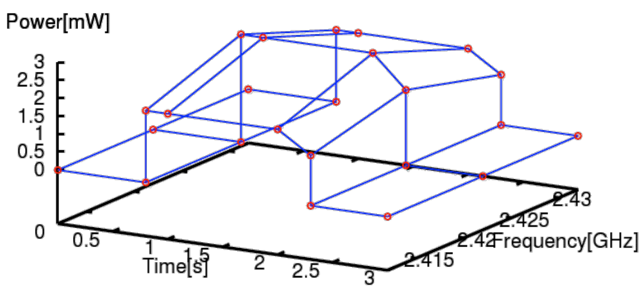
[1] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," IEEE Transactions on Mobile Computing, vol. 10, no. 1.

[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.

Veins

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

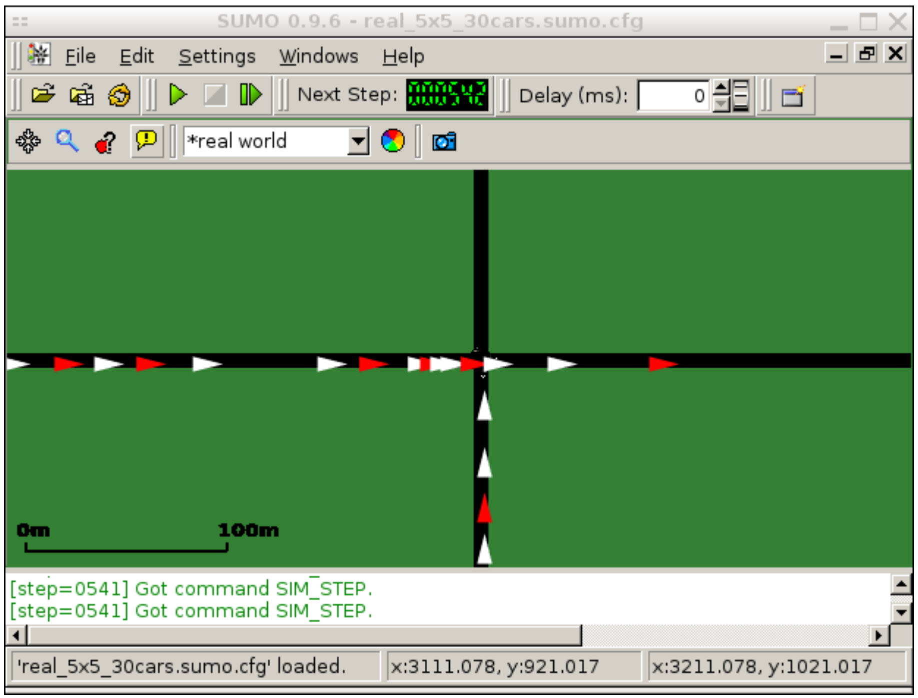
- MiXiM
  - Model library for OMNeT++ for PHY layer and mobility support
  - Event scheduling
  - Signal propagation
  - SINR / bit error calculation
  - Radio switching
  - …

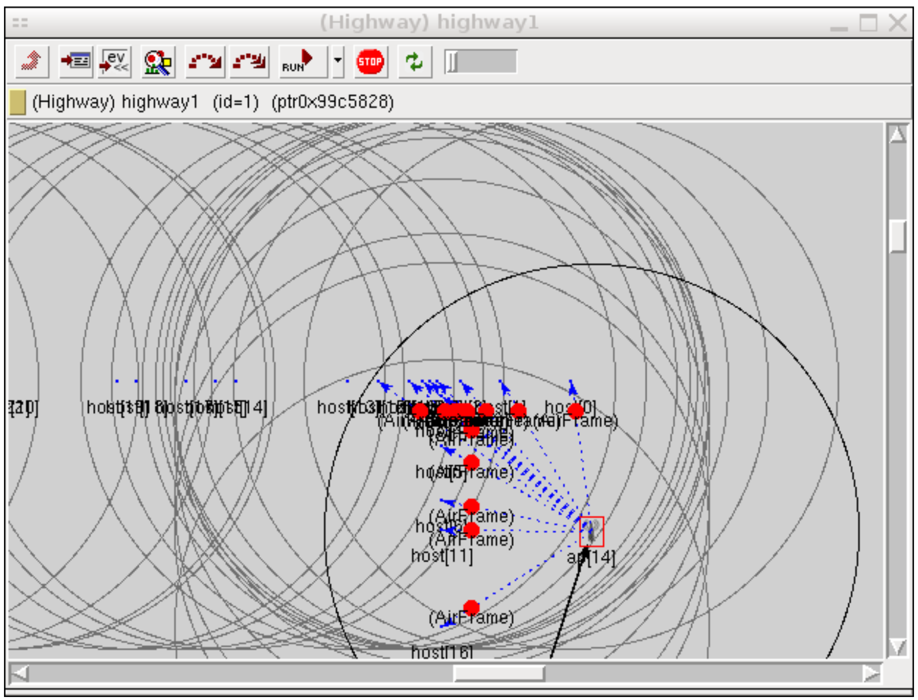


[1] A. Varga, "**The OMNeT++ Discrete Event Simulation System**," Proceedings of European Simulation Multiconference (ESM 2001), Prague, Czech Republic, June 2001

Veins

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

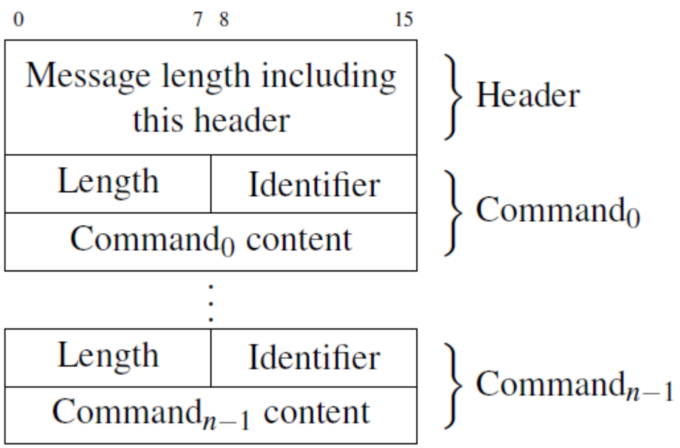




Veins

- Traffic Control Interface (TraCI)
  - Generic API
  - Exchange commands via TCP connection

- Simple request-response protocol

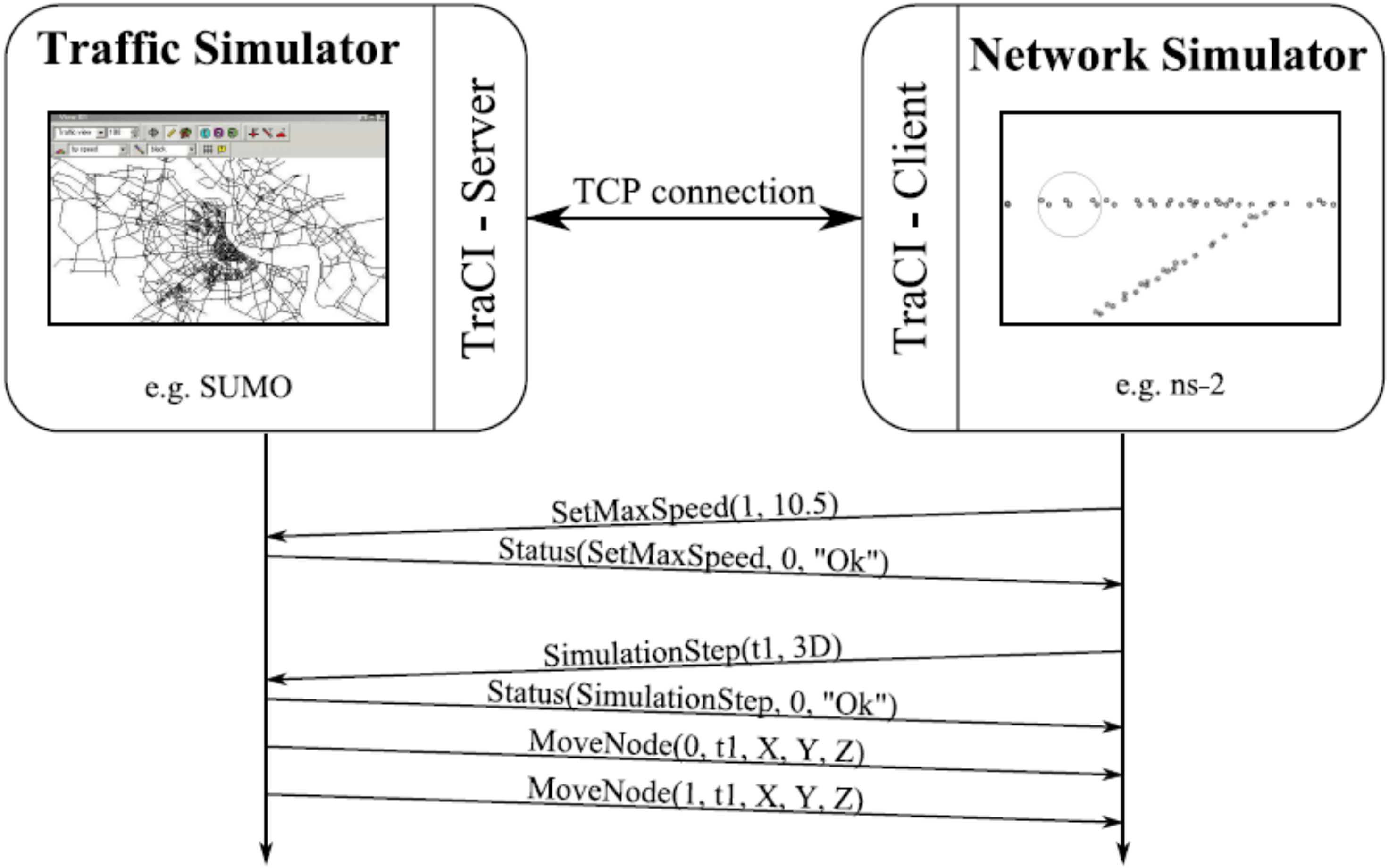


[1] Christoph Sommer, Zheng Yao, Reinhard German and Falko Dressler, "**Simulating the Influence of IVC on Road Traffic using Bidirectionally Coupled Simulators**," Proceedings of 27th IEEE Conference on Computer Communications (INFOCOM 2008): IEEE Workshop on Mobile Networking for Vehicular Environments (MOVE 2008), Phoenix, AZ, April 2008

[2] A. Wegener, M. Piorkowski, M. Raya, H. Hellbrück, S. Fischer, and J.-P. Hubaux, "**TraCI: An Interface for Coupling Road Traffic and Network Simulators**," Proceedings of 11th Communications and Networking Simulation Symposium (CNS'08), Ottawa, Canada, April 2008

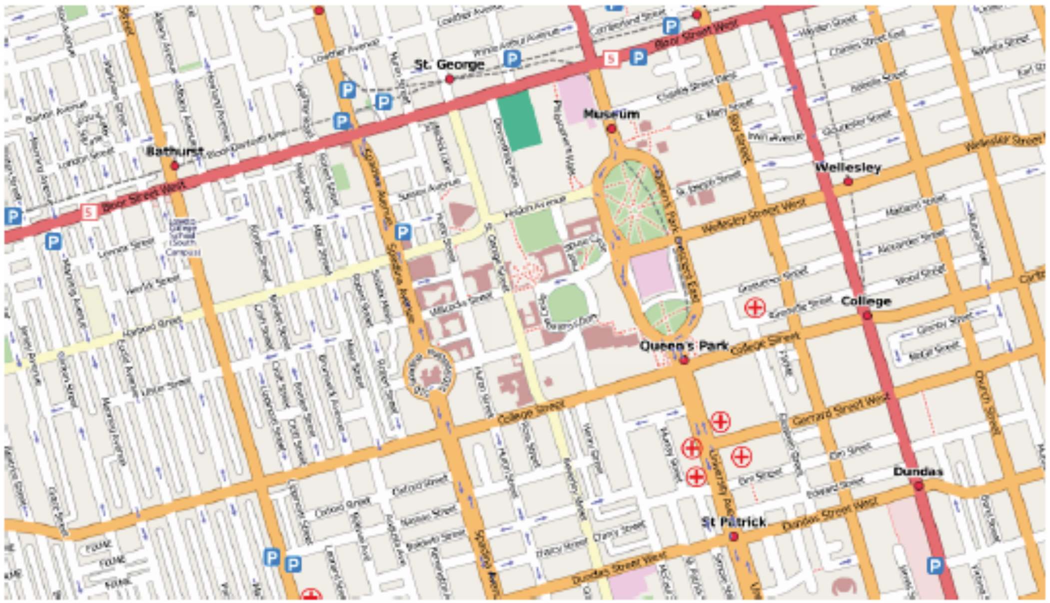
Veins

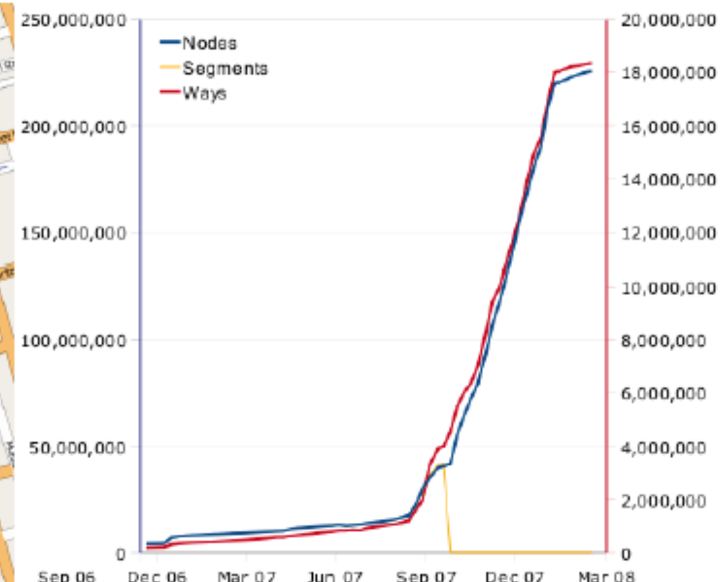
- TraCI: Message Sequence Chart

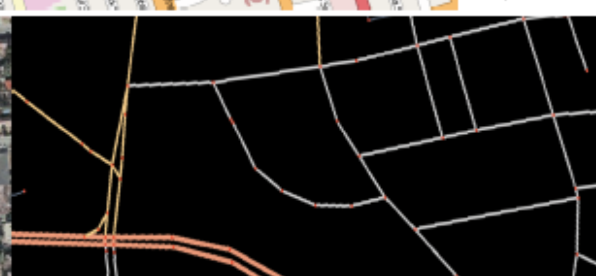


Simulation Scenarios

- Freely available road topology information
  - Geodatabase of OpenStreetMap project







WHAT WE'RE WORKING ON

Platooning (a.k.a. The Road Train)

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

Illustrations: PATH and SARTRE projects

Platooning

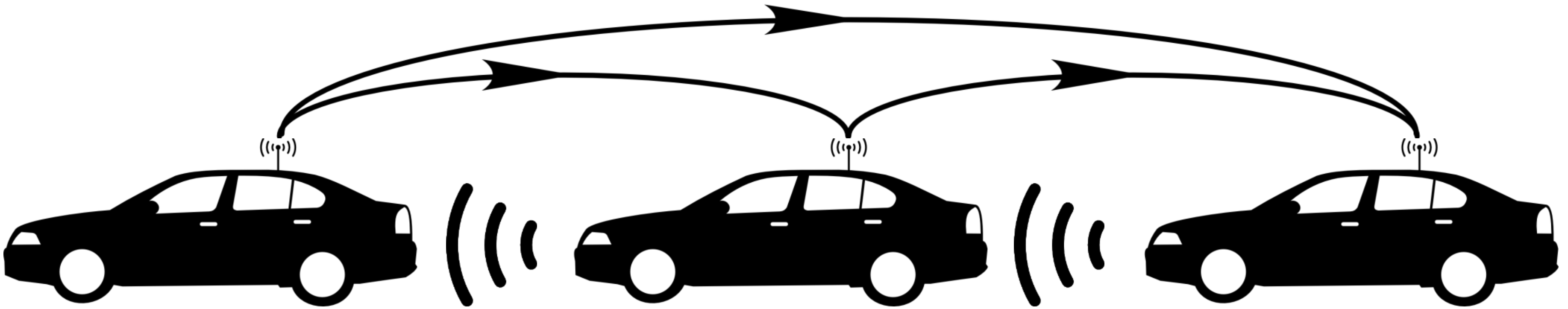
Time for another Video!

Volvo SARTRE Project

Controllers for Automated Car Following

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

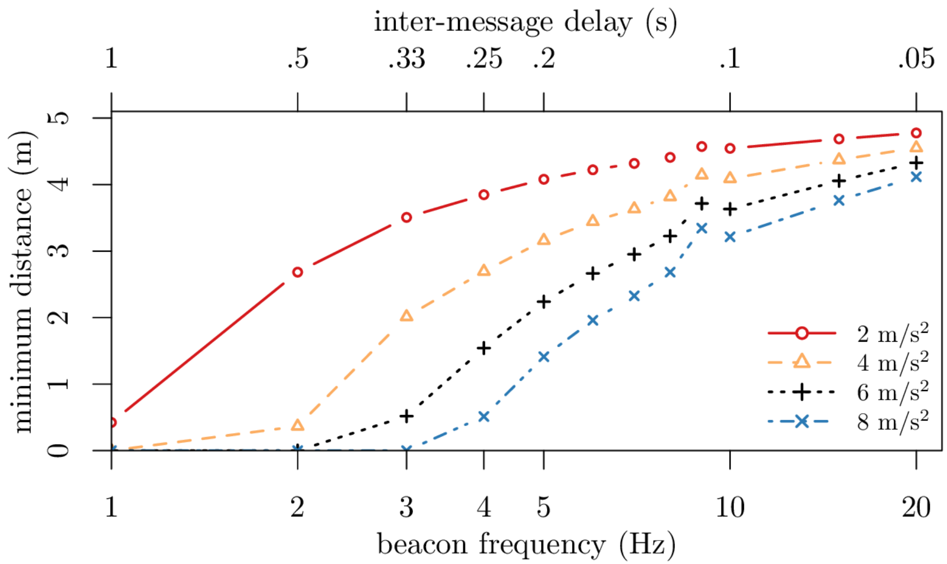
- CACC – Radar + IVC: distance $d = d_{des}$ (fixed)

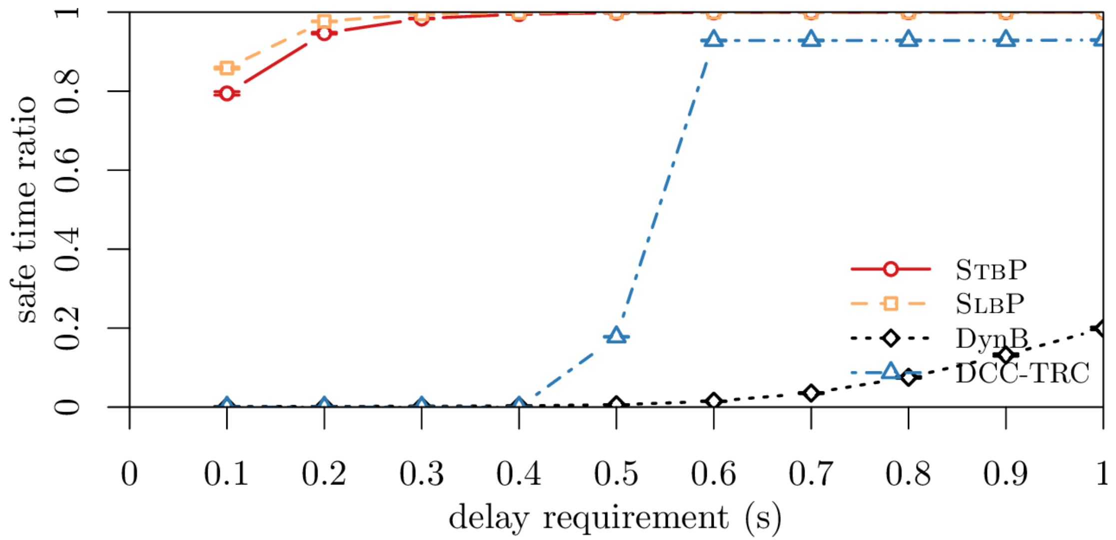


Networking Related Problems

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

Combining Tx Power Control with TDMA



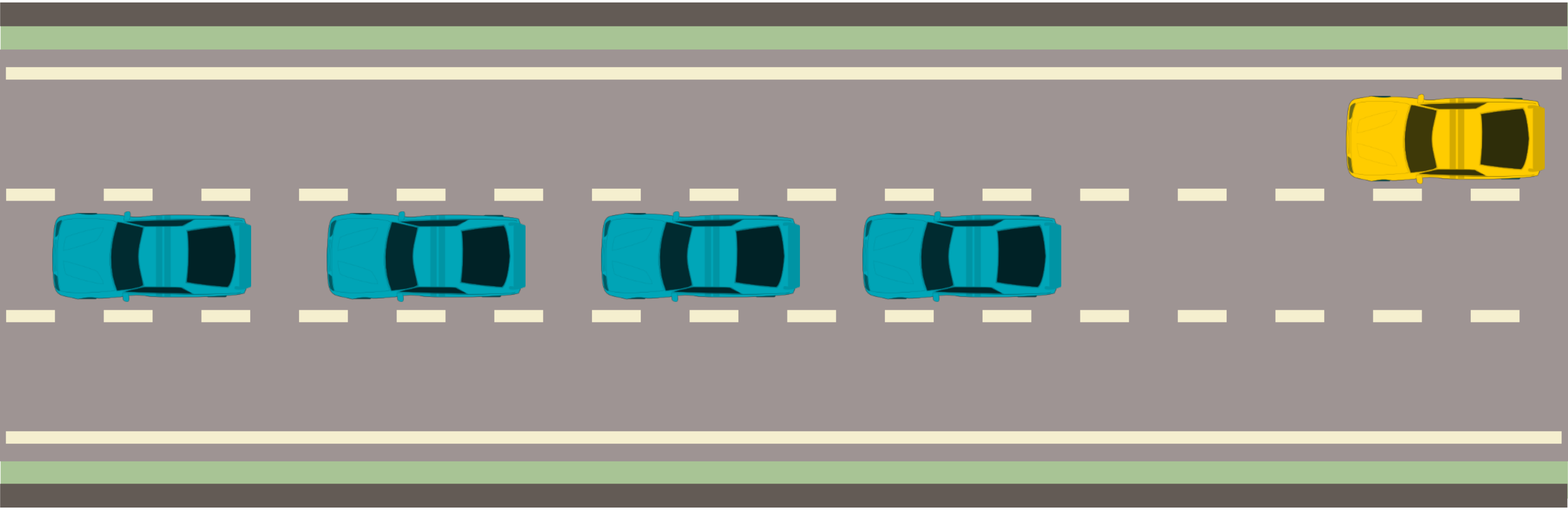


Infrastructure and Management Paradigms

- Centralized automated highway system (California PATH)
  - dedicated road infrastructure
  - AHS dictates positions, speeds, actions, etc…
  - 100% market penetration rate
- Shared infrastructure (Volvo SARTRE)
  - road is shared with non-automated vehicles
  - platoons are autonomous
  - leading vehicle driven by professional driver (or self driven car?)
  - progressive introduction

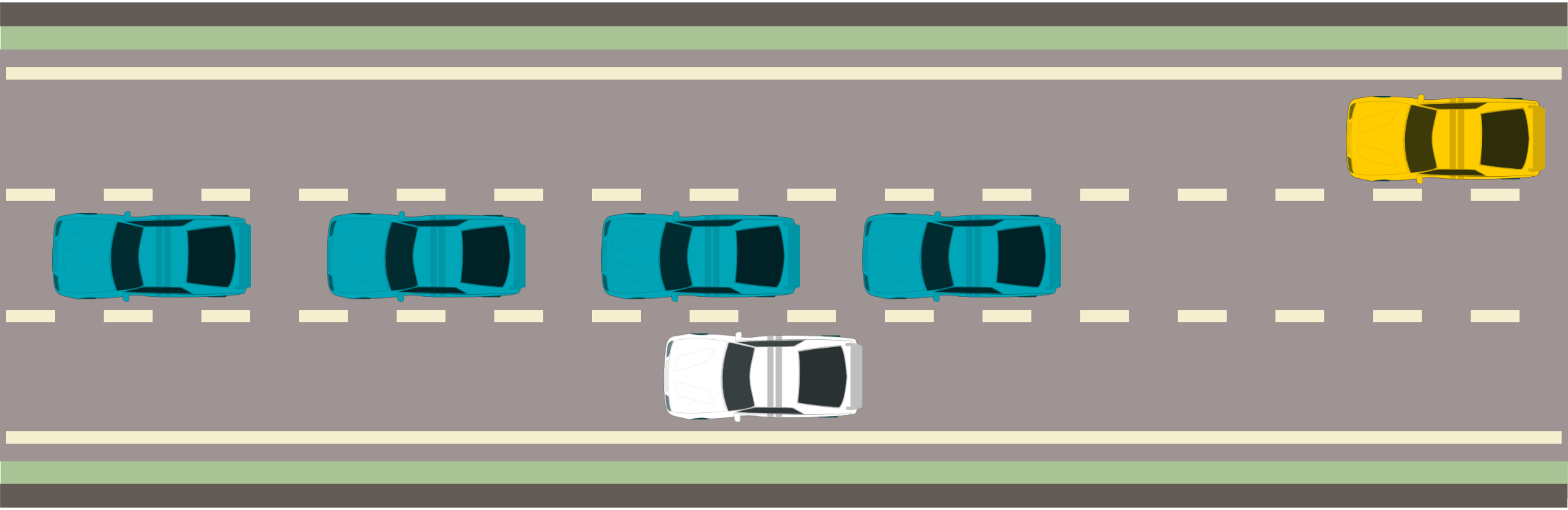
Maneuvers in Mixed Roads: the Open Problem

- Join-at-middle:



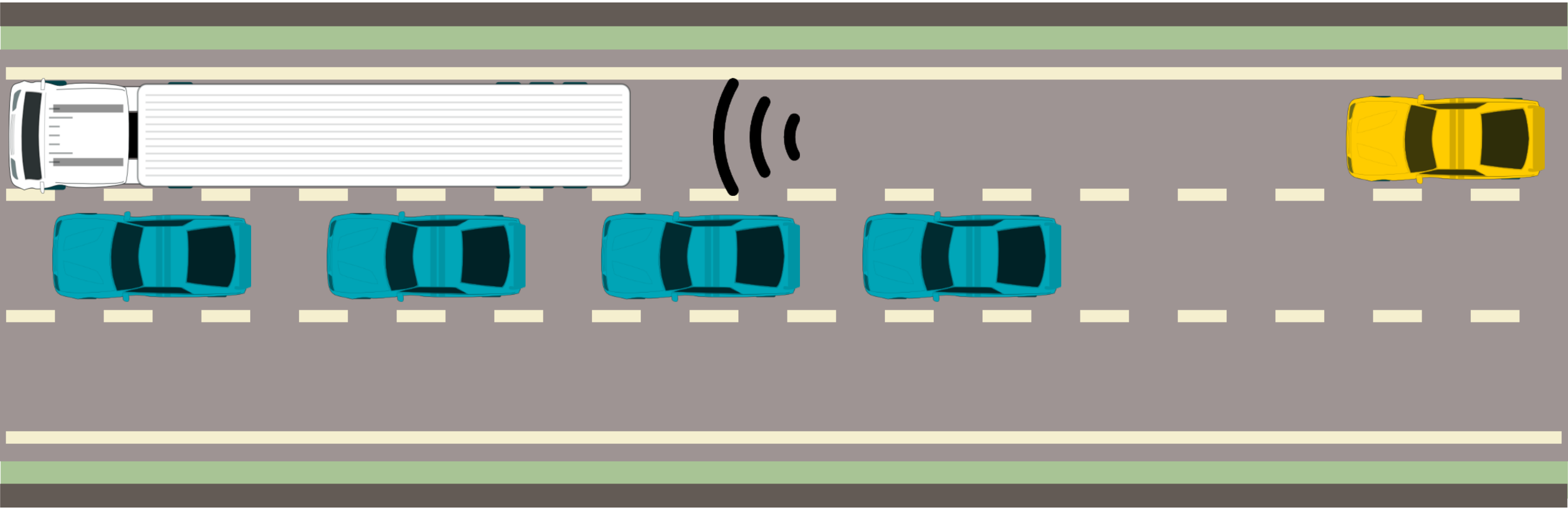
Maneuvers in Mixed Roads: the Open Problem

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



Maneuvers in Mixed Roads: the Open Problem

- Join-at-middle: slow vehicle interference



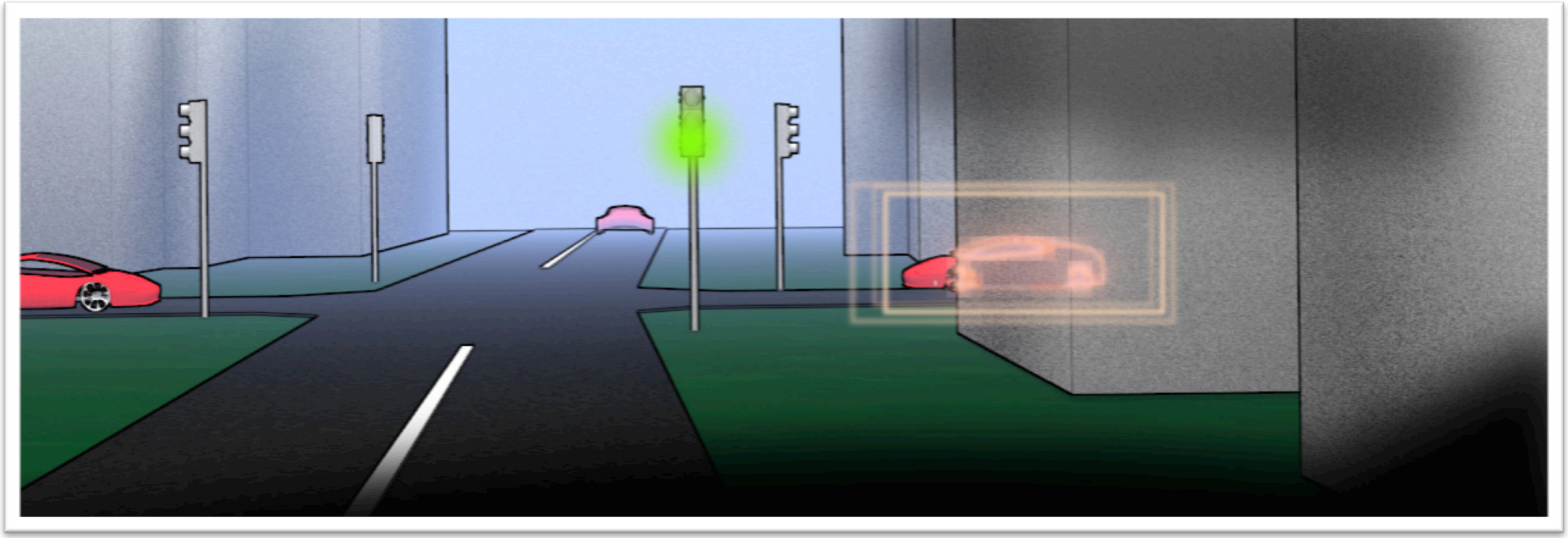
MASTER THESIS

Possible Thesis Topics

- Platooning (with us in Trento)
  - network related problems
  - development of application layer protocol for maneuvers

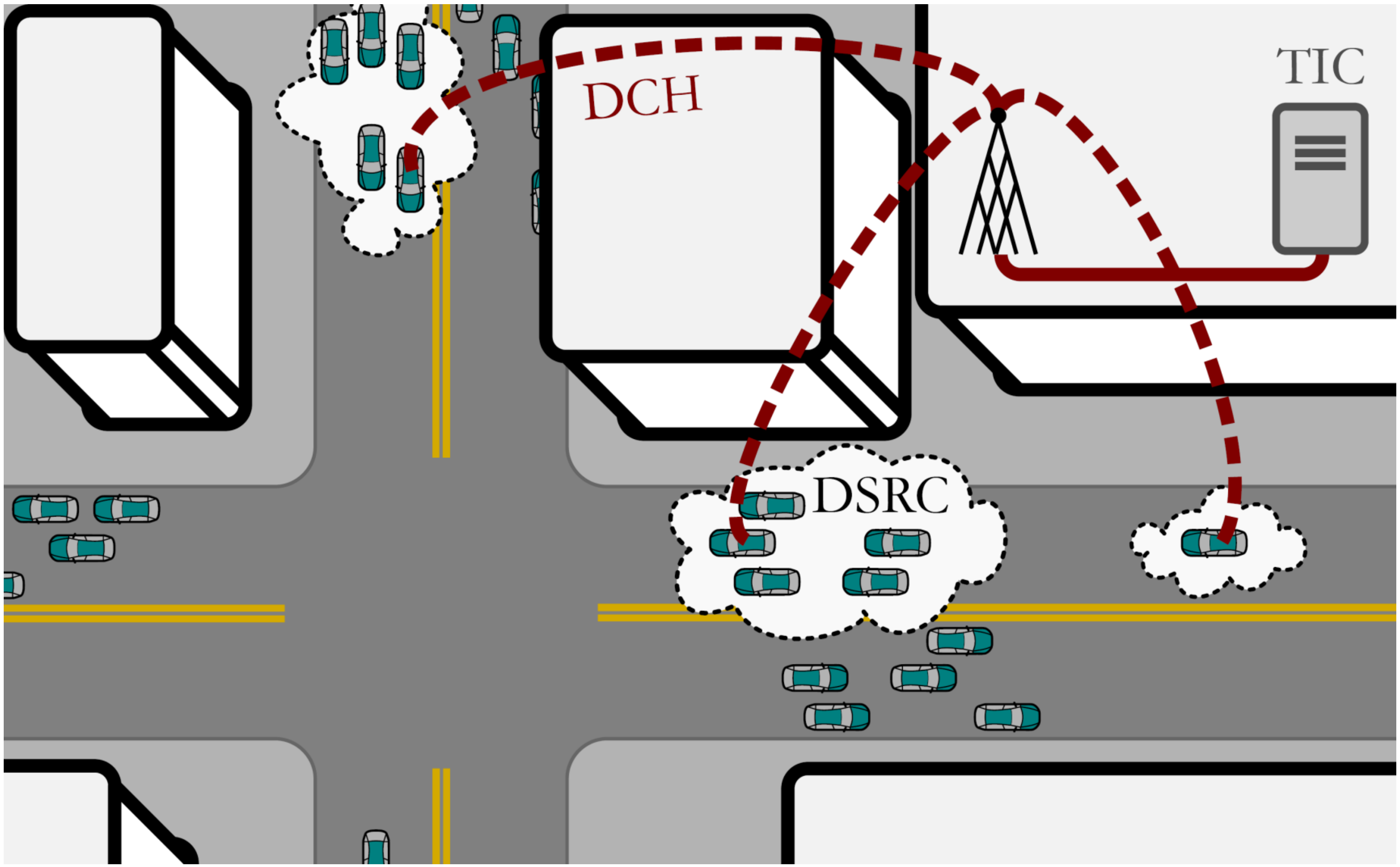
Possible Thesis Topics

- Intersection Collision Avoidance (w/ Stefan Joerer)



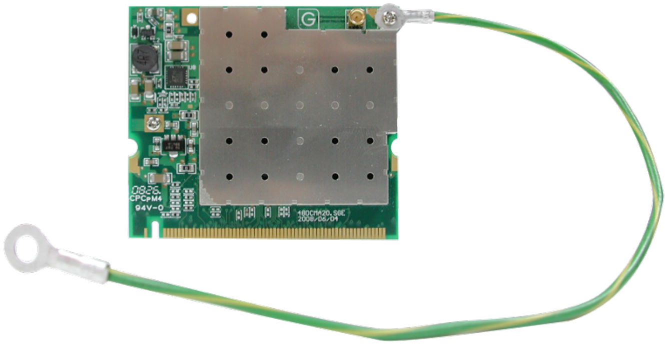
Possible Thesis Topics

- Simulation of Heterogeneous Network (LTE + 802.11p)



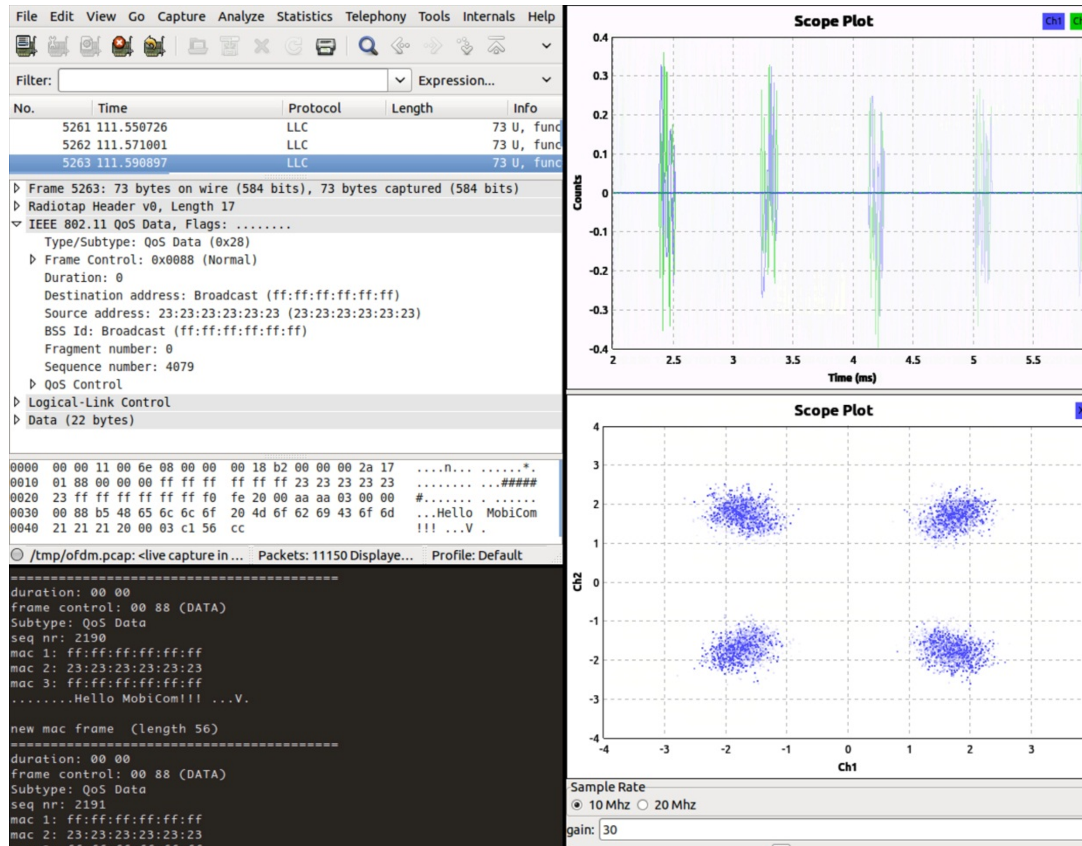
Possible Thesis Topics

- Hands on hardware (w/ us and University of Paderborn)



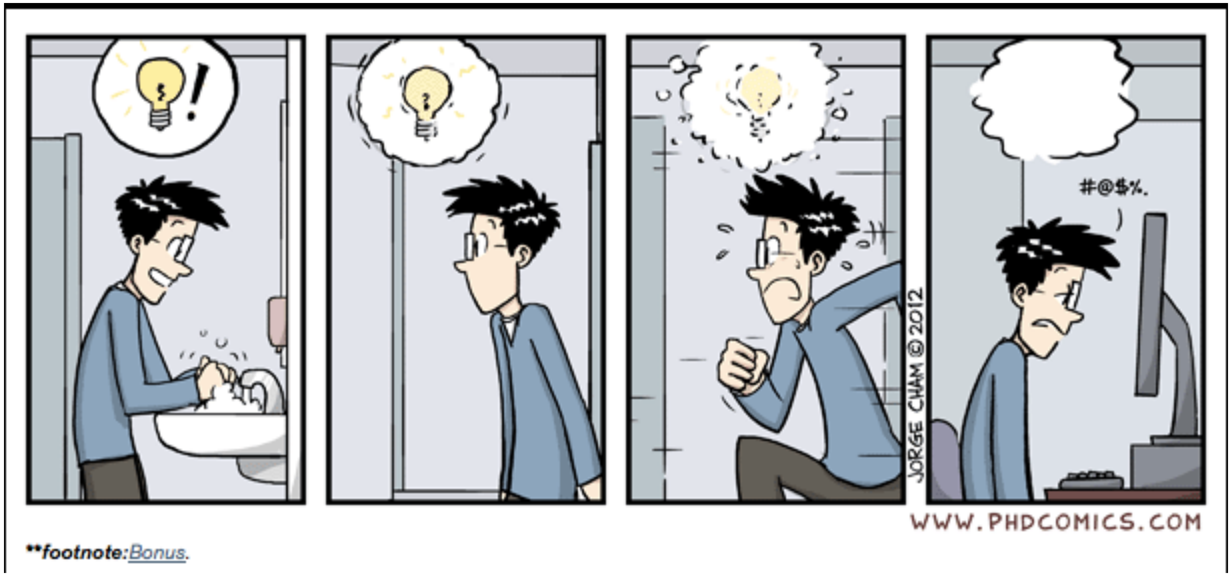
Possible Thesis Topics

- Software Defined Radios (with Bastian Bloessl)
  - tougher and more complicated to organize but…



Possible Thesis Topics

- Your ideas are welcome!



Thank you

Any question?