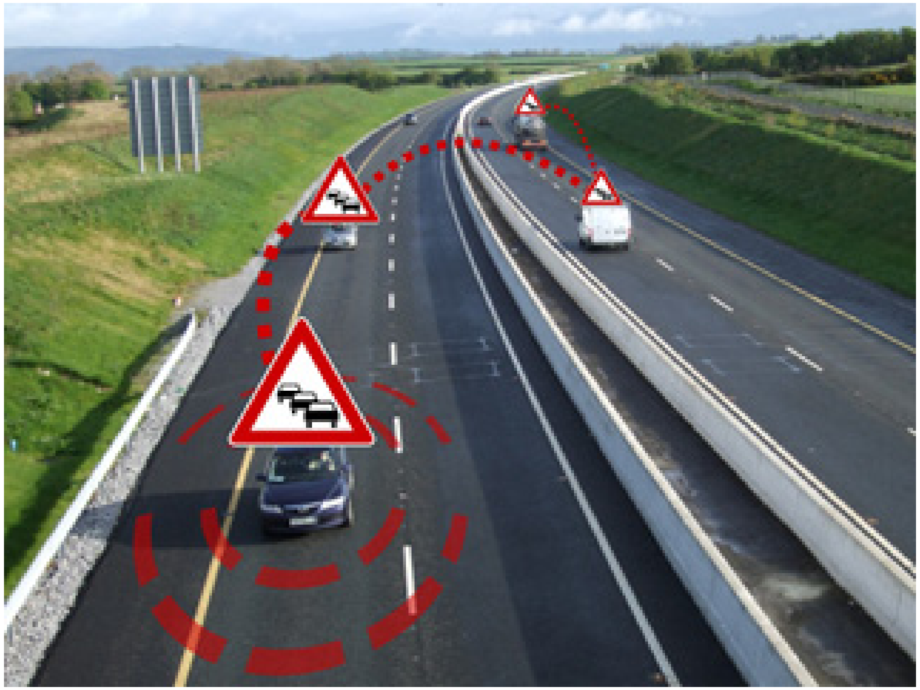
Vehicular Networking

Course Overview

- Vehicular Networking
- Part 1: ...in cars
  - Overview and use cases
  - Architectures
  - Bus systems
  - Electronic Control Units
  - Security and safety
- Part 2: ...of cars
  - Overview and use cases
  - Architectures
  - Communication systems
  - Applications
  - Security and safety



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About this slide deck

- These slides are designed to accompany a lecture based on the textbook "Vehicular Networking" by Christoph Sommer and Falko Dressler, published in December 2014 by Cambridge University Press.
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- This slide deck would not have been possible without the contributions of Falko Dressler, David Eckhoff, Reinhard German, and Kai-Steffen Jens Hielscher.
- Please leave this slide intact, but indicate modifications below.
  - Version 2015-02
    - Improved version for release on book website (Christoph Sommer)
- Updated versions of the original slide deck are available online [2].

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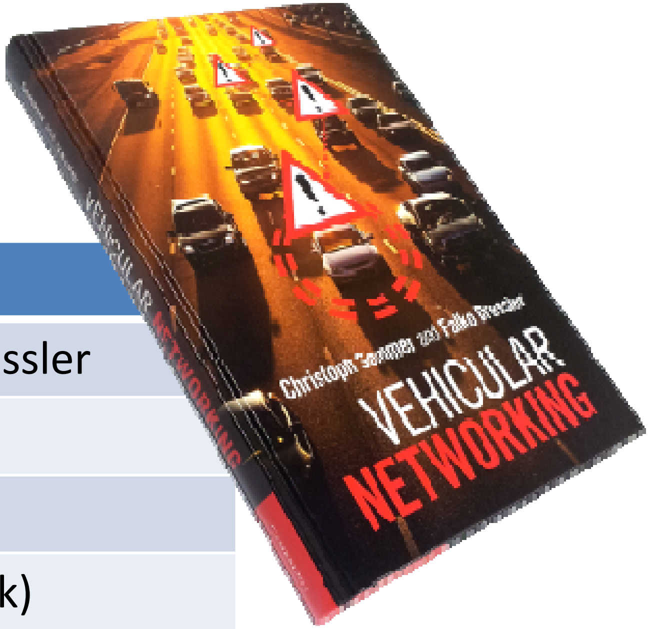
Course Material



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A Short Introduction

…to Vehicular Networking

Introduction

1970s

- Electronic Fuel Injection
- Centralized Warning Lights
- Cruise Control
- Central Locking
- ...

1980s

- Electronic transmission control
- Electronic climate control
- ASC (Anti Slip Control)
- ABS (Antilock Braking System)
- Phone
- Seat heater control
- Automatically dimming rear view mirror
- ...

1990s

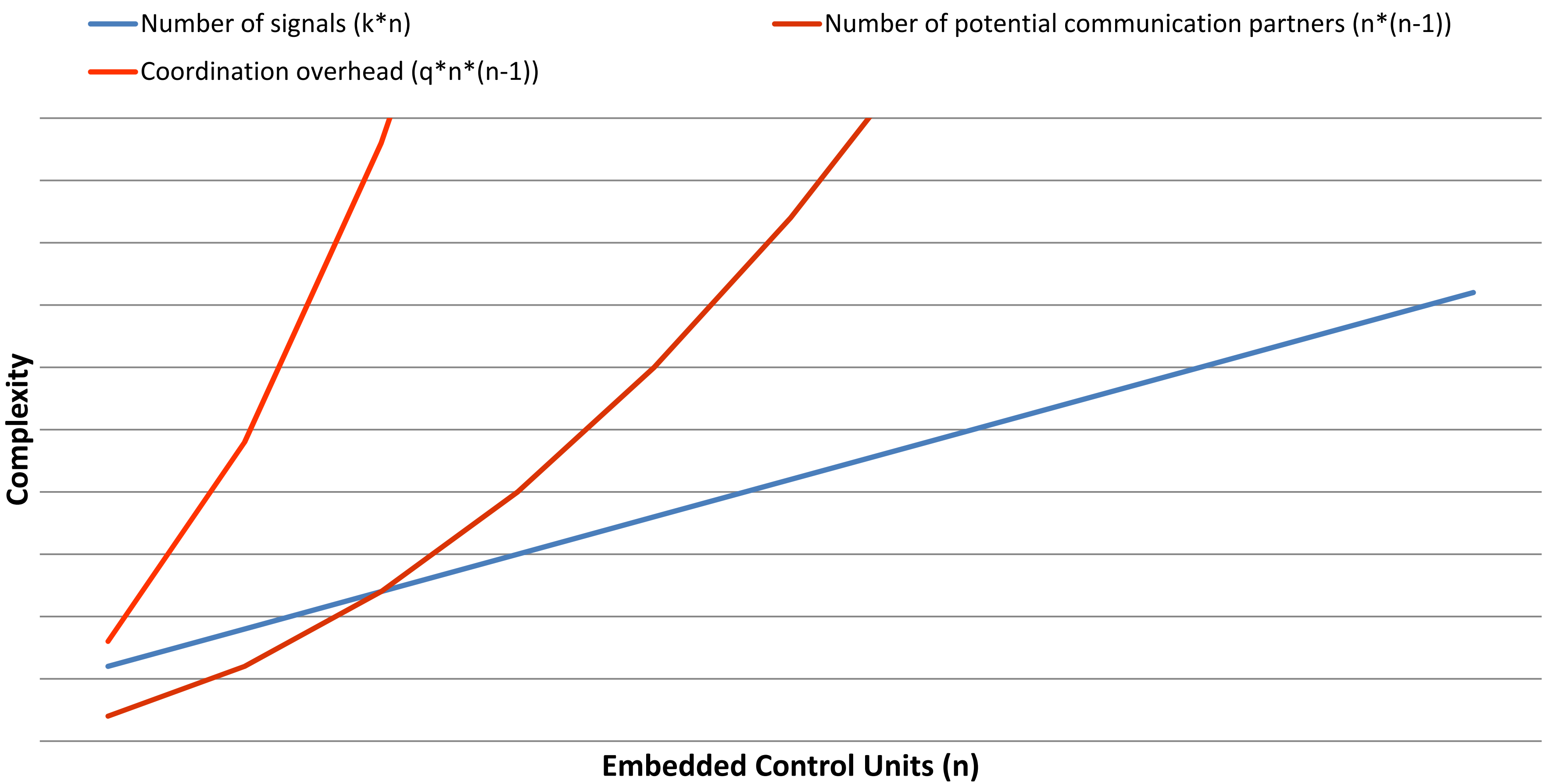
- navigation system
- CD changer
- ACC (Active Cruise Control)
- Airbags
- DSC (Dynamic Stability Control)
- Adaptive Transmission Control
- Roll stabilization
- Xenon light
- BMW Assist
- RDS / TMC
- Voice Recognition
- Emergency call
- ...

2000s

- ACC Stop & Go
- BFD
- ALC
- KSG
- 42 volt system
- Internet Portal
- GPRS, UMTS
- Telematics
- Online Services
- Bluetooth
- Car Office
- Local Hazard Warning
- Integrated Safety System
- Steer / Brake-By-Wire
- I-Drive
- Lane keeping support
- Personalization
- SW update
- Force Feedback Pedal
- ...

Data Source: U. Weinmann: Anforderungen und Chancen automobilgerechter Softwareentwicklung, 3. EUROFORUM-Fachkonferenz, Stuttgart, Juli 2002

Electronics need communication



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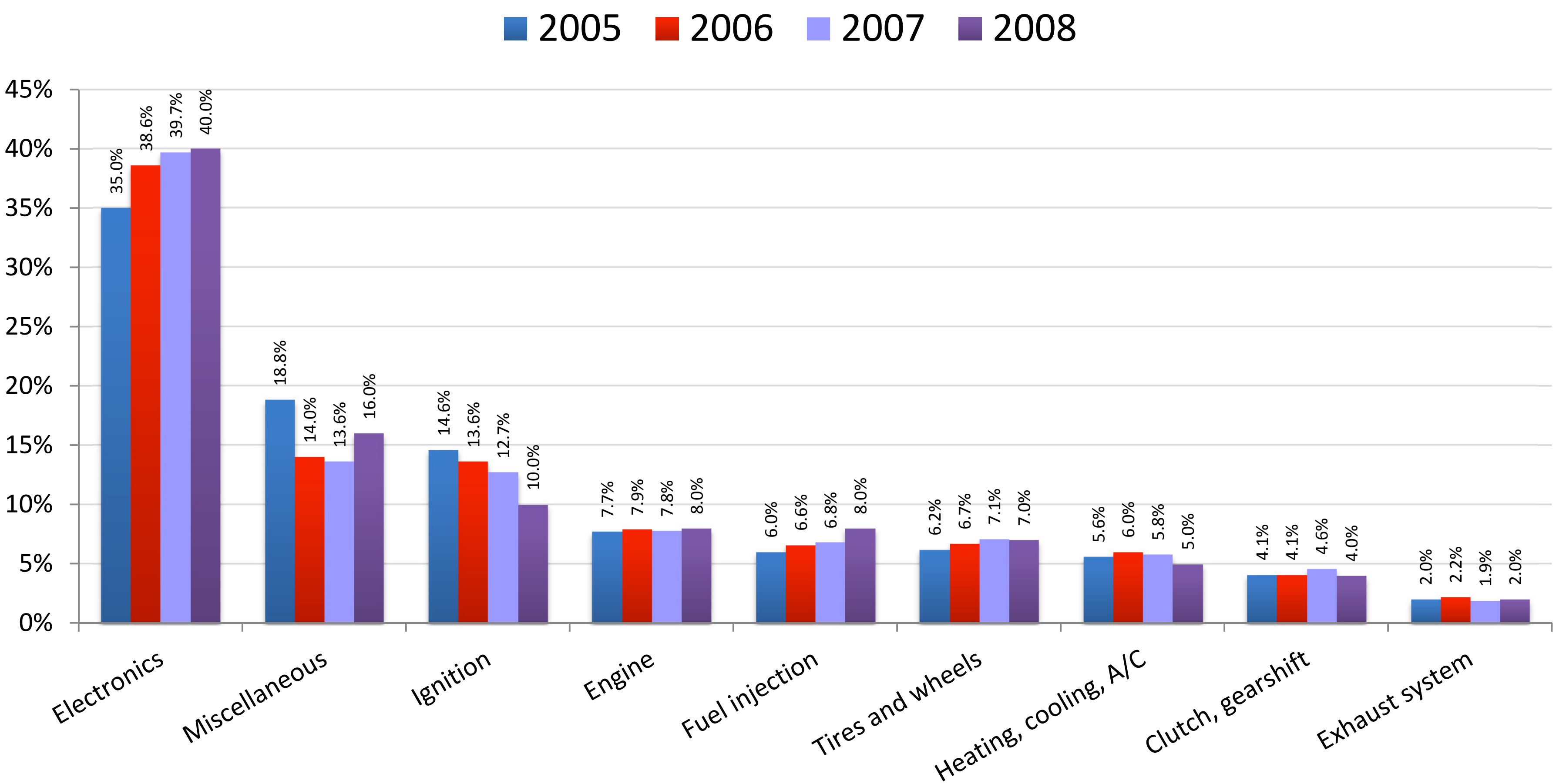
Component failure rate



Data Source: ADAC Vehicle Breakdown Statistics 2005-2008

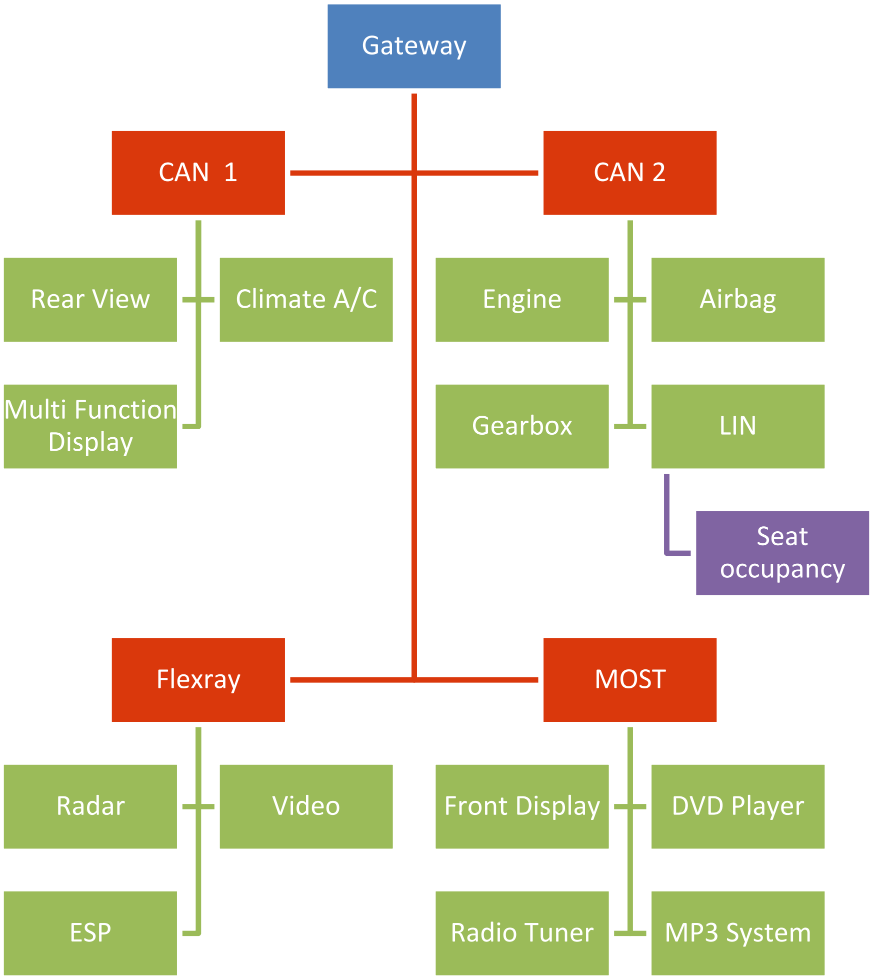
Bus systems

- Until the end of the 80s
  - Cars‘ control units are isolated, non-networked
  - dedicated wires connect sensors and actors
- Starting with the 90s
  - digital Bus systems
  - CAN-Bus
- Today
  - Rising demands on bus systems
  - networked functionality requires more than one control unit
    - Turn signal: > 8 distinct control units
  - Real time constraints
  - Multimedia

Bus systems

- Complexity is ever increasing
  - From 5 ECUs in a 1997 Audi A6
  - To over 50 ECUs in a 2007 Audi A4
  - Current middle and upper class vehicles carry 80 .. 100 networked Electronic Control Units (ECUs)
- Traditionally: one task ⇔ one ECU
- New trends:
  - distribution of functions across ECUs
  - integration of multiple functions on one ECU

Multiple bus systems

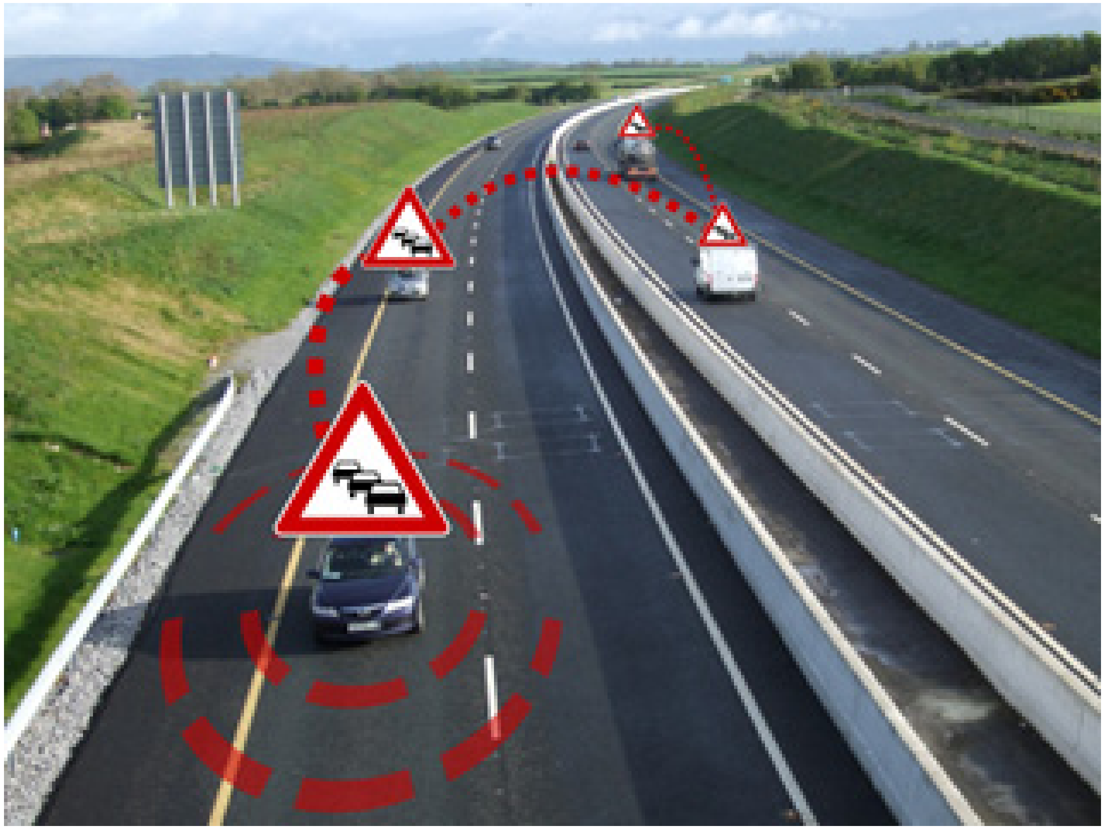


Electronics today

- Up to 100 ECUs
- Up to 30% of value creation
- Up to 90% of Innovations
- Up to 3km of wiring for power and data
- Up to 3800 interface points

Electronics tomorrow

- Data will leave confines of single car: inter-vehicle communication



Visionary Applications

- Lane assistant
  - Simple roadside beacons support lane detection
- Lateral collision avoidance
  - More advanced beacons on cars and motorcycles help maintain minimum separation
- Accident reporting
  - Broken down cars can automatically send simple report to central server
- Intersection assistance
  - Pairs of cars automatically coordinate complex maneuvers at intersections
- Cooperative driving
  - The future evolution of autonomous driving: vehicles actively support each other's route planning, navigating, driving

Visionary Applications

- ...and much (much) more:

Emergency Brake Light Warning, Accident Warning, Emergency Flashlights, Traffic Jam Warning, Weather Warning, Emergency Vehicle, Slow Vehicle, Moving and Static Road Works, Obstacle Warning, Intersection Maneuvering Assistance, Intersection Traffic Lights, Lane Change, Maneuvering Assistance, Longitudinal Maneuvering Assistance, Floating Car Data Collection, Free-Flow Tolling, Breakdown Call, Remote Diagnostics, Theft Detection, Emergency Call, Just-In-Time Repair Notification, Roadside Traffic Camera pull, In-vehicle signing pull, Regional Information pull, Car-specific Software Application Download pull, Electronic Payment pull, Logistic for goods being loaded and unloaded, Traffic Information Service pull, Traffic Information Service push, Electronic Payment push, Roadside Traffic Camera push, In-vehicle signing push, Car specific Software Application Download push, Telemetric Onboard/Off-board Diagnostics, Remote Vehicle Status Control, Fleet Management, Server based navigation, Remote lock-down, Remote entry, Mobile Office, Videophone, Personal Data Synchronization at home, General Map Downloads and Updates, Instant Messaging, General internet services, Internet Audio, continuous feed, Web Browsing, Movie rental, Remote Home Activation/Deactivation pull, Remote Home Control pull, Remote Home Activation/Deactivation push, Remote Home Control push, Voice Chat, Games, Electronic Toll Collection, Parking Unit Fee Payment (drive through payment), Goods and services discovery and payment, Guided Tour, Interactive Lights Dimming, Emergency Traffic Light Pre-emption, Traffic Light Assistant, …

Source: C2CCC, Aktiv-AS/VM

Challenges of communication

- Basic challenges
  - Timeliness
  - Throughput
- Communication in vehicles: stresses...
  - Robustness
  - Cost
- Communication across vehicles: also needs...
  - Interoperability
  - Reachability
  - Security
  - Privacy

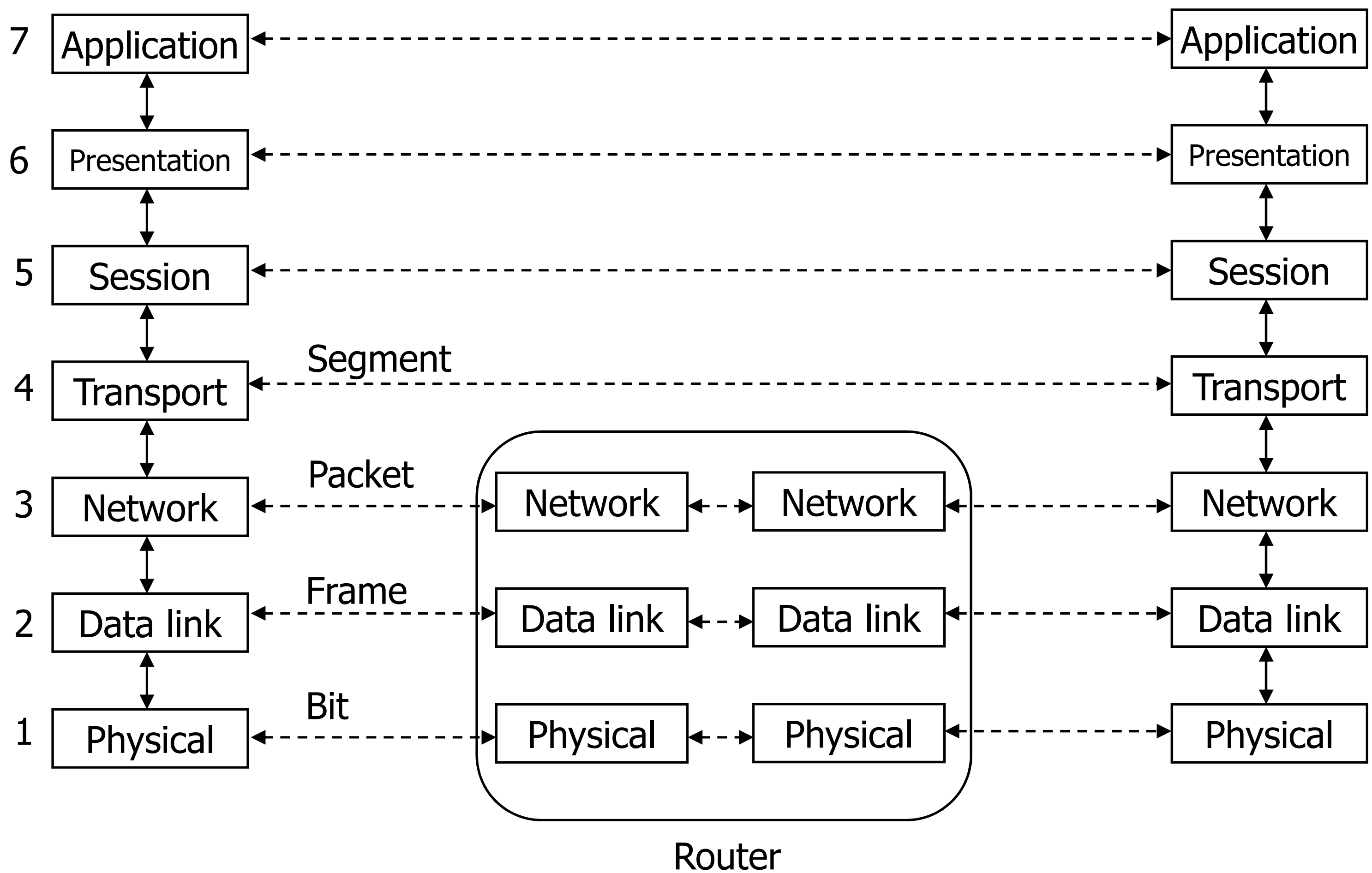
Part 1

In-Car Networking

ISO/OSI Layers

- Layered communication architecture
  - One layer ⇔ one function ⇔ one protocol
  - Layer interacts only with immediate base layer
  - Interfaces follow rigid specification
    - commonly by standards body
- ISO/OSI layered communication model
  - Defines 7 layers
    - see next slide
  - Common architectures relax rigid guidelines
    - cf. TCP/IP

ISO/OSI Layers, Example



ISO/OSI Layers, Functions in Detail

- Physical Layer
  - Specifies mechanical, electrical properties to transmit bits
  - Time synchronization, coding, modulation, ...
- Data Link Layer
  - Checked transmission of frames
  - Frame synchronisation, error checking, flow control, ...
- Network Layer
  - Transmission of datagrams / packets
  - Connection setup, routing, resource management, …
- Transport Layer
  - Reliable end to end transport of segments

ISO/OSI Layers, Functions in Detail

- Session Layer
  - Establish and tear down sessions
- Presentation Layer
  - Define Syntax and Semantics of information
- Application Layer
  - Communication between applications

- Our focus (in part 1 of lecture)
  - Physical Layer
  - Data Link Layer

Why bus systems?

- Lower cost
  - Material
  - Weight
  - Volume

- Higher modularity
  - customizability
    of vehicles
  - cooperation with Original Equipment Manufacturers (OEMs)

- Shorter development cycles
  - Re-usability of components
  - Standard protocols and testing plans ⇨ less errors

History

- First micro processors in vehicles in 1980s
- Communication via point to point connections
- Simple control lines, little real data transmission
- True data transmission for connection external diagnosis equipment
- Birth of standard for character transmission
  - via K-Line (ISO 9141)
- Finally: introduction of data busses for in-vehicle communication
- Later standardized as CAN (ISO 11898)
- Use in series production models starts 1991

Overview and Use Cases

- State of the art
  - K-Line and CAN are part of On Board Diagnosis (OBD) connector
  - Enables, e.g., reading engine parameters, catcon, oxygen (lambda) sensor
  - Mandatory for newly registered vehicles in both EU und U.S.

Use Cases

- Driveline
  - Engine and transmission control
- Active Safety
  - Electronic Stability Programme (ESP)
- Passive Safety
  - Air bag, belt tensioners
- Comfort
  - Interior lighting, A/C automation
- Multimedia and Telematics
  - Navigation system, CD changer

Classification: On board communication

- On board communication
  - Complex control and monitoring tasks
    - Data transmissions between ECUs / to MMI
    - E.g., engine control, ext. sensors, X-by-Wire
  - Simplification of wiring
    - Replaces dedicated copper wiring
    - E.g., central power locks, power windows, turn signal lights
  - Multimedia bus systems
    - Transmission of large volumes of data
    - E.g., Navigation unit, Radio/CD, Internet

Classification: Off board communication

- Off board communication
  - Diagnosis
    - Readout of ca. 3000 kinds of errors
    - Garage, exhaust emission testing
  - Flashing
    - Initial installation of firmware on ECUs
    - Adaptation of ECU to make, model, extras, ...
  - Debugging
    - Detailed diagnosis of internal status
    - During development

Classification by use case

Application	Message length	Message rate	Data rate	Latency	Robustness	Cost
Control and monitoring		★★	★★	★★★	★★★	★★
Simplified Wiring				★	★★	★
Multimedia	★	★★	★★★	★	★	★★★
Diagnosis						★
Flashing	★★		★★		★	
Debugging		★	★	★★		

Classification by Society of Automotive Engineers (SAE)

Class A

Data rate ~ 16 kBit/s	Cheap	Diagnosis, Sensor-Actor

↓

Class B

Data rate ~ 64 kBit/s	Error correcting	Networking ECUs

↓

Class C

Data rate ~ 1 MBit/s	Real time requirements	Drive train

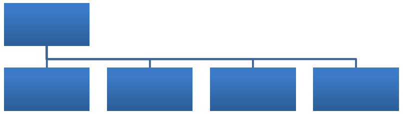
↓

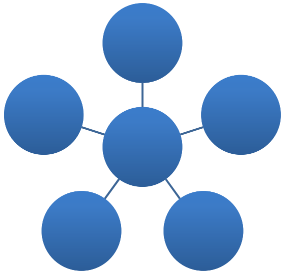
Class D

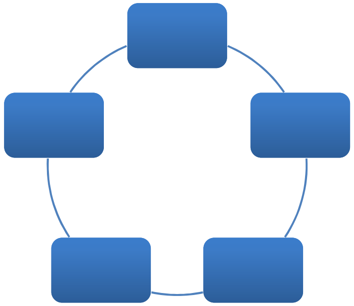
Data rate ~ 10 MBit/s	Low latency	X-By-Wire, Multimedia

Network Topologies

- Network topologies
  - Line
    - ☑ Cost
    - ☑ Complexity
    - ☐ Robustness
  - Star
    - ☐ Cost
    - ☑ Complexity
    - (☑) Robustness
  - Ring
    - ☑ Cost
    - ☐ Complexity
    - ☑ Robustness







Network Topologies

- Coupling of bus elements
  - Repeater
    - Signal amplification
    - Signal refreshing
  - Bridge
    - Medium / timing adaptation
    - Unfiltered forwarding
  - Router
    - Filtered forwarding
  - Gateway
    - Address adaptation
    - Speed adaptation
    - Protocol adaptation

1 – Phy	
Bus 1	**Bus 2**

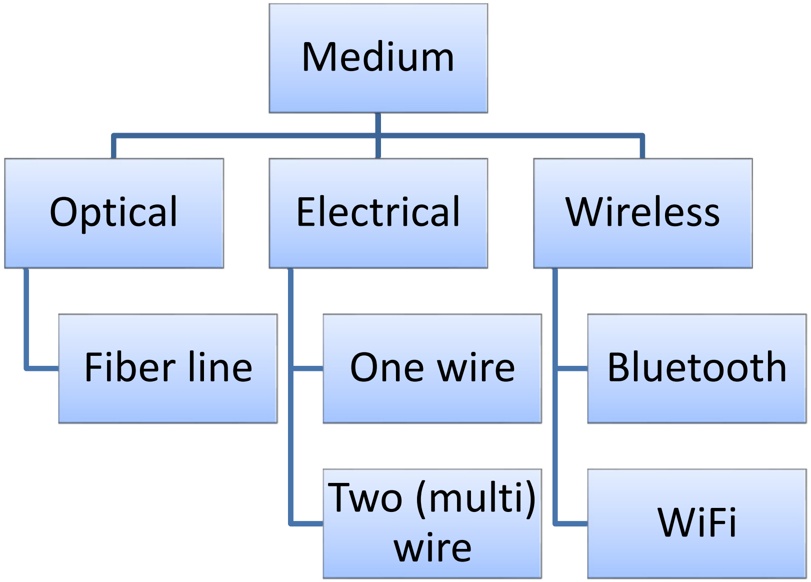
2 - Lnk	
1 - Phy	1 - Phy
Bus 1	**Bus 2**

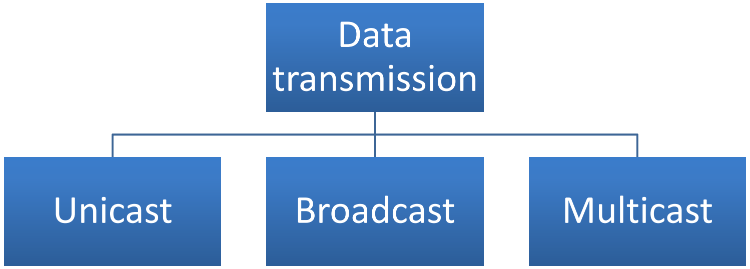
3 - Net	
2 - Lnk	2 – Lnk
1 - Phy	1 - Phy
Bus 1	**Bus 2**

7 - App	
3 - Net	3 - Net
2 - Lnk	2 – Lnk
1 - Phy	1 - Phy
Bus 1	**Bus 2**

Network Topologies

- Medium and Data transmission



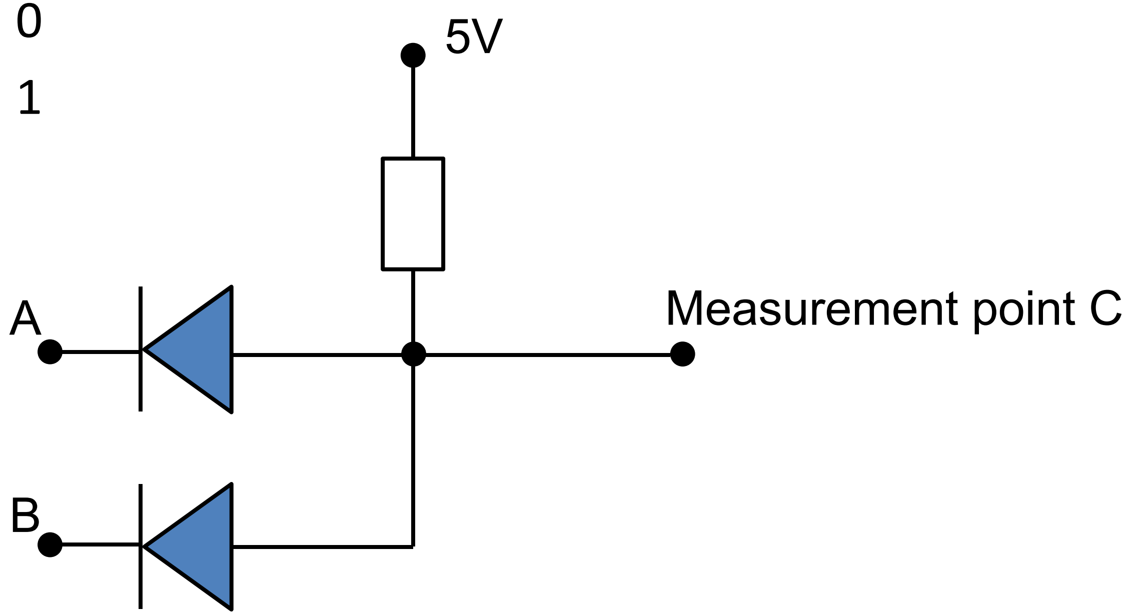


Network Topologies

- Concurrent bus access for typical wiring
  - Shared data line connected to pull-up resistors
  - Transistors can pull data line to GND (signal ground)
  - Base state
    - transistors non-conductive
    - pull up resistors raise bus level to *high*
  - One or more ECUs turn transistor conductive
    - This connects bus to signal ground
    - Bus level is *low* independent of other ECUs (⇨ dominant state)
  - Wired OR (if *low* $\triangleq$ 1) / Wired AND (if *low* $\triangleq$ 0)

Network Topologies

- Wired OR
  - Example (assuming negative logic)
    - 5V = logical 0
    - 0V = logical 1



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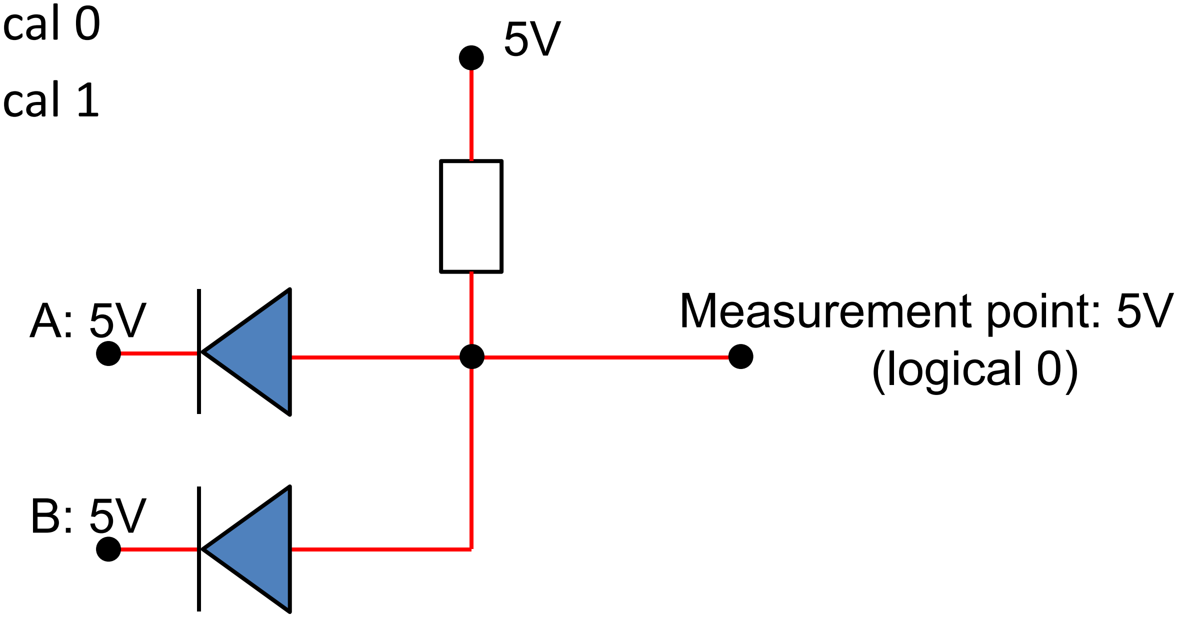
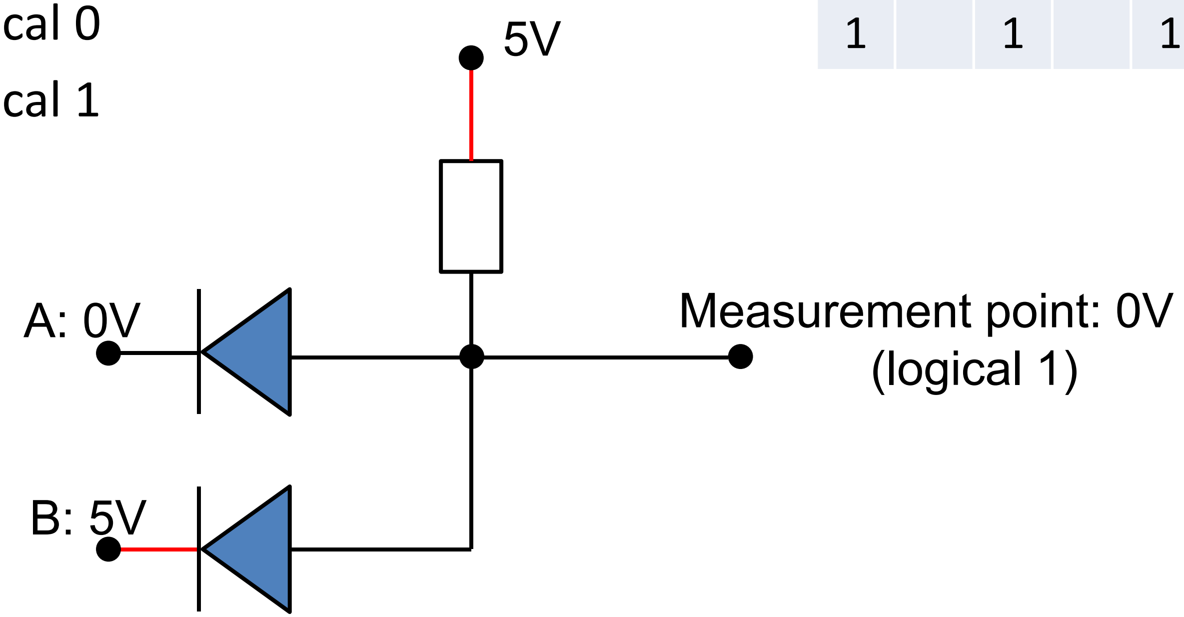


Network Topologies

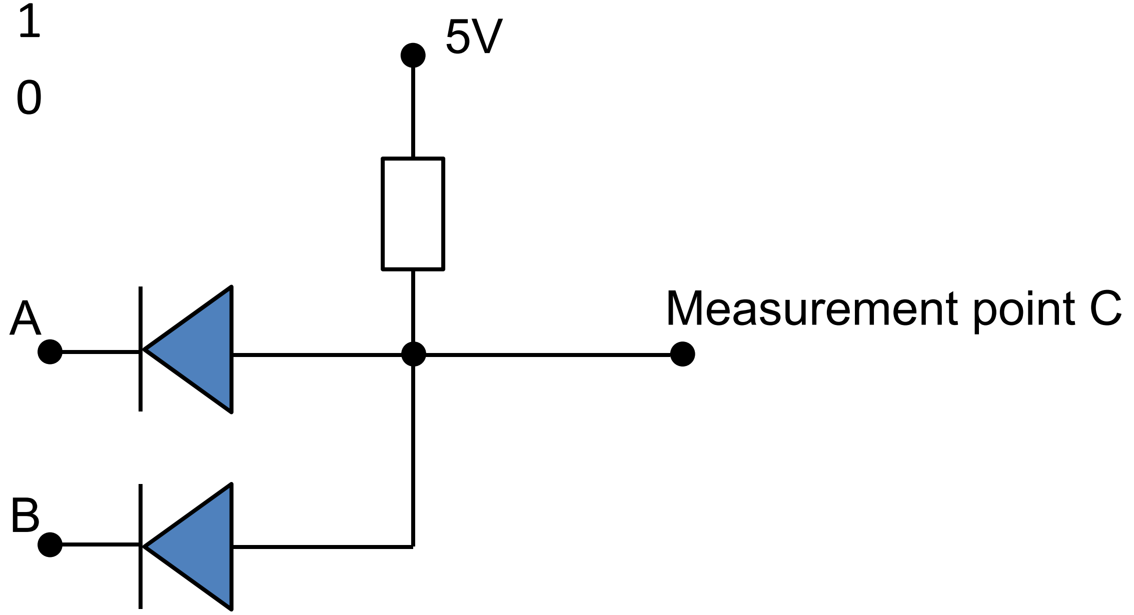
A	+	B	=	C
0		0		0
0		1		1
1		0		1
1		1		1

- Wired OR
  - Example (assuming negative logic)
    - 5V = logical 0
    - 0V = logical 1



Network Topologies

- Wired AND
  - Example (assuming positive logic)
    - 5V = logical 1
    - 0V = logical 0



Network Topologies

- Wired AND
  - Example (assuming positive logic)
    - 5V = logical 1
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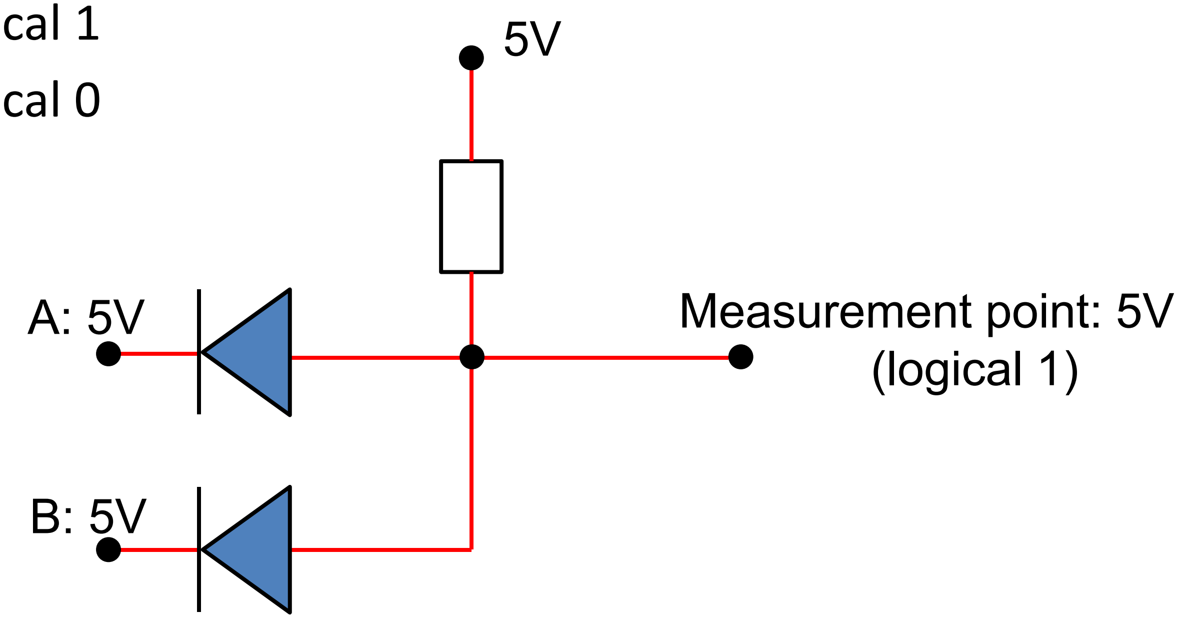
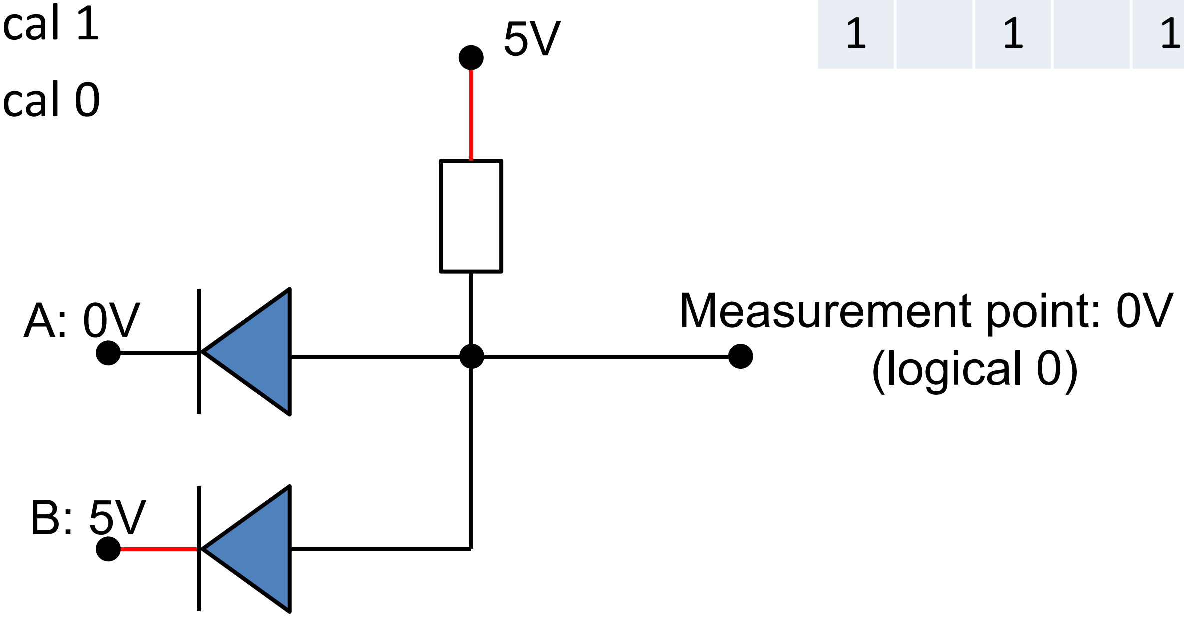


Network Topologies

- Wired AND
  - Example (assuming positive logic)
    - 5V = logical 1
    - 0V = logical 0

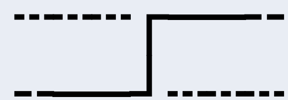
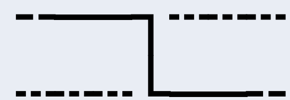
A	·	B	=	C
0		0		0
0		1		0
1		0		0
1		1		1



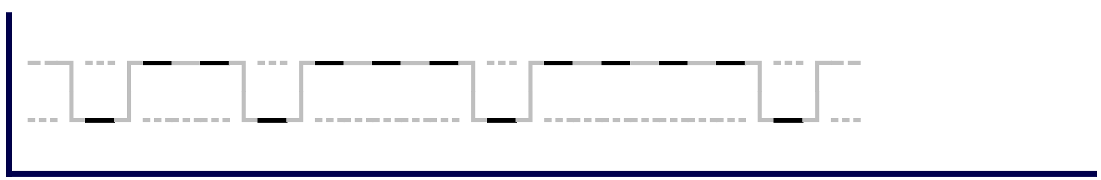
Network Topologies

- Wave effects
  - Wave effects: Reflections and ends of wire or connectors
  - Non negligible at high data rates, i.e., short bit lengths
  - Propagation velocity of a signal on in-vehicle bus:
    - $c \approx \frac{1}{3} c_0$
  - Signal delay on typical in-vehicle bus:
    - $t = \frac{l}{c} \approx 200\text{ns}$
  - Wave effects problematic if:
    - $t_{bit} < 10t$
  - Countermeasures
    - Add terminator plugs (resistor)
    - Minimize use of connectors

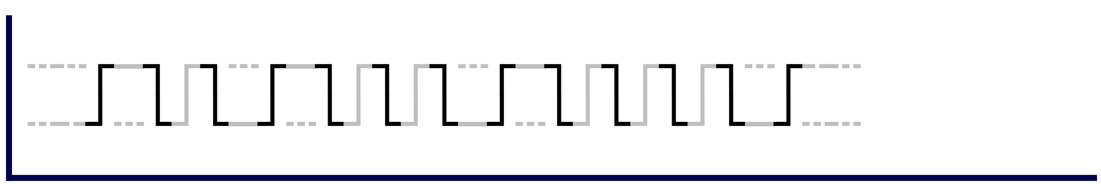
Bit coding

	logical 0	logical 1
Non return to Zero (NRZ)		
Manchester (original variant)		

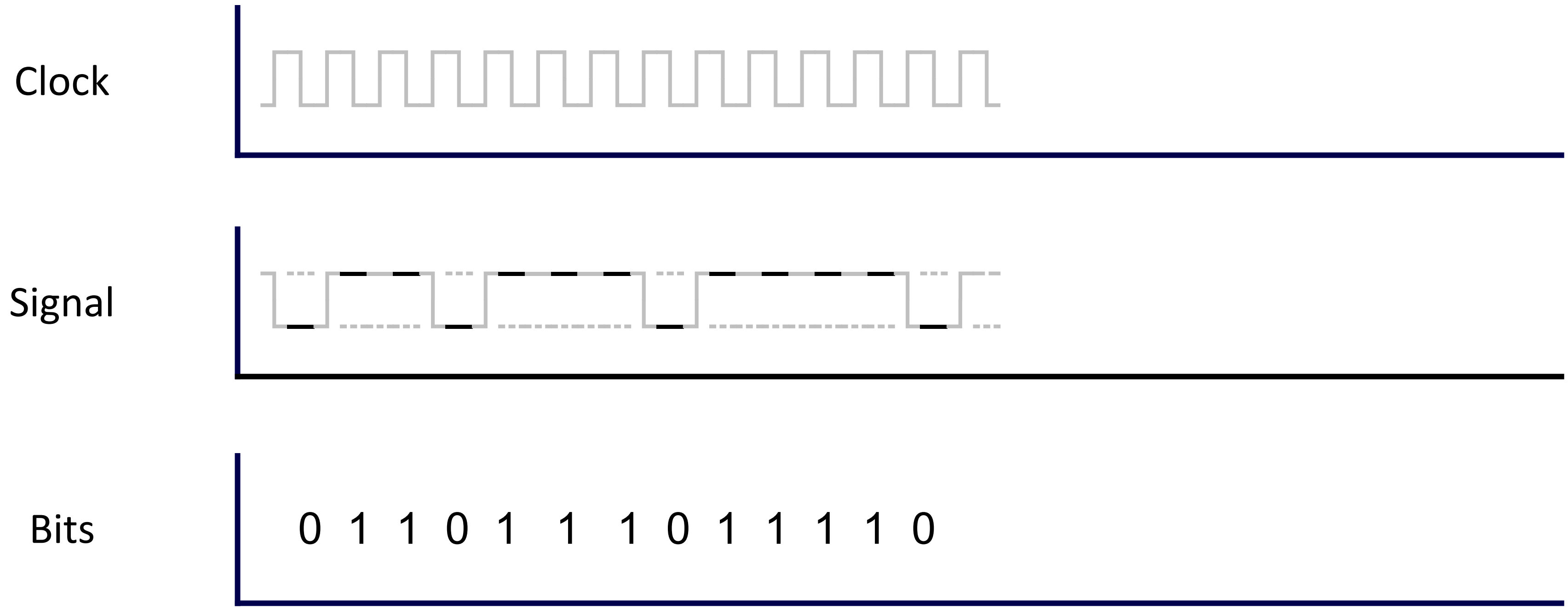
NRZ



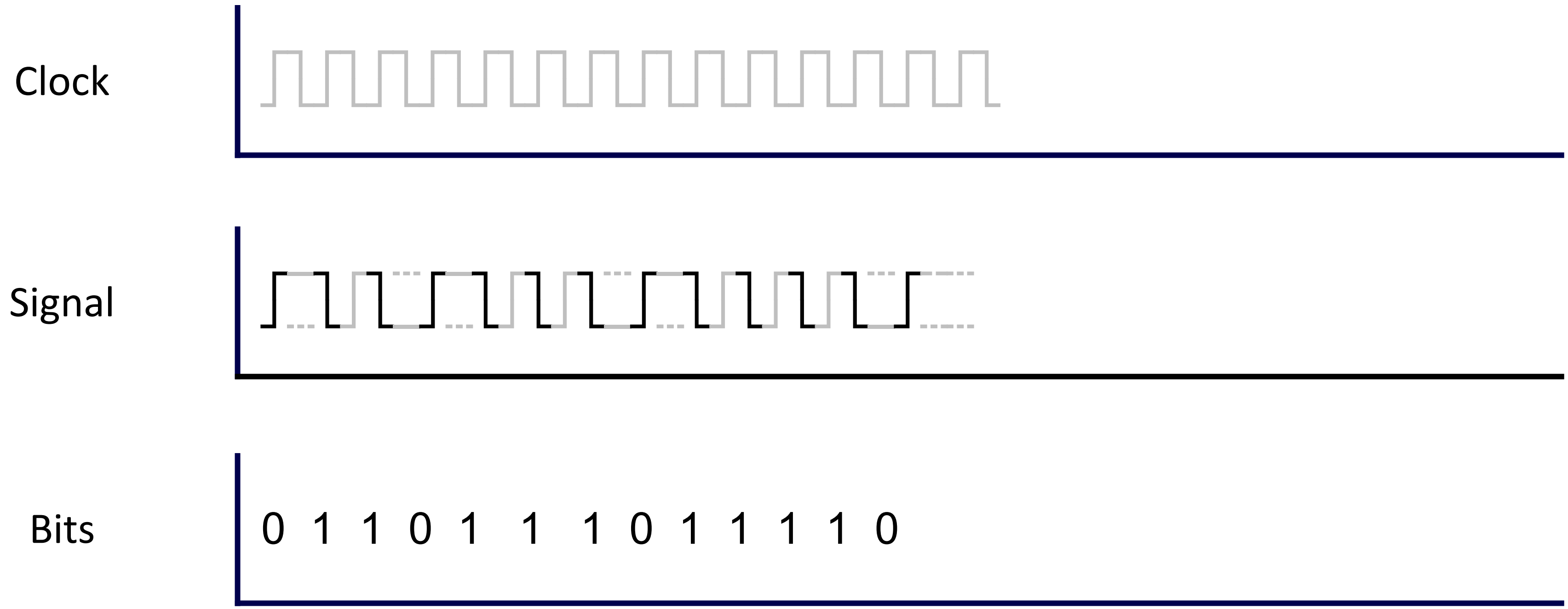
Manchester



Non Return to Zero (NRZ)

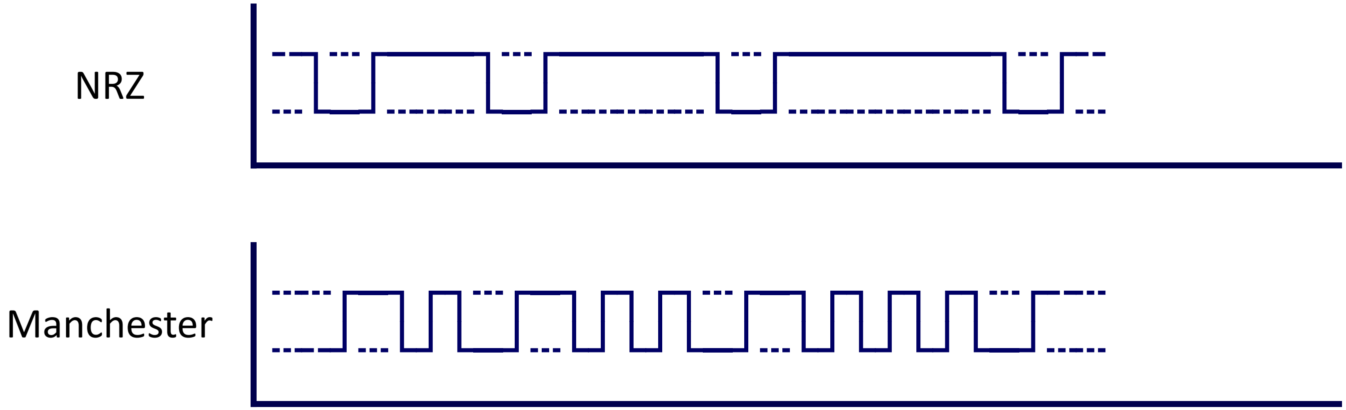


Manchester Code



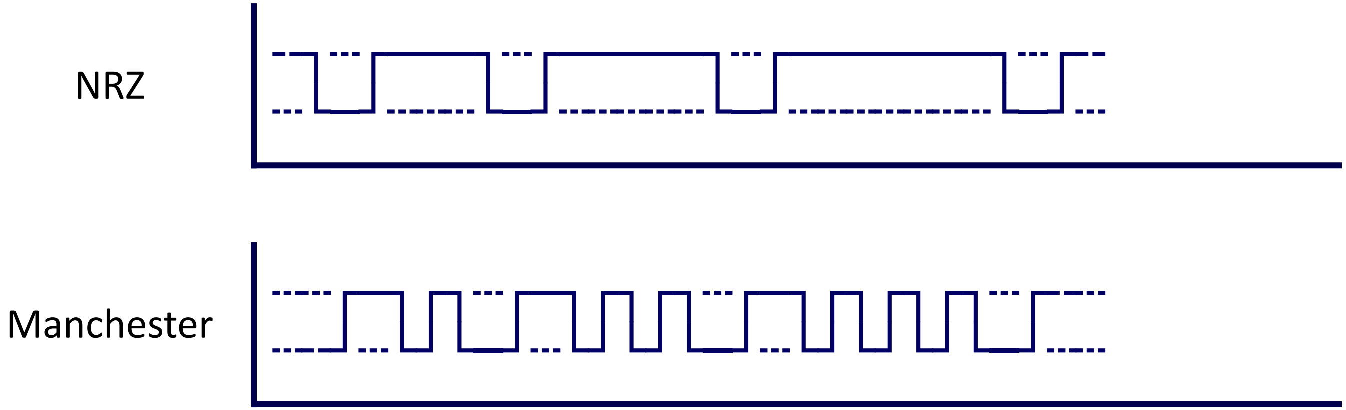
Reducing Electromagnetic interference (EMI)

- Add shieling to wires
- Use twisted pair wiring
- Reduce steepness of signal slope
- Use coding with few rising/falling signal edges (NRZ)



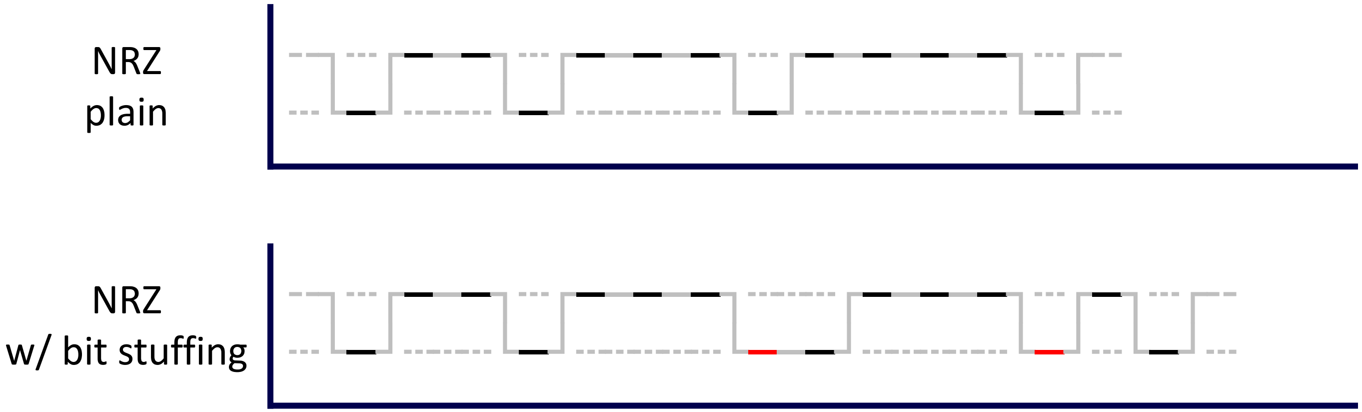
Clock drift

- Caused by natural variations of quartz, environment
- Receiver must sample signal at right time instant
- Clock drift leads to de-synchronization
- Bit timing has to be re-adjusted continually
- Commonly used: rising/falling signal edges

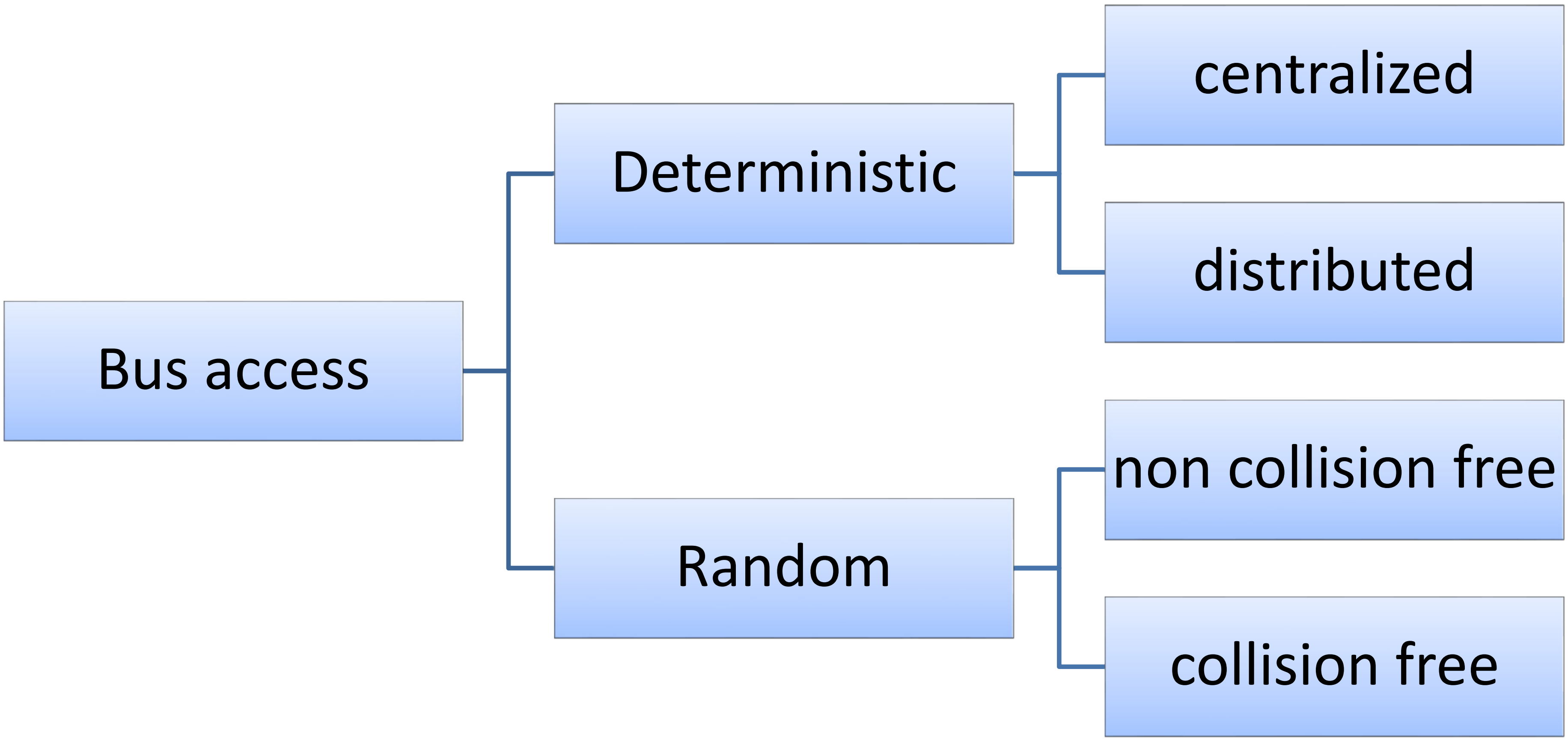


Bit stuffing

- Problem
  - When using NRZ coding, sending many identical bits leaves no signal edges that could be used to compensate for clock drift
- Solution
  - Insertion of extra bits after n consecutive identical bits
- Example (stuffing width: 3)

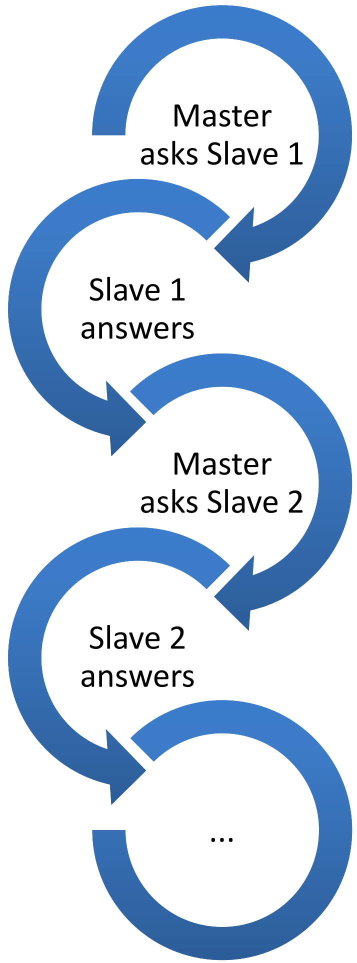


Classification according to bus access



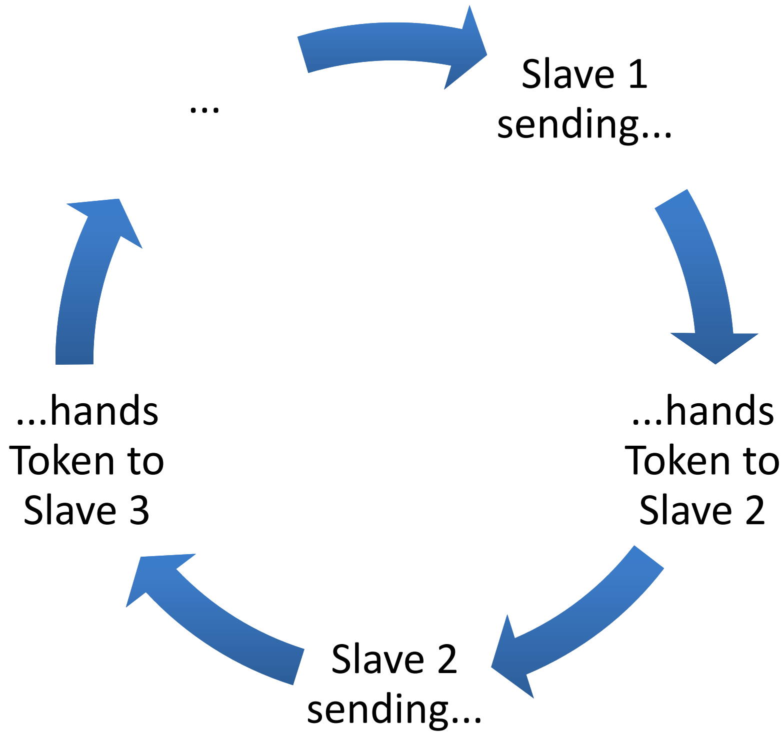
Deterministic, centralized

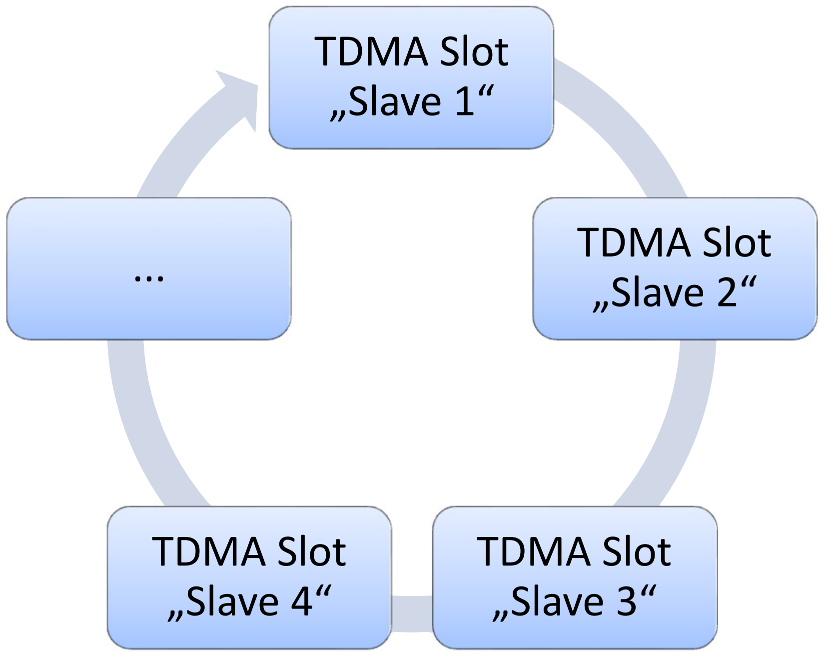
- Master-Slave protocols
- Simple request/response pattern



Deterministic, distributed

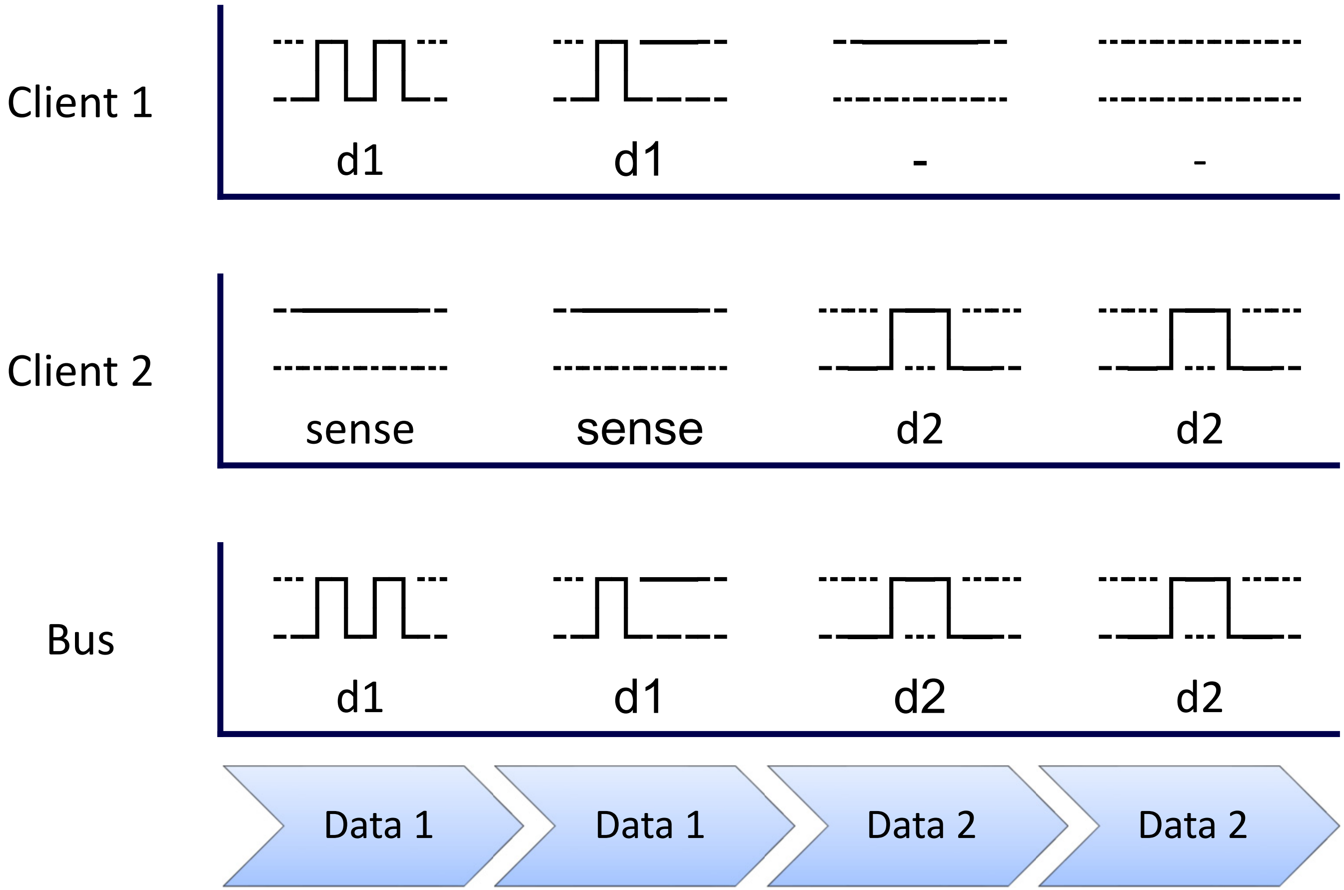
- Token based protocols, TDMA protocols





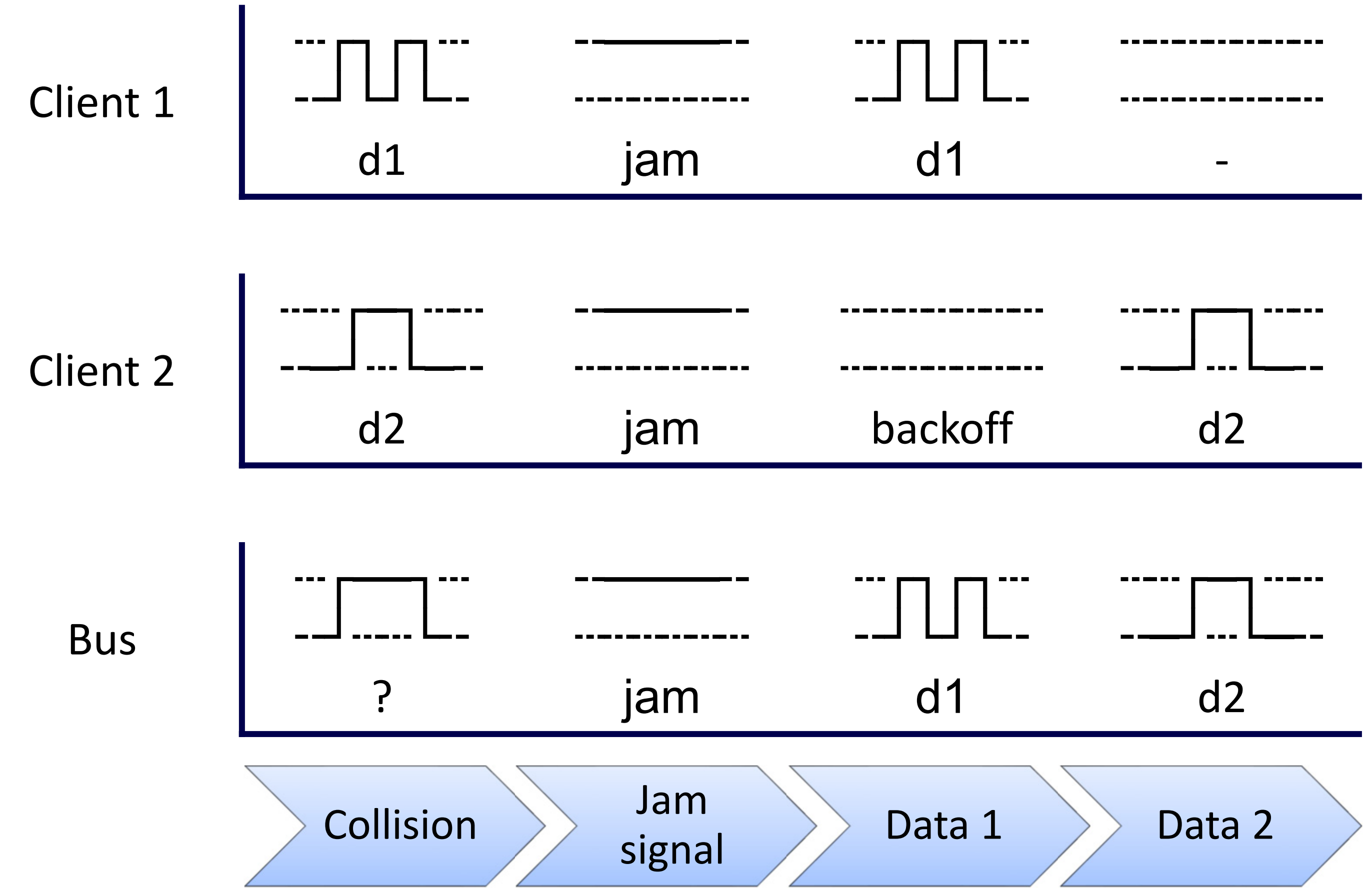
Random access, non collision free

- CSMA/CA (Collision Avoidance)



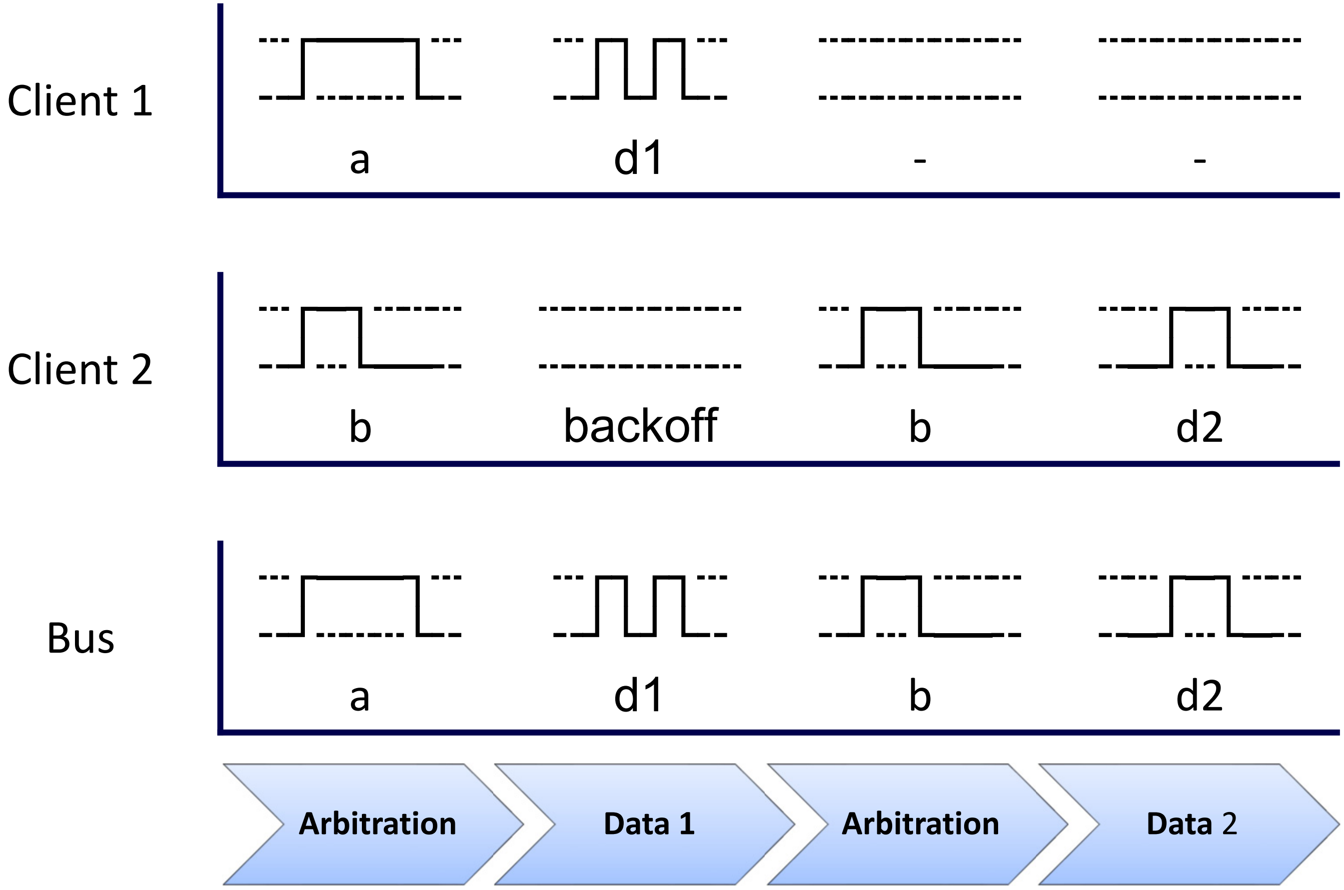
Random access, non collision free

- CSMA/CD (Collision Detection)



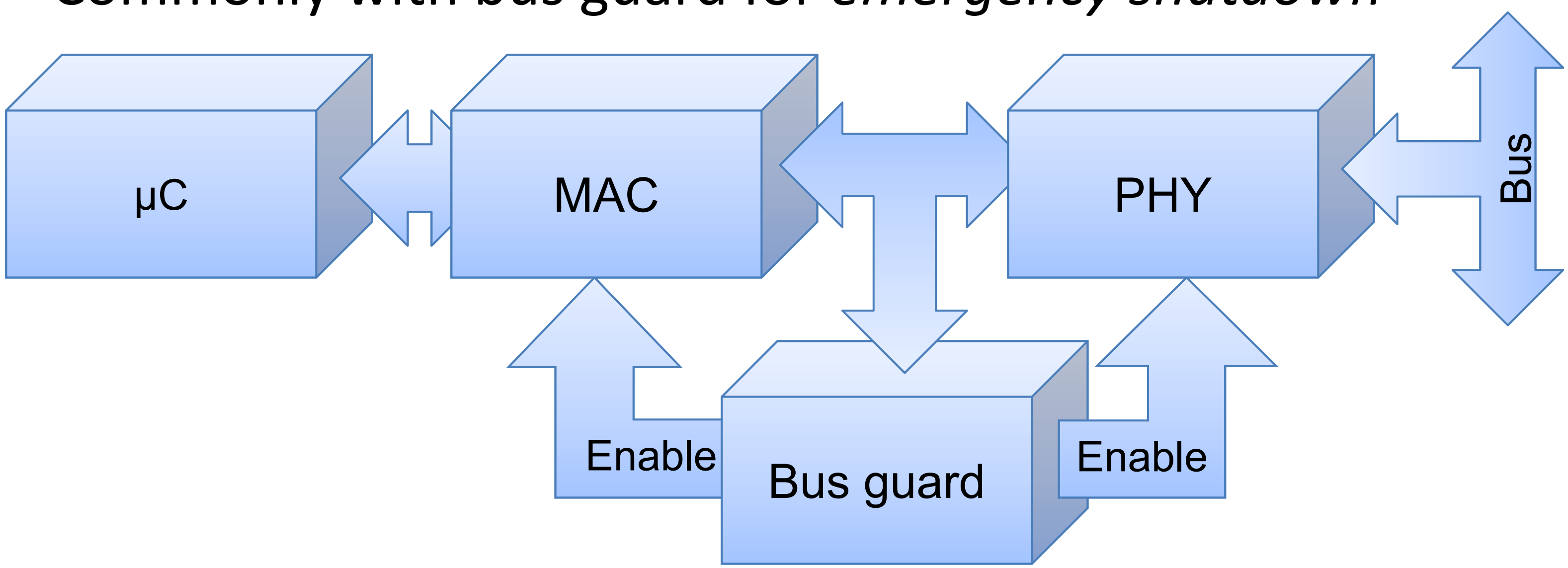
Random access, collision free

- CSMA/CR (Collision Resolution)



Typical structure of an ECU

- Separation by Layers
- Physical Layer: Transceiver / Bus driver
- Bus access: Communication controller
- Application layer: Microprocessor
- Commonly with bus guard for *emergency shutdown*



Main Takeaways

- Network Topologies
  - Single wire, two wire
  - Wired OR, wired AND
  - Non Return to Zero (NRZ) vs. Manchester coding
  - Clock drift, synchronization, bit stuffing

- Bus access
  - Deterministic, non-deterministic access
  - CSMA/CA, CSMA/CD, CSMA/CR
  - Bus guard

Protocols

K-Line, CAN, LIN, FlexRay, MOST, Ethernet

K-Line

The K-Line Bus

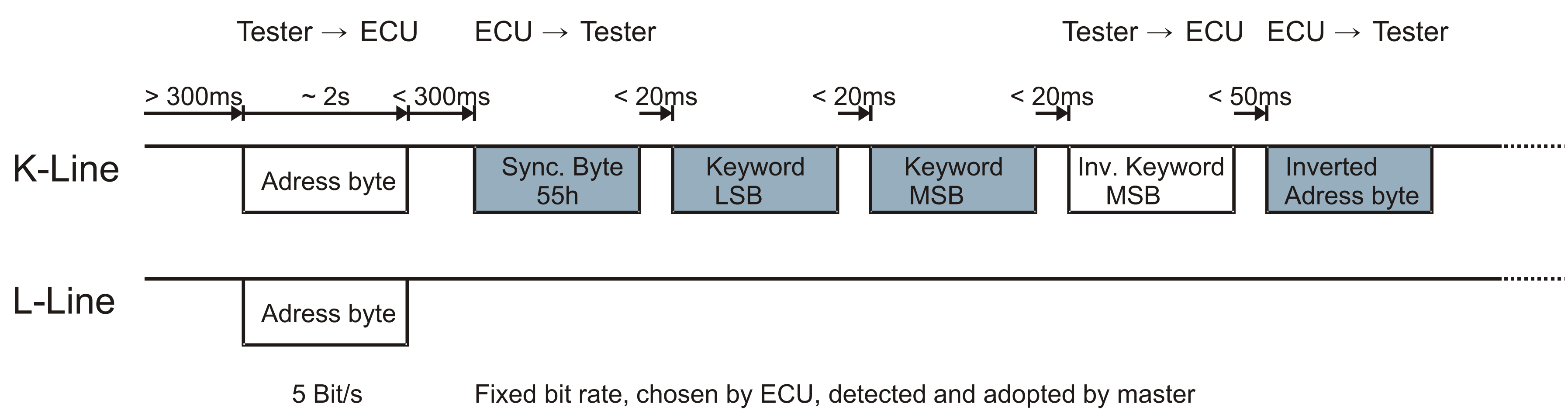
- The K-Line Bus
  - Industry standard of the 80s, much later standardized as ISO 9141
  - Numerous variants exist (esp. upwards of Link Layer)
  - Lecture focuses on ISO 14230: The KWP 2000 (Keyword Protocol)
  - Specifies Physical and Link layers
  - Bidirectional bus, communicating over 1 wire (the **K Line**)

The K-Line Bus

- The K-Line Bus (contd.)
  - Optional: additional unidirectional **L Line**
    - Allows mixed networks (using only K Line / using both K+L Line)
  - Mostly used for connecting ECU ⇔ Tester, seldom ECU ⇔ ECU
  - Logic levels are relative to on board voltage (< 20% and > 80%)
  - Bit transmission compatible to UART (Universal Asynchronous Receiver Transmitter): 1 start bit, 8 data bits, 1 stop bit, optional parity bit
  - Bit rate 1.2 kBit/s ... 10.4 kBit/s
    - Dependent on ECU, not Bus
    - Master must be able to handle multiple bit rates

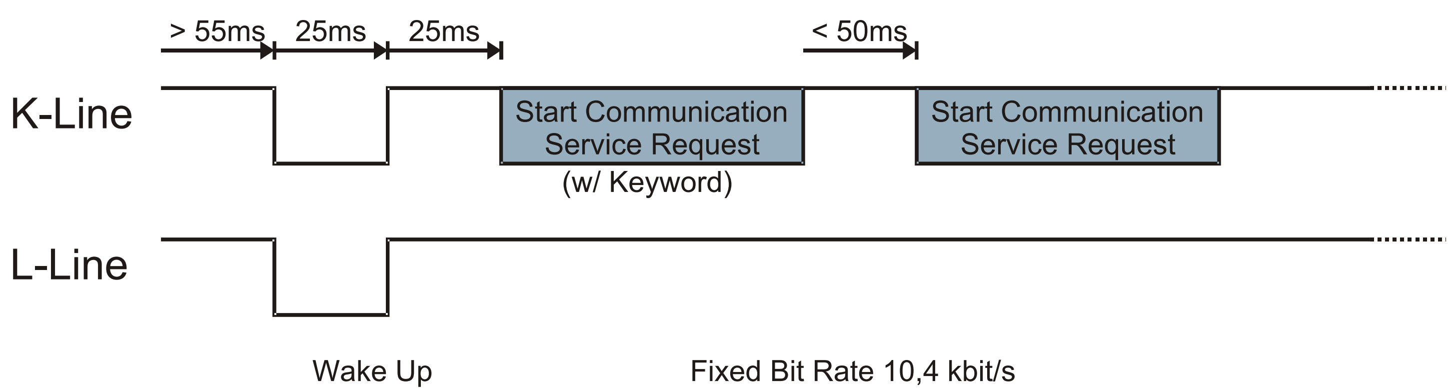
The K-Line Bus

- Protocol
  - Connection establishment (2 variants)
    - 5 Baud init
      - Master sends destination address (using 5 Bit/s)
      - ECU answers: 0x55 (01010101), keyword low Byte, keyword high Byte (with desired data rate)
      - Master derives bit rate from pattern, sends Echo (inv. High Byte)
      - ECU sends Echo (inv. Destination address)



The K-Line Bus

- Protocol
  - Connection establishment (2 variants)
    - Fast init (100 ms, Bitrate always 10,4 kBit/s)
      - Master sends *Wake Up* pattern (25 ms low, 25 ms pause)
      - Master sends *Start Communication Request,* includes dest address
      - ECU answers with keyword, after max. 50 ms
      - Keyword encodes supported protocol variants
        takes values from 2000 .. 2031 (KWP 2000)



The K-Line Bus

- Protocol
  - Communication always initiated by master
    - Master sends Request, ECU sends Response
  - Addressing
    - Address length is 1 Byte
    - Either: physical addressing (identifies specific ECU)
    - Or: functional addressing (identifies class of ECU) e.g., engine, transmission, ...
    - Differentiated via format byte
  - Duration of single transmission at 10.4 kBit/s
    - best case: 250 ms, worst case 5.5s
    - i.e., application layer data rate < 1 KB/s

The K-Line Bus

- Protocol header
  - Format Byte
    - Encodes presence and meaning of address bytes
    - Short packet length can be encoded in format byte; length byte then omitted
  - Destination address
  - Source address
  - Length
  - Payload
    - Up to 255 Byte
    - First Byte: Service Identifier (SID)
  - Checksum
    - Sum of all Bytes (mod 256)

0 .. 7	8 .. 15
Format byte	Destination
Source	Length
Payload...	
...	Checksum

The K-Line Bus

- Service Identifiers
  - Standard Service Identifiers
    - Session Initialization and teardown
      - 0x81h Start Communication Service Request
      - 0x82h Stop Communication Service Request
    - Configuring protocol timeouts
      - 0x83h Access Timing Parameter Request (optional)

  - Other SIDs are vendor defined
    - Passed on (unmodified) to application layer
    - Typical use: two SIDs per message type
      - First SID: Positive reply
      - Second: Negative reply

The K-Line Bus

- Error handling
  - If erroneous signal arrives
    - ECU ignores message
    - Master detects missing acknowledgement
    - Master repeats message
  - If invalid data is being sent
    - Application layer sends negative reply
    - Master / ECU can react accordingly

Use in On Board Diagnostics (OBD)

- Pin 7 of OBD connector is K-Line
- OBD uses stricter protocol variant
- Bit rate fixed to 10.4 kBit/s
- No changes in timing
- Header no longer variable
  - Length byte never included
  - Address always included
- Max. Message length is 7 Byte
- Shall use
  logical addressing by tester,
  physical addressing by ECUs

Main Takeaways

- K-Line
  - Mainly for diagnostics
  - Transmission uses UART signaling
  - Communication using Request-Response pattern

CAN

Controller Area Network

The CAN Bus

- „Controller Area Network“
- 1986
- Network topology: Bus
- Many (many) physical layers

- Common:
  - Up to 110 nodes
  - At 125 kBit/s: max. 500m

- Always:
- Two signal levels
  - low (dominant)
  - high (recessive)

The CAN Bus

- In the following: ISO 11898
  - Low Speed CAN (up to 125 kBit/s)
  - High Speed CAN (up to 1 MBit/s)
- Specifies OSI layers 1 and 2
  - Higher layers not standardized by CAN, covered by additional standards and conventions
  - e.g., CANopen
- Random access, collision free
  - CSMA/CR with Bus arbitration
  - (sometimes called CSMA/BA – bitwise arbitration)
- Message oriented
- Does not use destination addresses
  - Implicit Broadcast/Multicast

Physical layer (typical)

- High Speed CAN
  - 500 kBit/s
  - Twisted pair wiring
  - Branch lines max. 30 cm
  - Terminating resistor mandated (120 Ω)
  - Signal swing 2 V
  - Error detection must happen within one Bit's time

    ⇨ bus length is limited to $l \leq 50\mathrm{m} \times \frac{1\ \mathrm{MBit/s}}{\mathrm{data\ rate}}$

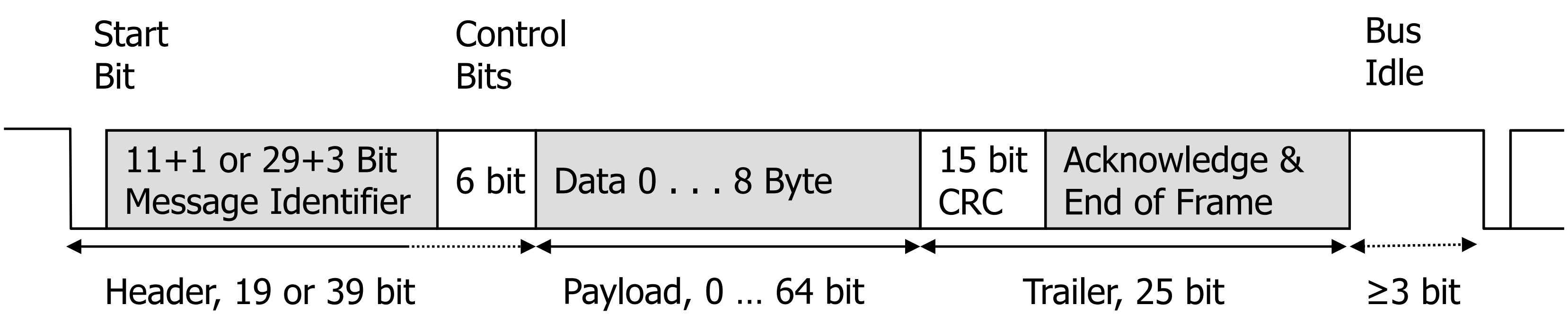
Physical layer (typical)

- Low Speed CAN
  - Up to 125 kBit/s
  - Standard two wire line suffices
  - No restriction on branch lines
  - Terminating resistors optional
  - Signal swing 5 V

- Single Wire CAN
  - 83 kBit/s
  - One line vs. ground
  - Signal swing 5 V

CAN in Vehicular Networks

- Address-less communication
  - Messages carry 11 Bit (CAN 2.0A) or 29 Bit (CAN 2.0B) message identifier
  - Stations do not have an address, frames do not contain one
  - Stations use message identifier to decide whether a message is meant for them
  - Medium access using CSMA/CR with bitwise arbitration
  - Link layer uses 4 frame formats
    Data, Remote (request), Error, Overload (flow control)
  - Data frame format:



CAN in Vehicular Networks

- CSMA/CR with bitwise arbitration
  - Avoids collisions by priority-controlled bus access
  - Each message contains identifier corresponding to its priority
  - Identifier encodes “0” dominant and “1” recessive: concurrent transmission of “0” and “1” results in a “0”
  - Bit stuffing: after 5 identical Bits one inverted Stuff-Bit is inserted
    (ignored by receiver)
  - When no station is sending the bus reads “1” (recessive state)
  - Synchronization happens on bit level,
    by detecting start bit of sending station

CAN in Vehicular Networks

- CSMA/CR with bitwise arbitration
  - Wait for end of current transmission
    - wait for 6 consecutive recessive Bits
  - Send identifier (while listening to bus)
  - Watch for mismatch between transmitted/detected signal level
    - Means that a collision with a higher priority message has occurred
    - Back off from bus access, retry later

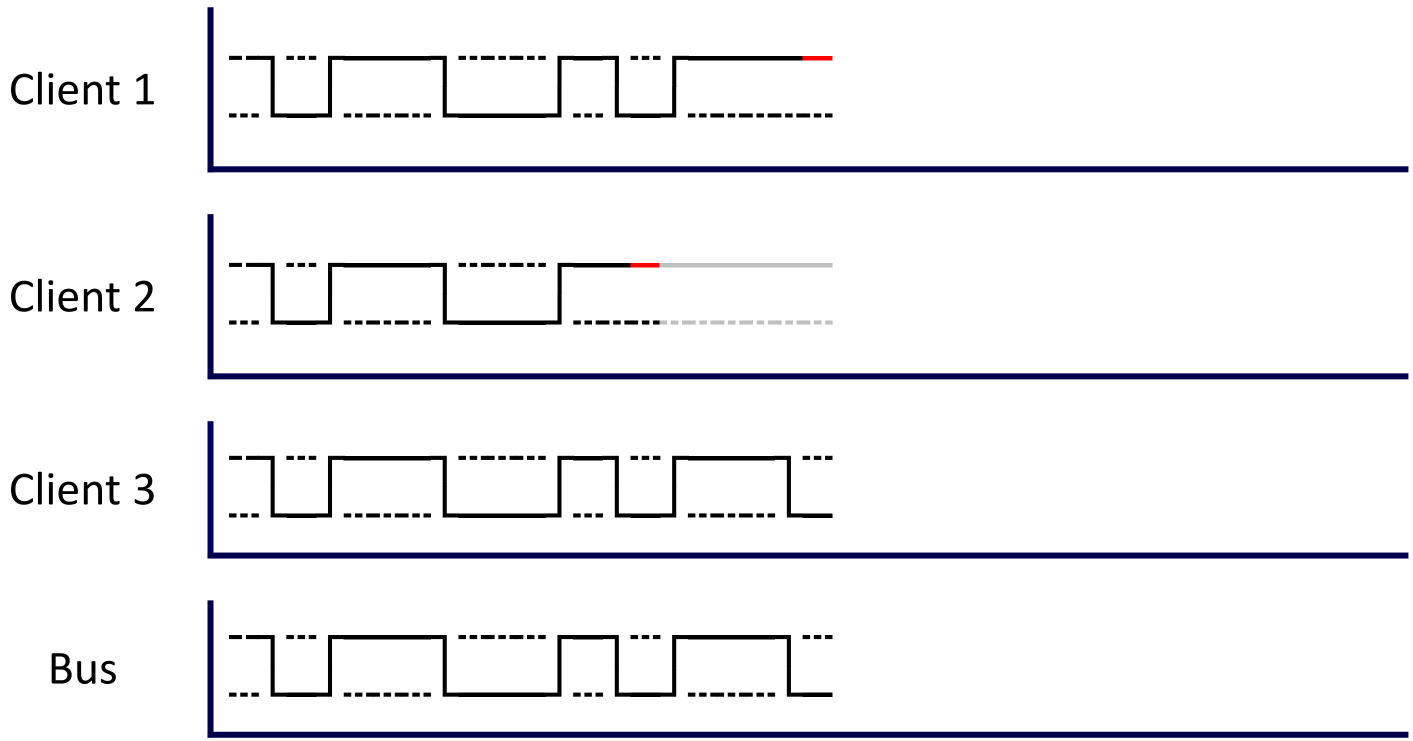
  - Realization of non-preemptive priority scheme
  - Real time guarantees for message with highest priority
    - i.e., message with longest “0”-prefix

The CAN Bus

- CSMA/CR with bitwise arbitration
  - Client 2 recognizes bus level mismatch, backs off from access

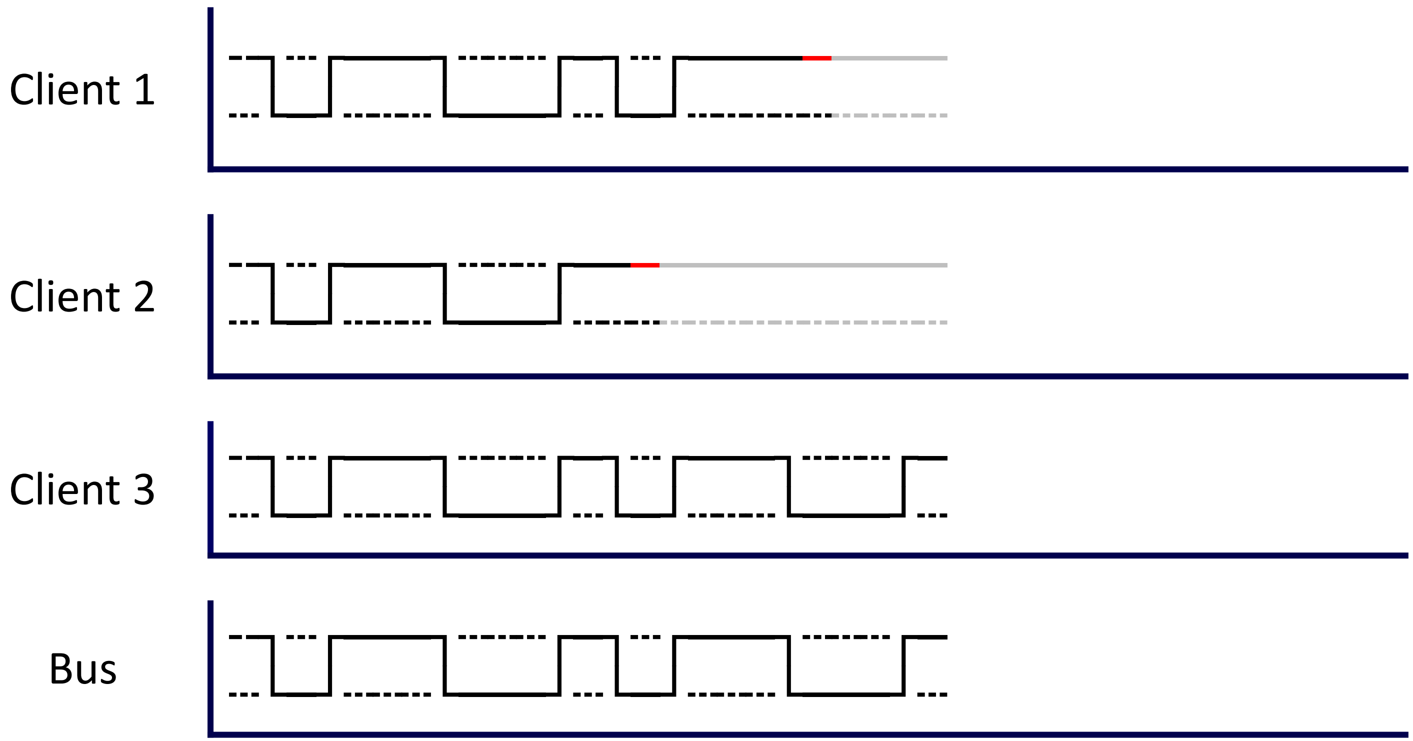
The CAN Bus

- CSMA/CA with bitwise arbitration (CSMA/CR)
  - Client 1 recognizes bus level mismatch, backs off from access



The CAN Bus

- CSMA/CA with bitwise arbitration (CSMA/CR)
  - Client 3 wins arbitration

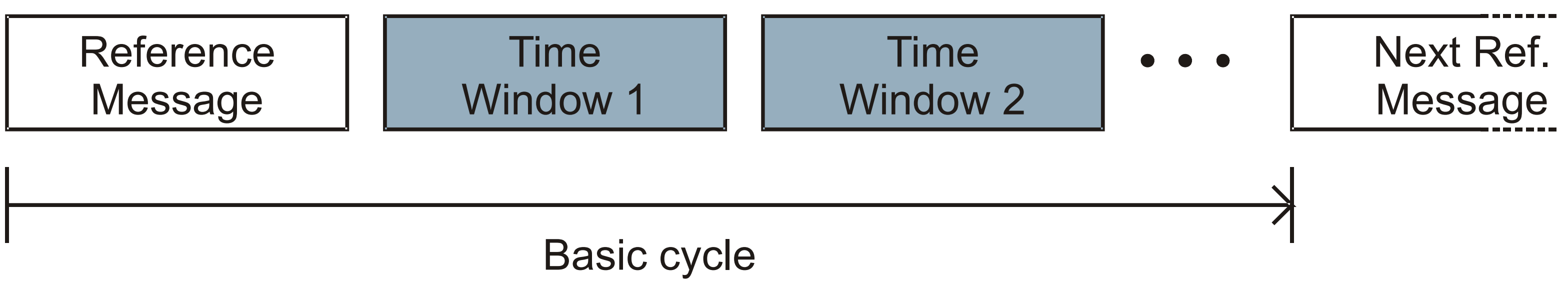


The CAN Bus

- CSMA/CA with bitwise arbitration (CSMA/CR)
  - Client 3 starts transmitting data

The CAN Bus: TTCAN

- Aside: Time-Triggered CAN (TTCAN)
  - ISO 11898-4 extends CAN by TDMA functionality
  - Solves non-determinism of regular CAN
    - Improves on mere “smart” way of choosing message priorities
  - One node is dedicated “time master” node
  - Periodically sends reference messages starting “basic cycles”
  - Even if time master fails, TTCAN keeps working
    - Up to 7 fallback nodes
    - Nodes compete for transmission of reference messages
    - Chosen by arbitration



The CAN Bus: TTCAN

- Aside: TTCAN Basic Cycle
  - Basic cycle consists of time slots
    - Exclusive time slot
      - Reserved for dedicated client
    - Arbitration time slot
      - Regular CAN CSMA/CR with bus arbitration
  - Structure of a basic cycle arbitrary, but static
  - CAN protocol used unmodified

    ➔ Throughput unchanged

  - TTCAN cannot be seen replacing CAN for real time applications
    - Instead, new protocols are being used altogether (e.g., FlexRay)

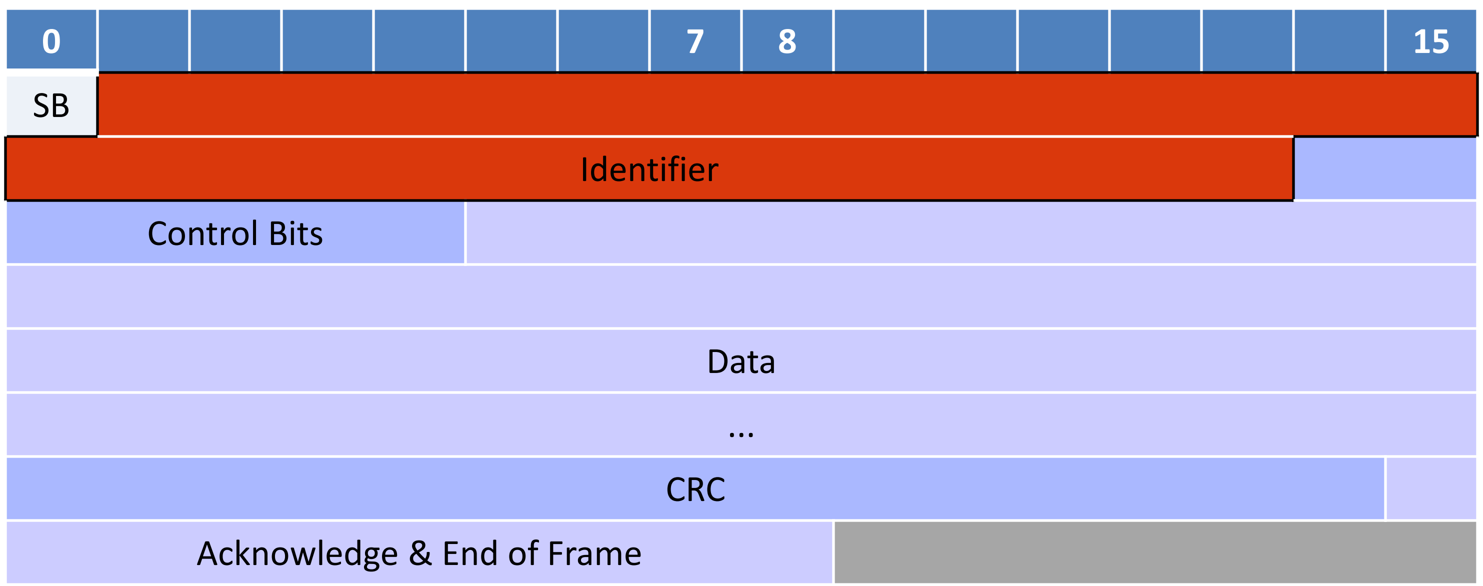
The CAN Bus

- Message filtering
  - Acceptance of messages determined by message identifier
  - Uses two registers
    - Acceptance Code (bit pattern to filter on)
    - Acceptance Mask (“1” marks relevant bits in acceptance code)

Bit	10	9	8	7	6	5	4	3	2	1	0
Acceptance Code Reg.	0	1	1	0	1	1	1	0	0	0	0
Acceptance Mask Reg.	1	1	1	1	1	1	1	0	0	0	0
Resulting Filter Pattern	**0**	**1**	**1**	**0**	**1**	**1**	**1**	**X**	**X**	**X**	**X**

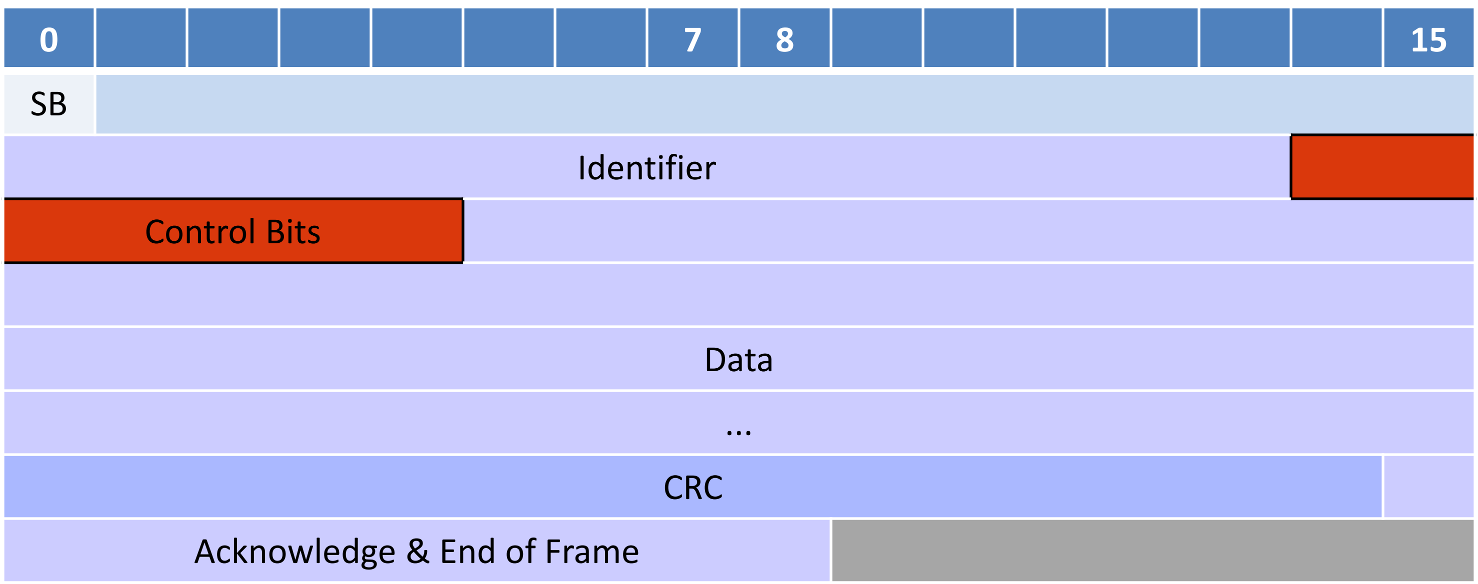
Data format

- NRZ
- Time synchronization using start bit and stuff bits (stuff width 5)
- Frame begins with start bit
- Message identifier 11 Bit (CAN 2.0A), now 29 Bit (CAN 2.0B)



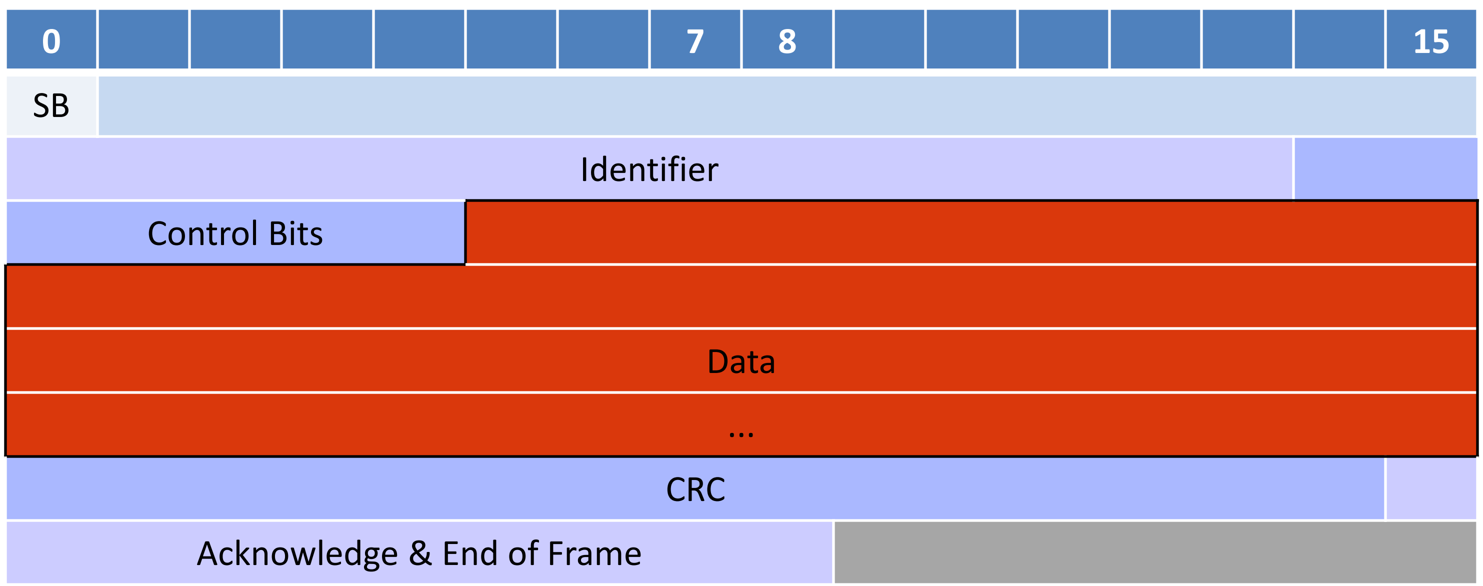
The CAN Bus

- Data format
  - Control Bits
    - Message type (Request, Data, Error, Overload)
    - Message length
    - ...



The CAN Bus

- Data format
  - Payload
    - Restriction to max. 8 Byte per message
    - Transmission time at 500 kBit/s: 260 µs (using 29 Bit ID)
    - i.e., usable data rate 30 kBit/s



The CAN Bus

- Error detection (low level)
  - Sender checks for unexpected signal levels on bus
  - All nodes monitor messages on the bus
    - All nodes check protocol conformance of messages
    - All nodes check bit stuffing
  - Receiver checks CRC
  - If any(!) node detects error it transmits error signal
    - 6 dominant Bits with no stuffing
  - All nodes detect error signal, discard message

The CAN Bus

- Error detection (high level)
  - Sender checks for acknowledgement
    - Receiver transmits dominant “0” during ACK field of received message
  - Automatic repeat of failed transmissions
  - If controller finds itself causing too many errors
    - Temporarily stop any bus access
  - Remaining failure probability ca. 10^{-11}

The CAN Bus: Transport Layers

- Not covered by ISO 11898 (CAN) standards
  - Fragmentation
  - Flow control
  - Routing to other networks

- Add transport layer protocol
  - ISO-TP
    - ISO 15765-2
  - TP 2.0
    - Industry standard
  - …

The CAN Bus: ISO-TP

- ISO-TP: Header
  - Optional: 1 additional address Byte
    - Regular addressing
      - Transport protocol address completely in CAN message ID
    - Extended addressing
      - Uniqueness of addresses despite non-unique CAN message ID
      - Part of transport protocol address in CAN message ID, additional address information in first Byte of TP-Header
  - 1 to 3 PCI Bytes (Protocol Control Information)
    - First high nibble identifies one of 4 types of message
    - First low nibble and addl. Bytes are message specific

<table>
<tr><th>0</th><th colspan="2">1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>(opt) Addl. Address</td><td>PCI high</td><td>PCI low</td><td colspan="2">(opt) Addl. PCI Bytes</td><td colspan="4">Payload</td></tr>
</table>

The CAN Bus: ISO-TP

- ISO-TP: Message type “Single Frame”
  - 1 Byte PCI, high nibble is 0
  - low nibble gives number of Bytes in payload
  - PCI reduces frame size from 8 Bytes to 7 (or 6) Bytes, throughput falls to 87.5% (or 75%, respectively)
  - No flow control

0		1	2	3	4	5	6	7
0	Len	Payload						

0	1		2	3	4	5	6	7
(Address)	0	Len	Payload					

The CAN Bus: ISO-TP

- ISO-TP: Message type „First Frame“
  - 2 Bytes PCI, high nibble is 1
  - low nibble + 1 Byte give number of Bytes in payload
  - After First Frame, sender waits for Flow Control Frame

0	1		2	3	4	5	6	7
(Address)	1	Len		Payload				

- ISO-TP: Message type „Consecutive Frame“
  - 1 Byte PCI, high nibble is 2
  - low nibble is sequence number SN (counts upwards from 1)
    - Application layer can detect packet loss
  - No additional error detection at transport layer

0	1		2	3	4	5	6	7
(Address)	2	SN	Payload					

The CAN Bus: ISO-TP

- ISO-TP: Message type „Flow Control Frame“
  - 3 Bytes PCI, high nibble is 3
  - low nibble specifies Flow State FS
  - FS=1: Clear to Send
    - Minimum time between two Consecutive Frames must be ST
    - Sender may continue sending up to BS Consecutive Frames, then wait for new Flow Control Frame
  - FS=2: Wait
    - Overload
    - Sender must wait for next Flow Control Frame
  - Byte 2 specifies Block Size BS
  - Byte 3 specifies Separation Time ST

0	1		2	3
(Address)	3	FS	BS	ST

The CAN Bus: TP 2.0

- TP 2.0
  - Connection oriented
  - Communication based on channels
  - Specifies Setup, Configuration, Transmission, Teardown

  - Addressing
    - Every ECU has unique logical address;
      additional logical addresses specify groups of ECUs
    - for broadcast und channel setup:
      logical address + offset = CAN message identifier
    - Channels use dynamic CAN message identifier

The CAN Bus: TP 2.0

- TP 2.0: Broadcast
  - Repeated 5 times (motivated by potential packet loss)
  - Fixed length: 7 Byte
  - Byte 0:
    - logical address of destination ECU
  - Byte 1: Opcode
    - 0x23: Broadcast Request
    - 0x24: Broadcast Response
  - Byte 2, 3, 4:
    - Service ID (SID) and parameters
  - Byte 5, 6:
    - Response: 0x0000
    - No response expected: alternates between 0x5555 / 0xAAAA

0	1	2	3	4	5	6
Dest	Opcode	SID, Parameter			0x55	0x55

The CAN Bus: TP 2.0

- TP 2.0: channel setup
  - Byte 0:
    - logical address destination ECU
  - Byte 1: Opcode
    - 0xC0: Channel Request
    - 0xD0: Positive Response
    - 0xD6 .. 0xD8: Negative Response
  - Byte 2, 3: RX ID
    - Validity nibble of Byte 3 is 0 (1 if RX ID not set)
  - Byte 4, 5: TX ID
    - Validity nibble of Byte 5 is 0 (1 if TX ID not set)
  - Byte 6: Application Type
    - cf. TCP-Ports

0	1	2	3	4	5	6
Dest	Opcode	RX ID	V	TX ID	V	App

The CAN Bus: TP 2.0

- TP 2.0: channel setup (II)
  - Opcode 0xC0: Channel Request
    - TX ID: CAN msg ID requested by self
    - RX ID: marked invalid
  - Opcode 0xD0: Positive Response
    - TX ID: CAN msg ID requested by self
    - RX ID: CAN msg ID of original sender
  - Opcode 0xD6 .. 0xD8: Negative Response
    - Reports errors assigning channel (temporary or permanent)
    - Sender may repeat Channel Request
  - After successful exchange of Channel Request/Response: dynamic CAN msg IDs now assigned to sender and receiver next message sets channel parameters

0	1	2	3	4	5	6
Dest	0xC0		1	TX ID	0	App

The CAN Bus: TP 2.0

- TP 2.0: set channel parameters
  - Byte 0: Opcode
    - 0xA0: Channel Setup Request (Parameters for channel to initiator)
    - 0xA1: Channel Setup Response (Parameter for reverse channel)
  - Byte 1: Block size
    - Number of CAN messages until sender has to wait for ACK
  - Byte 2, 3, 4, 5: Timing parameters
    - E.g., minimal time between two CAN messages
- TP 2.0: misc. channel management and teardown
  - Byte 0: Opcode
    - 0xA3: Test – will be answered by Connection Setup Response
    - 0xA4: Break – Receiver discards data since last ACK
    - 0xA5: Disconnect – Receiver responds with disconnect, too

0	1	2	3	4	5
0xA0	BS	Timing			

The CAN Bus: TP 2.0

- TP 2.0: Data transmission via channels
  - Byte 0, high nibble: Opcode
    - MSB=0 – Payload
      - /AR=0 – Sender now waiting for ACK
      - EOM=1 – Last message of a block
    - MSB=1 – ACK message only (no payload)
      - RS=1 – ready for next message (➔ flow control)
  - Byte 0, low nibble
    - Sequence number
  - Bytes 1 .. 7: Payload

Opcode Nibble			
0	0	/AR	EOM

Opcode Nibble			
1	0	RS	1

0		1	2	3	4	5	6	7
Op	SN	Payload						

Main Takeaways

- CAN
  - Still standard bus in vehicles
  - Message oriented
  - CSMA with bitwise arbitration
    - Impact on determinism
    - TTCAN (TDMA)
  - Error detection
  - Transport layer: ISO-TP vs. TP 2.0
    - Flow control, channel concept

LIN

Local Interconnect Network

The LIN Bus

- Local Interconnect Network (LIN)
- 1999: LIN 1.0
- 2003: LIN 2.0
  - Numerous extensions
  - Backwards compatible (only)
- Goal of LIN: be much cheaper than low speed CAN
  - Only reached partway
- specifies PHY and MAC Layer, API

LOCAL INTERCONNECT NETWORK

Photo © 2014 David Eckhoff

The LIN Bus

- Very similar to K-Line Bus
- Master-slave concept with self synchronization
  - no quartz needed
  - lax timing constraints
- LIN master commonly also part of a CAN bus
  - LIN commonly called a sub bus
- Bidirectional one-wire line, up to 20 kBit/s
- Bit transmission UART compatible
  - 1 Start Bit, 8 Data Bits, 1 Stop Bit
- Message oriented
  - No destination address

The LIN Bus

- Rudimentary error detection
  - Sender monitors bus
  - Aborts transmission on unexpected bus state
- No error correction
- Starting with LIN 2.0: Response Error Bit
  - Should be contained in periodic messages
  - Set (once) if slave detected an error in last cycle
- Static slot schedule in the master
  - “Schedule Table”
  - Determines cyclic schedule of messages transmitted by master
    → Bus timing mostly deterministic
  - Slaves do not need to know schedule
    → can be changed at run-time

The LIN Bus

- Data request (sent by master)
  - Sync Break (≥13 Low Bits, 1 High Bit)
    - Not UART compliant → uniquely identifiable
  - Sync Byte 0x55 (01010101)
    - Synchronizes bit timing of slave
  - LIN Identifier (6 data Bits (I0 to I5) + 2 parity Bits)
    - Encodes response's expected message type and length
    - 0x00 .. 0x3B: application defined data types, 0x3C .. 0x3D: Diagnosis, 0x3E: application defined, 0x3F: reserved
    - Parity Bits: $I0 \oplus I1 \oplus I2 \oplus I4$ and $\neg(I1 \oplus I3 \oplus I4 \oplus I5)$
- Data request triggers data response (⇨ next slide)

The LIN Bus

- Data response (sent by slave)
  - Slave responds with up to 8 Bytes of data
    - LSB first, Little Endian
    - length was defined by LIN Identifier
  - Frame ends with checksum
    - LIN 1.3: Classic Checksum (only data bytes)
    - LIN 2.0: Enhanced Checksum (data bytes + Identifier)
    - Checksum is sum of all Bytes (mod 256),
      plus sum of all carries

The LIN Bus

- Types of requests
  - Unconditional Frame
  - Event Triggered Frame
  - Sporadic Frame
  - ...
- Unconditional Frame
  - Most simple frame type
  - Designed for periodic polling of specific data point
  - Exactly one slave answers
  - LIN is a single master system → timing of unconditional frames fully deterministic
  - Sample use case:
    - Request “did state of front left door contact change?” every 15 ms
    - Receive negative reply by front left door ECU every 15 ms

The LIN Bus

- Types of requests
  - Unconditional Frame
  - Event Triggered Frame
  - Sporadic Frame
  - ...
- Event Triggered Frame
  - Simultaneous polling of multiple slaves, slave answers if needed
  - Collisions possible (→ non-determinism), detect by corrupt. data
    - master switches to individual polling via Unconditional Frames
  - Use whenever slaves unlikely to respond
  - Sample use case:
    - Request “did state of a door contact change?” every 15 ms
    - Change in state unlikely, simultaneous change extremely unlikely

The LIN Bus

- Types of requests
  - Unconditional Frame
  - Event Triggered Frame
  - Sporadic Frame
  - ...
- Sporadic Frame
  - Sent (by master) only when needed
  - Shared schedule slot with other Sporadic Frames
  - Use whenever polling for specific data only seldom needed
  - If more than one Sporadic Frame needs to be sent, master needs to decide for one → no collision, but still non-deterministic
  - Sample use case:
    - Request „power window fully closed?“ every 15 ms
    - ...only while power window is closing

The LIN Bus

- Sample schedule table

Slot	Type	Signal
1	Unconditional	AC
2	Unconditional	Rain sensor
3	Unconditional	Tire pressure
4	Event triggered	Power window
5	Sporadic	(unused) -OR- Fuel level -OR- Outside temp

The LIN Bus

- Doing Off-Board-Diagnosis of LIN ECUs
  - Variant 1: Master at CAN bus responds on behalf of ECU on LIN
    - Keeps synchronized state via LIN messages
  - Variant 2: Master at CAN bus tunnels, e.g., KWP 2000 messages
    - Standardized protocol
    - LIN dest address is 0x3C (Byte 1 is ISO dest address)
    - Dest ECU (according to ISO address) answers with address 0x3D
    - Independent of payload, LIN frame padded to 8 Bytes
    - LIN slaves have to also support KWP 2000
    - Contradicts low cost approach of LIN
    - “Diagnostic Class” indicates level of support

Main Takeaways

- LIN
  - Goals
  - Deployment as sub bus
  - Message types and scheduling
  - Determinism

Main Takeaways

- Overall
  - Design goals
  - Message orientation vs. address orientation,
  - Addressing schemes
  - Medium access
  - Flow control
  - Real time guarantees and determinism

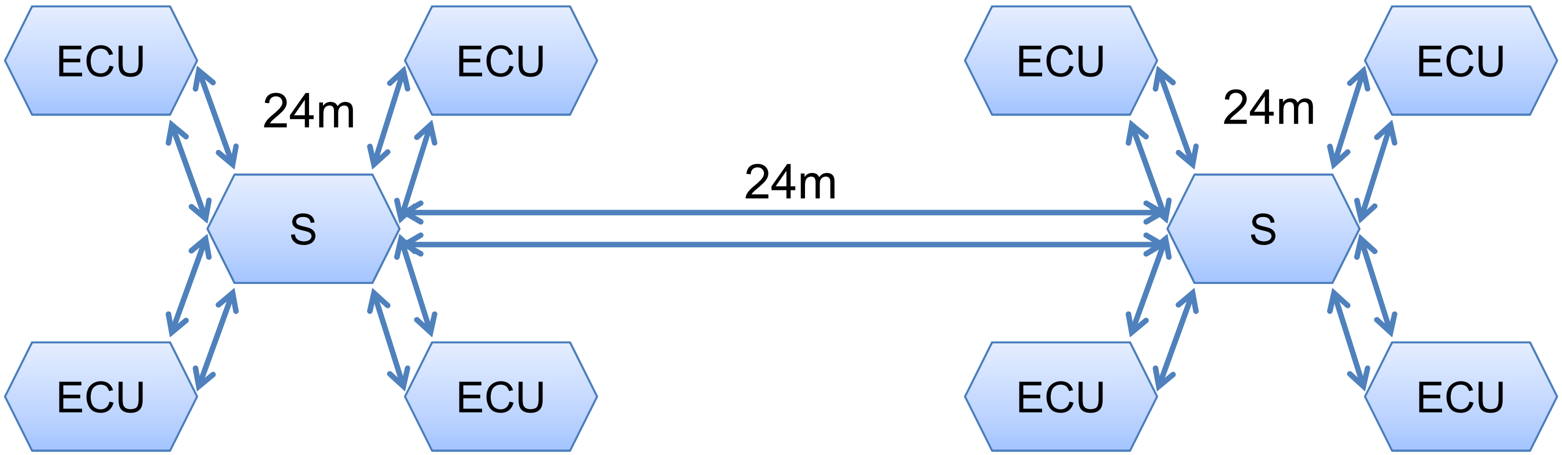
FlexRay

FlexRay

- Motivation
  - Drive/Brake/Steer-by-Wire
  - CAN bus is prone to failures
    - Line topology
    - No redundant links
  - CAN bus is slow
  - Need for short bus lines ⇨ deployment expensive, complicated
  - Non-determinism for all but one message class
    - Worst case delay unacceptably high
  - Early solutions by OEMs proprietary
    - TTCAN, TTP/TTA, Byteflight, ...
  - Foundation of consortium to develop new bus: FlexRay
    - BMW, VW, Daimler, GM, Bosch, NXP, Freescale
  - First series deployment at end of 2006 (BMW X5)

FlexRay

- Bus topology
  - Line, Star with bus termination
  - Max. distance per line: 24m
  - Optional use of second channel
    - Higher redundancy or(!) higher speed
    - Up to 10 MBit/s for single channel, 20 MBit/s for dual channel



FlexRay

- Bit transmission
  - Need synchronized clocks in sender and receiver
  - Thus, need additional bits for synchronizing signal sampling at receiver (done with each 1⇨0 flank)
  - Don’t use bit stuffing
    otherwise: message length becomes non-deterministic (cf. CAN)
  - New concept: frame each transmission, each frame, each Byte
    - Bus idle (1)
    - Transmission Start Signal (0)
      - Frame Start Signal (1)
        - Byte Start Signal (1)
        - Byte Start Signal (0)
        - 8 Bit Payload (…)
      - Frame End Signal (0)
    - Transmission End Signal (1)

FlexRay

- Bus access
  - Bus cycle (ca. 1 µs .. 7 µs)
    - Static Segment
    - Dynamic Segment (opt.)
    - Symbol Window (opt.)
    - Network Idle Time
  - Global *Cycle Counter* keeps track of bus cycles passed

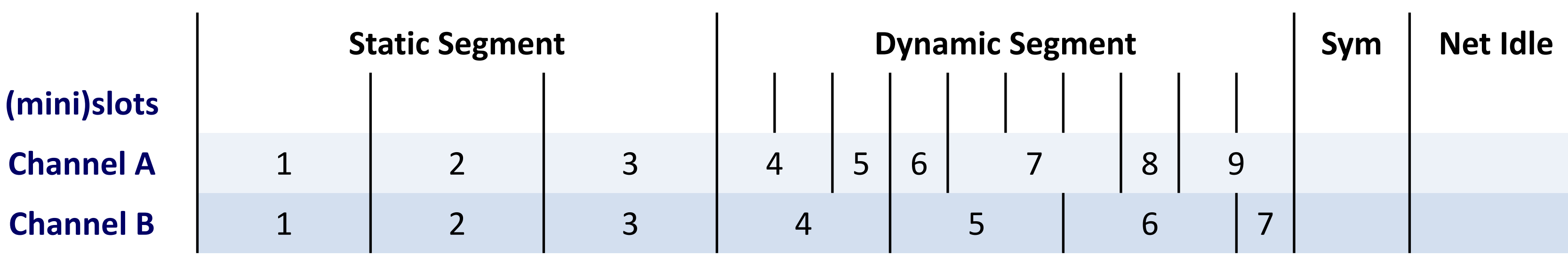
- Static Segment
  - Slots of fixed length (2 .. 1023)
  - One Message per Slot
  - Static assignment (of slot and channel) to ECUs (i.e., TDMA)

  ⇨ bus access is collision free, deterministic

FlexRay

- Dynamic Segment
  - Split into minislots (also statically assigned to ECUs)
  - Messages (usually) take up more than one minislot
  - Slot counter pauses while message is being transmitted
    (thus, slot counters of channels A and B soon desynchronize)
  - Lower priority messages have higher slot number
    (thus sent later, or not at all)

- Example:



FlexRay

- Message format
  - Control Bits
    - Bit 0: Reserved
      - Unused, always 0
    - Bit 1: Payload Preamble Indicator
      - In static segment:
        first 0 .. 12 Byte payload for management information
      - In dynamic segment:
        first 2 Byte payload contains Message ID (cf. UDP Port)

5 Bit	11 Bit	7 Bit	11 Bit	6 Bit		24 Bit
Control Bits	Frame ID	Length	Header CRC	Cycle Counter	Payload	CRC

FlexRay

- Message format
  - Control Bits
    - Bit 2: Null Frame Indicator
      - Indicates frame without payload
      - Allows sending “no message” also in static segment (fixed slot lengths!)
    - Bit 3: Sync Frame Indicator
      - Indicates frame may be used for synchronizing clock
      - To be sent by 2 .. 15 “reliable” ECUs
    - Bit 4: Startup Frame Indicator
      - Used for synchronization during bootstrap
      - Sent by cold start node (⇨ later slides)

5 Bit	11 Bit	7 Bit	11 Bit	6 Bit		24 Bit
Control Bits	Frame ID	Length	Header CRC	Cycle Counter	Payload	CRC

FlexRay

- Message format
  - Frame ID
    - Identifies message (≙ slot number)
  - Length
    - Length of payload (in 16 Bit words)
  - Header CRC
  - Cycle Counter
    - Global counter of passed bus cycles
  - Payload
    - 0 .. 127 16 Bit words (≙ 0 .. 254 Byte of payload)
  - CRC

5 Bit	11 Bit	7 Bit	11 Bit	6 Bit		24 Bit
Control Bits	Frame ID	Length	Header CRC	Cycle Counter	Payload	CRC

FlexRay

- Time synchronization
  - Need synchronized bit clock + synchronized slot counter
  - Want no dedicated time master ⇨ Distributed synchronization
  - Configure (typically) three nodes as “cold start nodes”

  - Cold start procedure (followed by all cold start nodes):
    - Check if bus idle
      - if bus not idle ⇨ abort (cold start already proceeding or unneeded)
    - Transmit wakeup (WUP) pattern
      - if collision occurs ⇨ abort
      - if no collisions occurred ⇨ this is the leading cold start node
  - Cold start procedure (leading cold start node):
    - Send Collision Avoidance Symbol (CAS)
    - Start regular operations (cycle counter starts at 0)
      - Set Bits: Startup Frame Indicator ⊕ Sync Frame Indicator

FlexRay

- Time synchronization
  - Cold start procedure (other cold start nodes)
    - Wait for 4 Frames of leading cold start node
    - Start regular operations
      - Set Bits: Startup Frame Indicator ⊕ Sync Frame Indicator
  - Cold start procedure (regular ECUs)
    - Wait for 2 Frames of 2 cold start nodes
    - Start regular operations

1	WUP	WUP	CAS	0	1	2	3	4	5	6	7	8	...
2	WUP	↯						4	5	6	7	8	...
3	↯							4	5	6	7	8	...
4										6	7	8	...
5										6	7	8	...

FlexRay

- Example configuration of timing
  - Use fixed payload length of 16 Byte
    (with header and trailer: 24 Bytes; with FSS, BSS, FES: ca. 250 Bits)
  - 10 Mbps data rate ⇨ 25 µs message duration
  - Add 5 µs guard to care for propagation delay and clock drift
    ⇨ 35 µs slot length in static segment
  - One macro tick: 1 µs (can use 1 .. 6 µs)
  - One minislot: 5 macro ticks: 5 µs
  - Tbit = 100 ns, sample rate of bus = Tbit/8 = 12.5 ns

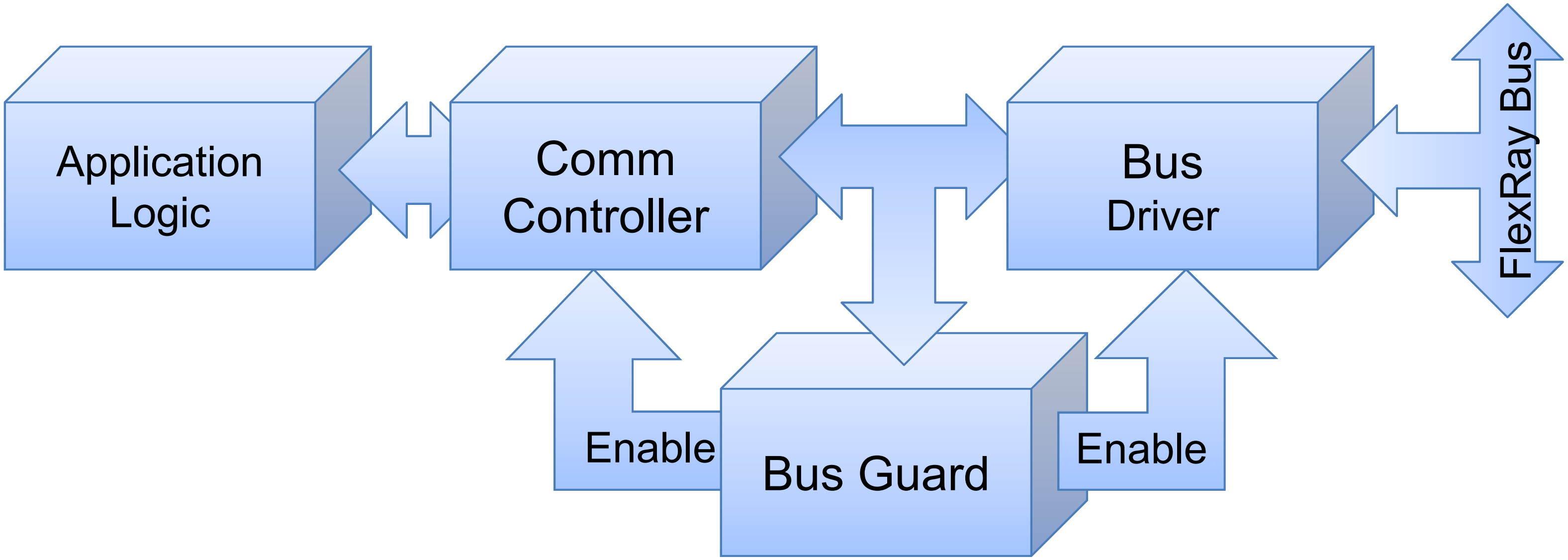
FlexRay

- Example configuration of timing (contd.)
  - Use 64 distinct communication cycles
  - Communication cycle duration: 5 ms
  - Use 3 ms for static segment
  - Remaining 2 ms used for dynamic segment, symbol window, network idle time

- Message repetition interval fully customizable, e.g.:
  - 2.5 ms (one slot each at start and end of static segment)
  - 5 ms (one slot each in every communication cycle)
  - 10 ms (one slot in every second communication cycle)
  - …

FlexRay

- Error prevention
  - Integrate bus guard
  - Implement separately from communication controller
  - Follows protocol steps in communication controller
  - Can only enable bus driver when allowed to communicate,
    or permanently disable in case of errors (*babbling idiot problem*)



FlexRay

- Error handling
  - Multiple measures for error detection
    - Check cycle counter value
    - Check slot counter value
    - Check slot timing
    - Check header CRC
    - Check CRC
  - Reaction to timing errors
    - Do not automatically repeat messages (⇨ non-determinism)
    - Switch to passive state instead
      - Stop transmitting messages
      - Keep receiving messages
        (might allow re-synchronization to bus)
  - Reaction to severe, non-recoverable errors
    - Completely switch off bus driver

FlexRay

- AUTOSAR TP
  - Transport protocol of FlexRay
  - Upwards compatible to ISO 15765-2 (ISO TP for CAN)
  - Adjusted and extended for FlexRay
  - Difference in addressing
    - In CAN: CAN message ID assigned arbitrarily
    - In FlexRay: Frame ID ≙ Slot Number (i.e., not arbitrary)
      ⇨ cannot use source/destination addresses as IDs in lower layer
    - Address encoded only (and completely) in TP header

  - Also:
    - New message types

1 .. 2 Byte	1 .. 2 Byte	1 .. 5 Byte	
Target Address	Source Address	PCI	Payload

FlexRay

- AUTOSAR TP
  - Frame types: Single Frame *Extended* / First Frame *Extended*
  - Larger *data length* (DL) field allows for longer payload
    - Four kinds of first frames can indicate payloads of up to 4 GiB

<table>
<tr><th></th><th colspan="2">PCI Byte 0</th><th colspan="2">PCI Byte 1</th><th colspan="2">PCI Byte 2</th><th colspan="2">PCI Byte 3</th><th colspan="2">PCI Byte 4</th></tr>
<tr><td>Single Frame</td><td>0</td><td>DL</td><td colspan="8"></td></tr>
<tr><td>Single Frame Extended*</td><td>5</td><td>0</td><td colspan="2">DL</td><td colspan="6"></td></tr>
<tr><td>First Frame</td><td>1</td><td colspan="3">DL</td><td colspan="6"></td></tr>
<tr><td>First Frame Extended*</td><td>4</td><td colspan="2">1</td><td>DL</td><td colspan="6"></td></tr>
<tr><td>“</td><td>4</td><td colspan="2">2</td><td colspan="3">DL</td><td colspan="4"></td></tr>
<tr><td>“</td><td>4</td><td colspan="2">3</td><td colspan="5">DL</td><td colspan="2"></td></tr>
<tr><td>“</td><td>4</td><td colspan="2">4</td><td colspan="7">DL</td></tr>
</table>

FlexRay

- AUTOSAR TP
  - Extended flow control
    - FS values allow triggering abort of ongoing transmission
      - FS=2: Overflow
      - FS=5: Cancel, Data Outdated
      - FS=6: Cancel, No Buffer
      - FS=7: Cancel, Other
    - ST split into two ranges to allow shorter separation times
      - 0x00 .. 0x7F Separation Time in ms
      - 0xF1 .. 0xF9 Separation Time in µs (new!)

<table>
<tr><th></th><th colspan="2">PCI Byte 0</th><th colspan="2">PCI Byte 1</th><th colspan="2">PCI Byte 2</th><th colspan="2">PCI Byte 3</th><th colspan="2">PCI Byte 4</th></tr>
<tr><td>Consecutive Frame</td><td>2</td><td colspan="2">SN</td><td colspan="7"></td></tr>
<tr><td>Consecutive Frame 2*</td><td>6</td><td colspan="2">SN</td><td colspan="7"></td></tr>
<tr><td>Flow Control Frame</td><td>3</td><td>FS</td><td colspan="2">BS</td><td colspan="2">ST</td><td colspan="4"></td></tr>
<tr><td>Acknowledge Frame*</td><td>7</td><td>FS</td><td colspan="2">BS</td><td colspan="2">ST</td><td>ACK</td><td>SN</td><td colspan="2"></td></tr>
</table>

FlexRay

- AUTOSAR TP
  - Extended flow control
    - CAN: Acknowledgement by transmitting dominant bit in ACK field
    - FlexRay: New Acknowledge Frame (AF)
    - Use after single frame or after all consecutive frames (as ACK) or immediately (as NACK)
    - Functions identical to Flow Control Frame, but adds *ACK* and *SN* nibbles
      - ACK is 1 or 0; SN indicates slot number of first defective frame
    - Sender may repeat failed transmissions at earliest convenience (alternately uses CF and CF2 frames)

	PCI Byte 0		PCI Byte 1	PCI Byte 2	PCI Byte 3		PCI Byte 4
Consecutive Frame	2	SN					
Consecutive Frame 2*	6	SN					
Flow Control Frame	3	FS	BS	ST			
Acknowledge Frame*	7	FS	BS	ST	ACK	SN	

MOST

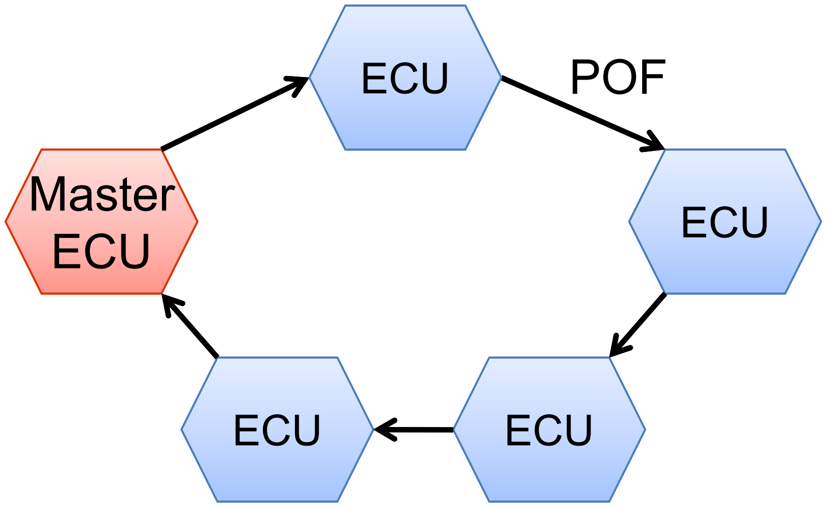
Media Oriented Systems Transport

MOST

- Media Oriented Systems Transport
  - specifies ISO layers 1 through 7
  - Does not focus on sensor/actor tasks
    (e.g., delay, fault tolerance),
    but on infotainment (e.g., jitter, data rate)
- History
  - Domestic Data Bus (D2B, later: Domestic Digital Bus) developed by Philips, later standardized as IEC 61030 (still in the 90s)
  - Little adoption in vehicles, thus SMSC soon develops a successor
  - 1998: MOST Cooperation standardizes MOST bus
    (Harman/Becker, BMW, DaimlerChrysler, SMSC)
  - December 2009: MOST 3.0E1 published
  - Today:
    MOST cooperation numbers 60 OEMs, 15 vehicle manufacturers

MOST

- Medium
  - Plastic Optic Fiber (POF) alternative (copper) variant specified, but little used
  - Data rates specified from 25 (MOST25) to 150 MBit/s (MOST150)
  - Manchester coded bit transmission
  - Dedicated timing master ECU (slaves adopt bit timing)
  - Logical bus topology: ring of up to 64 ECUs
  - Physical bus topology can differ



MOST

- Link Layer
  - Synchronous bit stream; all clocks synchronized to timing master
  - Stream divided into blocks; each block traverses ring exactly once
  - Blocks divided into 16 Frames
    - Frame size: 64 Byte (MOST25) to 384 Byte (MOST150)
    - Frame rate static but configurable; recommended: 48 kHz (DVD)
  - Frame divided into
    - Header (with boundary descriptor) and Trailer
    - Data: Synchronous Channel, Asynchronous Channel, Control Channel

MOST

- Link Layer
  - Synchronous Channel
    - Use case: audio or video
    - TDMA divides frame into streaming channels
      ⇨ deterministic
    - Reserved by messages on control channel
    - Thus, no addressing required
    - Maximum number of streaming channels limited by frame size

Streaming Channel 1	Streaming Channel 2	Streaming Channel 3	unused
CD-Audio, Device A	DVD-Video, Device B	...	

MOST

- Link Layer
  - Asynchronous Channel
    - Use case: TCP/IP
    - Random access with arbitration (based on message priority)

      ⇨ non-deterministic
    - Single message may take more than one frame
    - Short additional header contains source/destination address, length
    - Short additional trailer contains CRC
    - No acknowledgement, no automatic repeat on errors

1 Byte	2 Byte	1 Byte	2 Byte		4 Byte
Arbitration	Target Address	Len	Source Address	...	CRC

MOST

- Link Layer
  - Control Channel
    - Management and control data
    - Random access with arbitration (based on message priority)
    - Message length 32 Byte
      - MOST25 control channel uses 2 Bytes per frame
        ⇨ each message takes 16 Frames = 1 Block
    - Message reception is acknowledged by recipient
    - Failed transmissions are automatically repeated

1 Byte	2 Byte	2 Byte	1 Byte	17 Byte	2 Byte	1 Byte
Arbitration	Target Address	Source Address	Type	Data	CRC	Trailer

MOST

- Link Layer
  - Control Channel messages
    - Resource Allocation,
      Resource De-allocation:
      - manage streaming channels in synchronous segment
    - Remote Read,
      Remote Write
      - accesses registers and configuration of ECUs
    - Remote Get Source
      - query owner of streaming channels in synchronous segment
    - …
      - Other message types are transparently passed to upper layers

MOST

- Link Layer
  - Addressing
    - 16 Bit addresses
    - physical address
      - According to relative position in ring
      - Master gets 0x400
      - First slave gets 0x401
      - etc.
    - logical address
      - Assigned by master
      - Typically upwards of 0x100 (Master)
    - groupcast
      - Typically 0x300 + ID of function block
    - broadcast
      - Typically 0x3C8

MOST

- Ring disruption
  - Causes
    - ECU stops working
    - Plastic optic fiber gets damaged
  - Symptoms
    - Messages either not transmitted to recipient, or not back to sender thus: total failure of bus
  - Diagnosis
    - Ring disruption easily detected
    - Reason and affected ECUs impossible to determine
  - Workarounds
    - Vendor dependent, proprietary
    - often: use additional single-wire bus for further diagnosis

MOST

- Higher layers: Object oriented MOST Network Services
  - Function block (= class)
    - e.g. audio signal processing (0x21), audio amplifier (0x22), ...
    - Multiple classes per device, multiple devices per class
    - Every device implements function block 0x01 (MOST Netw. Services)
  - Instance
    - Uniquely identifies single device implementing certain function block
  - Property/Method
    - Property (get/set value)
    - Method (execute action)
  - Operation
    - Set/Get/... (Property), Start/Abort/... (Method)
  - 22.00.400.0 (20) ⇨ amplifier number 0: volume set to 20

MOST

- Higher layers: System boot and restart
  - Master node announces reset of global state
    (all devices change status to Not-OK and cease operations)
  - Master node initiates system scan
    - Iteratively polls all physical addresses for present function blocks
    - Devices answer with logical address, list of function blocks, and instance numbers
  - Master can detect ambiguous combinations of function blocks and instance numbers ⇨ will then assign new instance numbers
  - Master keeps table of all device’s operation characteristics
  - Master reports to all devices: status OK
  - MOST Bus is now operational

MOST

- Higher layers – MAMAC and DTCP
  - Trend towards all-IP in consumer electronics addressed in MOST by introducing MAMAC (MOST Asynchronous Media Access Control)
    - Encapsulates Ethernet and TCP/IP for transmission on MOST bus
    - but: not supported by MOST services; needs to be implemented in software
  - Concerns of music/film industry wrt. digital transmission addressed in MOST by introducing DTCP (Digital Transmission Content Protection)
    - As known from IEEE 1394 (FireWire)
    - Bidirectional authentication and key exchange of sender/receiver
    - Encrypted data transmission

In-Car Ethernet

In-Car Ethernet

- IEEE 802.3
- Bob Metcalfe, David R. Boggs
- 1973, Parc CSMA/CD Ethernet
  - 3 Mbit/s, 256 nodes, 1 km coax cable
- 1980- revised to become IEEE Std 802.3
- Next big thing?
  - "Automotive. Cars will have three networks.
    (1) Within the car.
    (2) From the car up to the Internet. And
    (3) among cars.
    IEEE 802 is ramping up for these standards now, I hope."
    --/u/BobMetcalfe on http://redd.it/1x3fiq

In-Car Ethernet

- Why?
  - Old concept:
    - Strictly separated domains
    - Each served by specialized bus
    - Minimal data interchange
  - Current trend:
    - Advanced Driver Assistance Systems (ADAS)
    - Sensor data fusion
      - (in-car, between cars)
    - Ex: Cooperative Adaptive Cruise Control (CACC)
  - Move from domain specific buses ⇨ general-purpose bus

Ethernet

- Physical layers
  - 10BASE5 (aka Thicknet, aka IEEE Std 802.3-1985)
    - Manchester coded signal, typ. 2 V rise
    - 10 Mbit/s over 500m coax cable
    - Nodes tap into core (“vampire tap”)
  - 10BASE2
    - 10 Mbit/s over “almost” 200m coax cable
    - BNC connectors, T-shaped connectors
- Medium access: CSMA/CD
  - Carrier sensed ⇨ medium busy
  - Collision ⇨ jam signal, binary exponential backoff (up to 16 times)

Ethernet

- Physical layers
  - 1000BASE-T
    - 1 Gbit/s over 100m
    - Cat 5e cable with 8P8C connectors,
      4 twisted pairs of wires,
      multi-level signal (-2, -1, 0, +1, +2),
      scrambling, …
    - Medium access
    - No longer shared bus, but point to point
    - Auto-negotiated (timing) master/slave
  - 100GBASE-ER4
    - 100 Gbit/s over 40 km
    - Plastic Optic Fiber (POF)
  - …

Ethernet

- Link layer
  - Lightweight frame type
  - Optional extensions, e.g., IEEE 802.1Q (identifier 0x8100)
  - Directly encapsulates higher layer protocols, e.g., IPv6 (0x86DD)
  - …or IEEE 802.2 Logical Link Control (LLC) frame (identifier is len)

(in Byte)

  - Error-checked, but only best effort delivery of data

<table>
<tr><th>0</th><th></th><th></th><th></th><th></th><th></th><th></th><th>7</th><th>8</th><th></th><th></th><th></th><th></th><th></th><th></th><th>15</th></tr>
<tr><td colspan="8">Preamble (1010..11)</td><td colspan="6">Destination MAC</td><td colspan="2"></td></tr>
<tr><td colspan="4">Source MAC</td><td colspan="4">(opt) 802.1Q tag</td><td colspan="2">Type/len</td><td colspan="6"></td></tr>
<tr><td colspan="16">Payload (commonly 42-1500 Byte, max 1982 Byte)</td></tr>
<tr><td colspan="4">Checksum</td><td colspan="12">(Idle time)</td></tr>
</table>

In-Car Ethernet

- In-car Ethernet?
  - Almost all “in-car” qualities absent
    - Heavy, bulky cabling
    - Huge connectors
    - Sensitive to interference
    - Needs external power
    - No delay/jitter/… guarantees
    - No synchronization
    - Etc…
  - But:
    - …can be easily extended:
    - New physical layers
    - Tailored higher-layer protocols

In-Car Ethernet

- One-Pair Ether-Net (OPEN) alliance SIG
  - Founded: BMW, Broadcom, Freescale, Harman, Hyundai, NXP
  - 2014: approx. 150 members
  - 100 Mbit/s on single twisted pair, unshielded cable
  - Power over Ethernet (IEEE 802.3at)
  - Manufactured by Broadcom, marketed as *BroadR-Reach*

- Reduced Twisted Pair Gigabit Ethernet (RTPGE) task force
  - Working on IEEE 802.3bp
  - 1 Gbit/s over up to 15m single twisted pair cable

In-Car Ethernet

- Upper layers: TSN
  - Many solutions (e.g., SAE AS6802 “Time Triggered Ethernet”)
  - Current: IEEE 802.1 Time Sensitive Networking (TSN) task group (aka Audio/Video Bridging AVB task group, up until 2012)
  - Promoted by *AVnu Alliance* SIG (cf. IEEE 802.11 / Wi-Fi Alliance)

- Concept
  - Needs TSN-enabled switches / end devices
  - Tight global time synchronization
  - Dynamic resource reservation on *streams* through network
  - IEEE 802.1AS… extensions
    - Layer 2 service
  - IEEE 802.1Q… extensions
    - Frame tagging standard

In-Car Ethernet

- IEEE 802.1AS Time Synchronizing Service
  - Subset of IEEE 1588 Precision Time Protocol (PTP)
  - Syncs clock value/frequency of all nodes
  - Election of “master” time master (grandmaster clock), disseminates sync information along spanning tree
- IEEE 802.1Qat Stream Reservation Protocol (SRP)
  - *Talker* advertises stream (along with parameters)
  - Advertisement is disseminated through network
  - Intermediate nodes check, block available resources, update advertisement with, e.g., newly computed worst case latency
  - *Listeners* check (annotated) advertisement, send registration message back to *Talker*
  - Intermediate nodes reserve resources, update multicast tree

In-Car Ethernet

- IEEE 802.1Qav etc. Traffic Shaping
  - Prioritize frames according to tags
  - Avoid starvation, bursts, …
  - e.g., Token bucket, with many more proposed
- IEEE 802.1Qbu Frame Preemption
  - Can cancel ongoing transmissions
    (if higher priority frame arrives)
- IEEE 802.1Qcb Media Redundancy
- …

Main Takeaways

- FlexRay
  - Motivation
  - Single or dual channel operation
  - Distributed operation
  - Static and dynamic segment
- MOST
  - Motivation
  - Topology and implications
  - Centralized operation
  - Synchronous and asynchronous channel
- Ethernet
  - Concept
  - Drawbacks of classic standards
  - New PHY layers
  - New upper layers (TSN)

ECUs

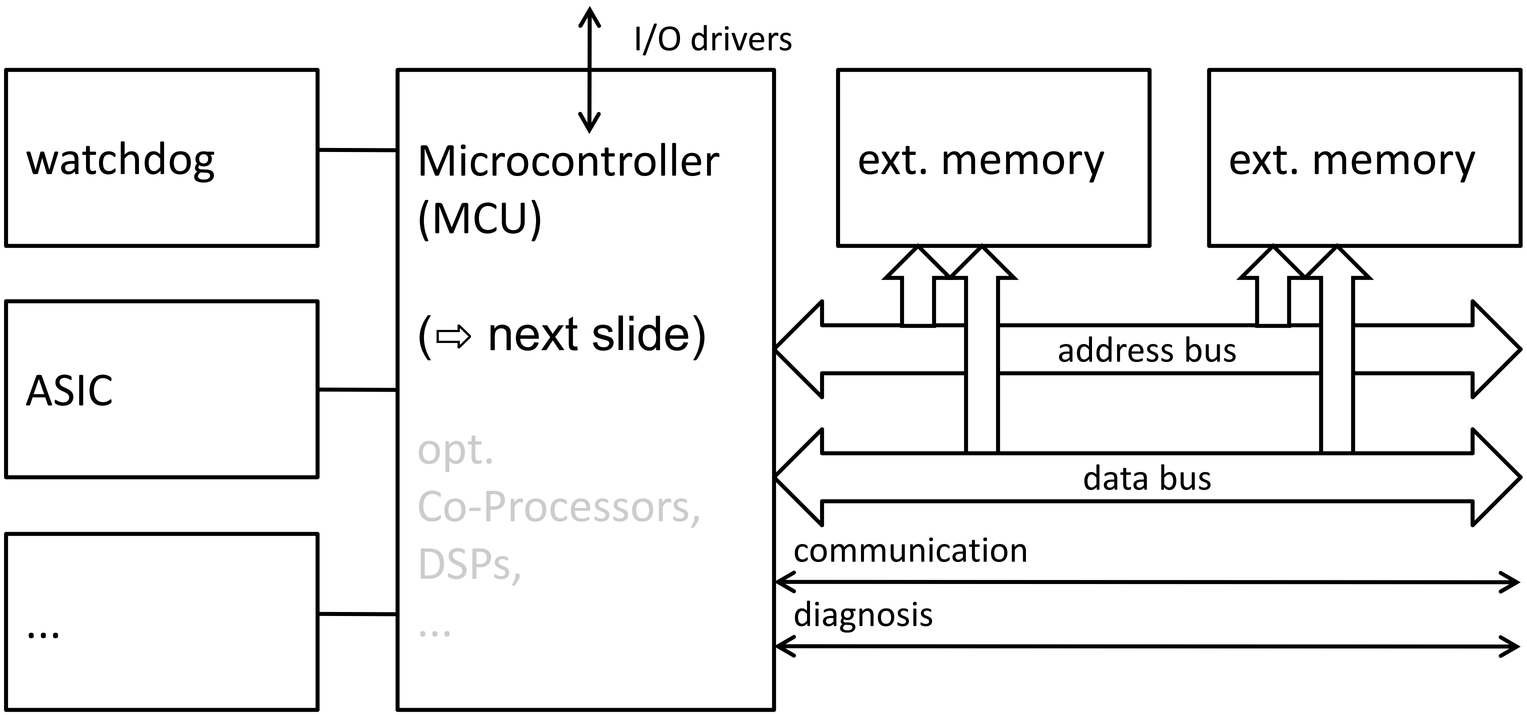
Electronic Control Units

Electronic Control Units (ECUs)

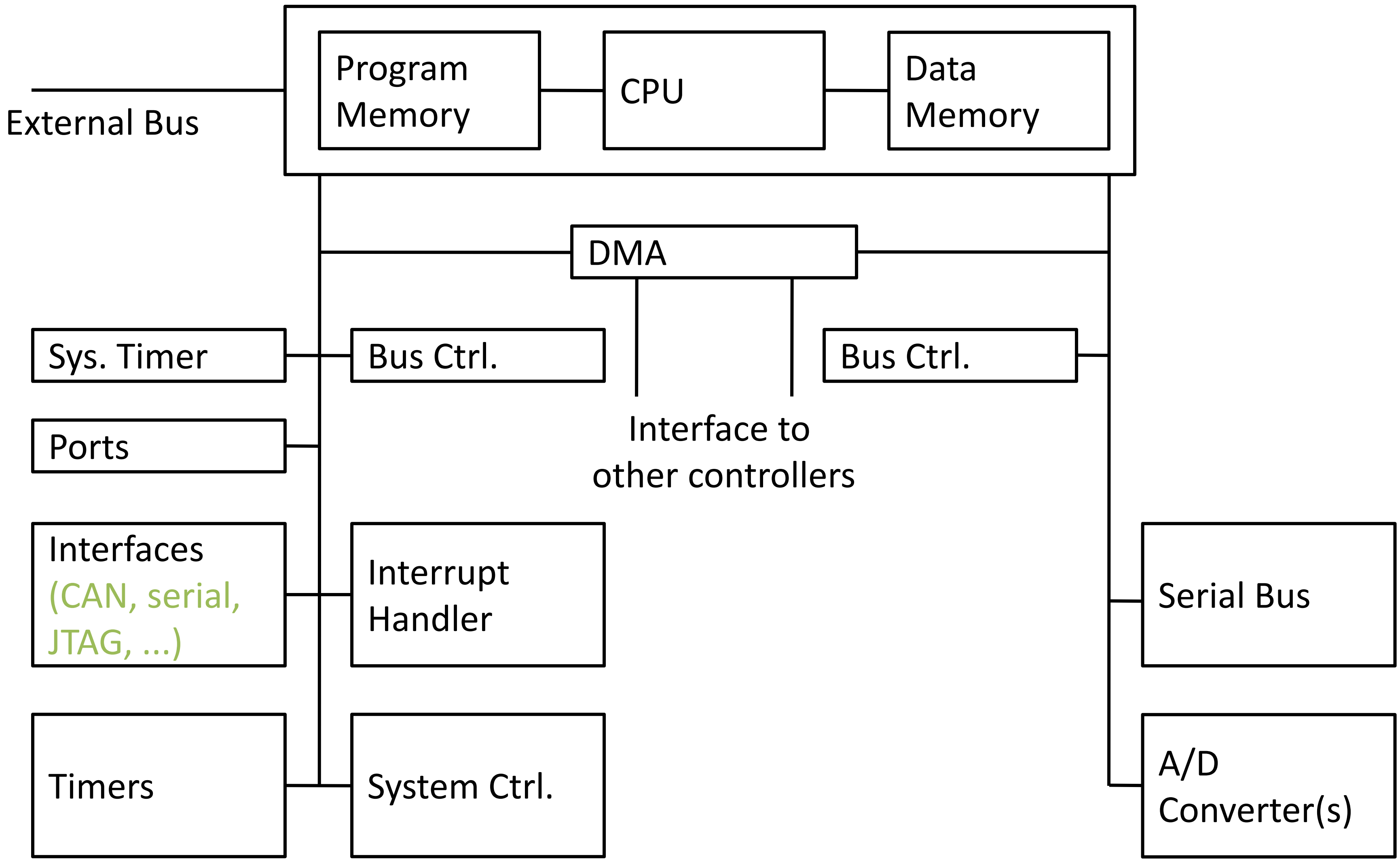
- Middle and upper class vehicles carry 80 .. 100 networked ECUs
- Each consisting of
  - Transceiver (for bus access)
  - Power supply
  - Sensor drivers
  - Actor drivers
  - …and an ECU Core (⇨ next slide)
- Depending on deployment scenario, ECU and components must be
  - Shock resistant
  - Rust proof
  - Water resistant, oil resistant
  - Heat resistant
  - …

ECU Core

- ≙ Personal Computer
- additional external guard hardware (e.g., watchdog) for safety critical applications



Architecture



Architecture

- Microcontroller (MCU)
  - 8, 16, 32 Bit
  - Infineon, Freescale, Fujitsu, ...
- Memory
  - Volatile memory
    - SRAM (some kByte)
    - Typically integrated into microcontroller
  - Non-volatile memory
    - Flash (256 kByte .. some MByte)
    - Serial EEPROM (some kByte, e.g., for error log)
- Power supply
  - DC/DC converter, e.g., to 5 V or 3.3 V

Architecture

- Clock
  - Quartz Xtal, some 10 MHz (⇨ ECU requires only passive cooling)
- External guard hardware
  - Watchdog
    - Expects periodic signal from MCU
    - Resets MCU on timeout
  - ASIC guard
    - For more complex / critical ECUs
    - ASIC sends question, MCU must send correct answer before timeout
    - Resets (or disables) ECU on timeout or error
- Internal Buses
  - Low-cost ECUs can use shared bus for address and data
  - Parallel

Architecture

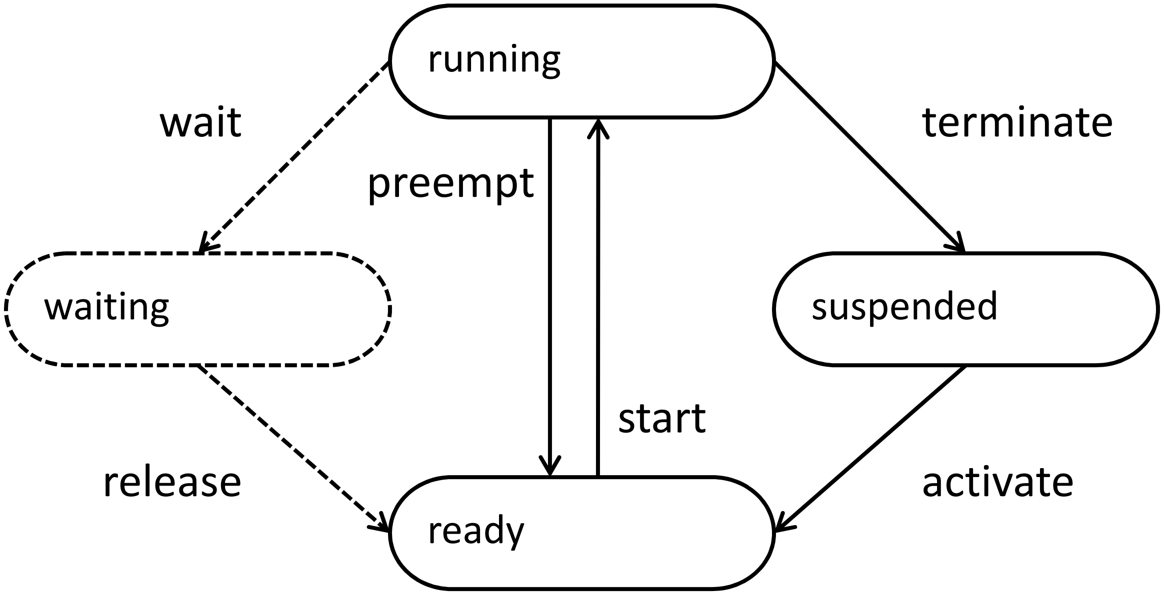
- Sensor drivers
  - Resistive sensors (e.g., simple potentiometer for length, angle)
  - Capacitive, inductive sensors (e.g., pressure, distance)
  - Active sensors (simple voltage / complex data output)
- Actor drivers
  - D/A conversion
  - High-power amplifiers
  - Bridges
- Further requirements
  - Electro-magnetic interference (EMI) characteristics
  - Mechanical robustness
  - Water resistance
  - Thermal resistance
  - Chemical resistance

Automotive Operating Systems

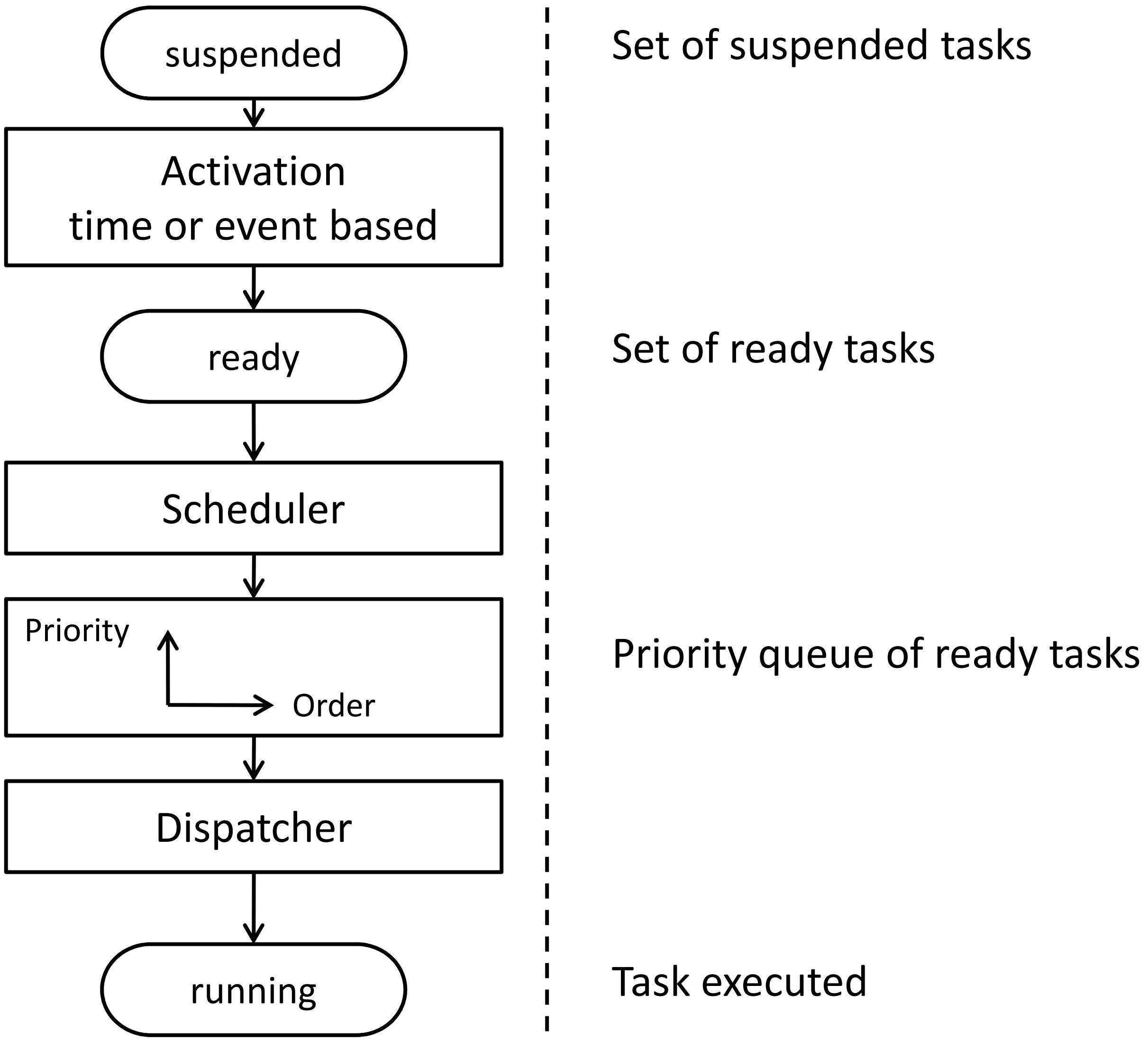
- Hardware abstraction
  - Often missing, hardware accessed directly
  - Recent trends towards operating systems
- Application Programming Interface (API)
  - Common for message transmission over external buses
- Software safeguards
  - E.g., stack overflow
  - Particularly helpful during development

Automotive Operating Systems

- Process States



Scheduling


suspended
Activation
time or event based
ready
Scheduler
Priority
Order
Dispatcher
running
Set of suspended tasks
Set of ready tasks
Priority queue of ready tasks
Task executed

Automotive Operating Systems

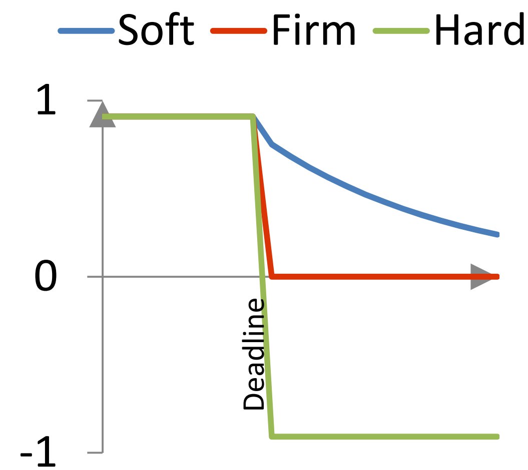
- Scheduling
  - The act of assigning an order of activation,
    given a process model, activation sequence, and deadlines
    - *dynamic*: Schedule is calculated at run time
    - *static*: Schedule is fixed, e.g., at compile time (⇨ fully deterministic)
  - *Feasible schedule*:
    all time constraints fulfilled, no deadline violated
  - Dispatcher coordinates context switches

- Context switches
  - For one process to change state to *running*, another process may need to be preempted
  - CPU registers etc. will now be occupied by new process, operating system takes care of persisting information

Real Time Properties

- Latency
  - Time difference from event to reaction
- Jitter
  - Difference of max and min latency
  - High importance in feedback control systems
- Execution time
  - Time difference of task start and end
  - Worst Case Execution Time (WCET)
    - Defined for program aspects, dependent on platform
    - Considers every possible cause of delay (interrupts, caching, …)
    - Important for guaranteeing determinism

Real Time Properties



- Soft deadline
  - Delivering result after soft deadline less helpful (reduced benefit)
  - e.g., car speeds up ⇨ radio gets louder
- Firm deadline
  - Delivering result after firm deadline useless (no benefit)
  - e.g., incoming traffic bulletin ⇨ SatNav powered up
- Hard deadline
  - Delivering result after hard deadline causes damage or harm (negative benefit)
  - e.g., brake pedal is pushed ⇨ car decelerates

Real Time Properties

- Real time systems
  - Internal image of system state in memory
  - State described by set of variables
  - Needs continuous update of image
- Real time architecture
  - Event triggered system
    - Image update with every change of state
  - Time triggered system
    - Image update in fixed intervals
    - internal or global clock (needs synchronization)

OSEK/VDX

- 1993
  - Founded as OSEK – "*Offene Systeme und deren Schnittstellen für die Elektronik im Kraftfahrzeug*"
  - BMW, Bosch, Daimler Chrysler, Opel, Siemens, VW, Univ. Karlsruhe
- 1994
  - Merged with VDX – "*Vehicle Distributed Executive*"
  - PSA und Renault

- Today
  - More than 50 partners
  - (Parts) standardized as ISO 17356 series
  - Standardizes common communications stack, network management, **operating system** (⇨ next slides), …
  - Many free implementations (freeOSEK, openOSEK, nxtOSEK, …)

OSEK/VDX

- Properties
  - Operating system for single processor
  - Static configuration
    - Tasks
    - Resources
    - Functions
  - Can meet requirements of hard deadlines
  - Programs execute directly from ROM
  - Very low memory requirements
  - Standardized system (⇨ “OSEK conformant ECUs”)

OSEK/VDX

- Configuration
  - Operating system configured at compile time
  - OSEK Implementation Language (OIL)
    - Scheduling strategy
    - Task priorities
    - …

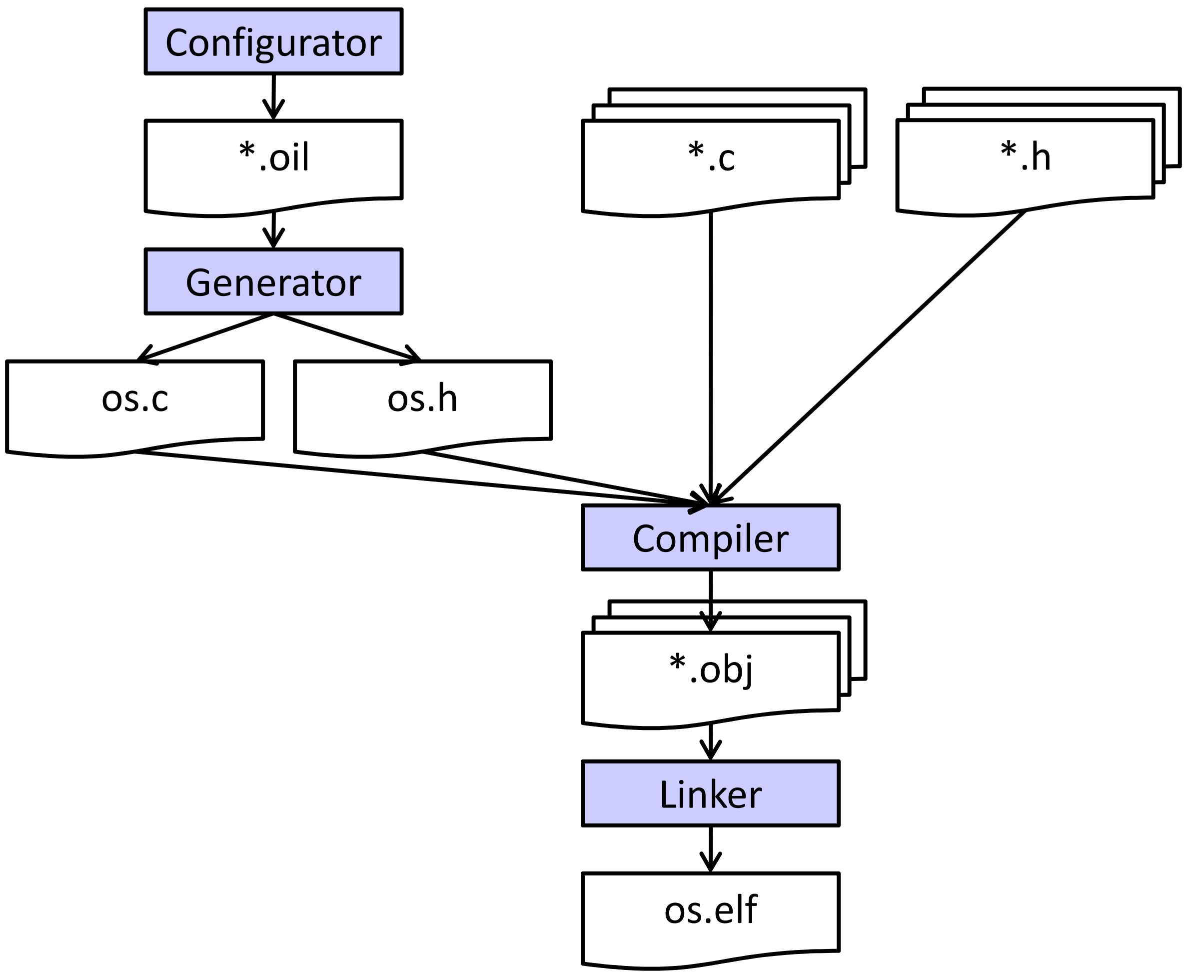
```
CPU OSEK_Demo
{

  OSEK_Example_OS
  {
    MICROCONTROLLER = Intel80x86;
    …
  };

  TASK Sample_TASK
  {
    PRIORITY = 12;
    SCHEDULE = FULL;
    AUTOSTART = TRUE;
    ACTIVATION = 1;
  };

  …
};
```

Building of OSEK/VDX firmware



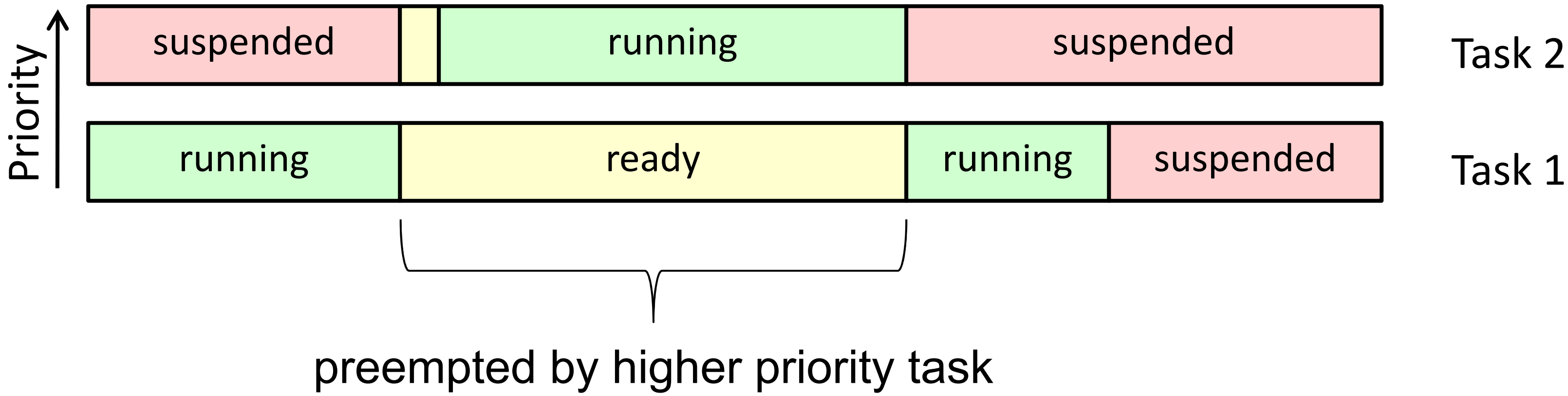
OSEK/VDX

- Tasks
  - Static priority
  - Relationships of tasks
    - Synchronization
    - Message exchange
    - Signaling
  - Support for time triggered services
  - Error management
  - C macros for definition provided

```
DeclareTask(SampleTask);
…
TASK(SampleTask) {
   /* read sensors, trigger actors */
   TerminateTask();
}
```

OSEK/VDX

- Scheduling
  - Scheduler always chooses highest priority task
  - Configurable modes:
    - Non preemptive: Tasks are never preempted
    - Preemptive: Higher priority tasks always preempt lower priority tasks
    - Mixed: Individual configuration of each task



AUTOSAR

- Traditional paradigm:
  one function ⇨ one ECU
  (incl. software and OS, supplied by OEM)

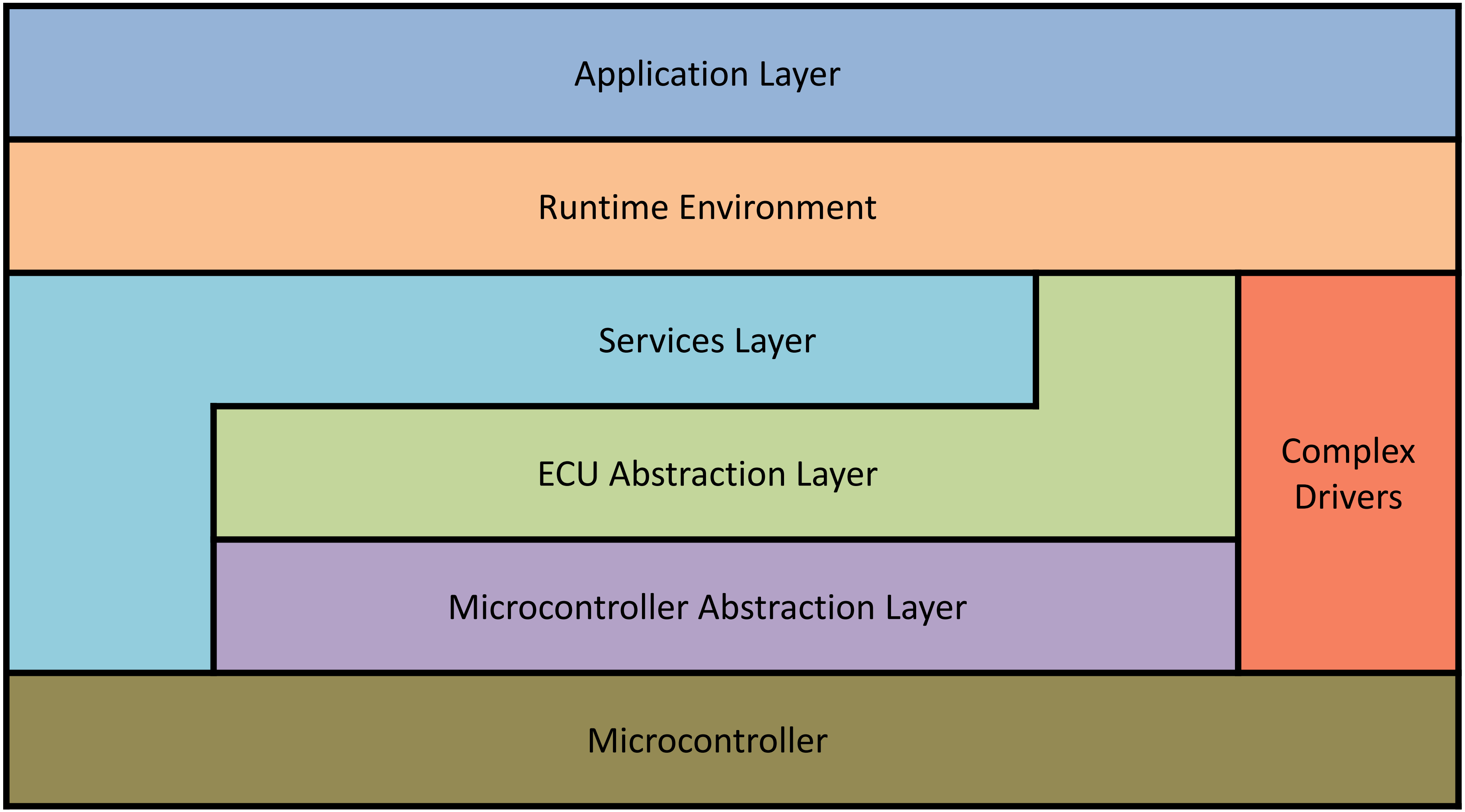
- AUTOSAR (*Automotive Open System Architecture*)
  Initiative of automobile manufacturers to make software development independent of operating system

- Mix and match of hardware and software
  - Integration at manufacturer
  - In-house development of software at manufacturer
  - Independence of/from OEM

AUTOSAR

- AUTOSAR Runtime Environment (RTE)
  - Middleware abstracting away from lower layers
- Application Software Components
  - Rely on strict interfaces, independent of MCU, Sensors, Actors

AUTOSAR



Application Layer
Runtime Environment
Services Layer
ECU Abstraction Layer
Microcontroller Abstraction Layer
Complex Drivers
Microcontroller

Main Takeaways

- ECUs
  - Principles
  - Architecture
  - Real-time properties (hard, firm, soft deadlines)
- OSEK/VDX
  - Motivation
  - Static configuration
  - Scheduling
- AUTOSAR
  - Motivation
  - Run Time Environment
  - Component Principle

Safety

Aspects of Safety

- Errors can lead to
  - material damage
  - bodily injury
- Check if errors might endanger human lives
  - Concerns not just systems for active safety (Airbag, ABS, ...)
  - Also concerns, e.g., engine ECU (sudden acceleration)
- Integral part of ECU development
  - “First and last step” when introducing new functionality

Aspects of Safety

- Terminology
  - Risk:
    - Quantitative measure of uncertainty
      <risk> = <occurrence probability> × <consequences>
  - Limit Risk:
    - Highest still acceptable risk
  - Safety:
    - Condition that does not exceed limit risk
      (cf. DIN VDE 31000, Part 2)

Aspects of Safety

- Terminology
  - Error:
    - Deviation of calculated, observed, or measured value from true, specified, or theoretical value
  - Fault:
    - DIN 40041: unpermitted deviation of one or more properties that allows the discrimination of machines or components
    - IEC 61508, Part 4: exceptional condition that might lead to a component no longer fulfilling (or only partly fulfilling) its function
  - Failure:
    - DIN 40041: Component ceases to function (within permissible use)
    - IEC 61508, Part 4: System ceases fulfilling the specified function
  - Malfunction:
    - (Potentially dangerous) consequence of failure
      - E.g., ABS: failure must not cause wheels to lock; instead: graceful degradation

Aspects of Safety

- Terminology
  - Functional Safety:
    - Subpart of safety that is reliant on correct function of safety relevant components (as well as external measures for reducing risk)
  - Reliability:
    - Probability that a component does not fail within a defined time window
  - Redundancy:
    - Duplication of components (where only one would be needed)
    - homogeneous redundancy:
      - components are identical
    - diverse redundancy:
      - components are not identical
    - E.g., dual circuit braking

Aspects of Safety

- Laws and Norms
  - Laws
    - minimum conditions (in the shape of general requirements)
    - no verification
    - but: product liability laws might require proof that development corresponds to state of the art
    - E.g., German Regulations Authorizing the Use of Vehicles for Road Traffic (StVZO)
  - Norms
    - e.g. RTCA DO-178B (ED-12B) for aeronautic software
    - IEC 61508: standard for the development of safety critical systems

Aspects of Safety

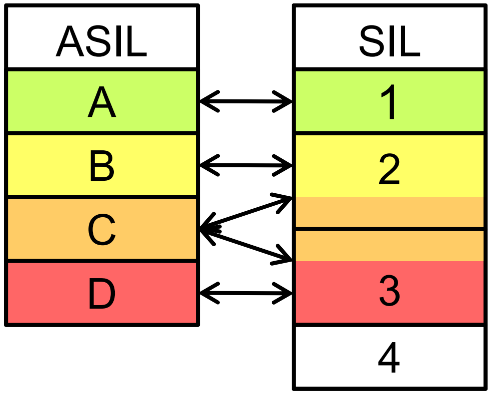
- IEC 61508
  - Two modes of operation
    - Low Demand Mode
    - High Demand Mode or Continuous Mode
  - Low Demand Mode
    - Safety critical system activated no more than twice per year (or maintenance interval)
    - Safety measures are passive (until needed)
    - E.g., airbag deployment on accident
  - High Demand Mode or Continuous Mode
    - Safety critical system activated more than twice per year (or maintenance interval)
    - Safety measures keep system within safety margins
    - E.g., ensure that airbag cannot misfire

Aspects of Safety

- IEC 61508
  - 4 Safety Integrity Levels (SIL)
    - Relate to safety measure, not complete system
    - Describes risk reduction by safety measure
    - SIL 4: highest demands
      system failure triggers catastrophic consequences
  - Process:
    - Damage and risk assessment
    - Determination of
      - Hardware Fault Tolerance (HFT)
      - Safety Failure Fraction (SFF)
    - Check if necessary SIL can be reached

Aspects of Safety

- ISO 26262
  - Adaption of IEC 61508 for automotive engineering
  - “Automotive 61508”
  - SIL ⇨ ASIL (Automotive Safety Integrity Level)



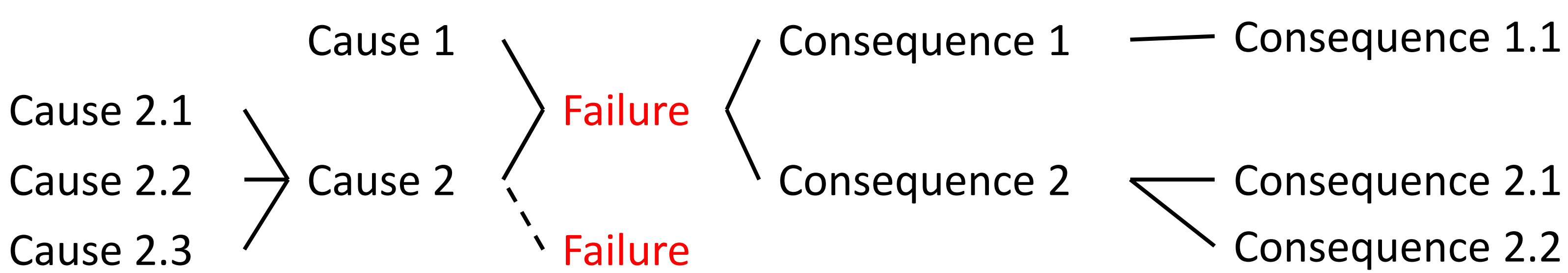
Aspects of Safety

- Methods for analyzing safety and reliability
  - Often rooted in aeronautic and space software development

- Covered in this lecture
  - Failure Mode Effect Analysis (FMEA)
    - Also called: Failure Mode Effect and Criticality Analysis (FMECA)
  - Fault Tree Analysis (FTA)
  - Event Tree Analysis (ETA)

Failure Mode Effect Analysis (FMEA)

- Step 1: list all possible failures
- Step 2: For each failure, list possible causes and consequences
  - Causes have causes
  - Consequences have consequences
  - Results in tree:



- Ex: FMEA for Yacht Autopilot
  - Cause: Wind sensor imprecise
    - ⇨ Failure: Wrong wind speed
      - ⇨ Consequence: Wrong drift calculation

Failure Mode Effect Analysis (FMEA)

- Step 3: transform tree to table
  - Risk priority number = Probability × Severity × Detectability

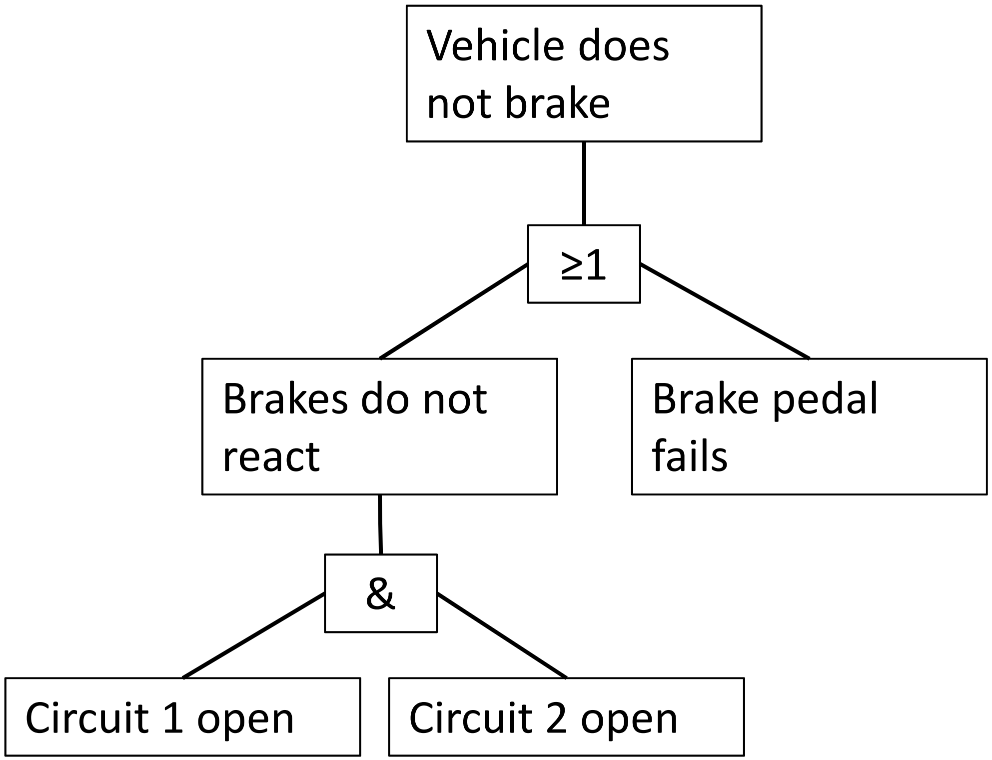
FMEA for Yacht Autopilot		Innsbruck, 2000-04-01			**Rating**				
Function	**Component**	**Failure**	**Consequence**	**Cause**	**P**	**S**	**D**	**RPN**	**Measures**
Lead ship from A to B	Determine position	Wrong position	Wrong course	Solar storms	1	5	1	5	
				GPS switched off	1	10	9	90	
				GPS precision reduced	1	5	9	45	
				GPS defective	1	10	9	90	
				GPS satellite defective	1	5	9	45	
	Determine wind speed	Wrong wind speed	Wrong drift calculation	Wind sensor imprecise	5	5	1	25	
			Wrong skipper warning	Wind changing too fast	10	9	5	450	
				Wind speed too low	10	9	5	450	
				Wind sensor gone	1	9	9	81	

Adapted from Kai Borgeest: “Elektronik in der Fahrzeugtechnik Hardware, Software, Systeme und Projektmanagement“ Vieweg/Springer, 2008

Fault Tree Analysis (FTA)

- DIN 25424-1,2
- Tree structure of causes
  - i.e., left half of FMEA
- Failures depend on causes
- Leafs: elementary causes
  (those that do not stem from other causes)
- Connect with logical OR/AND
- Logical OR (if one cause suffices)
  e.g., brake pedal fails ⇨ brake fails (even if other components ok)
- Logical AND
  e.g., dual circuit brake (both circuits have to fail)

Fault Tree Analysis (FTA)



Adapted from Kai Borgeest: "Elektronik in der Fahrzeugtechnik Hardware, Software, Systeme und Projektmanagement" Vieweg/Springer, 2008

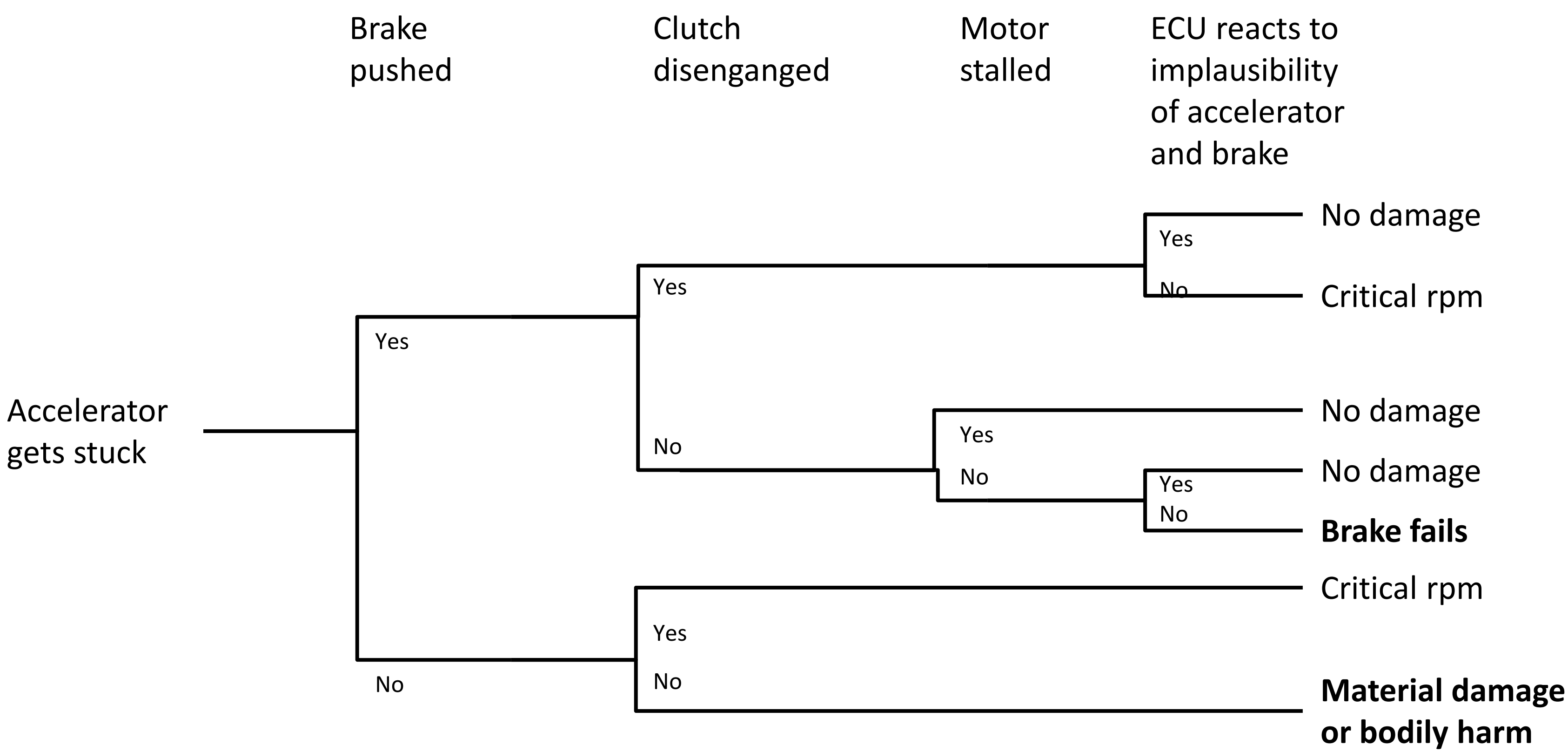
Fault Tree Analysis (FTA)

- Qualitative representation as tree
- Quantitative calculation:
  - OR for exclusive events:
    - $p(c) = p(a) + p(b)$
  - OR for arbitrary events:
    - $p(c) = p(a) + p(b) - p(a \times \mathrm{b})$
  - AND for independent events:
    - $p(c) = p(a) \times p(b)$
  - AND for dependent events:
    - $p(c) = p(a) + p(b|a)$
  - Difficulty: How probable are elementary events?

Event Tree Analysis (ETA)

- Analyzes consequences of faults
  (even if safety measures do not trigger)
- Process:
  - Start with individual fault
  - Fork, depending on which safety measures trigger
  - Multiple endings if more than one safety measure is in place
  - Results in tree of possible consequences
  - Limited quantitative analysis: hard to assign numbers to forks

Event Tree Analysis (ETA)



Adapted from Kai Borgeest: “Elektronik in der Fahrzeugtechnik Hardware, Software, Systeme und Projektmanagement“ Vieweg/Springer, 2008

Main Takeaways

- Aspects of Safety
  - Motivation
  - Terminology
  - Failure Mode Effect Analysis (FMEA)
  - Fault Tree Analysis (FTA)
  - Event Tree Analysis (ETA)
  - Commonalities and differences

Part 2

Car-to-X Networking

Car-to-X (C2X) communication patterns

- Vehicle-to-X (V2X),
- Inter-Vehicle Communication (IVC),
- Vehicular ad-hoc network (VANET),
- …

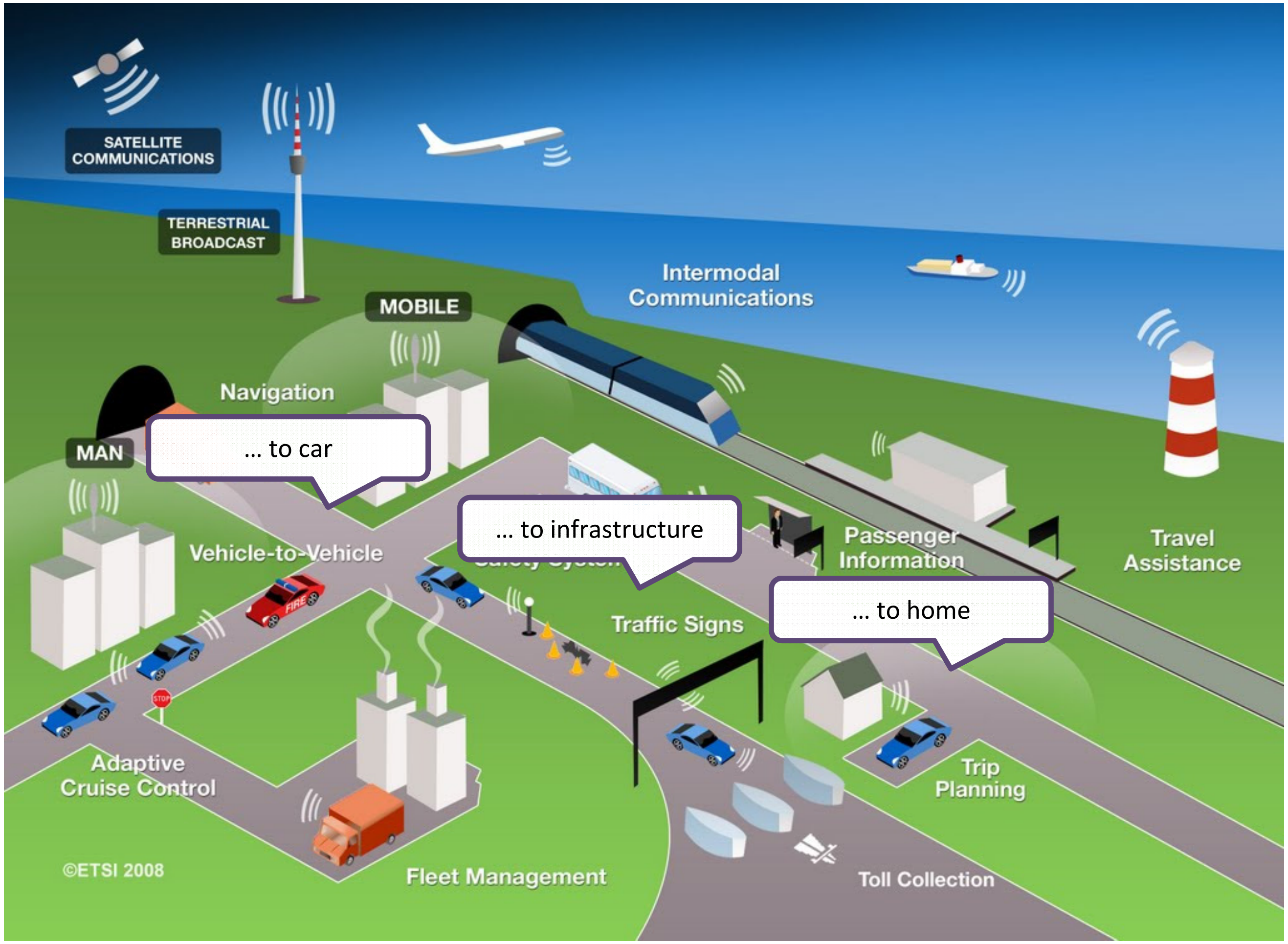
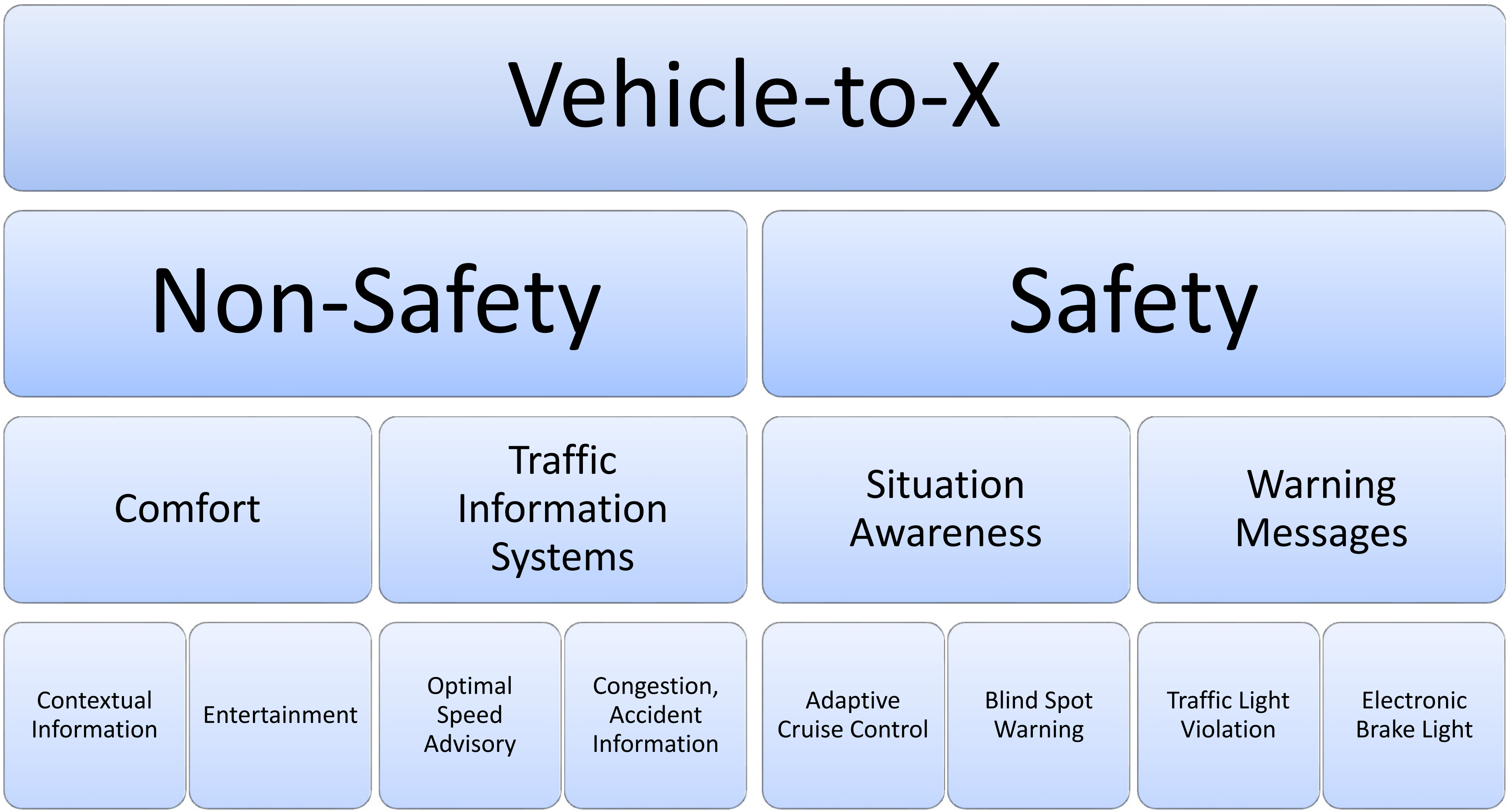


Illustration: ETSI

Use Cases

Illustration: CVIS

Taxonomy of Use Cases



Taxonomy of Use Cases

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 use cases

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

Application	Latency	Reliability	# Vehicles	Area	Persistence
Information Query	★	★	★★★	★★★	
Hazard Warning	★★★	★★	★★	★★★	
ACC, el. 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

- Numerous field operational tests
  - sim^TD (€ 69M), Aktiv (€ 60M), Smart Highway (€ 57M), Drive C2X (€ 19M), TeleFOT (€ 15M), SafeTrip (€ 10M), …
- Dedicated spectrum in U.S., Europe, Asia

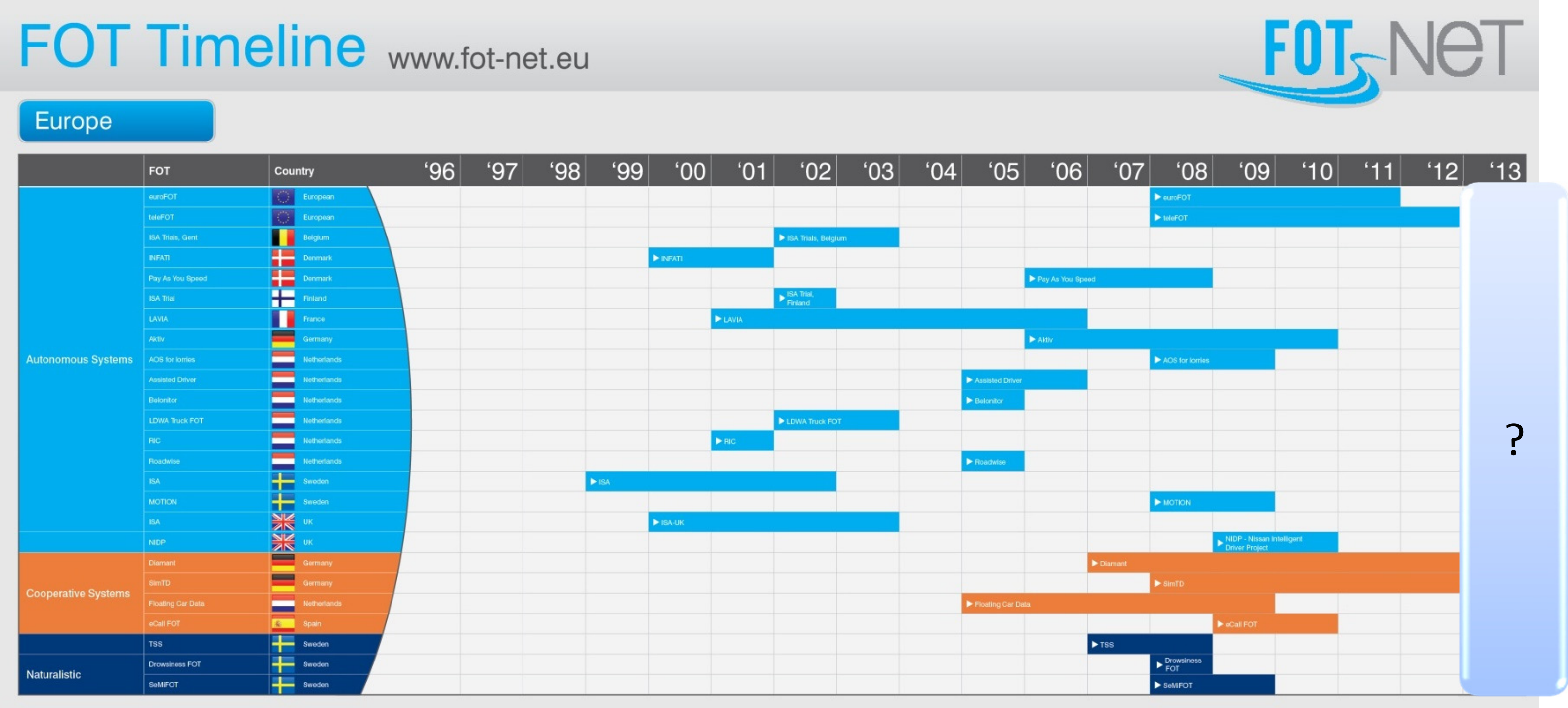
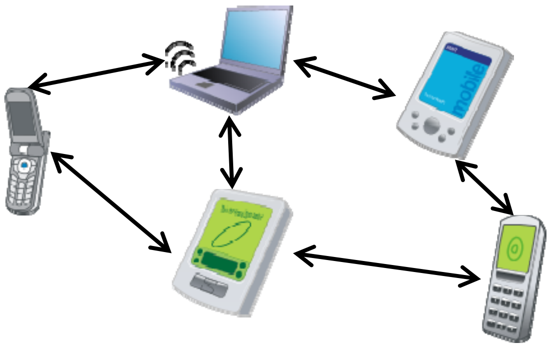
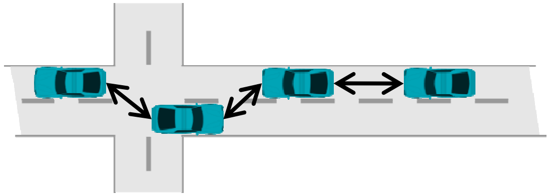


Illustration: FOT-NET Wiki

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, ...





[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
- …

Source: AKTIV CoCar

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

Adoption

- Prognosis (of providers!) in Germany and the U.S.
  - 14..15 years to 100% market penetration
- Compare to navigation systems in German cars
  - 13 years to 14% market penetration
  - And: it is very easy to retrofit a satnav!

[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

[2] Ulrich Dietz (ed.), “CoCar Feasibility Study: Technology, Business and Dissemination,” CoCar Consortium, Public Report, May 2009.

[3] Verband der Automobilindustrie e.V., “Auto 2007 – Jahresbericht des Verbands der Automobilindustrie (VDA), “, July 2007.

Challenges of C2X communication

Communication	• Highly varying channel conditions • High congestion, contention, interference • Tightly limited channel capacity
Networking	• Unidirectional Links • 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 • Heterogeneous user base

Technology

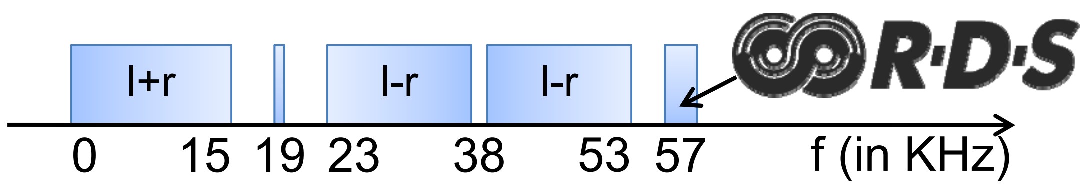
Communication paradigms and media

- **Wireless Communication Technologies**
  - **Infrastructure-based**
    - Broadcast
      - FM Radio, DAB/DVB, …
    - Cellular
      - GSM
2G Cellular
      - UMTS
3G Cellular
      - LTE / WiMAX
4G Cell.
  - **Infrastructureless**
    - 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

- Traffic Message Channel (TMC)
  - Contents (ALERT-C coded):
    - Validity period
    - Re-routing required?
    - North-east or south-west?
    - Spatial extent
    - Code in event table
      - International
    - Code in location table
      - Country/region specific
      - Must be installed in end device
  - No (real) security measures

101	Standing traffic (generic)
102	1 km of standing traffic
103	2 km of standing traffic
394	Broken down truck
1478	Terrorist incident

1	Deutschland
264	Bayern
12579	A8 Anschlussstelle Irschenberg

[1] ISO 14819-1, „Traffic and Traveller Information (TTI) - TTI messages via traffic message coding - Part 1: Coding protocol for Radio Data System (RDS-TMC) using ALERT-C“

[2] ISO 14819-2, „Traffic and Traveller Information (TTI) - TTI messages via traffic message coding - Part 2: Event and information codes for Radio Data System - Traffic Message Channel (RDS-TMC)“

Broadcast Media

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

  - Ex: 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, neuronal networks
      - Early warnings of predicted events
    - Restricted to major roads

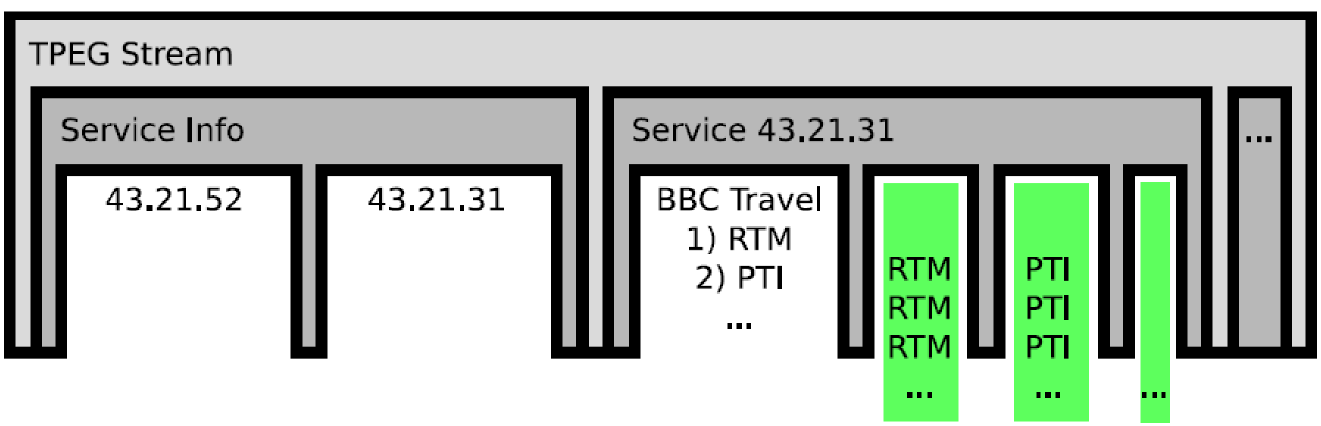
Broadcast Media

- Transport Protocol Experts Group (TPEG)
  - Planned successor of RDS-TMC/Alert-C
  - Published April 2000
  - Principles:
    - Extensibility
    - Media independence
  - Goals:
    - Built for "Digital Audio Broadcast" (DAB)
    - Unidirectional, byte oriented stream
    - Modular concept
    - Hierarchical approach
    - Integrated security

[1] ISO 18234-x, „Traffic and Travel Information (TTI) — TTI via Transport Protocol Experts Group (TPEG) data-streams"

Broadcast Media

- 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:



Transport Protocol Experts Group (TPEG)

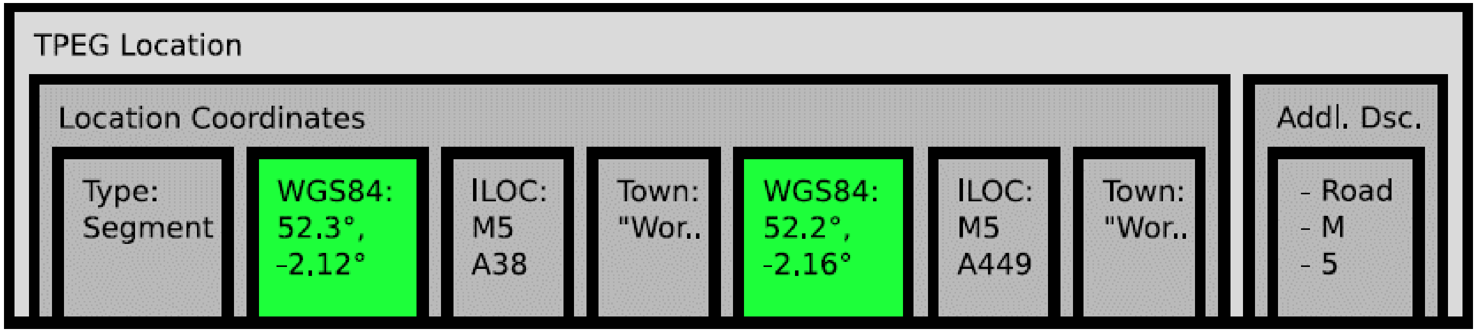
- tpegML: XML variant of regular (binary) TPEG

```
<?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)“

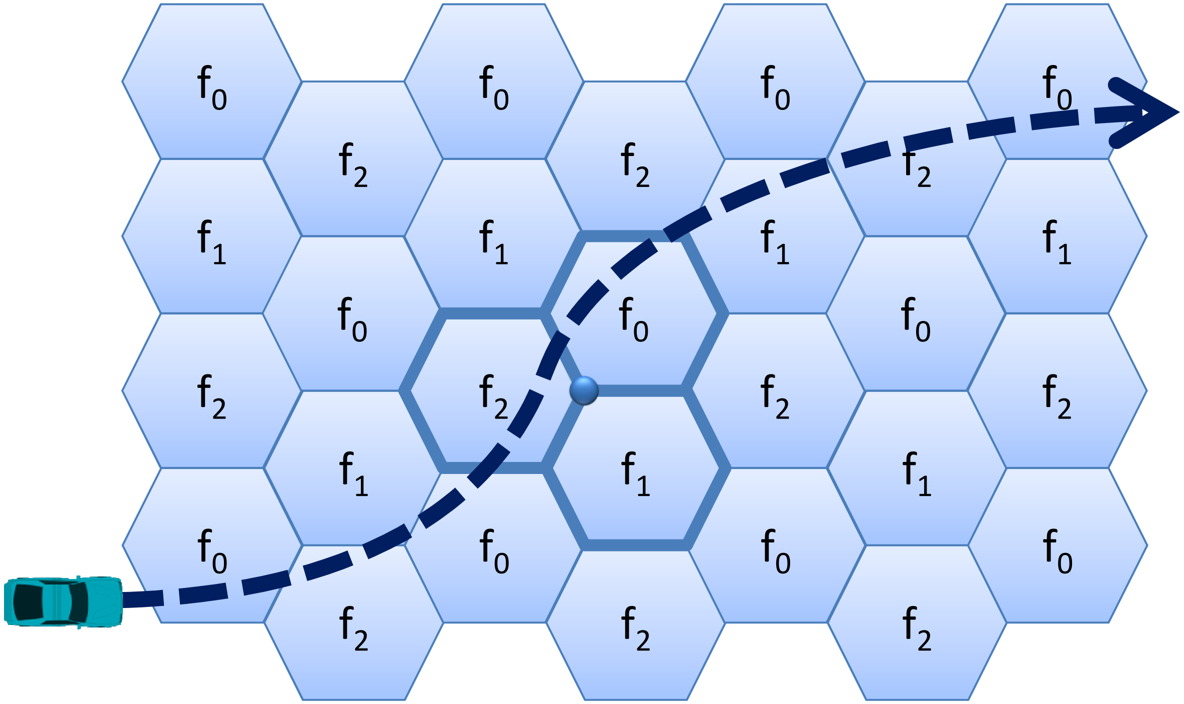
Transport Protocol Experts Group (TPEG)

- 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



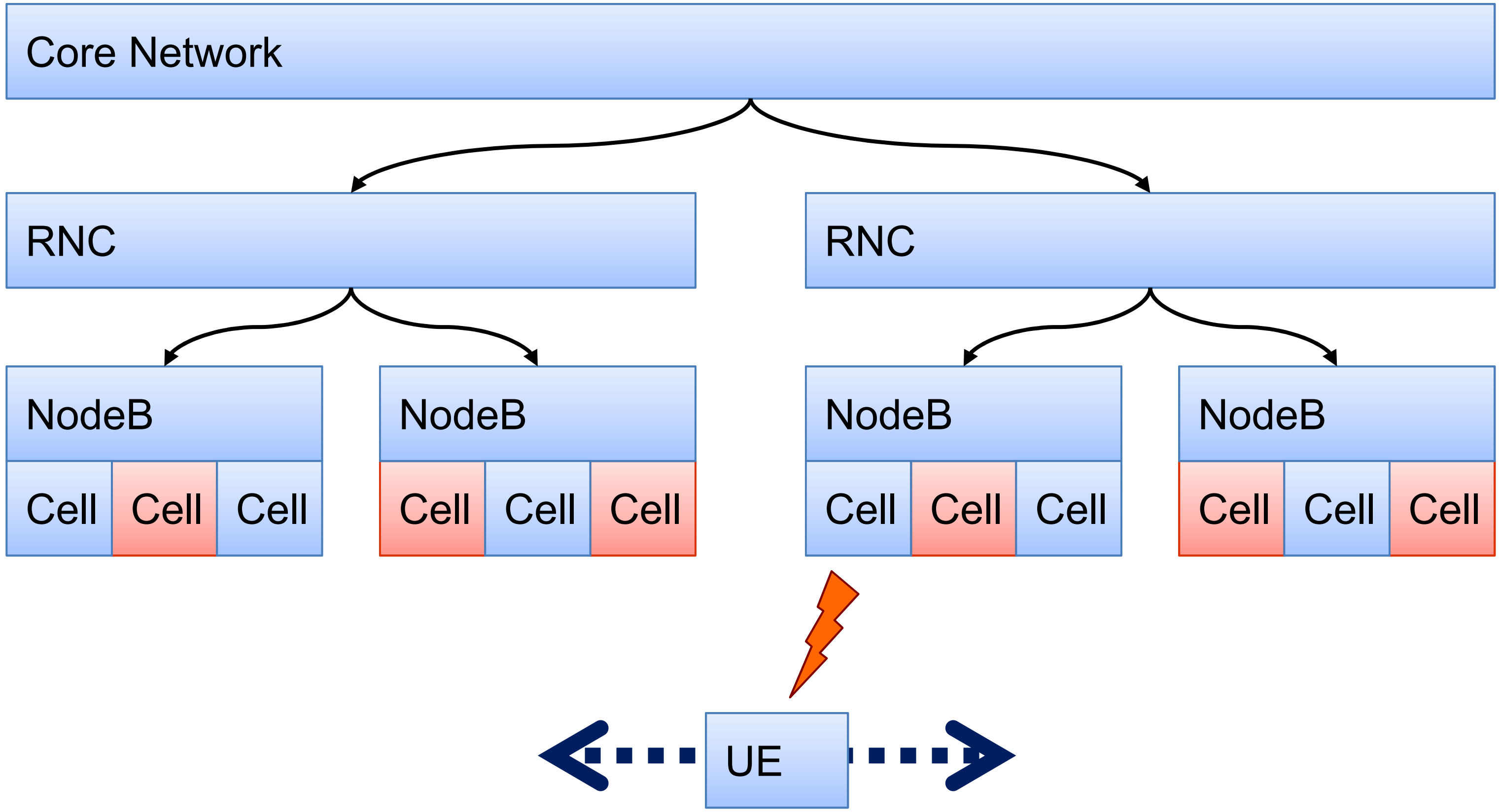
Cellular Networks

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



Concept

- Strict hierarchy of network components



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 (⇨ 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

- 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

Cellular Networks

- 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

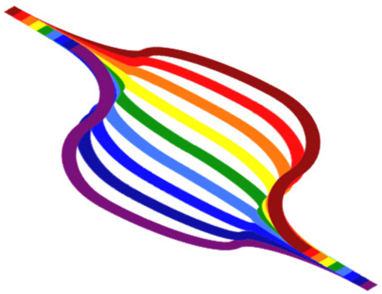
Cellular Networks

- 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)

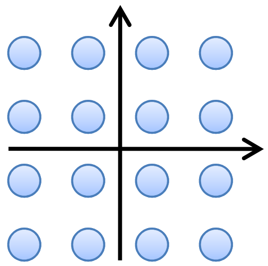
IEEE 802.11p

- 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
  - No integral within-network security
  - (Massively) shared spectrum (⇨ ISM)
  - No integral QoS
  - Multi-path effects reduce range and speed

IEEE 802.11p

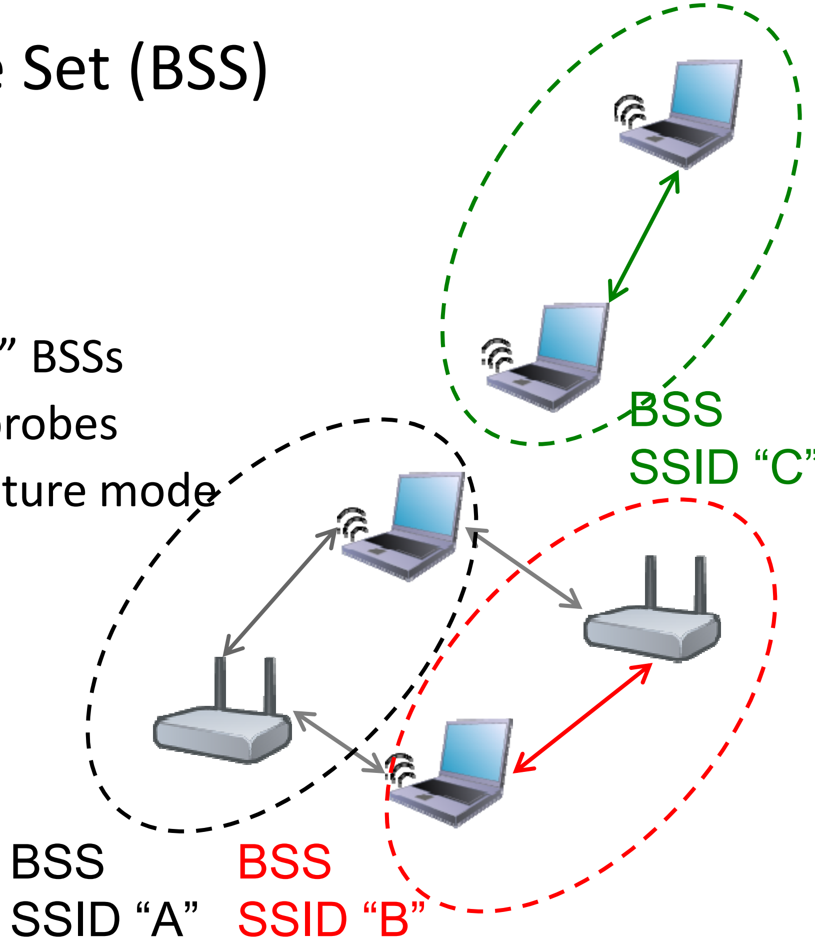


- IEEE 802.11p
  - PHY layer mostly identical to IEEE 802.11a
    - Variant with OFDM and 16 QAM
    - Higher demands on tolerances
    - Reduction of inter symbol interference because of multi-path effects
      - Double timing parameters
      - Channel bandwidth down to 10 MHz (from 20 MHz)
      - 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
    - ...



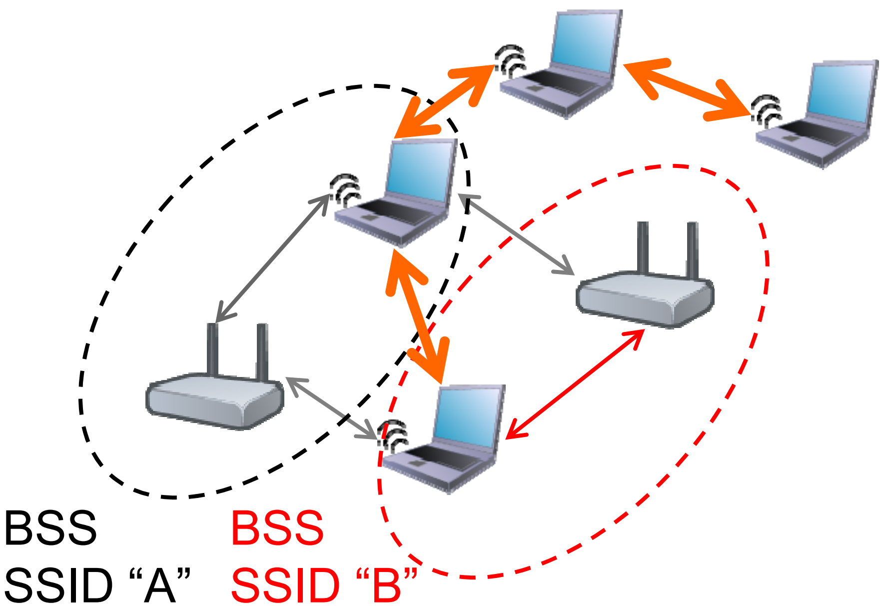
IEEE 802.11p

- 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

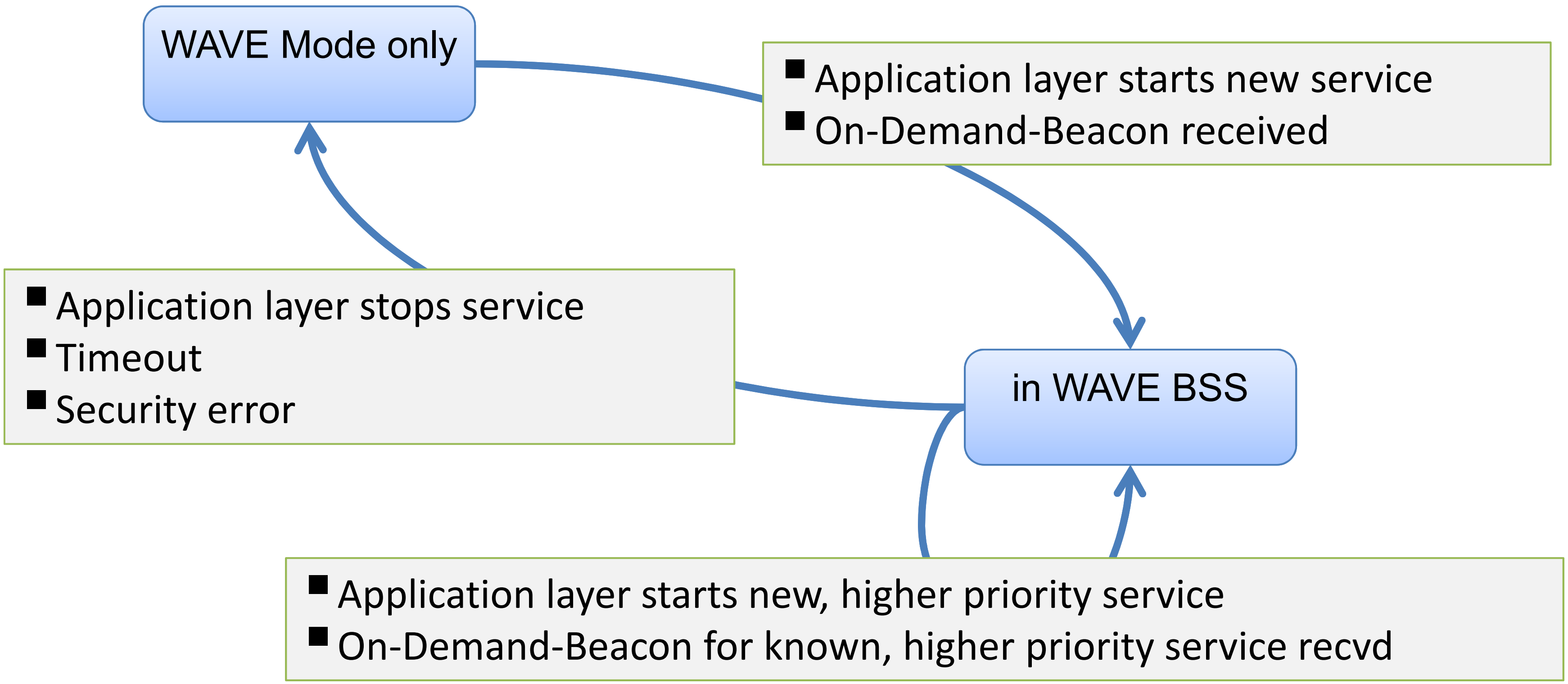


IEEE 802.11p

- New: 802.11 WAVE BSS
  - No strict separation between Host and Access Point (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 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

WAVE BSS Internal state machine

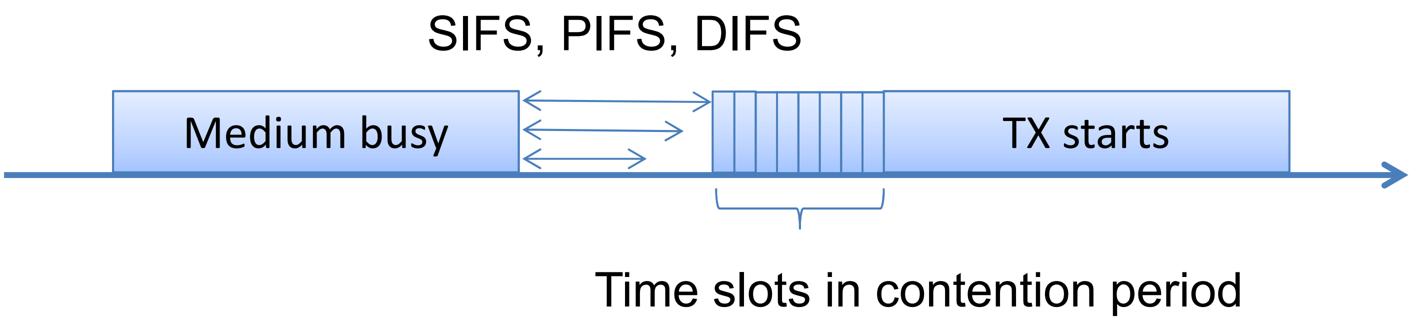
- Node will not join more than one WAVE BSS



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

IEEE 802.11p

- 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

IEEE 802.11p

- 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

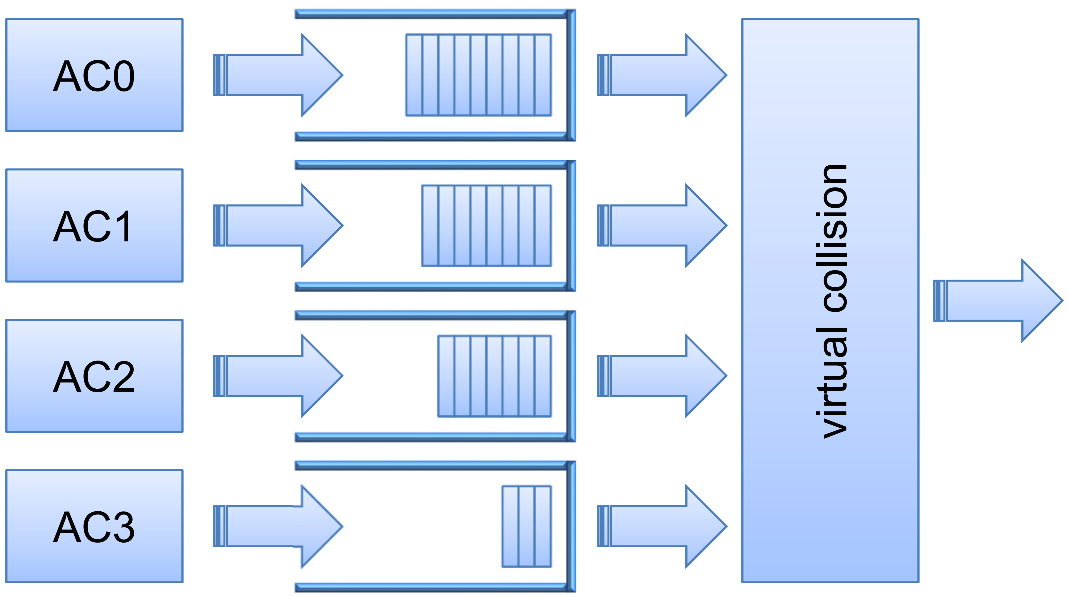
  - Backoff: Random slot count from interval [0, CW]
  - Decrement by one after channel was idle for one slot (only in contention period)
  - In cases b) and c), double CW (but no larger than CW_{max})
  - In case d), set CW to CW_{min}

IEEE 802.11p

- 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



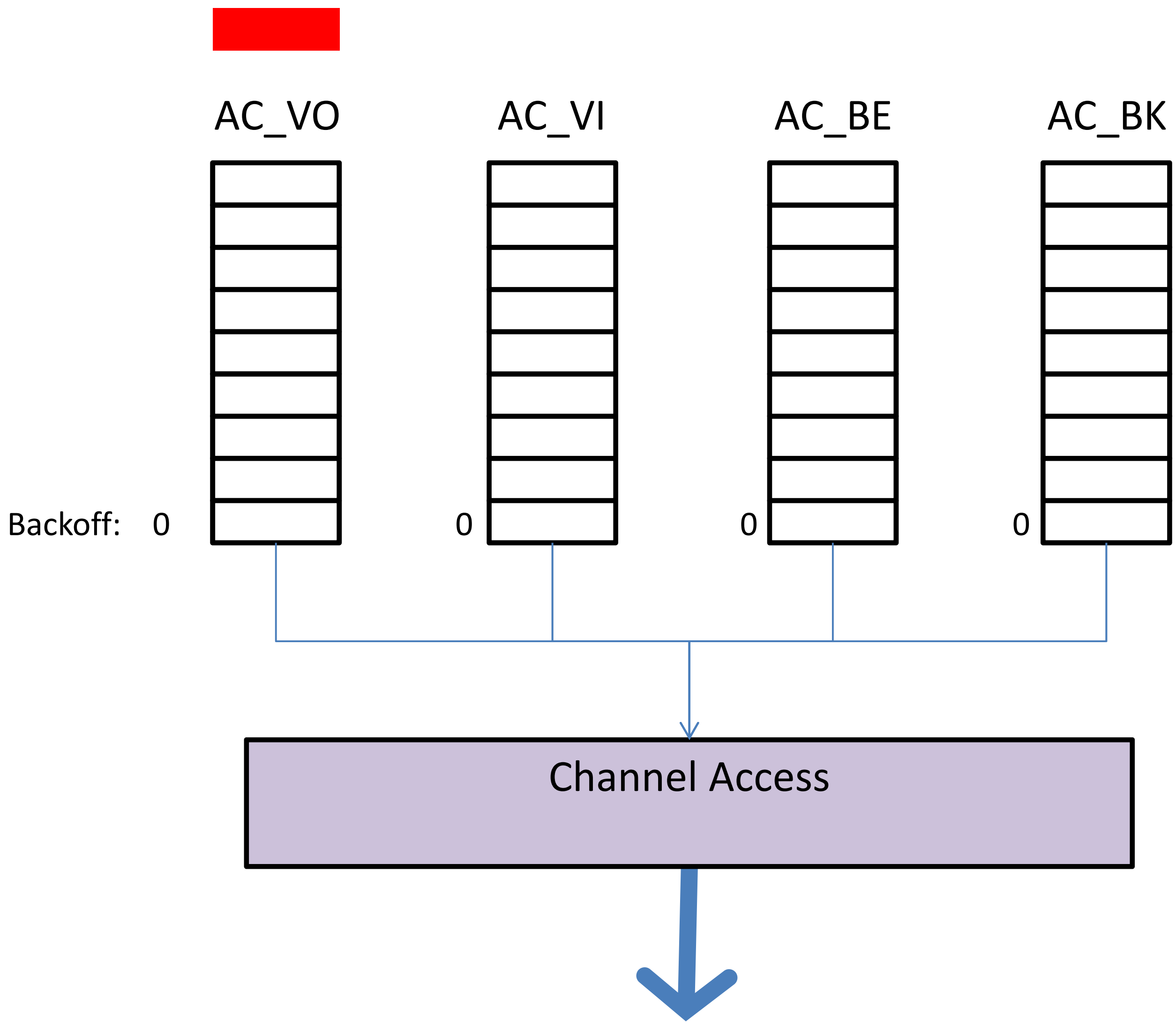
IEEE 802.11p

- QoS in 802.11p (HCF)
  - Parameterization

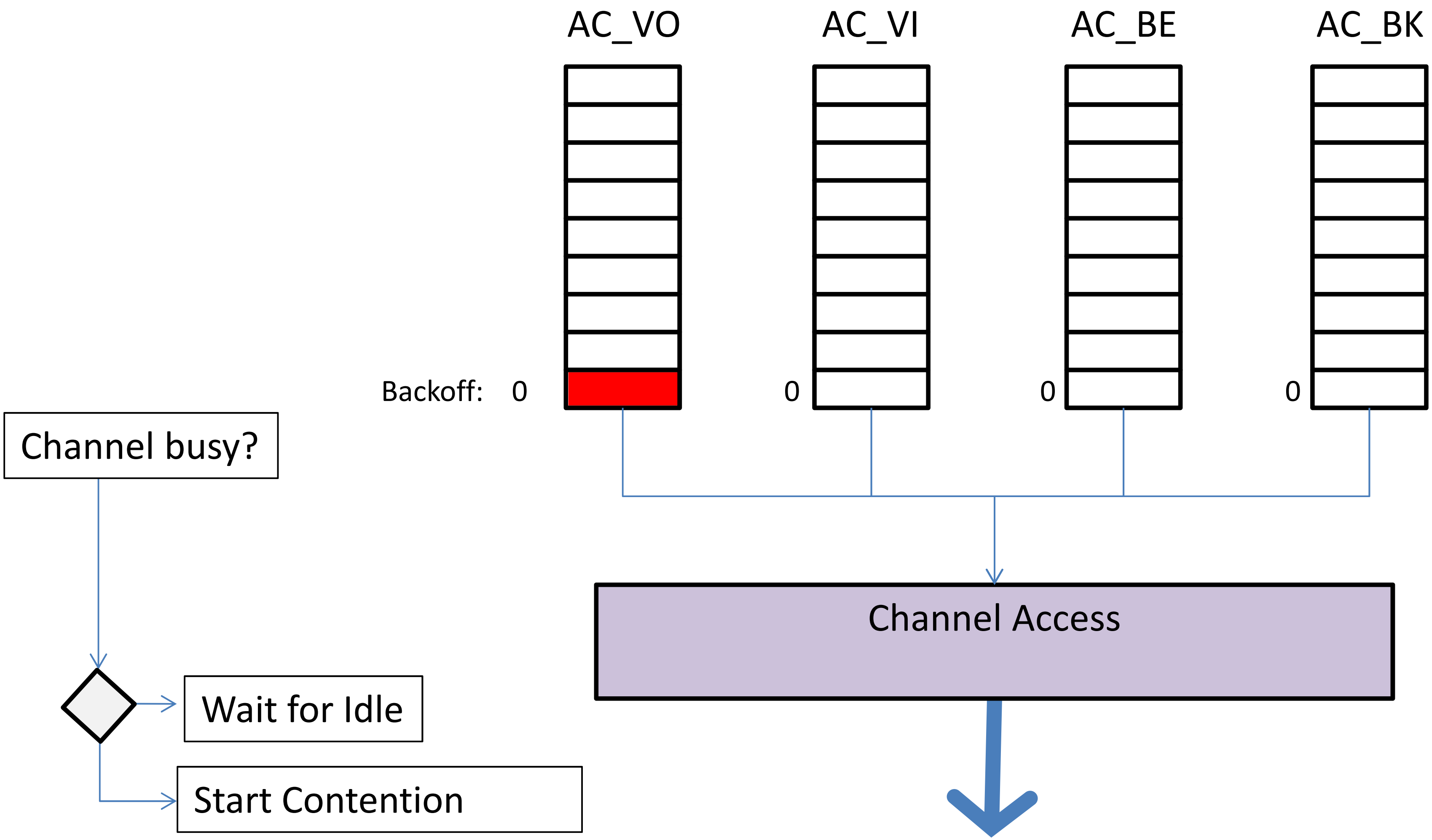
Parameter	Value
SlotTime	13µs
SIFS	32µs
CW_{min}	15
CW_{max}	1023
Bandwidth	3 .. 27 mbit/s

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

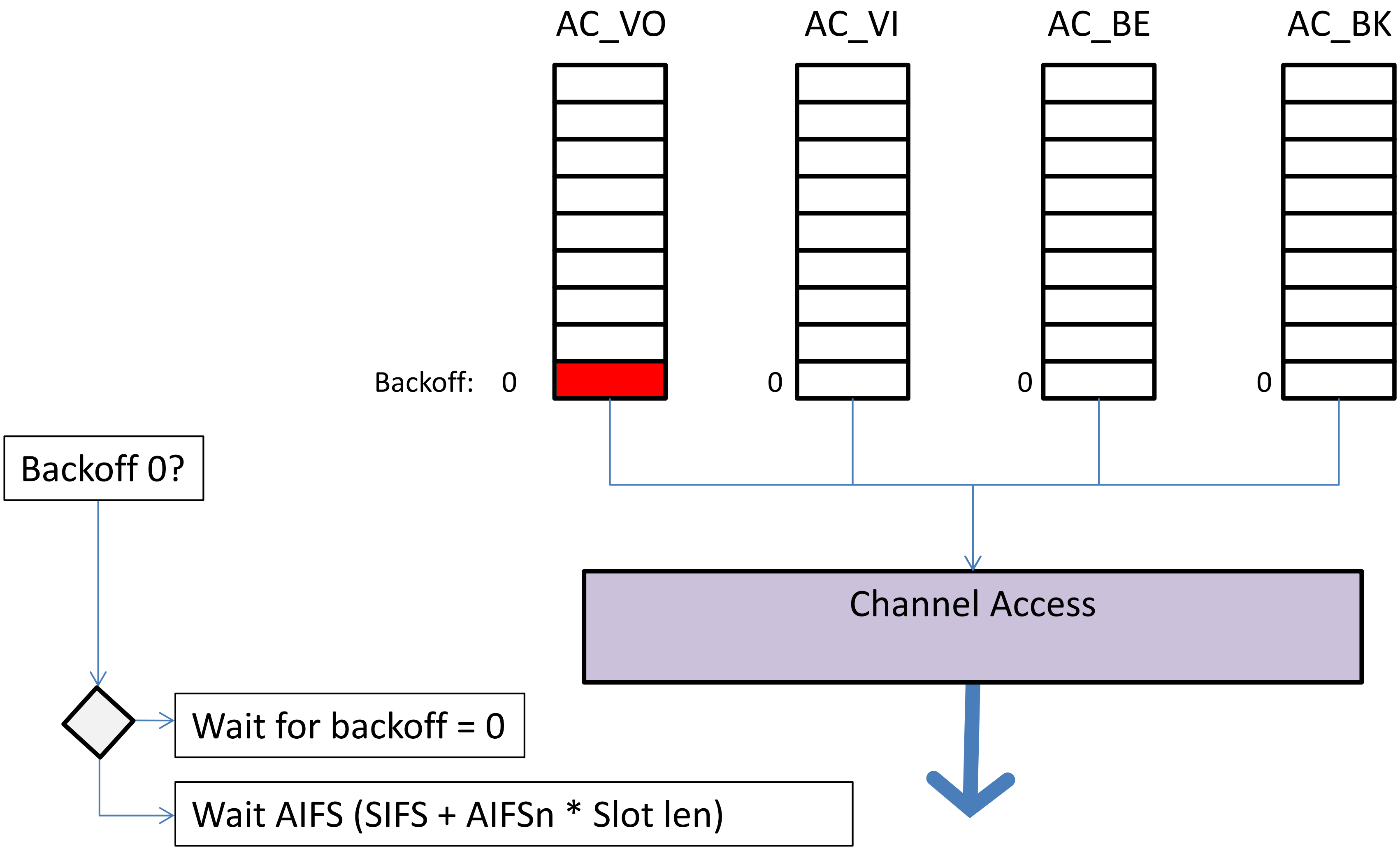


IEEE 802.11p

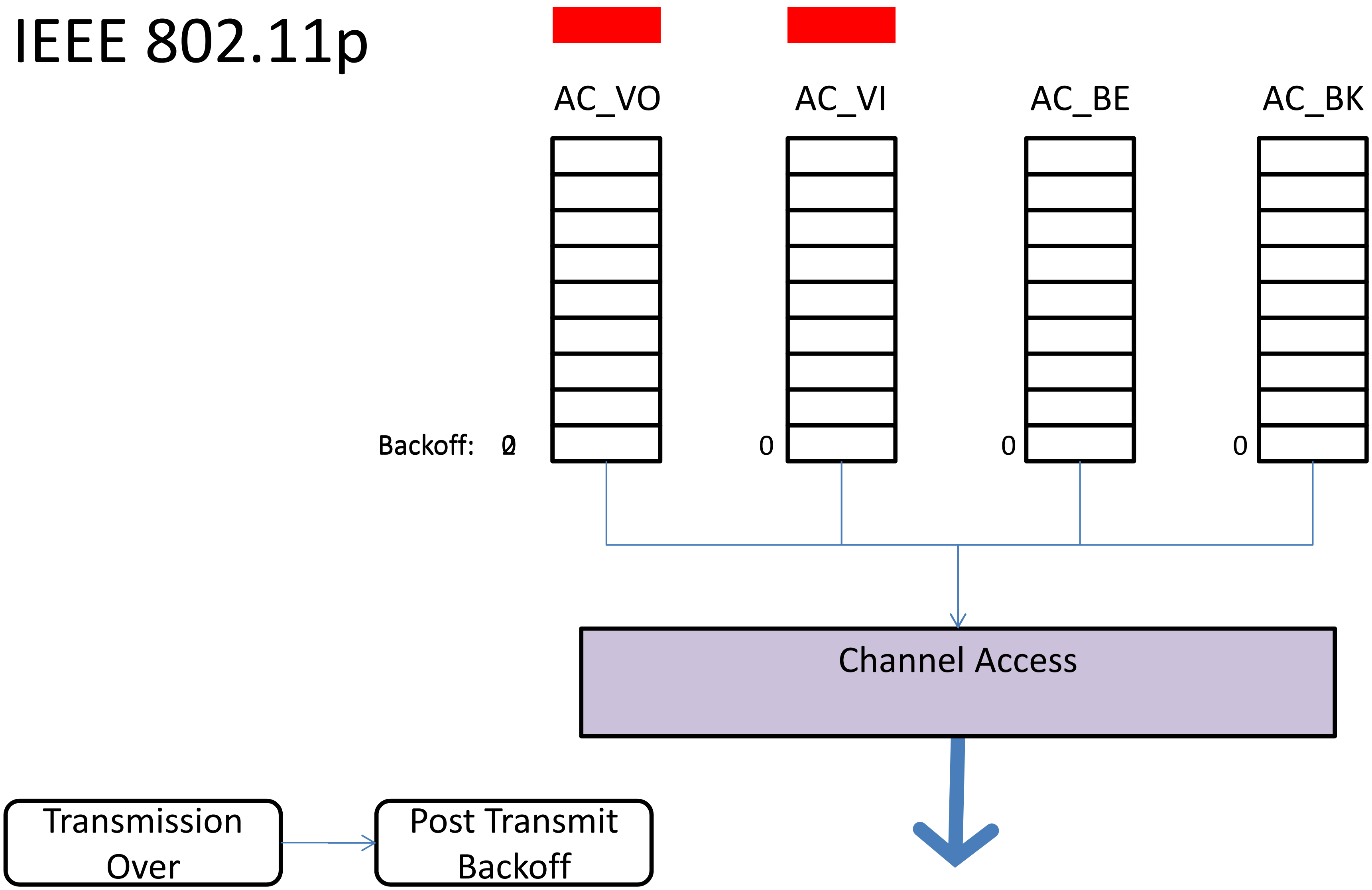


AC_VO
AC_VI
AC_BE
AC_BK
Backoff: 0
0
0
0
Channel busy?
Wait for Idle
Start Contention
Channel Access

IEEE 802.11p

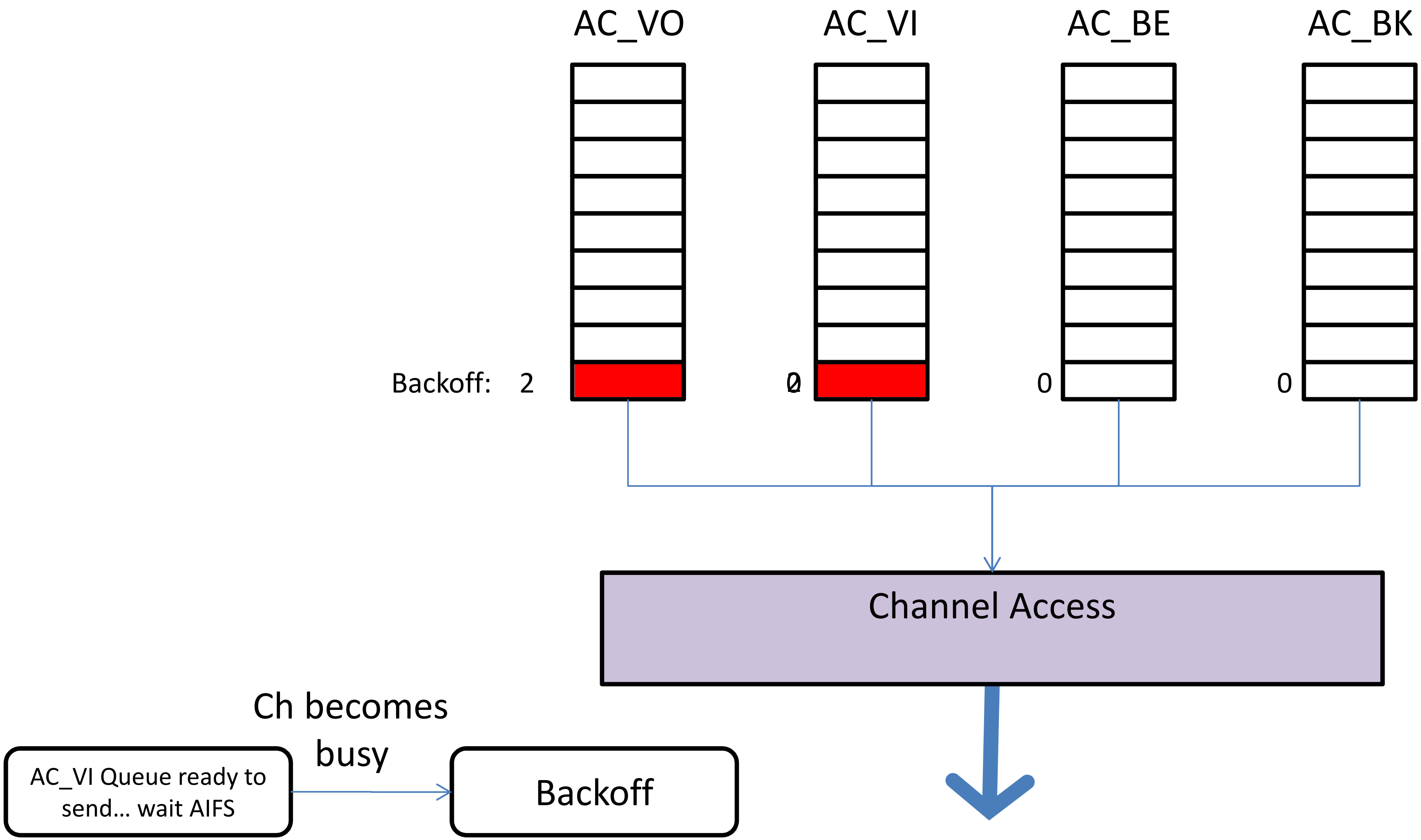

AC_VO
AC_VI
AC_BE
AC_BK
Backoff: 0
0
0
0
Backoff 0?
Channel Access
Wait for backoff = 0
Wait AIFS (SIFS + AIFSn * Slot len)

IEEE 802.11p

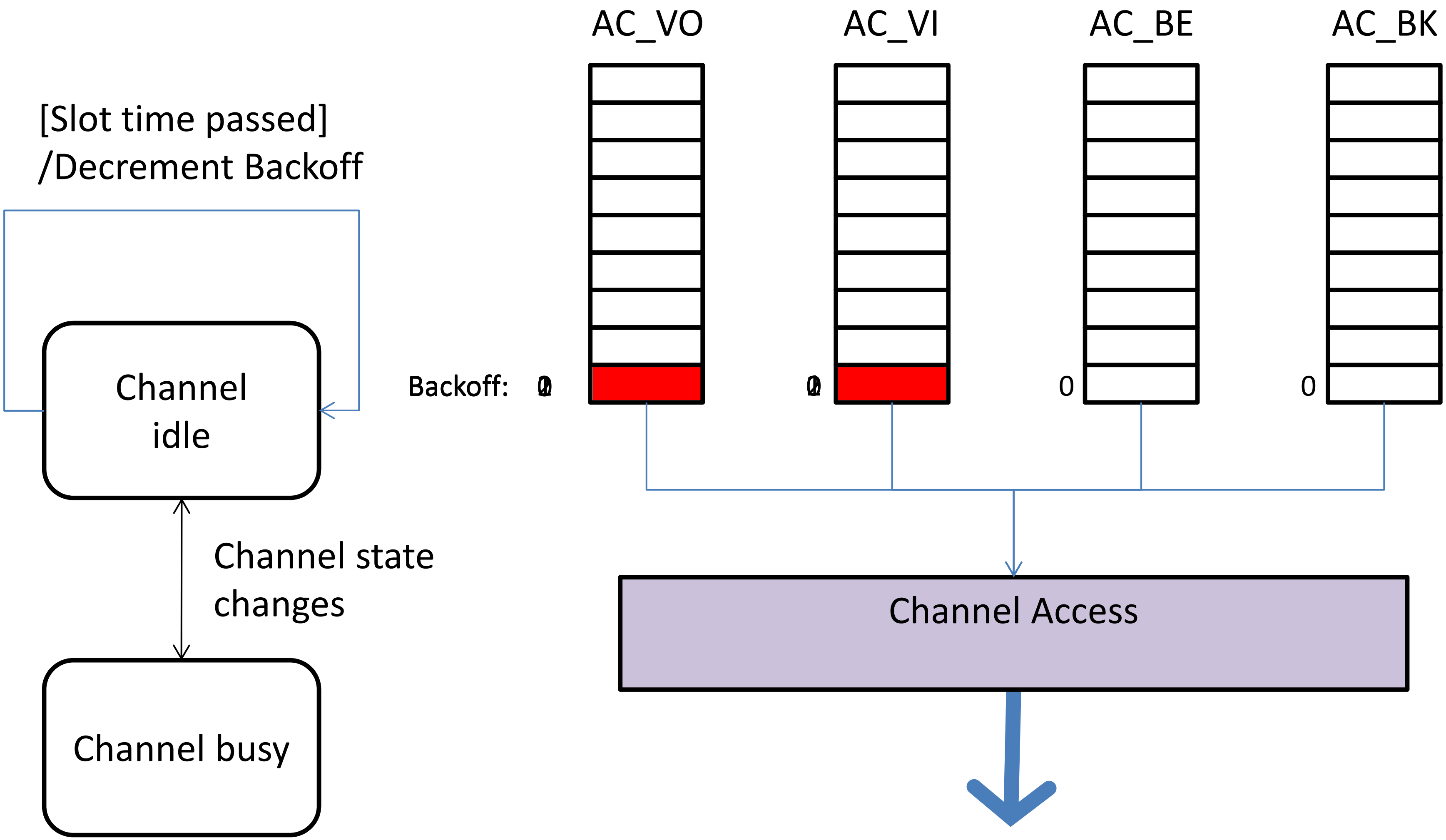


AC_VO
AC_VI
AC_BE
AC_BK
Backoff: 2
0
0
0
Channel Access
Transmission Over
Post Transmit Backoff

IEEE 802.11p

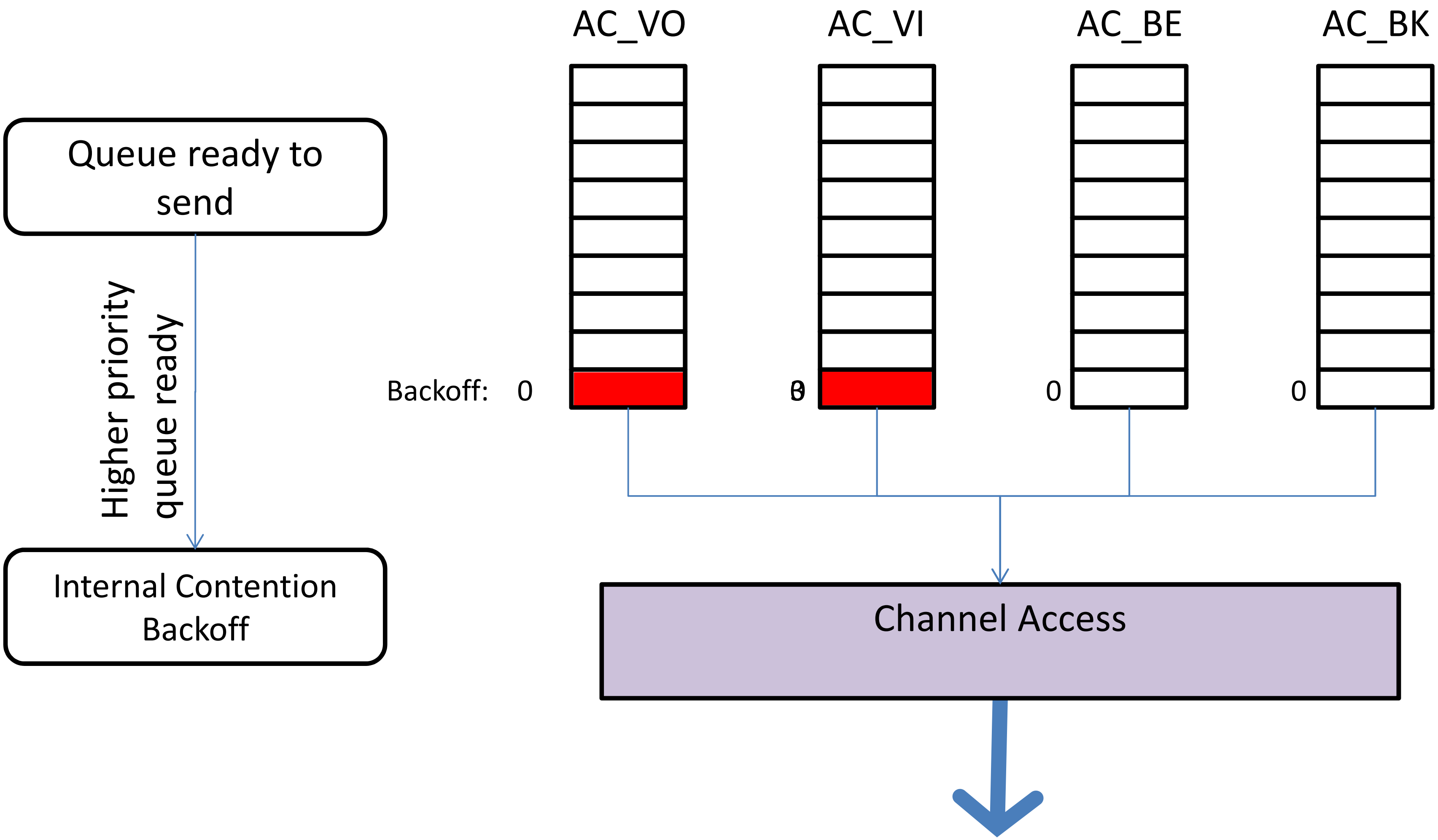

AC_VO
AC_VI
AC_BE
AC_BK
Backoff: 2
0
0
Channel Access
Ch becomes busy
AC_VI Queue ready to send… wait AIFS
Backoff

IEEE 802.11p



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

IEEE 802.11p

- QoS in WAVE
  - mean waiting time for channel access, given sample configuration (and TXOP Limit=0 ⇨ single packet)
  - when channel idle:
  - when channel busy:

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

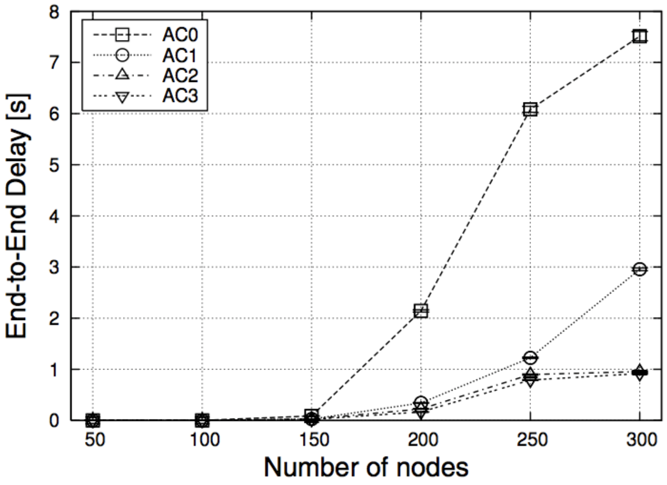


Figure Source: Eichler, S., "Performance evaluation of the IEEE 802.11p WAVE communication standard," Proceedings of 66th IEEE Vehicular Technology Conference (VTC2007-Fall), Baltimore, USA, October 2007, pp. 2199-2203

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 (⇨ 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 Standards: CALM

- Mixed-media communication
  - „Communications access for land mobiles“
  - ISO TC204 Working Group 16
  - Initiative to transparently use best possible medium
  - Integrates:
    - GPRS, UMTS, WiMAX
    - Infrared, Millimeter Wave
    - 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

- 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”)
      - 2 reserved channels, 1+4 channels for applications
    - ETSI Europe reserves 5 channels of 10 MHz

U.S. allocation	…	Critical Safety of Life	SCH	SCH	Control Channel (CCH)	SCH	SCH	Hi-Power Public Safety	…
European allocation		SCH	SCH	SCH	SCH	CCH	SCH	SCH	
IEEE Channel		172	174	176	178	180	182	184	
Center frequency		5.860 GHz	5.870 GHz	5.880 GHz	5.890 GHz	5.900 GHz	5.910 GHz	5.920 GHz	

[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

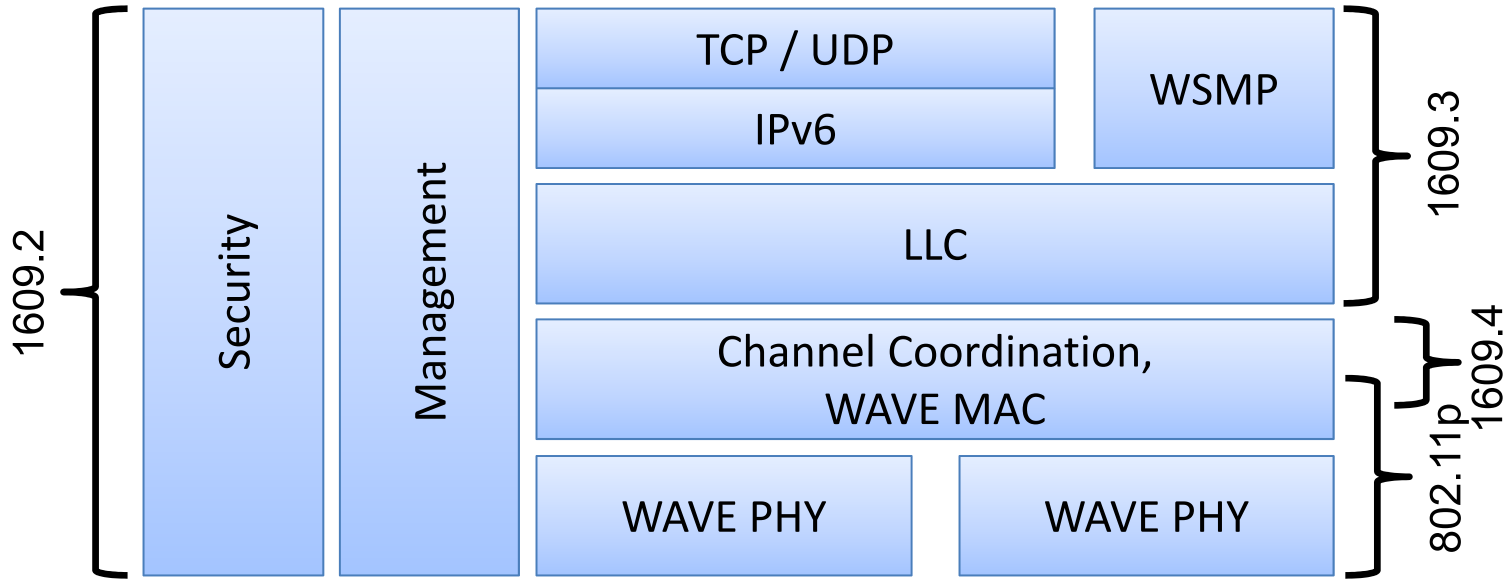
- Need for higher layer standards
  - Unified message format
  - Unified interfaces to application layer

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

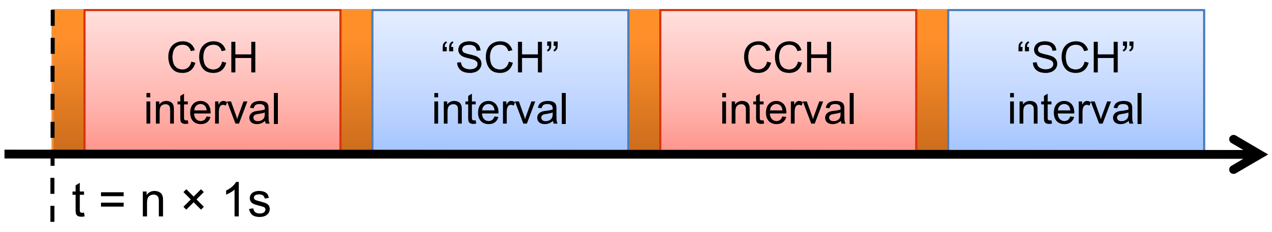


[1] Jiang, D. and Delgrossi, L., "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," Proceedings of 67th IEEE Vehicular Technology Conference (VTC2008-Spring), Marina Bay, Singapore, May 2008

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

IEEE 1609

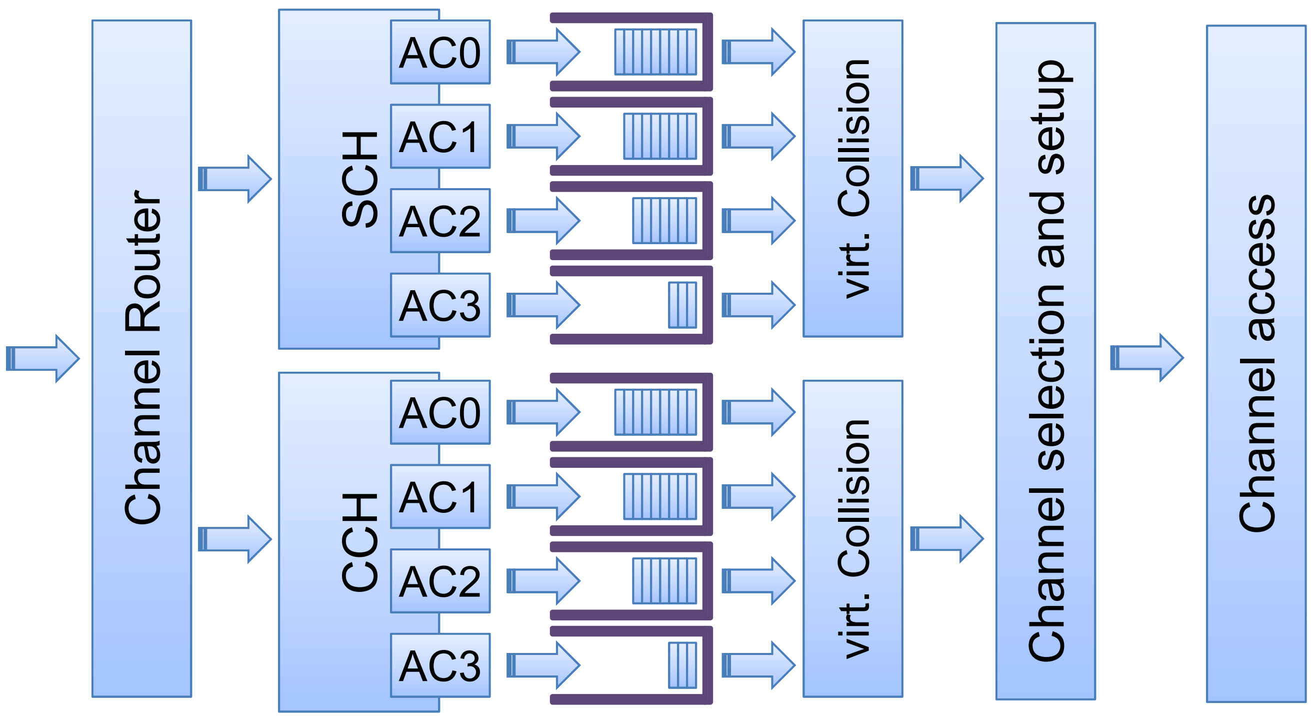
- Channel management
  - WAVE allows for both single radio devices & multi radio devices
  - Dedicated Control Channel (CCH) for mgmt and safety messages
    ⇨ single radio devices need to periodically listen to CCH
  - Time slots
    - Synchronization envisioned via GPS receiver clock
    - Standard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

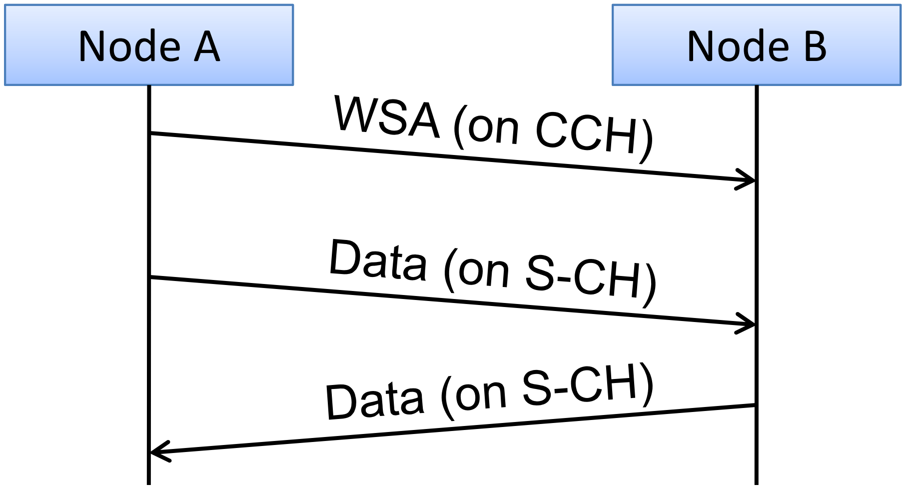


IEEE 1609

- Channel management
  - Control Channel (CCH):
    - Default channel upon initialization
    - WAVE service advertisements (WSA),
      WAVE short messages (WSM)
    - 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

- 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

- 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

- 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

IEEE 1609

- 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

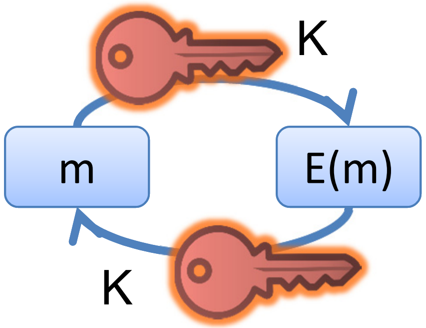
IEEE 1609

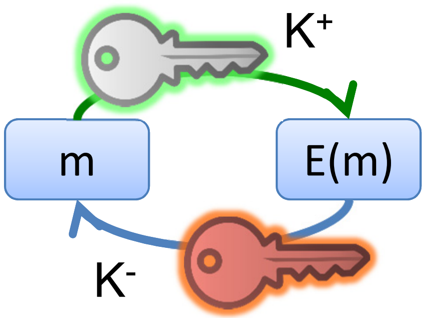
- Security in WAVE
  - Nature of WAVE messages mandates trust between nodes
    - Ex: Green wave for emergency vehicles
  - Security is built into WAVE (IEEE 1609.2)
  - WAVE can transparently sign, verify, encrypt/decrypt messages when sending and receiving
    - Ex: WSA → Secure WSA
  - Authorization 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
    - By time

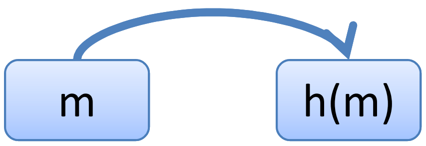
[1] IEEE Vehicular Technology Society, "**IEEE 1609.2 (Security Services)**," IEEE Std, July, 2006

IEEE 1609

- Security concepts
  - Basic security goals
    - Integrity, Confidentiality, Authenticity
    - Non-Repudiation
  - Mechanisms
    - Symmetric encryption
      - Secret Key Cryptography
      - Ex: Caesar cipher, Enigma, AES
    - Asymmetric encryption
      - Public Key Cryptography
      - Ex: RSA, ElGamal, ECC
    - (cryptographic) hashing
      - Ex: MD5, SHA-1

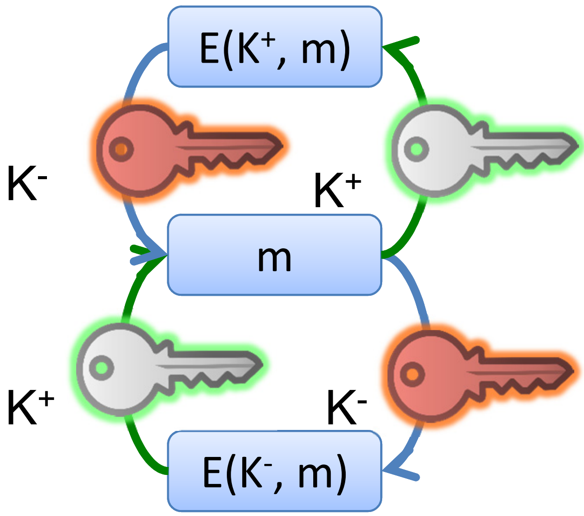






IEEE 1609

- 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

- Asymmetric Cryptography Example: RSA
  - Chose two primes: q, p with q != p
  - Calculate $n = p \cdot q$
  - Calculate $\phi(n) = (p - 1) \cdot (q - 1)$

    $\phi(x)$ gives number of (smaller) co-primes for x.

    Based on $\phi(a \cdot b) = \phi(a) \cdot \phi(b) \cdot (d/\phi(d))$ with $d = \gcd(a, b)$

    If x is prime, this is $x - 1$.
  - Choose e co-prime to $\phi(n)$ with $1 < e < \phi(n)$
  - Calculate d using EEA, so that $e \cdot d \bmod \phi(n) = 1$
  - Public Key: $K^+ = \{e, n\}$, Private Key: $K^- = \{d, n\}$.
  - En/Decryption:

    $M^e \bmod n = C$

    $C^d \bmod n = M$

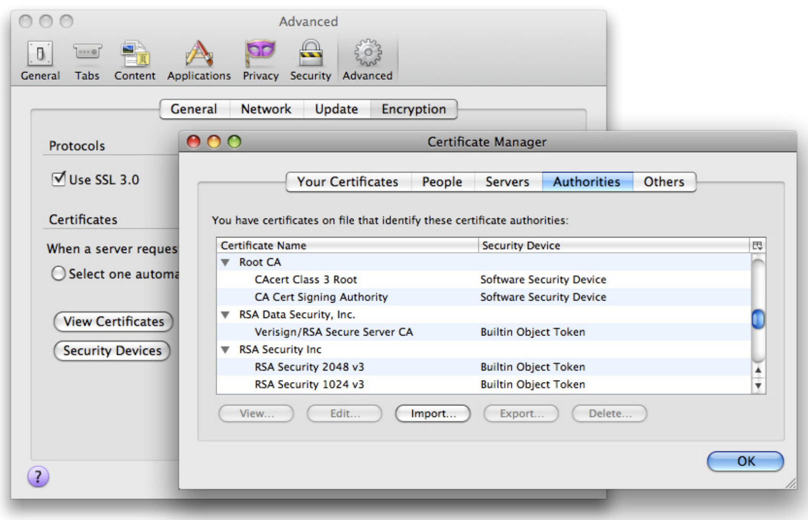
IEEE 1609

- Certificates
  - Encryption is useless without authentication
    - Alice ⇔ Eve ⇔ Bob
    - Eve can pretend to be Alice,
      replace K^+_A with 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 2019"
    - 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

- Implementation in WAVE
  - Certificate signature chains
    - Root certificate ⇨ certificate ⇨ certificate ⇨ payload
    - Root certificates pre-installed with system
    - Other certificates cannot be assumed to be present
  - Nodes must download certificates a
    - Include chain of certificates
    - …or SHA-256 of first certificate in chain

      (if receiver can be assumed to have all required certificates)



IEEE 1609

- 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):
    ECDSA (NIST p224), ECDSA (NIST p256), ECIES (NIST p256), ...

Complete packet format of a WSM:

Ex: 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

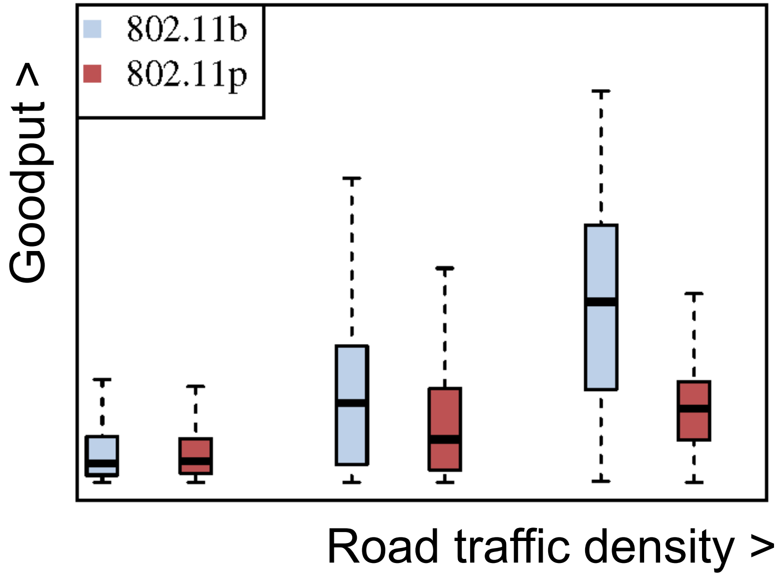
⇨ next slide

Complete packet format of a WSM (certificate part):

<table>
<tr><th>Length</th><th colspan="4">Field</th></tr>
<tr><td>1</td><td>certificate_version = 1</td><td></td><td></td><td></td></tr>
<tr><td>1</td><td rowspan="11">unsigned_certificate</td><td>subject_type = obu_identified</td><td></td><td></td></tr>
<tr><td>8</td><td>signer_id</td><td></td><td></td></tr>
<tr><td>1</td><td rowspan="4">scope</td><td>subject_name length</td><td></td></tr>
<tr><td>8</td><td>subject_name</td><td></td></tr>
<tr><td>2</td><td rowspan="2">applications</td><td>length of applications field</td></tr>
<tr><td>1</td><td>type = from_issuer</td></tr>
<tr><td>4</td><td>expiration</td><td></td><td></td></tr>
<tr><td>4</td><td>crl_series</td><td></td><td></td></tr>
<tr><td>1</td><td rowspan="3">public_key</td><td>length of public key field</td><td></td></tr>
<tr><td>1</td><td>algorithm = ecdsa nistp224..</td><td></td></tr>
<tr><td>29</td><td>public_key</td><td>point</td></tr>
<tr><td>32</td><td rowspan="2">signature</td><td rowspan="2">ecdsa_signature</td><td>r</td><td></td></tr>
<tr><td>32</td><td>s</td><td></td></tr>
</table>

Drawbacks of Channel Switching

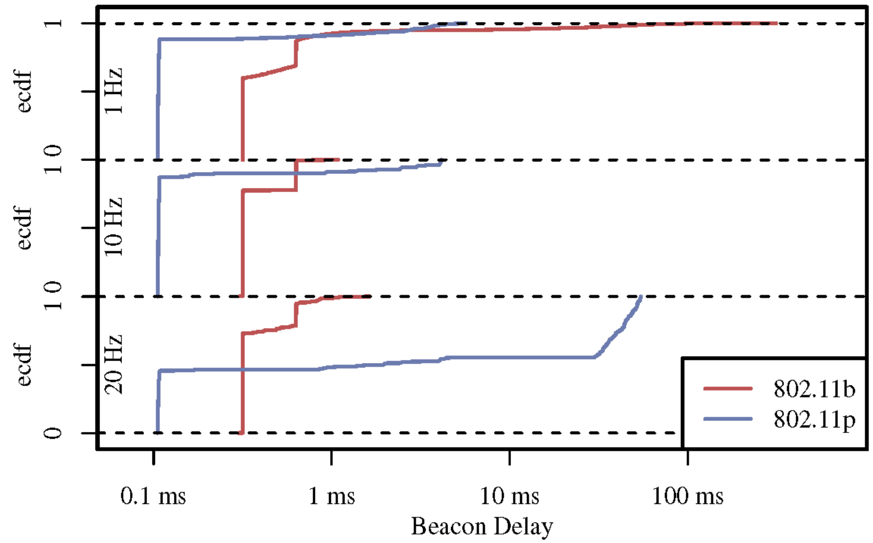
- 1) Goodput
  - User data must only be sent on SCH, i.e. during SCH interval
    ⇨ goodput cut in half



Picture source: 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) Latency
  - User data generated during CCH interval is delayed until SCH intv.



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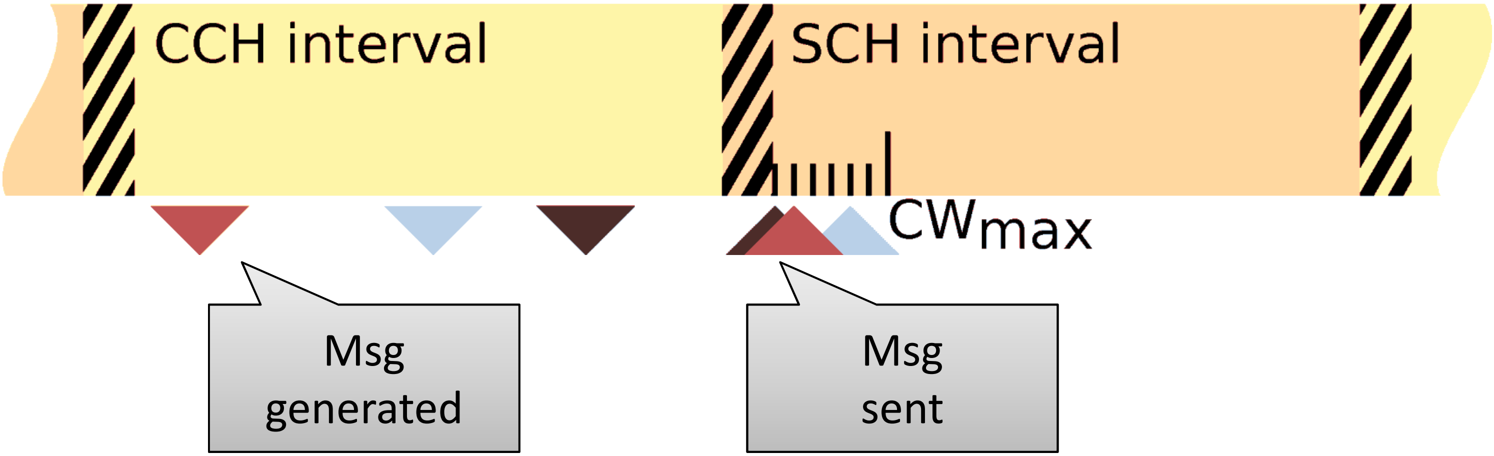
Drawbacks of Channel Switching

- 3) 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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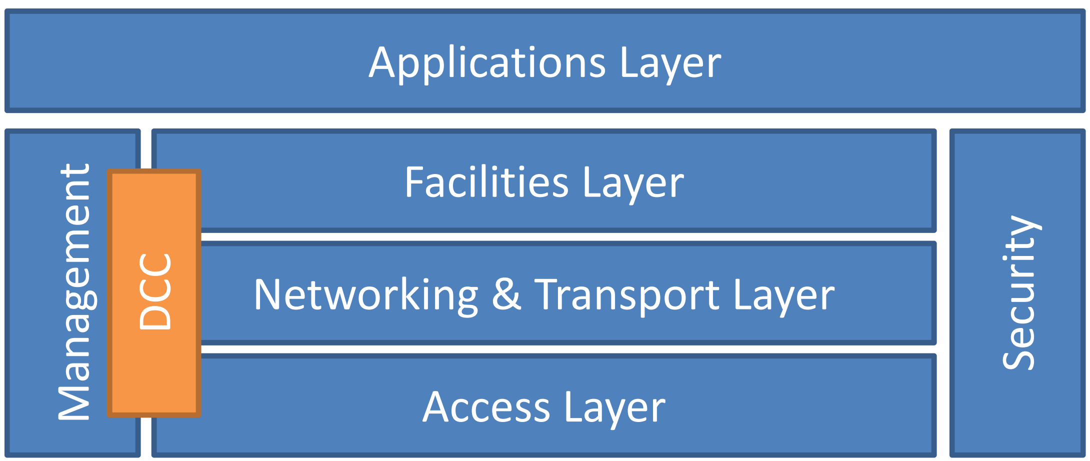
ETSI ITS G5

- 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

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



ETSI ITS G5

- 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

ETSI ITS G5

- Medium access
  - Separate EDCA systems
  - Different default parameters:

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

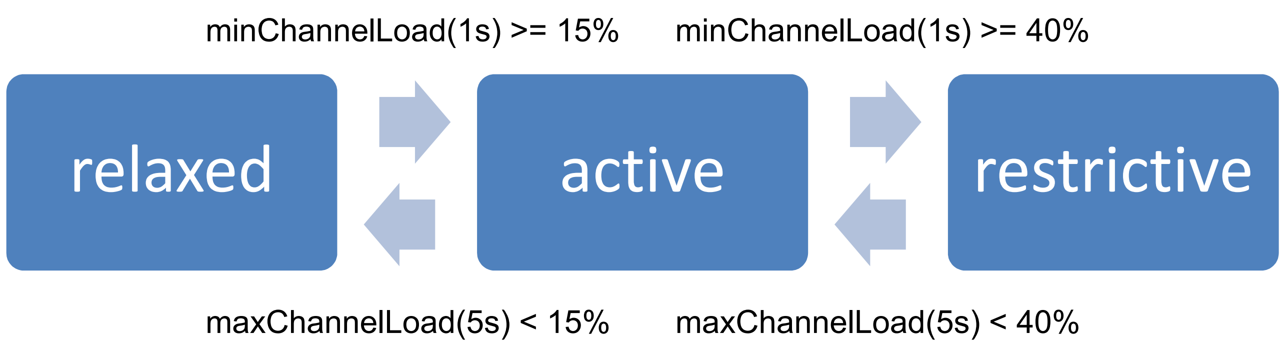
  - *Contention Window* – less distance to lower priority queues ⇨ less starvation of lower priority queues

ETSI ITS G5

- DCC
  - Core feature of ETSI ITS G5
  - Adaptive parameterization to avoid overload
  - Configurable parameters per AC:
    - TX power
    - Minimum packet interval
    - Sensitivity of CCA (Clear Channel Assessment)
    - Data rate
  - State machine determines which parameters are selected; available states:
    - Relaxed
    - Active (multiple sub states)
    - Restrictive

ETSI ITS G5

- DCC
  - State machine for Control Channel:



  - min/maxChannelLoad(x):
    record fraction of time in [t_{now}-x .. t_{now}] that channel was sensed busy
    subdivide interval into equal parts (e.g. 50 ms), take min/max
  - Channel busy ⇔ measured received power (signal or noise) above configured sensibility

ETSI ITS G5

- DCC
  - Selection of parameters when changing states
  - Service Channel: Active state has four sub-configurations
  - Control Channel: Single configuration for active state
  - *Example (“ref”*: Value remains unchanged)

	State					
	Relaxed	Active				Restrictive
		AC_VI	AC_VO	AC_BE	AC_BK	
TX power	33dBm	ref	25dBm	20dBm	15dBm	-10dBm
Min pkt interval	0,04s	ref	ref	ref	ref	1s
Data rate	3Mbit/s	ref	ref	ref	ref	12 Mbit/s
Sensitivity	-95 dBm	ref	ref	ref	ref	-65 dBm

ETSI ITS G5

- 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)

ETSI ITS G5

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

- 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

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

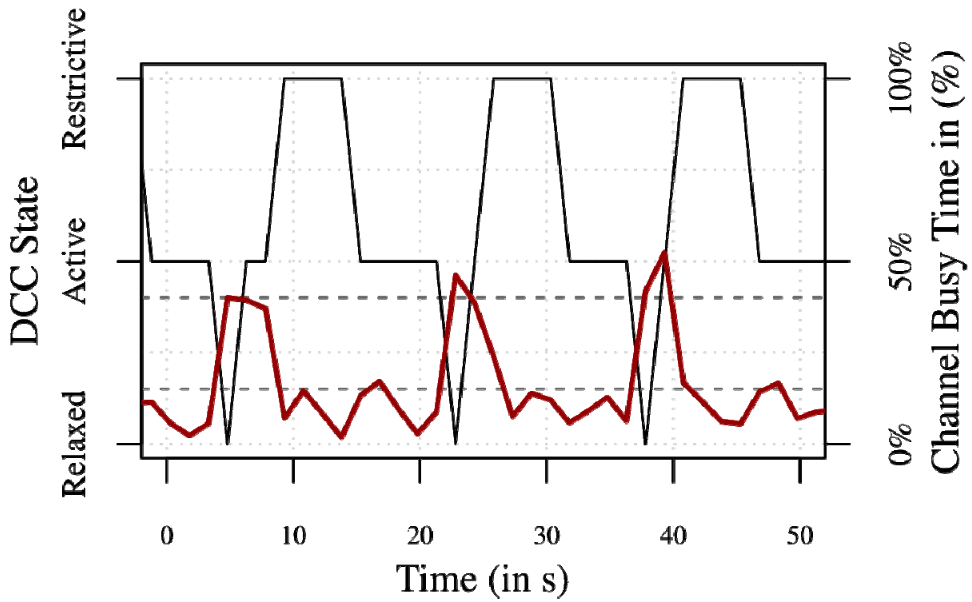
- Service Announcement
  - Message on Control Channel to advertise services offered on Service Channels
    - Channel number
    - Type of service
    - …
  - Similar to WAVE Service Announcement (WSA)
  - Receiver can tune (its second radio) to advertised channel

ETSI ITS G5

- 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

ETSI ITS G5: Analysis and Problems

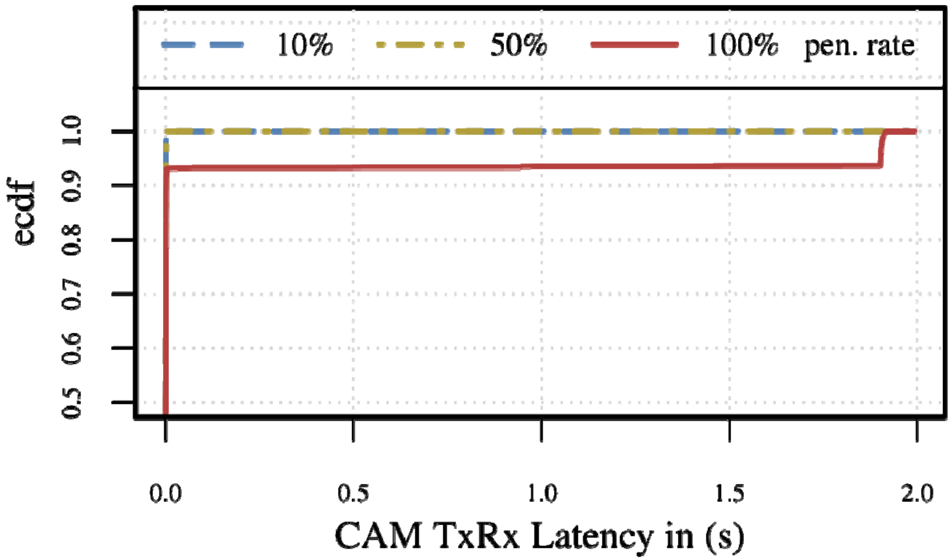
- Oscillating channel load (both local and global!)
  - …caused by channel access being too restrictive (standard parameters)



Picture source: 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.

ETSI ITS G5: Analysis and Problems

- Latencies
  - Choosing minimum packet intervals (TRC) too high can introduce high latencies



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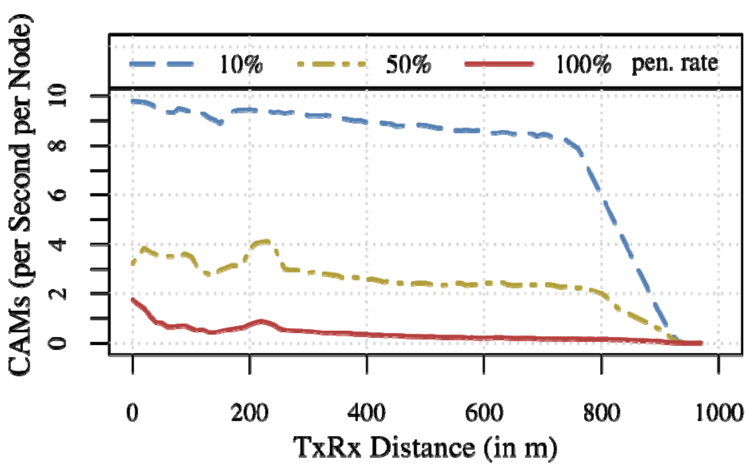
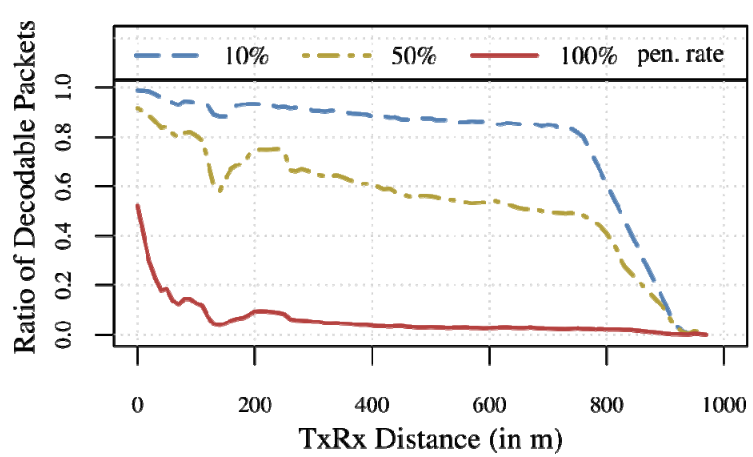
ETSI ITS G5: Analysis and Problems

- Update frequency
  - Standard parameters are too restrictive
  - Channel resources are not used optimally





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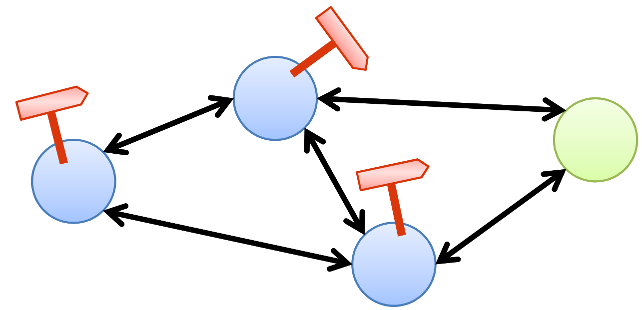
Main Takeaways

- Broadcast Media
  - TMC, TPEG
- UMTS
  - Channels, Pros / Cons
- DSRC/WAVE lower layers
  - 802.11p vs. old 802.11: commonalities and differences
  - HCF (EDCA QoS)
- IEEE 1609.* upper layers
  - Channel management
  - Security / Certificates
- ETSI ITS G5
  - Channel management
  - DCC: Decentralized Congestion Control
  - Message types
  - Commonalities and differences wrt. IEEE 1609.*

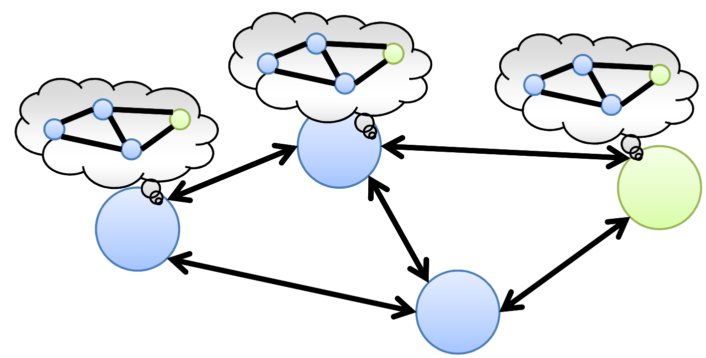
Broadcast, Geocast, Routing

Routing

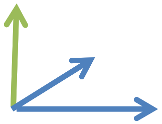
- Classical approaches to routing
  - Distance Vector Routing
    - Nodes keep vector
      of known destinations,
      store distance and next hop
    - Ex: DSDV



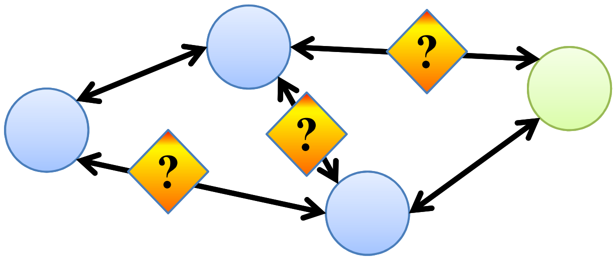
  - Link State Routing
    - Nodes keep track of
      of all links in network
    - Pro: fast and guaranteed
      convergence
    - Con: high overhead
    - Ex: OLSR



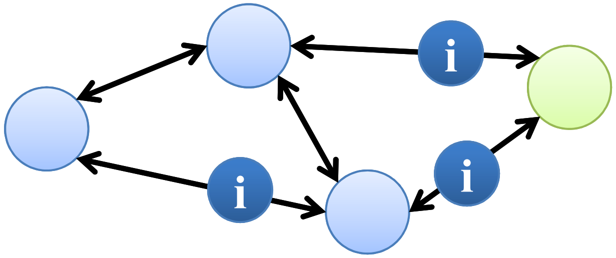
Routing



- Classical approaches to routing (II)
  - Reactive (on demand) routing
    - Routes established when needed
    - Routing messages only exchanged if (or while) user data is exchanged
    - Unused routes expire
    - Ex: AODV, DYMO

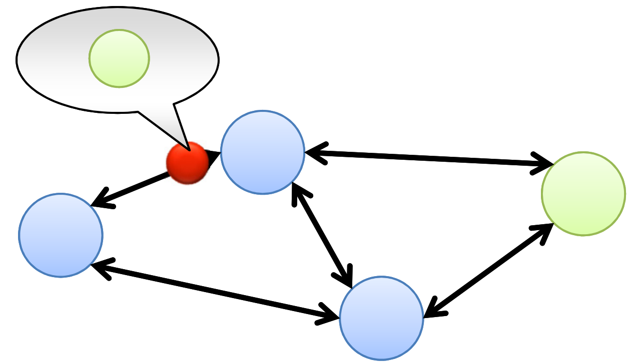


  - Proactive (table driven) routing
    - Routes are established and maintained continuously
    - No route setup delay when data needs to be sent
    - High overhead
    - Ex: OLSR, DSDV

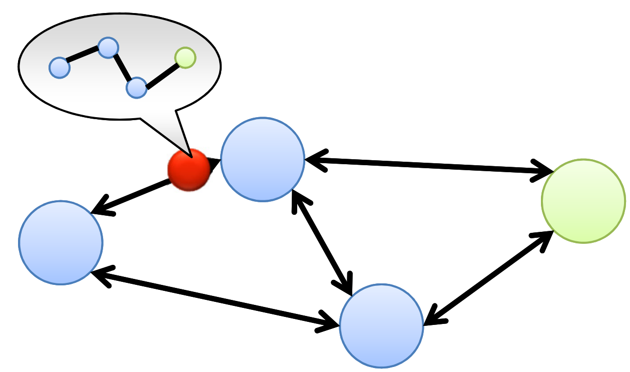


Routing

- Classical approaches to routing (III)
  - Hop-by-Hop Routing
    - Each packet contains destination address
    - During routing, each hop choses best next hop
    - Ex: AODV

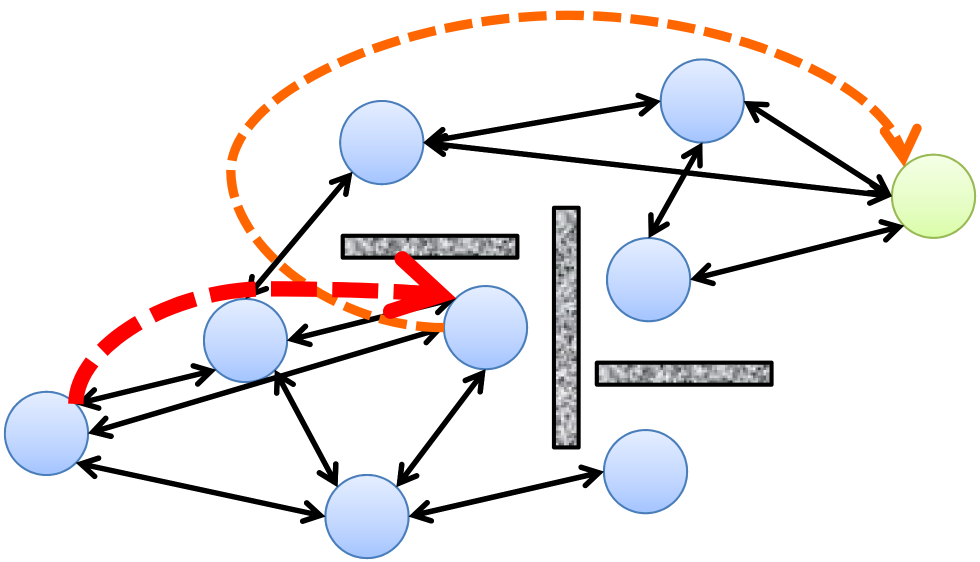


  - Source Routing
    - Each packet contains complete route to destination
    - During routing, nodes rely on this information
    - Ex: DSR



Routing

- 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



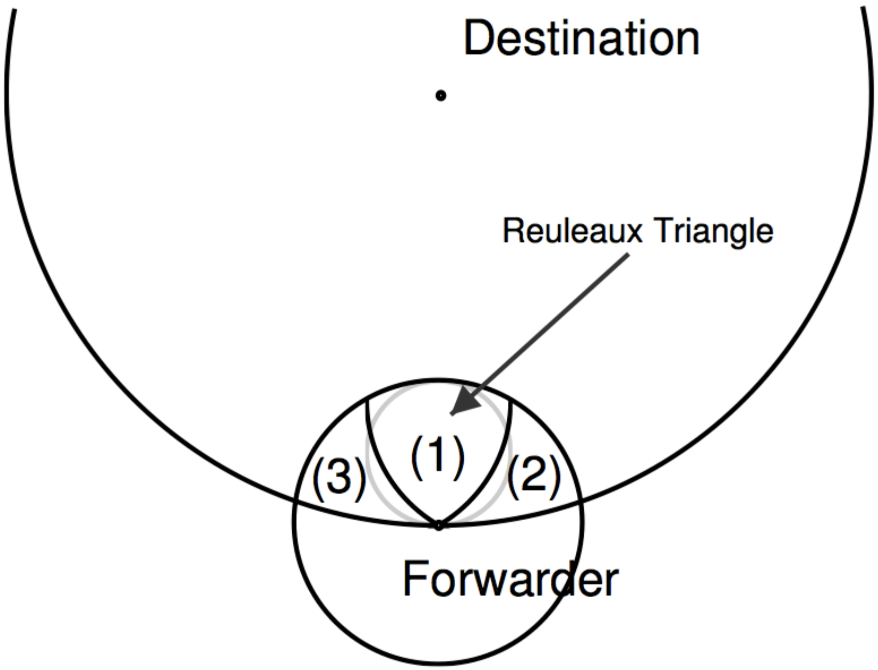
Routing

- Georouting: CBF
  - „Contention Based Forwarding“
  - 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

[1] Füßler, Holger and Widmer, Jörg and Käsemann, Michael and Mauve, Martin and Hartenstein, Hannes, "**Contention-based forwarding for mobile ad hoc networks**," *Ad Hoc Networks*, vol. 1 (4), pp. 351-369, 2003

Routing

- Georouting: CBF
  - Potential forwarders are contained in Reuleaux triangle (1)
    (use estimated communication range for thickness of triangle)
  - Waiting time is T = 1-P
    $$P(f,z,n) = \max\left\{0, \frac{\text{dist}(f,z) - \text{dist}(n,z)}{r_{radio}}\right\}$$
    (z: destination, f: last hop forwarder)
  - If last hop overhears no node forwarding the message, message is re-sent for nodes in (2), then (3)



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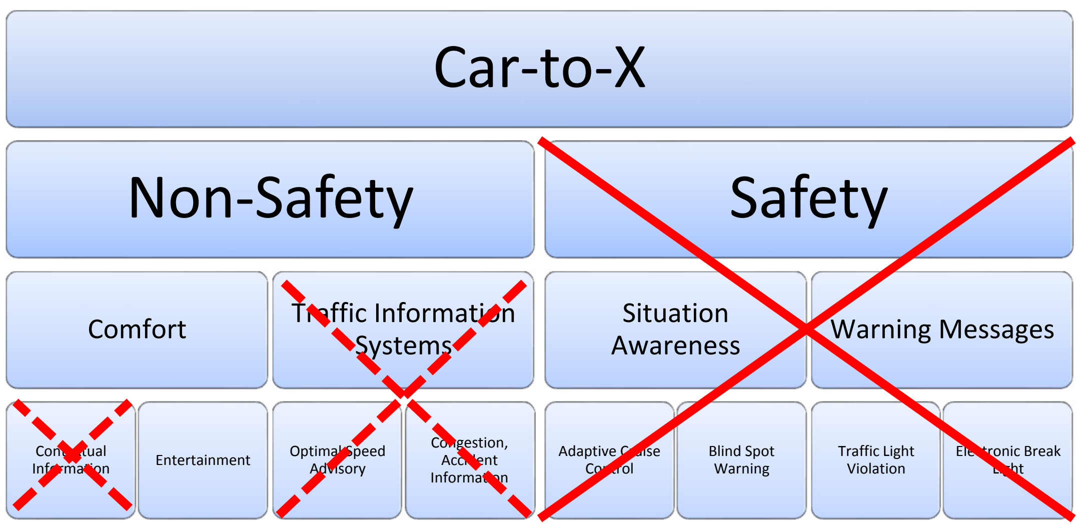
Routing

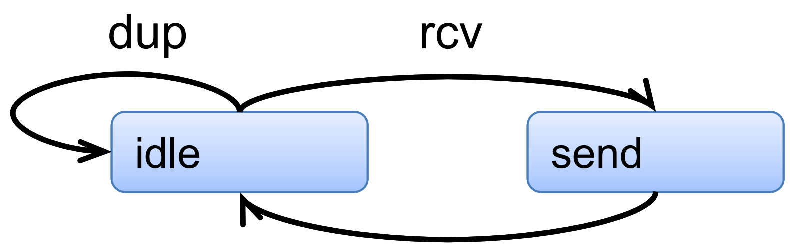
- Reflection on classical routing approaches
  - Q: Can (classical) routing work in VANETs?
  - A: Only in some cases.
  - Commonly need multicast communication, low load, low delay
  - Additional challenges and opportunities:
    network partitioning, dynamic topology, complex mobility, …



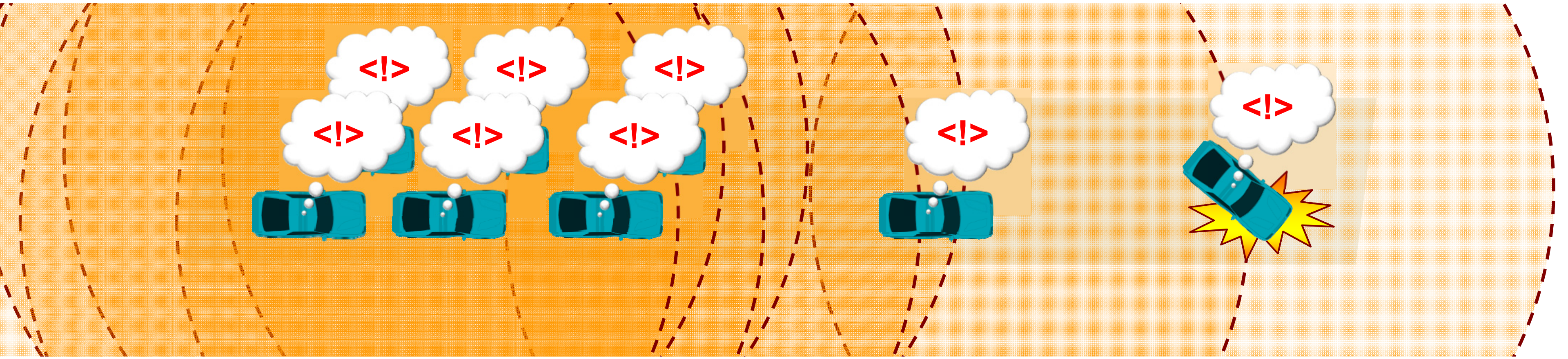
[1] Toor, Yasser and Mühlethaler, Paul and Laouiti, Anis and Fortelle, Arnaud de La, "**Vehicle Ad Hoc Networks: Applications and Related Technical Issues,**" IEEE Communications Surveys and Tutorials, vol. 10 (3), pp. 74-88, 2008

Flooding

- Flooding (Multi-Hop Broadcast)
  - Simplest protocol: „Smart Flooding“:



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



Flooding

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

Flooding

- 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

- VANET specific solution: Broadcast Suppression
  - 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

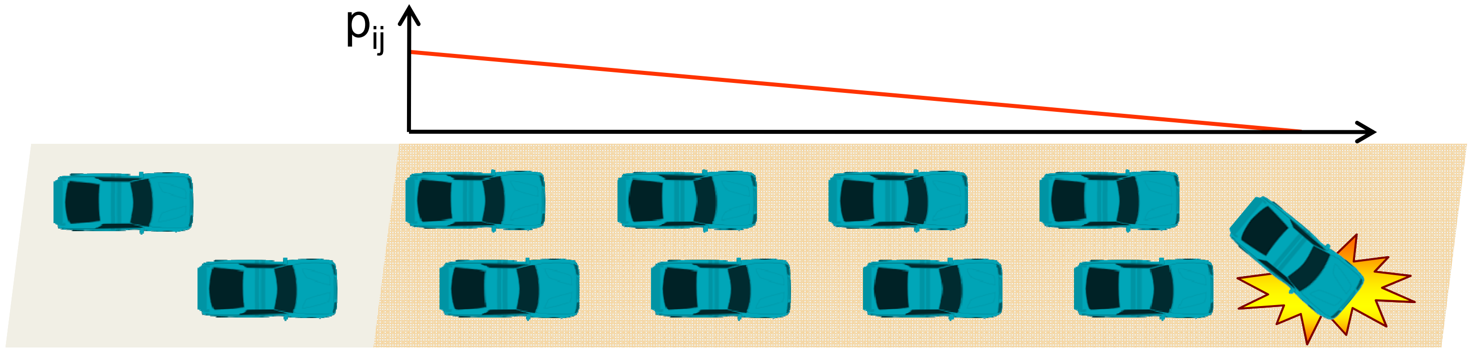
[1] Wisitpongphan, Nawaporn and Tonguz, Ozan K. and Parikh, J. S. and Mudalige, Priyantha and Bai, Fan and Sadekar, Varsha, "**Broadcast Storm Mitigation Techniques in Vehicular Ad Hoc Networks**," IEEE Wireless Communications, vol. 14 (6), pp. 84-94, December 2007

Flooding

- Broadcast Suppression
  - Estimate distance to sender as $0 \leq \rho_{ij} \leq 1$ based on R ("approximate transmission radius")
  - Variant 1: GPS based
    - $\rho_{ij} = \begin{cases} 0 & \text{if } D_{ij} < 0 \\ \frac{D_{ij}}{R} & \text{if } 0 \leq D_{ij} < R \\ 1 & \text{otherwise} \end{cases}$
  - Variant 2: RSS based
    - $\rho_{ij} = \begin{cases} 0 & \text{if } RSS_x \geq RSS_{max} \\ \frac{RSS_{max} - RSS_x}{RSS_{max} - RSS_{min}} & \text{if } RSS_{min} \leq RSS_x \leq RSS_{max} \\ 1 & \text{otherwise} \end{cases}$

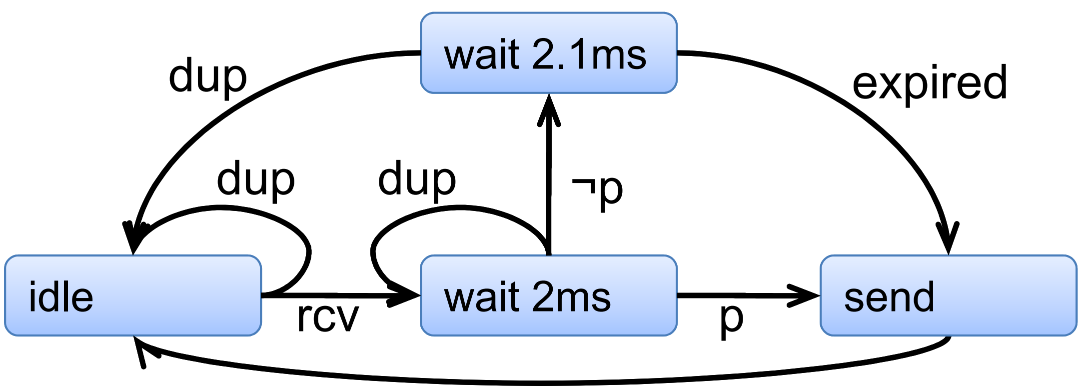
Flooding

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



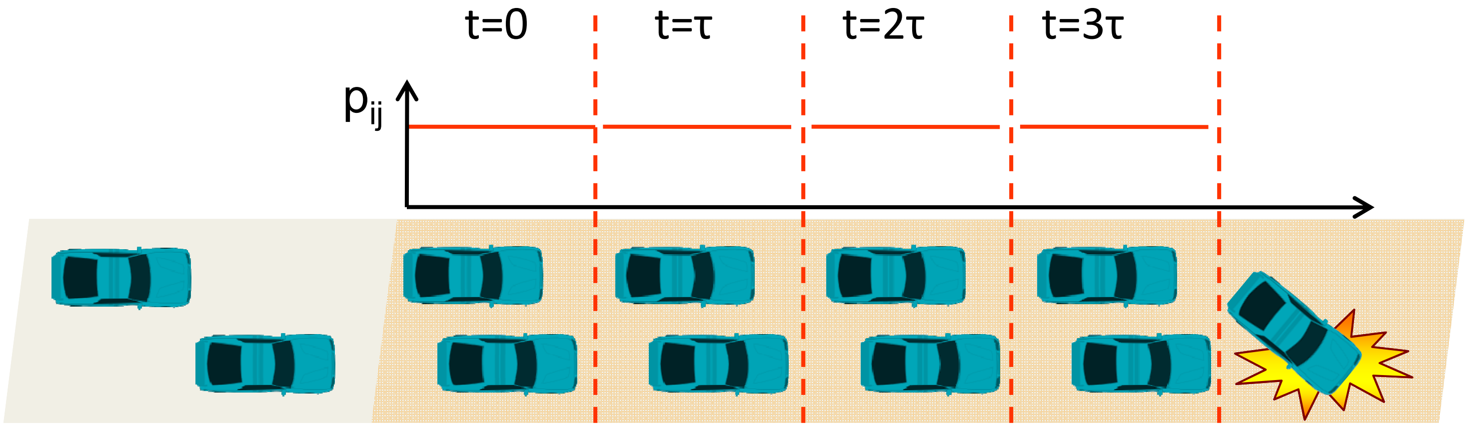
Flooding

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



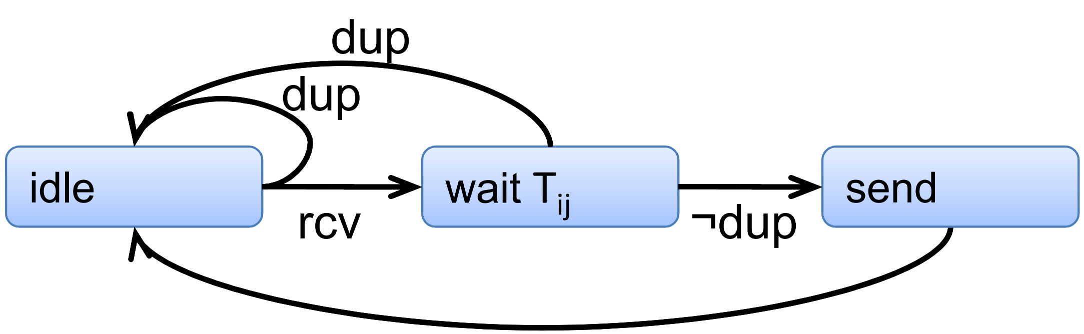
Flooding

- Broadcast Suppression
  - 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



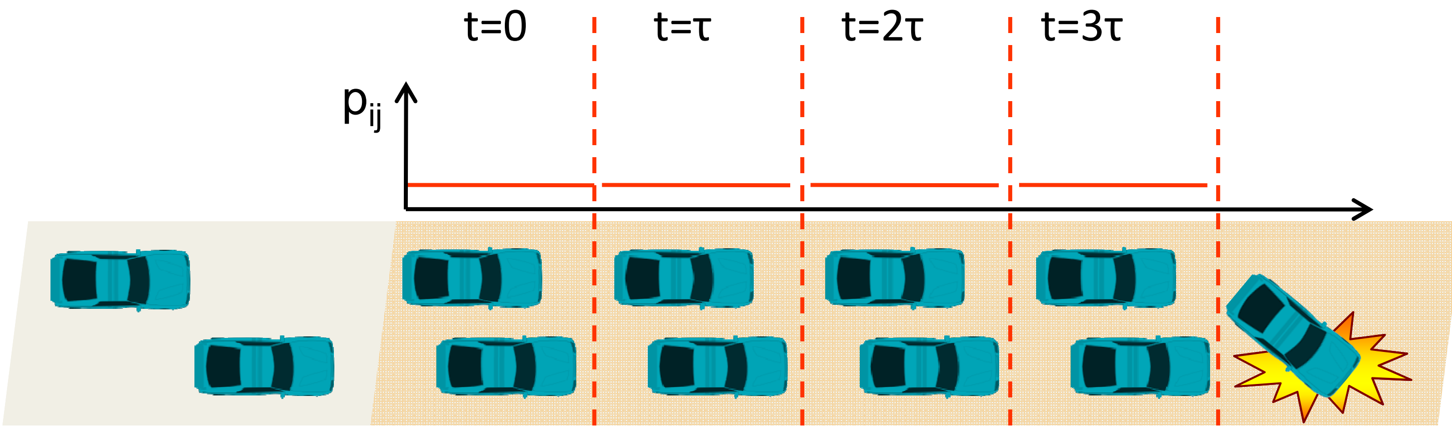
Flooding

- Broadcast Suppression
  - Slotted 1-persistence
    - Divide “communication range“ into N_s slots of length τ
    - Nodes wait before re-broadcast, waiting time $T_{ij}=\tau\times\lceil N_s(1-\rho_{ij})\rceil$
    - Duplicate elimination takes care of suppression of broadcasts



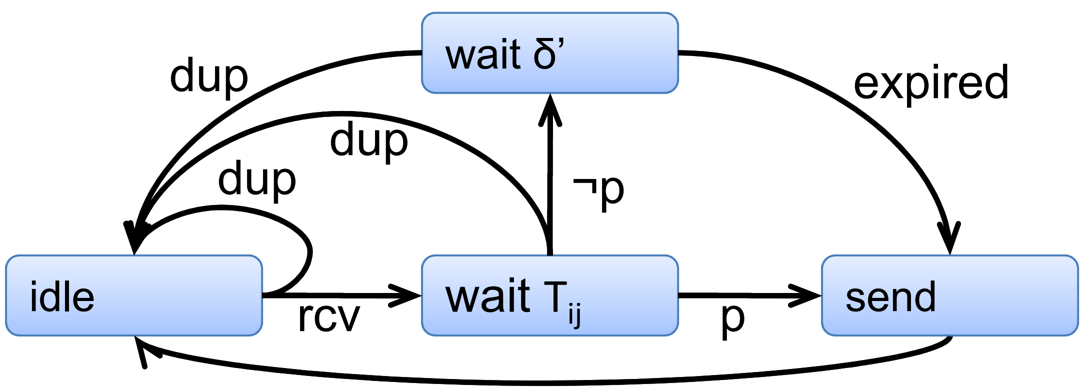
Flooding

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



Flooding

- Broadcast Suppression
  - 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 $\delta' > \max(T_{ij})$

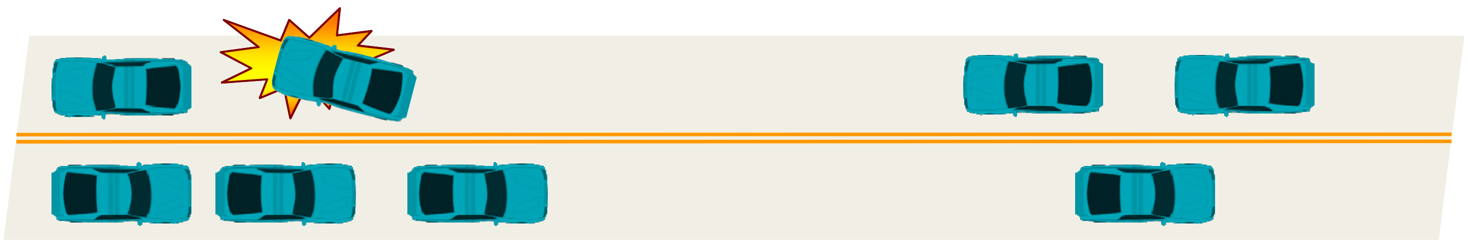


Flooding

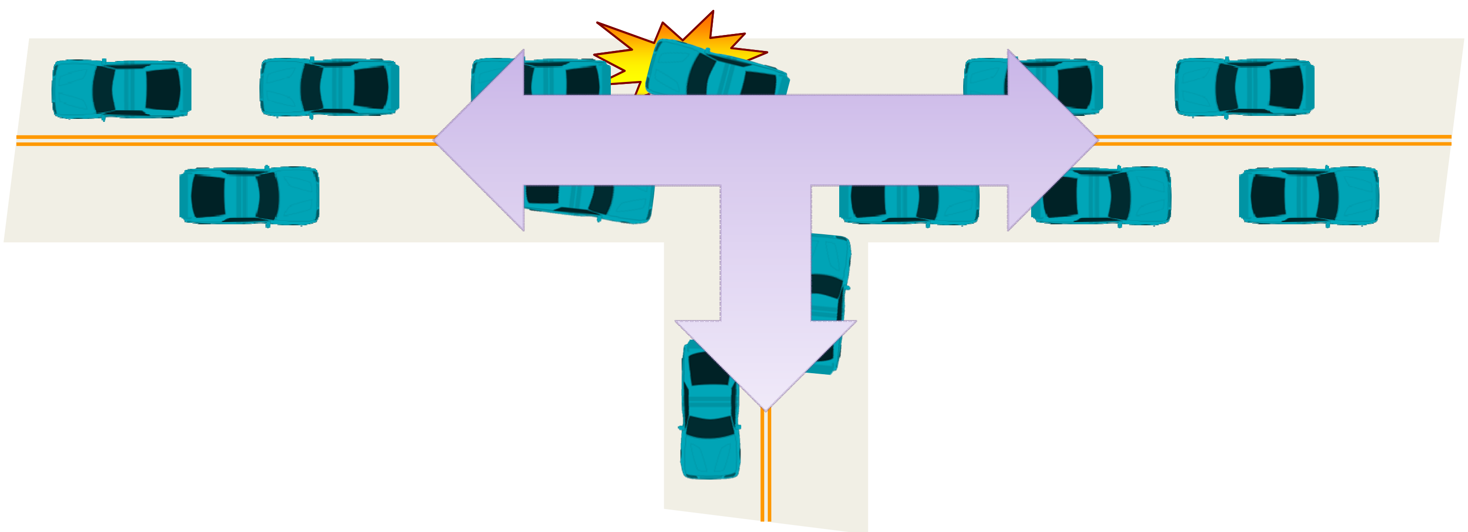
- Broadcast Suppression
  - Solves Broadcast Storm Problem
  - Maximizes distance per hop
  - Minimizes packet loss
  - But: Much higher per-message delay

Remaining problems

- Temporary network fragmentation

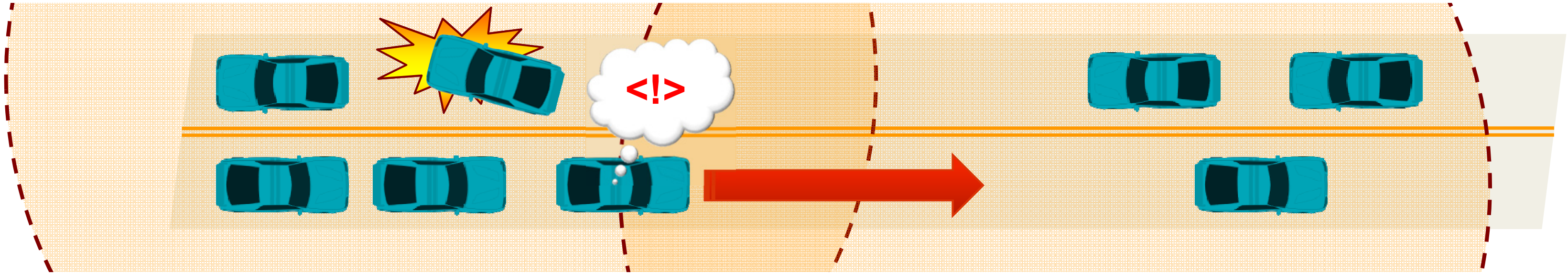


- Undirected message dissemination



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



[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

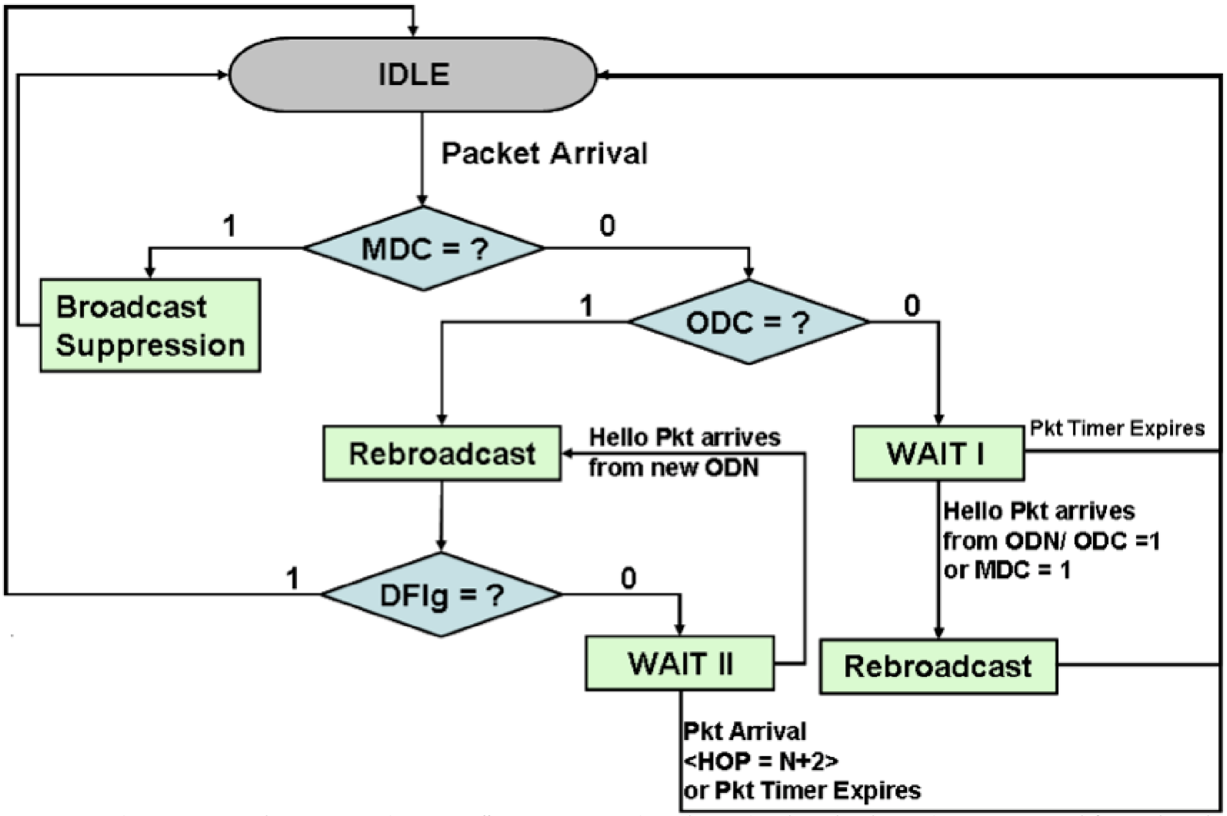
Flooding + X

- 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

- DV-CAST
  - Algorithm:



Picture source: 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

Flooding + X

- DV-CAST
  - Decision matrix:

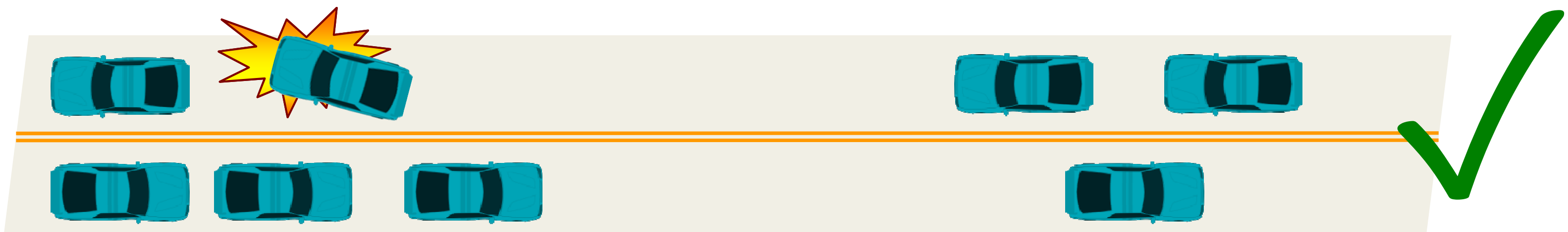
MDC	ODC	DFlg	Derived Scenario	Actions Taken by DV-CAST Protocol
1	×	1	Well Connected	Broadcast Suppression
1	×	0	Well Connected	Help relay the packet by doing broadcast suppression
0	1	1	Sparsely Connected	Rebroadcast and assume that the ODN will help relay or rebroadcast
0	1	0	Sparsely Connected	Rebroadcast and help carry & forward the packet to the first new neighbor in the opposite direction or in the message direction encountered
0	0	×	Totally Disconnected	Wait and forward the packet to the first neighbor in the opposite direction or in the message direction encountered.

Flooding + X

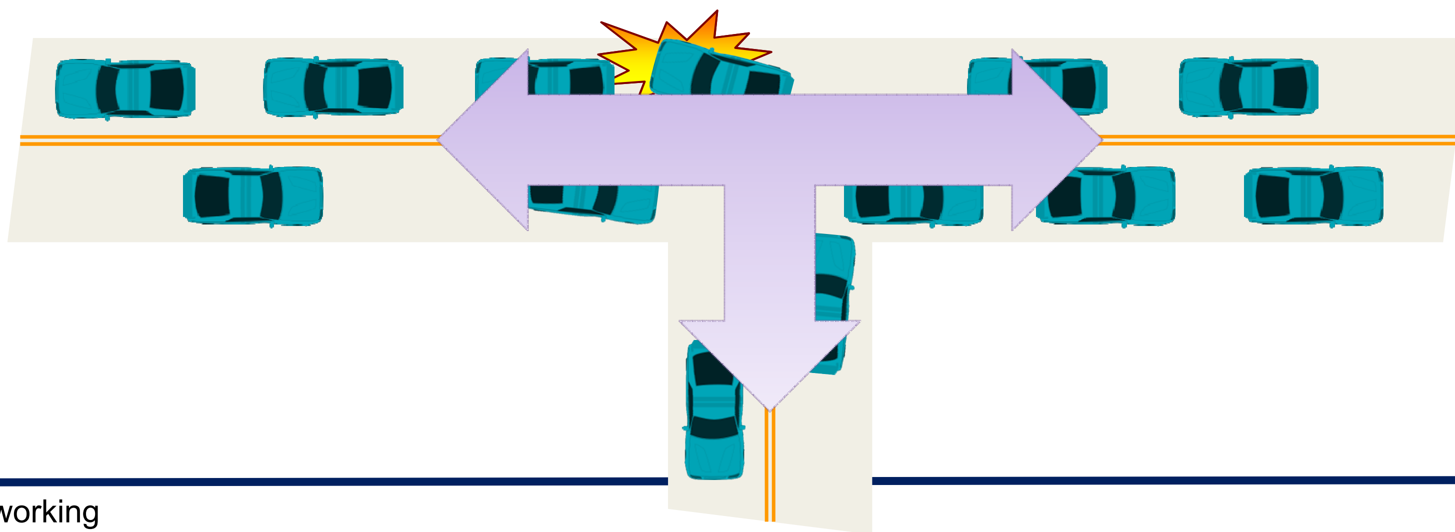
- DV-CAST
  - Simulation results show that (on freeways with low to medium node densities) DV-CAST beats simple flooding in terms of broadcast success rate and distance covered

Intermediate Summary

- Remaining problems
  - Temporary network fragmentation (solved)

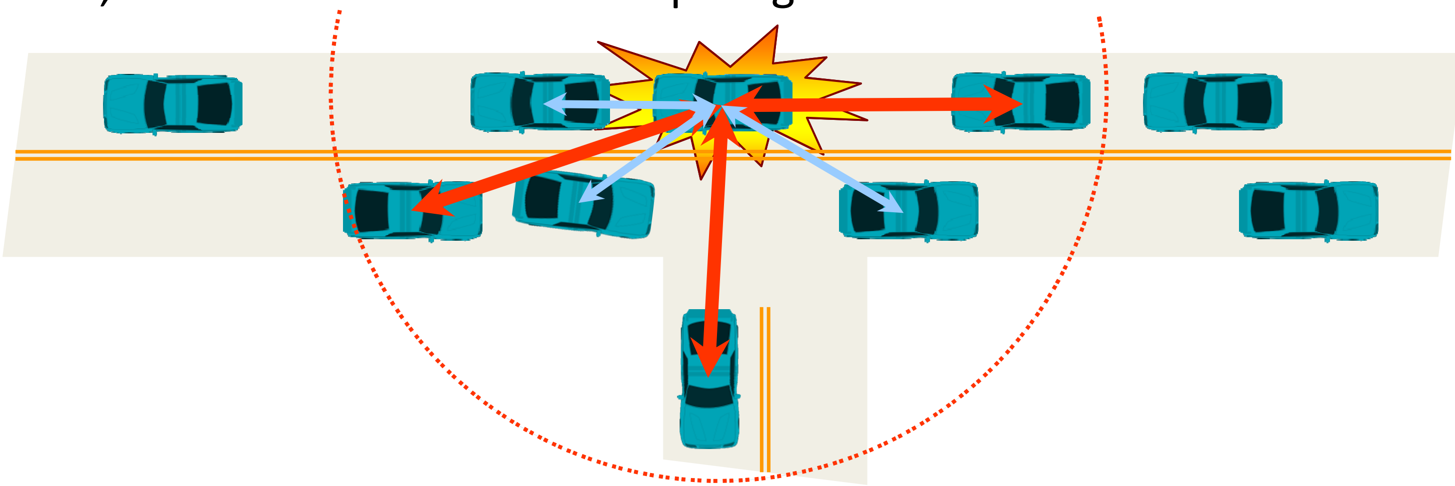


  - Undirected message dissemination



Geocast

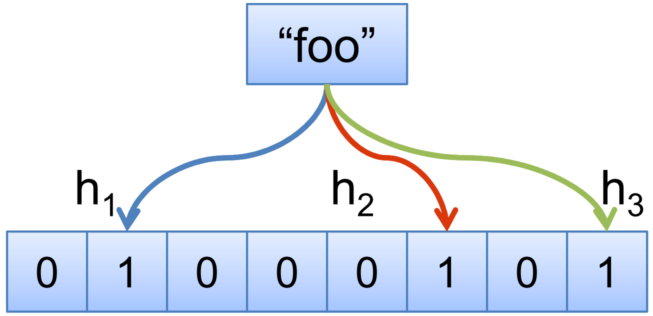
- TO-GO
  - „Topology-Assisted Geo-Opportunistic Routing“
  - Nodes periodically send *Hello* beacons; Contents:
    - Number of neighbors
    - Bloom filter of neighbor IDs
    - IDs of neighbors furthest down the road/roads
  - Thus, nodes know about all 2-hop neighbors



[1] Lee, K.C. and Lee, U. and Gerla, M., "**Geo-Opportunistic Routing for Vehicular Networks**," *IEEE Communications Magazine*, vol. 48 (5), pp. 164-170, May 2010

Geocast

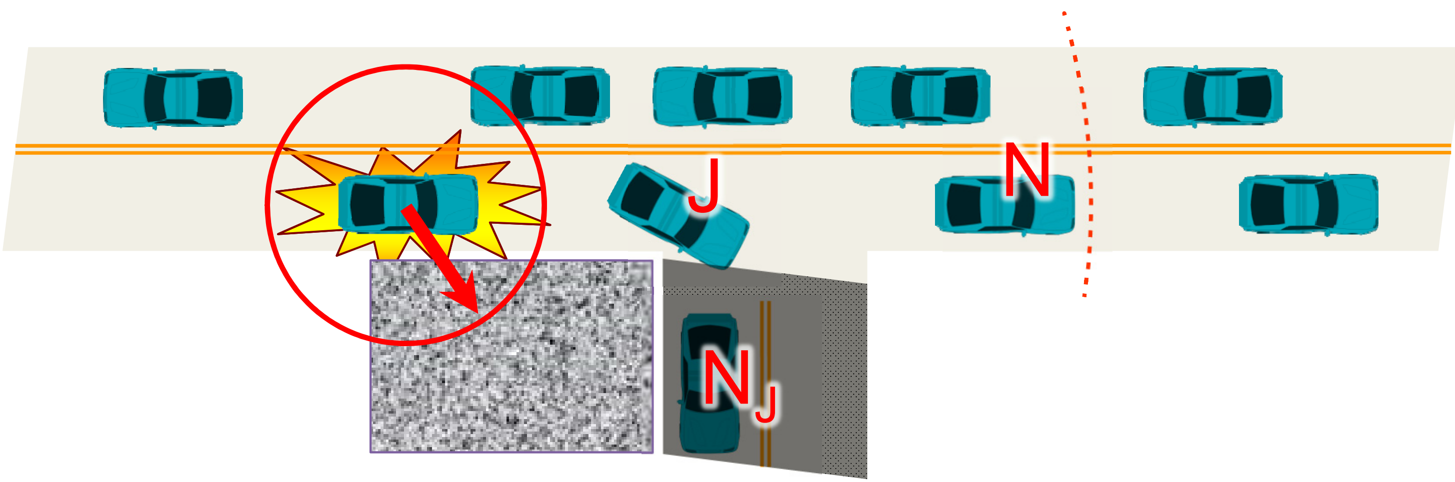
- Bloom Filter
  - Idea:
    - Bloom filter is a bit field X
    - Hash functions h_1 to h_k map input data x → one bit (each) in X
    - Insertion of x: Set $X[h_i(x)] \leftarrow 1 \quad \forall i \in [1..k]$
    - Test for $x \in X$: Check $X[h_i(x)] \stackrel{?}{=} 1 \quad \forall i \in [1..k]$
  - Probabilistic test for "$x \in X$"
    - Possible results: no / maybe (→ chance of false positives)
  - Allows for very compact representation of X



[1] Bloom, Burton H., "**Space/time trade-offs in hash coding with allowable errors**," *Communications of the ACM*, vol. 13 (7), pp. 422-426, 1970

Geocast

- TO-GO
  - 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 (and running in greedy mode), pick N else, pick J



Geocast

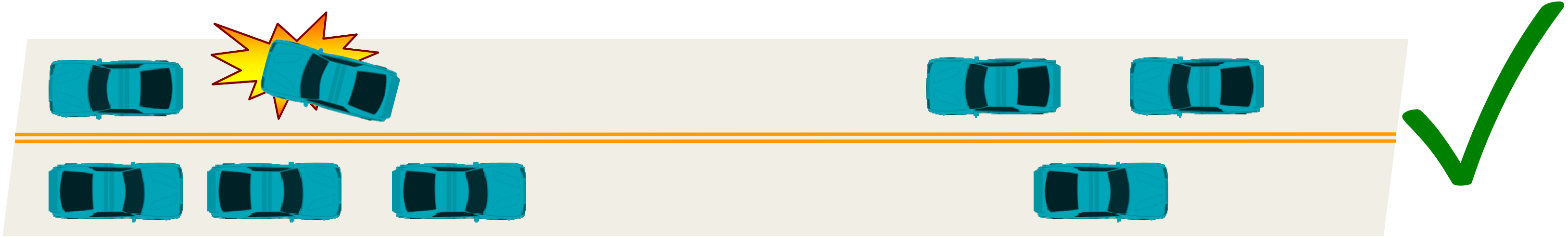
- TO-GO
  - Step 2: Find Forwarding Set (FS)
    - Nodes in the FS will compete for relaying of the message
    - Only one node in FS should relay
      thus, all nodes in FS must hear each other
    - Finding optimal solution is *NP complete*
    - TO-GO uses approximation:
    - Bloom filter entries indicate who can hear whom
    - Given the target node T,
      find its neighbor M with the maximum number of neighbors
    - Include all those neighbors in FS, which
      - can hear M, and
      - are heard by M, and
      - are heard by all current members of FS

Geocast

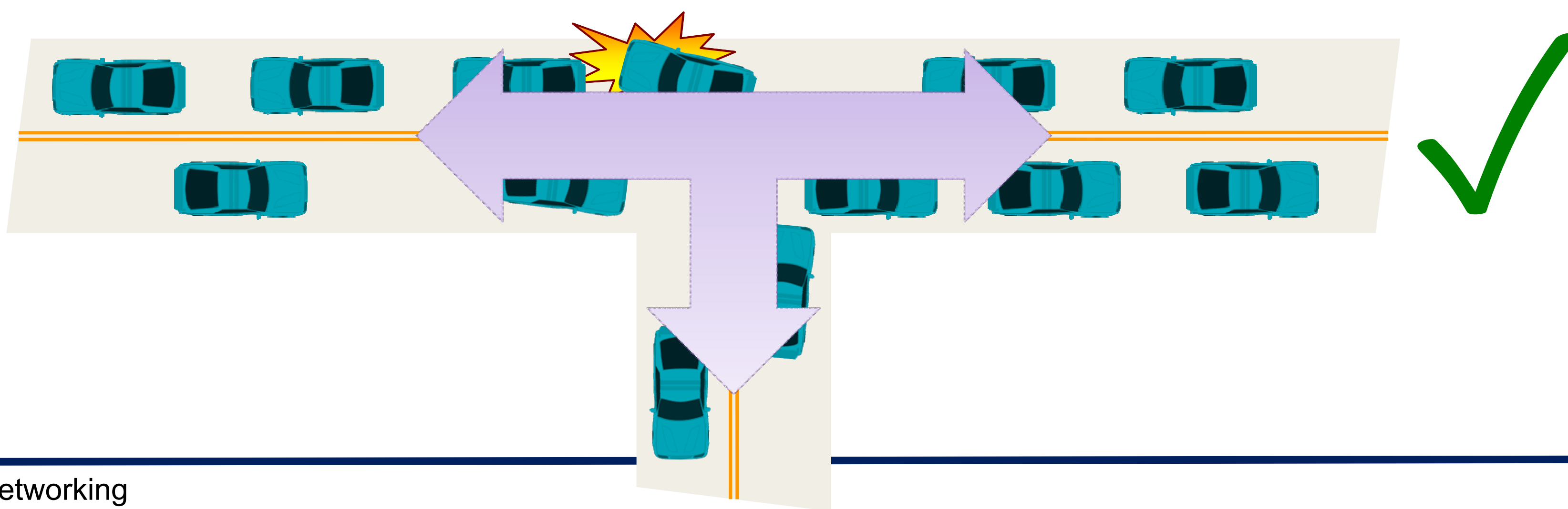
- TO-GO
  - Step 3: Multicast message to all nodes in FS
    - Nodes in the FS compete for relaying of the message
    - Ensure maximum progress within FS
    - Delay re-broadcast by t
    - Suppress re-broadcast if another nodes forwards within t
    - $t = \tau \times d_T/d_{max}$
      with:
    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

Intermediate Summary

- Remaining problems
  - Temporary network fragmentation (solved)

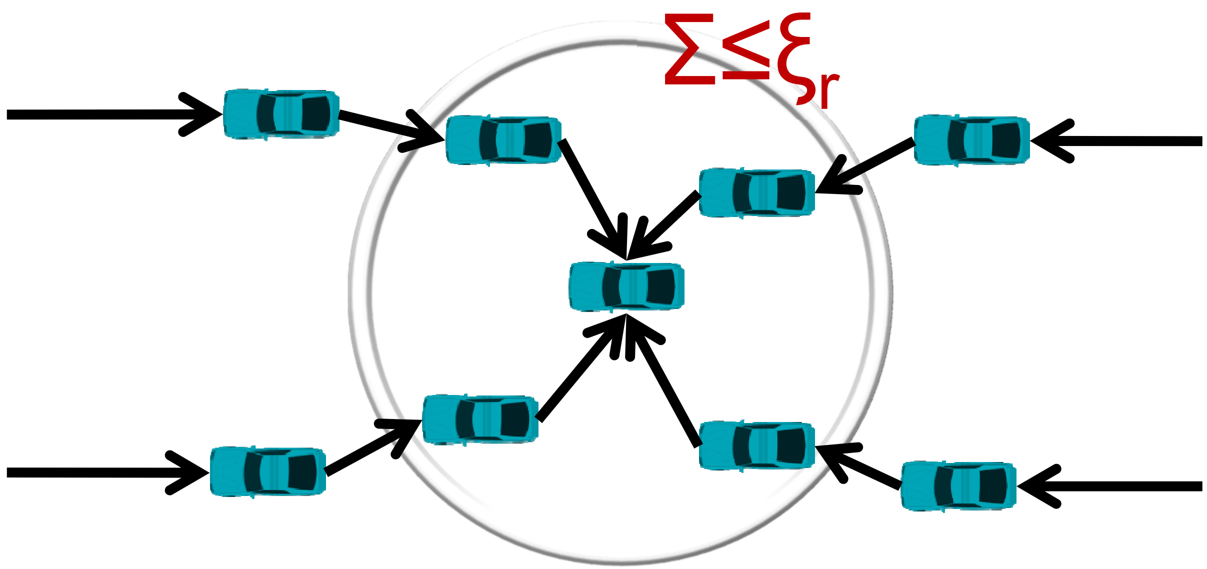


  - Undirected message dissemination (solved)



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

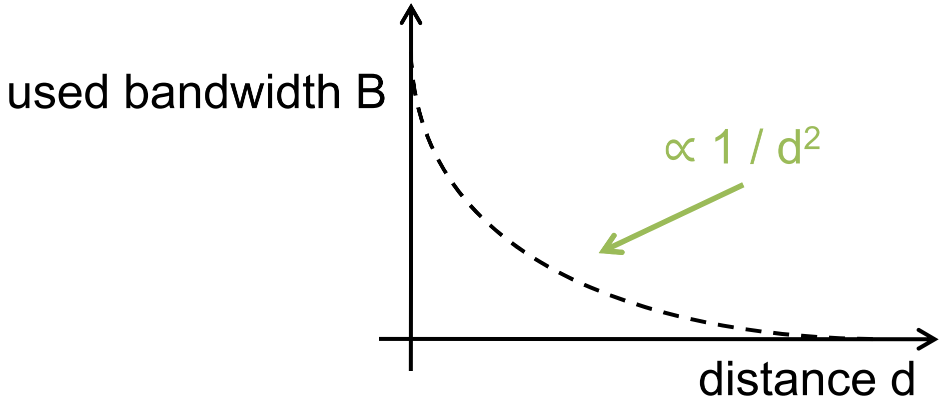


[1] B. Scheuermann, C. Lochert, J. Rybicki, and M. Mauve, "**A Fundamental Scalabiliy Criterion for Data Aggregation in VANETs**," in ACM MobiCom 2009. Beijing, China: ACM, September 2009

Scalability

- Solution?
  - Define maximum dissemination range of any information
  - Reduce update frequency with increasing distance
  - Aggregate information as distance increases

- Pre-condition for scalability of dissemination approach?
- Used bandwidth reduces as distance to source increases
- Upper bound: $1 / d^2$



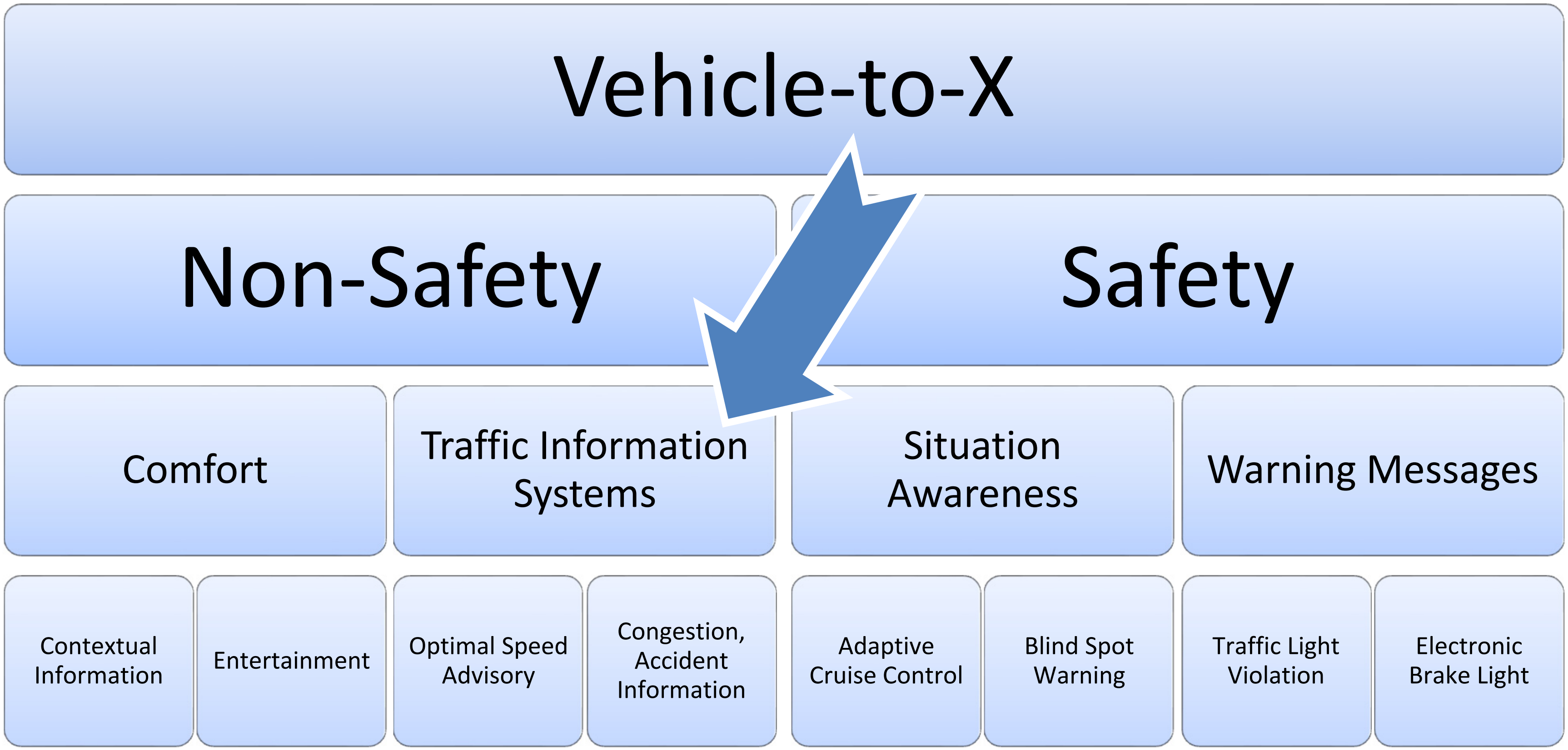
Main Takeaways

- 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

Beaconing and TIS

Traffic Information Systems

You are here:



[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

- 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

Motivation

- Problem of traditional TIS:
  - High delay
    - „Jams reported no earlier than they dissolved on their own“
  - Low data rate
    - Can only send few, most important bulletins
  - Low reliability
    - Centralized system
    - Human factor
    - Radio reception / Internet connection

Motivation

- Goal: use vehicles as both information sink and source
  - Vehicles measure road conditions, travel time, …
  - … disseminate information to neighbors
  - … help relay information further
  - and can promptly react to new information
- Typical requirements
  - Vehicle-to-vehicle communication
    - Technology? Availability?
  - GPS receiver
    - Precision?
  - Digital road map
    - Same data basis?

Motivation

- Data
  - Must be kept current
  - High spatial resolution
  - But: no random access
- Users
  - Distributed in wide area
  - Mobile
  - Data source and sink

PeerTIS

- PeerTIS
  - Based on cellular communication (UMTS)
  - Paradigm: Peer-to-Peer
- Benefits
  - UMTS
    - Established technology
    - Infrastructure already present
  - Peer-to-Peer
    - Resources scale with number of participants
    - Decentralized System → Independence, robustness, ...

[1] J. Rybicki, B. Scheuermann, M. Koegel, and M. Mauve, "**PeerTIS - A Peer-to-Peer Traffic Information System**," in 6th ACM International Workshop on Vehicular Inter-Networking (VANET 2009). Beijing, China: ACM, September 2009, pp. 23–32

PeerTIS

- PeerTIS
  - Based on cellular communication (UMTS)
  - Paradigm: Peer-to-Peer
- Drawbacks
  - UMTS
    - High latency, high packet loss
    - Cost?
  - Peer-to-Peer
    - Coordination
    - Security?

[1] J. Rybicki, B. Scheuermann, M. Koegel, and M. Mauve, "**PeerTIS - A Peer-to-Peer Traffic Information System**," in 6th ACM International Workshop on Vehicular Inter-Networking (VANET 2009). Beijing, China: ACM, September 2009, pp. 23–32

PeerTIS

- Stored (and exchanged) information
  - Road
  - Mean speed
  - Time
  - User ID
- Properties
  - High spatial resolution
  - High precision
  - Short query interval

PeerTIS

- Data
  - Structured
  - Geo-referenced
- Typical use case
  - Join PeerTIS network
  - Calculate naïve route
    - …and alternatives
  - Query data
    - segment by segment
  - Pick best route, start driving
  - Periodically check for updates
- Observation
  - Query pattern of segments not random, but predictable

PeerTIS

- Peer-to-Peer
  - All users treated equally
- Technique
  - Unstructured overlay networks
  - Structured paradigms
- Distributed Hash Tables (DHTs)
  - Create hash value of information to store
  - Use as index for information storage and retrieval
  - Each user is assigned part of the key space,
    stores information that has hash value in assigned range

PeerTIS

- Joining a PeerTIS network
  - Split any node’s key space in two
  - Take over half of data, assigned range

PeerTIS

- Drawback of unmodified DHT algorithm:
  - Hashing leads to random distribution of data
  - Leads to long query times, high load, …

PeerTIS

- Improved storage in PeerTIS:
  - Content Addressable Network (CAN), but: no hashing
  - Physical neighbors responsible for neighboring areas
  - Thus: faster lookup of information close by
  - Optimization:
    hop-by-hop forward
    of query to all hosts;
    results appended on
    reverse path

PeerTIS

- Additional optimization
  - Exploit time correlation of queries (initial query, then periodic updates):
  - Store address of all nodes that answered initial query
  - Try getting updates directly from these nodes

PeerTIS

- Third optimization
  - Exploit spatial distribution of nodes

  - Do not assign random geographic area to nodes.
  - Instead, chose area close to their start of route

  - Result: more resources allocated to areas of high traffic density

PeerTIS

- Evaluation:
  - Impact on network load tolerable for low to medium density
  - Even distribution of network load
  - Speed superior to naïve P2P algorithm

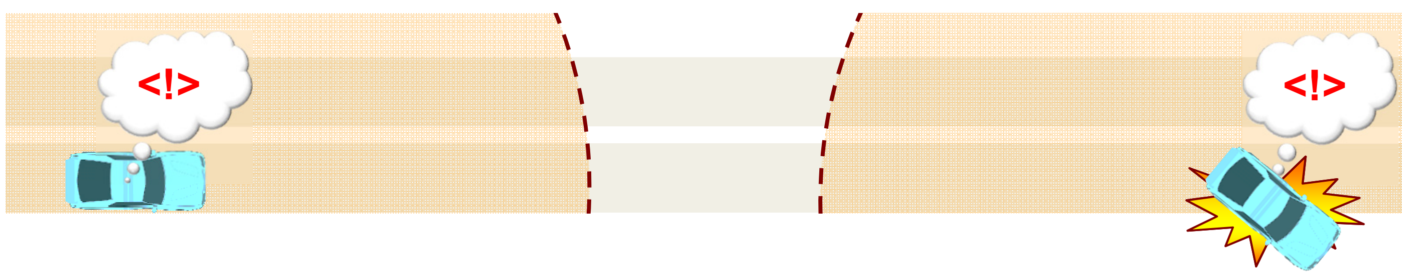
PeerTIS

- Possible improvements
  - Subscribe to (bigger) changes in data
  - Multicast distribution of data

- Open Questions
  - Replication of data?
  - Security?
  - Going infrastructure-less?
  - Heterogeneous map data?

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)



[1] L. Wischhof, A. Ebner, H. Rohling, M. Lott, and R. Halfmann, "**SOTIS - A Self-Organizing Traffic Information System**," Proceedings of 57th IEEE Vehicular Technology Conference (VTC2003-Spring), Jeju, South Korea, April 2003

SOTIS

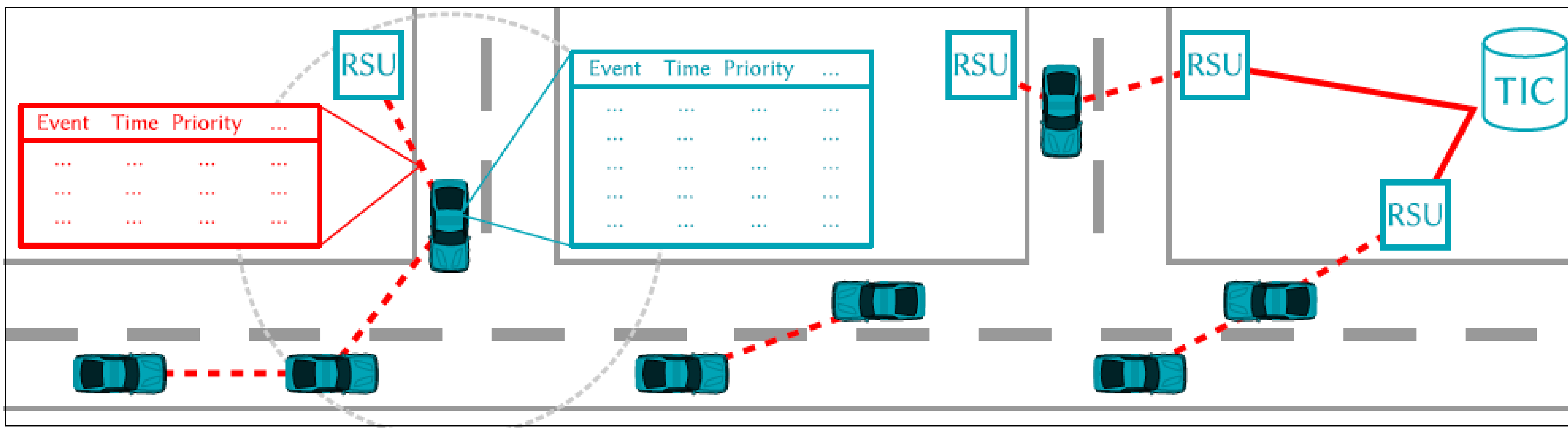
- Evaluation
  - Speed of information dissemination depends on traffic density and market penetration, varies in 120 .. 600 km/h

SOTIS

- 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
  2. Freeway scenario vs. inner city
  3. Own protocol ⇔ other, future, and legacy protocols
- How to do better?
  1. Dynamically incorporate optional infrastructure
  2. Dynamically adapt beacon interval
  3. Dynamically use all free(!) channel capacity

Adaptive Traffic Beacon (ATB)

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

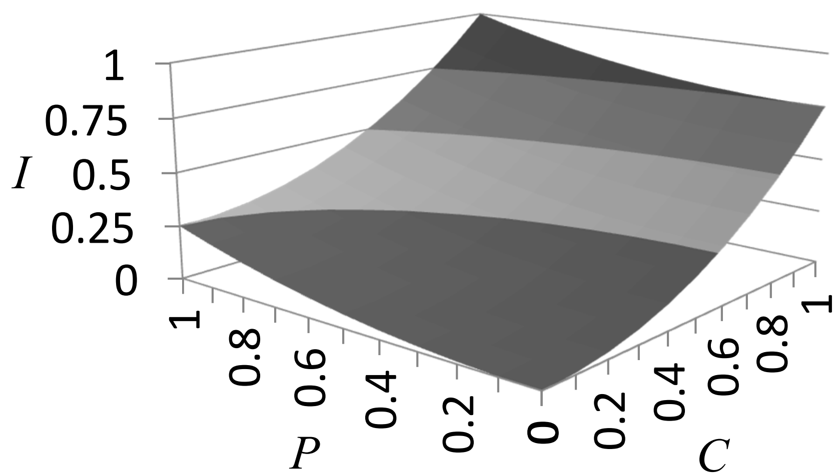


Picture source: C. Sommer, O. K. Tonguz, F. Dressler, "**Traffic Information Systems: Efficient Message Dissemination via Adaptive Beaconing**," IEEE Communications Magazine, vol. 49 (5), pp. 173-179, May 2011

Adaptive Traffic Beacon (ATB)

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

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



Adaptive Traffic Beacon (ATB)

- Adaptive selection of beacon interval ΔI

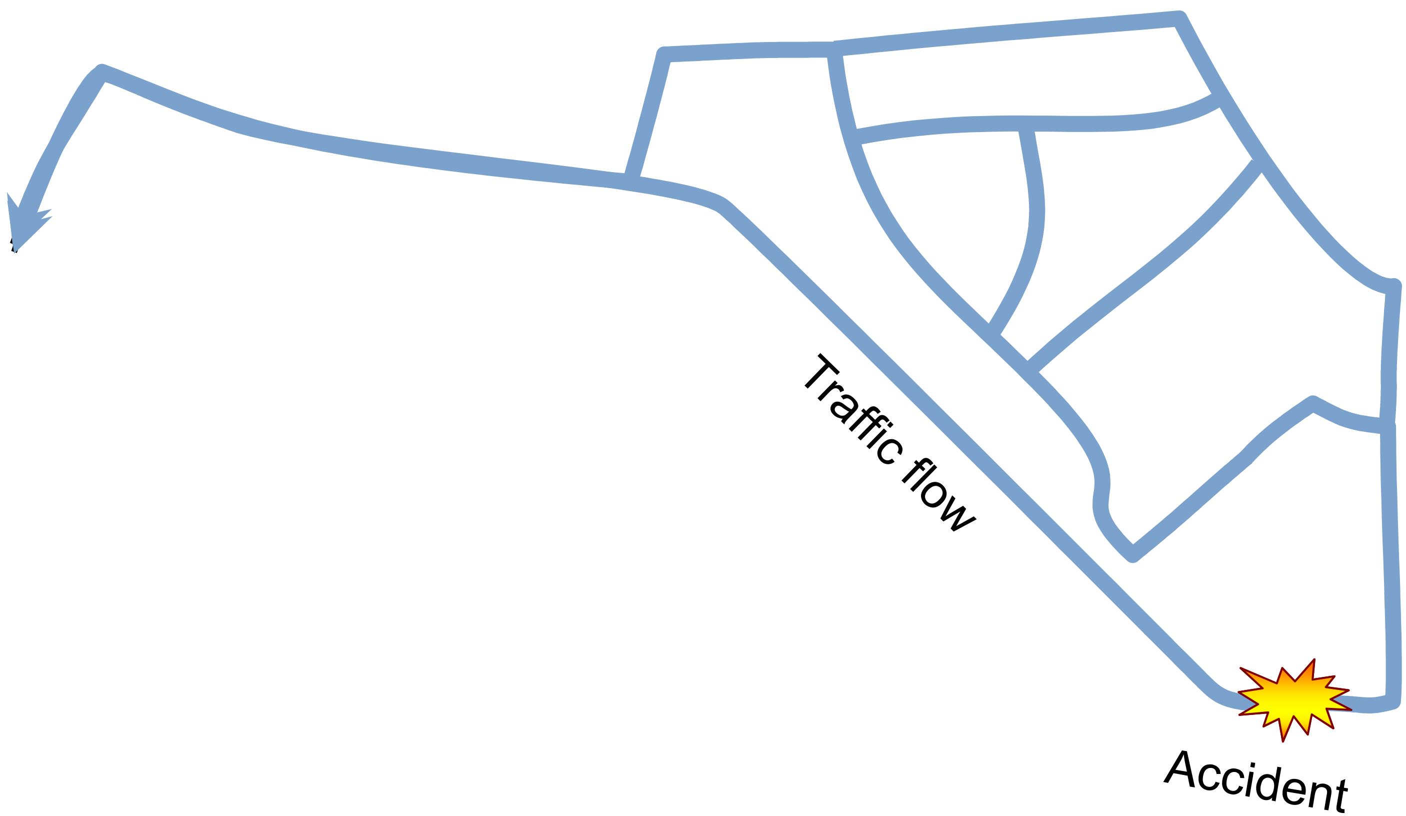
  - Calculation of message utility P based on metrics of (ex.)
    - A: age of information
    - D_e: distance to source of information
    - D_r: distance to closest Road Side Unit (RSU)
    - B: ratio of beacon contents received from Road Side Unit (RSU)

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

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

Envisioned Scenario

- Highly dynamic network



Simulative Performance Analysis

- Comparison with static beaconing
  - Static beaconing gets better as beaconing frequency increases
    - but channel load increases sharply
  - ATB performs as good as static beaconing at highest frequencies
    - at the same time keeps load lower than at lowest frequency

Main Takeaways

- Traffic Information System (TIS)
  - Goals
  - Principles
- PeerTIS
  - Use of infrastructure
  - DHT, CAN concepts
- SOTIS
  - Beacons
  - Knowledge bases
- ATB
  - Adaptivity

Privacy

Motivation

- Aspects of privacy
  - Privacy of location
    - Where is the target individual?
    - Where was the target individual at a given time?
    - Where will the target individual likely be at a given time?
  - Privacy of interests
    - Hobbies, services, news sources, …
  - Privacy of social standing
    - Job, income, debt, home, contractual obligations, …
  - Privacy of social network
    - Family, friends, friends-of-friends, acquaintances, …

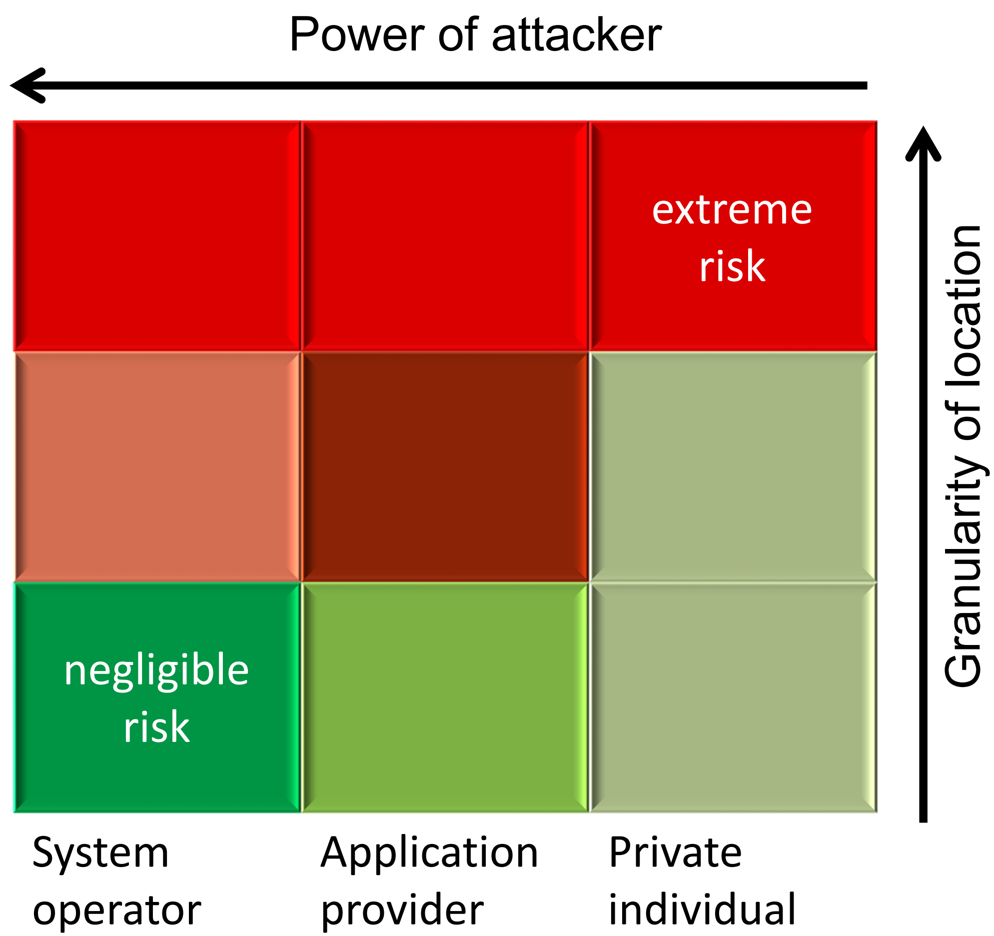
Motivation

- Who (and how powerful) is the attacker?
  - Government
    - Can mandate access to all information
  - System operator
    - Can obtain access to all information
  - Service provider
    - Has access to all information
  - Application developer
    - Can access device

  - Company
    - High coverage using wide area deployments (e.g., WiFi-APs)
  - Organization
    - Good coverage via cooperations
  - Private individual
    - Must target individual areas

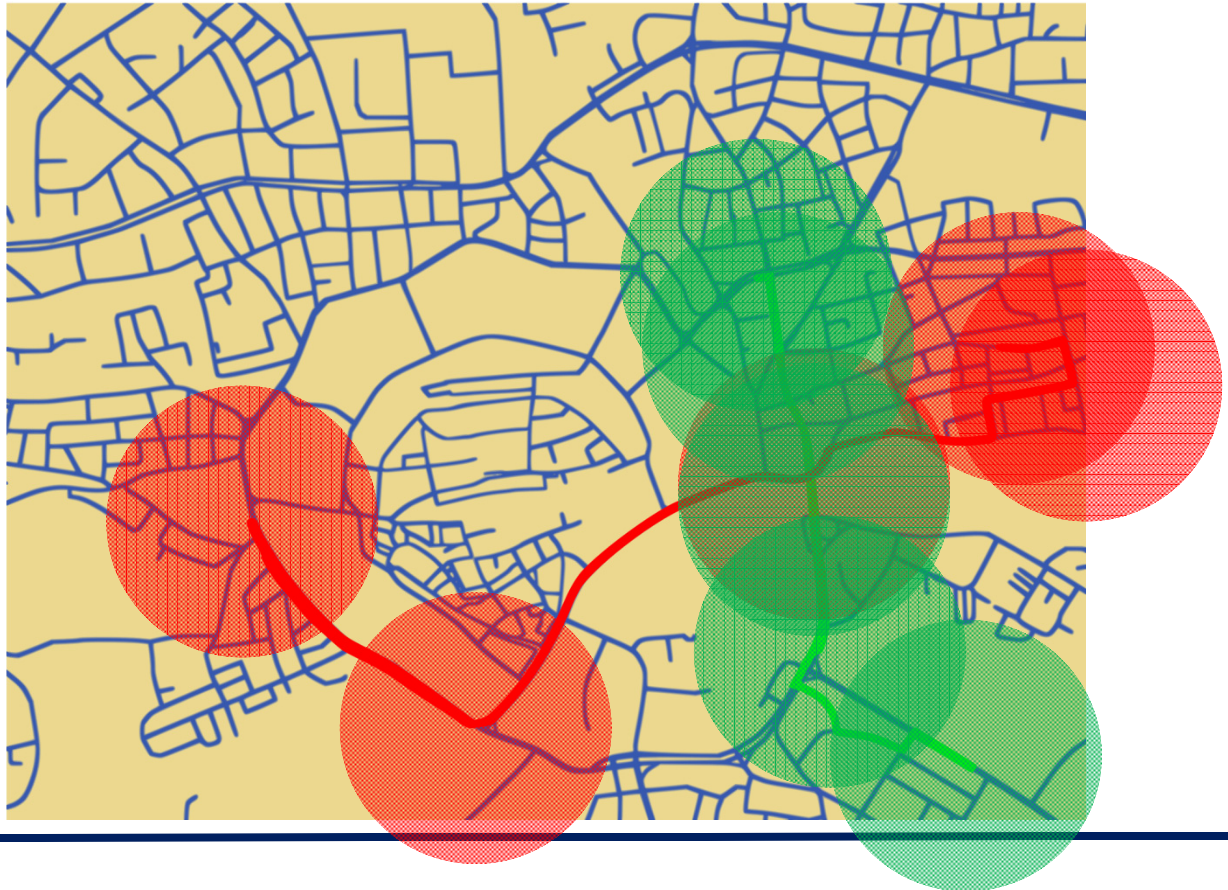
Motivation

- Level of risk



Motivation

- Tracking
  - Vehicles periodically send Hello Beacons, received by observers
  - Beacons contain uniquely-identifying information



Motivation

- Safety and Security
  - Authentication, Authorization, Accounting, Auditing, ...
  - ...often need unique identification of peers
- Conflicts with users' privacy
  - Very long life-cycle of vehicles
  - Information can be aggregated over very long time periods
  - Correlating identity ⇔ location allows for tracking

[1] Dötzer, Florian, "**Privacy Issues in Vehicular Ad Hoc Networks**," Proceedings of 5th International Workshop on Privacy Enhancing Technologies (PET 2005), vol. LNCS 3856, Cavtat, Croatia, May 2005, pp. 197-209

Consequences

- Examples:
- Police records movement traces
  - Citation for breaking the speed limit
- Employer identifies parking vehicles
  - Keeps records of when employees come and go
- Insurance company buys movement traces
  - Denies contract renewal because of too many trips to hospital

Privacy

- Need to protect against
  - Identification of vehicle
  - Re-identification of vehicle
- Identifying properties
  - Characteristic properties of application, system, radio
    - Timing, packet size, RF-fingerprint, ...
  - Plain identifiers
    - MAC address, IP address, Login, ...
    - Certificate (necessary for participation!)
- Absolute Anonymity?
  - Made impossible by most protocols and/or use cases

[1] A. Pfitzmann, and M. Hansen, Anonymity, Unobservability, and Pseudonymity: A Proposal for Terminology, H. Federrath (Ed.), Designing Privacy Enhancing Technologies, LNCS 2009, pp. 1-9, 2000

Anonymity

Anonymity is…

"the state of being not identifiable
within a set of subjects,
the anonymity set"

(Pfitzmann/Hansen)

[1] A. Pfitzmann, and M. Hansen, Anonymity, Unobservability, and Pseudonymity: A Proposal for Terminology, H. Federrath (Ed.), Designing Privacy Enhancing Technologies, LNCS 2009, pp. 1-9, 2000

Pseudonymity

- Communication using pseudonyms
  - Sign messages using pseudonymous certificates
  - Receiver can check if signed by trusted CA
  - Base identity never revealed to other vehicles
- Revocation of Pseudonyms
  - Dissemination of Certificate Revocation List (CRL)
    via Internet, RSUs, or Car-to-Car
  - Open questions: availability, scalability (speed, size of CRL)
  - CA knows mapping from base identity ⇨ pseudonym;
    can revoke all related pseudonyms

Pseudonymity

- Obtaining pseudonymous certificates
  1. Certificate authority (CA) sends base identities to manufacturer
  2. Manufacturer installs one base identity each in new cars
  3. When cars start operating, they create pseudonyms and have them signed by CA (using their base identity)

Pseudonymity

- Limits of pseudonymity
  1. Does not (per se) prevent re-identification
     - Re-identification can still reveal identity of user
     - Ex from [1]:
       - Knowledge of census tract (1500 people each) for home and workplace
       - Reduces anonymity set to ≤ 5 people (for 25% of population)
       - Reduces anonymity set to ≤ 2 people (for 7% of population)
  2. Operator knows mapping from pseudonym ⇔ identity

[1] Golle, P. and Partridge, K., "On the Anonymity of Home/Work Location Pairs," Proceedings of 7th International Conference on Pervasive Computing, vol. LNCS 5538, Nara, Japan, May 2009, pp. 390-397

Pseudonymity

- Goal
  - Vehicles periodically send Hello Beacons, received by observers
  - Now: use of many pseudonymous identifiers to prevent tracking

Pseudonym Pools

- How to prevent re-identification?

- Pseudonym pools
  - Create pool of pseudonyms (instead of single one)
  - Switch between different pseudonyms
- Validity
  - No restrictions
  - Spatial restrictions
  - Temporal restrictions
- Switching strategies
  - How to enhance anonymity?
  - Tradeoff between safety and privacy
    - MUST have static identifiers for safety, MUST NOT have for privacy

Pseudonym Pools

- Pseudonym selection strategies:

- Fully random
- Periodic
  - Switch to another pseudonym every x seconds
- Geographic
  - Switch to another pseudonym depending on region
- Context sensitive
  - Switch when confusion of (potential) attackers is maximal
    - Wait for high number of neighbors
    - Wait for neighbors with similar position, angle, speed, …

[1] B. Chaurasia and S. Verma, “Maximizing anonymity of a vehicle through pseudonym updation,” in 4th International Conference on Wireless Internet (WICON 2008), Maui, HI, November 2008

[2] M. Gerlach and F. Guttler, “Privacy in VANETs using Changing Pseudonyms - Ideal and Real,” in 65th IEEE Vehicular Technology Conference (VTC2007-Spring), Dublin, Ireland, April 2007, pp. 2521–2525.

Pseudonym Pools

- Enhanced strategies:

- Random Silent Periods
  - After switching pseudonyms, cease transmitting for random time

- Group strategic approaches
  - Coordinate silent periods among neighbors
  - Coordinate pseudonym changes among neighbors
  - Elect group leader, establish encrypted tunnel, use as proxy

[1] L. Huang, K. Matsuura, H. Yamane, and K. Sezaki, "Enhancing wireless location privacy using silent period," in IEEE Wireless Communications and Networking Conference (WCNC 2005), New Orleans, LA, March 2005

[2] K. Sampigethaya, L. Huang, M. Li, R. Poovendran, K. Matsuura, and K. Sezaki, "CARAVAN: Providing location privacy for VANET," in Embedded Security in Cars (ESCAR 2005), Tallinn, Estonia, July 2005

Pseudonym Pools

- How to prevent tracking by operator?

- Destroy operator's mapping of pseudonym(s) ⇔ identity:
- Exchange of pseudonyms among vehicles
  - Hand over key material to random neighbor
  - Take over pseudonym of neighbor

- Blind signatures
  - Encrypt 100 pseudonyms, transmit to CA for signing
  - CA requests, checks contents of 80
  - Blindly signs remaining 20 (if successful)

[1] D. Eckhoff, C. Sommer, T. Gansen, R. German, and F. Dressler, "Strong and Affordable Location Privacy in VANETs: Identity Diffusion Using Time-Slots and Swapping," in 2nd IEEE Vehicular Networking Conference (VNC 2010). Jersey City, NJ: IEEE, December 2010, pp. 174–181.

[2] F. Schaub, F. Kargl, Z. Ma, and M. Weber, "V-tokens for Conditional Pseudonymity in VANETs," in IEEE Wireless Communications and Networking Conference (WCNC 2010). Sydney, Australia: IEEE, April 2010.

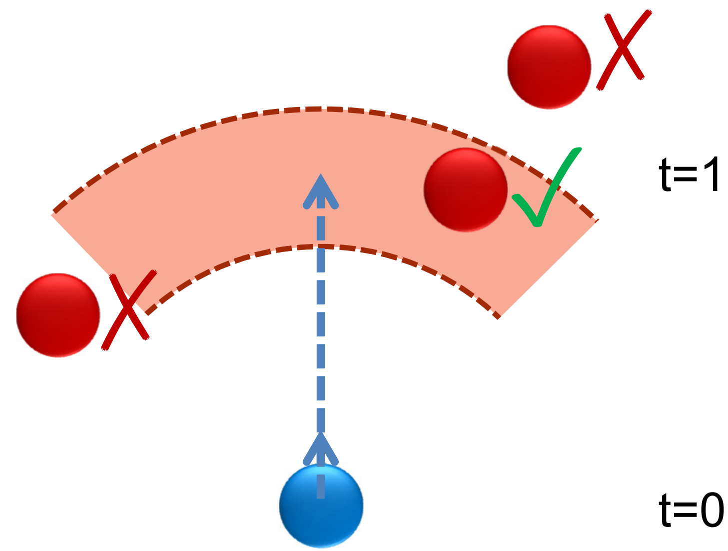
Quantifying Privacy

- How to compare different strategies?
  - Need a way to quantify privacy
- Next slides: three selected privacy metrics
  - Maximum Tracking Time
  - Anonymity Set Size
  - Entropy
- Still: impact of strategies hard to gauge
  - Need to know power/methods of attacker
  - Also: scenario dependent (traffic density, network topology, …)

Quantifying Privacy

- Dead Reckoning
  - Simplest algorithm to track cars

- Algorithm
  1. Predict new position based on heading, speed
  2. Consider maximum change in speed, maximum turning angle
  3. Remove candidates with positions that differ too much



Quantifying Privacy

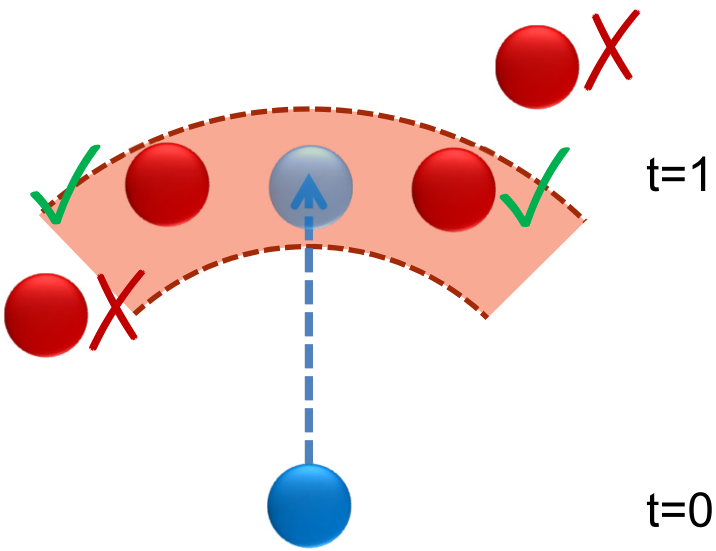
- Privacy Metric: Maximum Tracking Time
  - How long was an attacker able to follow a vehicle's path?
  - The shorter, the better

- Algorithm
  - For every vehicle, keep track of current position, start timer
  - Correlate position samples over time (e.g., via dead reckoning)
  - If correlation impossible (or leads to false result), stop timer

- Drawbacks of Max Tracking Time
  - Distinguishing correct/false results needs *oracle*
  - Prediction can yield more than one potential position, thus:
    Tendency to underestimate maximum tracking time, i.e., to overestimate level of privacy

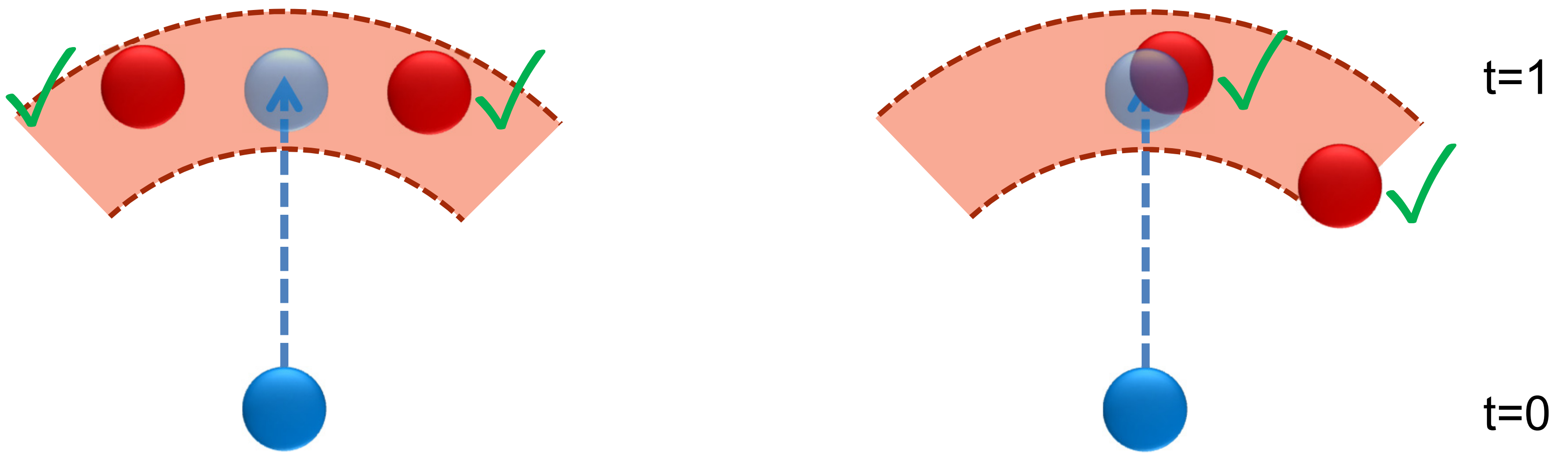
Quantifying Privacy

- Privacy Metric: Anonymity Set Size
  - Recall: anonymity set ⬄ all nodes indistinguishable from target
    - Target T located in one of vehicles a_i
  - Metric: cardinality of anonymity set
    - $A_T = \{a_1, a_2, \cdots, a_i, \cdots, a_n,\}$
    - $|A_T| = n$
- Indication of degree of uncertainty



Quantifying Privacy

- Anonymity Set Size: Problem
  - Not every vehicle a_i is equally probable, thus:
    Tendency (of anonymity set size) to overestimate level of privacy



$$|A_T| = 2 \quad =? \quad |A_T| = 2$$

Quantifying Privacy

- Towards a solution:
- Consider *probabilities* of members in anonymity set
  - Let p_i: probability of i-th node of anonymity set being the target individual T
  - Let sum of all p_i be 1
  - $A_T = \{a_1, a_2, \cdots, a_i, \cdots, a_n\}$
  - $|A_T| = n$
  - $\sum_{i=1}^{|A_T|} p_i = 1$

Quantifying Privacy

- Privacy Metric: (information theoretic) entropy
  - Degree of uncertainty for mapping node ⇔ target
  - Calculate entropy $\mathcal{H}_p$ as:
    - $\mathcal{H}_p = -\sum_{i=1}^{|A|} p_i \times \log_2 p_i$
  - $\mathcal{H}_{p,max} = -\sum_{i=1}^{|A|} p_i \times \log_2 p_i = \log_2 |A| \qquad \text{if } \forall p_i = \frac{1}{|A|}$
  - i.e., maximum entropy if all probabilities p_i equal:

[1] A. Serjantov and G. Danezis. „Towards an Information Theoretic Metric for Anonymity“. In 2nd International Workshop on Privacy Enhancing Technologies (PET 2002), pages 259–263, San Francisco, CA, April 2002

Quantifying Privacy

- Benefit of using entropy as privacy metric:

- Example 1:
  - Equal probability of mappings in anonymity set
  - Let $p_0 = 50\%;\ p_1 = 50\%$
  - $\mathcal{H} = -(.50 \log_2 .50 + .50 \log_2 .50) = 1$

- Example 2:
  - (Very) unbalanced mappings
  - Let $p_0 = 99\%;\ p_1 = 1\%$
  - $\mathcal{H} = -(.99 \log_2 .99 + .01 \log_2 .01) \approx .08$

  - Very low level of anonymity (even though equal set size)

Main Takeaways

- Threats to privacy
- Definition of anonymity

- Pseudonyms
  - Pseudonymous certificates
  - Selection strategies

- Quantifying privacy
  - Maximum tracking time
  - Anonymity set size
  - (Information theoretic) entropy
  - Pros / Cons

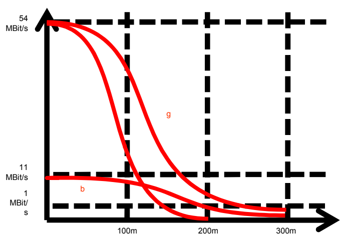
Performance Evaluation

…how to tell what works and what does not

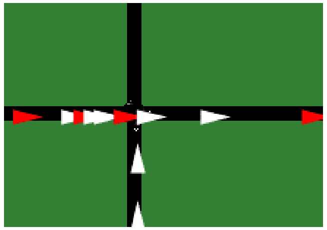
Approaches to Performance Evaluation

- Field Operational Tests
  - \+ Highest degree of realism
  - \- no in-depth investigations of network behavior
  - \- Non-suppressible side effects
  - \- Limited extrapolation from field operational tests
    - some 100 vehicles ⇔ 2% market penetration? (or 10%, or 100%)

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



- Simulation
  - Can serve as middle ground



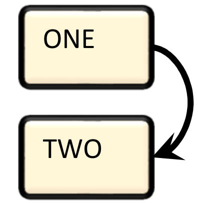
Requirements for Simulation

- 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

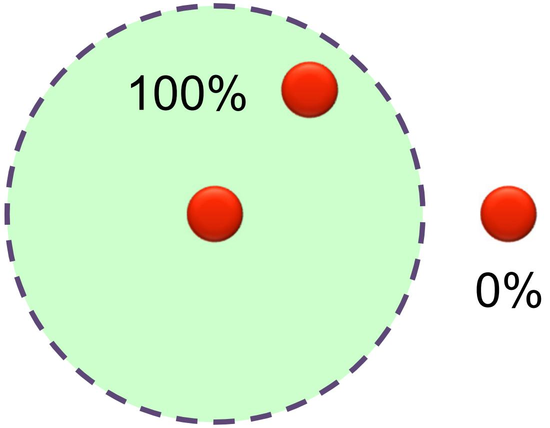


- Dedicated simulation tools
  - Discrete Event Simulation (DES) kernel
  - Manages queue of events (e.g., “an IP fragment was received”)
  - Delivers events to simulation models
- Model libraries
  - Simulate components’ reaction to events
  - E.g., HTTP server, TCP state machine, radio channel, human,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

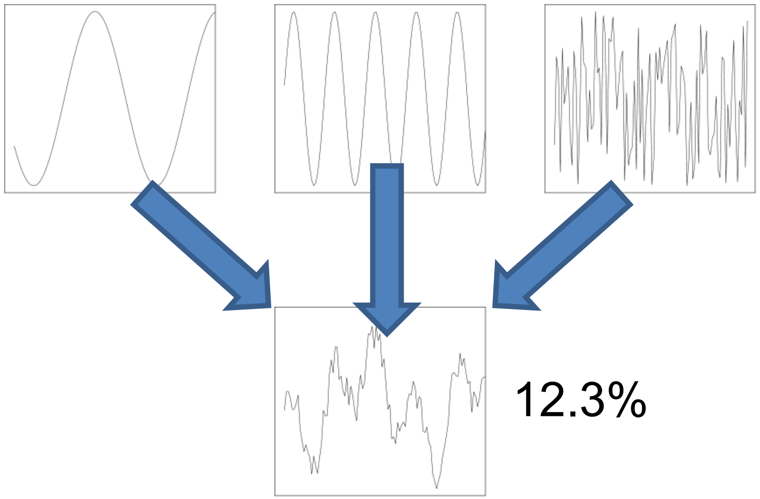
Engine	Language	Library	Language
OMNeT++	C++	MiXiM	C++
ns-2 / ns-3	C++	ns-2 / ns-3	Objective Tcl / Python
JiST	Java	SWANS	Java

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)

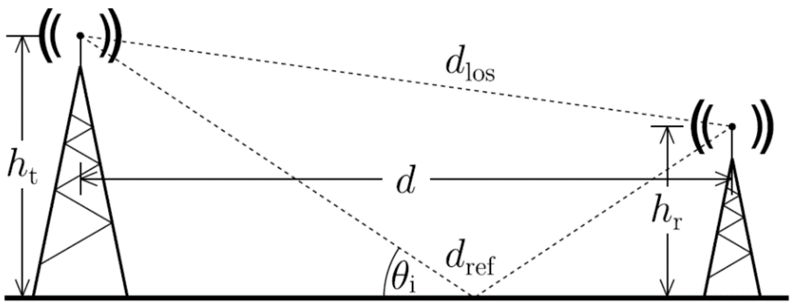


Modeling Radio Propagation

- Signal attenuation
  - Received power depends on
    - transmitted power,
    - antenna gains
    - loss effects
  - $P_r[\mathrm{dBm}] = P_t[\mathrm{dBm}] + G_t[\mathrm{dB}] + G_r[\mathrm{dB}] - \sum L_x[\mathrm{dB}]$
- Free space path loss
  - $L_{\mathrm{freespace}}[dB] = 20\lg\left(4\pi\frac{d}{\lambda}\right)$
- Empirical free space path loss
  - $L_{\mathrm{freespace,emp}}[dB] = 10\lg\left(4\pi\frac{d}{\lambda}\right)^{\alpha}$

Modeling Radio Propagation

- Two Ray Interference path loss



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

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

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

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

Illustration source: C. Sommer and F. Dressler, "Using the Right Two-Ray Model? A Measurement based Evaluation of PHY Models in VANETs," Proceedings of 17th ACM International Conference on Mobile Computing and Networking (MobiCom 2011), Poster Session, Las Vegas, NV, September 2011.

Modeling Radio Propagation

- Comparison: Two Ray Interference vs. Free Space

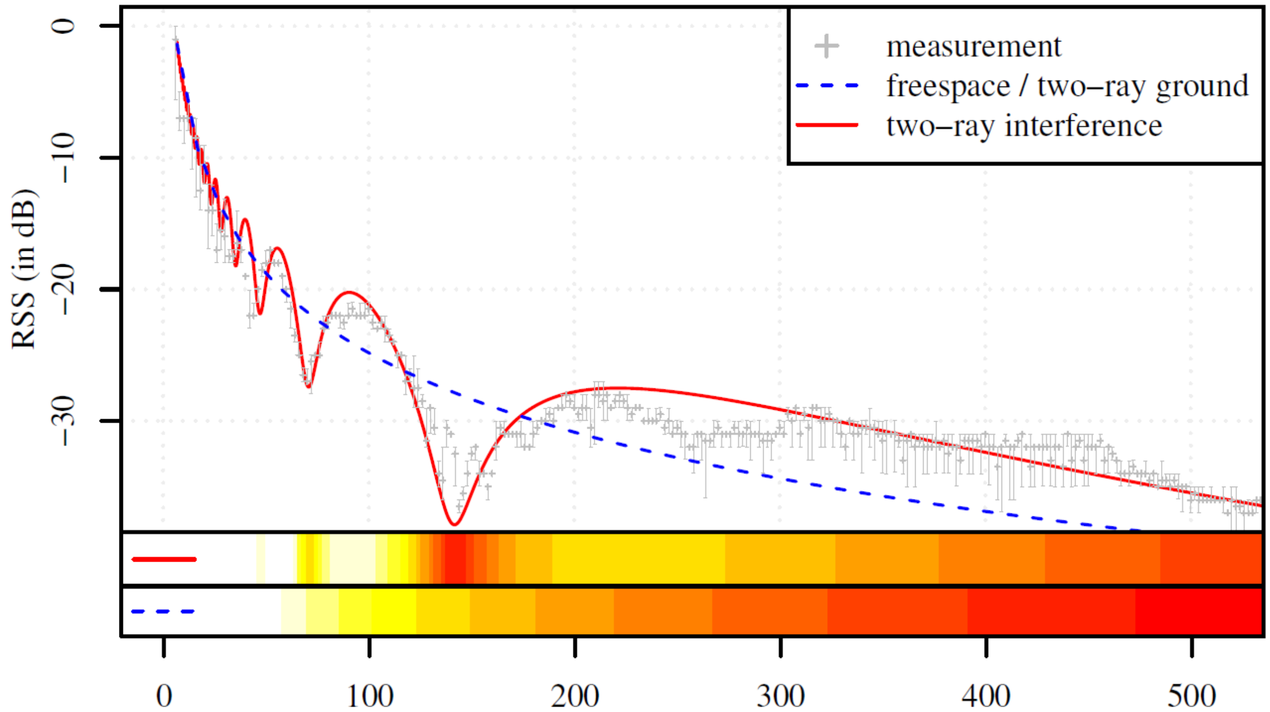


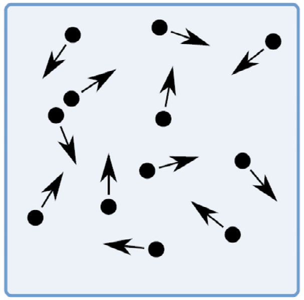
Illustration source: C. Sommer and F. Dressler, "Using the Right Two-Ray Model? A Measurement based Evaluation of PHY Models in VANETs," Proceedings of 17th ACM International Conference on Mobile Computing and Networking (MobiCom 2011), Poster Session, Las Vegas, NV, September 2011.

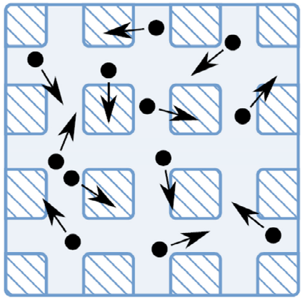
Modeling Radio Propagation

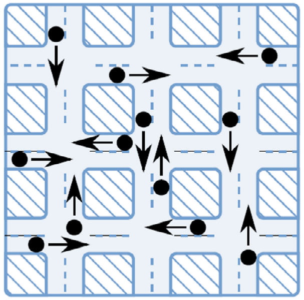
- Lognormal shadowing
  - Lognormal distribution of losses via random process
  - $L_{\mathrm{lognorm}}[\mathrm{dB}] \sim \mathcal{N}(0, \sigma^2)$
- Very(!) simple obstacle model
  - Take into account:
    distance through matter,
    number of walls
  - $L_{\mathrm{obs}}[\mathrm{dB}] = \beta n + \gamma d_m$

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







[1] J. Yoon, M. Liu, and B. Noble, "**Random waypoint considered harmful**," Proceedings of 22nd IEEE Conference on Computer Communications (IEEE INFOCOM 2003), vol. 2, San Francisco, CA, March 2003, pp. 1312-1321

Illustration source: C. Sommer, "Car-to-X Communication in Heterogeneous Environments," PhD Thesis (Dissertation), Department of Computer Science, University of Erlangen, June 2011

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

[1] V. Naumov, R. Baumann, and T. Gross, "**An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces**," Proceedings of 7th ACM International Symposium on Mobile Ad Hoc Networking and Computing (ACM Mobihoc 2006), Florence, Italy, March 2006, pp. 108-119

[2] M. Fiore, J. Härri, F. Filali, and C. Bonnet, "**Vehicular Mobility Simulation for VANETs**," Proceedings of 40th Annual Simulation Symposium (ANSS 2007), March 2007, pp. 301-309

[3] H-Y. Huang, P-E. Luo, M. Li, D. Li, X. Li, W. Shu, and M-Y. Wu, "**Performance Evaluation of SUVnet With Real-Time Traffic Data**," IEEE Transactions on Vehicular Technology, vol. 56 (6), pp. 3381-3396, November 2007

Modeling Mobility

- Improved approach: 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

- Latest approach: Bidirectional coupling
  - Road traffic simulator and network simulator run in parallel, exchange data in both directions
  - Network traffic can influence road traffic

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

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

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
    - …

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

Modeling Road Traffic

- Road traffic microsimulation
  - Ex.: PTV VISSIM
  - Car following and lane change model
    - Wiedemann (psycho-physiological model)
  - High precision modeling
    - Pedestrians
    - Motorbikes
  - Comparatively slow simulation, thus limited to small area

[1] VISSIM website, http://vision-traffic.ptvgroup.com/

[2] Wiedemann R.: Simulation des Straßenverkehrsflusses. Schriftenreihe des IfV, 8. Institut für Verkehrswesen. Universität Karlsruhe, 1974.

Modeling Car Following

- Krauss car following model
  - Maximum velocity v_{max} ⇔ safe gap g_{des} ⇔ dawdle factor ϵ
  - $v_{safe} = v_l + \frac{g - g_{des}}{\tau_b + \tau}$
  - $v_{des} = \min\{v_{max}, v + a\Delta t, v_{safe}\}$
  - $v(t + \Delta t) = \max\{0, v_{des} - \eta\}$
  - $\eta = \mathrm{rand}[0, \epsilon a]$

- Intelligent Driver Model (IDM)
  - Desired velocity v_0 ⇔ safe distance s^*
  - $s^* = s_0 + s_1\sqrt{\frac{v}{v_0}} + vT + \frac{v\Delta v}{2\sqrt{ab}}$
  - $\dot{v} = a\left(1 - \left(\frac{v}{v_0}\right)^\delta - \left(\frac{s^*}{s}\right)^2\right)$

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

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

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

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

VSimRTI

- “V2X Simulation Runtime Infrastructure”
- Inspired by High Level Architecture (HLA).
- Multiple Simulators connect to VSimRTI
  - Application Simulator
  - Traffic Simulator
  - Communication Simulator
  - Environment Simulator
- Each simulator needs only be extended by a common coupling interface, the “Federate Ambassador”

[1] B. Schünemann. "V2X simulation runtime infrastructure VSimRTI: An assessment tool to design smart traffic management systems." Computer Networks 55.14 (2011): 3189-3198.

iTETRIS

- EU FP7 project to create a simulation framework for ETSI ITS
- NS-3, SUMO, and Application Simulator are connected to iCS process
- iCS process takes care of synchronization and control, implements part of the ETSI ITS “Facilities Layer”

[1] J. Härri, P. Cataldi, D. Krajzewicz, R. J. Blokpoel, Y. Lopez, J. Leguay, C. Bonnet, and L. Bieker, “Modeling and simulating ITS applications with iTETRIS,” in 6th ACM Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks (PM2HW2N 2011). Miami Beach, FL: ACM, October 2011, pp. 33–40

Veins

http://veins.car2x.org

- Oldest and most cited of the three
- Open Source vehicular network simulation *framework*
- Module library for OMNeT++ network simulator
  ⇨ Based on well-established simulator, easy to use for research and teaching
  ⇨ Easily extensible, re-configurable for new projects
  - Diverse modules of IVC-specific channels and protocol stack complement other module frameworks
- Road traffic simulation as auxiliary part
  - SUMO simulator

[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

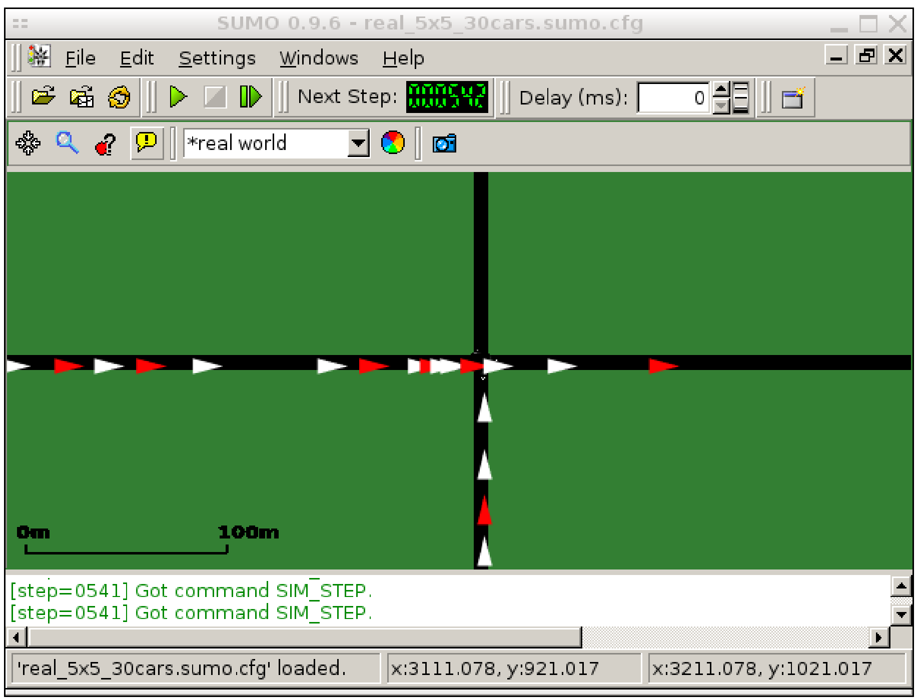
- OMNeT++
  - Discrete-Event Simulation (DES) kernel
    - Simulate model's reaction to queue of events
  - Main use case: network simulation
    - e.g., MANETs, Sensor nodes

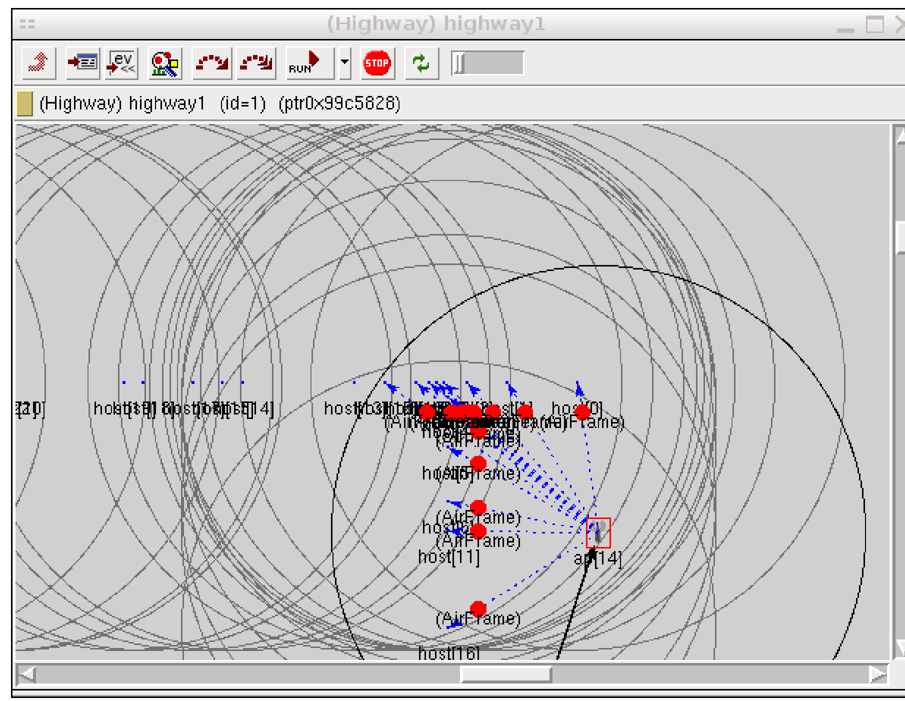
- MiXiM
  - Model library for OMNeT++ for PHY layer and mobility support
  - Event scheduling
  - Signal propagation
  - SINR / bit error calculation
  - Radio switching
  - …

[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
  - OMNeT++ sends request for simulator parameters, vehicle position, etc. ⇨ SUMO responds
  - Can also “subscribe” to changes in the simulation ⇨ automatically receive change notifications for vehicle positions, vehicles starting in the simulation, etc.

[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

Simulation Scenarios

- Mobility model consists of two parts
  - Motion constraints
  - Traffic demand
- Motion constraints are…
  - Road topology
  - Speed limits
  - …
- Traffic demand is…
  - Which cars start where
  - How driver behaves during trip
  - …

[1] J. Härri, F. Filali, and C. Bonnet, “A framework for mobility models generation and its application to inter-vehicular networks,” in 2005 International Conference on Wireless Networks, Communications and Mobile Computing. Maui, HI: IEEE, June 2005, pp. 42–47.

Simulation Scenarios

- Nowadays, motion constraints are easy to obtain
  - Freely available road topology and speed limit information from OpenStreetMap project
- Traffic demand is much harder
  - Often no publicly available information on traffic flows
  - If synthetic traffic demand does not match motion constraints, scenario fails
    - E.g. only few cars using main roads + lots of cars using small roads ⇨ traffic lights not calibrated to this demand ⇨ gridlock

Metrics

- Assumed “benefit” of solutions depends fully on metric
- Ex.: when is it beneficial to take a detour around an accident?
  - Might be beneficial in terms of travel time
  - …but **not** beneficial in terms of CO_2 emissions

[1] C. Sommer, R. Krul, R. German and F. Dressler, "Emissions vs. Travel Time: Simulative Evaluation of the Environmental Impact of ITS," Proceedings of 71st IEEE Vehicular Technology Conference (VTC2010-Spring), Taipei, Taiwan, May 2010

Main Takeaways

- Approaches to performance evaluation
  - Pros/Cons
- Requirements for simulation
  - Models, Scenarios, Metrics
- Simulation
  - Modeling network traffic
  - Modeling road traffic
- Scenarios
  - What’s in a scenario?
- Metrics

Vehicular Networking