Wireless Mesh and Vehicular Networks

Technologies, Beaconing, and Routing in Vehicular Networks

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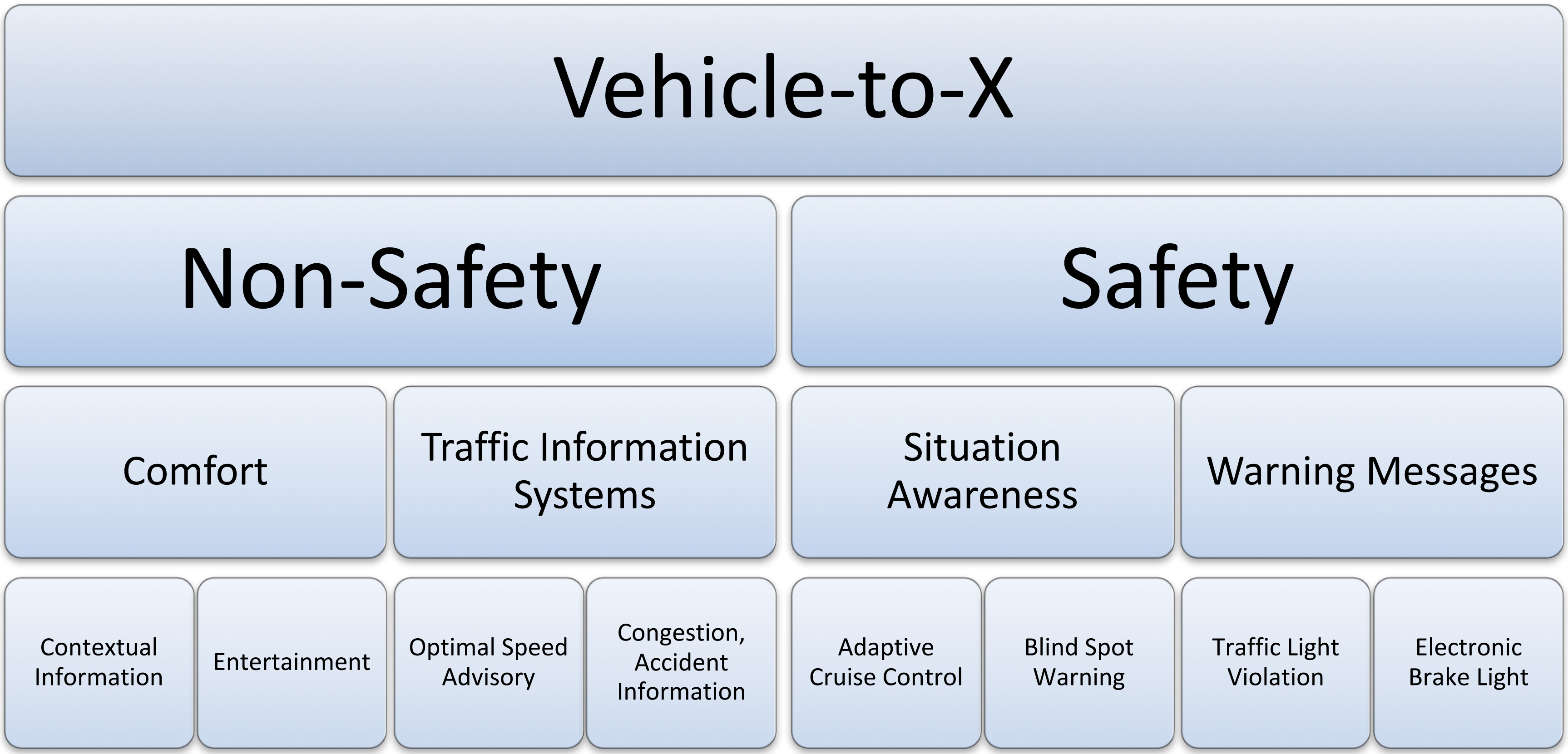
with special thanks to
Falko Dressler, Christoph Sommer, Bastian Bloessl, Stefan Joerer, David Eckhoff

- Taxonomy of Use Cases



- 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

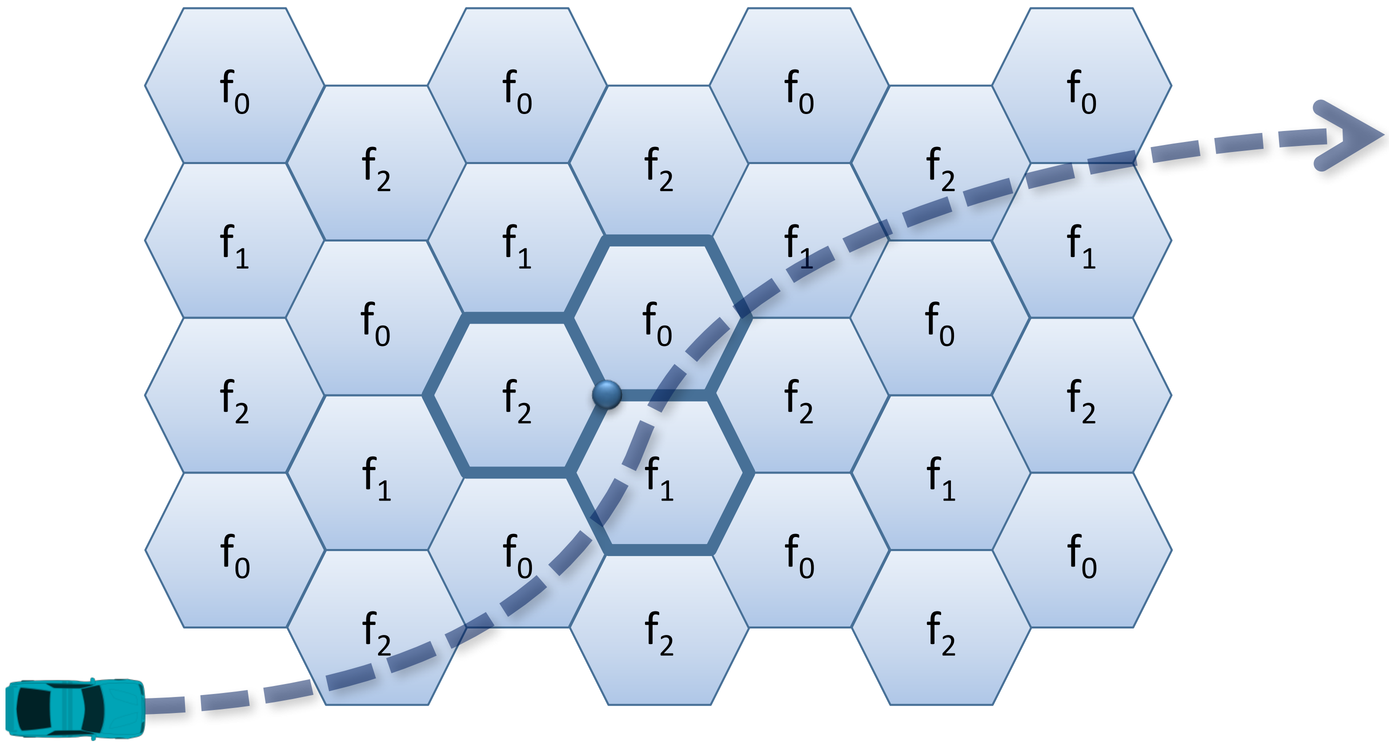
A (rough) outline of the Vehicular Networks topics

- ~~Application: why VN?~~
- Communication: technologies, alternatives, protocols, challenges
- Simulation: evaluating vehicular networks without vehicles and without networks. Tools and models

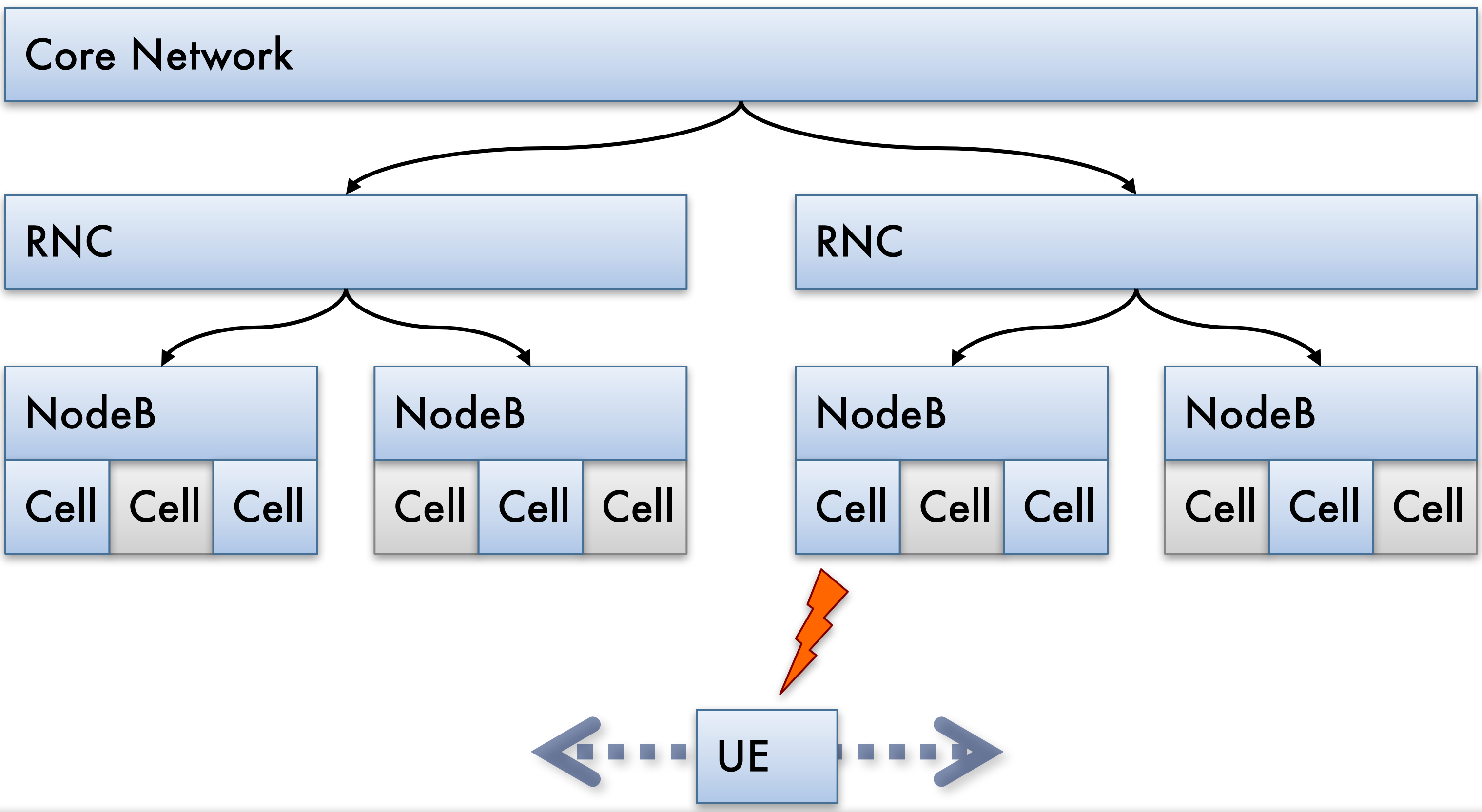
(Some of them)

COMMUNICATION TECHNOLOGIES

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

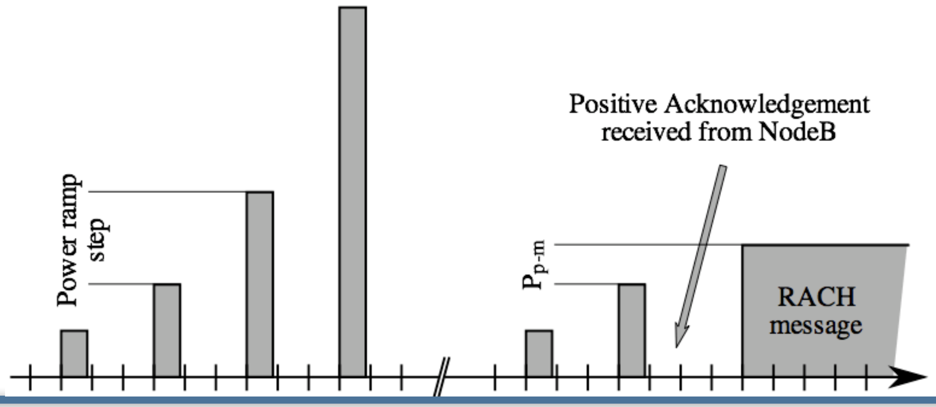


- Strict hierarchy of network components



- 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

- FACH
  - Time slots managed by base station
  - Delay on the order of 10 ms per 40 Byte and UE
  - Capacity severely limited (in non-multicast networks)
  - Need to know current cell of UE
- RACH
  - Slotted ALOHA – random access by UEs
    - Power ramping with Acquisition Indication
  - Delay approx. 50 ms per 60 Byte and UE
  - Massive interference with other UEs

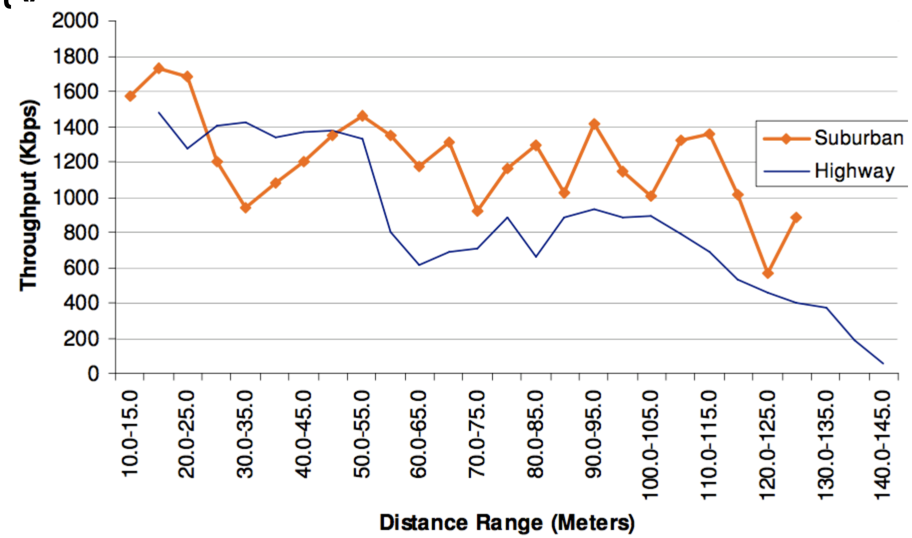


- DCH
  - Delay: approx. 250 ms / 2 s / 10 s for channel establishment
    - Depends on how fine-grained UE position is known
  - Maintaining a DCH is expensive
    - Closed-Loop Power Control (no interference of other UEs)
    - Handover between cells
  - Upper limit of approx. 100 UEs

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 (➩ ideal for cellular networks)

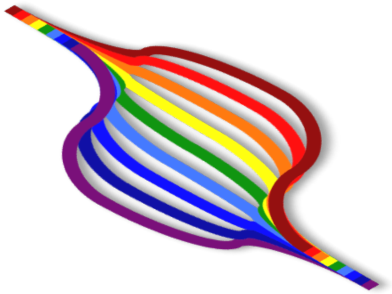
- IEEE 802.11{a,b,g,n,ac} for Car-to-X communication?
  - Can’t be in infrastructure mode and ad hoc mode at the same time
  - Switching time consuming
  - Association time consuming
  - No integral within-network security
  - (Massively) shared spectrum (➪ ISM)
  - No integral QoS
  - Multi-path effects reduce range and speed

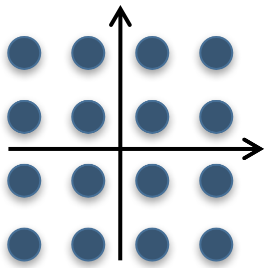


[1] Fay Hui, Prasant Mohapatra. „Experimental Characterization of Multihop Communications in Vehicular Ad Hoc Network“. In Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks, 2005

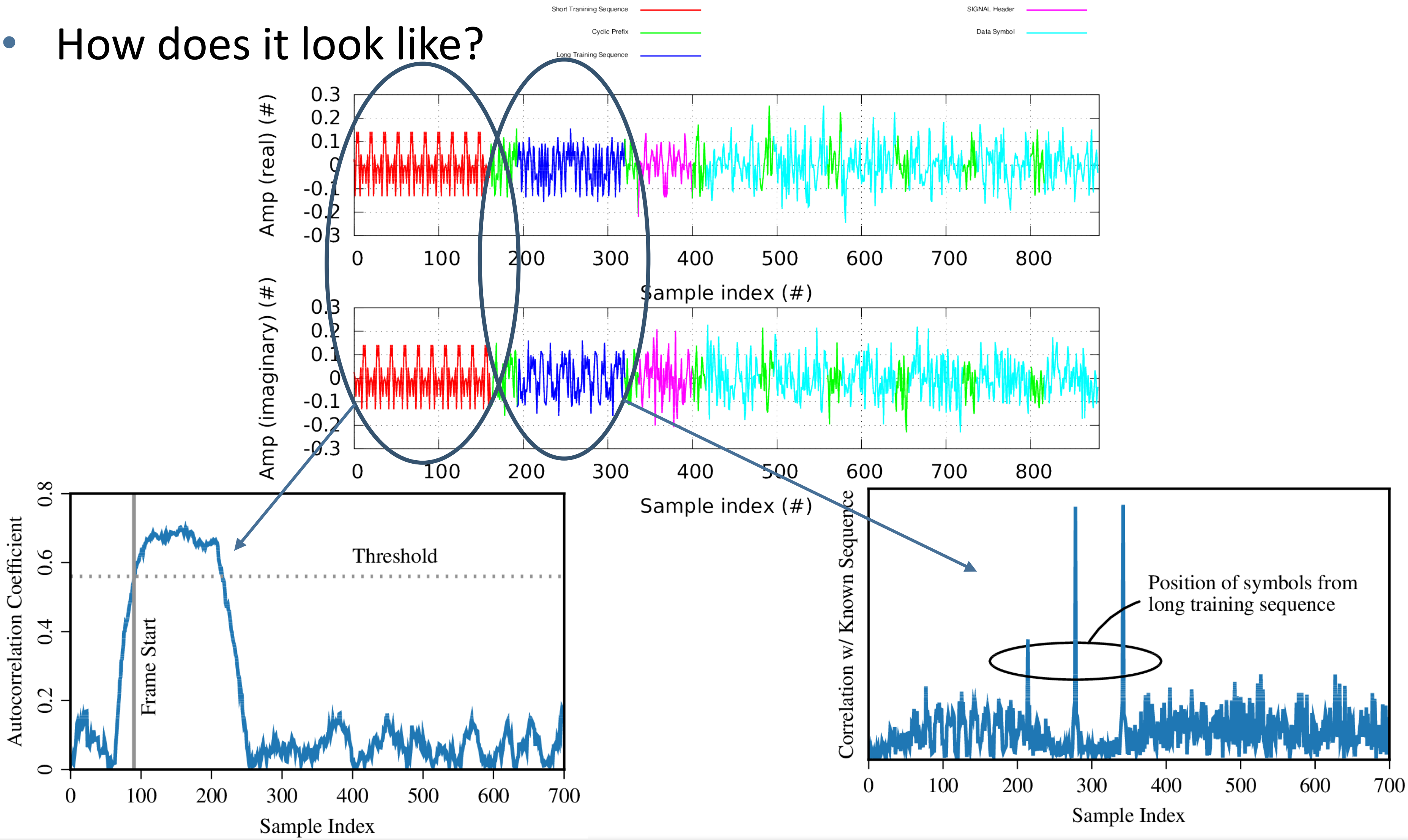
IEEE 802.11p

- New lower layers for
  "Wireless Access in Vehicular Environments" (WAVE)
  - PHY layer mostly identical to IEEE 802.11a
    - Variant with OFDM and 16 QAM
    - Higher demands on tolerances
    - 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
    - ...

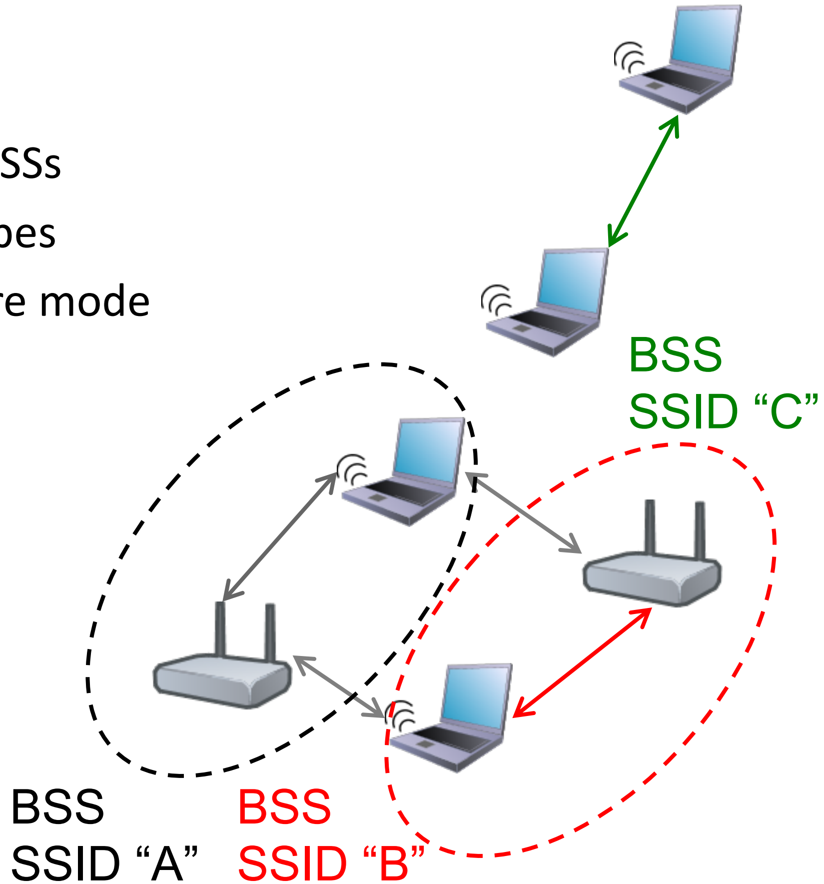




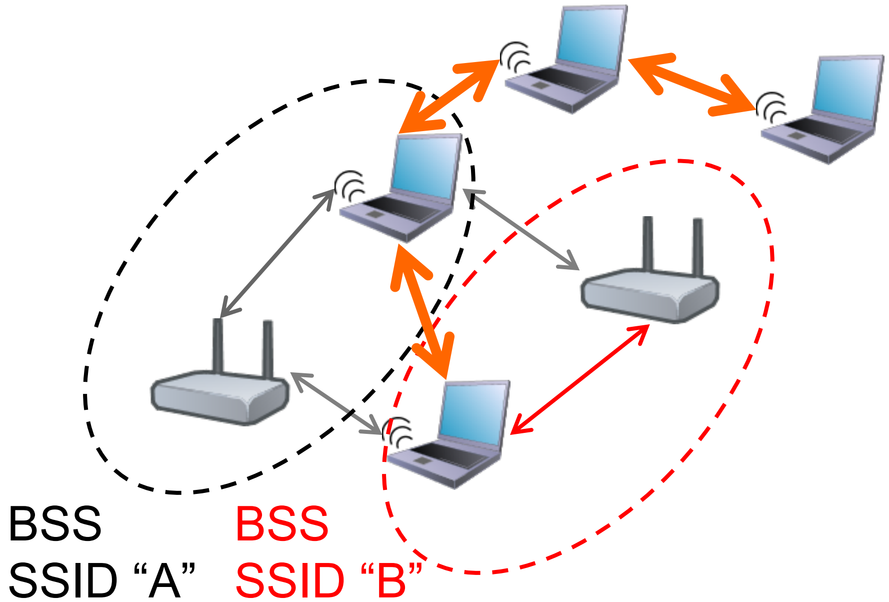
- How does it look like?



- 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

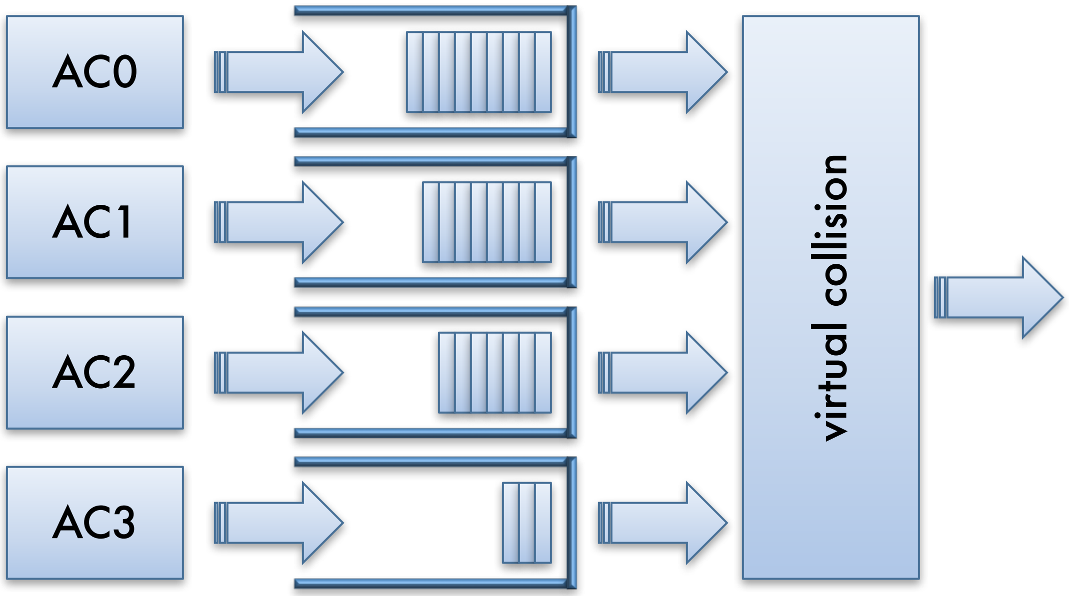


- New: 802.11 OCB Mode (Outside of the Context of a BSS)
  - Default mode of nodes in WAVE
  - Nodes may always use Wildcard BSS in packets
  - Nodes will always receive Wildcard BSS packets
  - May join BSS and still use Wildcard BSS



- IEEE 802.11 Hybrid Coordination Function (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)

- Map 8 user priorities ➪ 4 access categories ➪ 4 queues
- Queues compete independently for medium access



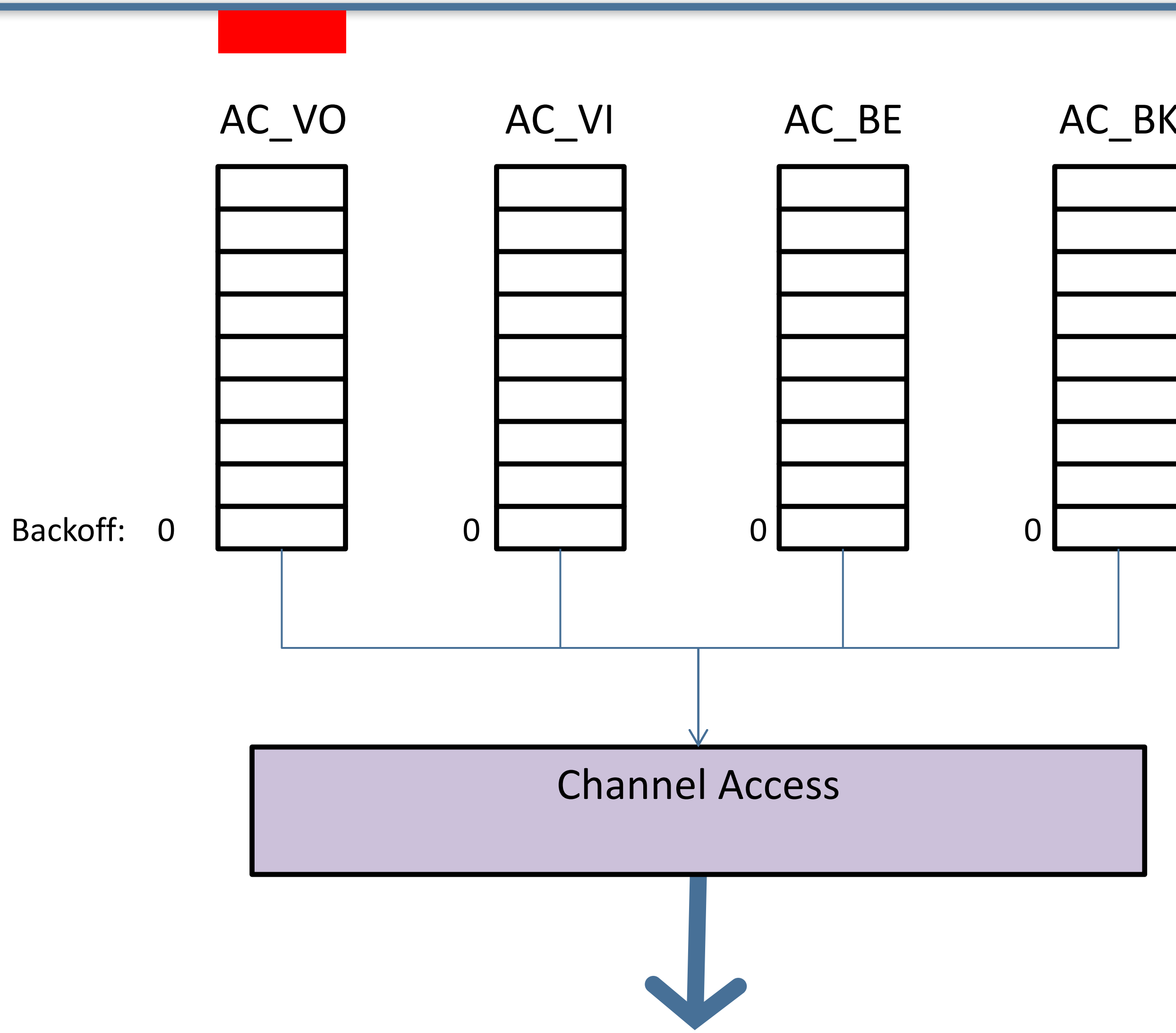
- Parameterization

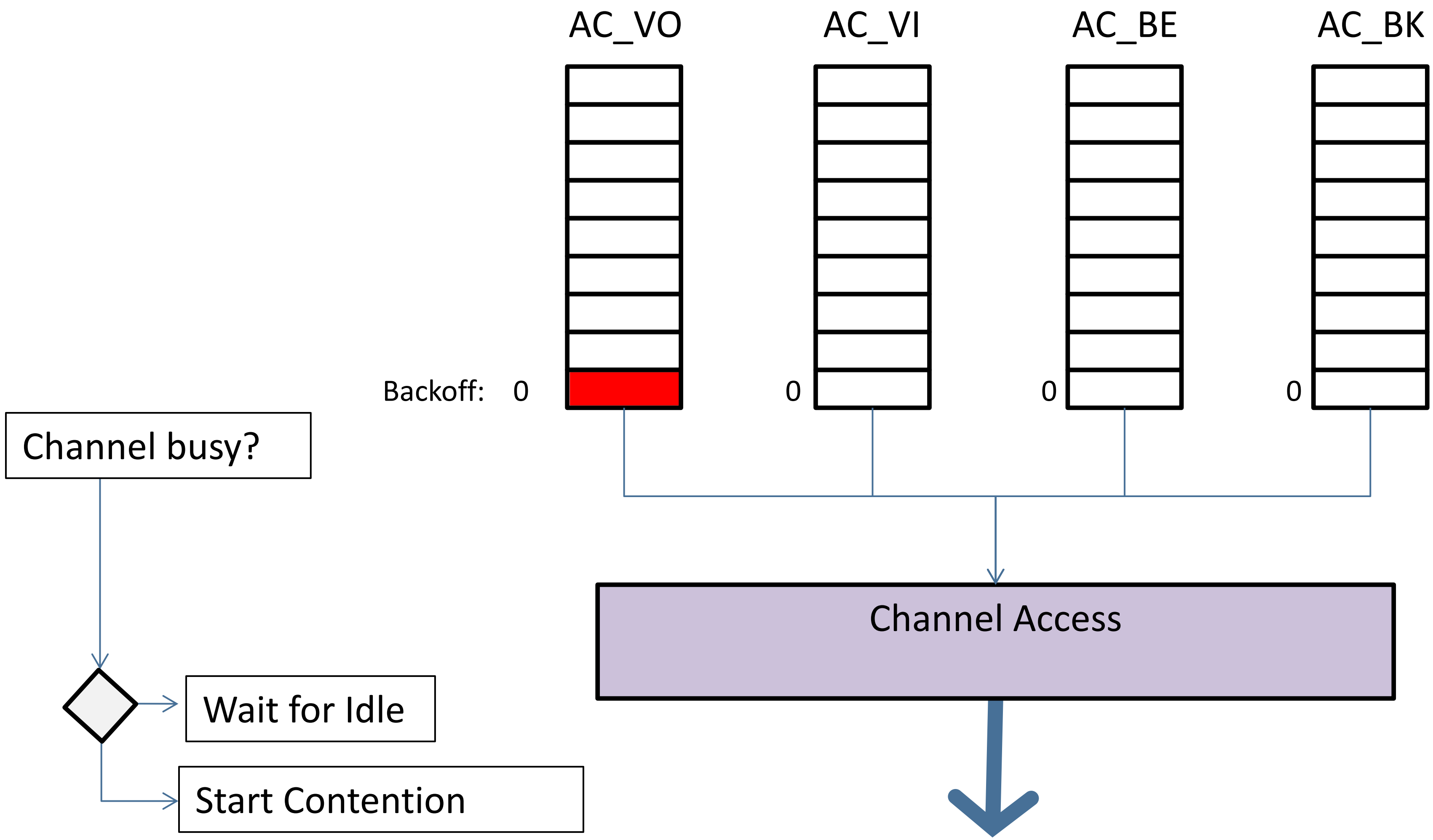
Parameter	Value
SlotTime	13µs
SIFS	32µs
CW_{min}	15
CW_{max}	1023
Bandwidth	3 .. 27 mbit/s

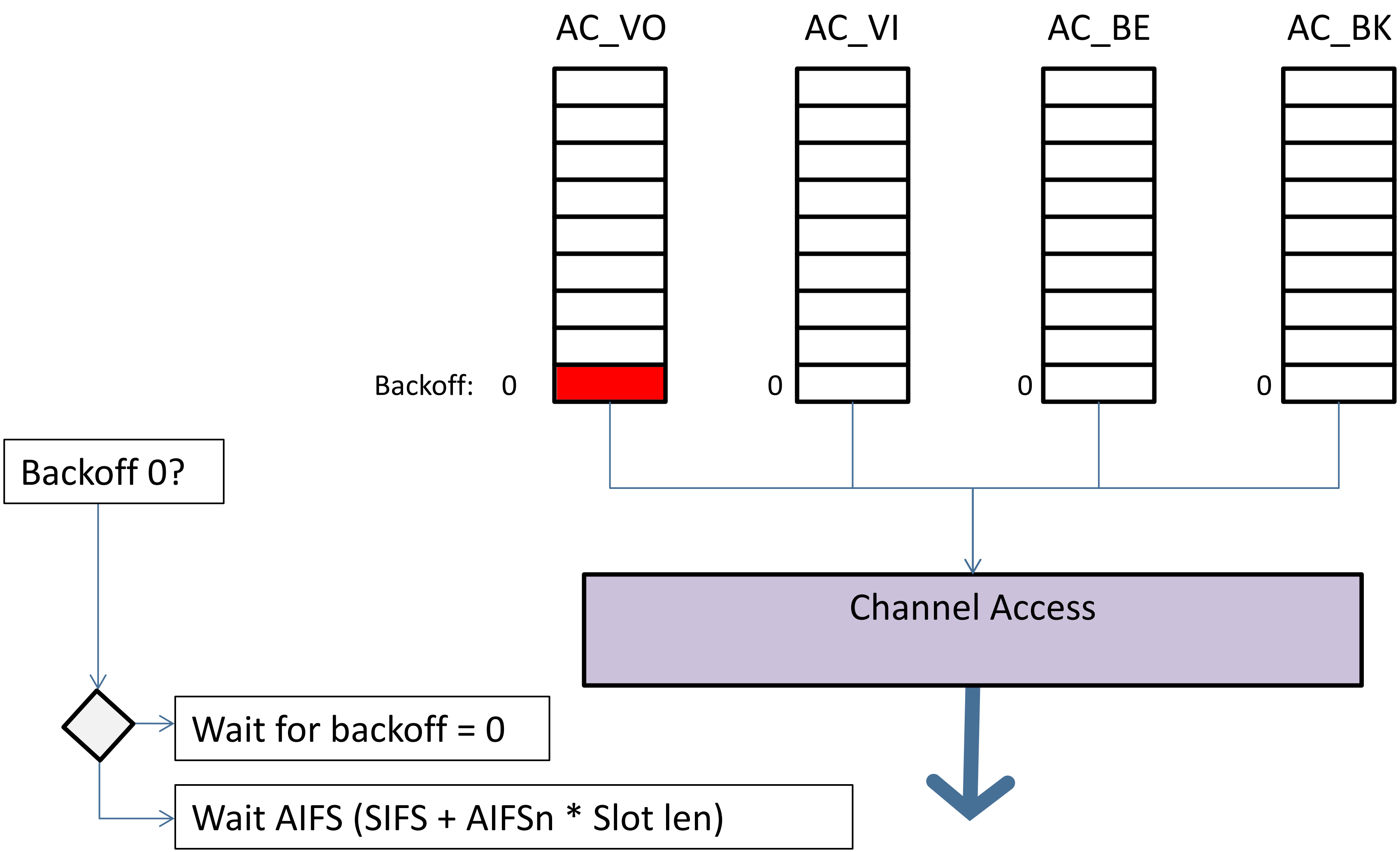
- Sample queue configuration

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

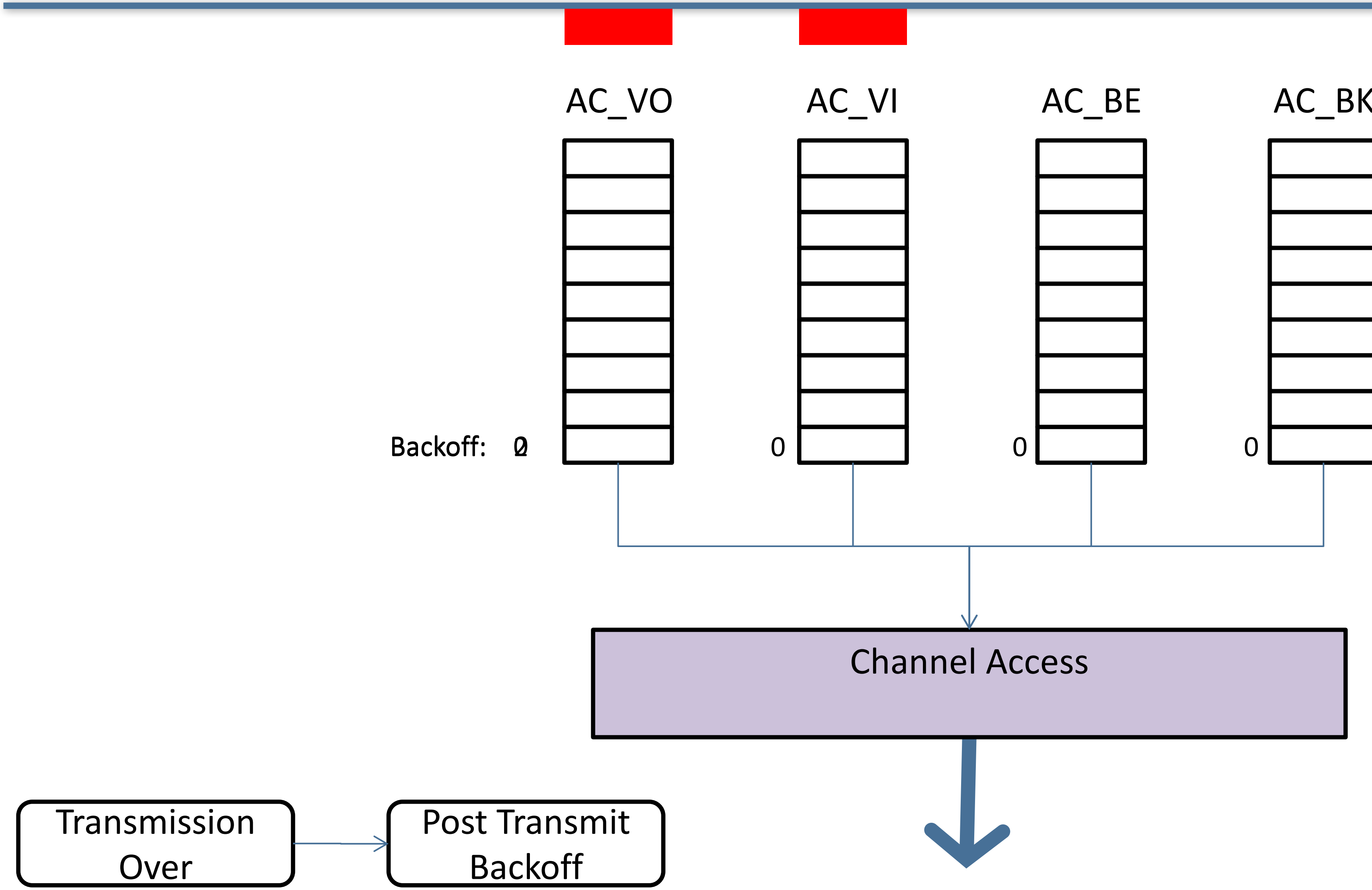
IEEE 802.11p




AC_VO
AC_VI
AC_BE
AC_BK
Backoff: 0
0
0
0
Channel busy?
Channel Access
Wait for Idle
Start Contention

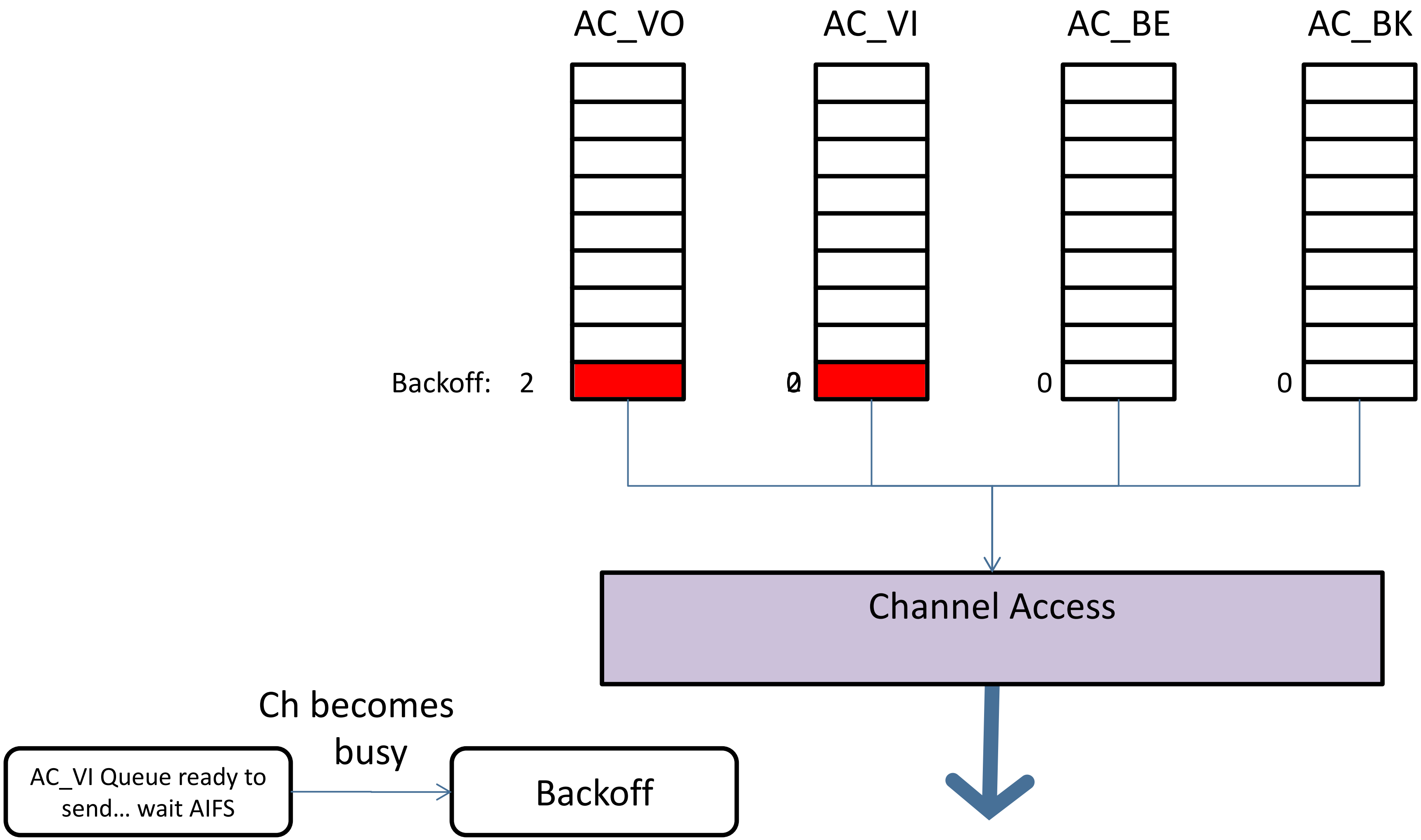

AC_VO
AC_VI
AC_BE
AC_BK
Backoff: 0
0
0
0
Backoff 0?
Channel Access
Wait for backoff = 0
Wait AIFS (SIFS + AIFSn * Slot len)

IEEE 802.11p

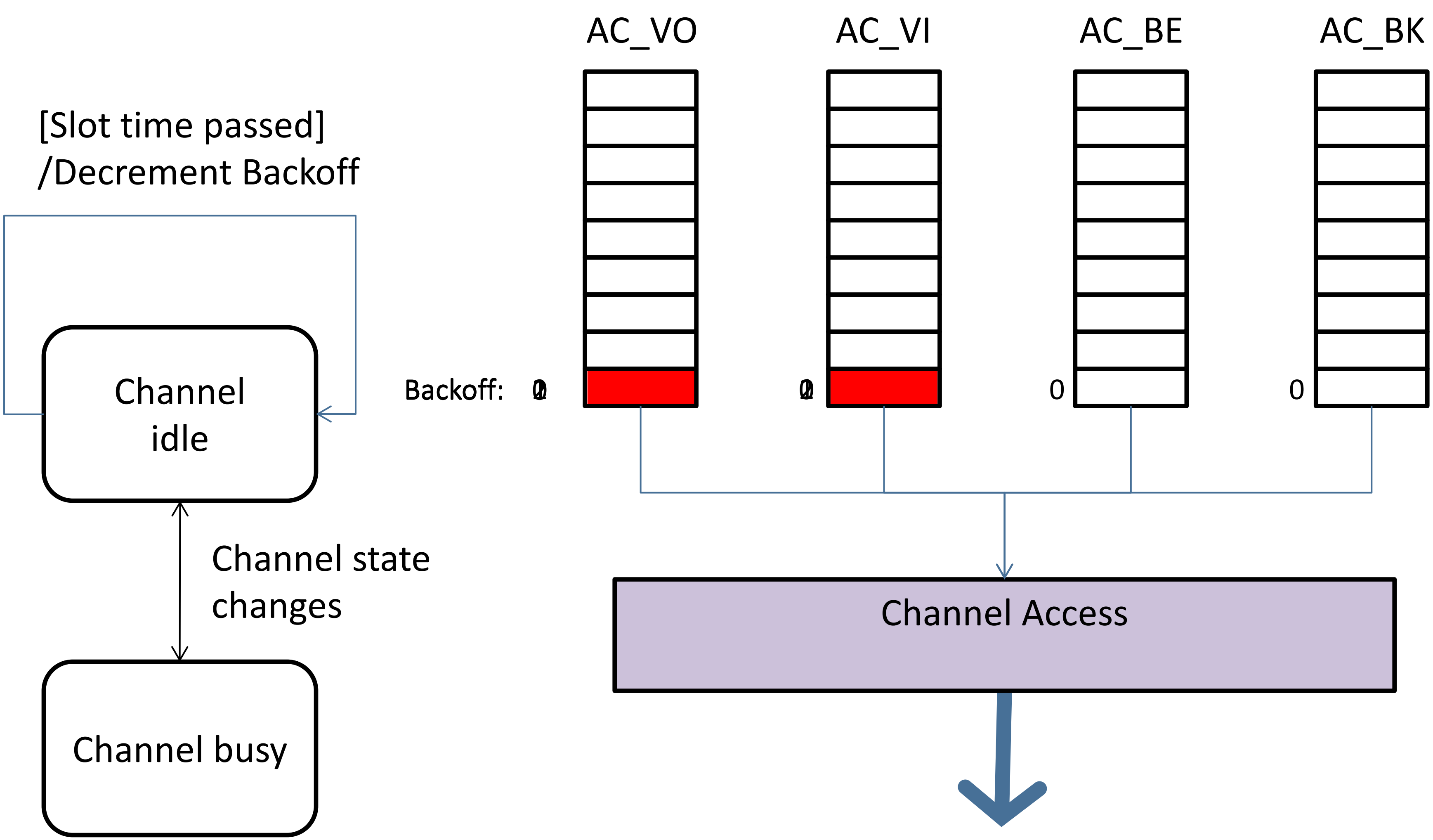


AC_VO
AC_VI
AC_BE
AC_BK
Backoff: 2
0
0
0
Channel Access
Transmission Over
Post Transmit Backoff

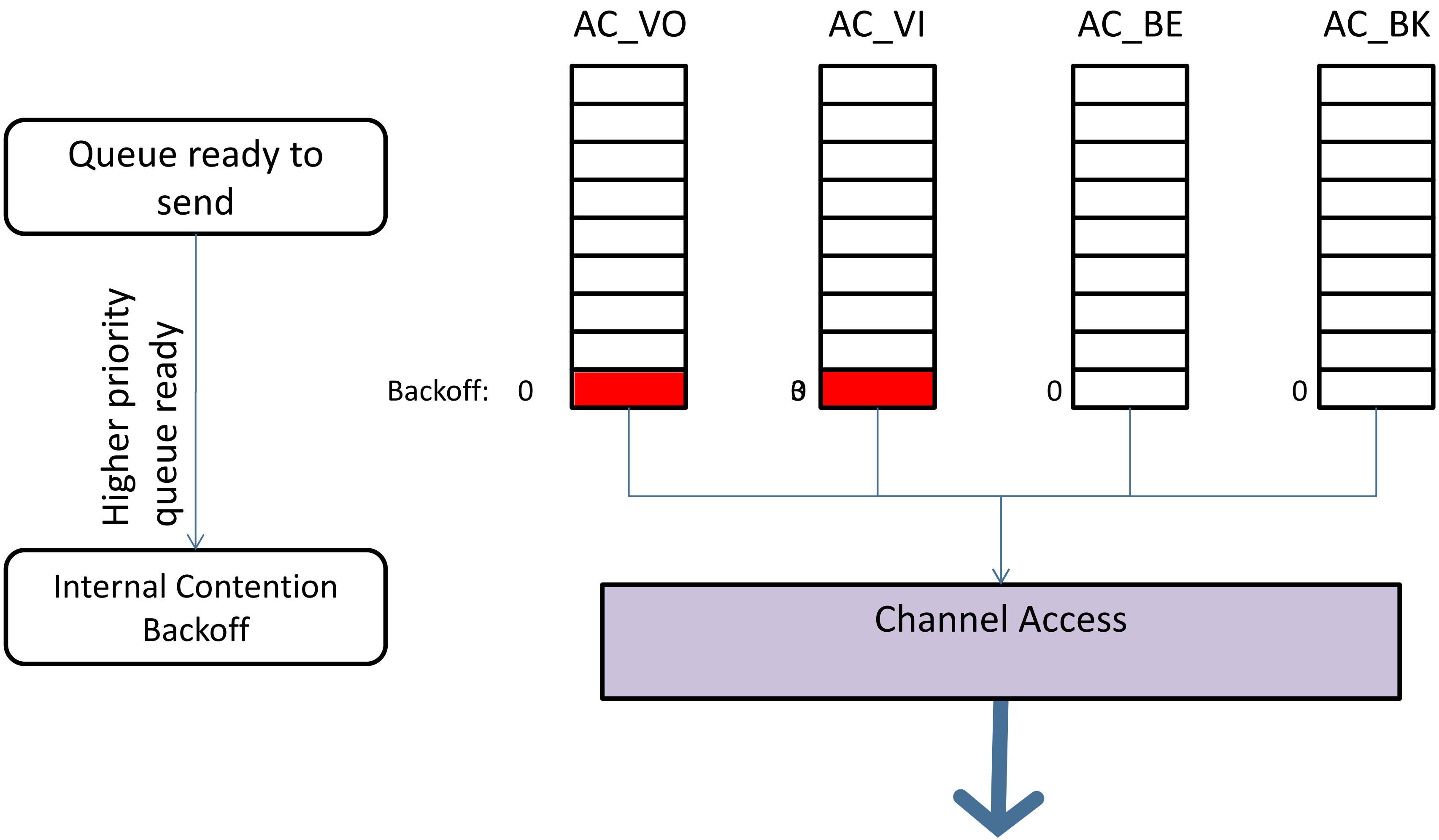
IEEE 802.11p



AC_VO
AC_VI
AC_BE
AC_BK
Backoff: 2
0
0
0
Channel Access
Ch becomes busy
AC_VI Queue ready to send… wait AIFS
Backoff


AC_VO
AC_VI
AC_BE
AC_BK
[Slot time passed]
/Decrement Backoff
Channel idle
Channel state changes
Channel busy
Backoff:
0
0
Channel Access

IEEE 802.11p

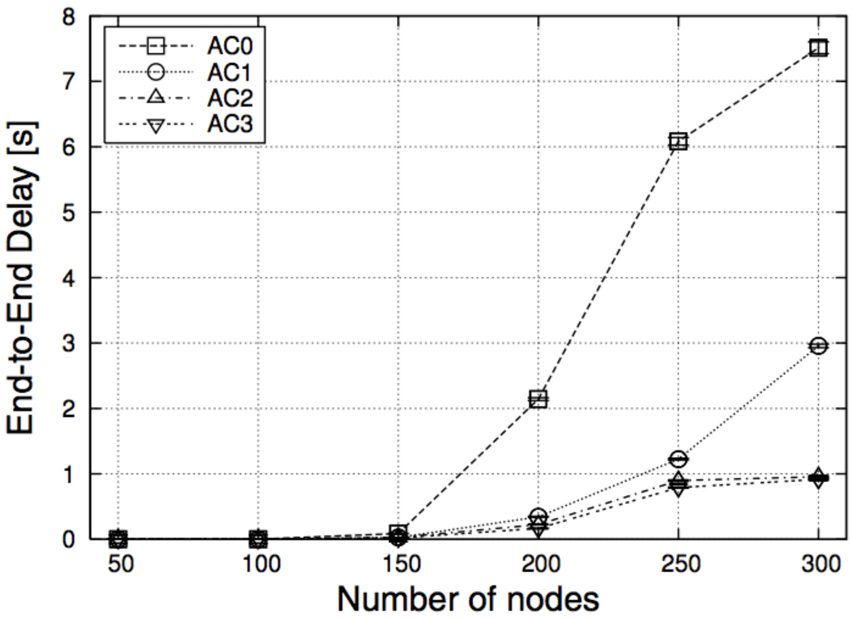

AC_VO
AC_VI
AC_BE
AC_BK
Queue ready to send
Higher priority queue ready
Internal Contention Backoff
Backoff: 0
0
0
Channel Access

- QoS in WAVE
  - mean waiting time for channel access, given sample configuration (and TXOP Limit=0 ➪ single packet)

■ Single Node:

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

■ Multiple Nodes:



[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. IEEE 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

- Pros of 802.11p/Ad hoc
  - Smallest possible latency
  - Can sustain operation without network operator / provider
  - Network load highly localized
  - Better privacy (➪ later slides)
- 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 PROTOCOLS

- 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

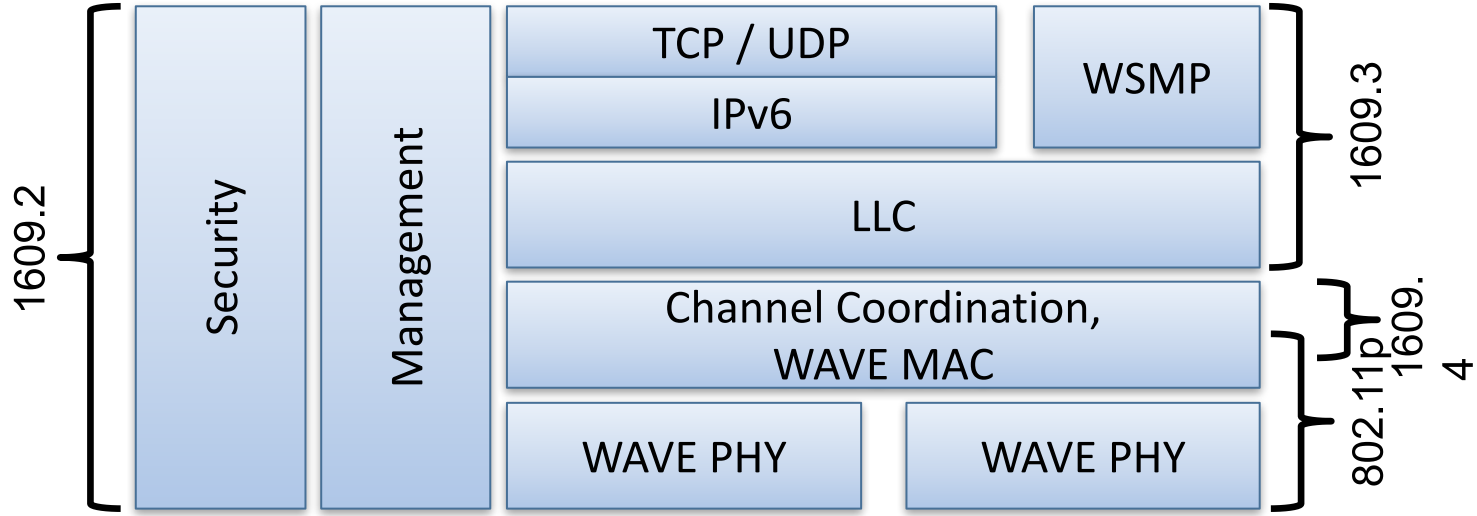
Higher Layer Standards for IEEE 802.11p

- 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.* 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.



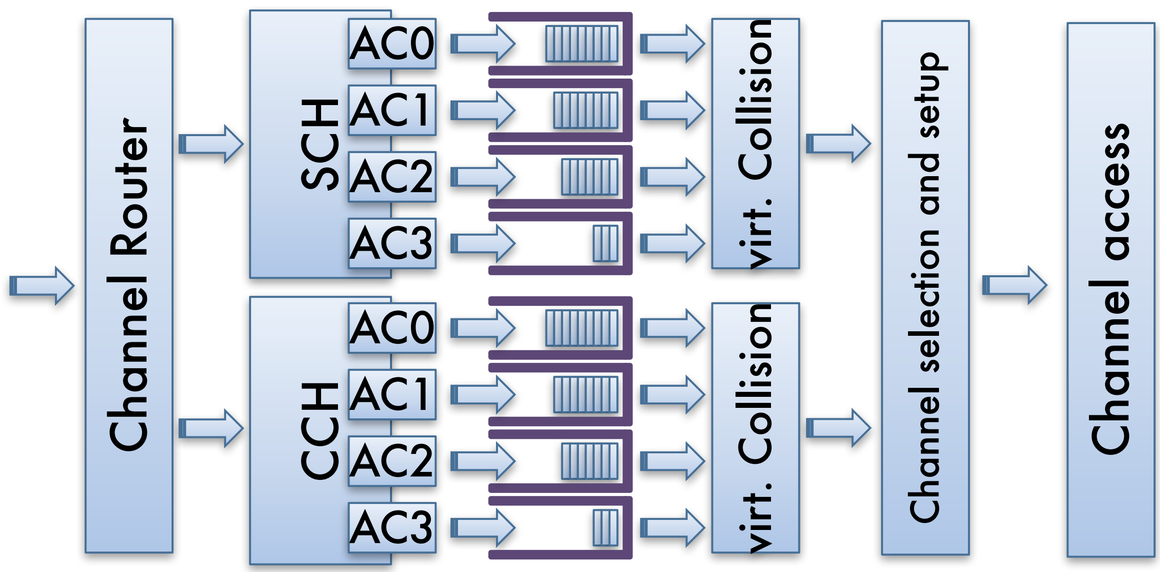
[1] Jiang, D. and Delgrossi, L., "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," Proceedings of 67th IEEE Vehicular Technology Conference (VTC2008-Spring), Marina Bay, Singapore, May 2008

[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)

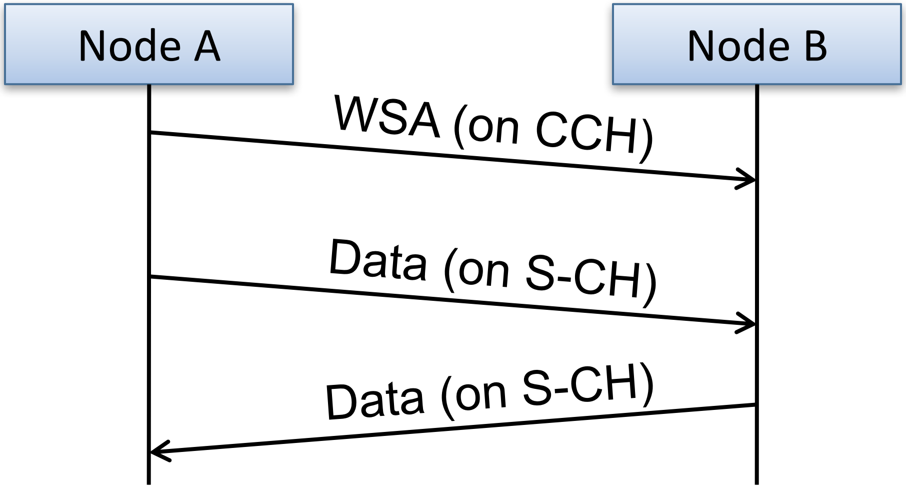
[1] IEEE Vehicular Technology Society, "IEEE 1609.4 (Multi-channel Operation)," IEEE Std, November, 2006

- 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



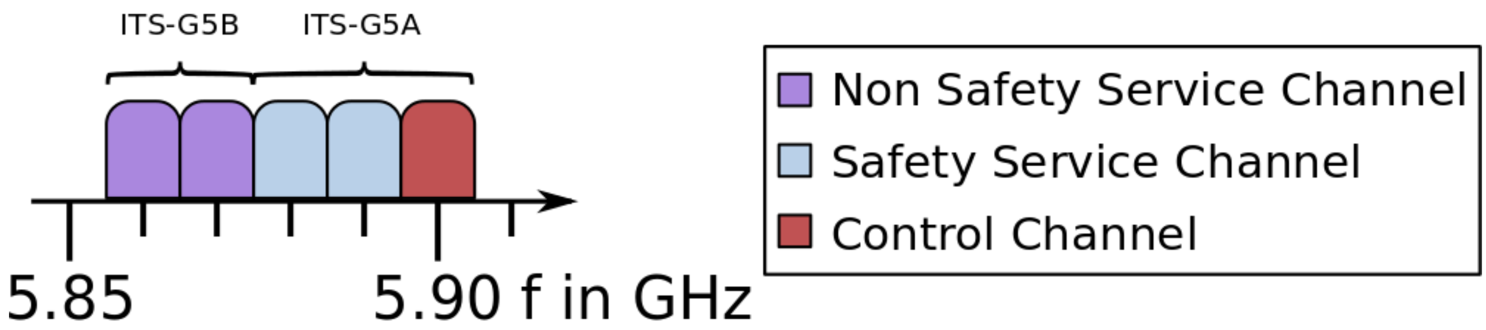
- Channel management
  - Control Channel (CCH):
    - Default channel upon initialization
    - WAVE service advertisements (WSA), WAVE short messages (WSM)
    - Channel parameters take fixed values
  - Service Channel (SCH):
    - Only after joining WAVE BSS
    - WAVE short messages (WSM), IP data traffic (IPv6)
    - Channel parameters can be changed as needed

- 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, as well as the required channel parameters to decode them

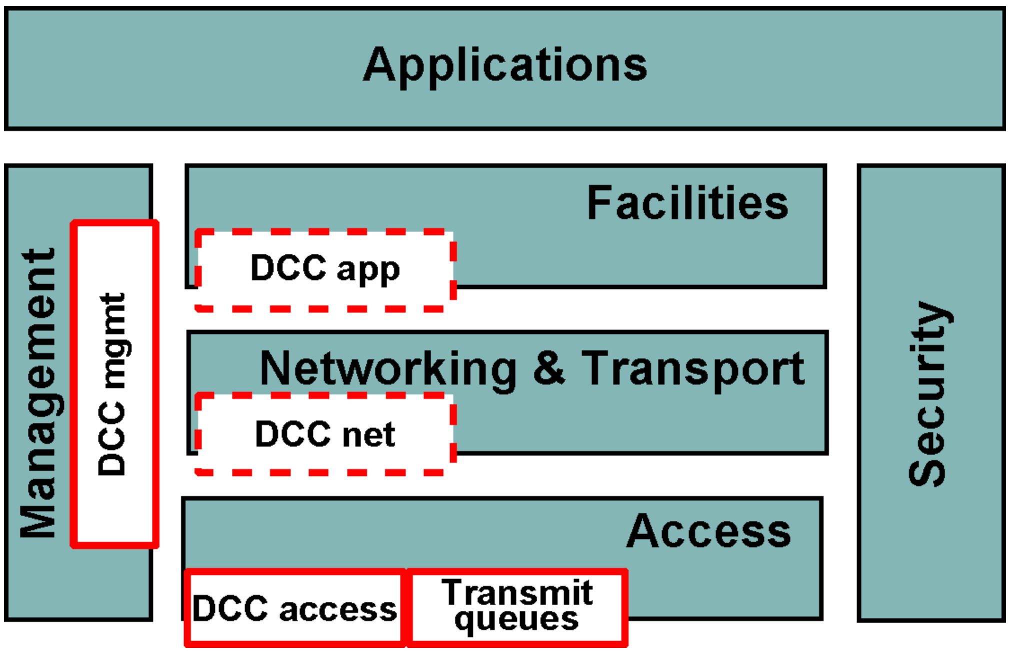


ETSI ITS G5

- Motivation
  - European standardization effort based on IEEE 802.11p
  - Standardization to include lessons learned from WAVE
  - Different instrumentation of lower layers
  - Different upper layer protocols
  - Different channel assignment
    - ITS-G5A (safety)
    - IST-G5B (non safety)



- Protocol stack
  - PHY and MAC based on IEEE 802.11p
  - Most prominent change:
    cross layer Decentralized Congestion Control (DCC)



- Channel management
  - Multi radio, multi antenna system
    - No alternating access
      - ⇨ Circumvents problems with synchronization
      - ⇨ No reduction in goodput
    - Direct result of experiences with WAVE
  - One radio tuned to CCH
    - Service Announcement Message (SAM)
    - Periodic: Cooperative Awareness Messages (CAM)
    - Event based: Decentralized Environment Notification Message (DENM)
  - Addl. radio tuned to SCH
    - User data

- Cooperative Awareness Message
  - Periodic (up to 10Hz) safety message
  - Information on state of surrounding vehicles:
    - Speed, location, …
  - Message age highly relevant for safety
    - Need mechanisms to discard old messages
  - Safety applications rely on CAMs:
    - Tail end of jam
    - Rear end collision
    - Intersection assistance…
  - Sent on CCH
  - Generated every 100ms .. 1s, but only if Δangle (>4°), Δposition (>5m), Δspeed (>1m/s)

- Decentralized Environmental Notification Message (DENM)
  - Event triggered (e.g., by vehicle sensors)
    - Hard braking
    - Accident
    - Tail end of jam
    - Construction work
    - Collision imminent
    - Low visibility, high wind, icy road, …
  - Messages have (tight) local scope, relay based on
    - Area (defined by circle/ellipse/rectangle)
    - Road topology
    - Driving direction

BEACONING: 1-HOP BROADCAST

Beaconing: 1-hop Broadcast

- ETSI ITS CAMs (Cooperative Awareness Messages)
  - Periodic (up to 10Hz) safety message
  - Information on state of surrounding vehicles:
    - Speed, location, …
  - Message age highly relevant for safety
    - Need mechanisms to discard old messages
- IEEE 1609 BSMs (Basic Safety Messages)
- … but

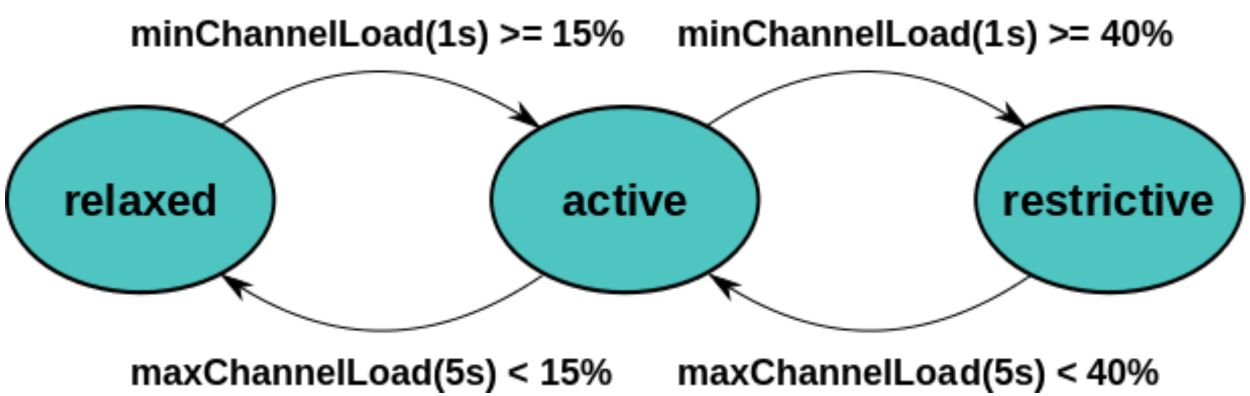
Beaconing: 1-hop Broadcast

- 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 ⇔ other, future, and legacy protocols
- How to do better?
  - Dynamically adapt beacon interval
  - Dynamically use all free(!) channel capacity

Decentralized Congestion Control (DCC)

- Core feature of ETSI ITS G5
- Adaptive parameterization to avoid overload
- Configurable parameters per AC:
  - TX power (Transmit Power Control, TPC)
  - Minimum packet interval (Transmit Rate Control, TRC)
  - Data rate (Transmit Datarate Control, TDC)
  - Sensitivity of Clear Channel Assessment (DCC Sensitivity Control, DSC)
- State machine determines which parameter set is selected; available states:
  - Relaxed
  - Active (multiple sub states)
  - Restrictive

- Measure min/maxChannelLoad(x)
  - Min/max channel load in [t_{now}-x .. t_{now}]
  - Channel load: fraction of time that channel was sensed busy during measuring interval (ex: $T_m \approx 1s$)
  - Channel busy: Average received power (signal or noise) during probing interval (ex: $T_p \approx 10\mu s$) above carrier sense threshold
- State machine for Control Channel:

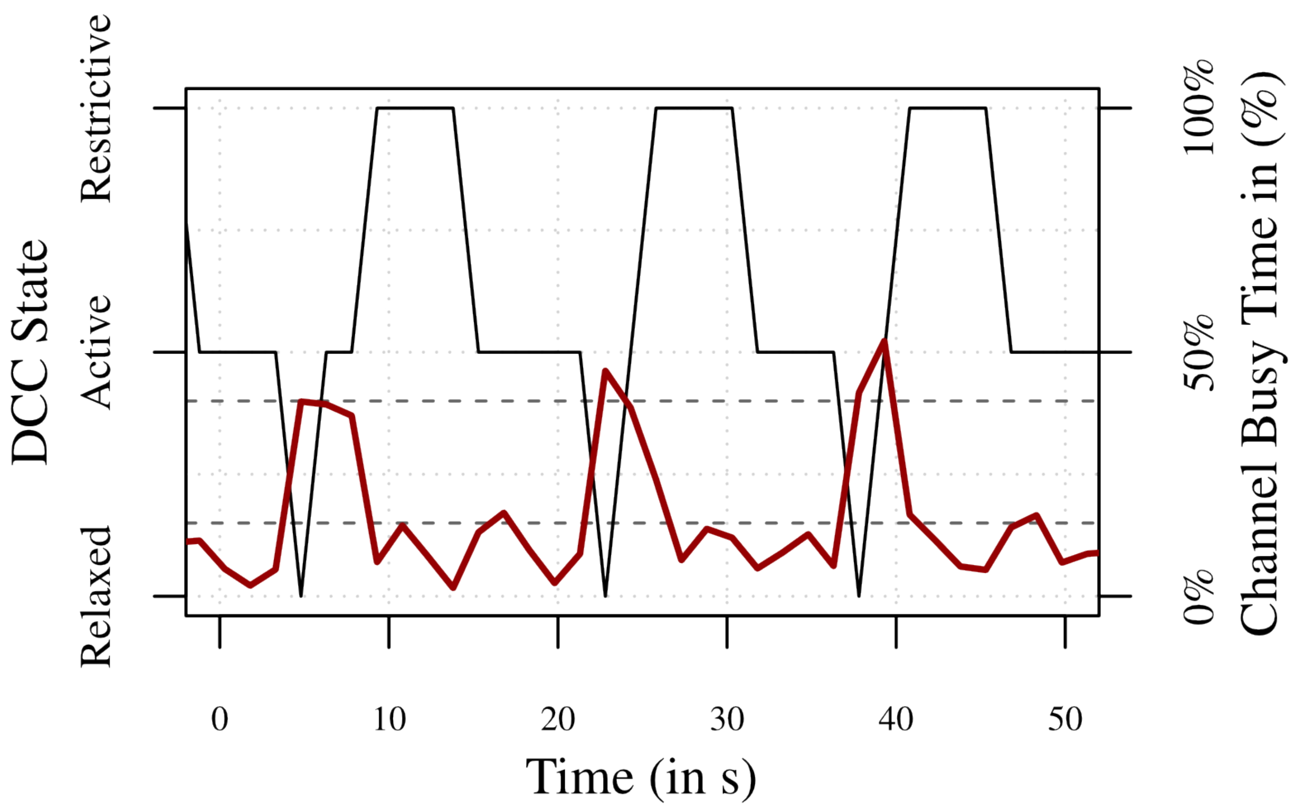


- Example: Control Channel
  - TX power: relaxed: 33 dBm ➪ active: ref ➪ restrictive: -10 dBm
  - "ref": Value remains unchanged
  - Remember:
    - 33 dBm ➪ $10^{3.3}$ mW ➪ 2000 mW
    - -10 dBm ➪ 10^{-1} mW ➪ 0.1 mW

	State					
	Relaxed	Active				Restrictive
		AC_VI	AC_VO	AC_BE	AC_BK	
TX power	33 dBm	ref	25dBm	20dBm	15dBm	-10 dBm
Min pkt interval	0.04 s	ref	ref	ref	ref	1 s
Data rate	3 Mbit/s	ref	ref	ref	ref	12 Mbit/s
CCA threshold	-95 dBm	ref	ref	ref	ref	-65 dBm

Decentralized Congestion Control (DCC)

- Oscillating channel load (both local and global!)
  - …caused by channel access being too restrictive (standard parameters)



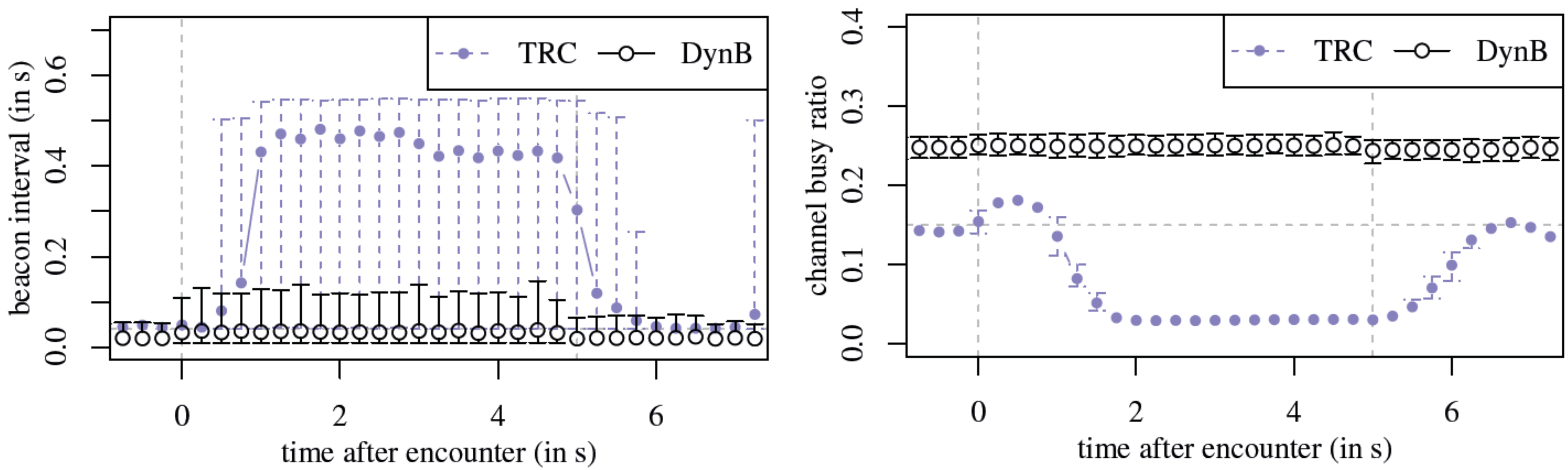
[1] David Eckhoff, Nikoletta Sofra and Reinhard German, "A Performance Study of Cooperative Awareness in ETSI ITS G5 and IEEE WAVE," Proceedings of 10th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2013), Banff, Canada, March 2013.

- Consider 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 I
- Base calculation of I on:
  - Channel busy time fraction b_t
  - Number of neighbors N
  - Desired interval I_{des}
  - Desired channel busy time fraction b_{des}
- $I = I_{des} + r \times (I_{max} - I_{des})$
  - With $I_{max} = (N + 1) \times I_{des}$
    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 Beaconing Can Help," Proceedings of 32nd IEEE Conference on Computer Communications (INFOCOM 2013), Mini-Conference, Turin, Italy, April 2013

DynB – Dynamic Beaconing

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



Application-based: Jerk Beaconing

- Jerk:
  - physical quantity measuring variation of acceleration over time

$$\Delta_a = a(t) - a(t_{\text{sent}})$$

  - using an estimation of jerk we compute the beacon interval

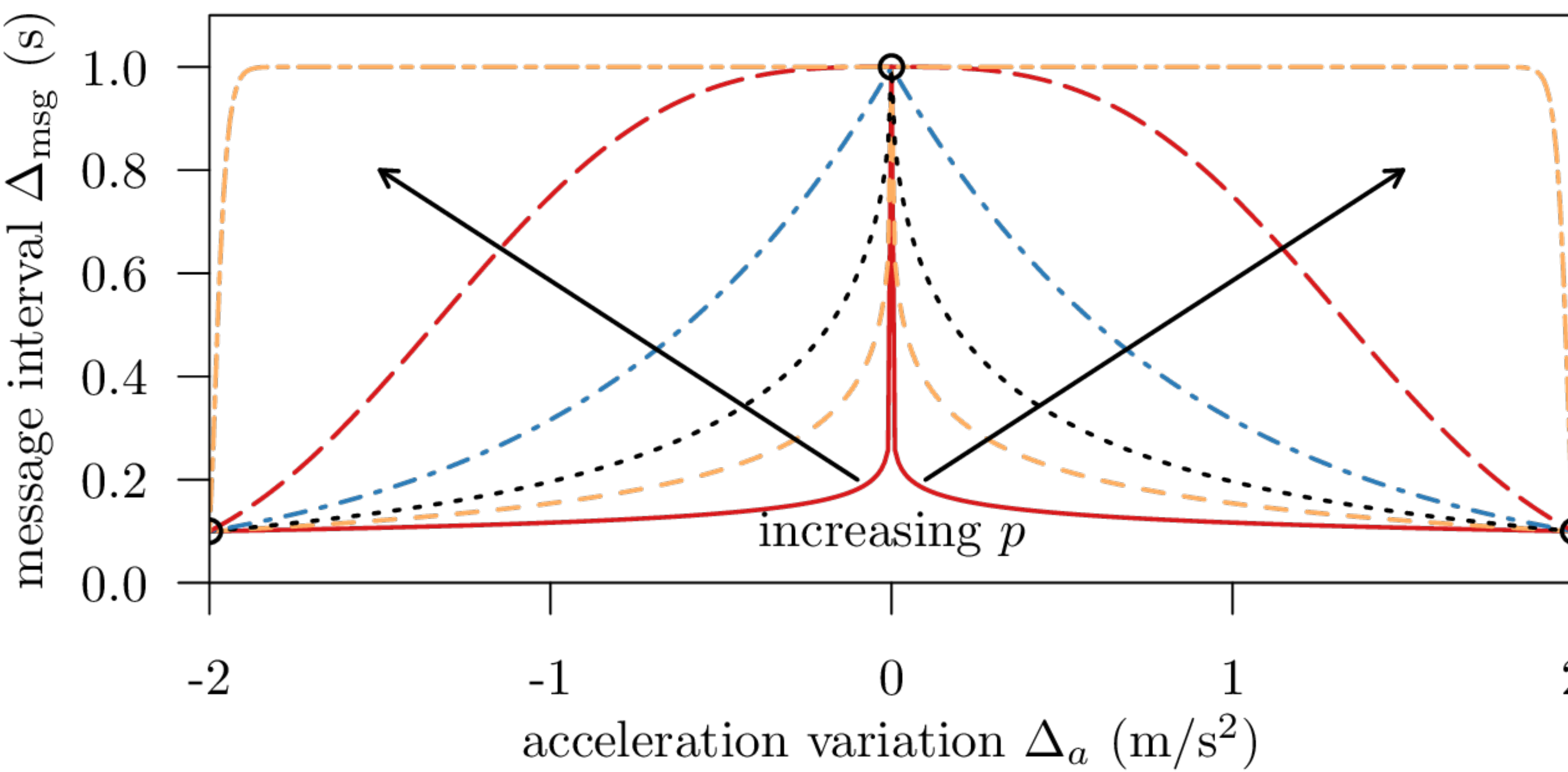
$$\Delta_{\text{msg}}(\Delta_a) = \max\left(e^{-\alpha|\Delta_a|^p} \cdot \max_{\text{bi}}, \min_{\text{bi}}\right)$$

  - tunable parameters:
    - minimum beacon interval
    - maximum beacon interval
    - sensitivity
- Main idea:
  - the more constant the system, the lower the requirement
  - send updates only when needed, use prediction otherwise

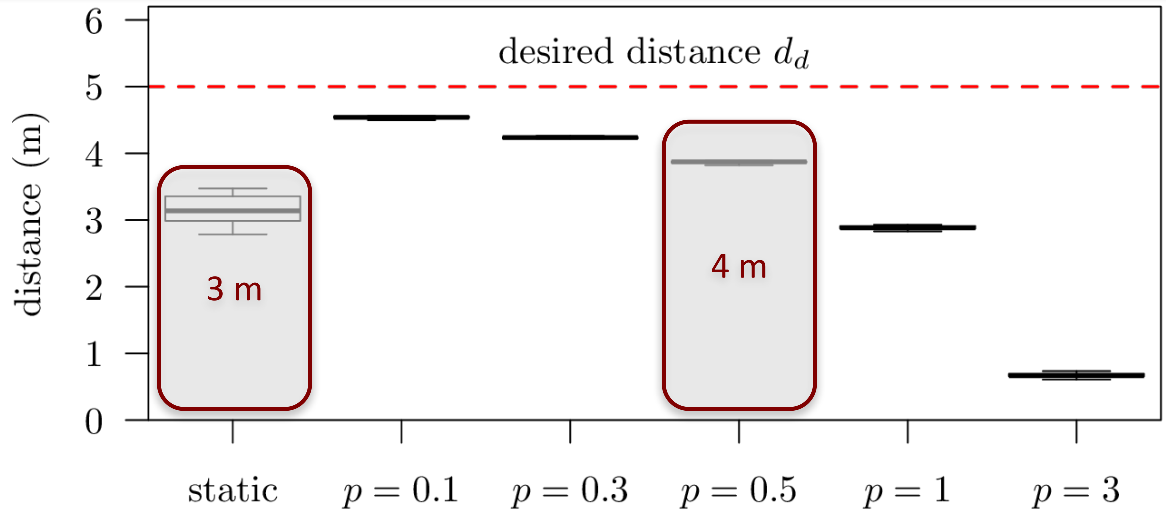
$$v(t) = v(t_{\text{sent}}) + a(t_{\text{sent}}) \cdot (t - t_{\text{sent}})$$

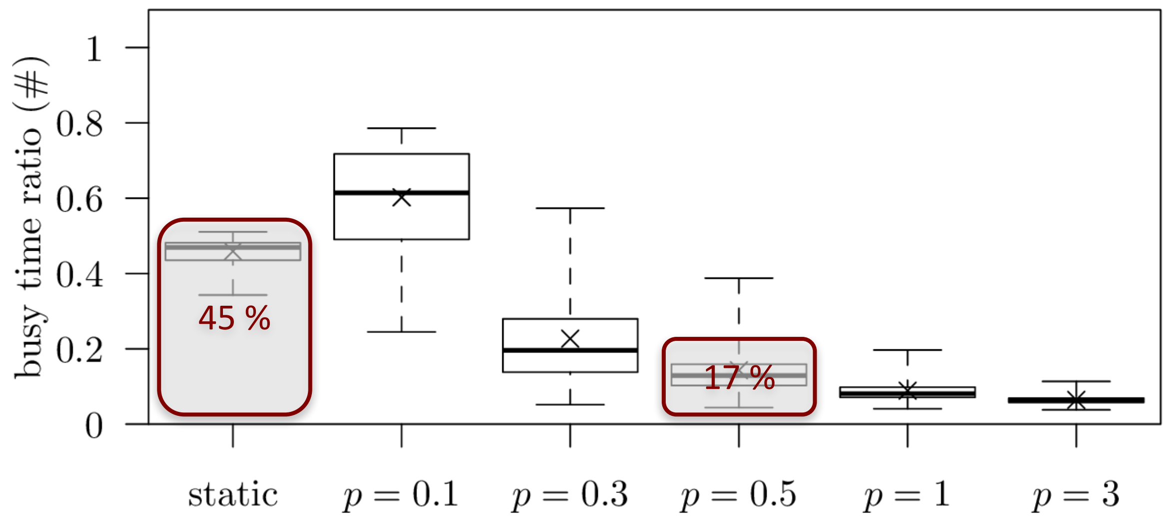
Jerk Beaconing

$$\Delta_{\text{msg}}(\Delta_a) = \max\left(e^{-\alpha|\Delta_a|^p} \cdot \max_{\text{bi}}, \min_{\text{bi}}\right)$$

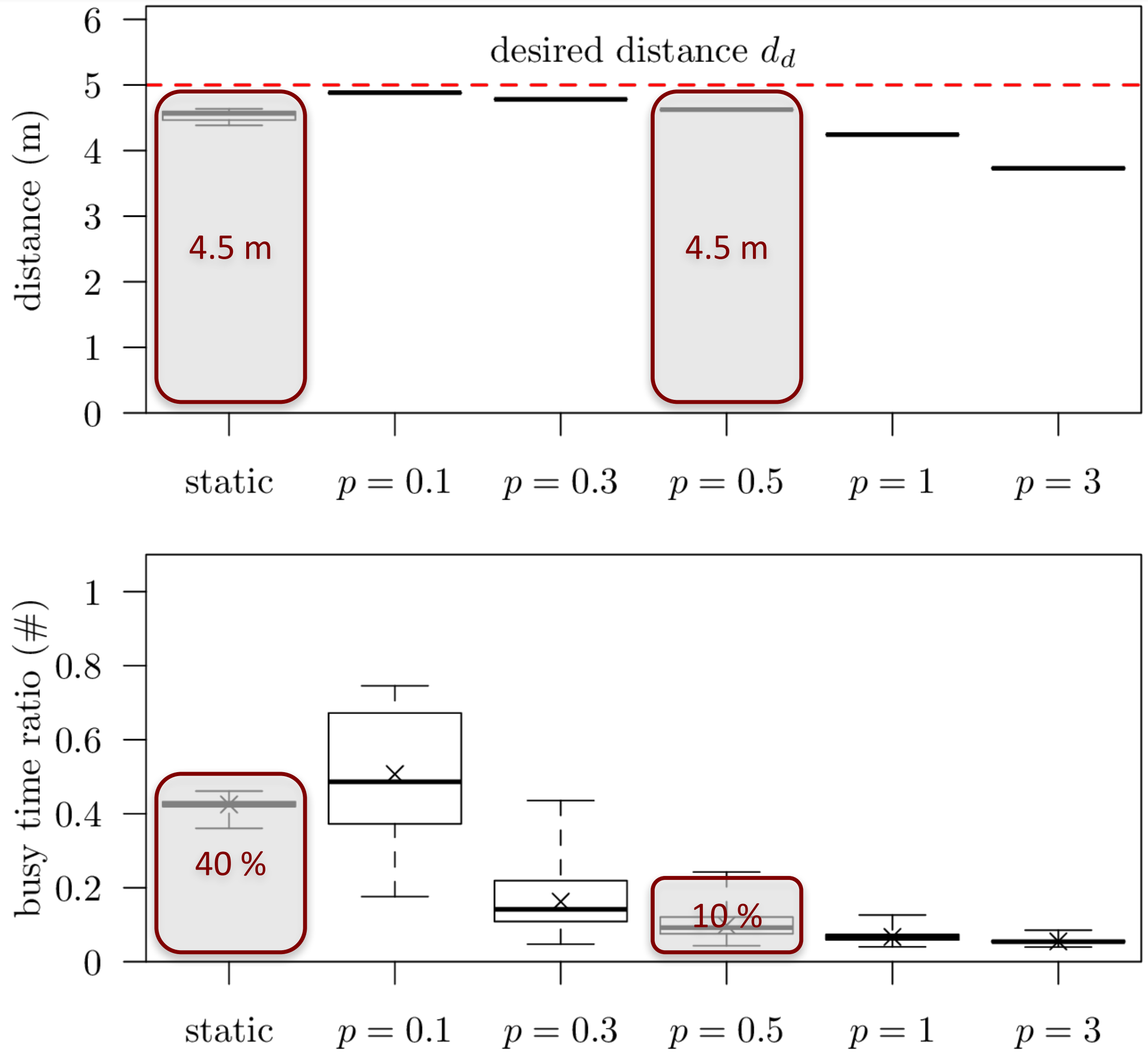


Evaluation: Strong shock waves





Evaluation: Moderate shock waves



Routing techniques in Vehicular Networks

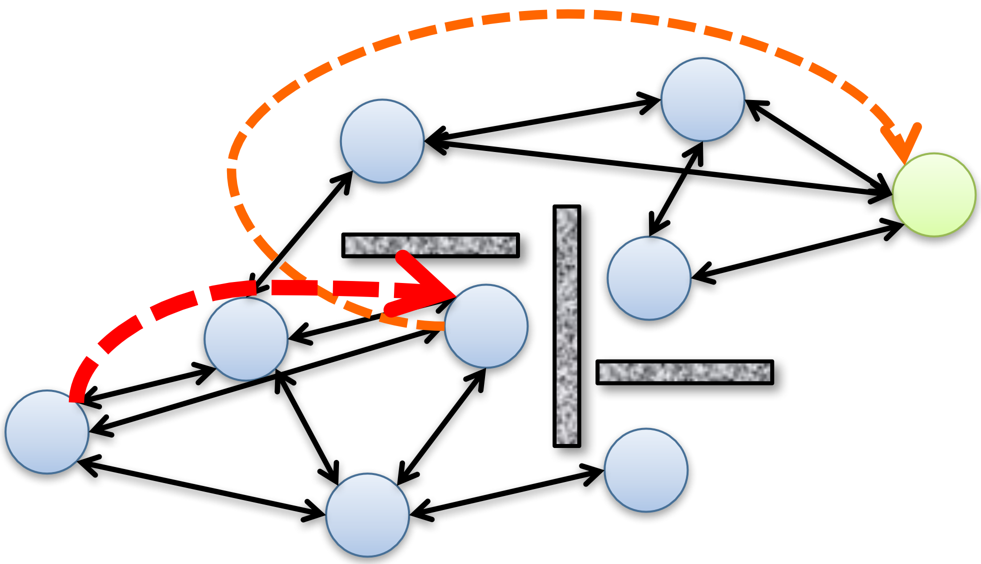
MULTI-HOP FORWARDING

Classical routing

- Might not be suited for Vehicular Networks…
  - Distance vector
    - Each node stores a vector of (dst, cost, next-hop)
  - Link state
    - Known topology + Dijkstra
    - Fast convergence vs. overhead
  - Reactive (on demand)
    - Establish routes only when needed
  - Proactive (table driven)
    - Continuously maintain routes up to date
  - Hop by hop
    - Intermediate nodes chose the next hop for a packet
  - Source routing
    - Packets include the full route

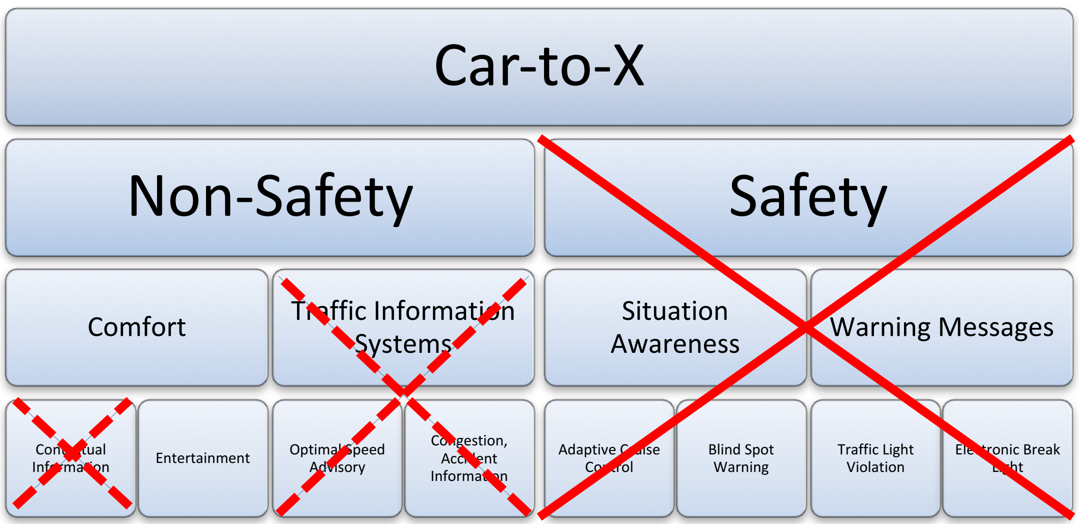
Georouting

- Primary metrics: position / distance to destination
- Requires node positions to be known (at least for the destination)
- Two operation modes (typ.):
  - Greedy mode: choose next hop according to max progress
  - Recovery mode: escape dead ends (local maxima)
- Must ensure that message never gets lost



Routing

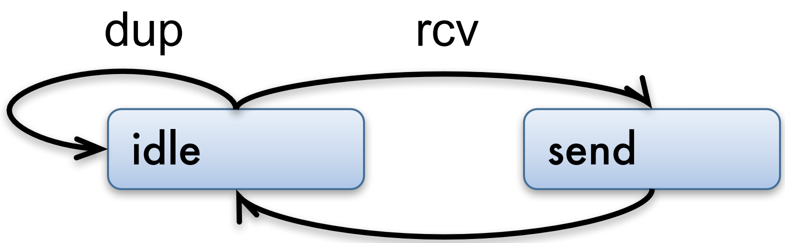
- Q: Can (classical) routing work in VANETs?
- A: Only in some cases.
- Commonly need multicast communication, low load, low delay
- Additional challenges and opportunities:
  network partitioning, dynamic topology, complex mobility, …



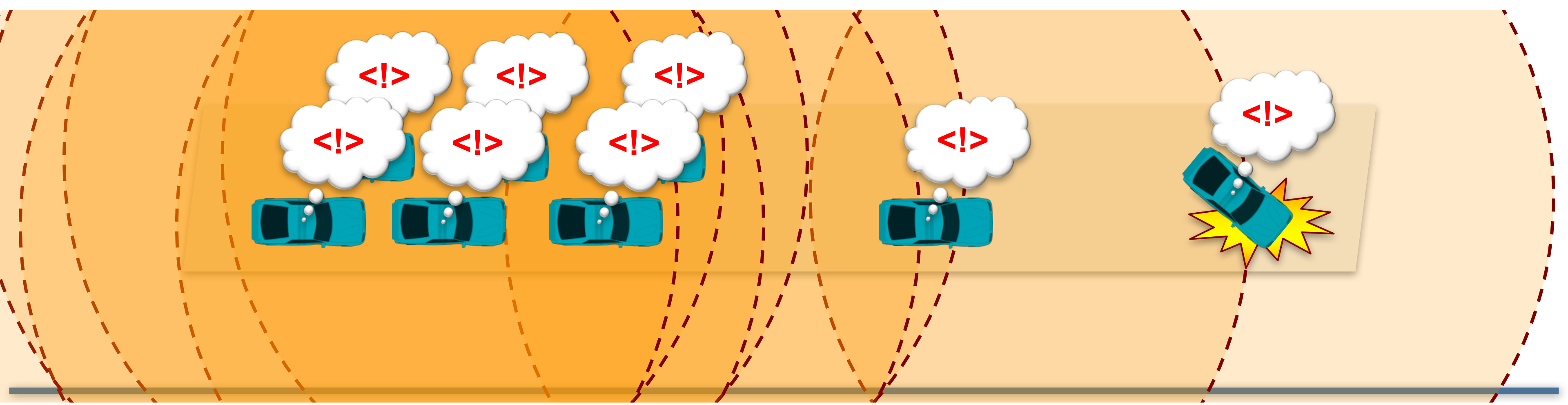
[1] Toor, Yasser and Mühlethaler, Paul and Laouiti, Anis and Fortelle, Arnaud de La, "Vehicle Ad Hoc Networks: Applications and Related Technical Issues," IEEE Communications Surveys and Tutorials, vol. 10 (3), pp. 74-88, 2008

"Smart" Flooding

- Flooding: Multi-Hop Broadcast
- Simplest protocol: "Smart Flooding":



  - Problem: Broadcast Storm
    - Superfluous re-broadcasts overload channel



Flooding: Broadcast suppression

- Motivation
  - Needs no neighbor information
  - Needs no control messages
  - Maximizes distance per hop
  - Minimizes packet loss
- Approach
  - Node receives message, estimates distance to sender
  - Selectively suppresses re-broadcast of message
  - Alternatives
    - weighted p-persistence
    - slotted 1-persistence
    - slotted p-persistence

[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

Flooding: Broadcast suppression

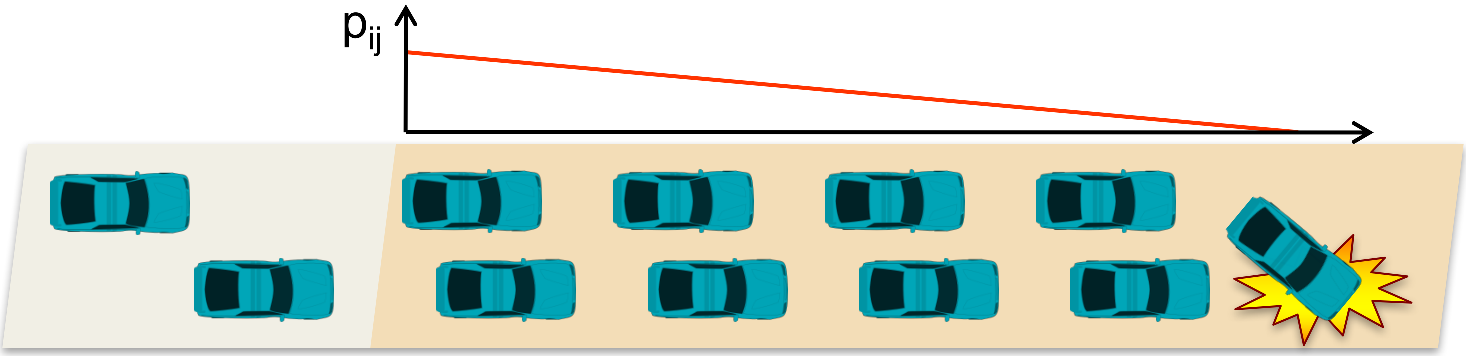
- Estimate distance to sender as $0 \leq \rho_{ij} \leq 1$
- GPS based

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

- RSS based

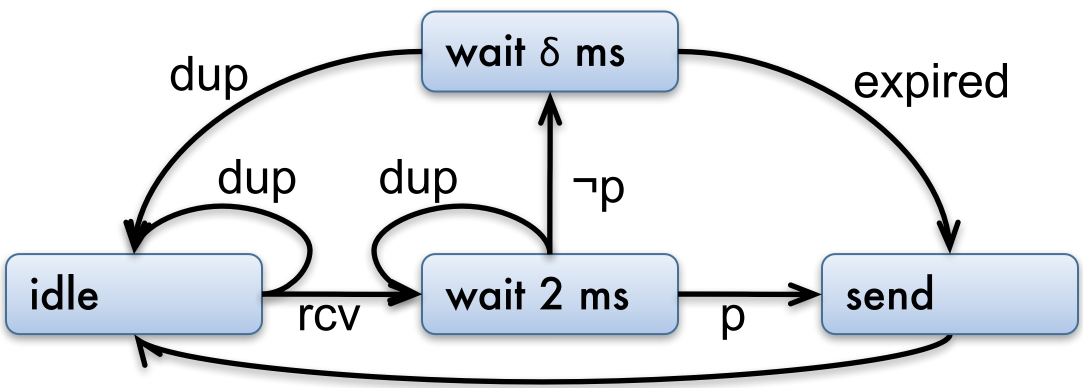
$$\varrho_{ij} = \begin{cases} 0 & \text{if } RSS_x < RSS_{min} \\ \dfrac{RSS_{max} - RSS_x}{RSS_{max} - RSS_{min}} & \text{if } RSS_{min} \leq RSS_x < RSS_{max} \\ 1 & \text{otherwise} \end{cases}$$

- Weighted p-persistence
  - Probabilistic flooding with variable p_{ij} for re-broadcast
  - Thus, higher probability for larger distance per hop

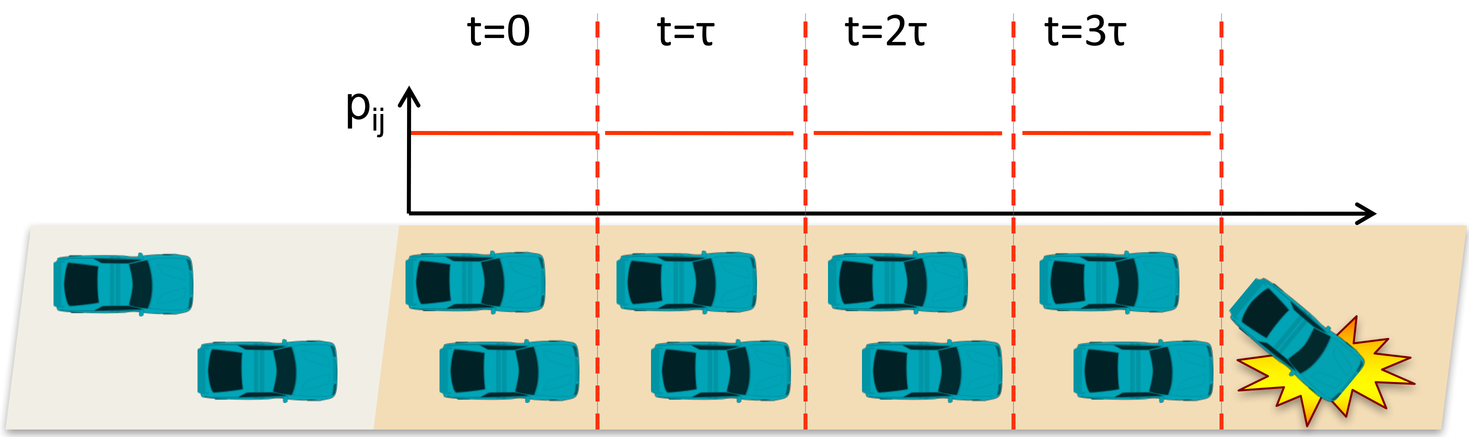


Flooding: Broadcast suppression

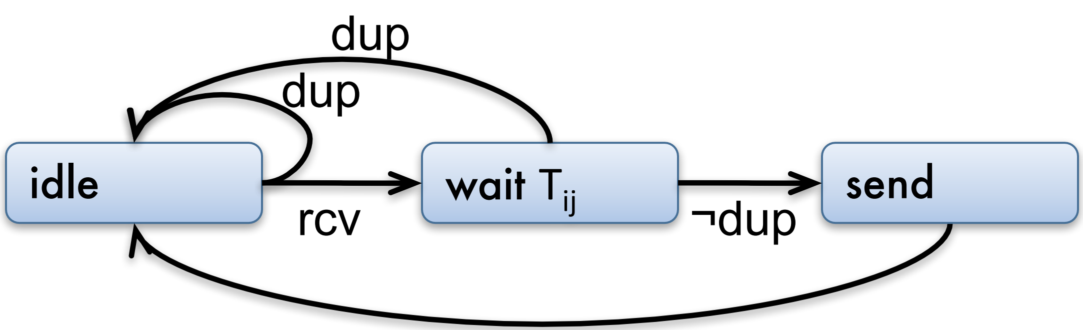
- Weighted p-persistence
  - Wait WAIT_TIME (e.g., 2 ms)
  - choose p = min(ρij) of all received packets (probability for re-broadcast of packet)
  - Ensure that at least one neighbor has re-broadcast packet



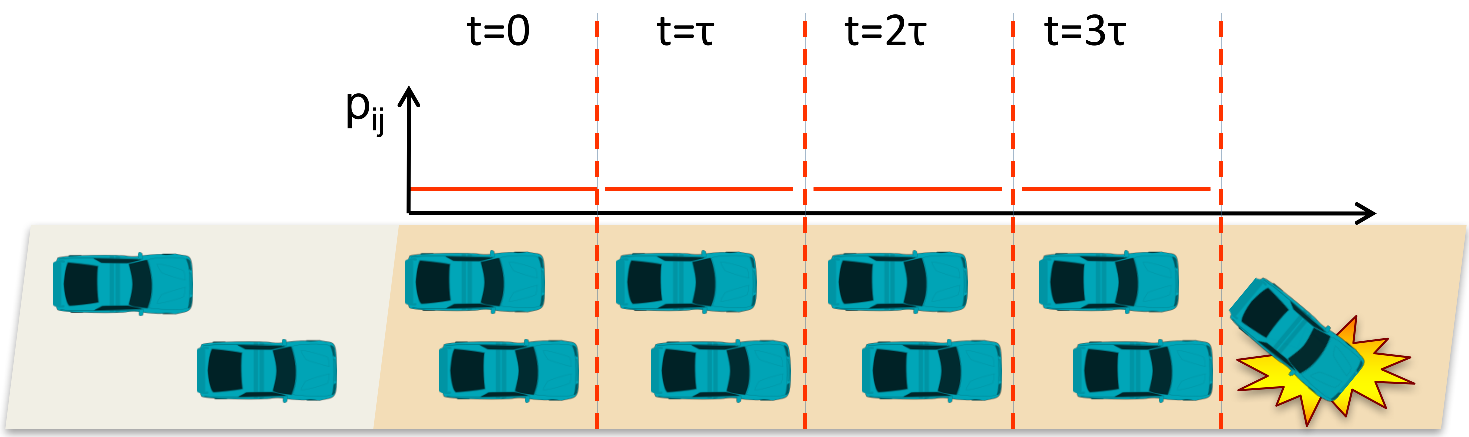
- Slotted 1-persistence
  - Suppression based on waiting and overhearing
  - Divide length of road into slots
  - More distant slots send sooner
  - Closer slots send later (or if more distant slots did not re-broadcast)
  - Thus, higher probability to transmit over longer distance



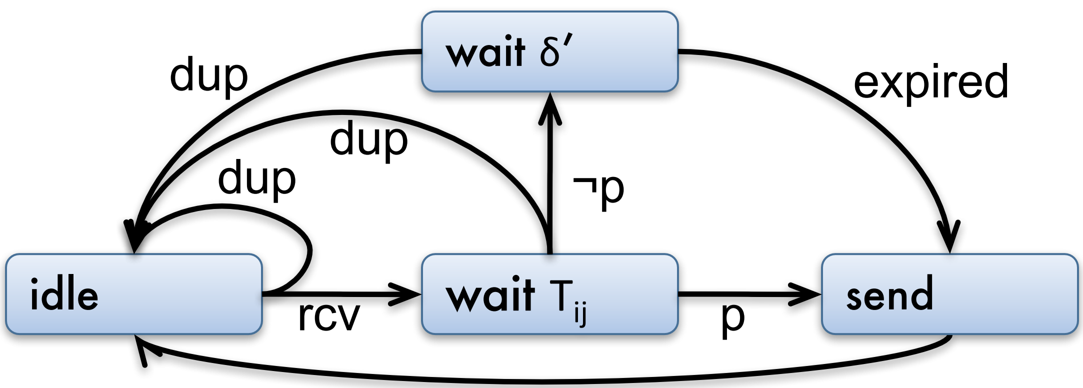
- Slotted 1-persistence
  - Divide “communication range“ into Ns slots of length τ
  - Nodes wait before re-broadcast, waiting time depending on slot
  - Duplicate elimination takes care of suppression of broadcasts



- Slotted p-persistence
  - Cf. slotted 1-persistence
  - Fixed forwarding probability p (instead of 1)

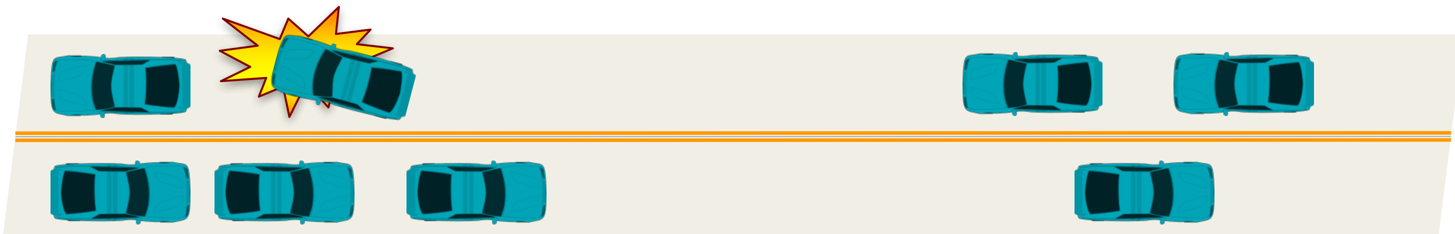


- Slotted p-persistence
  - Wait for T_{ij} (instead of fixed WAIT_TIME)
  - Use probability p (instead of 1)
  - Ensure that at least one neighbor has re-broadcast the packet by waiting for $\delta' > \max(T_{ij})$

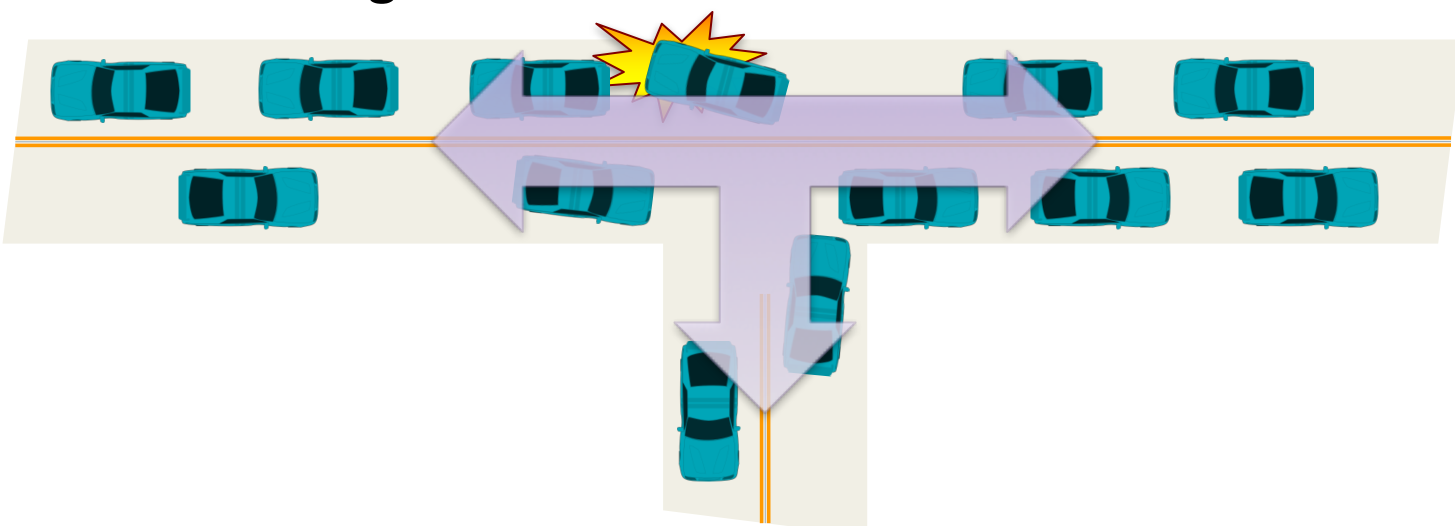


Flooding: Remaining problems

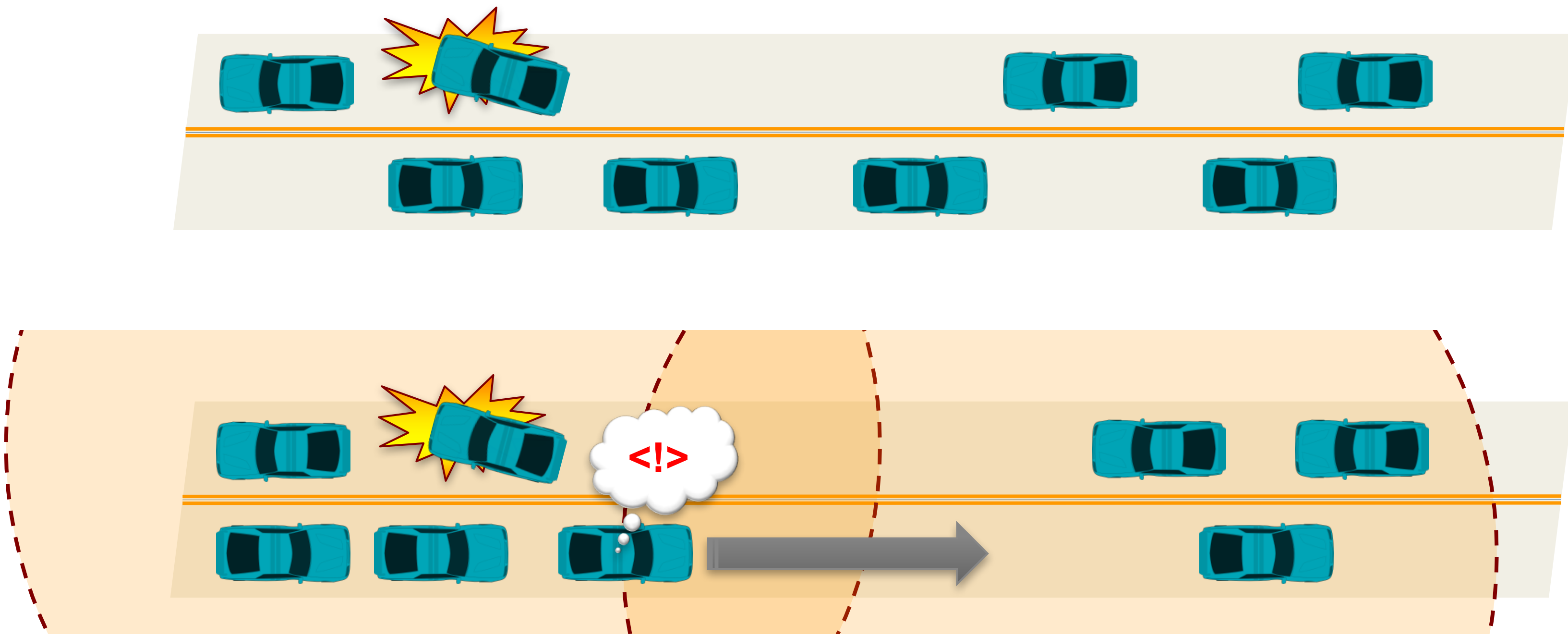
- Temporary network fragmentation



- Undirected message dissemination

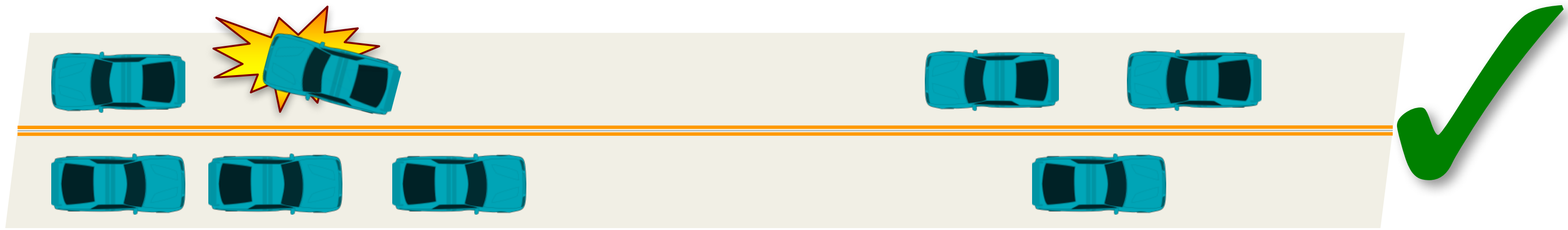


- Idea: detect current scenario, switch between protocols
- Check for fragmented network
  - Network connected → perform broadcast suppression

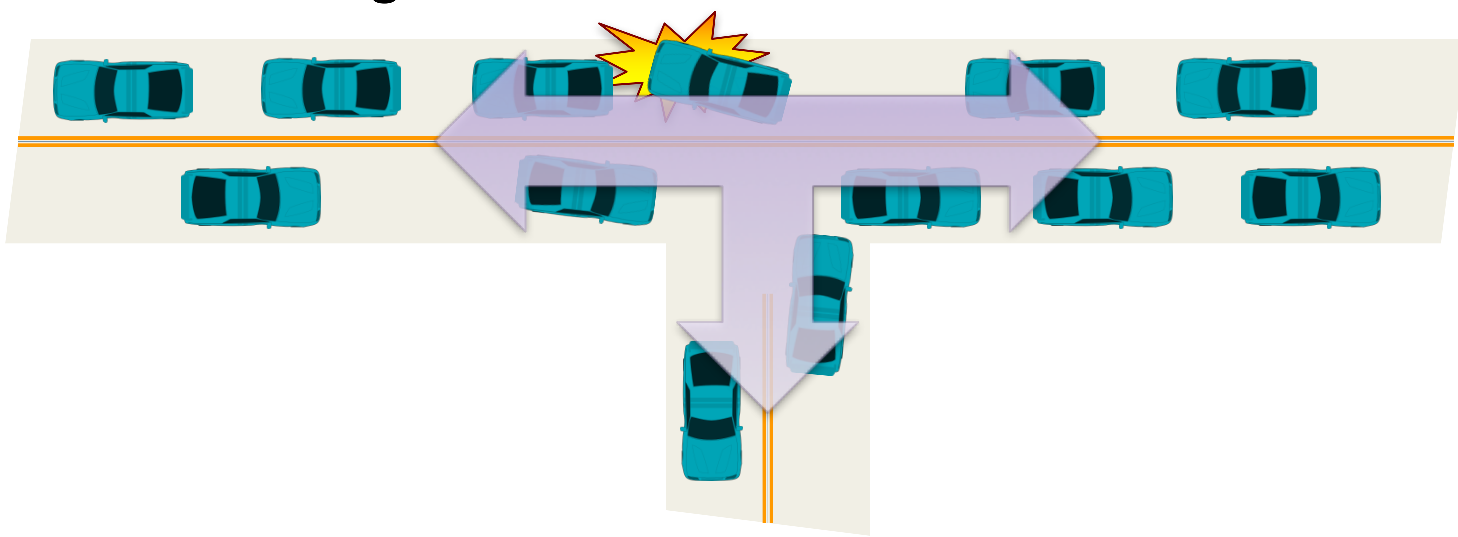


[1] Tonguz, Ozan K. and Wisitpongphan, N. and Bai, F., "DV-CAST: A distributed vehicular broadcast protocol for vehicular ad hoc networks," IEEE Wireless Communications, vol. 17 (2), pp. 47-57, April 2010

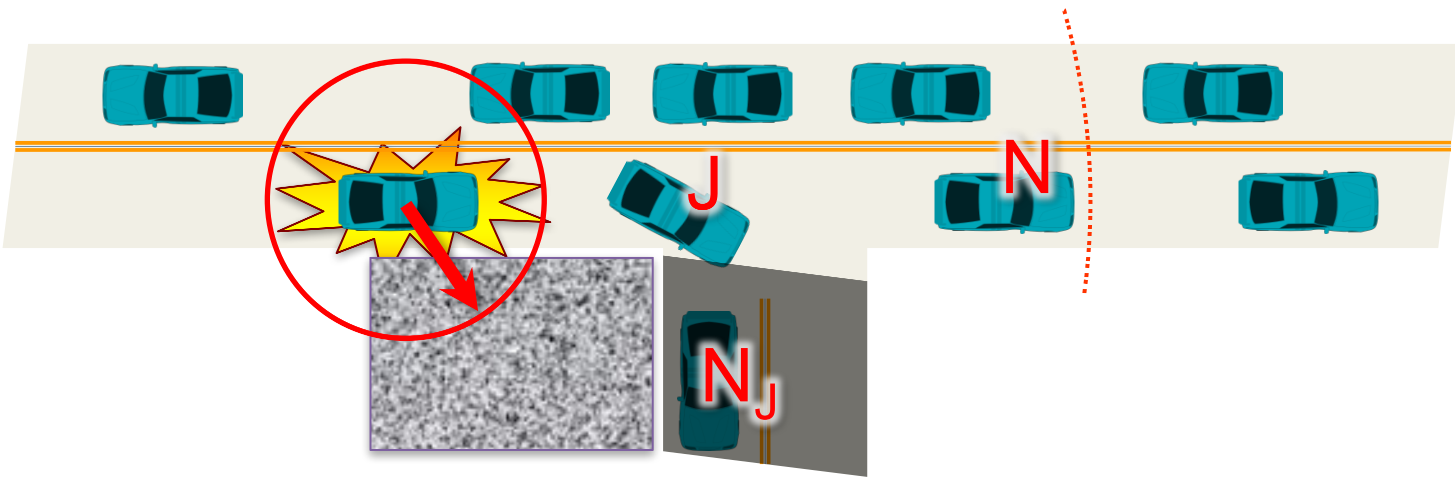
- Temporary network fragmentation



- Undirected message dissemination



- Step 1: Find best next hop (Target Node, T)
  - Find N: Furthest neighbor towards destination
  - Find J: Furthest neighbor towards destination, currently on junction
  - Find N_J: Furthest neighbor towards destination, as seen by J
  - if N, N_J are on the same road,
    pick N
    else, pick J



- Step 2: Find Forwarding Set (FS)
  - Nodes in the FS will compete for relaying of the message
  - Only one node in FS should relay
    thus, all nodes in FS must hear each other
  - Finding optimal solution is NP complete
  - TO-GO uses approximation

Geocast: TO-GO

- Step 3: Multicast message to all nodes in FS
  - Nodes in the FS compete for relaying of the message
  - Ensure maximum progress within FS
  - Delay re-broadcast by t
  - Suppress re-broadcast if another nodes forwards within t
  - $t = \tau \times d_T / d_{max}$
    with:
    - τ : Maximum delay per hop
    - d_T: Distance to Target Node
    - d_{max}: Distance from last hop to Target Node

- Temporary network fragmentation

- Undirected message dissemination