Vehicular Communications

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Extra-Vehicle Car-to-X (C2X) Networking

Introduction

Car-to-X (C2X) communication patterns

- Vehicle-to-X (V2X)
- Inter-Vehicle Communication (IVC)
- Vehicular Ad-hoc NETwork (VANET)
- ….

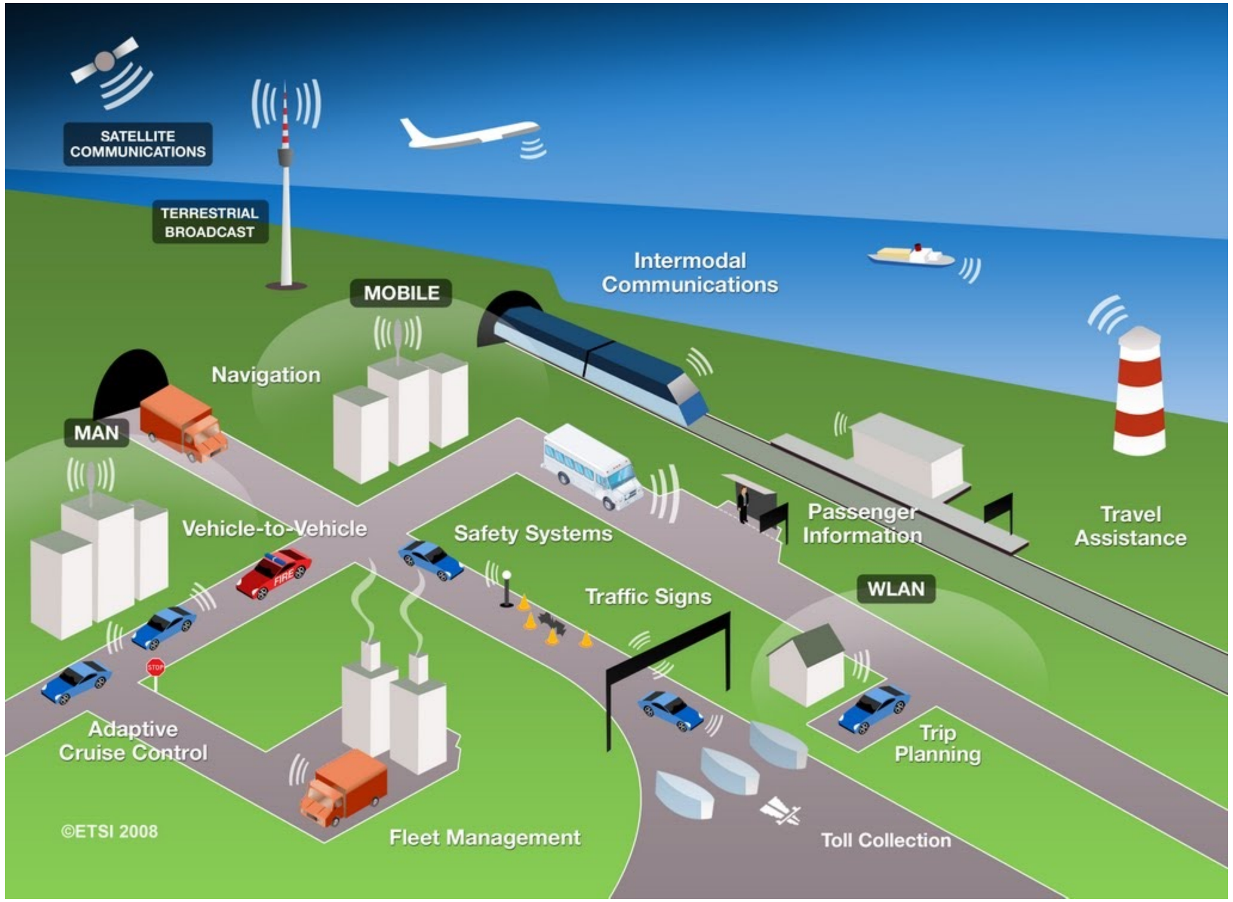


Figure: ETSI

Use cases

Figure: CVIS

Taxonomy of the 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

Taxonomy of the use cases (cont.)

Vehicle-to-X

Non-Safety	Safety
Many messages	Few messages
High data rate	Small packet size
Low latency demands	High latency demands
Low reliability demands	High reliability demands

Diversity of the use cases

Application	Distance	Time	Recipient
Hazard warning	250 m	10 s	All
Location based service	1 – 5 km	Weeks	Subscribers
City wide alarm	20 km	Hours	All
Travel time information	5km	Minutes	All
File sharing	250 m	Minutes (Index) Days (Content)	Subscribers (Index) Peers (Content)
Interactive Services	1 – 5 km	Minutes	Subscribers

[1] Bai, F. and Krishnamachari, B., "Exploiting the Wisdom of the Crowd: Localized, Distributed Information-Centric VANETs," IEEE Communications Magazine, vol. 48 (5), pp. 138-146, May 2010

Diversity of the requirements

Application	Latency	Reliability	# Vehicles	Area	Persistence
Information Query	⦿	⦿	⦿⦿⦿	⦿⦿⦿	
Hazard Warning	⦿⦿⦿	⦿⦿	⦿⦿	⦿⦿⦿	
ACC, Brake Light	⦿⦿⦿	⦿⦿	⦿	⦿	
Cooperative Awareness	⦿⦿	⦿⦿⦿	⦿	⦿	⦿
Intersection Assistance	⦿⦿	⦿⦿⦿	⦿⦿	⦿⦿	⦿
Platooning	⦿⦿⦿	⦿⦿⦿	⦿⦿	⦿	⦿

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

Motivation

- 1970s: bold ideas
  - Very visionary, infrastructure-less solutions
  - Unsupported by current technology
- Early interest of government and industry
  - Working prototypes in: Japan CACS (1973–1979), Europe Prometheus (1986–1995), U.S. PATH (1986–1992)
  - No commercial success
- 1980s: paradigm shift
  - From complete highway automation → driver-advisory only
  - Infrastructure-less → infrastructure-assisted
  - chicken-and-egg type of standoff
- New technology re-ignites interest
  - Latest-generation cellular communication ⇨ early "Car-to-X" systems
  - E.g., On Star (1995), BMW Assist (1999), FleetBoard (2000), and TomTom HD Traffic (2007)
- Sharp increase in computing power
  - Supports fully-distributed, highly reactive ad-hoc systems

[1] W. Zimdahl, "Guidelines and some developments for a new modular driver information system," in 34th IEEE Vehicular Technology Conference (VTC1984), vol. 34., Pittsburgh, PA: IEEE, May 1984, pp. 178–182.

Renewed interest of government and industry

- Several Field Operational Tests (FOTs) in many countries across the world

	FOT	Country	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Autonomous Systems	AOS	🇳🇱							⦿	⦿	⦿							
	Assisted Driver	🇳🇱					⦿	⦿										
	EuroFOT	🇪🇺								⦿	⦿	⦿	⦿					
	LDWA Truck FOT	🇳🇱	⦿	⦿	⦿													
	TeleFOT	🇪🇺								⦿	⦿	⦿	⦿	⦿				
Cooperative Systems	COOPERS	🇫🇷						⦿	⦿	⦿	⦿	⦿						
	DIAMANT	🇩🇪								⦿	⦿	⦿	⦿	⦿	⦿			
	DRIVE C2X	🇪🇺											⦿	⦿	⦿	⦿		
	FOTsis	🇪🇺											⦿	⦿	⦿	⦿		
	ParckR	🇳🇱											⦿	⦿				
	PRESERVE	🇪🇺											⦿	⦿	⦿	⦿		
	SCOREF	🇫🇷										⦿	⦿	⦿	⦿			
	SIMTD	🇩🇪								⦿	⦿	⦿	⦿	⦿				
	SPITS	🇳🇱									⦿	⦿	⦿					

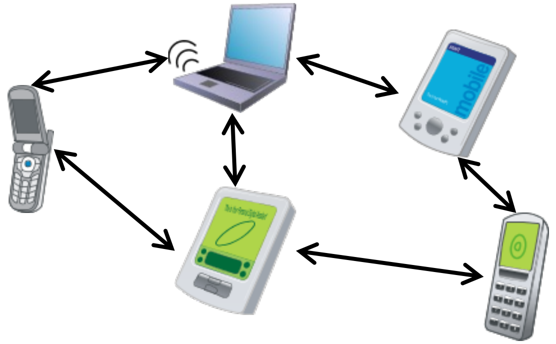
Renewed interest of government and industry (cont.)

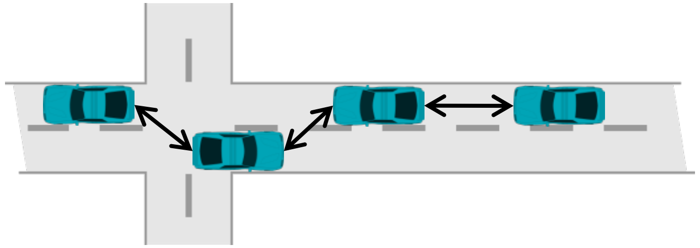
- Several Field Operational Tests (FOTs) in many countries across the world

	FOT	Country	’01	’02	’03	’04	’05	’06	’07	’08	’09	’10	’11	’12	’13	’14	’15	’16
Naturalistic Study	2-BE-SAFE	🇪🇺 🇮🇱 🇦🇺									◉	◉	◉					
	BikeSAFE	🇸🇪												◉				
	BikeSAFER	🇸🇪												◉	◉			
	DaCoTa	🇪🇺										◉	◉	◉				
	INTERACTION	🇪🇺 🇦🇺								◉	◉	◉	◉	◉				
	PROLOGUE	🇪🇺 🇮🇱									◉	◉	◉					
	SEEKING	🇦🇹											◉	◉	◉			
	SVRAI	🇫🇷										◉	◉	◉	◉	◉	◉	◉
	TSS	🇸🇪							◉	◉								
	UDRIVE	🇪🇺												◉	◉	◉	◉	◉

Motivation

- Traditional Network
  - Connection: wired
  - Nodes: non-moving
  - Configuration: static
- Mobile Ad-Hoc Network (MANET)
  - Connection: wireless
  - Nodes: mobile
  - Configuration: dynamic
  - (Infrastructure: optional)
- Vehicular Ad-Hoc Network (VANET)
  - Not: “MANET on wheels”
  - Different topology dynamics, communication patterns, infrastructure, etc.





[1] M. Scott Corson and Joseph Macker, “Mobile Ad-Hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations,” RFC 2501, January 1999

Freeway ⇔ Urban

- 1D mobility
- Bimodal connectivity
  - Stable connection (vehicles on same lane)
  - AND
  - Unstable connection (vehicles on opposite lane)
- High speed
- ….

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

Levels of infrastructure support

- Pure ad-hoc communication
- Stationary Support Units (SSU)
  - Radio-equipped autonomous computer
  - Inexhaustible storage, energy supply
  - Known position, high reliability
- Roadside Units (RSU)
  - SSU plus ….
  - Ethernet NIC, UMTS radio, ….
  - Connected to other RSUs
- Traffic Information Center (TIC)
  - Central server connected to RSUs

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
- ….

Convergence towards heterogeneous approaches

- Same system needs to work in multiple environments
  - Vehicle starts to drive in city with infrastructure support
  - Continues driving on freeway (still with infrastructure support)
  - Loses infrastructure support when turning onto local highway
  - Finishes driving in city without infrastructure support

Challenges of C2X communication

Communication	• Highly-varying channel conditions • High congestion, contention, interference • Tightly-limited channel capacity
Networking	• Uni-directional links • Multi-radio/multi-network • Heterogeneous equipments
Mobility	• Highly-dynamic topology • But: predictable mobility • Heterogeneous environment
Security	• No (or no reliable) uplink to central infrastructure • Ensuring privacy • Heterogeneous user base

Extra-Vehicle Car-to-X (C2X) Networking

Technology

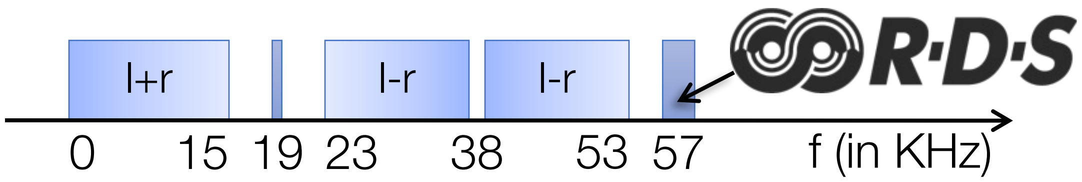
Communication paradigms and media

- Wireless Communication Technologies
  - Infrastructure-based
    - Broadcast
      - FM Radio, DAB/DVB, …
    - Cellular
      - GSM — 2G Cellular
      - UMTS — 3G Cellular
      - LTE / WiMAX — 4G Cell.
  - Infrastructure-less
    - Short Range
      - Millimeter, Infrared, Visible
      - 802.15.1 Bluetooth
      - 802.15.4 ZigBee
    - Medium Range
      - 802.11 Wi-Fi
      - DSRC / WAVE

[1] Dar, K. *et al.*, "Wireless Communication Technologies for ITS Applications," IEEE Communications Magazine, vol. 48 (5), pp. 156-162, May 2010

Broadcast media

- Traffic Message Channel (TMC)
  - Central management of traffic information
  - Data sources are varied
    - Federal/local/city police, road operator, radio, …
  - Transmission in RDS channel of FM radio
    - BPSK modulated signal at 57 KHz, data rate 1.2 kBit/s
    - RDS group identifier 8A (TMC), approx. 10 bulletins per minute



[1] ISO 62106, "Specification of the radio data system (RDS) for VHF/FM sound broadcasting in the frequency range from 87,5 to 108,0 MHz"

Broadcast Media (cont.)

- Traffic Message Channel (TMC)
  - Geographic information: distributed in the form of location code lists
  - Each country issues one or more tables with location codes
    - Uniquely identified by country ID (`cid`) and table code (`tabcd`)
    - Within each table: each location is identified by a location code (`lcd`) in the range 1 – 63487
  - Italy: `cid` = `25`, `tabcd` = `1`
  - No (real) security measures

Event Code List	
22	Service area, fuel station closed
101	Standing traffic (generic)
102	1 km of standing traffic
103	2 km of standing traffic
394	Broken down truck
909	Flash floods
1478	Terrorist incident
1533	Sports meeting (queuing traffic)

https://wiki.openstreetmap.org/wiki/TMC/Event_Code_List

Broadcast Media (cont.)

- Traffic Message Channel (TMC)
  - Each country issues one or more tables with location codes (given by the ISO 14819-3 standard)
    - Locations fall into three different classes: points (`P`), lines (`L`), and areas (`A`)
    - They are subdivided into several classes, and within each class into types (first number) and subtypes (second number)
    - Each location can have references to other locations within the same table
      - E.g., to which road a bridge belongs, which motorway junctions follow each other or to which administrative area a point belongs

Broadcast Media (cont.)

lcd	class	Definition	Value
1	A1.0	Continent	**Name**: Europa
2	A3.0	Country	Name: Italia
21	A7.0	Order 1 area	**Name**: Emilia Romagna
26	A8.0	Order 2 area	**Name**: Parma
126	L1.1	Motorway	**Number**: A1, **From**: Milano, **To**: Napoli
156			**Number**: A15, From: Parma, To: La Spezia
253			**Number**: TG-PR, **Name**: Tangenziale Di Parma (ss9), From: Piacenza, **To**: Reggio Emilia
1128	P1.1	Motorway intersection	**Road name**: Milano-Napoli, **Name**: Allacciamento A15 Parma-La Spezia
1705			**Road name**: Parma-La Spezia, **Name**: Allacciamento A1 Milano-Napoli
1129	P1.3	Motorway junction	**Road name**: Milano-Napoli, **Name**: Parma
1706			**Road name**: Parma-La Spezia, **Name**: Parma Ovest
2778			**Road name**: Tangenziale Di Parma (ss9), **Name**: Innesto Ss9 Via Emilia (direzione Re)
2786			**Road name**: Tangenziale Di Parma (ss9), **Name**: Innesto Ss9 Via Emilia (direzione Pc)
3674	P1.11	Cross-roads	**Road name**: Via Emilia, **Name**: Casello Parma Ovest A15 Parma - La Spezia
3669			**Road name**: Via Emilia, **Name**: Parma Est/Innesto Tangenziale Di Parma
3672			**Road name**: Via Emilia, **Name**: Parma Ovest/Innesto Tangenziale Di Parma
13910			**Road name**: Asolana, **Name**: Parma/Innesto Tangenziale Di Parma
10270			**Road name**: Asolana, **Name**: Parma/Innesto Tangenziale Di Parma

Broadcast Media (cont.)

- Traffic Message Channel (TMC)
  - Regional value-added services
    - *Navteq Traffic RDS* (U.S.), *trafficmaster* (UK), *V-Trafic* (France)

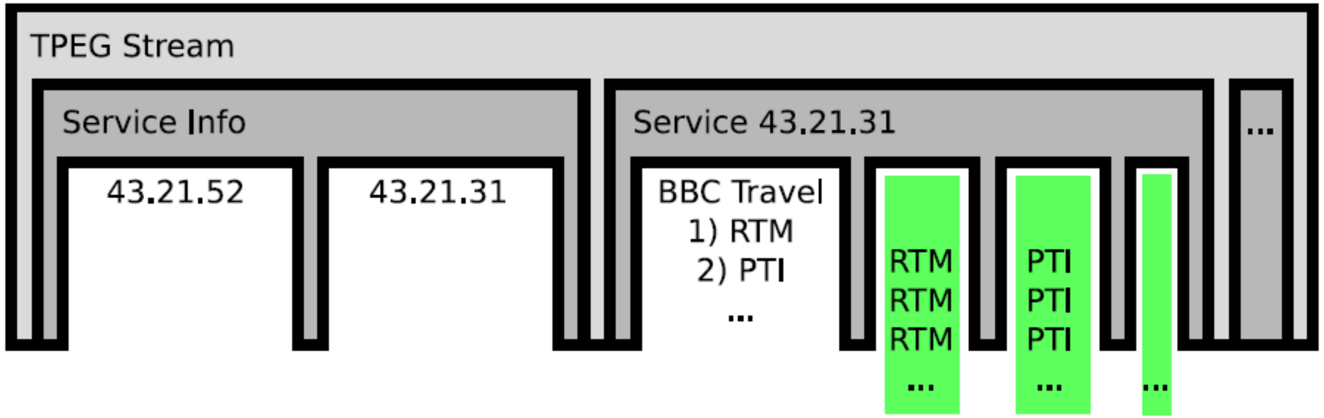
  - E.g., TMCpro
    - Private service of Navteq Services GmbH
    - Financed by per-decoder license fee
    - Data collection and processing
      - Fully automatic
      - Deployment of 4000+ sensors on overpasses
      - Use of floating car data
      - Downlink from traffic information centers
    - Event prediction
      - Expert systems, neural networks
      - Early warnings of predicted events
    - Restricted to major roads

Broadcast Media (cont.)

- Transport Protocol Experts Group (TPEG)
  - Planned successor of RDS-TMC
  - Principles: extensibility, media independence
  - Goals
    - Built for “Digital Audio Broadcast” (DAB), is language independent
    - Designed for unidirectional (broadcast) and bi-directional communication channels (e.g., IP), byte-oriented stream
    - Modular concept
    - Hierarchical approach (with asynchronous framing and a hierarchical data frame structure)
    - Integrated security (CRC error detection capabilities on different protocol levels, and assumes that the underlying communication layers provide error correction)
    - Facilitates transmission of service provider names, service names, network information, etc.
    - Supports dynamic (“on-the-fly”) location referencing methods → Does not need a pre-loaded location database (e.g. TMC Location Tables)

Transport Protocol Experts Group (TPEG)

- Information types defined by "TPEG Applications"
  - RTM - Road Traffic Message
  - PTI - Public Transport Information
  - PKI - Parking Information
  - CTT - Congestion and Travel-Time
  - TEC - Traffic Event Compact
  - WEA - Weather information for travelers
- Modular concept



- Broadcast services
  - Infoblu 🇮🇹
- Mobile broadband (IP-based) services
  - HERE 🇮🇹
  - TomTom Traffic 🇮🇹 🇻🇦 🇸🇲

Transport Protocol Experts Group (TPEG) (cont.)

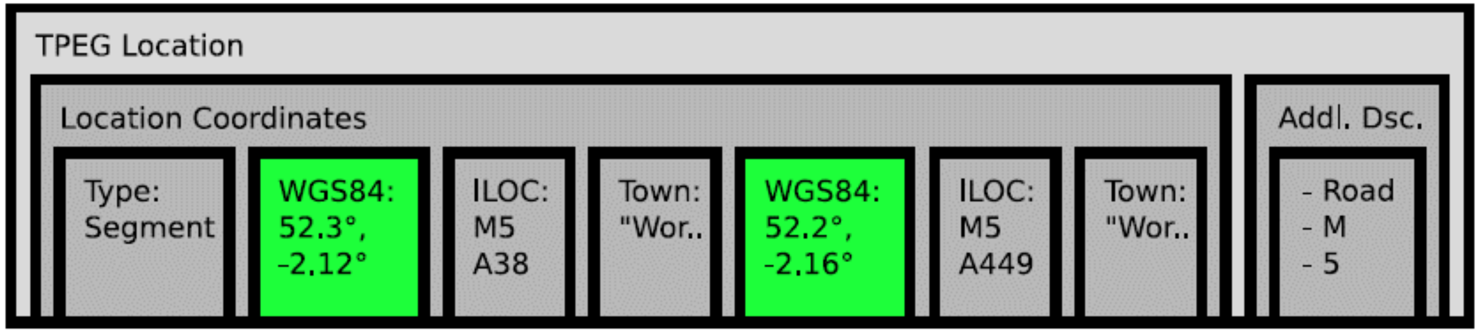
- tpegML: XML variant of regular (binary) TPEG

```xml
<?xml version="1.0" encoding="ISO-8859-1"?>
<!DOCTYPE tpeg_document PUBLIC "-//EBU/tpegML/EN"
      "http://www.bbc.co.uk/travelnews/xml/tpegml_en/tpegML.dtd">
<tpeg_document generation_time="2007-09-19T07:22:44+0">
        <tpeg_message>
                <originator country="UK" originator_name="BBC Travel News"/>
                <summary xml:lang="en">M5 Worcestershire - Earlier accident
                      southbound between J5, Droitwich and J6, Worcester, heavy
                      traffic.</summary>
                <road_traffic_message>
                        <!-- ... tpeg-rtmML ... -->
                </road_traffic_message>
        </tpeg_message>
        <tpeg_message>
                <originator country="UK" originator_name="BBC Travel News"/>
                <summary xml:lang="en">A420 Oxfordshire - The Plain closed westbound
                      at the A4158 Iffley Road junction in Oxford, delays expected.
                      Diversion in operation.</summary>
                <road_traffic_message>
                        <!-- ... tpeg-rtmML ... -->
                </road_traffic_message>
        </tpeg_message>
</tpeg_document>
```

[1] ISO 24530-x, „Traffic and Travel Information (TTI) — TTI via Transport Protocol Experts Group (TPEG) Extensible Markup Language (XML)“

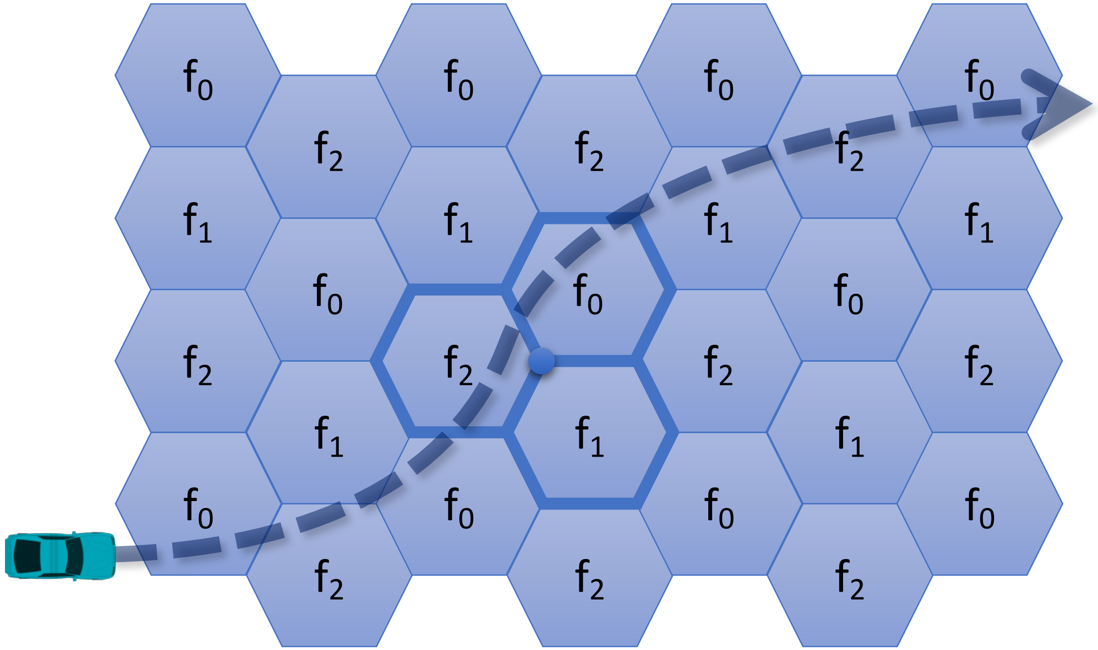
Transport Protocol Experts Group (TPEG) (cont.)

- Hybrid approach to geo-referencing: one or more of
  - WGS84-based coordinates
  - ILOC (Intersection Location)
    - Normalized, shortened textual representation of street names intersecting at desired point
  - Human-readable plain text
  - Code in hierarchical location table



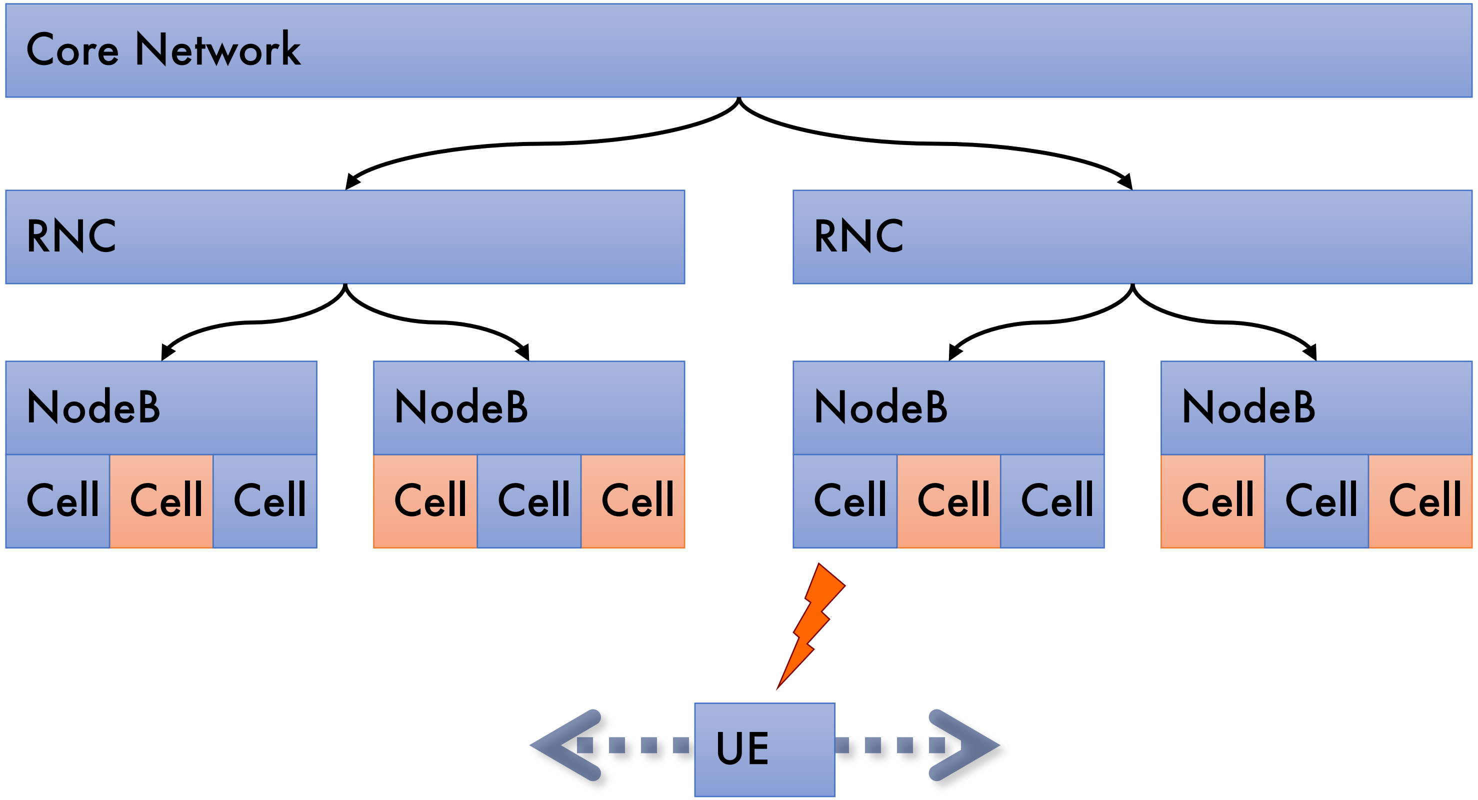
Cellular Networks

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



Cellular Networks (cont.)

- Strict hierarchy of network components



Cellular Networks (cont.)

- *Can UMTS support C2X communication?*
  - E.g., UTRA FDD Release 99 (W-CDMA)
  - Speed of vehicles should not be 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) in uplink and Forward Access Channel (FACH) in downlink
  - Dedicated channels
    - E.g., Dedicated Transport Channel (DCH) for uplink/downlink

Cellular Networks (cont.)

- 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
  - Delay approx. 50 ms per 60 Byte and UE
  - Massive interference with other UEs

Cellular Networks (cont.)

- 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 (cont.)

- *So: can UMTS support C2X communication?*
  - At low market penetration: yes
  - Eventually:
    - Need to invest in much smaller cells (e.g., along freeways) → 5G small cells
    - Need to implement multicast functionality (MBMS)
  - Main use case for UMTS: centralized services
    - E.g., Google Maps Traffic
      - Collect information from UMTS devices
      - Storage of data on central server
      - Dissemination via Internet (→ ideal for cellular networks)

IEEE 802.11p

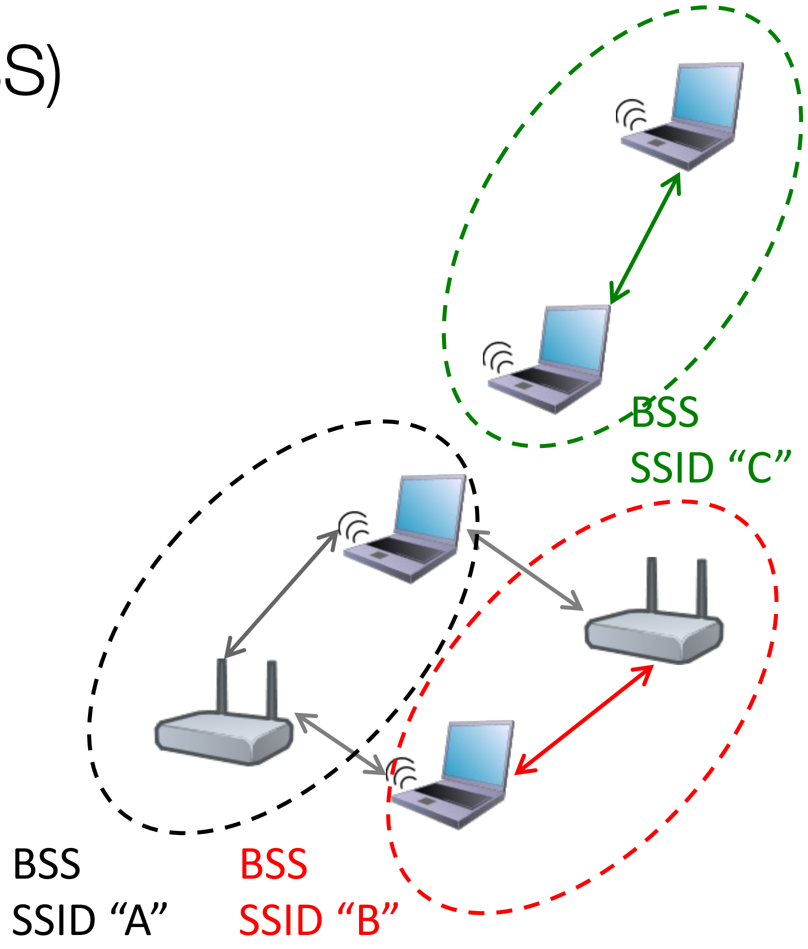
- *IEEE 802.11{a,b,g,n} for C2X communication?*
  - Can't be in infrastructure mode *and ad-hoc* mode at the same time
  - Switching time consuming
  - Association time consuming
  - No integral within-network security
  - (Massively) shared spectrum (→ ISM)
  - No integral QoS
  - Multi-path effects reduce range and speed

IEEE 802.11p (cont.)

- IEEE 802.11p
  - 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
      - Range up to 1 km, 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, etc.)
    - Multi-frequency and multi-radio capabilities
    - New *ad-hoc* mode

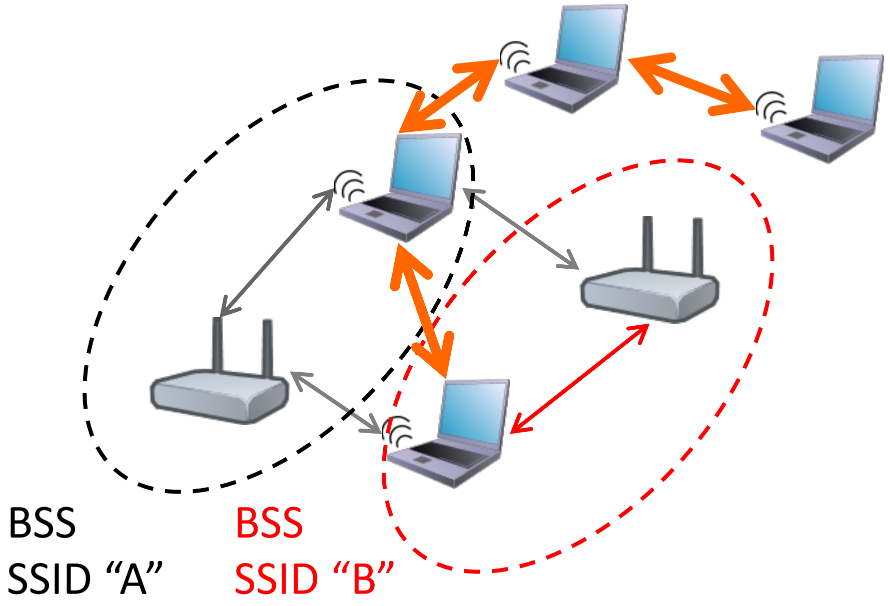
IEEE 802.11p (cont.)

- 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 (AP) sends beacon
    - Authentication dialogue
    - Association dialogue
    - Node has joined BSS



IEEE 802.11p (cont.)

- New: IEEE 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

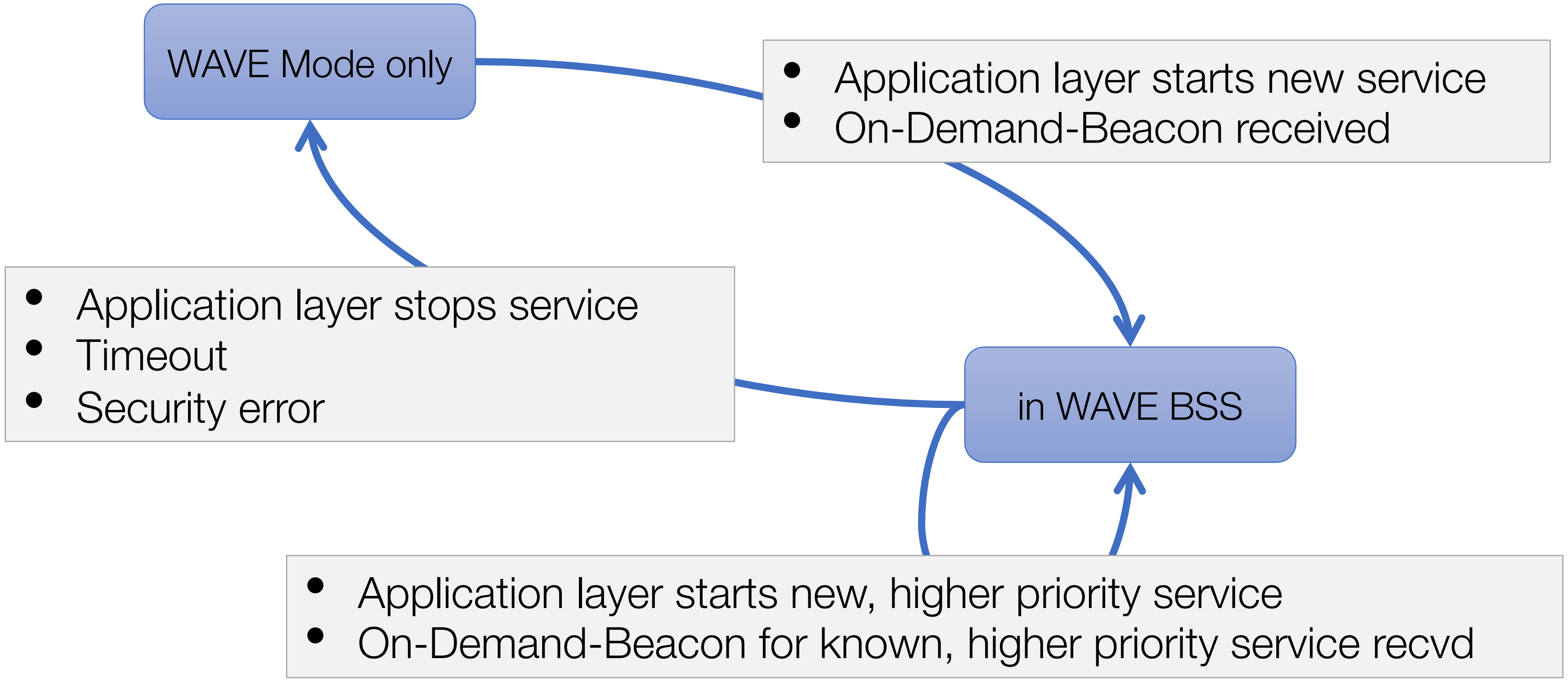


IEEE 802.11p (cont.)

- New: IEEE 802.11 WAVE BSS
  - No strict separation between Host and AP
  - Instead, loose classification according to:
    - Equipment: Roadside Unit (RSU) / On-Board Unit (OBU)
    - Role in data exchange: Provider / User
  - No technical difference between Provider and User
  - Provider sends On-Demand Beacon
    - Analogous to standard IEEE 802.11-Beacon
    - Beacon contains all information and parameters needed to join
  - User configures lower layers accordingly
    - Starts using provided service
    - No additional exchange of data needed
  - BSS membership now only implied
    - BSS continues to exist even after provider leaves

IEEE 802.11p – WAVE BSS internal state machine

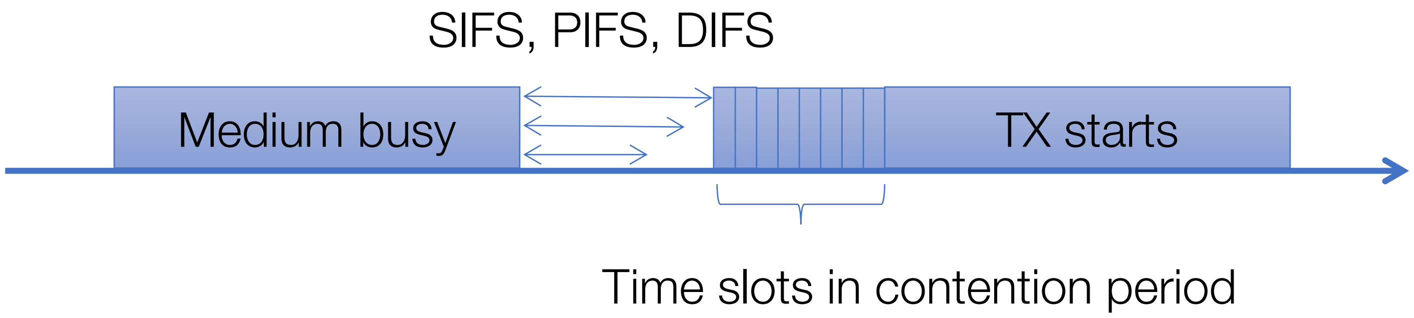
- Node will not join more than one WAVE BSS



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

IEEE 802.11p (cont.)

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



  - Priority access via Short Interframe Space (SIFS) for ACK, CTS, etc., and DCF Interframe Space (DIFS) for payload
  - Wait until medium has been free for duration of DIFS
  - If medium busy, wait until idle, then wait DIFS plus random backoff time

IEEE 802.11p (cont.)

- IEEE 802.11 Distributed Coordination Function (DCF)
  - Backoff if
    a) Node is ready to send and channel becomes busy
    b) A higher priority queue (→ next slides) becomes ready to send
    c) Unicast transmission failed (no ACK)
    d) Transmission completed successfully

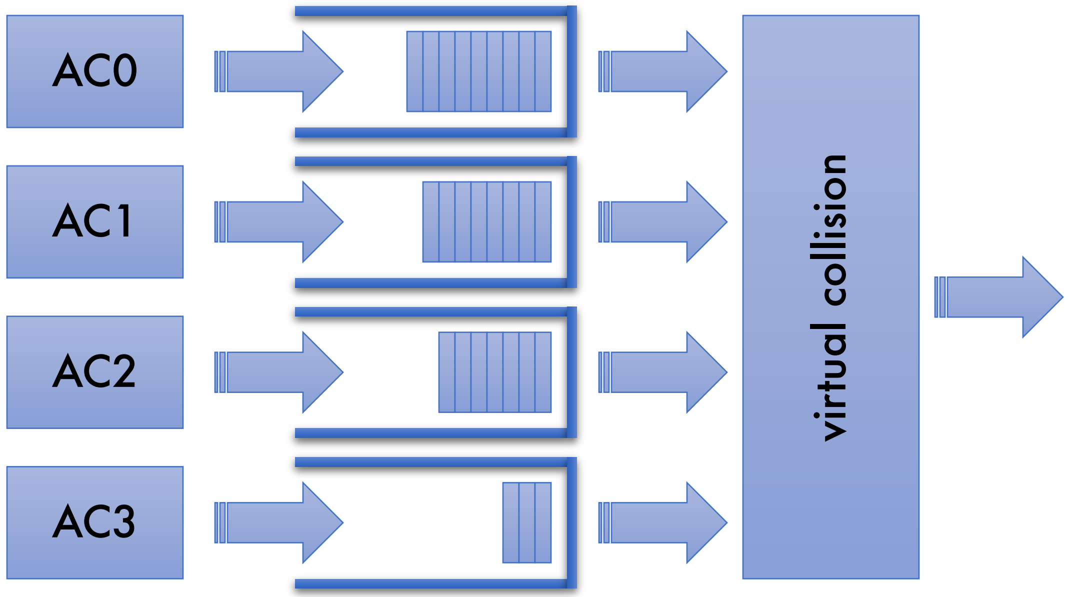
  - Backoff: random slot count from interval [0, CW]
  - Decrement by one after channel was idle for one slot (only in contention period)
  - In cases b) and c), double CW (but no larger than CW_{max})
  - In case d), set CW to CW_{min}

IEEE 802.11p (cont.)

- QoS in IEEE 802.11p (Hybrid Coordination Function, HCF)
  - DIFS → Arbitration Inter-Frame Space (AIFS)
  - Classify user data into 4 Access Categories (ACs)
    - AC0: Background (AC_BK) – lowest priority
    - AC1: Best Effort (AC_BE)
    - AC2: Video (AC_VI)
    - AC3: Voice (AC_VO) – highest priority
  - Each ACs has different CW_{min}, CW_{max}, AIFS, Transmit Opportunity (TXOP) limit (max. continuous transmissions)
  - Management data uses DIFS (not AIFS)

IEEE 802.11p (cont.)

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



IEEE 802.11p (cont.)

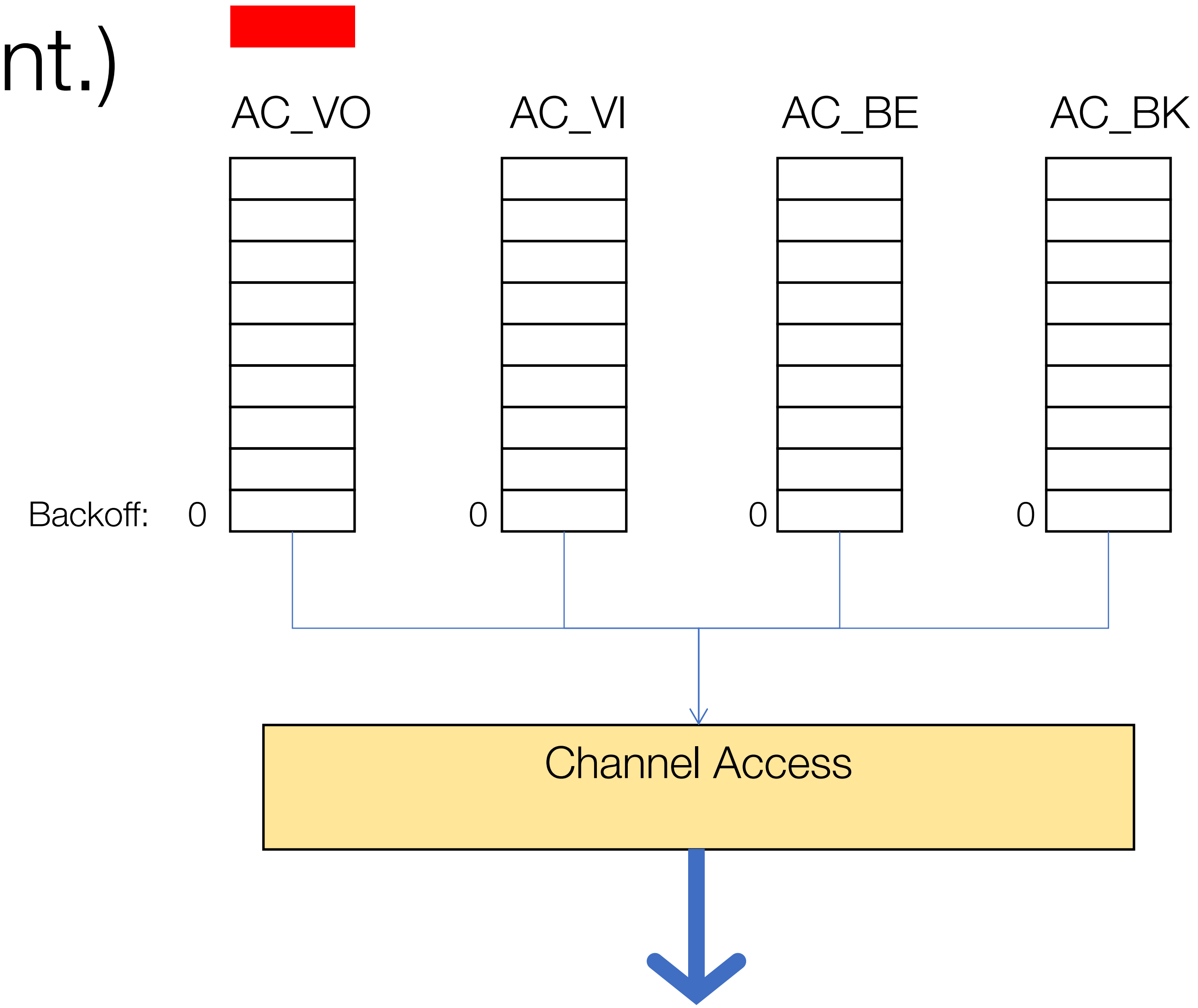
- QoS in IEEE 802.11p (HCF)
  - Parameterization

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

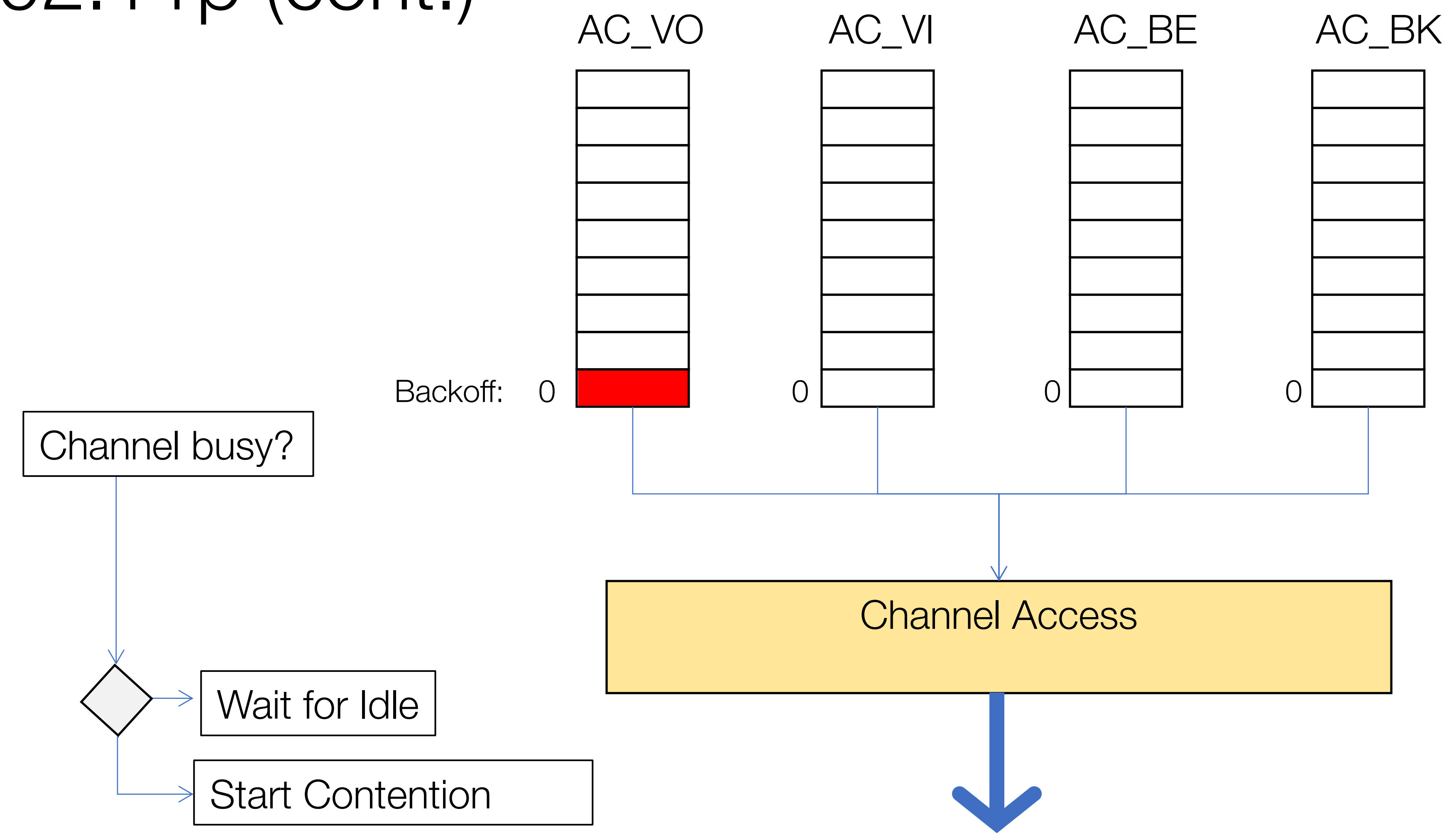
  - Sample queue configuration

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

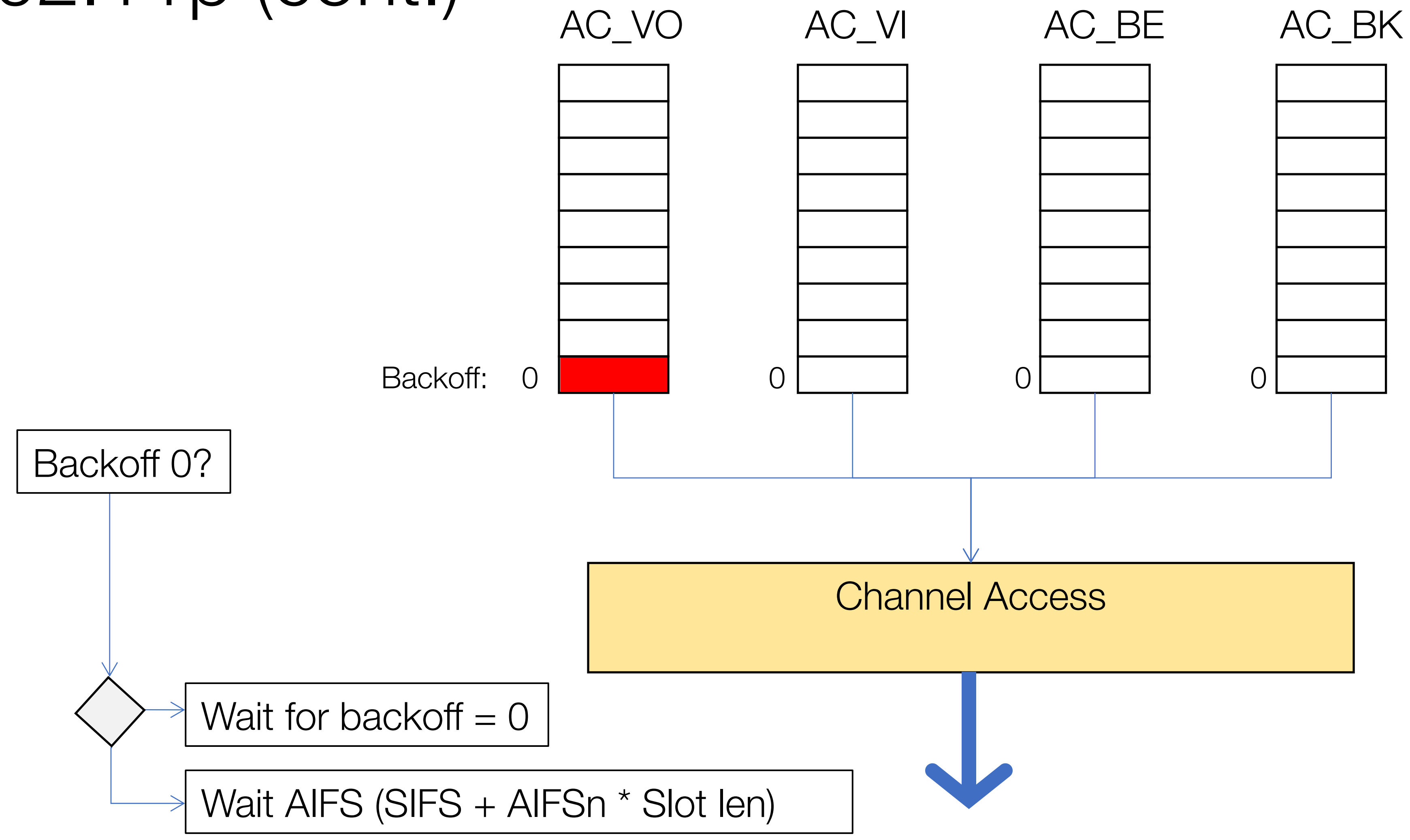
IEEE 802.11p (cont.)



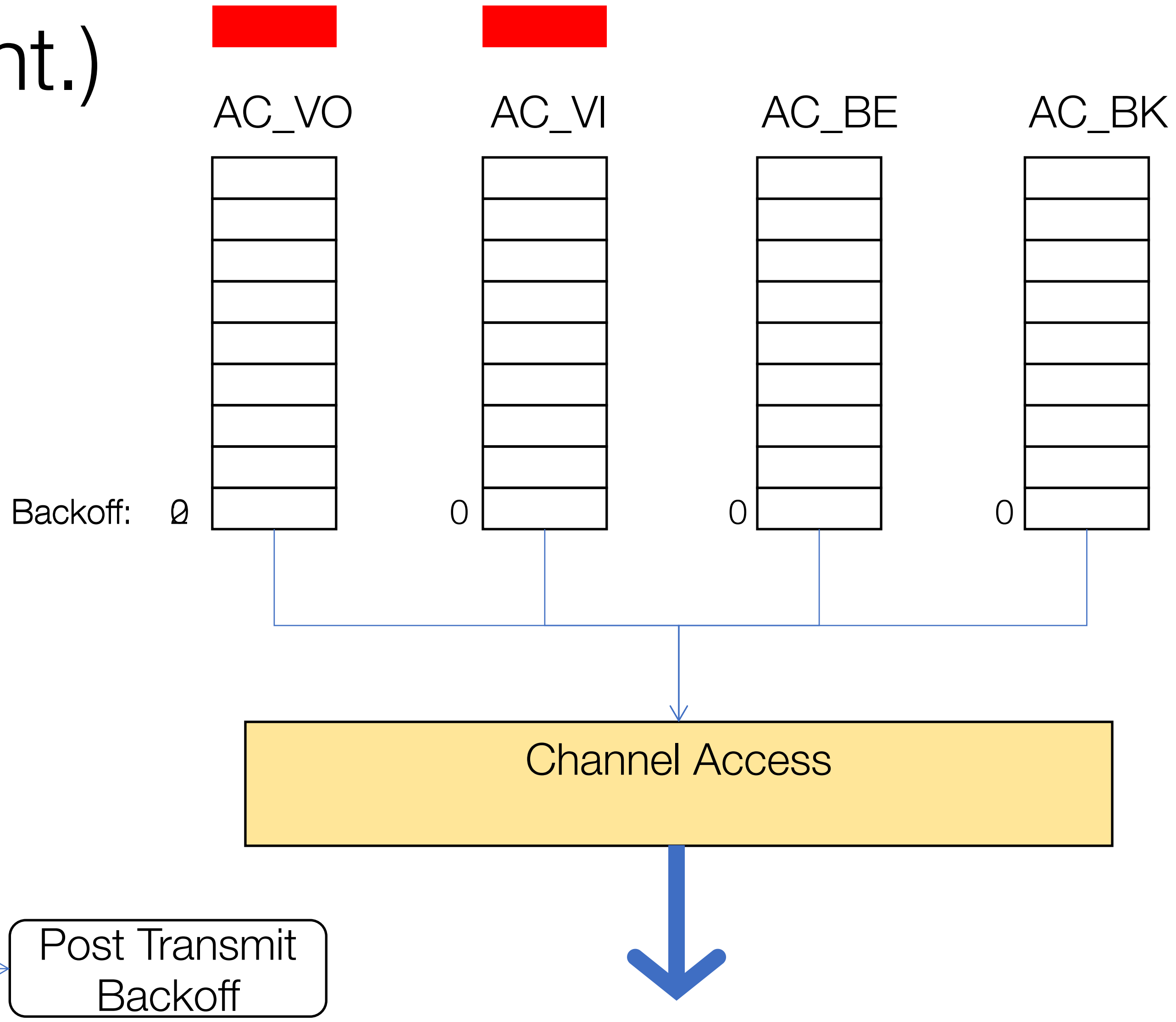
IEEE 802.11p (cont.)



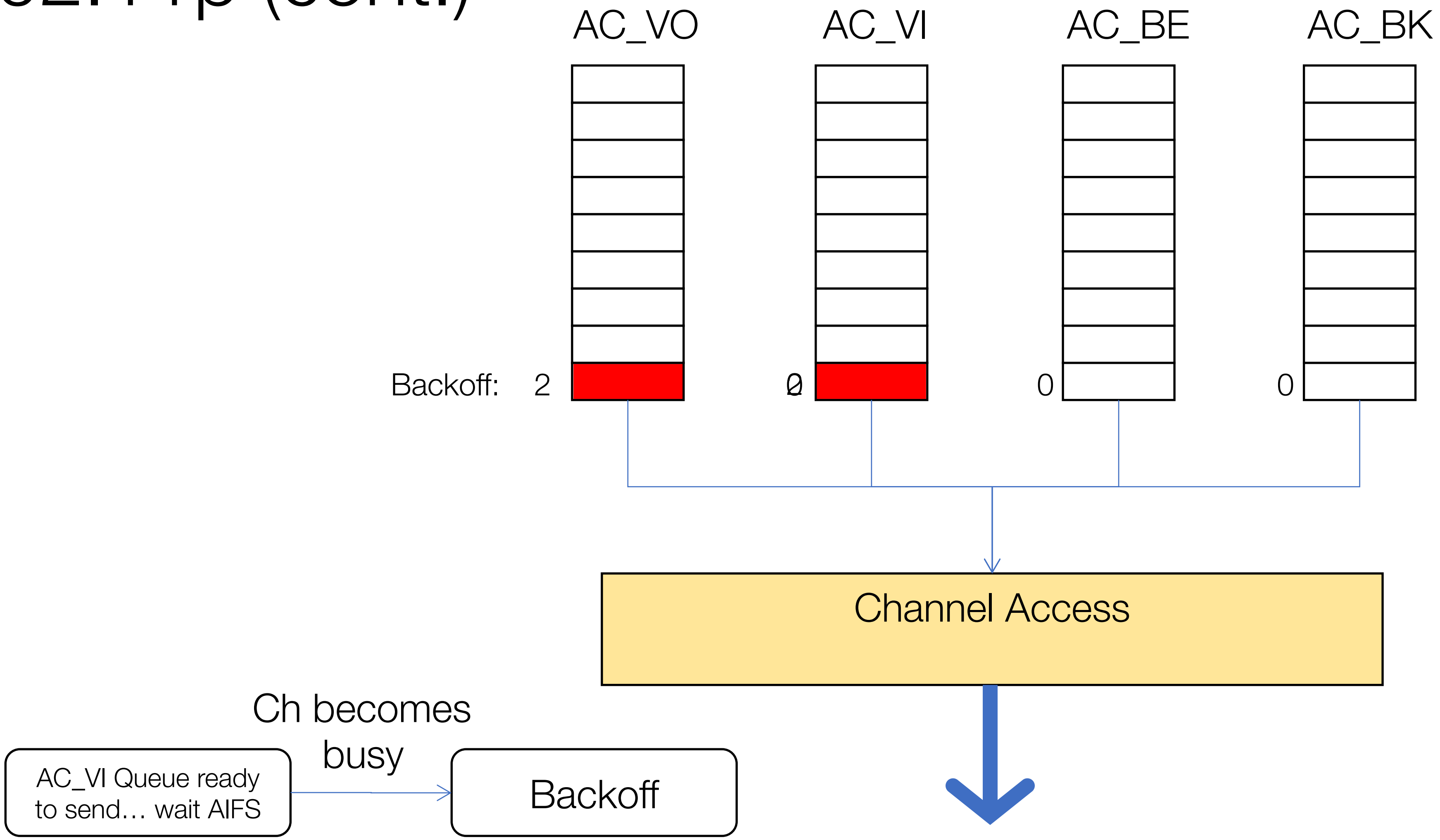
IEEE 802.11p (cont.)



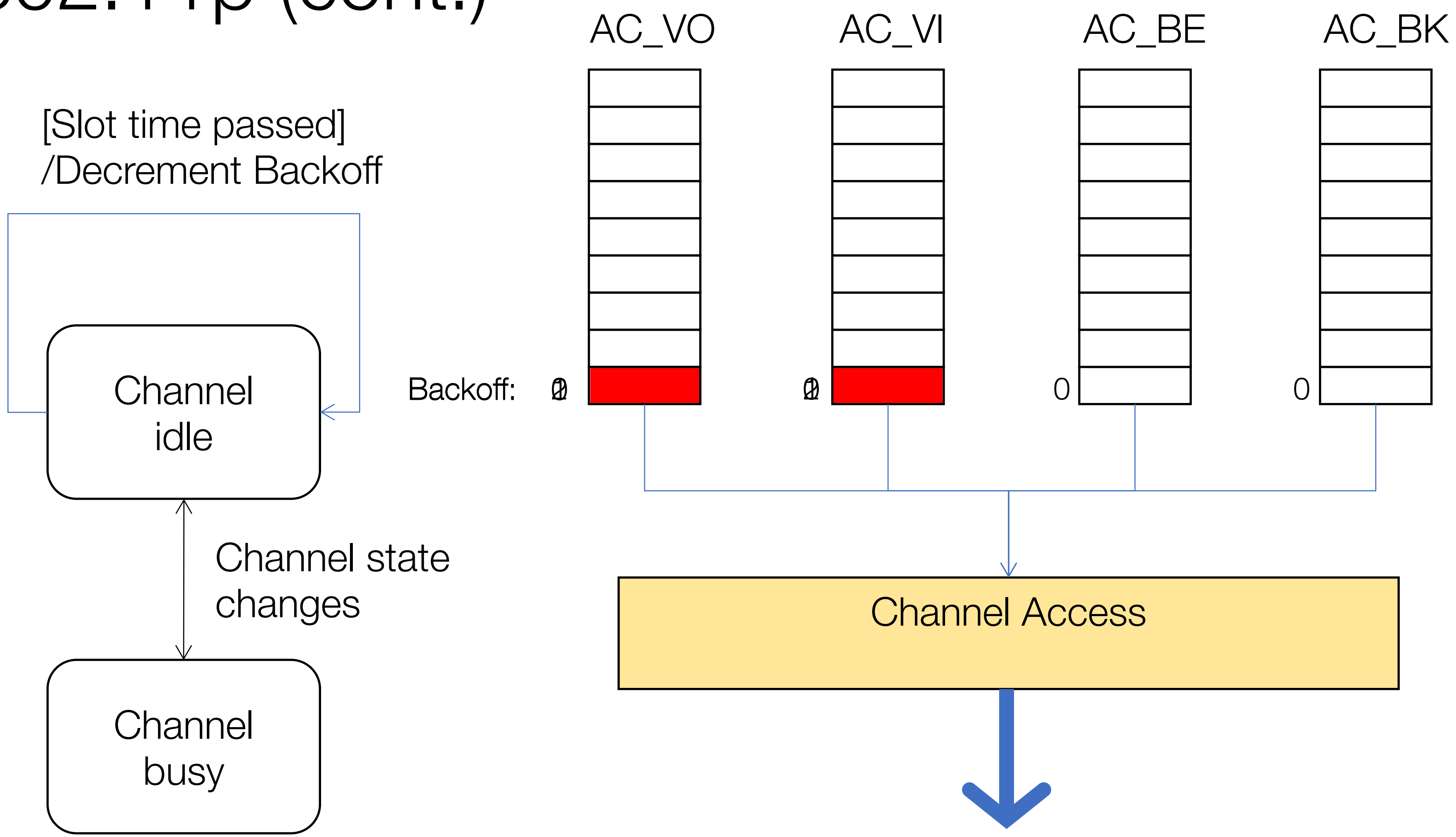
IEEE 802.11p (cont.)



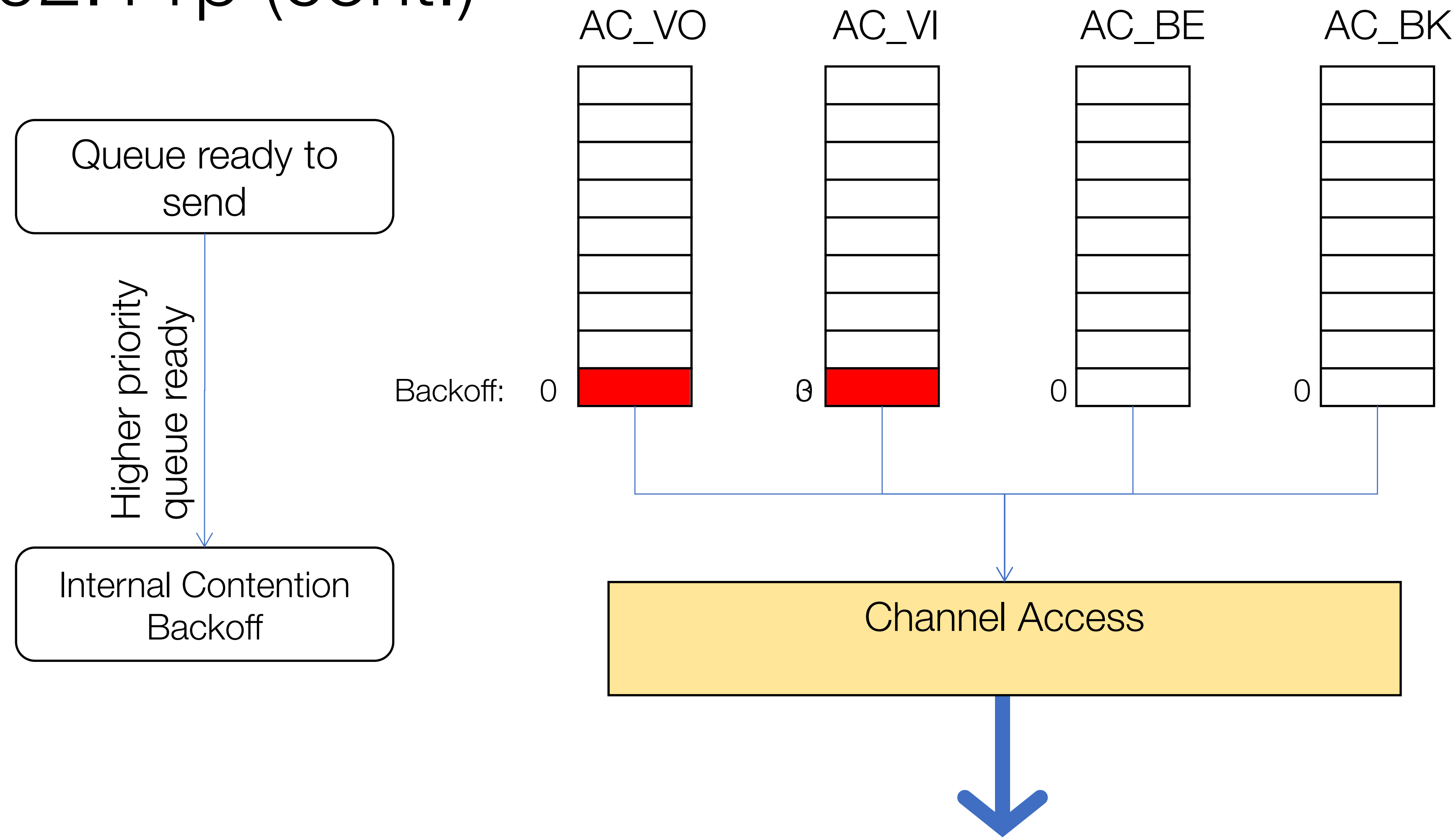
IEEE 802.11p (cont.)



IEEE 802.11p (cont.)



IEEE 802.11p (cont.)



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

UMTS/LTE vs. IEEE 802.11p (cont.)

- Pros of IEEE 802.11p/*ad-hoc*
  + Smallest possible latency
  + Can sustain operation without network operator/provider
  + Network load highly localized
  + Better privacy (→ later slides)

- Cons of IEEE 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: CALM

continuous communications for vehicles

- Mixed-media communication
  - “Communications Access for Land Mobiles”
  - ISO TC204 WG16
  - Based on IPv6
  - Initiative to transparently use best possible medium
  - Integrates:
    - GPRS, UMTS, WiMAX
    - Infrared, mmWave
    - Wi-Fi, WAVE
    - Unidirectional data sources (DAB, GPS, ...)
    - WPANs (BlueT, W-USB, ...)
    - Automotive bus systems (CAN, Ethernet, ...)

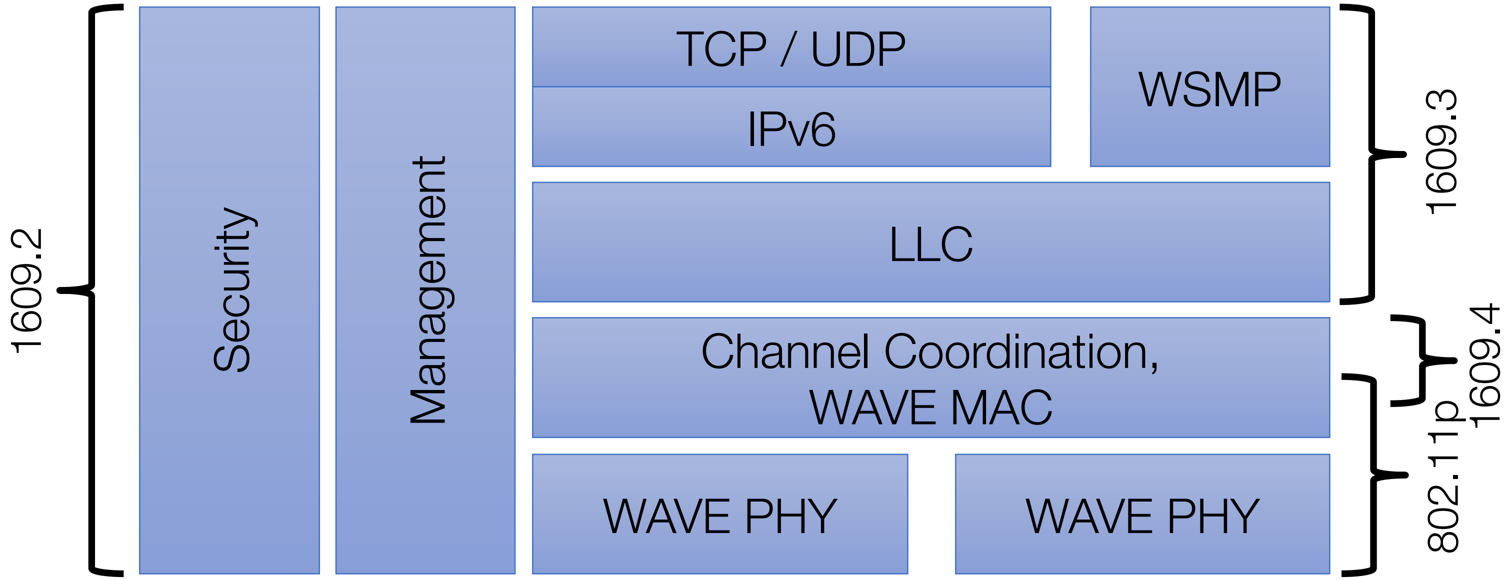
[1] ISO 21210, “Intelligent transport systems -- Communications access for land mobiles (CALM) -- IPv6 Networking“

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 1609.2: Security
- IEEE 1609.3: Network services
- IEEE 1609.4: Channel mgmt.
- IEEE 1609.11: Application “electronic payment”

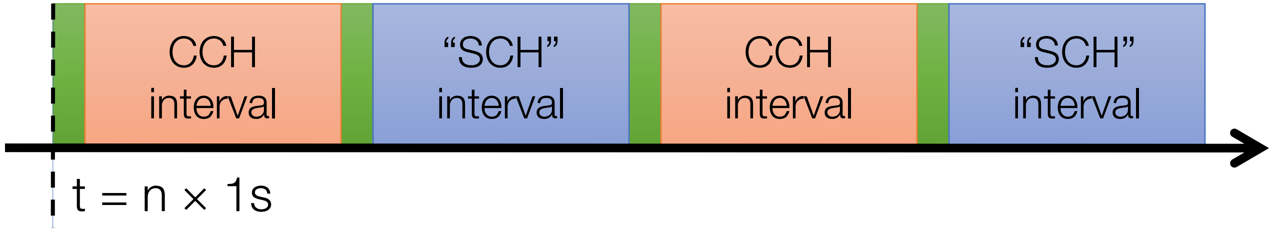


[1] Jiang, D. and Delgrossi, L., "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," Proceedings of 67th IEEE Vehicular Technology Conference (VTC2008-Spring), Marina Bay, Singapore, May 2008

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

IEEE 1609

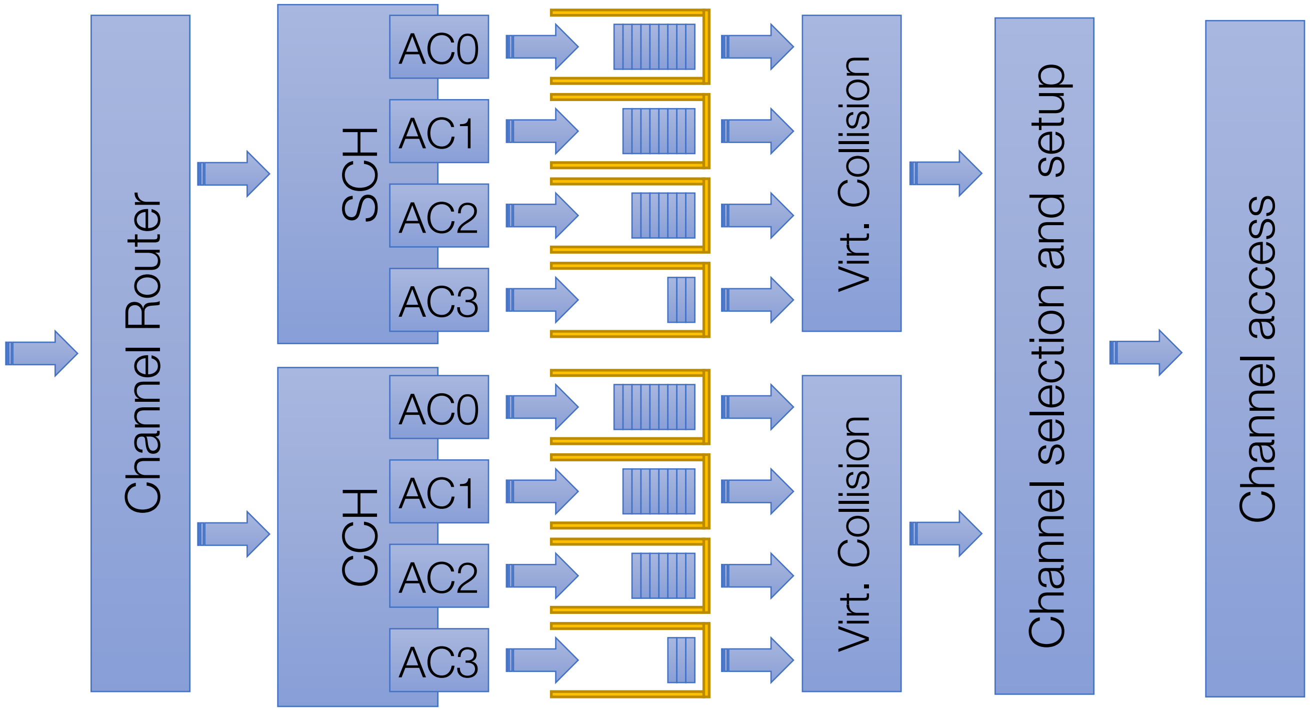
- Channel management
  - WAVE allows for both single radio devices & multi radio devices
  - Dedicated Control Channel (CCH) for management and safety messages
    - Single radio devices need to periodically listen to CCH
  - Time slots
    - Synchronization envisioned via GPS receiver clock
    - Standard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

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

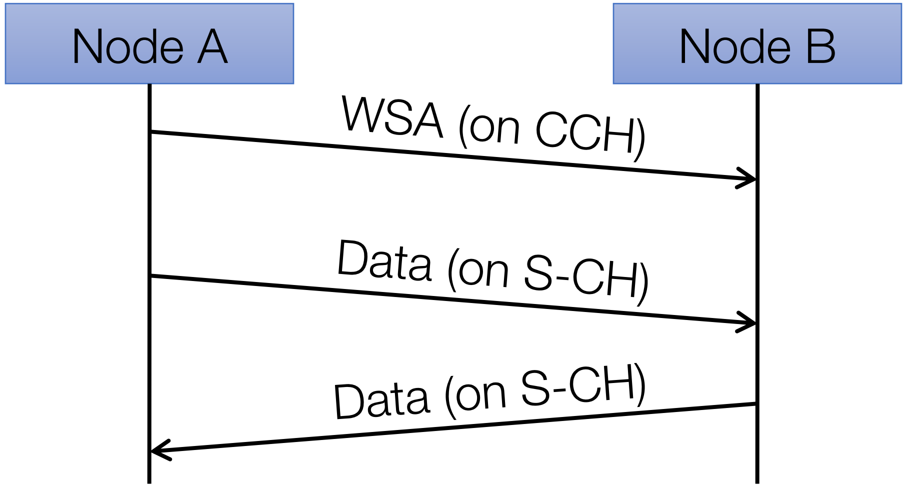


IEEE 1609 (cont.)

- 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

IEEE 1609 (cont.)

- 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



IEEE 1609 (cont.)

- 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

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 (cont.)

- 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 (cont.)

- 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
  - All OBUs listen to host multicast address, all RSUs listen to router multicast address

IEEE 1609 (cont.)

- Channel quality monitoring
  - Nodes store received WSAs, know SCH occupancy

  - Received Channel Power Indicator (RCPI) polling
    - Nodes can send RCPI requests
    - Receiver answers with Received Signal Strength (RSS) of packet

  - Transmit Power Control (TPC)
    - Nodes can send TPC requests
    - Receiver answers with current transmission power and LQI

  - Dynamic Frequency Selection (DFS)
    - Nodes monitor transmissions on channel (actively and passively)
    - If higher priority third party use (e.g., RADAR) is detected, nodes cease transmitting

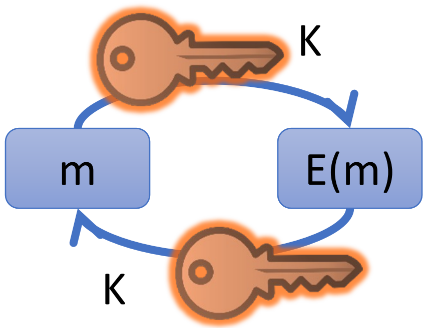
IEEE 1609 (cont.)

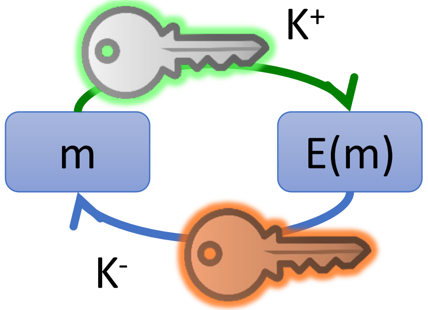
- Security in WAVE
  - Nature of WAVE messages mandates trust between nodes
    - E.g., green wave for emergency vehicles
  - Security is built into WAVE (IEEE 1609.2)
  - WAVE can transparently sign, verify, encrypt/decrypt messages when sending and receiving
  - Authorization of messages needed
    - By role: CA, CRL-Signer, RSU, Public Safety OBU (PSOBU), OBU
    - By application class (PSID) and/or instance (PSC)
    - By application priority
    - By location and time

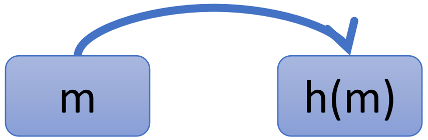
[1] IEEE Vehicular Technology Society, "IEEE 1609.2 (Security Services)," IEEE Std, July, 2006

IEEE 1609 (cont.)

- Security concepts
  - Basic security goals
    - Integrity, Confidentiality, Authenticity
    - Non-Repudiation
  - Mechanisms
    - Symmetric encryption
      - Secret Key Cryptography
      - E.g., Caesar cipher, Enigma, AES
    - Asymmetric encryption
      - Public key cryptography
      - E.g., RSA, ElGamal, ECC
    - (Cryptographic) hashing
      - E.g., MD5, SHA-1





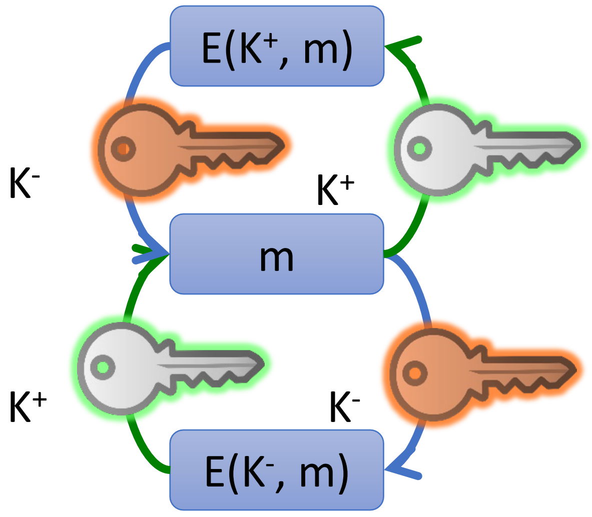


IEEE 1609 (cont.)

- Asymmetric Cryptography
  - Relies on certain mathematical procedures being very hard to invert
    - Product ⇔ factorization (RSA)
    - Nth power ⇔ Nth logarithm (DH, ElGamal)
  - Two keys: Public Key (K^+), Private Key (K^-)

  - Can be used in both directions
  - Encryption: $E(K^+, m)$, Signing: $E(K^-, h(m))$

  - Drawback:
    - Much slower than symmetric cryptography



IEEE 1609 (cont.)

- Certificates
  - Encryption is useless without authentication
    - Alice ⇔ Eve ⇔ Bob
    - Eve can pretend to be Alice, replace K^+_A with her own key K^+_E
  - Solution: use Trusted Third Party (TTP) and certificates
    - TTP signs (Name, Key) tuple, vouches for validity and authorization: “Alice has Public Key K^+_A, may participate as OBU until 2024”
    - not: “~~whoever sends this packet is Alice~~”
    - not: “~~whoever sends this packet has Public Key~~ $\cancel{K^+_A}$”
  - Send K^+_A together with certificate vouching for tuple

IEEE 1609 (cont.)

- Implementation in WAVE
  - X.509 formats too large ⇨ new WAVE certificate format
    - Version
    - Certificate
      - Role (RSU, PSOBU, OBU, ...)
      - Identity (dependent on role)
      - Restrictions (by application class, priority, location, …)
      - Expiration date
      - Responsible CRL
      - Public Keys
    - Signature
  - New: Restriction by location (e.g.: none, inherited from CA, circle, polygon, set of rectangles)
  - Public key algorithms (motivated by key size)
    - Elliptic Curve Digital Signature Algorithm (ECDSA), using NIST p224 or NIST p256
    - Elliptic Curve Integrated Encryption Scheme (ECIES), using NIST p256)

Complete packet format of a WSM

E.g., Signed WSM of an OBU, Certificate issuer is known

Length	Field			
1	WSM version			
1	Security Type = signed(1)			
1	Channel Number			
1	Data Rate			
1	TxPwr_Level			
4	PSID			
1	PSC Field Length			
7	PSC			
2	WSM Length			
1	WSM Data	signer	type = certificate	
125			certificate	
2		unsigned_wsm	message flags	
32			application_data	
8			transmission_time	
4			transmission_location	latitude
4				longitude
3				elevation_and_confidence
28		signature	ecdsa_signature	r
28				s

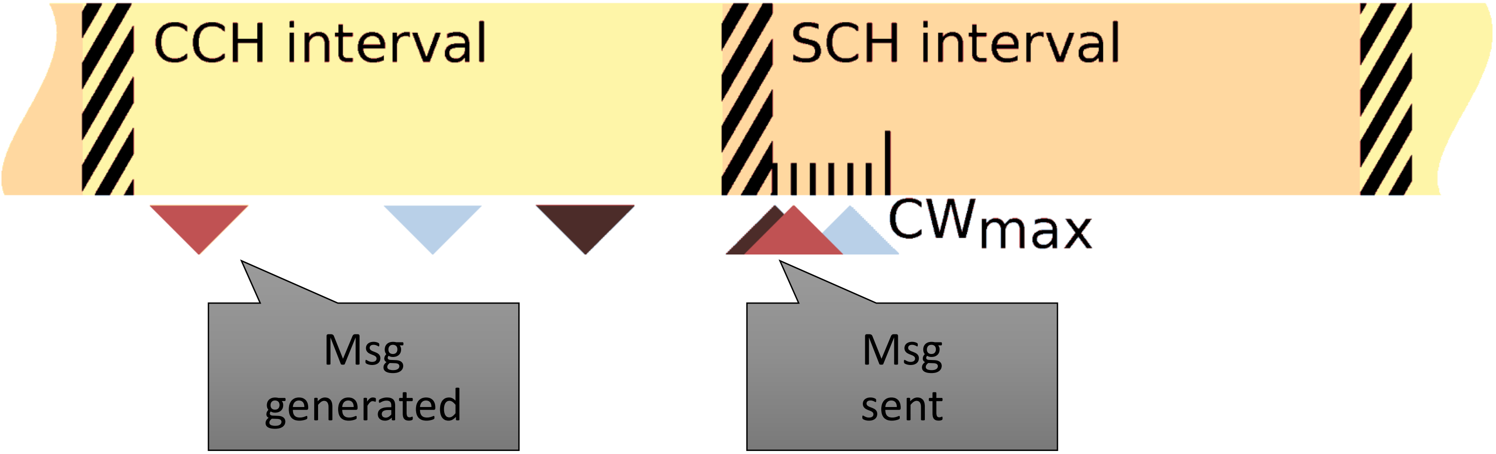
⇨ next slide

Complete packet format of a WSM (certificate part)

Length	Field			
1	certificate_version = 1			
1	unsigned_certificate	subject_type = obu_identified		
8		signer_id		
1		scope	subject_name length	
8			subject_name	
2			applications	length of applications field
1				type = from_issuer
4		expiration		
4		crl_series		
1		public_key	length of public key field	
1			algorithm = ecdsa nistp224..	
29			public_key	point
32	signature	ecdsa_signature	r	
32			s	

Drawbacks of Channel Switching

- 1) Goodput*
  - User data must only be sent on SCH, i.e. during SCH interval → goodput cut in half
- 2) Latency
  - User data generated during CCH interval is delayed until SCH intervention
- 3) Collisions
  - Delay of data to next start of SCH interval: increased frequency of channel accesses directly after switch; increased collisions, packet loss



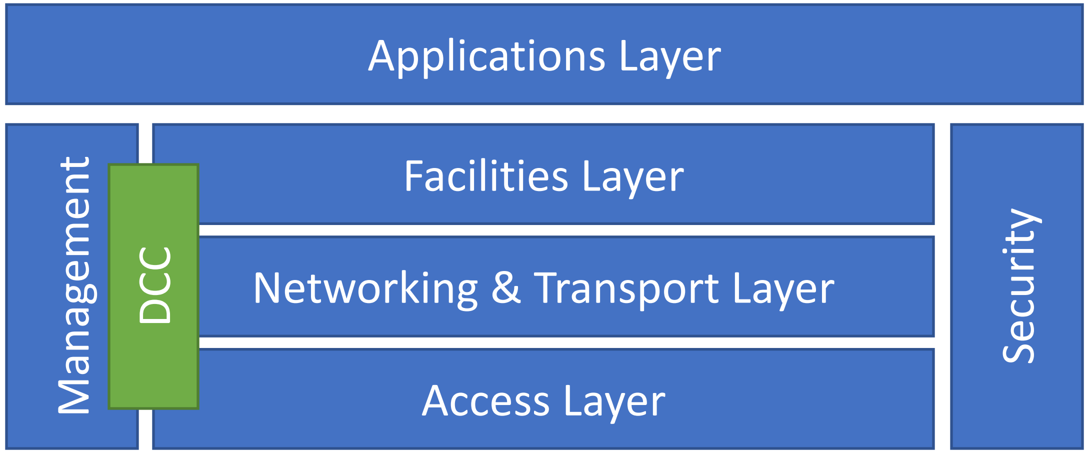
*Application-level throughput of a communication, i.e., the number of useful information bits delivered by the network to a certain destination per unit of time; this amount of data excludes protocol overhead bits as well as retransmitted data packets

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
  - Fine-grained service channel assignment
    - ITS-G5A (safety)
    - IST-G5B (non safety)

ETSI ITS G5 (cont.)

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



ETSI ITS G5 (cont.)

- 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)
  - Additional radio tuned to SCH
    - User data

ETSI ITS G5 (cont.)

- Cooperative Awareness Message (CAM)
  - 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, etc.
  - Sent on CCH
  - Generated every 100 ms …. 1 s, but only if Δangle (>4°), Δposition (>5m), Δspeed (>1m/s)

ETSI ITS G5 (cont.)

- CAM format

Length[byte]	Field		
1	messageId (0=CAM, 1=DENM)		
8	generationTime		
4	StationId		
1	StationCharacteristics	mobileITSStation	
1		privateITSStation	
1		physicalRelevantITSStation	
8+8+4	ReferencePositon	Longitude/Longitude/Elevation	
4		Heading	
32+4		Streetname/RoadSegment ID	
1		Position/Heading Confidence	
1	CamParameters	vehicleCommonParameters	vehicleType
2+2			Length/Width
4			Speed
2			Acceleration
1			AccelerationControl (break, throttle, ACC)…
1			exteriorLights
1			Occupancy
1+1			crashStatus/dangerousGoods

ETSI ITS G5 (cont.)

- 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, etc.
  - Messages have (tight) local scope, relay based on
    - Area (defined by circle/ellipse/rectangle)
    - Road topology
    - Driving direction

ETSI ITS G5 – DENM format (excerpt)

Length[byte]	Field		
1	messageId (0=CAM, 1=DENM)		
6	generationTime		
4	Management	Originator ID	Who sent this?
2		Sequence Number	
1		Data Version	Is this an update on a situation?
6		Expiry Time	Is this still valid?
1		Frequency	When can I expect an update?
1		Reliability	Should I trust a single notification?
		IsNegation	Does this cancel an earlier notification?
1	Situation	CauseCode	
1		SubCauseCode	
1		Severity	
4	LocationContainer	Situation_Latitude	
4		Situation_Longitude	
2		Situation_Altitude	
4		Accuracy	
N-40		Relevance Area	

ETSI ITS G5 (cont.)

- Service Announcement
  - Message on CCH to advertise services offered on SCHs
    - Channel number
    - Type of service, etc.
  - Similar to WAVE Service Announcement (WSA)
  - Receiver can tune (its second radio) to advertised channel

ETSI ITS G5 (cont.)

- Security and privacy
  - No published specification (yet)
    - Kerberos or WAVE-like PKI
    - Restrict participation to authorized vehicles
    - Sign messages
    - Limit V2I and I2V traffic where possible
  - Use pseudonyms to protect privacy
    - Use base identity (in permanent storage) to authenticate with infrastructure
    - Infrastructure generates pseudonym for vehicle

UNIVERSITÀ DI PARMA

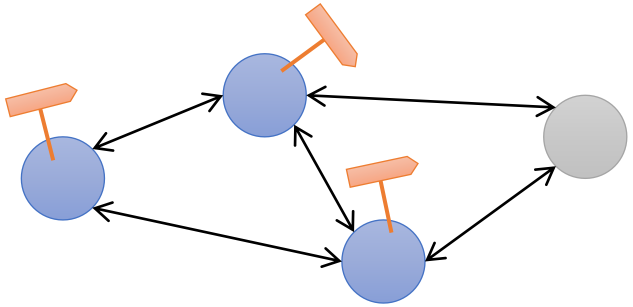
MOTORVEHICLE UNIVERSITY OF EMILIA-ROMAGNA

Extra-Vehicle Car-to-X (C2X) Networking

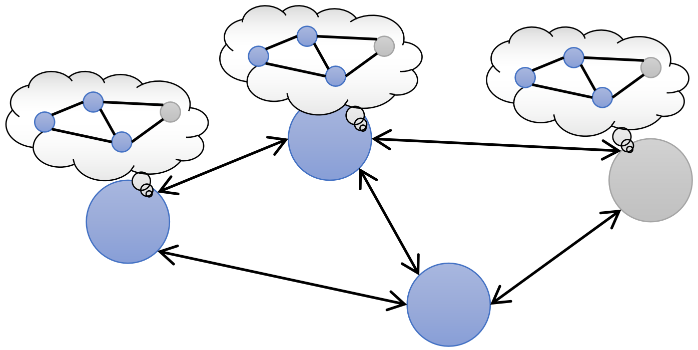
Routing: Broadcast, Geocast, Routing

Routing

- Classical approaches to routing
  - Distance Vector Routing
    - Nodes keep vector of known destinations, store distance and next hop
    - E.g., Destination-Sequenced Distance-Vector Routing (DSDV)

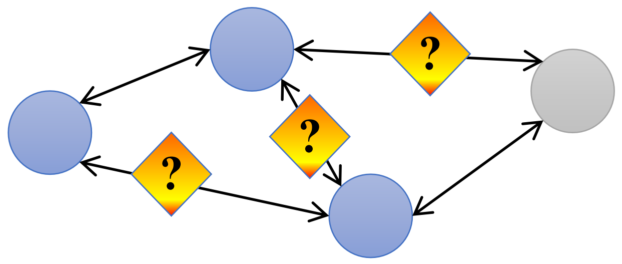


  - Link State Routing
    - Nodes keep track of of all links in network
    - Pros: fast and guaranteed convergence
    - Cons: high overhead
    - E.g., Optimized Link State Routing Protocol (OLSR)

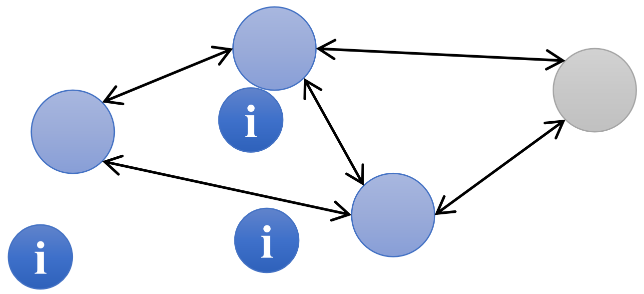


Routing (cont.)

- Classical approaches to routing
  - Reactive (on demand) routing
    - Routes established when needed
    - Routing messages only exchanged if (or while) user data is exchanged
    - Unused routes expire
    - E.g., Ad hoc On-Demand Distance Vector (AODV), Dynamic Manet On Demand (DYMO)

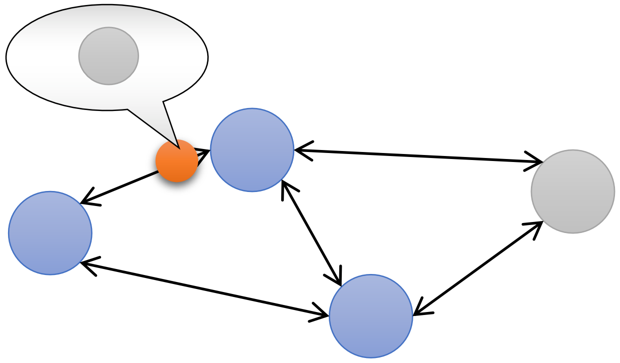


  - Proactive (table driven) routing
    - Routes are established and maintained continuously
    - No route setup delay when data needs to be sent
    - High overhead
    - E.g., OLSR, DSDV

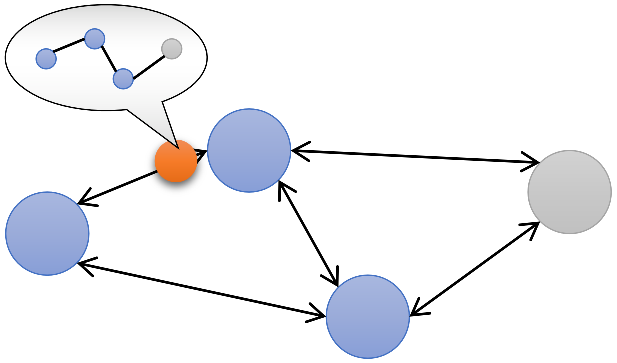


Routing (cont.)

- Classical approaches to routing
  - Hop-by-Hop Routing
    - Each packet contains destination address
    - During routing, each hop choses best next hop
    - E.g., AODV

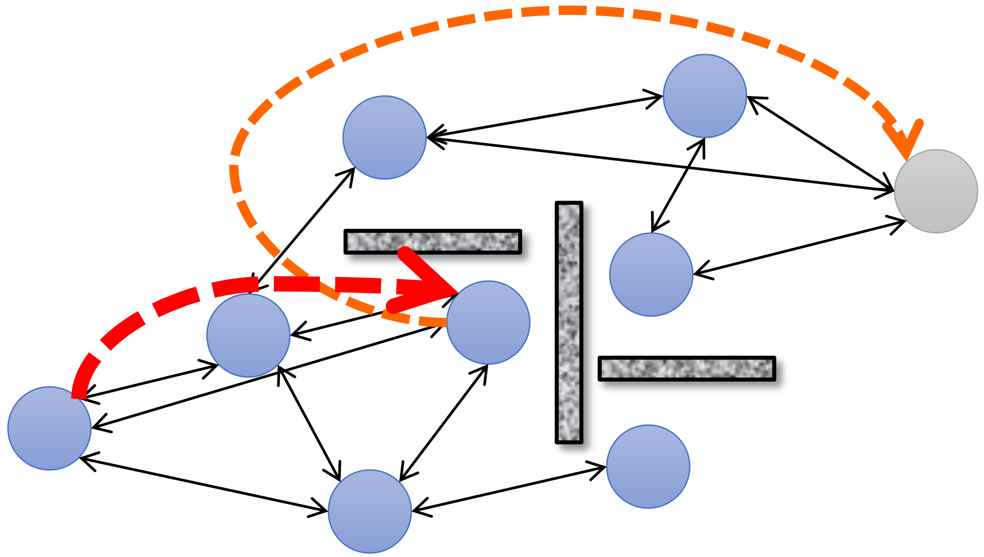


  - Source Routing
    - Each packet contains complete route to destination
    - During routing, nodes rely on this information



Routing (cont.)

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

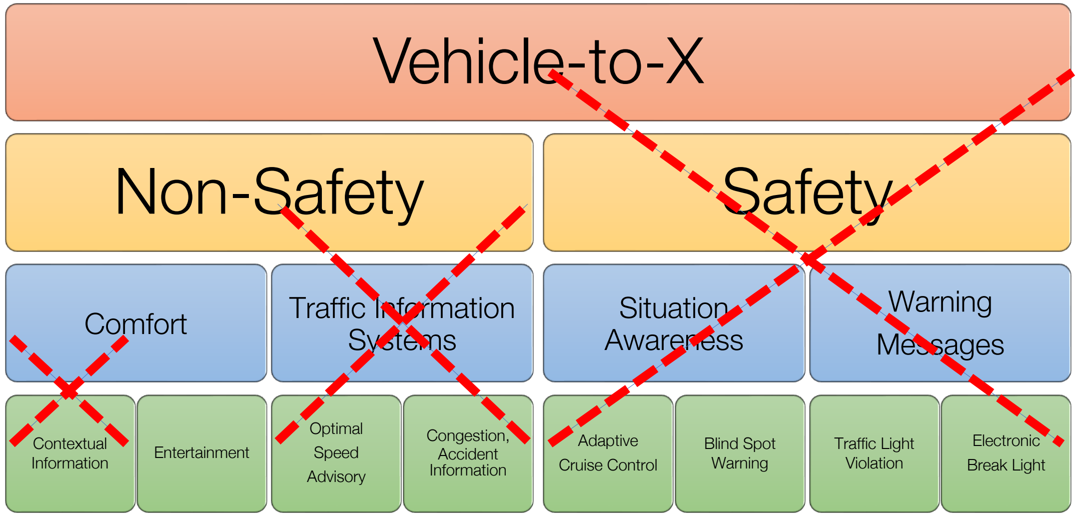


Routing (cont.)

- Georouting: Contention Based Forwarding (CBF)
  - Reduction (or complete avoidance) of duplicates
- Outline
  - Given: position of message destination, position of last hop
  - Do not forward message immediately, but wait for time T
  - Choose wait time *T* according to suitability of node
  - Do not forward message if another forward was overheard
- Problem
  - Potential forwarders must be able to overhear each others’ transmissions

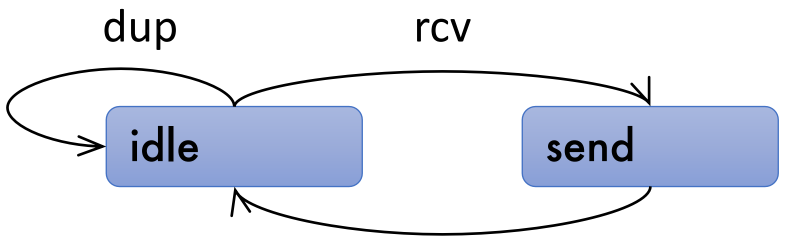
Routing (cont.)

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

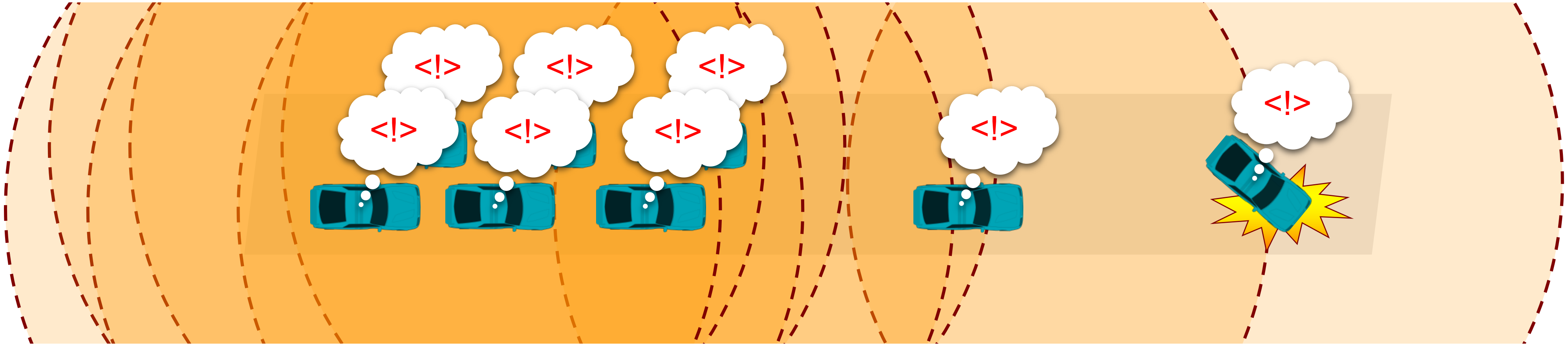


Flooding

- Flooding (multi-hop broadcast)
  - Simplest protocol: „Smart Flooding“:



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



Flooding (cont.)

- Consequences of a broadcast storm
  - Interference → impact on other systems
  - Collision → impact on other users
  - Contention → impact on other applications

Flooding (cont.)

- Solving the Broadcast Storm problem

- Classical approaches
  - Lightweight solutions (e.g., probabilistic flooding)
  - Exchange of neighbor information, cost/benefit estimations
  - Topology creation and maintenance (Cluster, Cord, Tree, …)

- Drawbacks
  - Blind guessing (or scenario dependent parameterization)
  - Additional control message overhead
  - Continuous maintenance of topology

Flooding (cont.)

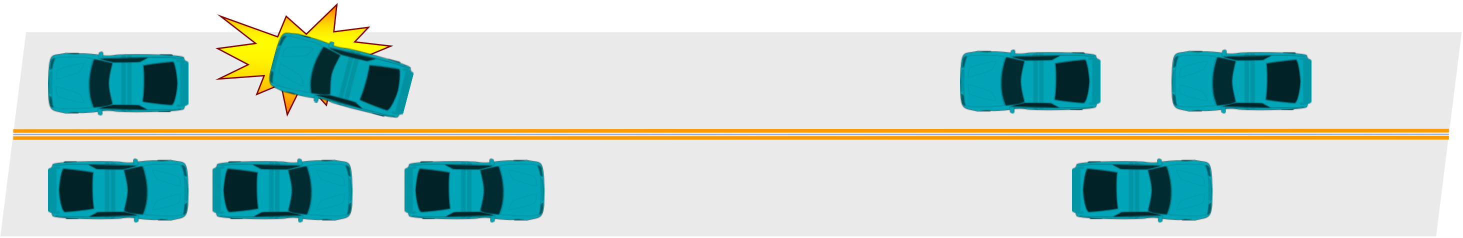
- VANET specific solution: Broadcast Suppression
  - Needs no neighbor information and no control messages
  - Maximizes distance per hop
  - Minimizes packet loss

- Approach
  - Node receives message, estimates distance to sender
  - Selectively suppresses re-broadcast of message

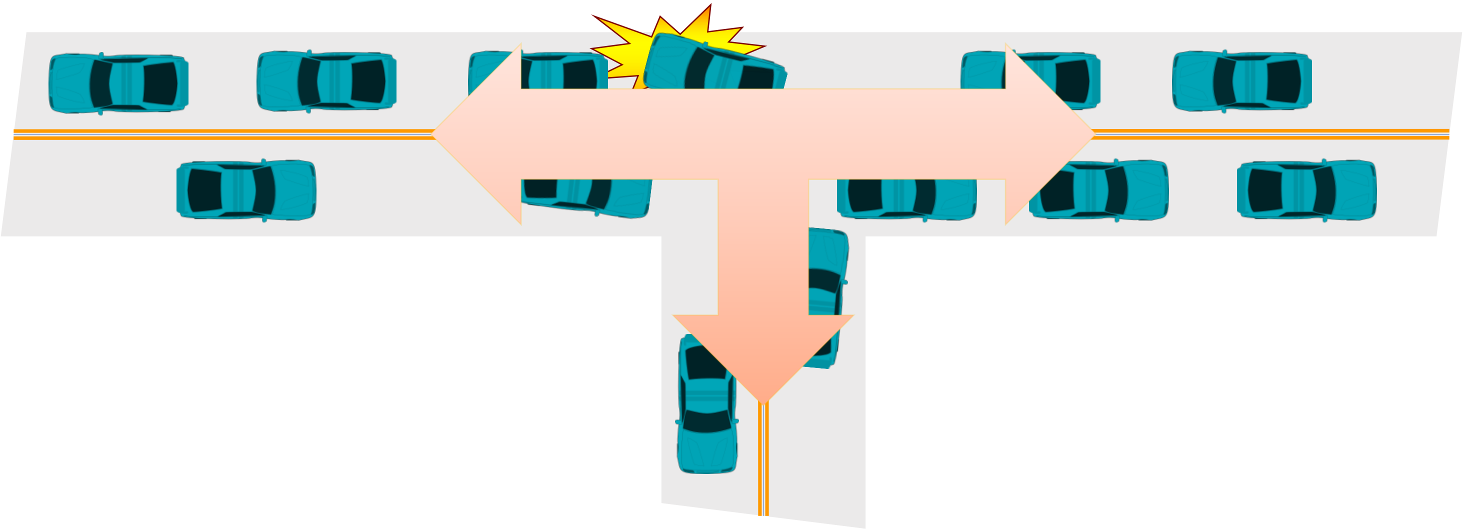
[1] Wisitpongphan, Nawaporn and Tonguz, Ozan K. and Parikh, J. S. and Mudalige, Priyantha and Bai, Fan and Sadekar, Varsha, "**Broadcast Storm Mitigation Techniques in Vehicular Ad Hoc Networks**," IEEE Wireless Communications, vol. 14 (6), pp. 84-94, December 2007

Remaining problems

- Temporary network fragmentation

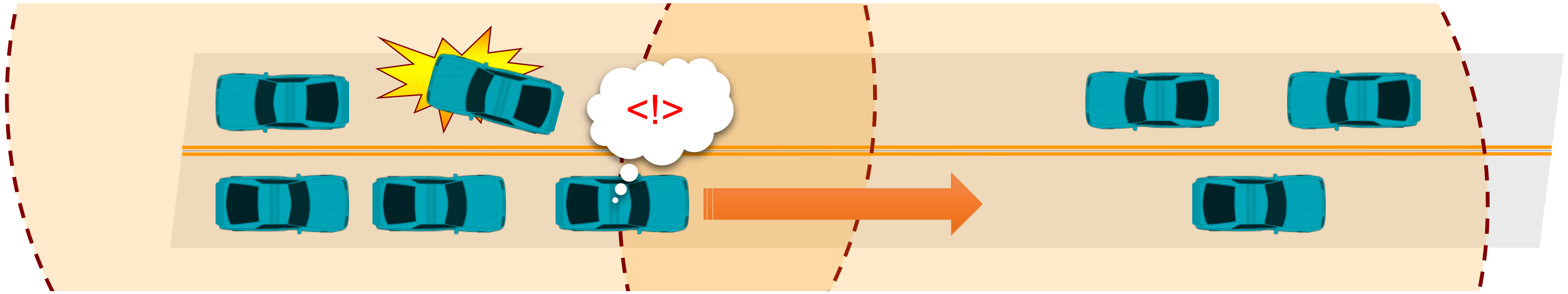


- Undirected message dissemination



Flooding + X

- DV-CAST
  - Idea: detect current scenario, switch between protocols
  - Check for fragmented network
    - Network connected → perform broadcast suppression
    - Network fragmented → perform Store-Carry-Forward
  - doi:10.1109/MWC.2010.5450660



Flooding + X (cont.)

- DV-CAST: Mechanism
  - Nodes periodically send *Hello* beacons containing position, speed
  - Nodes maintain 3 neighbor tables
    - Same direction, ahead
    - Same direction, driving behind
    - Opposite direction
  - Messages contain source position and Region of Interest (ROI)

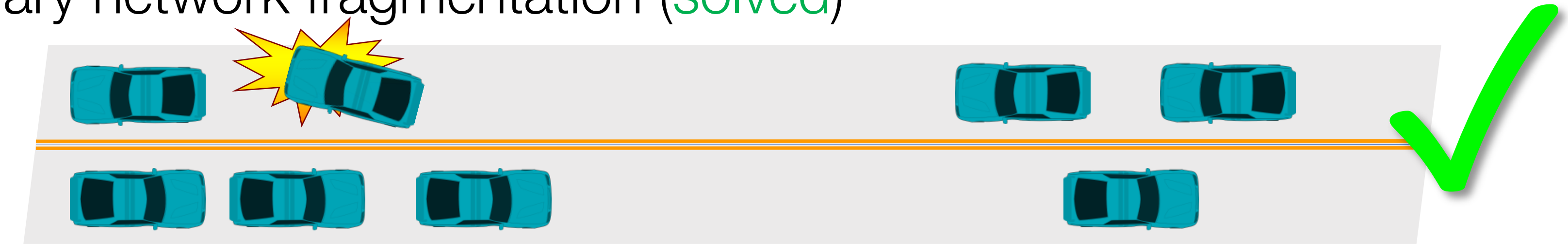
  - For each message received, evaluate 3 Flags:
    - Destination Flag (DFlg):
      Vehicle in ROI, approaching source
    - Message Direction Connectivity (MDC):
      ∃ neighbor driving in same direction, further away from source
    - Opposite Direction Connectivity (ODC):
      ∃ neighbor driving in opposite direction

Flooding + X (cont.)

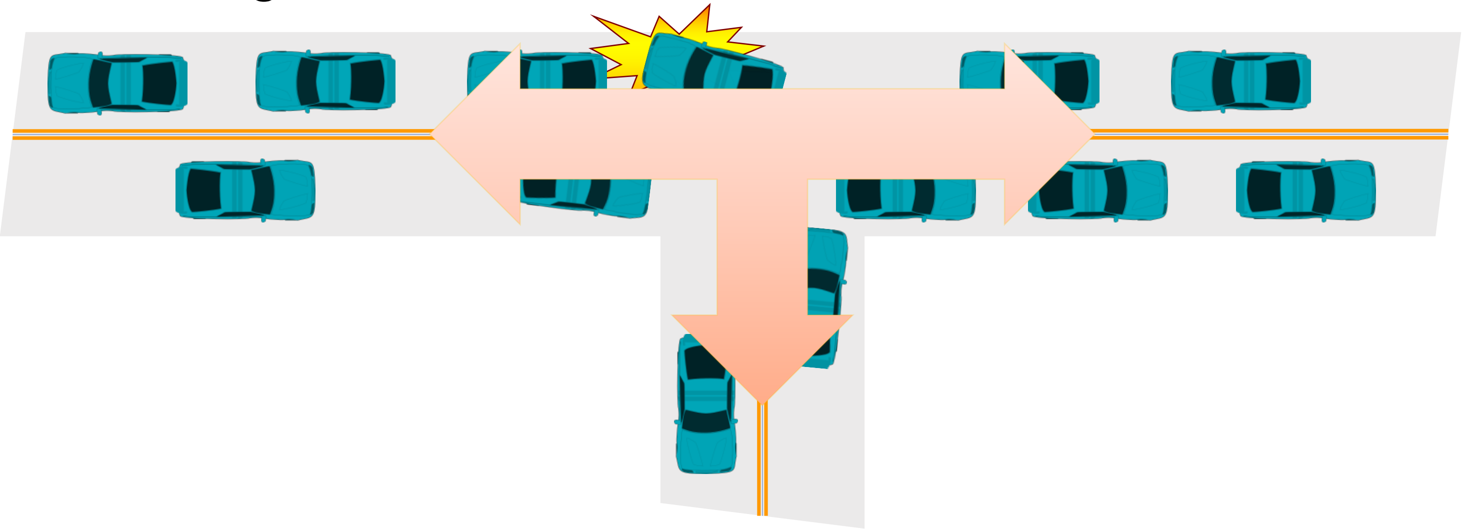
- DV-CAST
  - Simulation results show that (on freeways with low to medium node densities) DV-CAST beats simple flooding in terms of broadcast success rate and distance covered

Intermediate Summary

- Remaining problems
  - Temporary network fragmentation (solved)

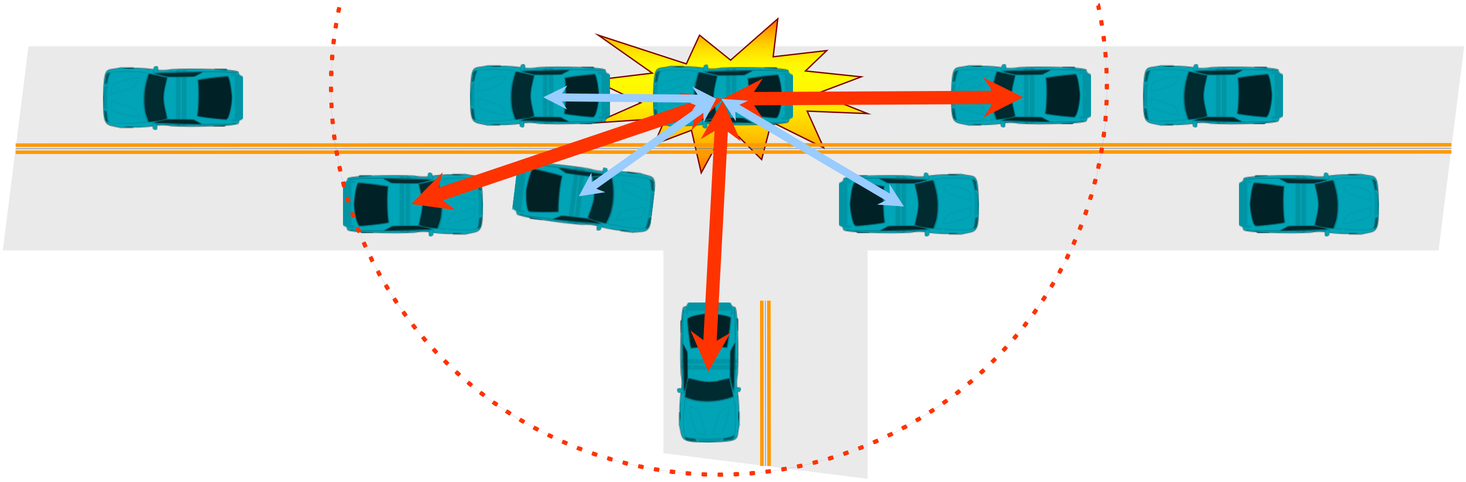


  - Undirected message dissemination



Geocast

- Topology-Assisted Geo-Opportunistic Routing (TO-GO)
  - Nodes periodically send *Hello* beacons; Contents:
    - Number of neighbors
    - Bloom filter of neighbor IDs
    - IDs of neighbors furthest down the road/roads
  - Thus, nodes know about all 2-hop neighbors
  - doi:10.1109/MCOM.2010.5458378



Intermediate Summary

- Remaining problems
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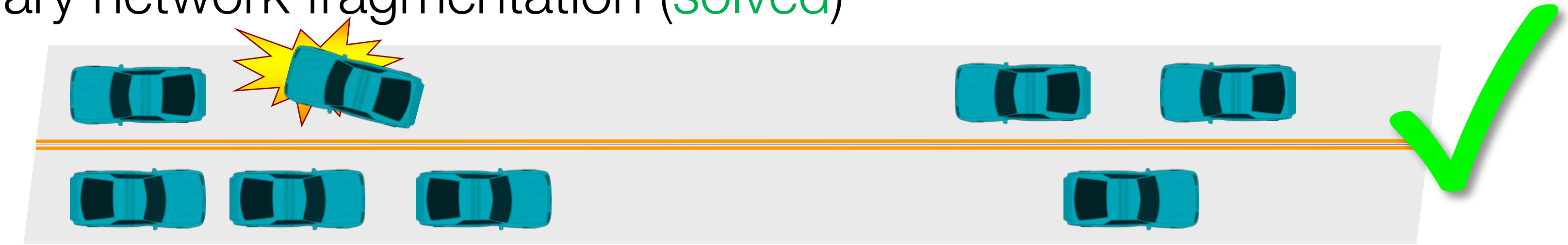
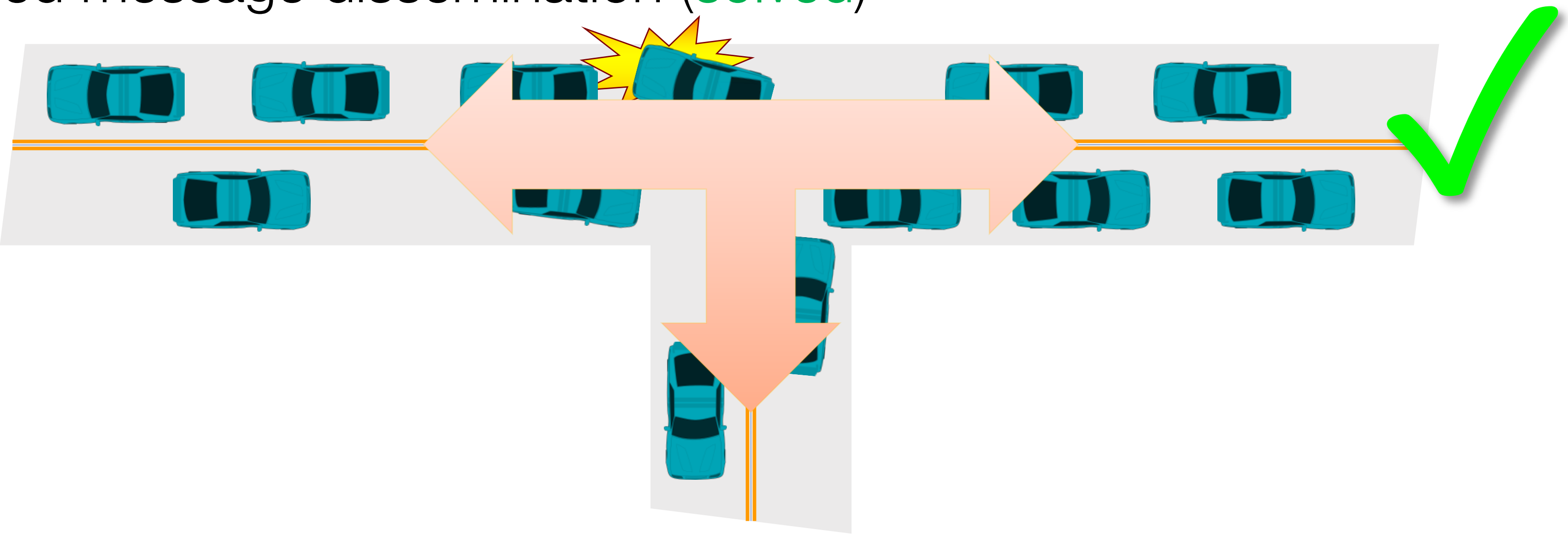
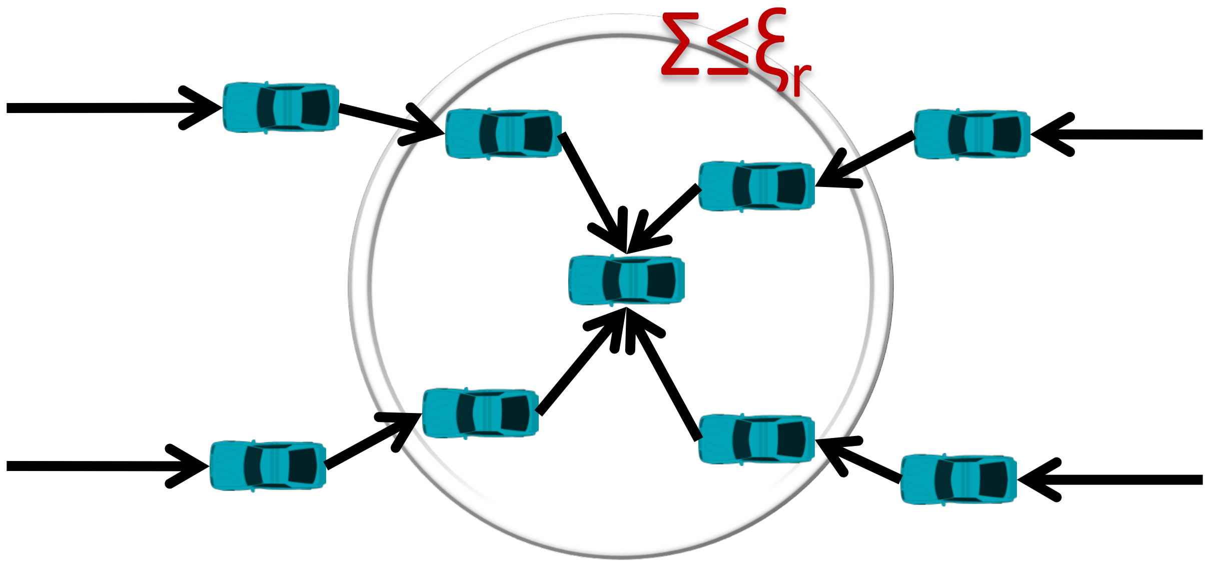


  - Undirected message dissemination (solved)



Scalability

- Do the presented approaches scale?
- Analytical evaluation [1]
  - Capacity of wireless channel is limited
  - Amount of information transported across any (arbitrary) border must be upper-bounded



[1] B. Scheuermann, C. Lochert, J. Rybicki, and M. Mauve, "A Fundamental Scalabiliy Criterion for Data Aggregation in VANETs," in ACM MobiCom 2009. Beijing, China: ACM, Sept. 2009

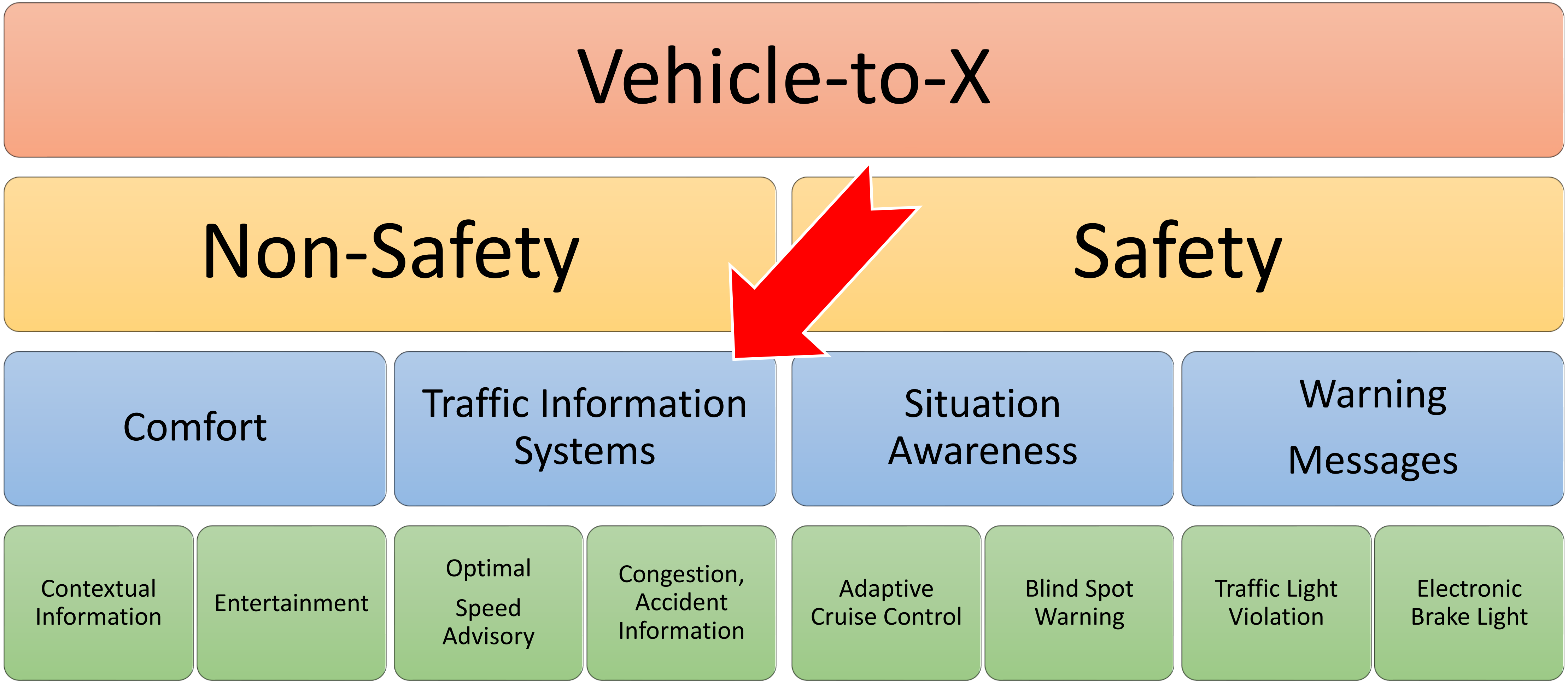
Main Takeaways

- Classic information dissemination
  - Distance vs. link-state
  - Reactive vs. proactive
  - Hop-by-hop vs. source routing
  - Geo-routing (CBF)
- Examples of VANET-centric information dissemination
  - Flooding (Weighted/Slotted 1/p-Persistence)
  - Fragmentation (DV-Cast)
  - Directedness (To-Go)
- Scalability

Extra-Vehicle Car-to-X (C2X) Networking

Beaconing and TIS – Traffic Information Systems

Here we are


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

Motivation

- Goals:
  - Increase comfort
  - Reduce (or avoid) traffic jams
  - Relieve driver
  - Decrease travel times
  - Smooth traffic flow
  - Decrease Emissions (?)
    - CO_2, NO_X, Noise, ...

- Recall: Traditional TIS
  - Traffic Information Center (TIC) collects data, creates bulletins
  - Bulletins are disseminated via RDS-TMC or TPEG
  - Navigation assistant reacts by re-routing

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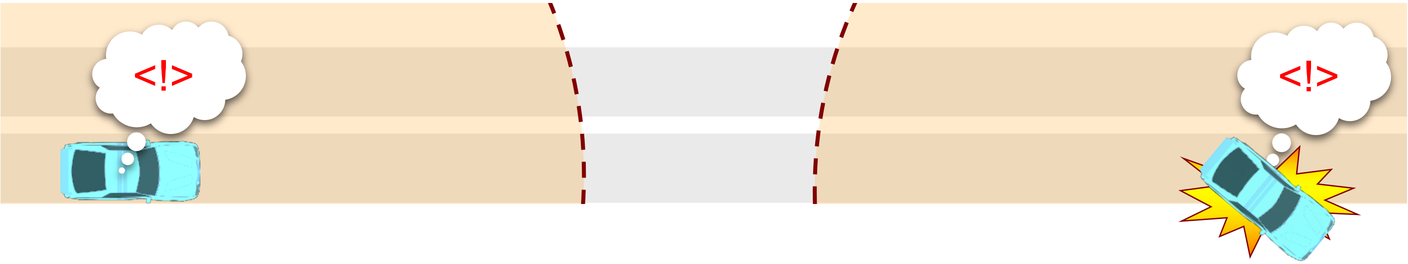
SOTIS

- Self-Organizing Traffic Information System (SOTIS)
  - Each node maintains local knowledge base
  - Periodically sends single-hop broadcasts with information (Beacon)
    - Weather information gets sent with longer interval
    - Accident messages get sent with shorter interval
  - Integrates received information with knowledge base
- Techniques
  - WiFi (IEEE 802.11) in Ad-hoc-Mode
  - SODAD (Segment-oriented data abstraction and dissemination)

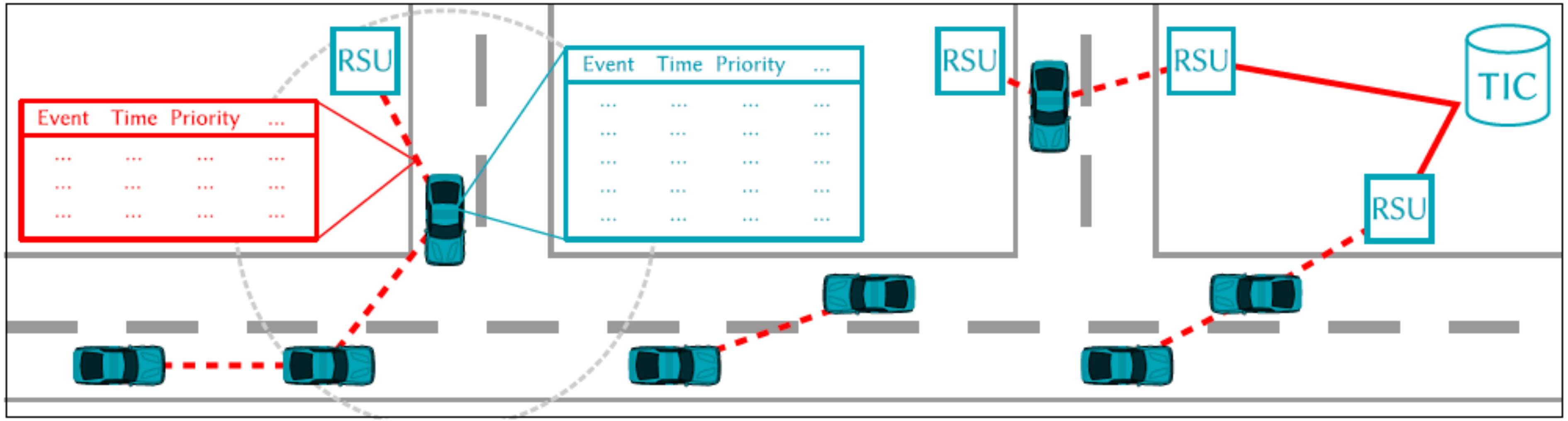


SOTIS (cont.)

- Evaluation: speed of information dissemination depends on traffic density and market penetration
- Open issues
  1. Infrastructure-less operation: needs high marked penetration
  2. Required/tolerable beacon interval highly dependent on scenario
  3. Design needs dedicated channel capacity
- Real networks are heterogeneous
  1. Roadside infrastructure present vs. absent, freeway scenario vs. inner city
  2. Own protocol ⇔ other, future, and legacy protocols
- How to do better?
  1. Dynamically incorporate optional infrastructure, dynamically adapt beacon interval, dynamically use all free(!) channel capacity

Adaptive Traffic Beacon (ATB)

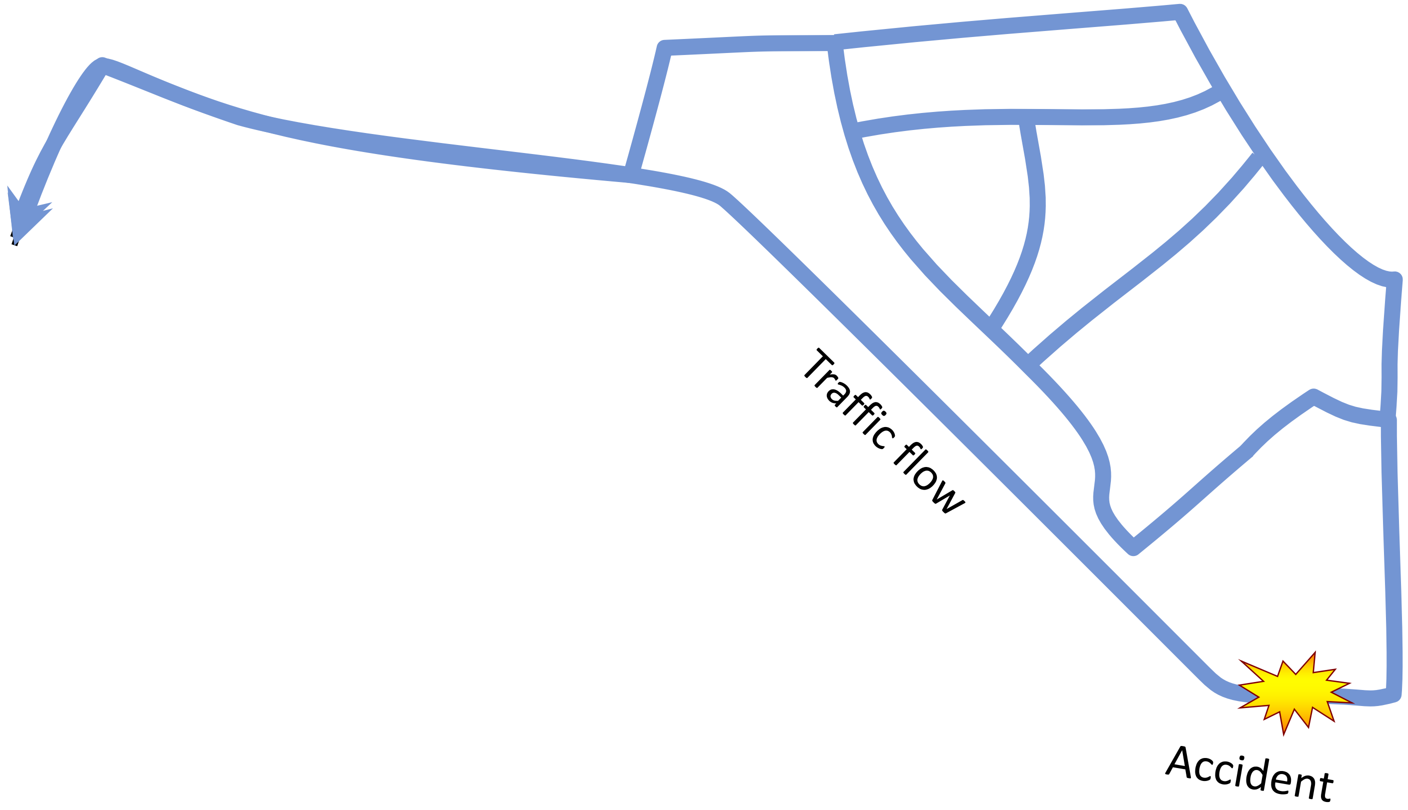
- Adaptive use of infrastructure
  - Independent operation
  - Road Side Units
  - Traffic Information Center uplink



Picture source: C. Sommer, O. K. Tonguz, F. Dressler, "Traffic Information Systems: Efficient Message Dissemination via Adaptive Beaconing," IEEE Communications Magazine, vol. 49 (5), pp. 173-179, May 2011

Envisioned Scenario

- Highly dynamic network



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