

M2-RTS

Réseaux du Futur

ITS: IEEE 802.11p / MAC

membre de
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Département Télécommunications
Services & Usages

INSA LYON

Réseaux du Futur - ITS

- Intelligent Transportation Systems
  - Definition, history, current status
  - Evolution and envisioned applications
- ITS: vehicular mobility
  - Models, validation tests, simulation tools, analysis
- ITS: the IEEE 802.11p standard
  - RF signal propagation, PHY layer
  - MAC layer, V2V/V2I communication
- ITS: data management and applications
  - IEEE 1609, communication paradigms





IEEE 802.11p



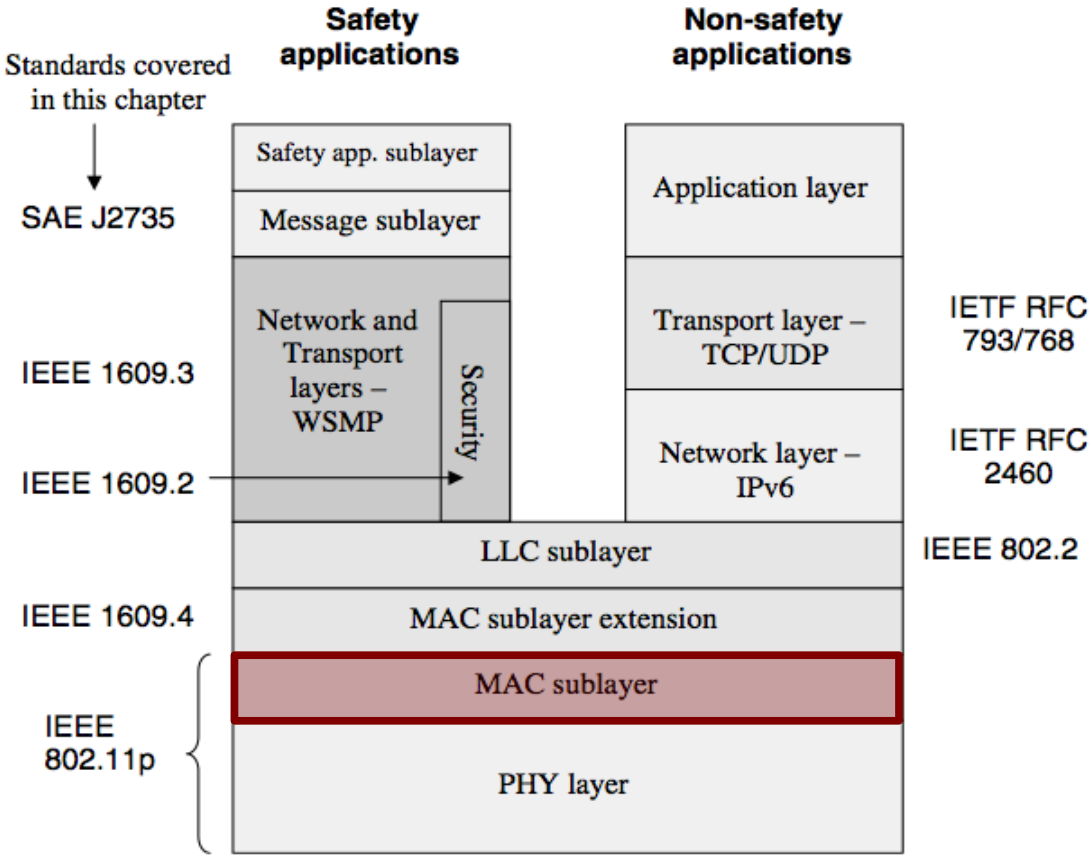






OSI Layering

- IEEE 802.11p / MAC layer









IEEE 802.11p

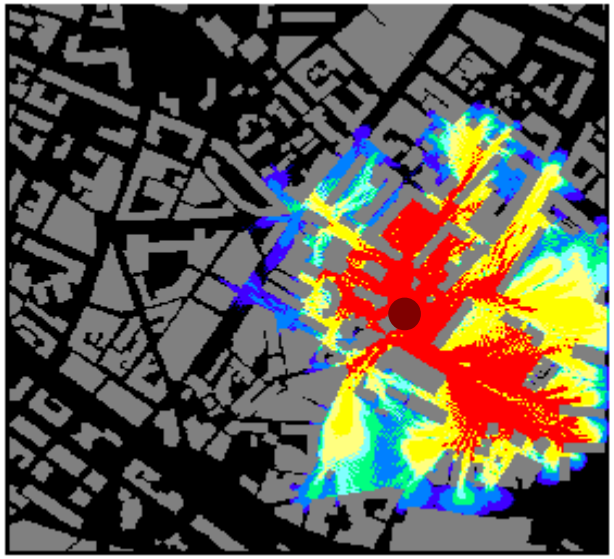
- Data rate adaptation
  - Problem and standard solution
  - Vehicular environments
- Medium access control
  - Problem
  - Standard solutions
  - 802.11p implementation
- Architecture and experimental tests
  - WBSS
  - Throughput and handover



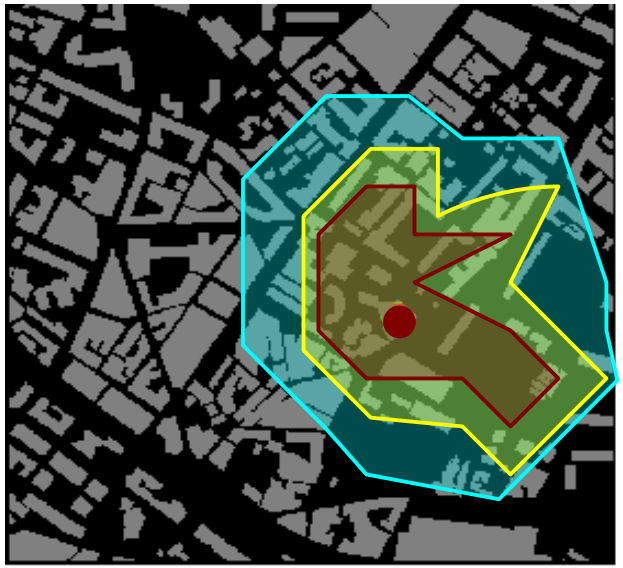


IEEE 802.11p / MAC

- From physical transmission to networking (I)
  - a **layer 2** view of node transmission



RF signal propagation



achievable data rates

Q. how to choose the data rate (i.e., modulation)?

A. layer 2 **rate adaptation!**

IEEE 802.11p / MAC

- Data rate adaptation: basics

54 Mbps or 6 Mbps ?





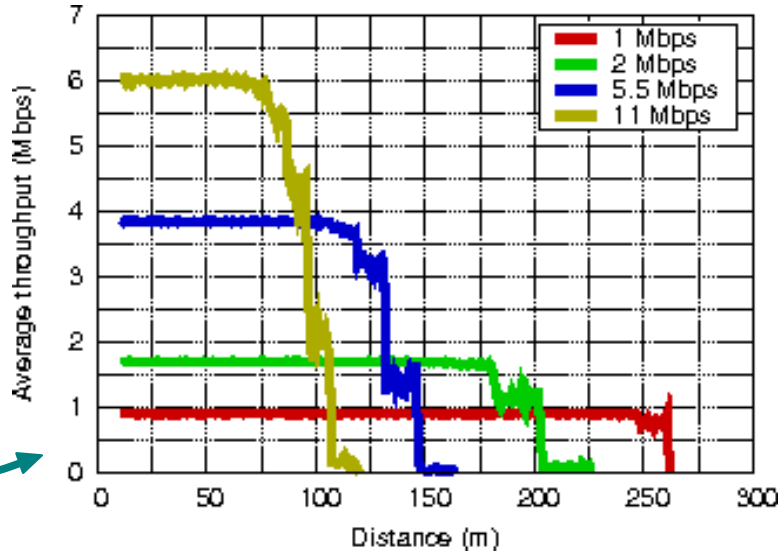
- data rate is determined by *modulation at sender*
- **higher data rate**

  ▼

  more **complex modulation**

  ▼

  higher SINR required



1. ***ideal propagation environment:*** *SINR only depends on **distance** between nodes*
2. *higher data rates have a shorter reach*
3. *to reach distant nodes a transmitter is forced to adapt its data rate*







IEEE 802.11p / MAC

- Data rate adaptation: basics

54 Mbps or 6 Mbps ?



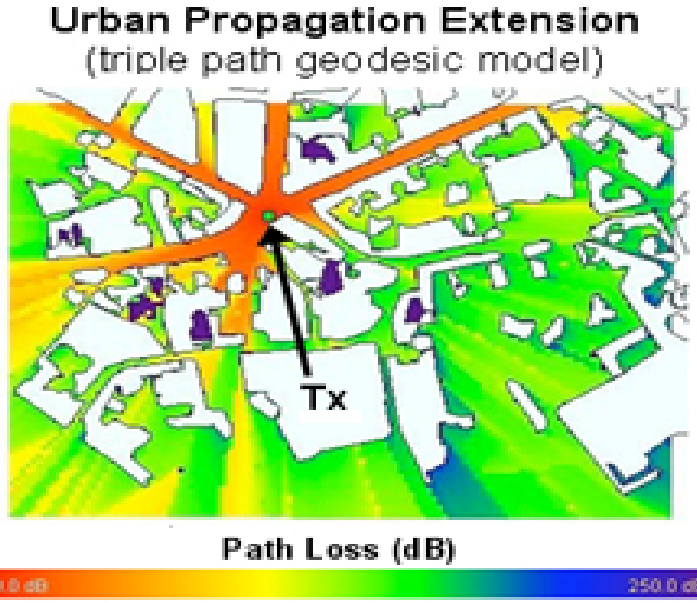
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  ▼

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  ▼

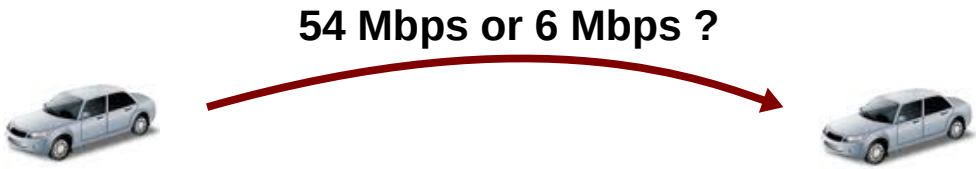
  higher SINR required



1. ***real propagation environment:*** *SINR does not only depend on* ***distance***
2. *we cannot rely on distance to choose the data transmission rate at sender*
3. *...yet, the data rate depends on SINR!*

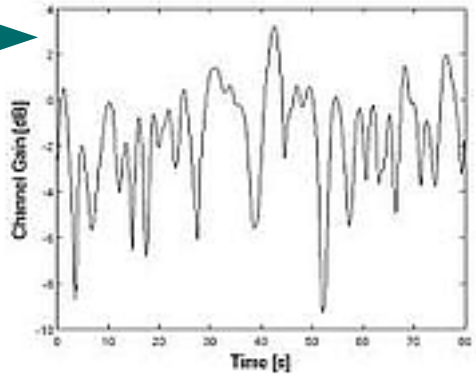
IEEE 802.11p / MAC

- Data rate adaptation: basics



- achievable data rates **depend on SINR**, but...
- ...in WiFi, typical solutions are **unbound from SINR**
  - only **available at receiver** → *introduce SINR feedback loop?*
  - **unreliable!**
  - **multiple** receivers?

different SINR for each receiver of a broadcast transmission



instant SINR is not reliable

- IEEE 802.11 protocol family: **no recommendation**!

IEEE 802.11p / MAC

- Data rate adaptation: basics
  - typical **WiFi** solution: **A**uto **R**ate **F**allback, **ARF**
    - **trial-and-error** approach

> ***set*** *data rate to* ***basic rate***
> ***every 10 consecutive*** *frames correctly ACK'ed*
> ***increase*** *data rate of one step*
> ***every 2 consecutive*** *frames unACK'ed*
> ***decrease*** *data rate of one step*

    - maximum reliability for **important messages**

> ***send*** *all control messages at* ***basic rate***

    - maximum reliability for messages to **multiple receivers**

> ***send*** *all broadcast messages at* ***basic rate***

  - note: *actual implementations are* ***vendor-specif c*** *and not public!*

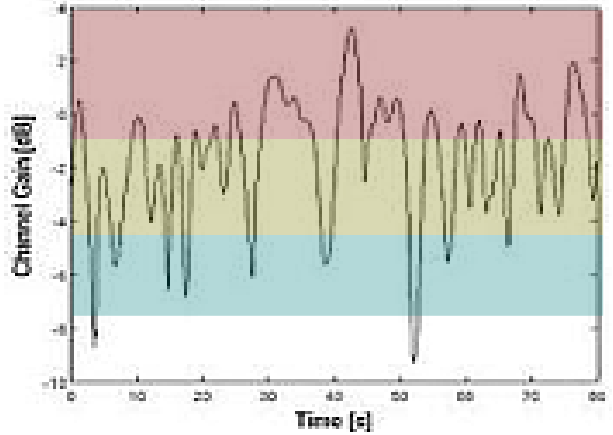




IEEE 802.11p / MAC

- Data rate adaptation: vehicular networks
  - does ARF work in **vehicular environments**?
  - experimental performance comparison

[1] ARF
[2] window-based ARF → *ARF on a (large enough) window of sent packet*
[3] SINR-based



- *54 Mbps*
- *24 Mbps*
- *6 Mbps*
- *insuff cient SINR*

→ *associate a modulation (data rate) to a SINR interval:* ***requires feedback!***

[4] SINR-based w/ packet bursts → *send bursts of packets upon handshaking the data rate with receiver*

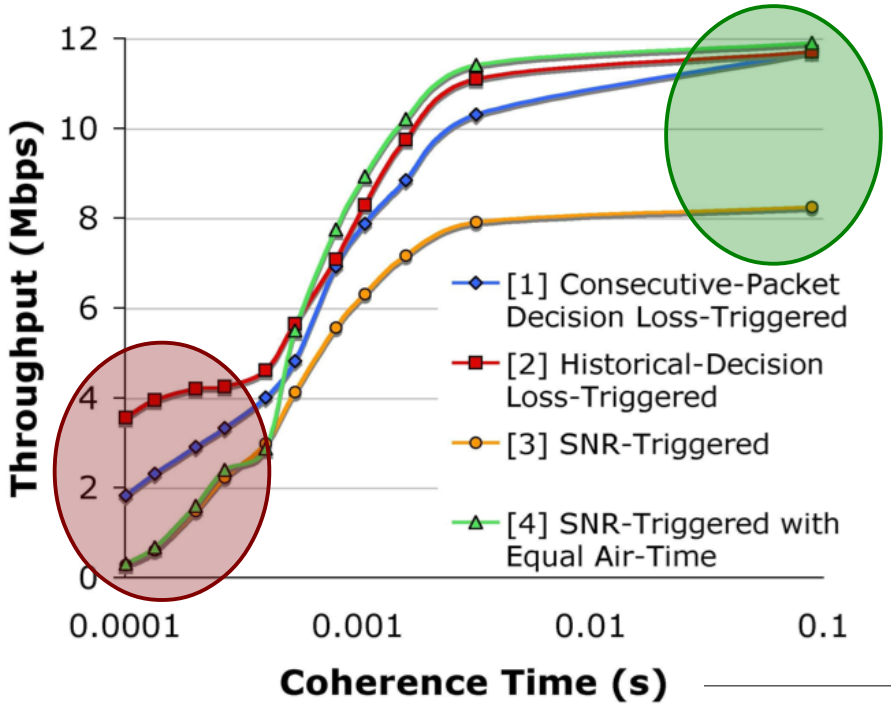




IEEE 802.11p / MAC

- Data rate adaptation: vehicular networks
  - does ARF work in **vehicular environments**?

results of tests in a **controlled** (lab) environment



static / indoor

mobile / outdoor

schemes perform similarly in static or indoor environments...

*...but **mobile outdoor** environments induce signif cant differences!*

depends on speed of transmitter, receiver and mobile obstacles



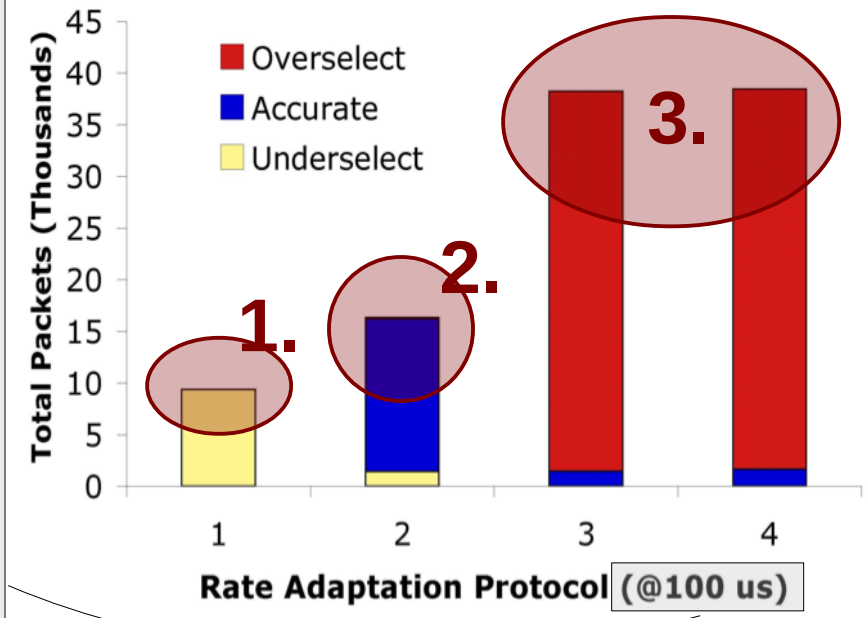




IEEE 802.11p / MAC

- Data rate adaptation: vehicular networks
  - does ARF work in **vehicular environments**?

focus on **fast-fading** channel with **small coherence time**









1. ***ARF is too pessimistic****: hard to have 10 consecutive successful transmissions, easy to have 2 consecutive losses*

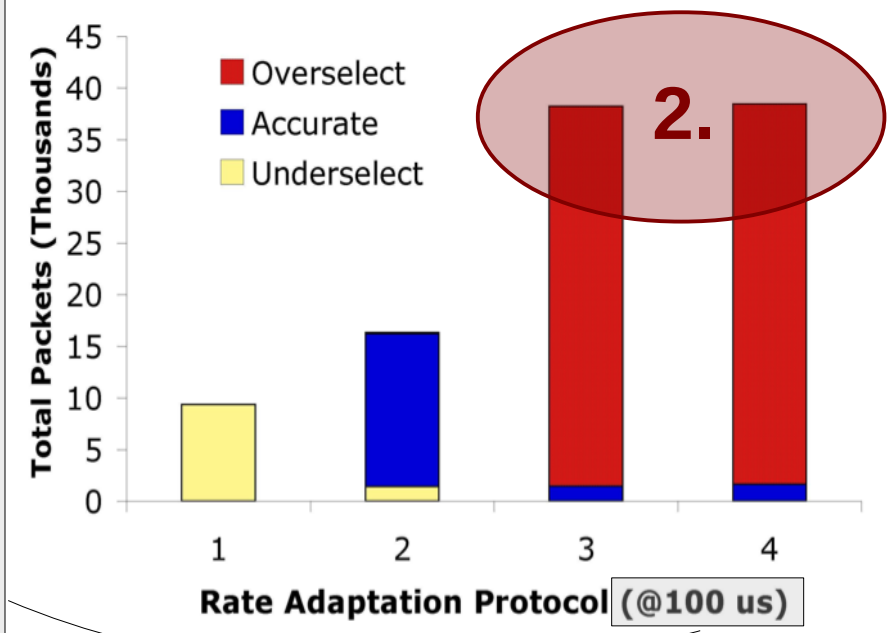
2. ***window-based ARF is the best****: evaluating over a longer time period avoids underselection of rates as in standard ARF*

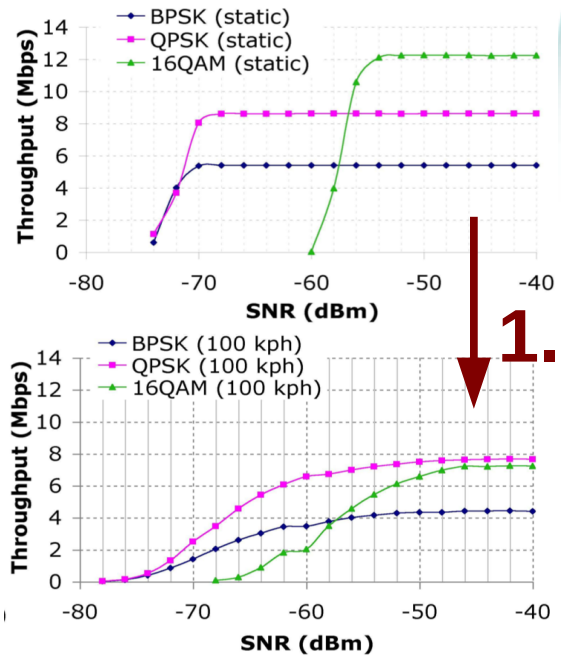
3. ***SINR-based largely overselect****: why?*

IEEE 802.11p / MAC

- Data rate adaptation: vehicular networks
  - does ARF work in **vehicular environments**?

focus on **fast-fading** channel with **small coherence time**







1. *a same **modulation** performs differently in static and mobile cases with same **SINR***

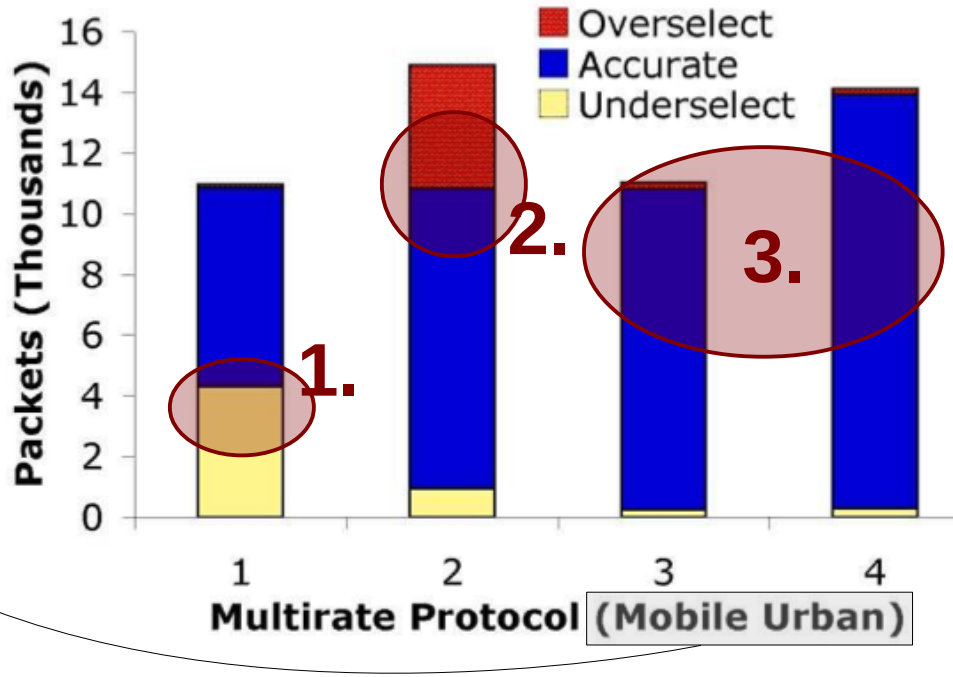
2. *SINR-based schemes designed for static/indoor are **too optimistic** and overselect*

IEEE 802.11p / MAC

- Data rate adaptation: vehicular networks
  - does ARF work in **vehicular environments**?

real-world **vehicular environment**

results of tests in a **real-world** environment









1. ***ARF is pessimistic****: same reasons as before*

2. ***window-based ARF now overselects****: cannot track the faster dynamics of a real-world environment*

3. ***SINR-based is now the best****: after* ***training for the vehicular environment****, it can adapt to the fast channel variations and provide the best performance*

IEEE 802.11p / MAC

- Data rate adaptation
  - **summary**
  - **no specif cations** in the **IEEE 802.11p** protocol
  - traditional **WiFi** solutions **cannot be reused**
    - *mobile/outdoor environments are way more challenging than static/indoor ones*
  - SINR-based solutions seem more f t to vehicular environments...
  - ...but further work is needed
    - *need for actual IEEE 802.11p cards with complete PHY layer implementation*
  - **who knows what vendors will implement?**





IEEE 802.11p

- Data rate adaptation
  - Problem and standard solution
  - Vehicular environments
- Medium access control
  - Problem
  - Standard solutions
  - 802.11p implementation
- Architecture and experimental tests
  - WBSS
  - Throughput and handover





IEEE 802.11p / MAC

- From physical transmission to networking (II)
  - a **layer 2** view of concurrent node transmission

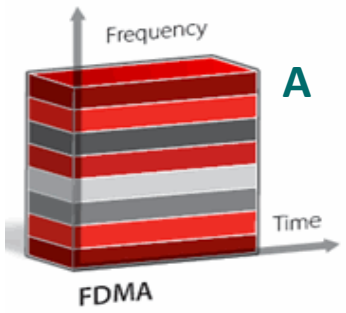


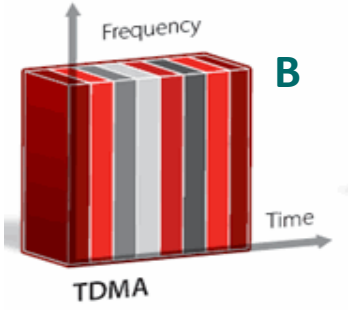
Q. how to make multiple transmitters coexist?

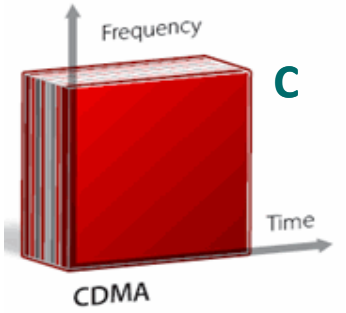
A. layer 2 **medium access control!**

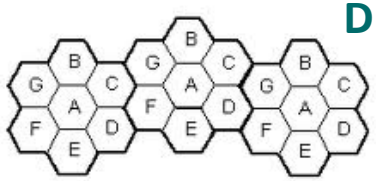
IEEE 802.11p / MAC

- Medium access in broadcast networks
  - **goal**: allow multiple transmitting stations access a **shared channel** → *wireless medium implies broadcast transmissions!*
  - traditional approaches to multiple access
    - **A.** frequency division (**FDMA**) – one channel per user
    - **B.** time division (**TDMA**) – separate stations in time
    - **C.** code division (**CDMA**) – assing one *code* to each user
    - **D.** space division (**SDMA**) – re-assignment at distance









IEEE 802.11p / MAC

- Medium access in broadcast networks
  - all previous methods are **collision-free**...
  - ...but require some **centralized coordination**
    - *dynamic allocation of channel, slot, code, reuse*
  - such coordination is typically provided by
    - elected **master nodes** (e.g., static wired networks)
    - fixed **infrastructured nodes** (e.g., cellular networks)
  - however, ITS networks shall be **spontaneous**
    - *lack of central coordination, all nodes are peers*

Q. how to manage medium access in such case?

A. random access techniques!

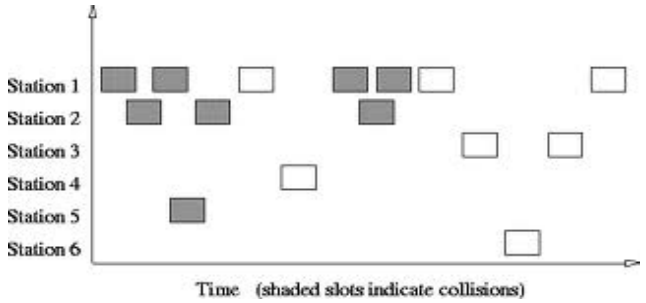
- can generate collisions, but can also manage them



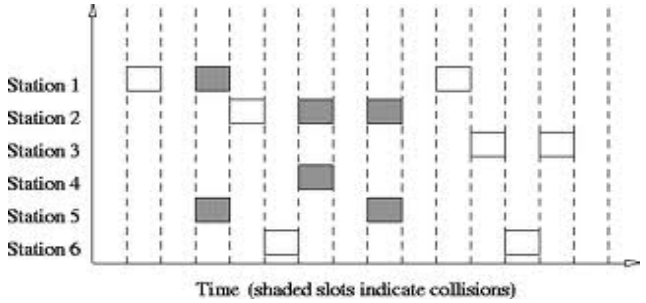


IEEE 802.11p / MAC

- Medium access in (ad-hoc) wireless networks
  - **random access**: basic solutions
  - basic **idea** of random access: **pure aloha**
    - when a node has some data to transmit, it sends a frame
    - if two frames collide, nodes can retry after some time



  - enhanced **synchronized** version: **slotted aloha**
    - same as aloha, but...
    - ...time is **slotted** and frames have f xed duration

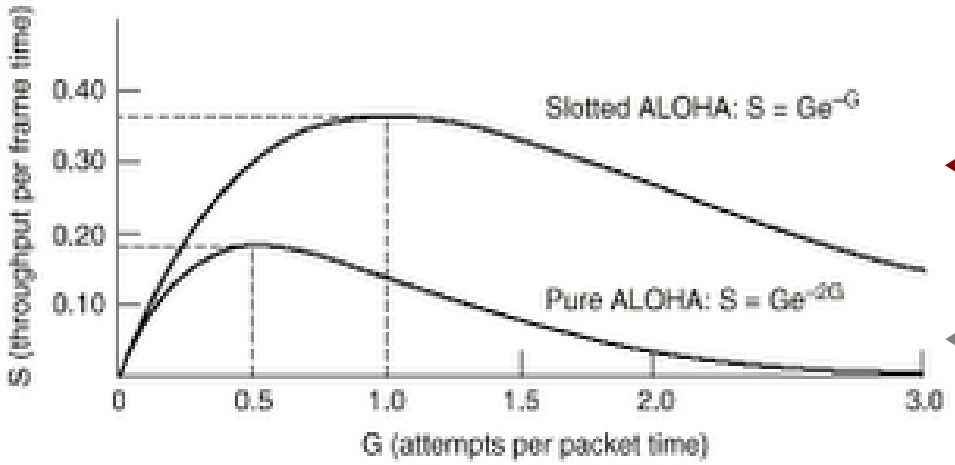






IEEE 802.11p / MAC

- Medium access in (ad-hoc) wireless networks
  - **random access**: problems of basic solutions
  - **pure aloha** is too unorganized
    - nodes incur in too many **collisions**
  - **slotted aloha** is too strict
    - too many **slots are wasted**



performance with
– frames of fixed length
– Poisson arrivals and retransmissions

G is the network load
[average frames transmitted in the network per frame duration]





IEEE 802.11p / MAC

- Medium access in (ad-hoc) wireless networks
  - **random access**: advanced solutions
  - unslotted, nodes check if **channel is idle** before sending: **carrier sense multiple access** (**CSMA**)
    - non-persistent ▶ *if the channel is busy wait some time*
    - 1-persistent ▶ *if the channel is busy wait for it to become idle and then transmit*

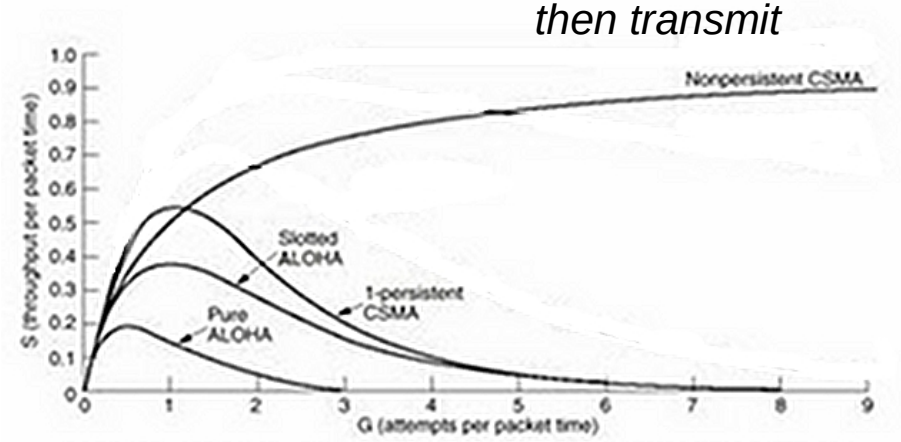


Fig. 4-4. Comparison of the channel utilization versus load for various random access protocols.

non-persistent CSMA
+ can theoretically reach full channel utilization
– poor performance under low loads
– delays at high loads

1-persistent CSMA
+ best performance under low loads
– excessive collisions as load grows



IEEE 802.11p / MAC

- Medium access in IEEE 802.11p
  - **CSMA implementation**
  - four types of **InterFrame Space** (IFS)
    - Short InterFrame Space (**SIFS**)
      shortest IFS, minimum time between two transmissions, used to separate transmissions belonging to a same dialogue
    - Point coordination InterFrame Space (**PIFS**)
      high-priority IFS, used to gain control of the channel to send important control messages
    - Distributed InterFrame Space (**DIFS**)
      standard IFS, used to separate transmissions of different dialogues
    - Extended InterFrame Space (**EIFS**)
      longest IFS, used to avoid collisions (see next)
  - SIFS < PIFS < DIFS < EIFS
    - in 802.11p, SIFS/PIFS/DIFS are 16 s, 25 s, and 34 s





IEEE 802.11p / MAC

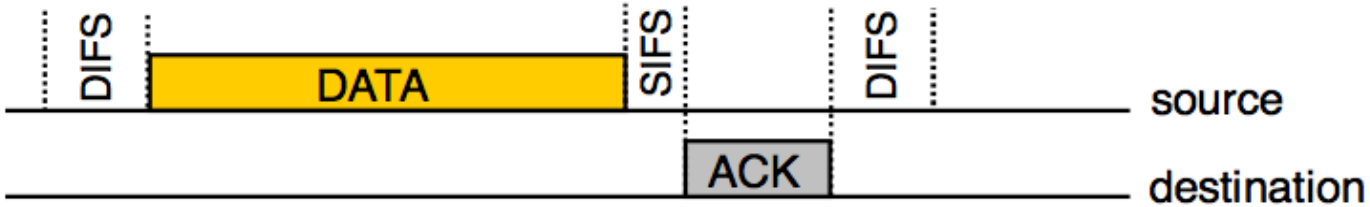
- Medium access in IEEE 802.11p
  - **CSMA implementation**
  - three types of frames
    - **control** – acknowledgement (ACK), handshaking (RTS,CTS)
    - **data** – higher-layers information
    - **management** – connection establishment/release, authentication





IEEE 802.11p / MAC

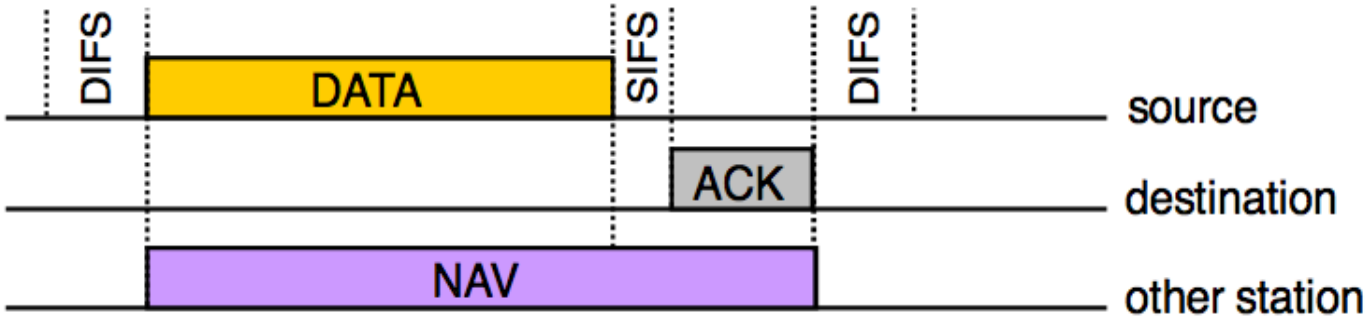
- Medium access in IEEE 802.11p
  - **CSMA implementation**
  - basic Carrier Sense Multiple Access
  - if a node needs to **transmit data**
    1. senses the channel (**carrier sensing**) for a DIFS period
    2. if the channel is idle for DIFS, it transmits
    3. if the channel is busy during the DIFS period, the station waits until the channel becomes idle again (1-persistent)
  - if a node **receives the data** correctly
    - replies with an ACK after a SIFS from the end of reception



IEEE 802.11p / MAC

- Medium access in IEEE 802.11p
  - **CSMA implementation**
  - carrier sensing is performed in two ways in 802.11p
  - **physical carrier sensing** – *the node senses the channel by means of its network interface*
  - **virtual carrier sensing** – *the node uses information about ongoing transmissions to avoid collisions*

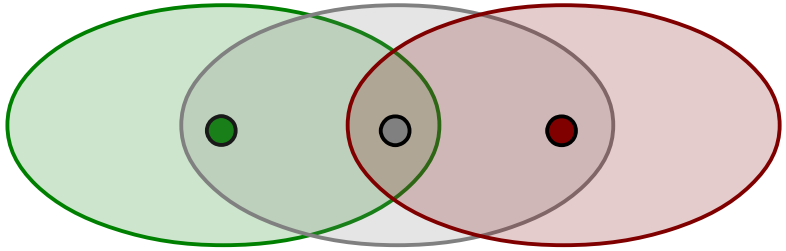
    " all frames contain a duration field: nodes use such value to set a network allocation vector (NAV) and stay silent until the NAV expires "



IEEE 802.11p / MAC

- Medium access in IEEE 802.11p
  - **CSMA implementation**
  - why using **virtual carrier sensing**?
    - *hidden terminals!*

● and ● cannot hear each other









without virtual carrier sensing

- ● sends DATA to ●
- ● wants to access the channel but hears the DATA from ●
- ● waits the end of DATA, then senses the channel idle for DIFS and transmits ► **collision!**

with virtual carrier sensing

- ● sends DATA to ●
- ● wants to access the channel but hears the DATA from ●
- ● sets its NAV according to DATA, then waits until NAV expiration before trying to access the channel ► **ok!**

IEEE 802.11p / MAC

- Medium access in IEEE 802.11p
  - **CSMA implementation**
  - channel contention is performed on a **frame basis**
    - one single data frame is sent at a time
  - transmissions can **fail** due to
    - **errors** *induced by the wireless channel*
    - **collisions** *generated by the medium access protocol*
  - ACKs are used to recover from errors
    - Automatic Retransmission reQuest (**ARQ**): **stop&wait**

only one in-fly frame is allowed per node

    - unAck'ed frames are retransmitted up to *retryLimit* times

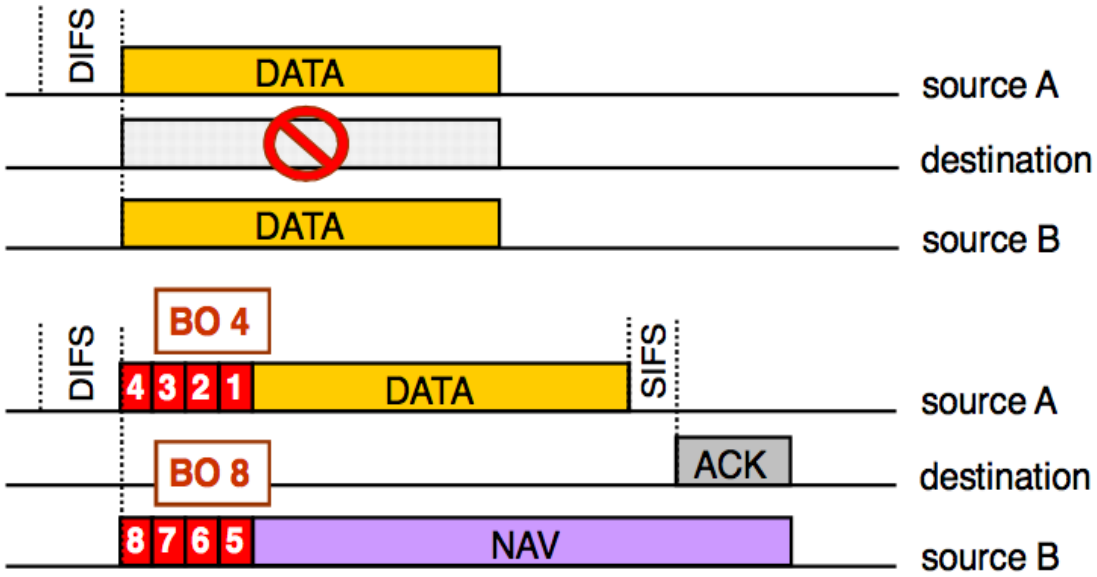
depends on the frame size – larger frames have smaller limits





IEEE 802.11p / MAC

- Medium access in IEEE 802.11p
  - **CSMA / CA implementation**
  - focusing on **collisions**
    - 1-persistent CSMA is **too aggressive**
    - IEEE 802.11p improves it with **Collision Avoidance** (**CA**)



*after the channel has been sensed idle for DIFS, nodes start a **random backoff** (BO) before transmitting*

IEEE 802.11p / MAC

- Medium access in IEEE 802.11p
  - **CSMA / CA implementation**
  - after DIFS expires (and channel is still idle!)
    - contending nodes **extract a BO**
    - BOs are **decremented** by each node
    - the node whose BO goes to zero f rst **transmits**
    - other nodes
      - sense that a transmission has started
      - **freeze their BO** to the current value
      - set their NAV according to the DATA frame duration
  - when the transmission ends (channel idle or NAV expiration)
    - contending nodes all **wait DIFS**
    - contending nodes **resume their BOs** decrement





IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **CSMA / CA implementation**
- a node sucessfully completing a transmission always extract a new BO (**post-backoff**), *even if it has no data to send*
- after DIFS from the end of its transmission, it starts **decrementing its BO**, *even if it has no data to send*
  - if the node has some data to send before the BO ends, it will send it once the BO is down to 0 — *return to normal behavior*
  - if the node does not have any data to send when the BO reaches a value 0, it will be allowed to send its next frame **waiting only a DIFS** idle time — *reduce latency in low load networks*

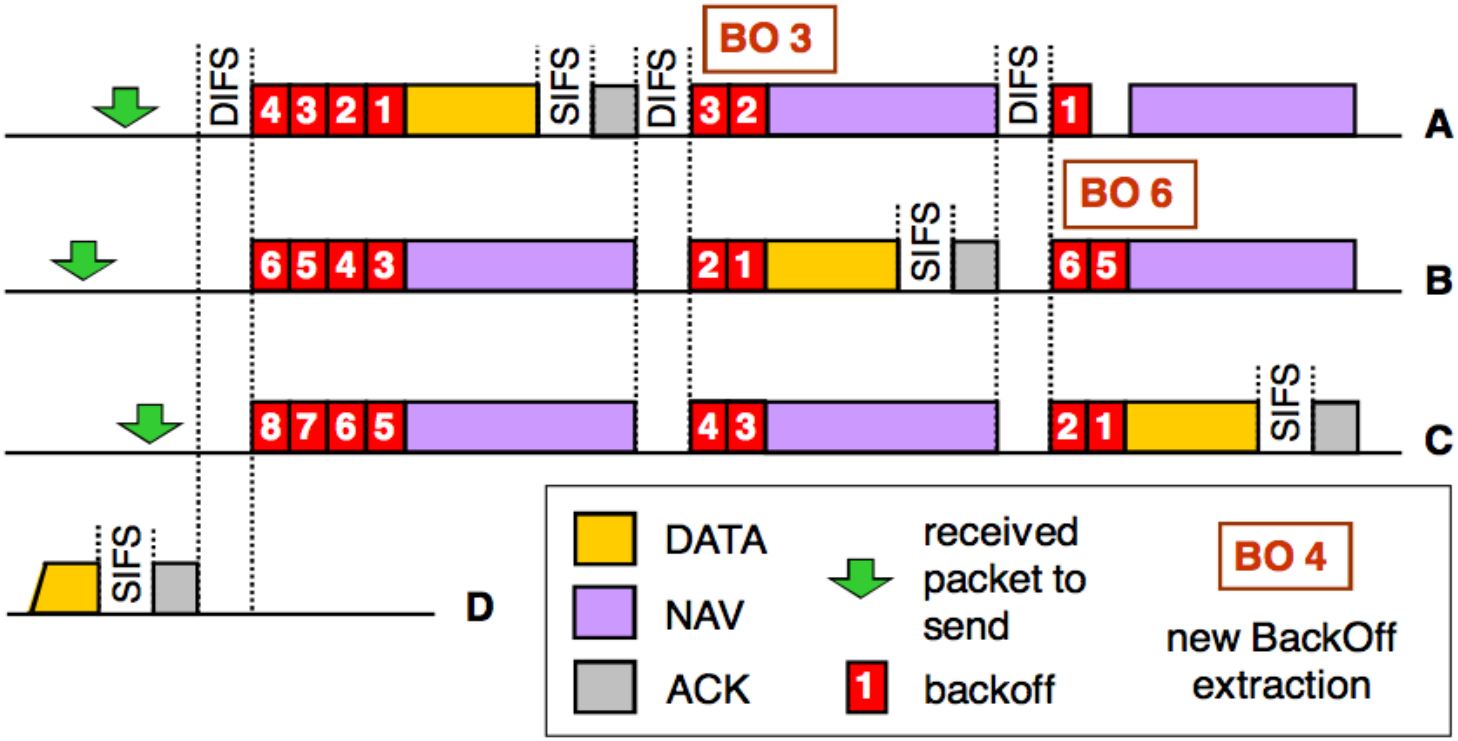




IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **CSMA / CA implementation**
- **example** – *3 contending nodes*



IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **CSMA / CA implementation**
- CA **mitigates** collisions, does not eliminate them
  - *two nodes can extract the same BO value*
- the **probability of collision** depends on
  1. the **number** of contending nodes

     more nodes ► higher probability that a same BO is extracted

  2. the **range** of BO values

     larger BO pool ► lower chance that a same BO is extracted

- denser networks result in more frequent collisions
  - can be countered by increasing the BO range...
  - ...but at **some cost in terms of delay**!





IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **EIFS utilization**
- the PHY layer can inform the MAC layer of some sensed **erroneous** transmission
- the error might be related to the present node only
  - *other nodes may have correctly received the frame*
- the node must **avoid interfering** with the potential ongoing transmission
  - **stay silent** for a time equal to
    1. the **SIFS** between the erroneous and the ACK frame
    2. the transmission time of the possible **ACK**
    3. the following mandatory **DIFS**
- SIFS + t_{ACK} + DIFS = **EIFS**

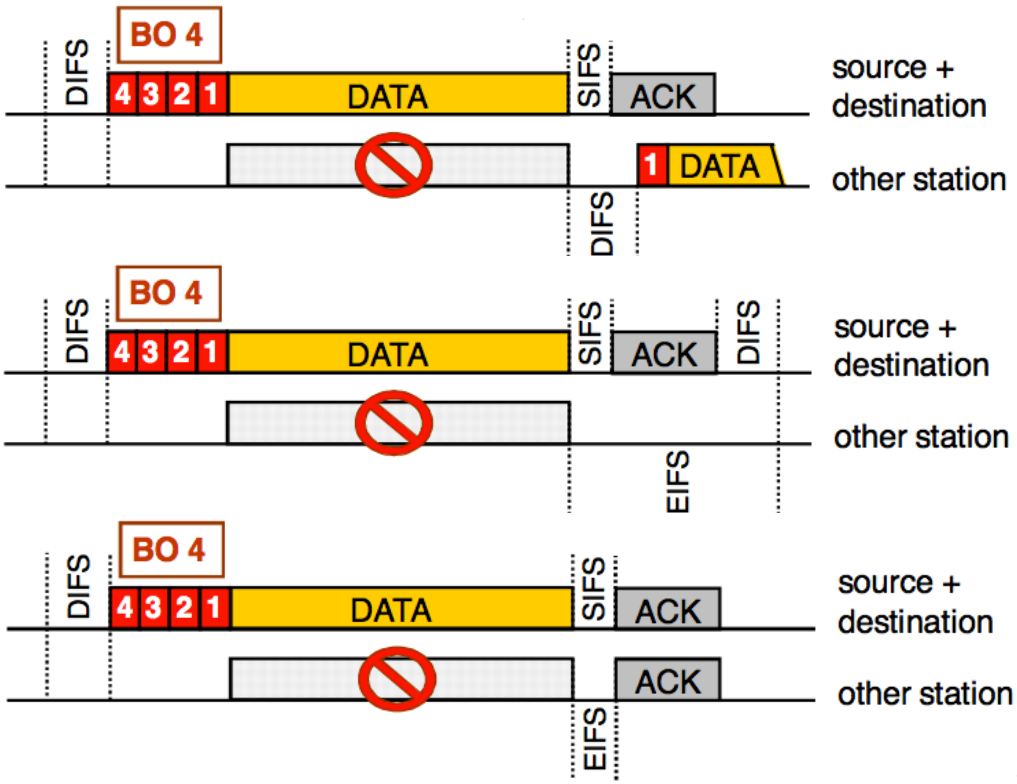




IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **EIFS utilization**
- **example** – *one erroneous reception*



without ***EIFS*** ***collision***

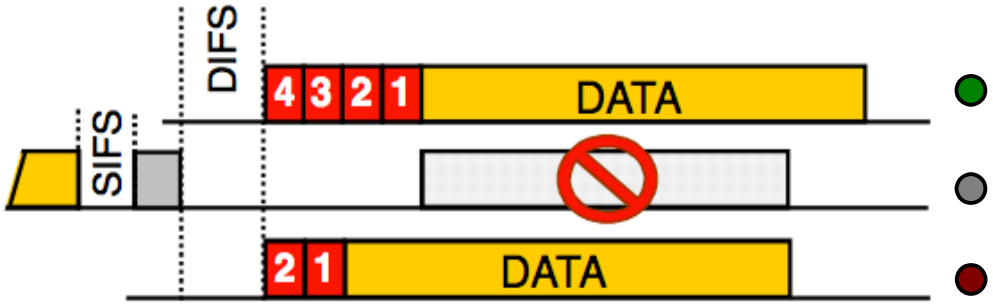
with ***EIFS*** ***no collision***

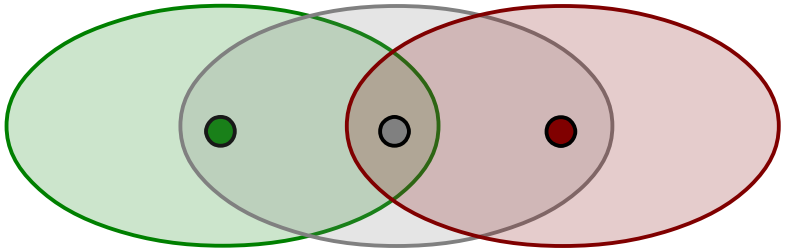
with ***EIFS*** ***recovering***

IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **CSMA / CA problems**
- CSMA / CA shows two major problems
  1. long latency in **detecting collisions**
     - the only way to detect a collision is a **missing ACK**
     - must wait until the whole DATA frame has been sent
  2. weakness to **hidden terminals**
     - **out-of-range** transmitters can still determine collisions

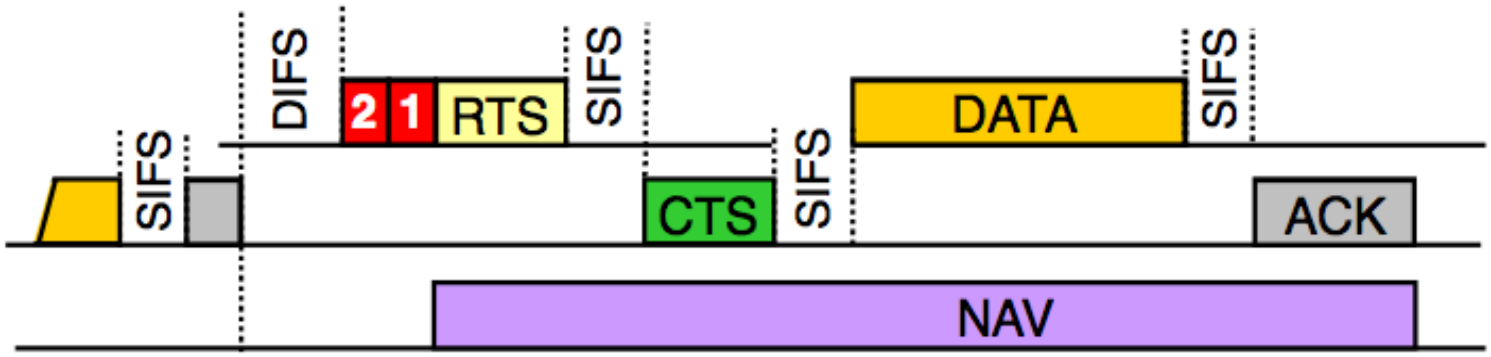




IEEE 802.11p / MAC

Medium access in IEEE 802.11p

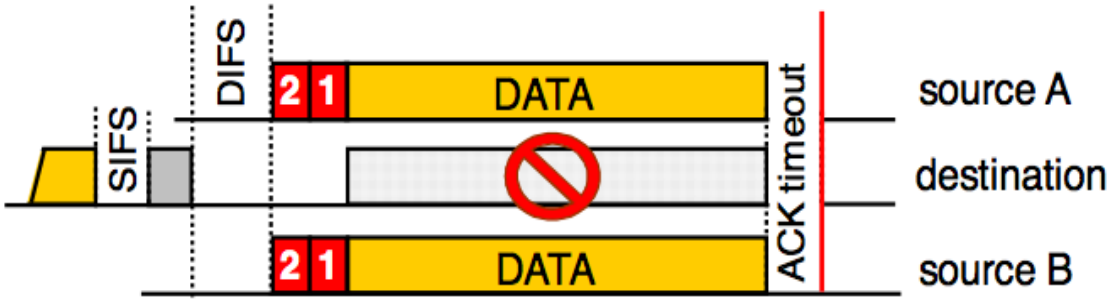
- **RTS / CTS handshake**
- IEEE 802.11p solution: **handshaking** phase before actual data transmission
  - The sender asks permission to transmit the data with a Ready To Send (RTS) control frame
  - The receiver grants transmission with a Clear To Send (CTS) control frame



IEEE 802.11p / MAC

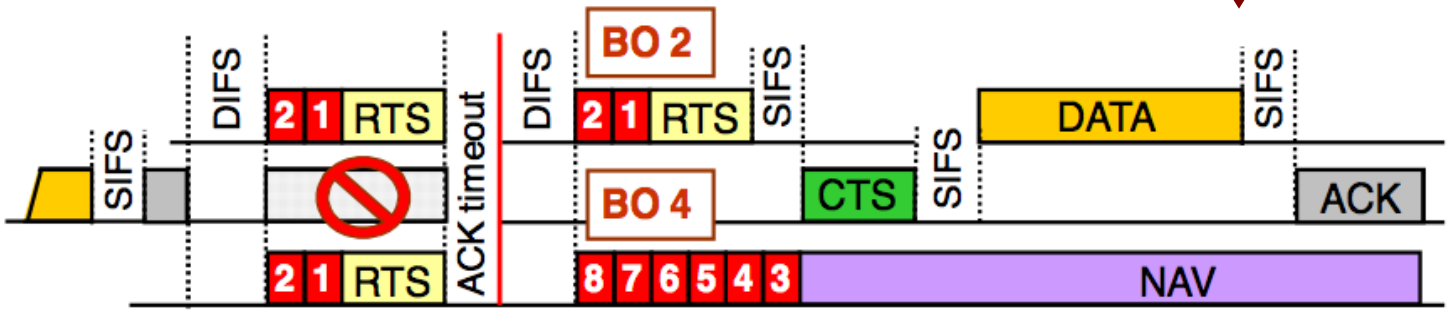
Medium access in IEEE 802.11p

- **RTS / CTS handshake**
- RTS / CTS **reduce** collision detection latency
  - collisions are detected at the end of the **fast handshake**



*without **RTS / CTS***

*with **RTS / CTS***



IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **RTS / CTS handshake**
- RTS (20 bytes) and CTS (14 bytes)
  - **small** control frames – especially if compared to data
  - still add **overhead** – transmitted at slow basic rate
- RTS / CTS handshake is used before **large frames**
  - only DATA frames larger than a **RTS/CTS threshold** are preceded by the handshake
- RTS / CTS and NAV management
  - *neighboring nodes set/update their NAV upon **every** RTS / CTS / DATA / ACK frame reception*

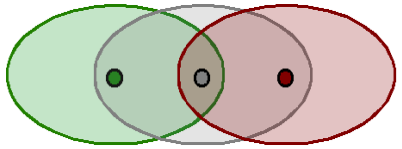


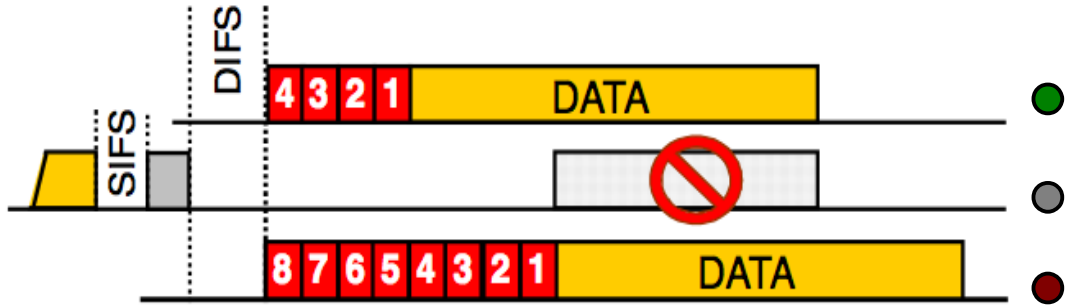


IEEE 802.11p / MAC

Medium access in IEEE 802.11p

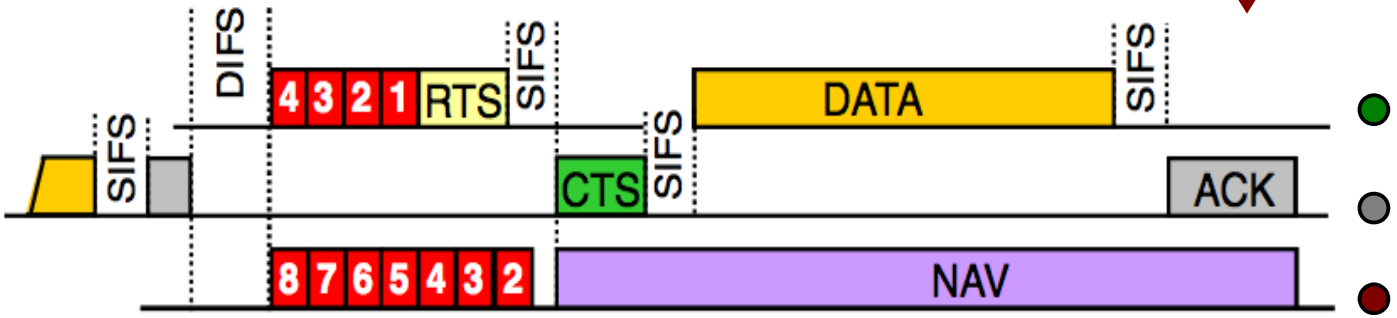
- **RTS / CTS handshake**
- RTS / CTS **mitigates** the hidden terminal problem





*without **RTS / CTS***

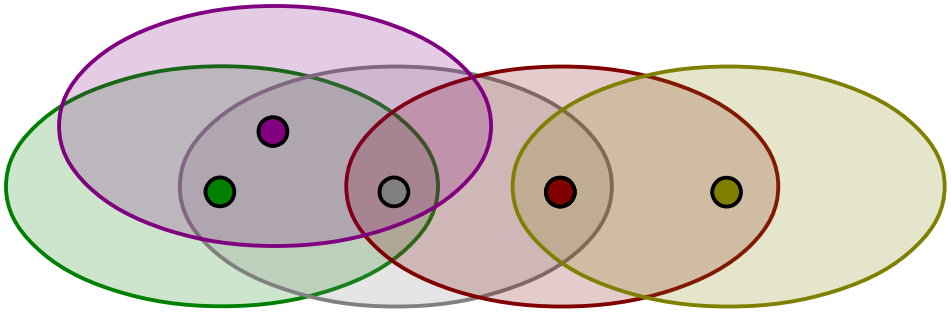
*with **RTS / CTS***



IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **open problems** *in the standard*
- **complex** hidden terminal

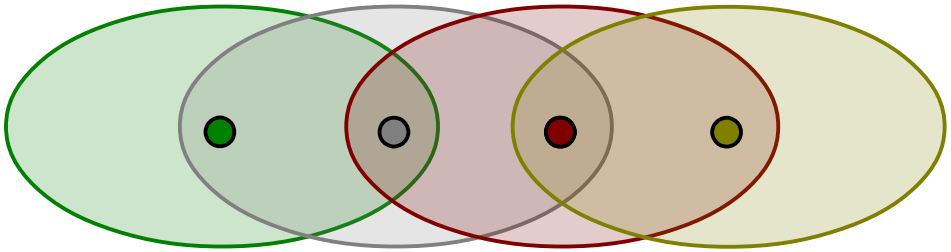


- sends DATA to ● + ● sends RTS to ●
- sends DATA to ● + ● sends CTS to ●
- does not receive CTS from ● (collision with DATA from ●)
- can transmit and cause a collision at ● and ●

IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- **open problems** *in the standard*
- **exposed** terminal



● sends RTS to ●

● sends CTS to ●

● receives RTS from ● and refrain from transmitting to ●

...but transmission from ● to ● would not cause a collision!







IEEE 802.11p / MAC

Medium access in IEEE 802.11p

- enhanced distributed channel access (**EDCA**)
- employed to **prioritize traff c**
  - Important in vehicular networks, where **safety** (real-time) and **accessory** (best-effort) traff c coexist
- 4 **Traff c Categories** (TCs), implemented as different MAC-layer queues
- TCs are distinguished by
  1. minimum/maximum **contention window** size
  2. different **AIFS** (Arbitration InterFrame Space) that replace the original DIFS, that is identical for all traff c



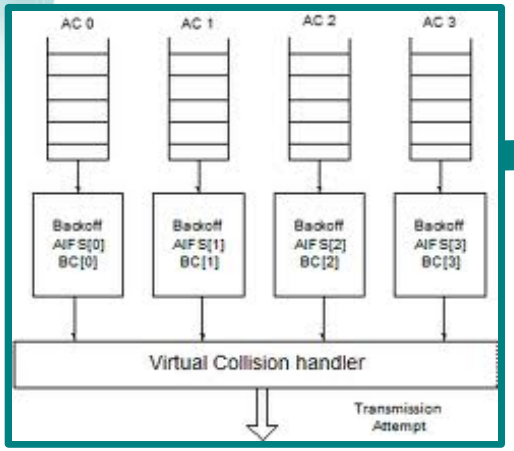


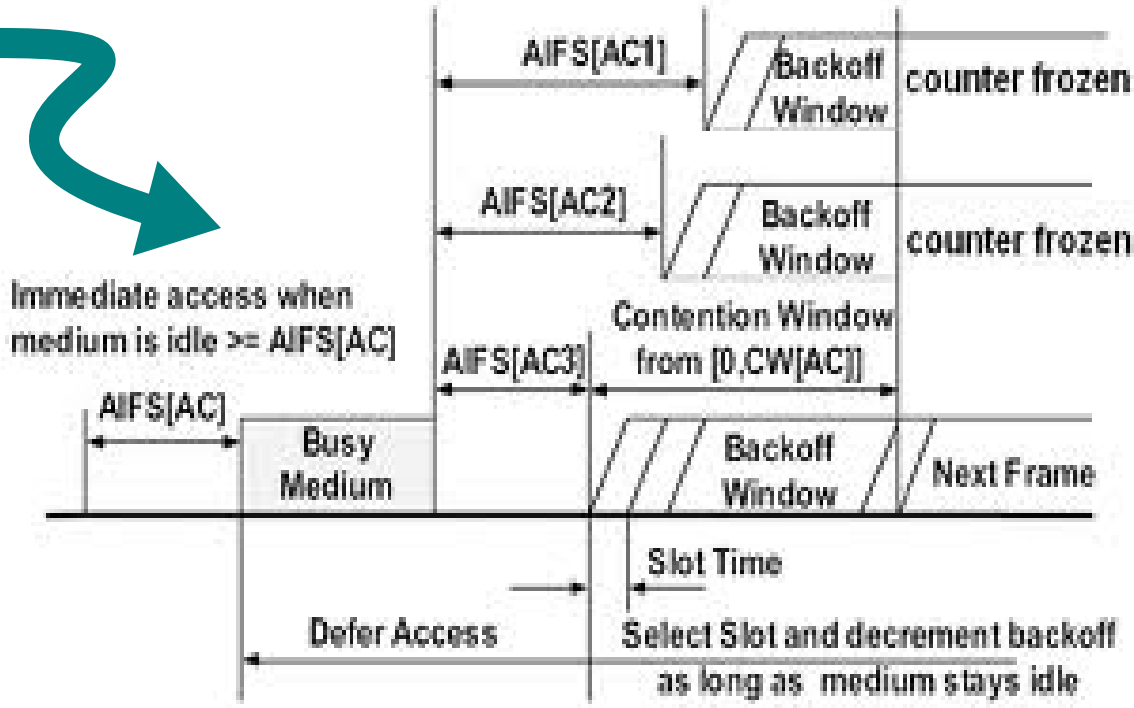
smaller CWs and shorter AIFS imply higher priority

IEEE 802.11p / MAC

Traff c priority in IEEE 802.11p

- Enhanced Distributed Channel Access (**EDCA**)











IEEE 802.11p

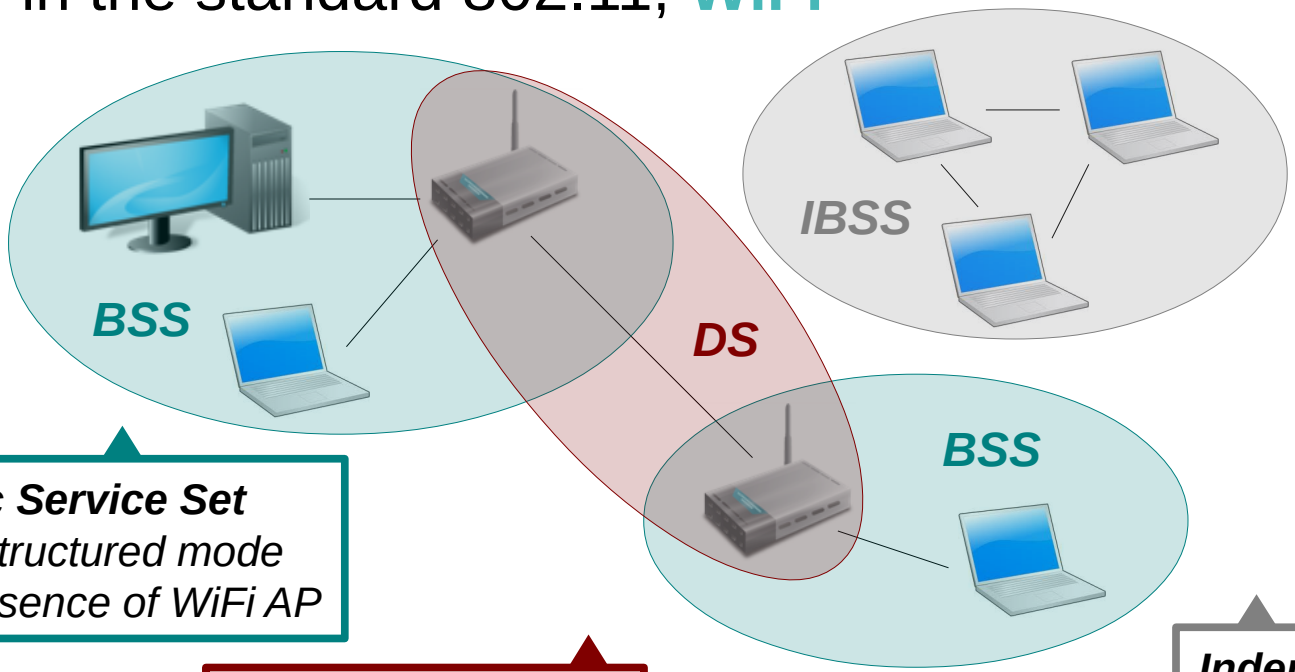
- Data rate adaptation
  - Problem and standard solution
  - Vehicular environments
- Medium access control
  - Problem
  - Standard solutions
  - 802.11p implementation
- Architecture and experimental tests
  - WBSS
  - Throughput and handover





IEEE 802.11p / MAC

- IEEE 802.11p MAC layer architecture
  - in the standard 802.11, **WiFi**



Basic Service Set
Infrastructured mode in presence of WiFi AP

Distribution Set
WiFi AP backbone in infrastructured mode

Independent BSS
WiFi ad hoc mode

IEEE 802.11p / MAC

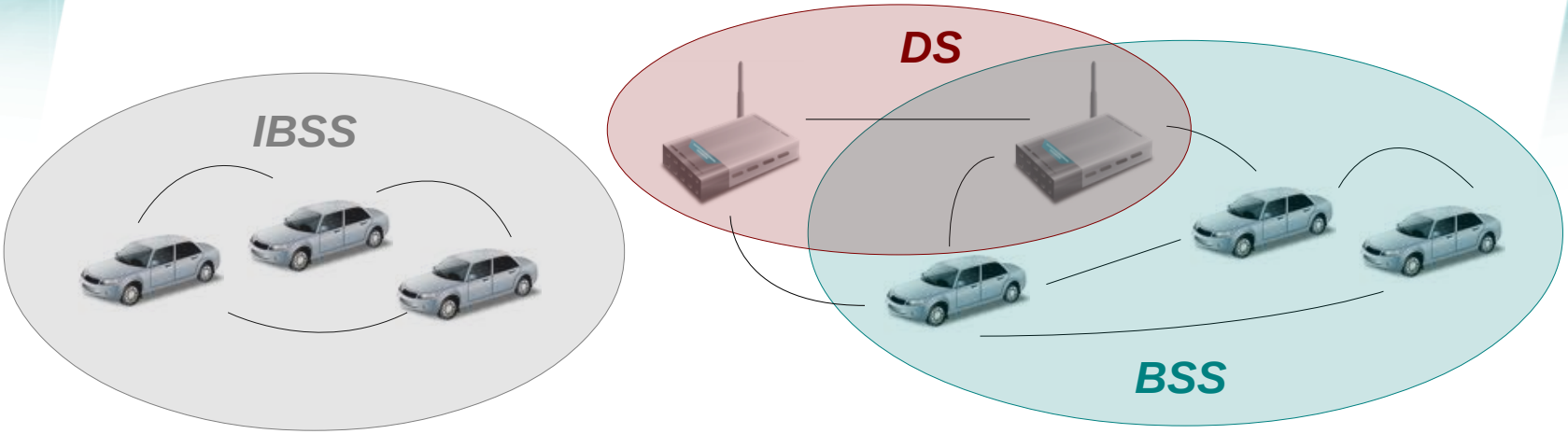
- IEEE 802.11p MAC layer architecture
  - in the standard 802.11, **WiFi**
  - **BSS** join process
    1. **scanning** to obtain the (I)BSS identif ers (**BSSID**s)
       - **passive** – wait for beacons broadcasted by APs every 100ms
       - **active** – poll APs for immediate beacon transmission
    2. **authentication**
       - **open** – send MAC, get ACK/NACK from AP
       - **shared key** – challenge & response with AP using known key
    3. **association**
       - association request/response with AP
       - new AP possibly informs old AP via DS
  - **IBSS** join process: **scanning only**





IEEE 802.11p / MAC

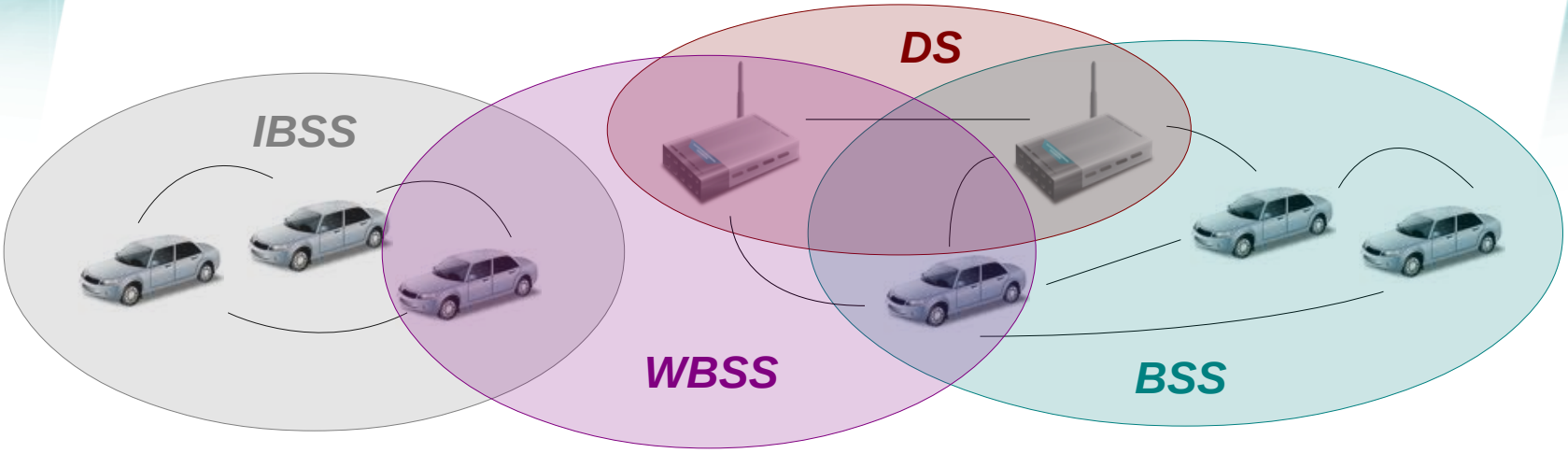
- IEEE 802.11p MAC layer architecture
  - adaptation to **vehicular environments**



- same architecture, but much **faster dynamics**
  - fast alternance of **short-lived** communication links
- ...scanning to acquire BSSIDs takes **too long**
  - **BSS association** is even worse

IEEE 802.11p / MAC

- IEEE 802.11p MAC layer architecture
  - adaptation to **vehicular environments**



- introduction of **WAVE** (Wireless Access in Vehicular Environments)
  - a **wildcard BSSID** allows **broadcast-like** access to vehicles or APs within any BSS, IBSS, DS
  - a **WAVE BSS** (WBSS) can be instantly formed / deleted
    - ▶ *no need for association, authentication or even BSSID acquisition!*

IEEE 802.11p / MAC

- f eld tests with IEEE 802.11
  - typical **controlled vehicular environment**



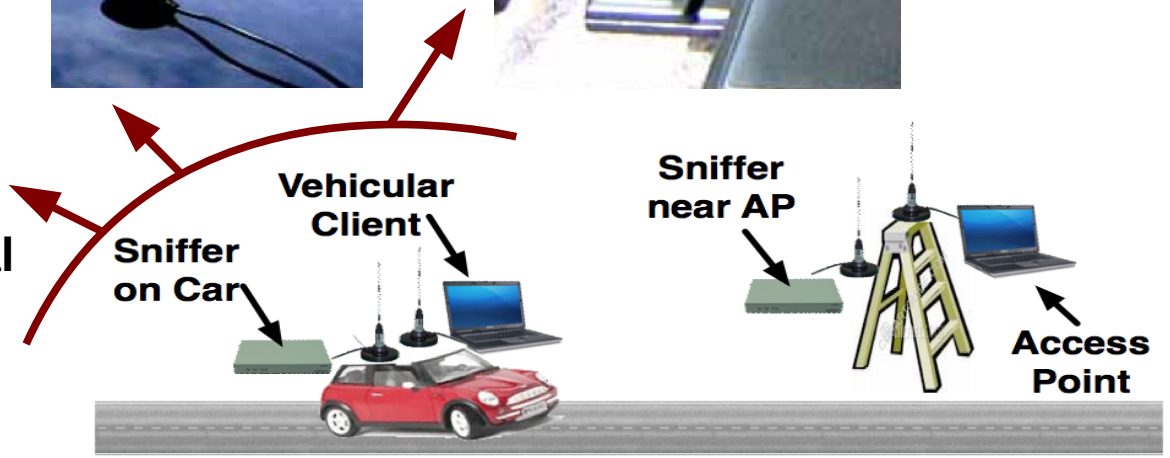
High-gain external antenna with magnetic base

GPS receiver connected to laptop



Laptop + WiFi card connected to the external antenna





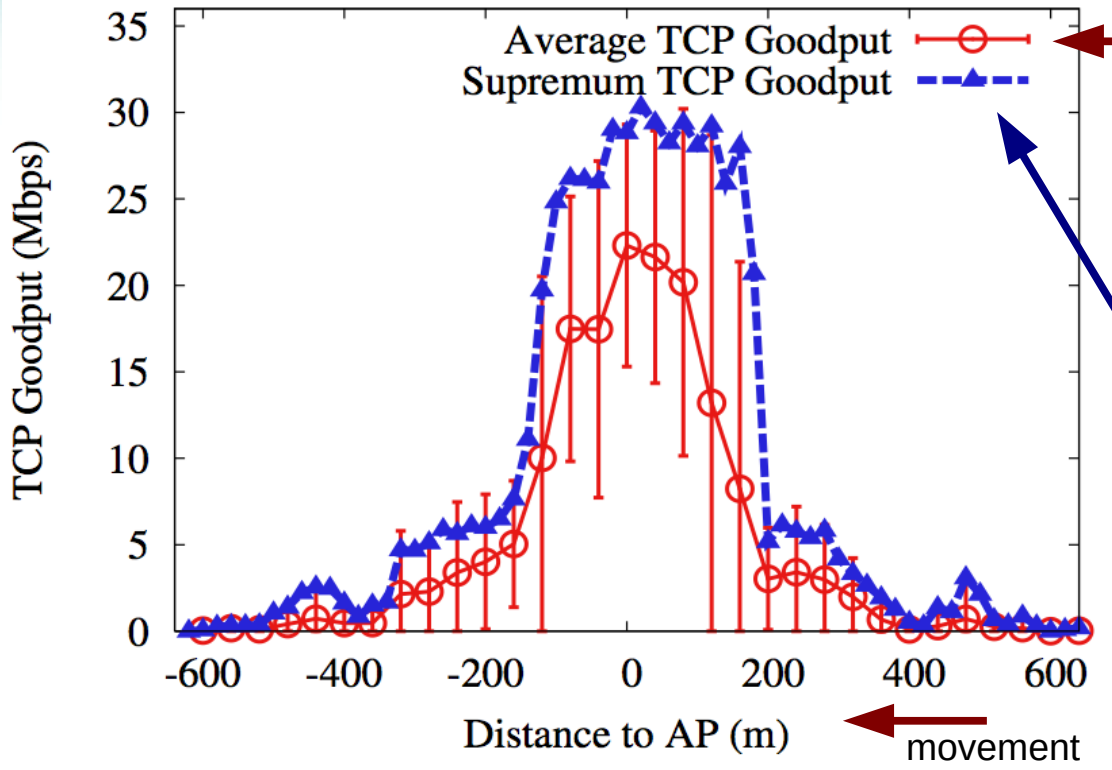






IEEE 802.11p / MAC

- f eld tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **communication**



average goodput: mean over multiple runs, with standard deviation

supremum goodput: achieved in one single best run

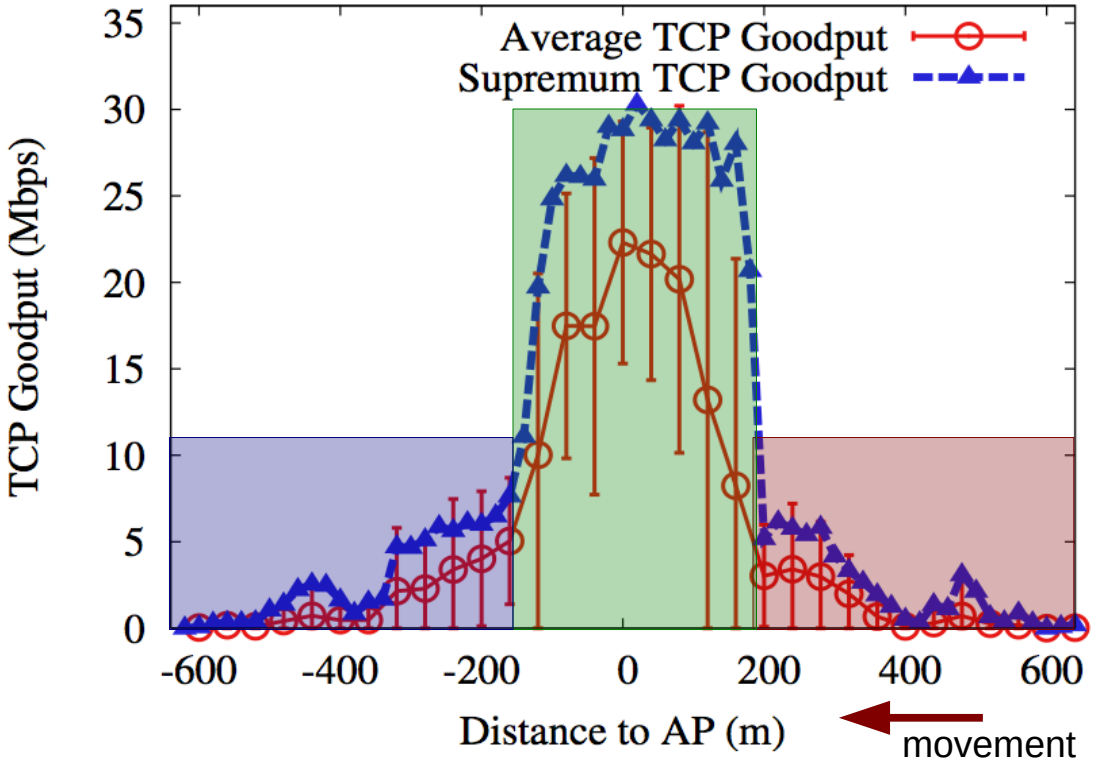






IEEE 802.11p / MAC

- field tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **communication**



***entry** phase*
- scan & AP selection
- BSSID association
- ARP run
- TCP handshake

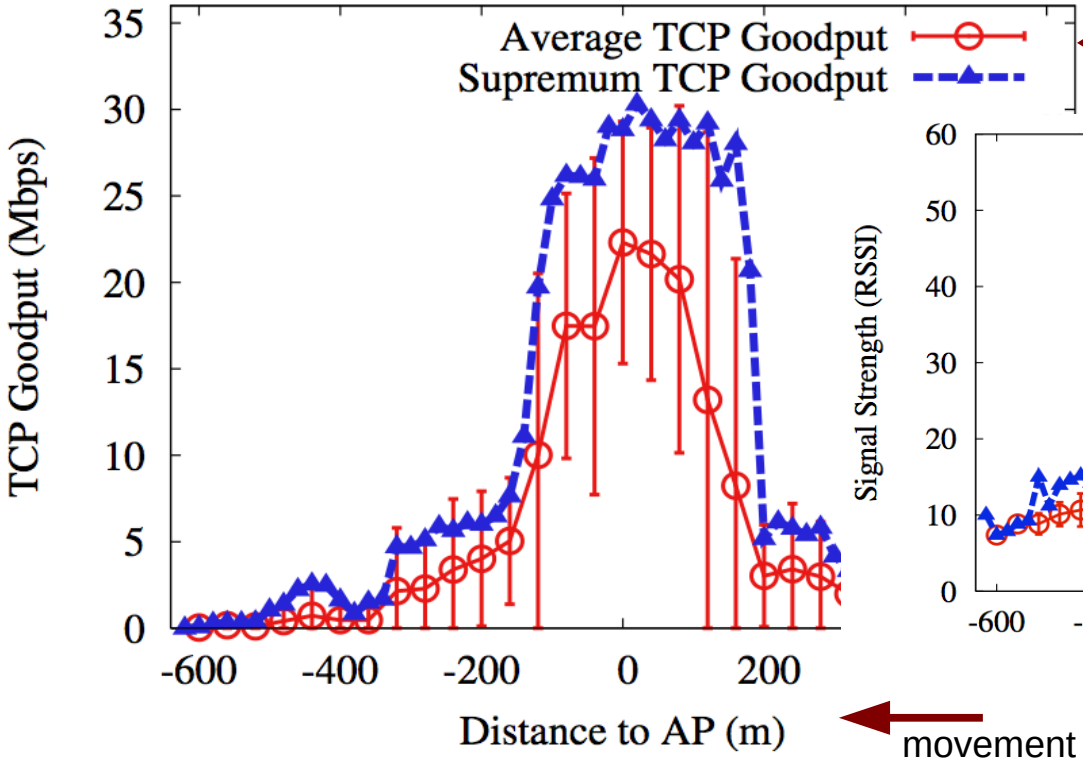
***production** phase*
- maximum throughput

***exit** phase*
- connection loss

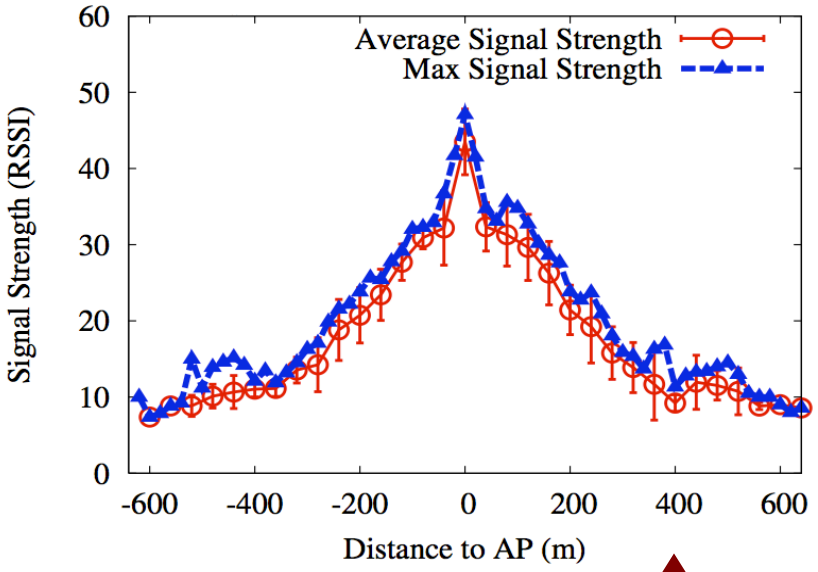


IEEE 802.11p / MAC

- f eld tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **communication**



very **diverse** result over multiple identical runs



movement

not due to signal f uctuations!

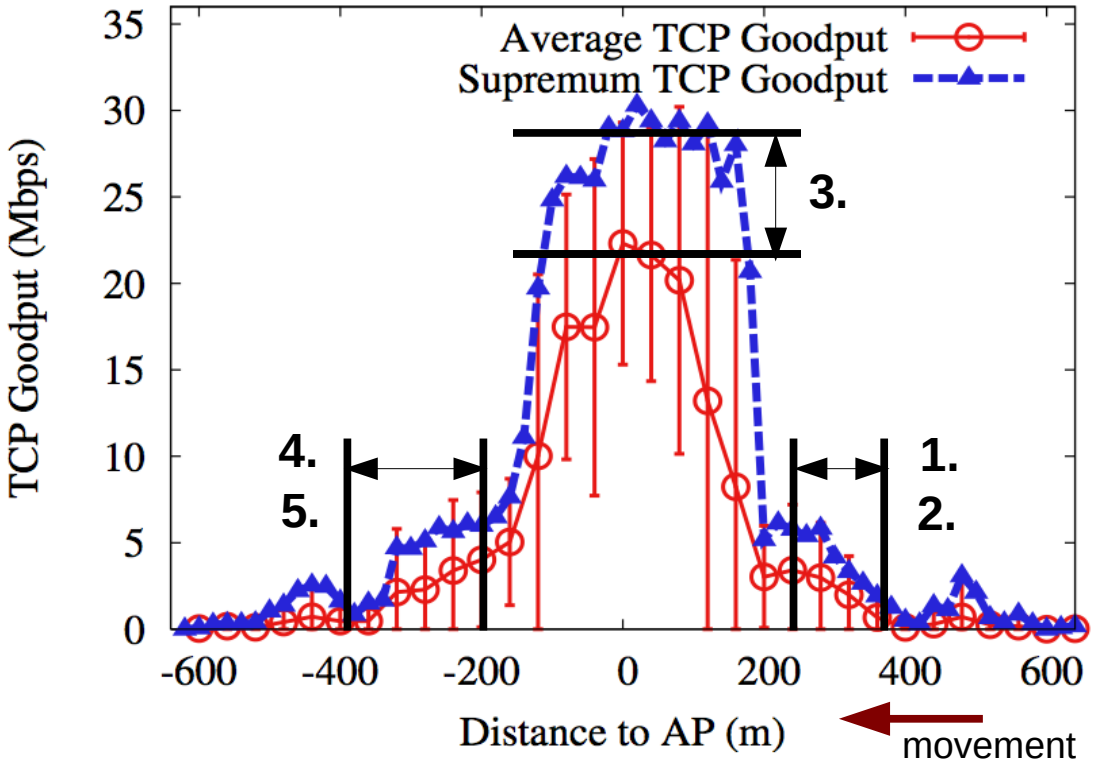






IEEE 802.11p / MAC

- field tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **communication**



suboptimal performance due to MAC / transport **protocol operation**!







1. lengthy **scan**
2. **association** timeouts

\+

3. slow **data rate** adaptation

\+

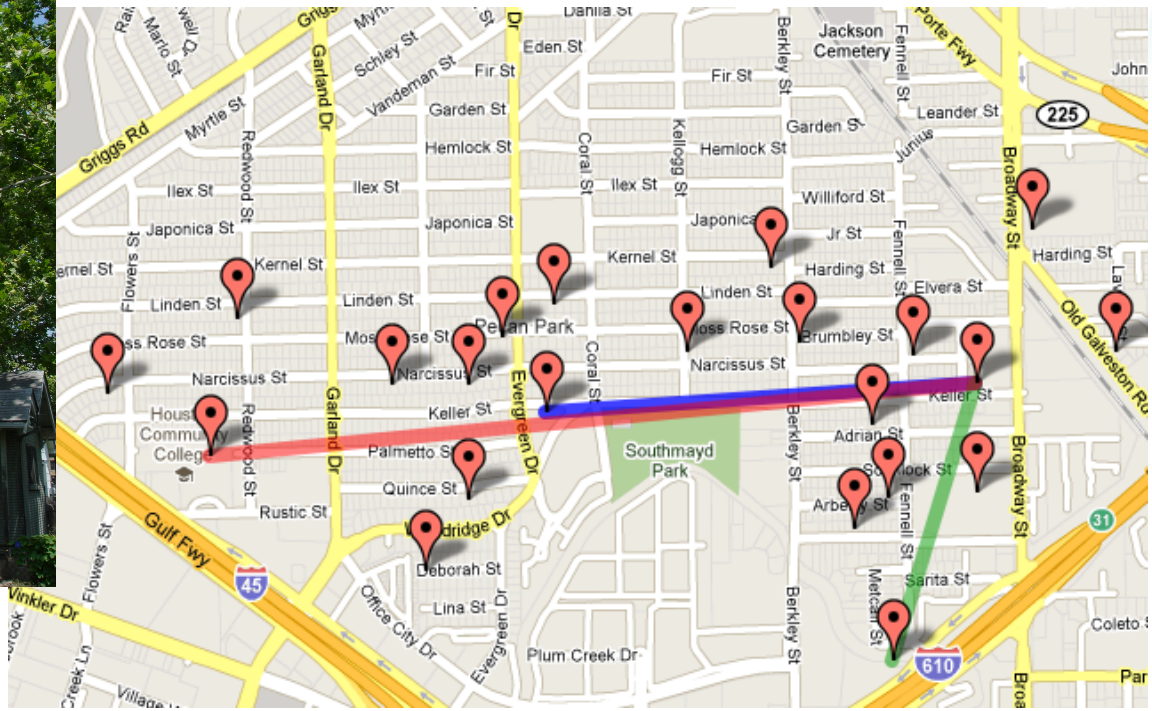
4. data rate **overestimation**
5. **TCP** timeouts

IEEE 802.11p / MAC

- f eld tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **handoff**



◀ typical 802.11 AP with antenna

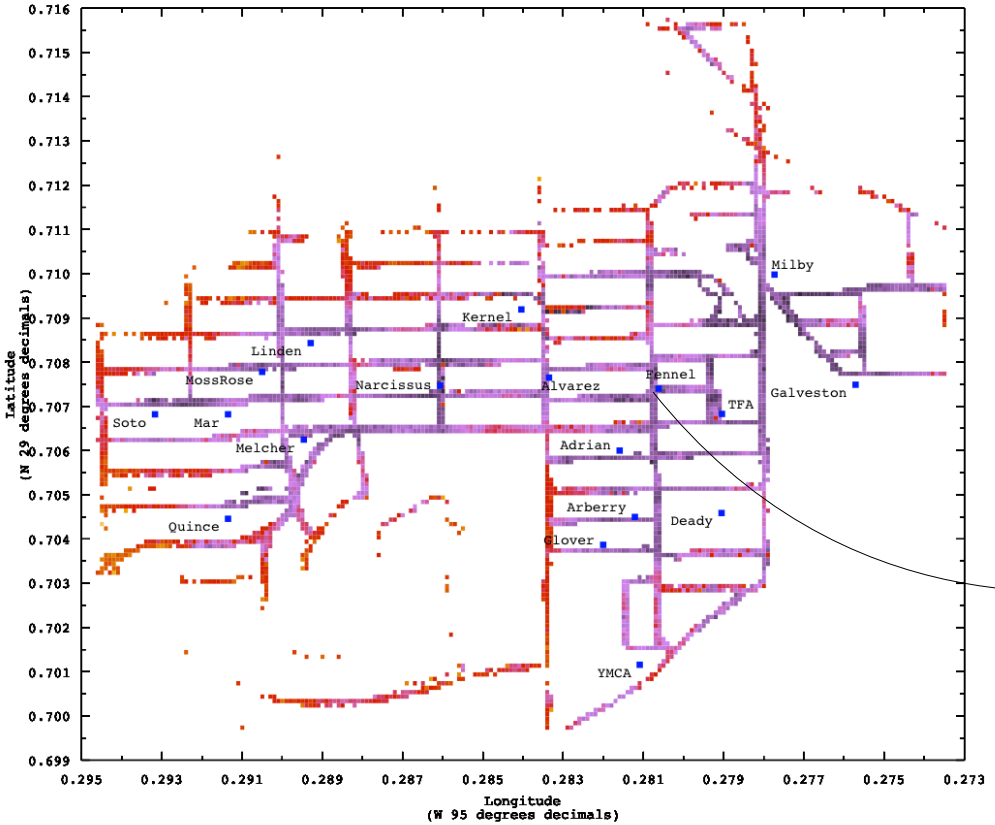


APs deployment ▶

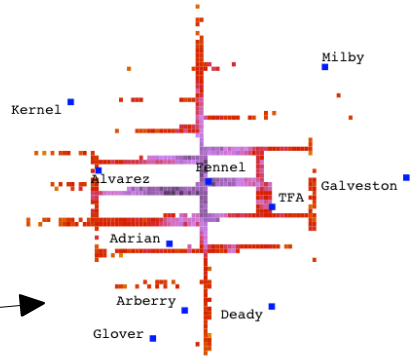


IEEE 802.11p / MAC

- field tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **handoff**



overall network coverage with signal strength

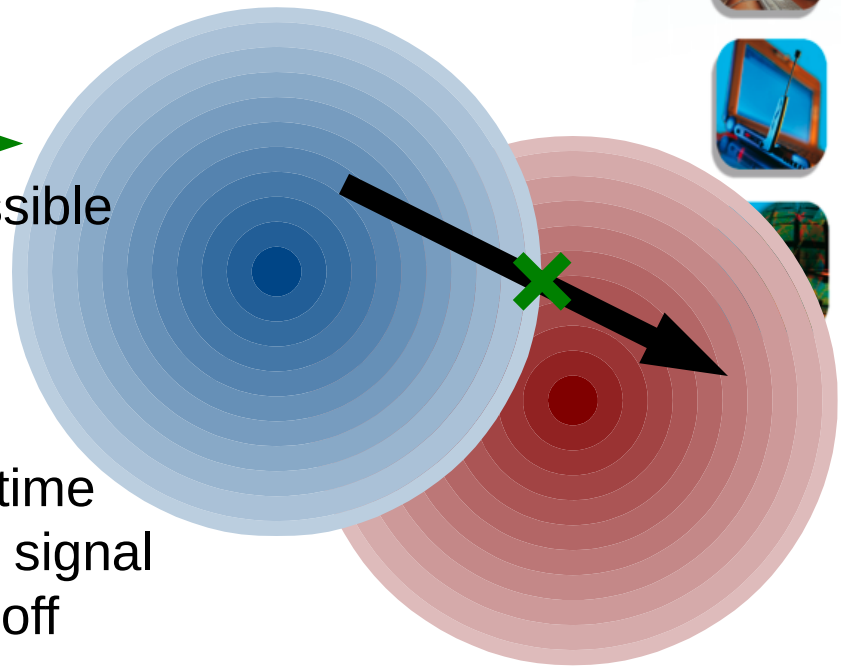


single AP coverage



IEEE 802.11p / MAC

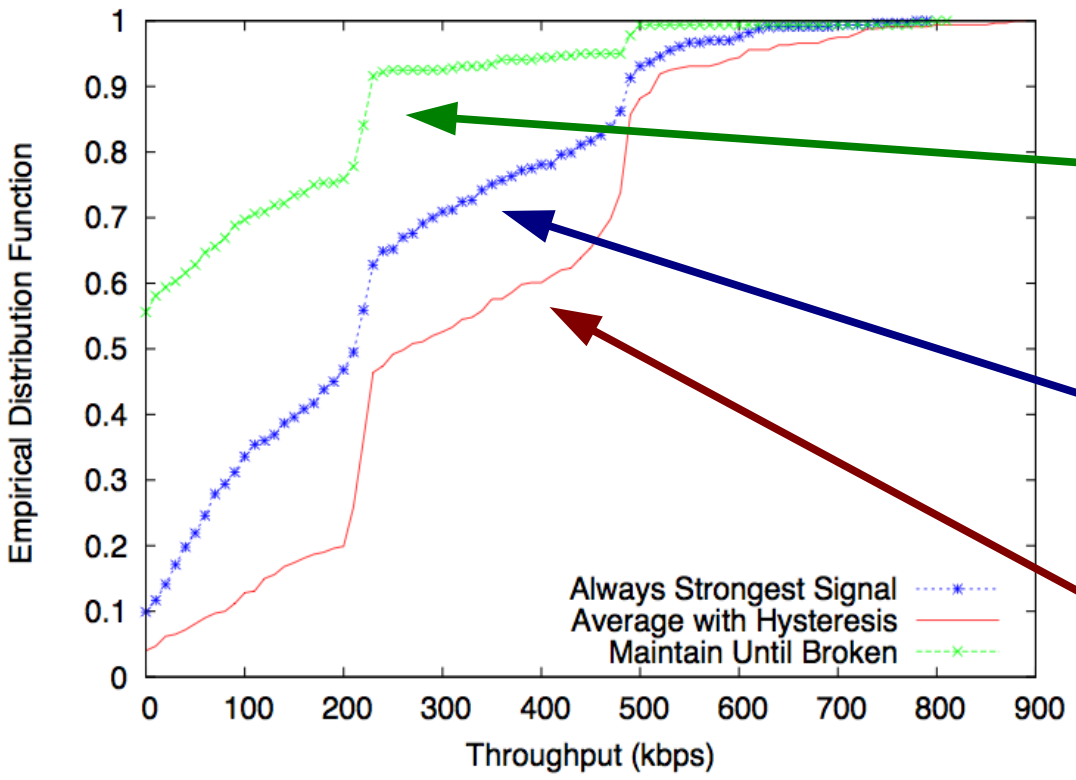
- f eld tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **handoff**
  - **handoff** : association process to a new AP
    - *when to perform an handoff? To which new AP?*
  - experimental techniques
    1. **maintain until broken** →
       - keep current AP as long as possible
    2. **always strongest signal**
       - follow the strongest signal
    3. **average with hysteresis**
       - take the average signal over a time window + introduce a minimum signal improvement threshold to handoff





IEEE 802.11p / MAC

- field tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **handoff**



maintain until broken
default handoff policy in many 802.11 cards

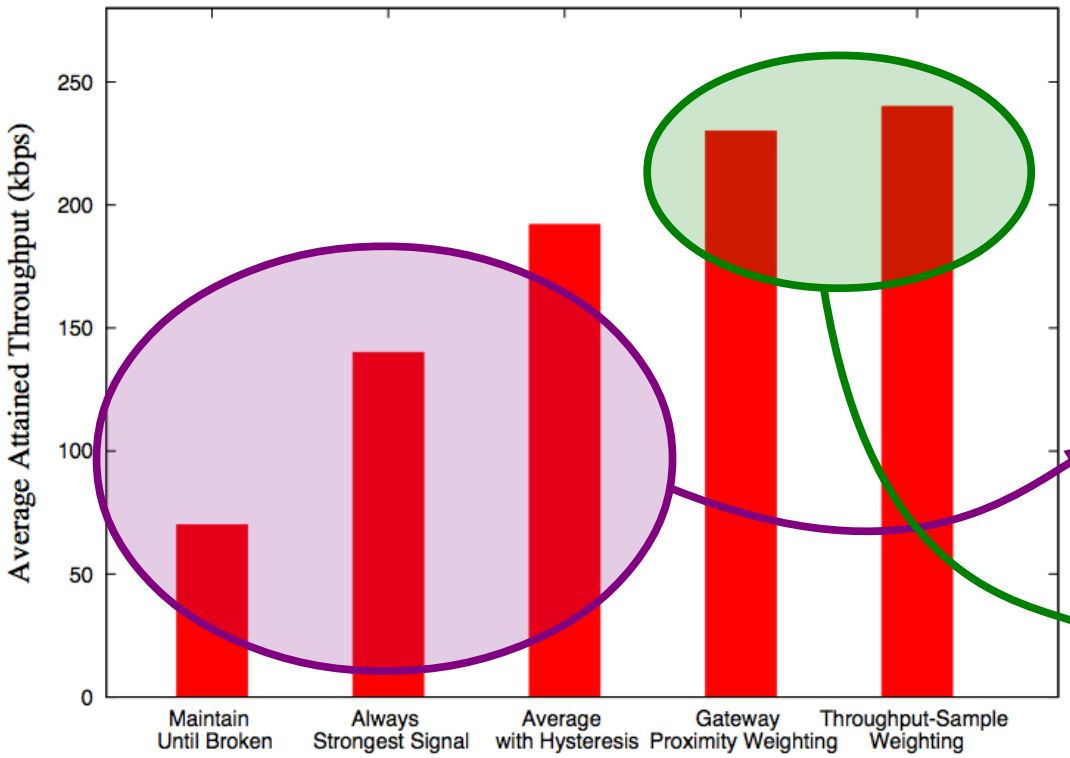
always strongest signal
excessive **(de)association** rate results in suboptimal throughput

average w/ hysteresis
uses an EWMA filter and a gain threshold on **SINR** from each AP in range



IEEE 802.11p / MAC

- f eld tests with IEEE 802.11
  - vehicle-to-infrastructure (**V2I**) **handoff**



considering the mesh network peculiarities, the handoff can be further ref ned!

- maintain until broken
- always strongest signal
- average w/ hysteresis

mesh-specif c handoff techniques, considering APs diversity induced by the backbone topology



IEEE 802.11p / MAC

- IEEE 802.11p MAC
  - **summary**
  - medium access control
    - **CSMA / CA** – from 802.11 (**WiFi**)
    - **traff c prioritization** – from 802.11e (**QoS** extensions)
  - architecture
    - **BSS**, **IBSS**, **DS** – from 802.11 (**WiFi**)
    - **WAVE** access and WBSS – *original*
  - f eld tests reveal that **improvements are needed**
    - **protocol operations** cause 50% under-utilization
    - poor **handoff support** causes connectivity holes
    - **DS backbone nature** (wired / mesh) has an impact





IEEE 802.11p / MAC

Bibliography

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- **D. Hadaller**, **S. Keshav**, **T. Brecht**, **S. Agarwal**, *"Vehicular Opportunistic Communication Under the Microscope"*, ACM MobiSys 2007
- **A. Giannoulis**, **M. Fiore**, **E. Knightly**, *"Supporting Vehicular Mobility in Urban Multi-hop Wireless Networks"*, ACM MobiSys 2008



