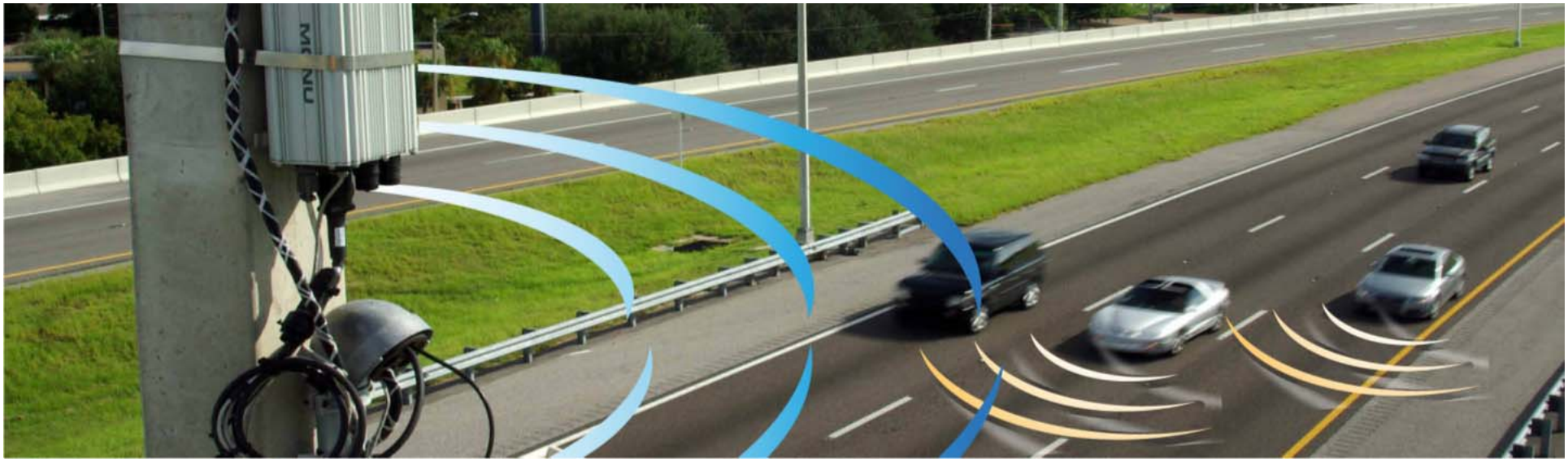


Heterogeneous V2X Networks for Connected and Automated Vehicles

Prof. Dr. Javier Gozalvez , j.gozalvez@umh.es
Co-authors: M. Sepulcre, R. Molina, O. Altintas

Universidad Miguel Hernandez de Elche, Spain
President, IEEE Vehicular Technology Society

UNIVERSITAS Miguel Hernández de Elche

Current status

- First release of connected vehicles standards have been finalized worldwide
  - Based on IEEE 802.11p and operating in 5.9GHz (EU and US) band or in 760 MHz band (Japan)
  - ETSI ITS-G5 (EU), IEEE WAVE (US), ARIB T109 (Japan)

- Worldwide deployment plans
  - 1st Toyota cars with V2X since the end of 2015
  - GM selling Cadillac CTS units from 2017 with 802.11p V2V
  - Initial V2X deployment in Europe could begin in 2019 (C2C-CC)

Current status

- Day one applications: limited set only for information purposes

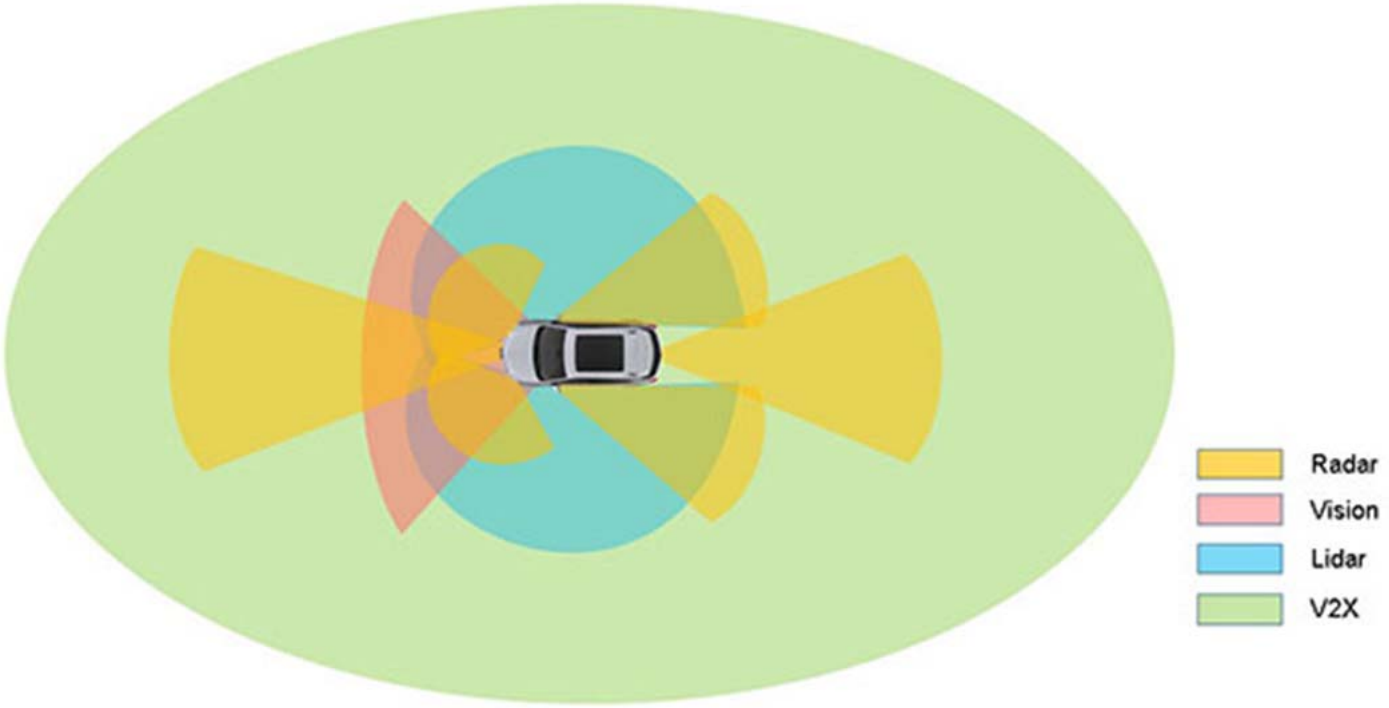
#	Day 1 Services			Bundle
1	Emergency electronic brake light	V2V	Safety	1
2	Emergency vehicle approaching	V2V	Safety	1
3	Slow or stationary vehicle(s)	V2V	Safety	1
4	Traffic jam ahead warning	V2V	Safety	1
5	Hazardous location notification	V2I	Motorway	2
6	Road works warning	V2I	Motorway	2
7	Weather conditions	V2I	Motorway	2
8	In-vehicle signage	V2I	Motorway	2
9	In-vehicle speed limits	V2I	Motorway	2
10	Probe vehicle data	V2I	Motorway	2
11	Shockwave damping	V2I	Motorway	2
12	GLOSA / Time To Green (TTG)	V2I	Urban	3
13	Signal violation/Intersection safety	V2I	Urban	3
14	Traffic signal priority request by designated vehicles	V2I	Urban	3

Source: C-ITS Platform. Final Report. Jan 2016

Should autonomous vehicles be connected?

Should autonomous vehicles be connected?

- V2X: part of a vehicle Active Safety Driver Assistance System



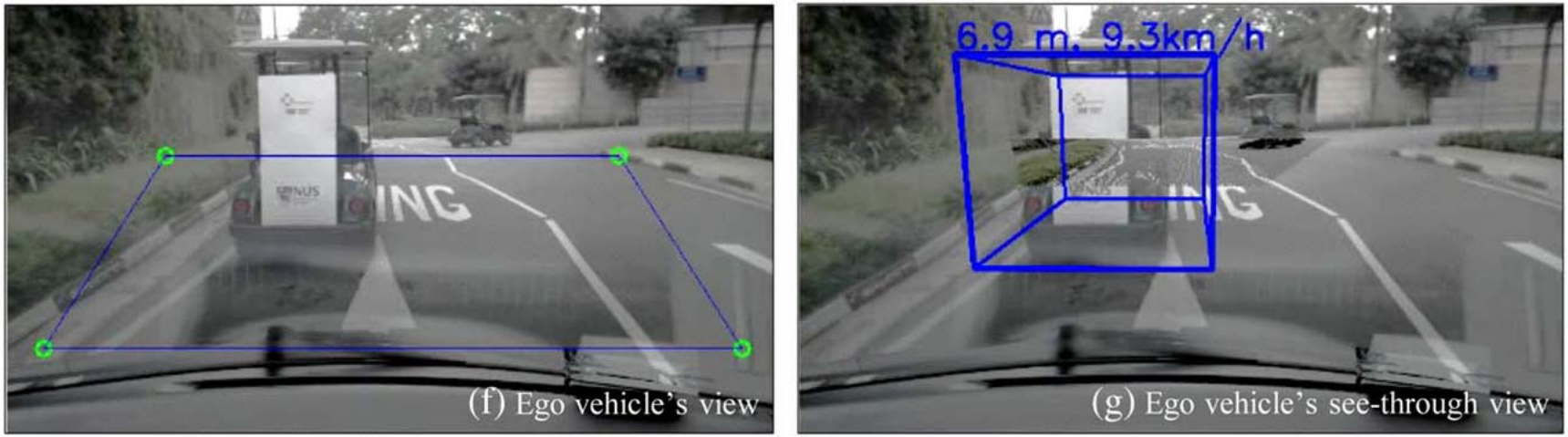
Source: RENESAS Electronics America Inc.

Should autonomous vehicles be connected?

- Cooperative driving
  - V2X facilitates communicating planned maneuvers
    - Reduces misunderstandings about intended maneuvers: communicating intentions directly rather than having to infer them indirectly from observed actions

Should autonomous vehicles be connected?

- Cooperative perception
  - V2X provides additional sources of information beyond those that can be sensed directly by onboard sensors
    - Beyond sensor line of sight



S. W. Kim et al., "Multivehicle Cooperative Driving Using Cooperative Perception: Design and Experimental Validation," in IEEE Transactions on Intelligent Transportation Systems, vol. 16, no. 2, pp. 663-680, April 2015

Should autonomous vehicles be connected?

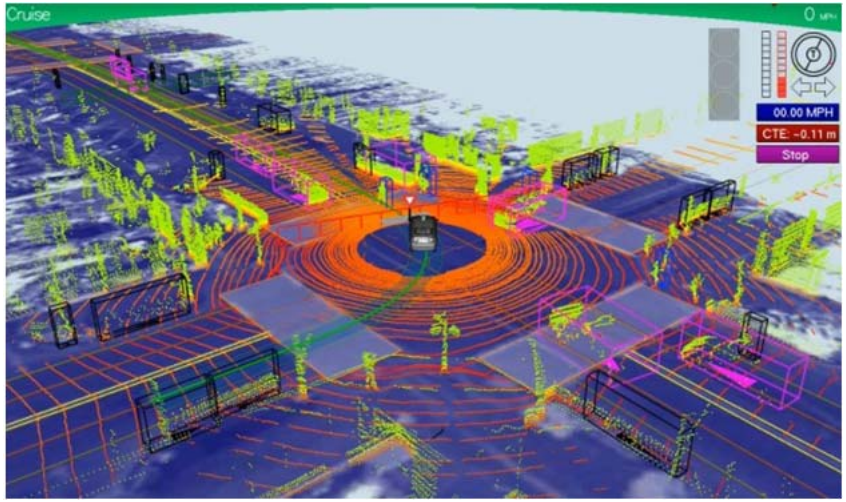
- Cooperative perception
  - V2X provides additional sources of information beyond those that can be sensed directly by onboard sensors
    - Beyond sensor line of sight
    - Internal vehicle characteristics
    - Locations & speeds of other vehicles
  - V2X improves quality of information and reduces uncertainties
    - Higher accuracy and lower noise from sensors on other vehicles
    - Faster detection of changes in conditions

Steven E. Shladover, “Cooperative (rather than autonomous) vehicle-highway automation systems”, IEEE Intelligent Transportation Systems Magazine, vol. 1(1), pp. 10-19, Jan 2009.

Challenges in connected automated driving

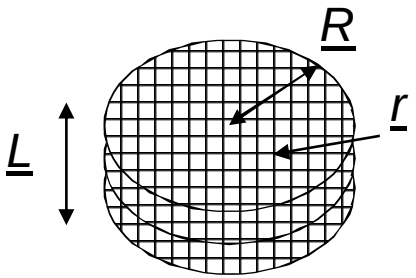
Challenges in connected automated driving

- Cooperative perception
  - How much information should be exchanged?
    - See-through use case:
      - Kim et al: 691Kbyte (raw) – 50K-110Kbyte (compressed image)
      - 5G-PPP “5G automotive vision”: 10Mbps throughput
    - Google self-driving cars generate 750Mb of data per second



Challenges in connected automated driving

- Cooperative perception
  - How much information should be exchanged?
    - See-through use case:
      - Kim et al: 691Kbyte (raw) – 50K-110Kbyte (compressed image)
      - 5G-PPP “5G automotive vision”: 10Mbps throughput
    - Alternatives to exchanging raw sensor data
      - Position and size of objects (Cooperative Observation Service)
      - Occupancy grids



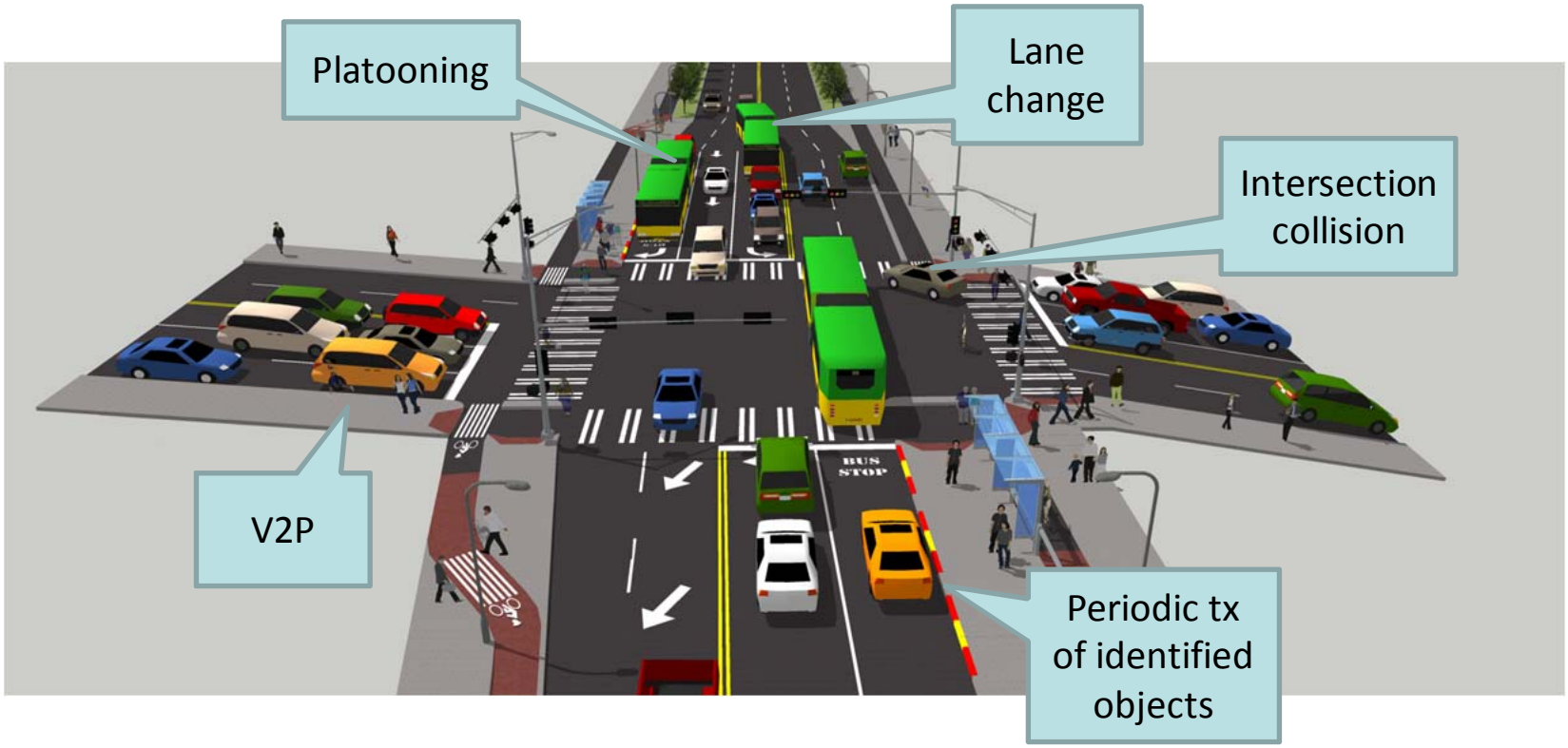
  - Uncertainty of remote information: delay, errors and security

Challenges in connected automated driving

- Cooperative driving
  - Increased road capacity: higher communications load
  - Challenge: coexistence of machines & humans in scenarios where cars will have different comms & sensing capabilities
    - "A Preliminary Analysis of Real-World Crashes Involving Self-Driving Vehicles", UMTRI, Oct. 2015
      - "the current best estimate is that self-driving vehicles have a higher crash rate per million miles traveled than conventional vehicles"
      - "self-driving vehicles were not at fault in any crashes they were involved in"

Challenges in connected automated driving

- Will we be ready to (successfully) handle all use cases running simultaneously?



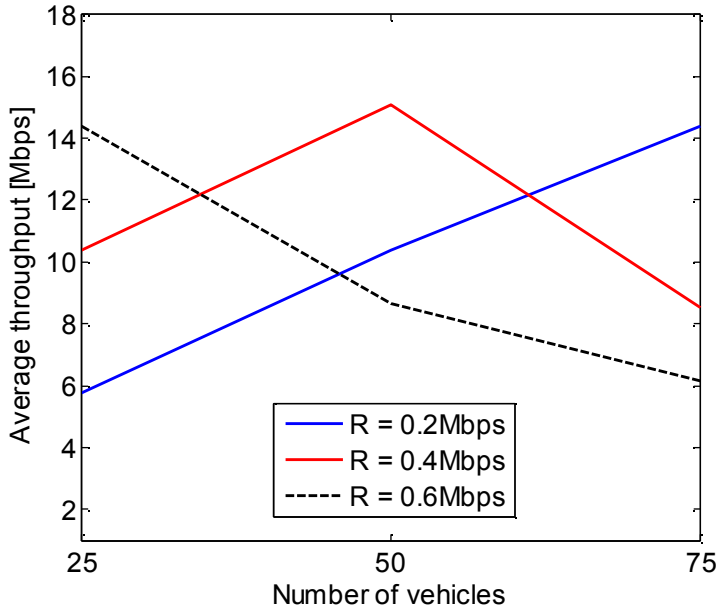
UNIVERSITAS Miguel Hernández de Elche

Challenges in connected automated driving

- Will we be ready to (successfully) handle all use cases running simultaneously?
  - 802.11p can face significant challenges

Throughput Traffic Test Results Half-Rates on Channel 172 (Mbps) Without Channel Switch								
Rates	3M	4.5M	6M	9M	12M	18M	24M	27M
TCP	2.36	3.37	4.34	6.32	7.97	11.23	13.54	14.75
UDP	2.38	3.50	4.37	6.99	9.00	12.96	15.81	17.32

Source: Arada Systems LocoMate™ ASD data sheet



Average Throughput (Mbps)

UNIVERSITAS Miguel Hernández de Elche

V2X communications for future connected & automated driving

UNIVERSITAS Miguel Hernández de Elche

V2X for future connected & automated driving

- Possible options
  - Optimize 802.11p (transmission parameters, advanced geo-networking, transport, etc.)

Optimize 802.11p

- Scalability is critical in vehicular networks
  - Congestion control protocols: mainly adjust transmission frequency and (sometimes) power of beacon messages
- 6Mbps (QPSK ½) has been generally used as the default data rate for beaconing in vehicular networks

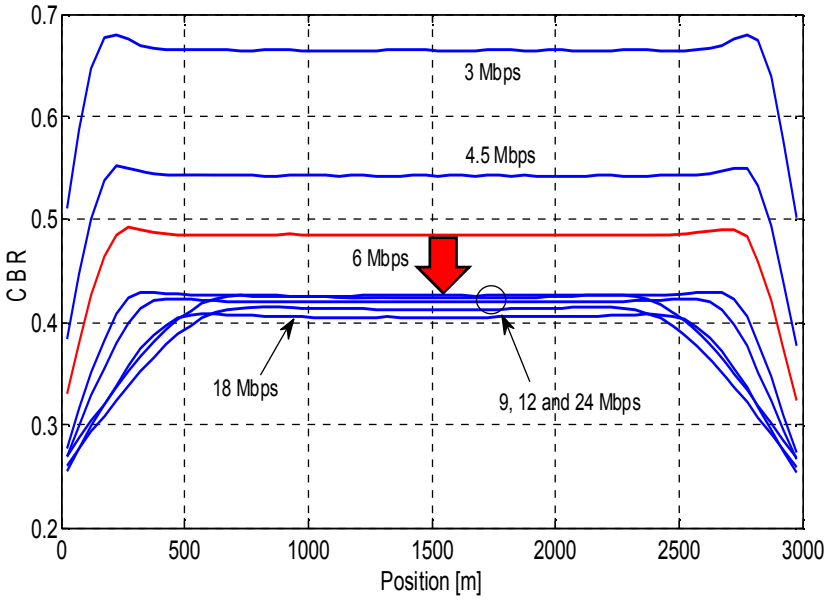
D. Jiang, Q. Chen, L. Delgrossi, "Optimal data rate selection for vehicle safety communications", Proc. ACM VANET, San Francisco, pp. 30-38, 15 Sept. 2008

- Fundamental trade-off
  - High data rates result in short packet durations, thus producing lower channel load levels and interferences for a given tx power
  - High data rates require higher tx power levels to maintain a communications range

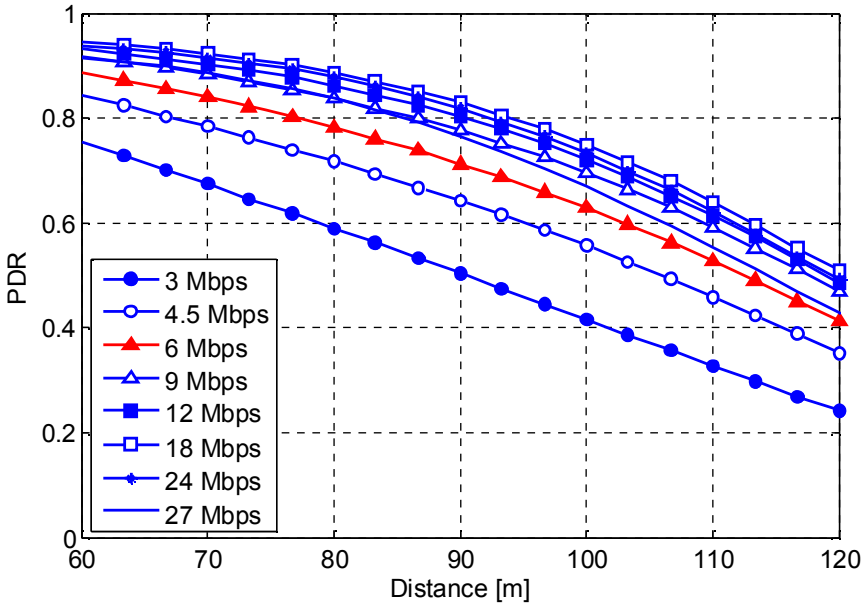
Optimize 802.11p

- Simulation: vehicles configured with same data rate & tx power needed to achieve PDR=0.95 at Communications Range=100m

Higher data rates can reduce CBR around 20%



Reduction of CBR results in higher PDR at target distance with higher data rates



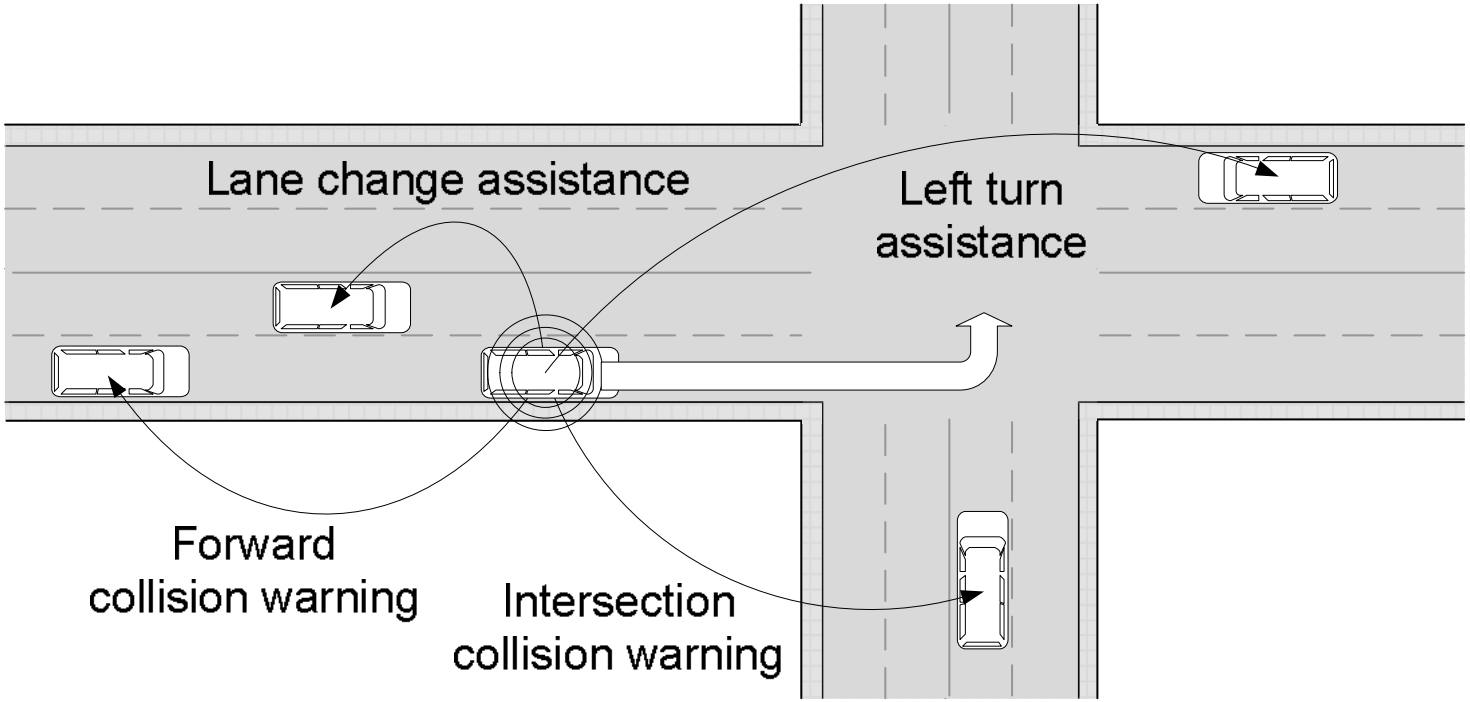
Urban street with 6 lanes, 50 veh/km/lane, 10Hz, WINNER+ B1 propagation model

M. Sepulcre, J. Gozalvez, B. Coll-Perales, "Why 6Mbps is not (always) the Optimum Data Rate for Beaconing in Vehicular Networks", accepted, IEEE Transactions Mobile Computing, 2017.

UNIVERSITAS Miguel Hernández de Elche

Optimize 802.11p

- Vehicles running simultaneously multiple applications



Optimize 802.11p

- Vehicles running simultaneously multiple applications
  - Message Handler: SAE (Society of Automotive Engineers) J2735 DSRC Message Set Dictionary
    - Considers: applications can require a different transmission frequency of beacon messages
    - Ignores: each application could also require a different communication range
  - MERLIN- optiMum powER and message rate controL for multIple applicatioNs:
    - Jointly considers the requirements from all the applications
    - Optimization process to select the configuration of communication parameters that minimizes the channel load

M. Sepulcre, J. Gozalvez, “Power and Message Rate Control for Vehicular Networks in Multi-Application Scenarios”, under evaluation, IEEE Transactions on ITS.

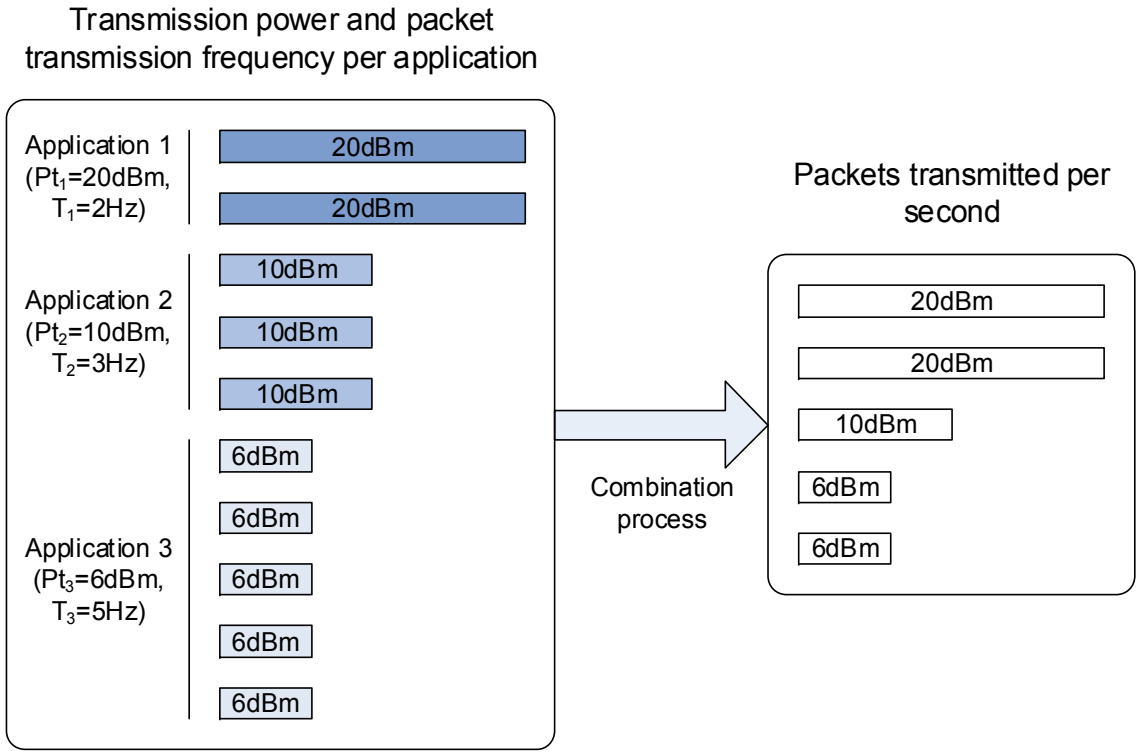
Optimize 802.11p

- Vehicles running simultaneously multiple applications
  - PRESTO- PoweR and mESsage raTe cOntrol for multiple applications:
    - Computes for each application the configuration of communication parameters that satisfies its requirements
    - Combines the configurations and identifies a set of communication parameters that satisfies the requirements of all applications

M. Sepulcre, J. Gozalvez, “Power and Message Rate Control for Vehicular Networks in Multi-Application Scenarios”, under evaluation, IEEE Transactions on ITS.

Optimize 802.11p

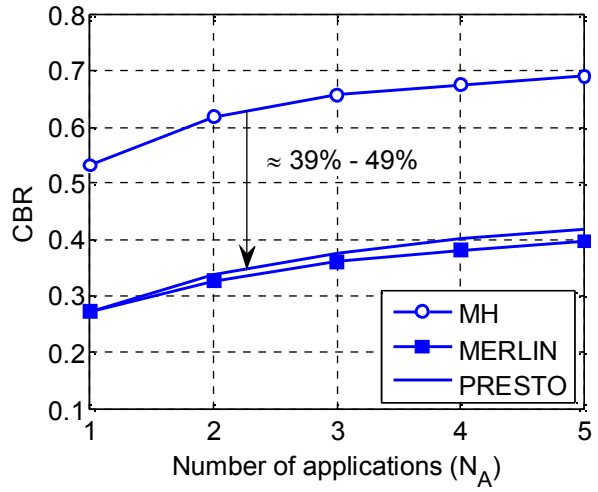
- Vehicles running simultaneously multiple applications
  - PRESTO- PoweR and mESsage raTe cOntrol for multiple applications:
    - Computes for each application the configuration of communication parameters that satisfies its requirements
    - Combines the configurations and identifies a set of communication parameters that satisfies the requirements of all applications



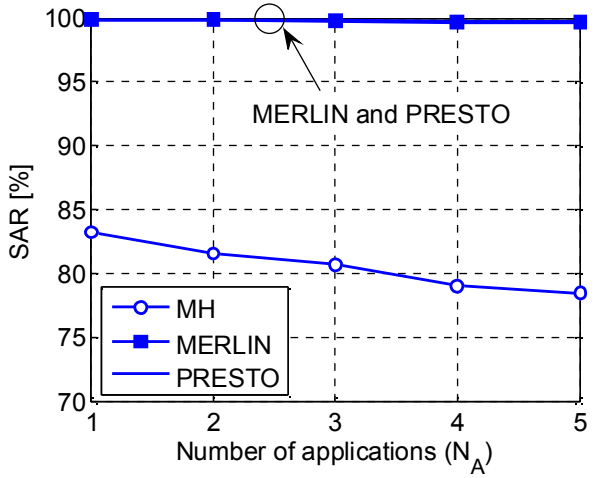
UNIVERSITAS Miguel Hernández de Elche

Optimize 802.11p

- Vehicles running simultaneously multiple applications



Channel Busy Ratio (CBR): % of time that a vehicle senses the channel as busy



SAR: % of vehicles with satisfied application requirements

M. Sepulcre, J. Gozalvez, "Power and Message Rate Control for Vehicular Networks in Multi-Application Scenarios", under evaluation, IEEE Transactions on ITS.

UNIVERSITAS Miguel Hernández de Elche

V2X for future connected & automated driving

- Possible options
  - Optimize 802.11p (transmission parameters, advanced geo-networking, transport, etc.)
  - Stop using IEEE 802.11p and use a new technology

Cellular V2X

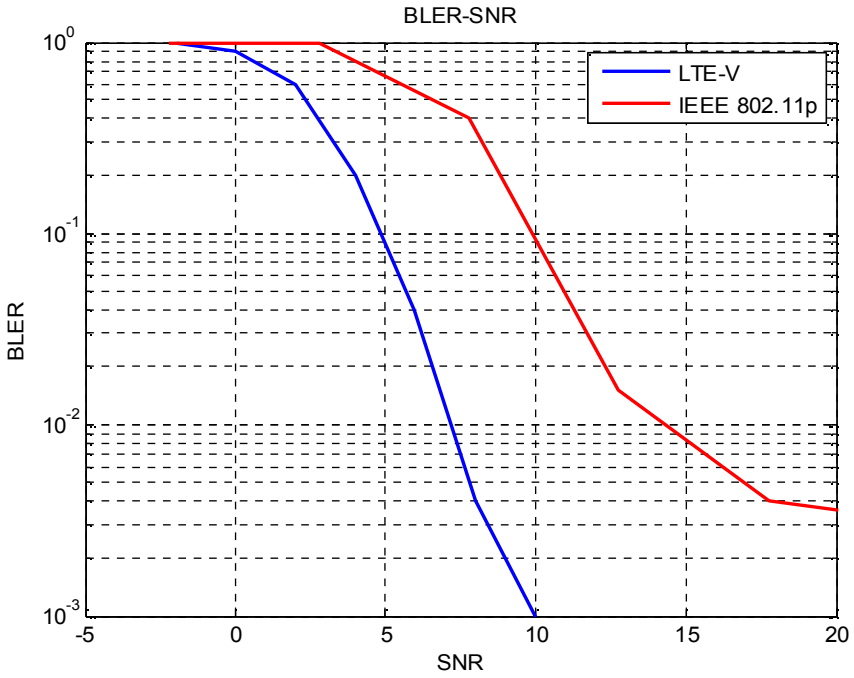
- Cellular tech are being embedded into connected vehicles
  - Introduction of LTE modems in cars by most car manufacturers
    - 60% cellular penetration in new light vehicles by 2021 (Strategy Analytics)
    - 32% of new cellular accounts in the US in 1Q 2016 are for connected cars (Chetan Sharma Consulting)
  - Leverage on existing cellular infrastructure
    - Trials completed in Finland and Netherlands using LTE to transmit C-ITS messages

Cellular V2X

- Cellular V2X or LTE-V as part of 3GPP Release 14
  - C-V2X defines two transmission modes
    - Sidelink comms with in-and out-of cellular coverage (PC5 interface)
      - Mode 3: vehicles directly communicate, but selection & management of resources done by cellular infrastructure
      - Mode 4: vehicles autonomously select and manage the radio resources without any cellular infrastructure support
      - LTE-D (3GPP Release 12)
      - Enhancements to LTE Direct PHY/MAC
      - Reuses service & app layers defined by automotive community as well as security and transport layers
    - Network communications
      - LTE Broadcast (Release 9)

Cellular V2X

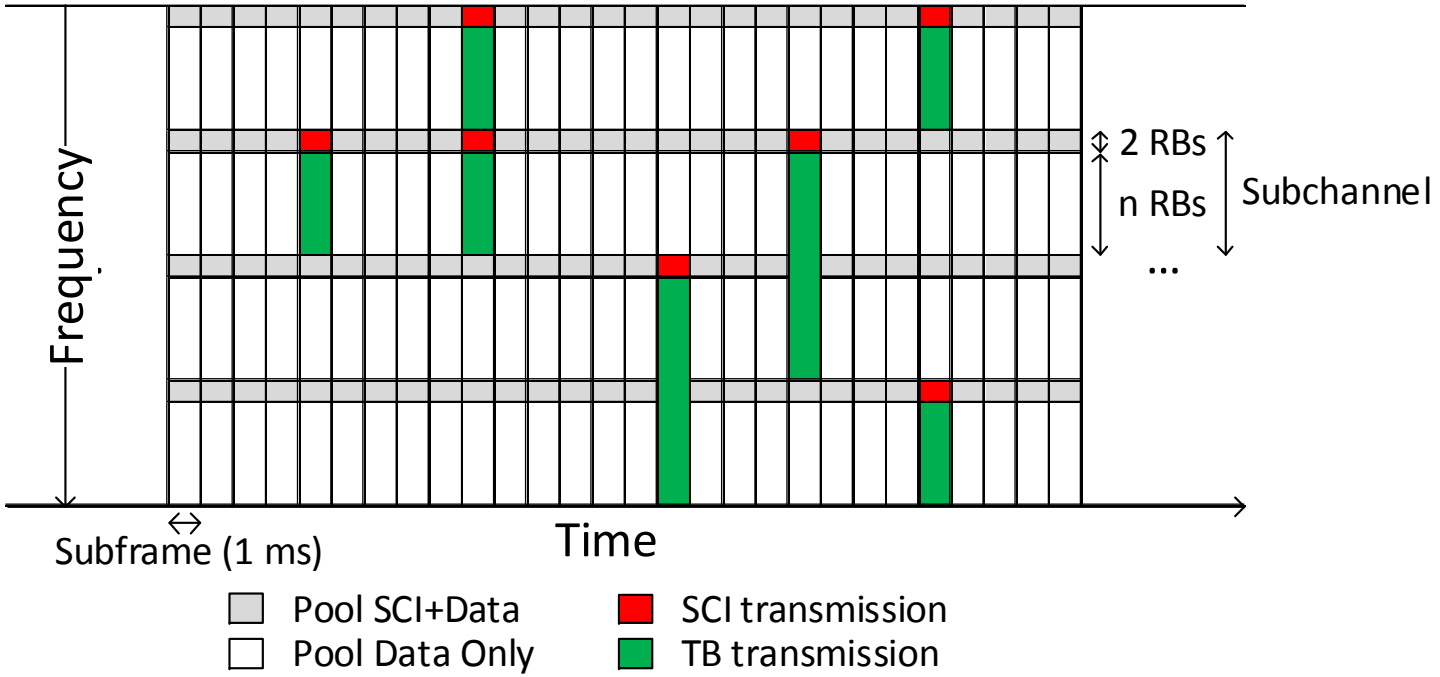
- LTE-V mode 4: alternative to 802.11p
  - Superior physical layer performance



UNIVERSITAS Miguel Hernández de Elche

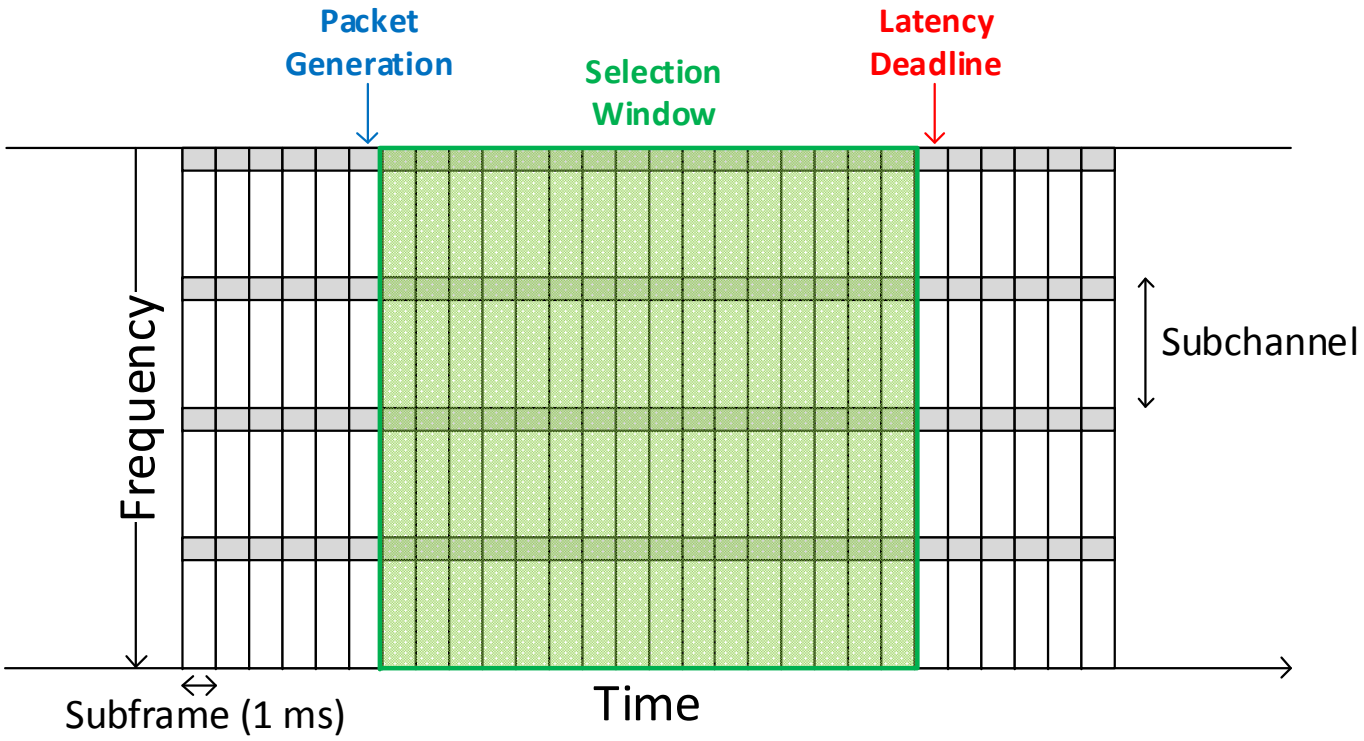
Cellular V2X

- LTE-V mode 4: network perform. depends on distributed scheduling
  - Mode 4 organizes RBs into frequency sub-channels



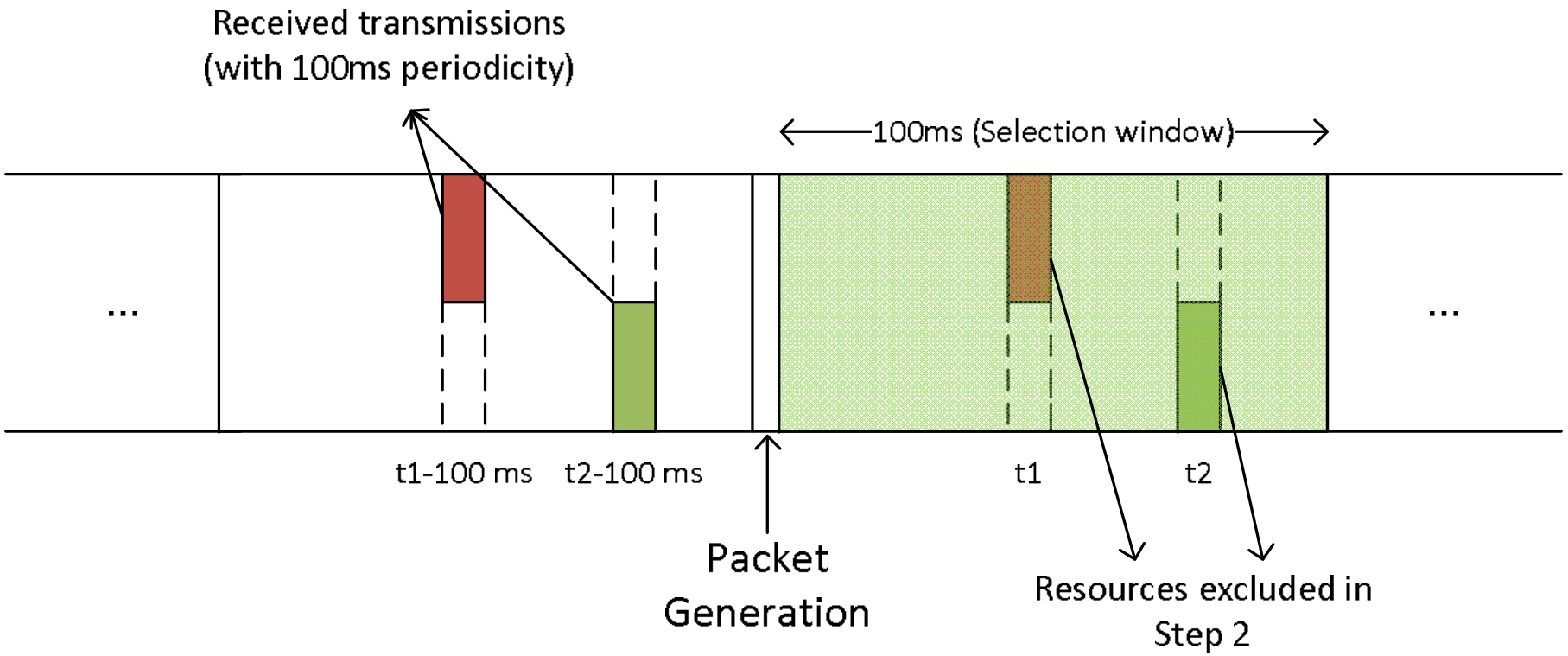
Cellular V2X

- LTE-V mode 4: Sensing-based Semi-Persistent Scheduling



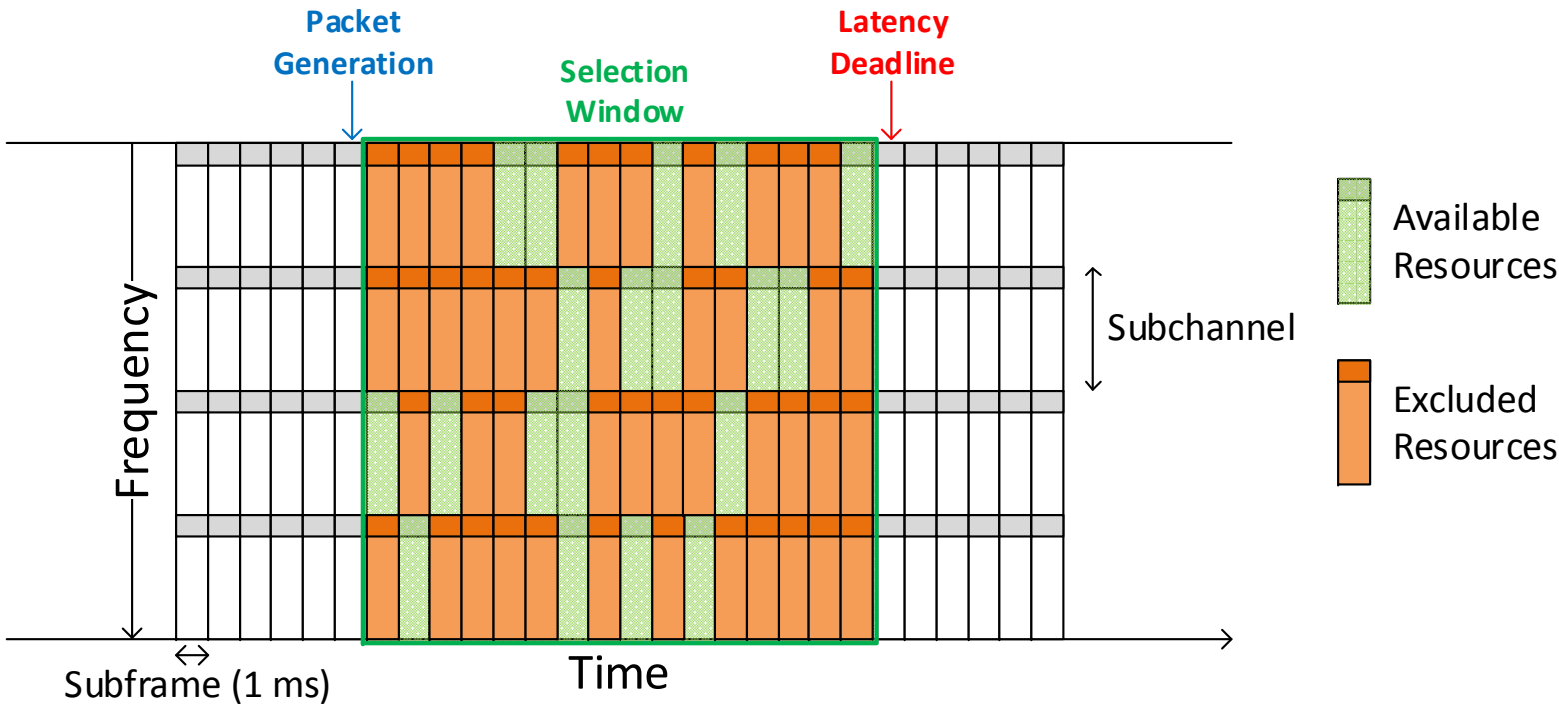
Cellular V2X

- LTE-V mode 4: Sensing-based Semi-Persistent Scheduling



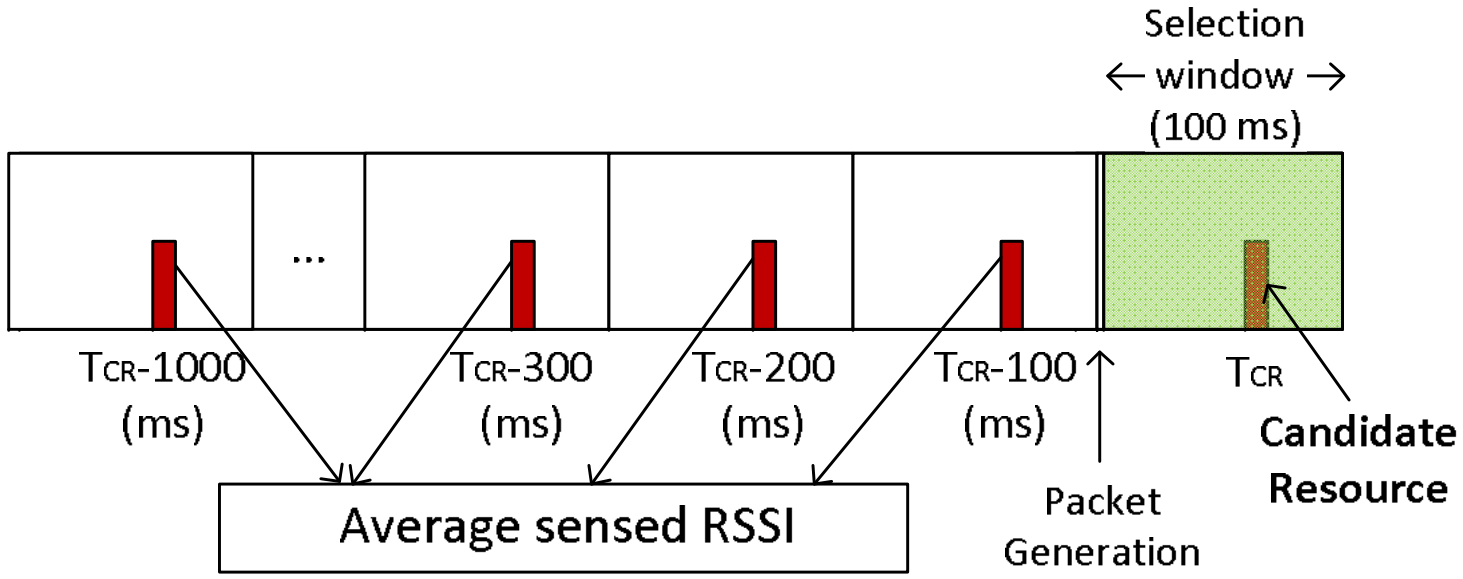
Cellular V2X

- LTE-V mode 4: Sensing-based Semi-Persistent Scheduling



Cellular V2X

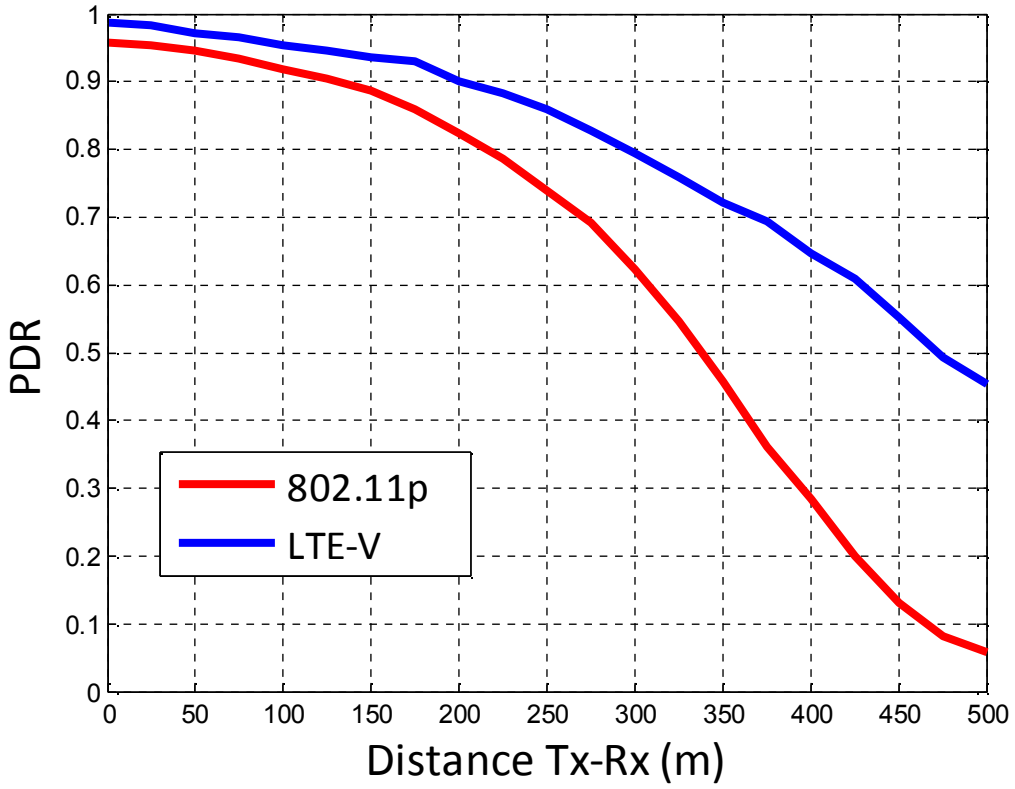
- LTE-V mode 4: Sensing-based Semi-Persistent Scheduling



- Possible for each packet to be transmitted twice
  - If 1st copy is transmitted in sub-frame *SF* ⇨ 2nd copy transmitted in candidate resource selected randomly within time interval [*SF*-15ms; *SF*+15ms]

Cellular V2X

- LTE-V mode 4 vs 802.11p
  - Highway scenario with 6 lanes & 120 vehicles/km
  - Beacon packets every 100ms, 6Mbps data rate, 23dBm tx power

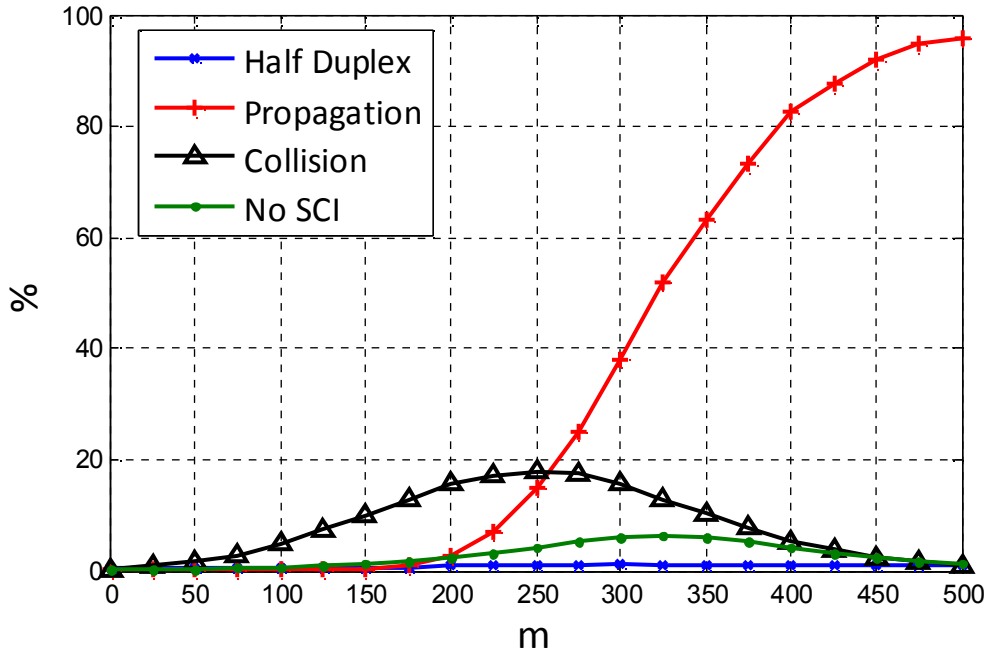


UNIVERSITAS Miguel Hernández de Elche

Cellular V2X

- LTE-V mode 4: there is room for improvement
  - Beacon packets every 100ms, 6Mbps data rate, 23dBm tx power

Percentage of TBs incorrectly received per type of transmission error as a function of the distance between transmitter and receiver

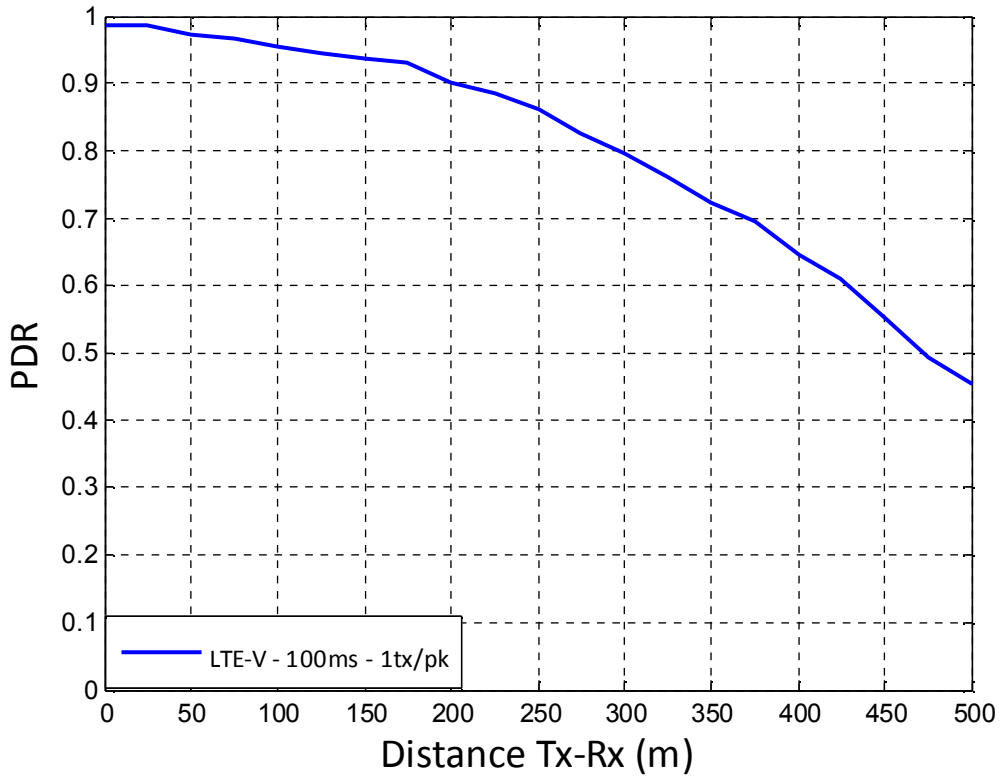


R. Molina-Masegosa and J. Gozalvez, "System Level Evaluation of LTE-V2V Mode 4 Communications and its Distributed Scheduling", Proc. IEEE VTC2017-Spring, June 2017.

UNIVERSITAS Miguel Hernández de Elche

Cellular V2X

- Support of autonomous driving with LTE-V mode 4
  - Beacon packets transmitted every 100ms for connected vehicles

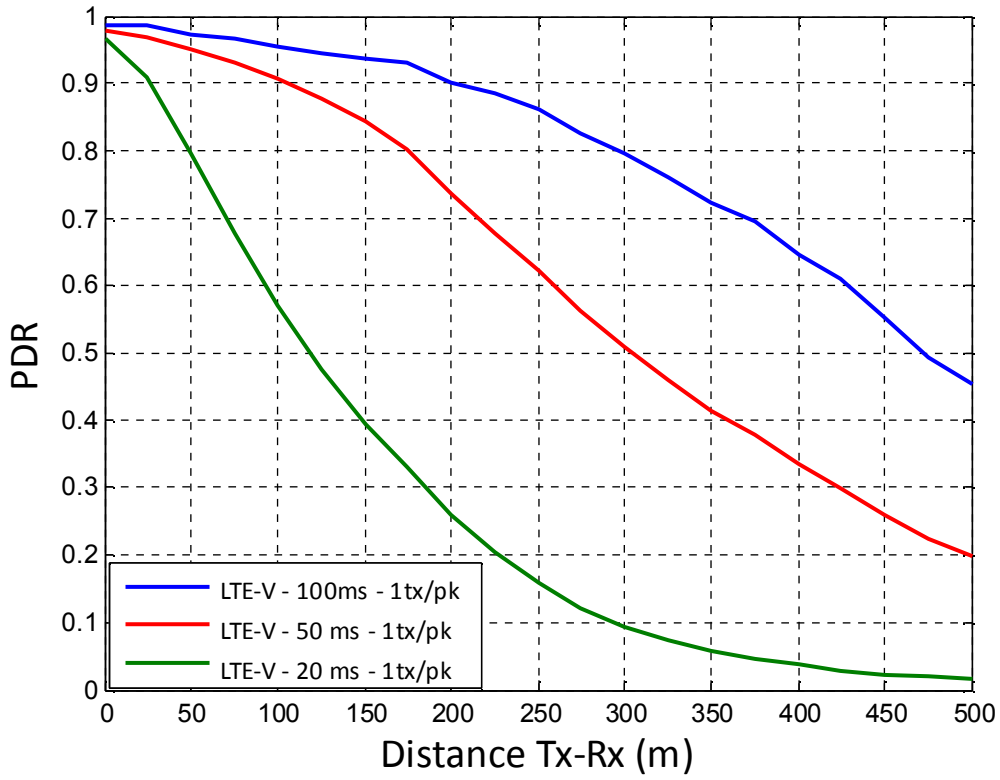


Highway with 6 lanes ,120 vehicles/km, 6Mbps bit rate, 23dBm tx power

UNIVERSITAS Miguel Hernández de Elche

Cellular V2X

- Support of autonomous driving with LTE-V mode 4
  - Beacon packets transmitted every 100ms for connected vehicles
  - Automated driving applications: packets every 20ms or 50ms

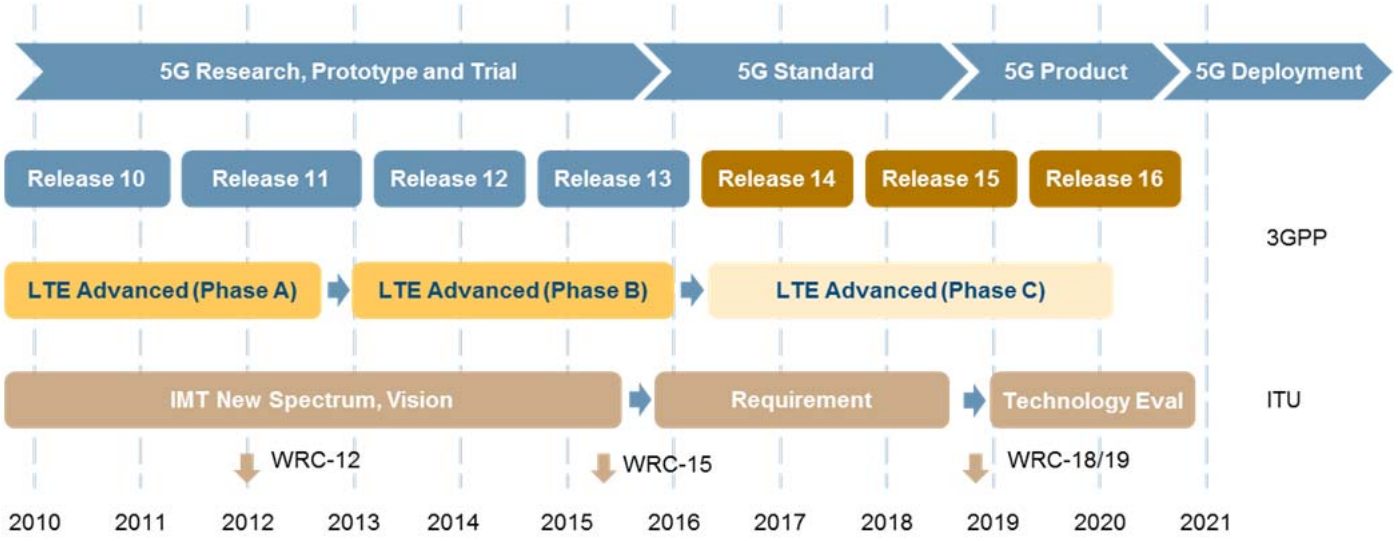


Highway with 6 lanes ,120 vehicles/km, 6Mbps bit rate, 23dBm tx power

UNIVERSITAS Miguel Hernández de Elche

Cellular V2X

- Timeline
  - C-V2X 3GPP Release 14 products ready by 2018-2019?
  - IEEE, ETSI and ISO: developed services and facilities on top PHY/MAC



Source: Huawei

  - NHTSA: possible mandate of 802.11p V2V on all new light vehicles
  - Average age of all light vehicles is 11.5 years on US roads and 9.73 years in the EU

V2X for future connected & automated driving

- Possible options
  - Optimize 802.11p (transmission parameters, advanced geo-networking, transport, etc.)
  - Stop using IEEE 802.11p and use a new technology
  - Use IEEE 802.11p and add new technologies

Heterogeneous V2X networks

Fundamental reason: a single technology cannot satisfy all needs

- Ready for deployment
- High capacity in dense scenarios and high bandwidth
- Reliability under dense scenarios & adverse propagation conditions
- Low latency even under dense communication conditions
- Ubiquitous connectivity
- Possibility for geo-broadcast support
- Integration of security/privacy

Heterogeneous V2X networks

Practical reasons: because they will be there anyway

Heterogeneous V2V

Heterogeneous V2V

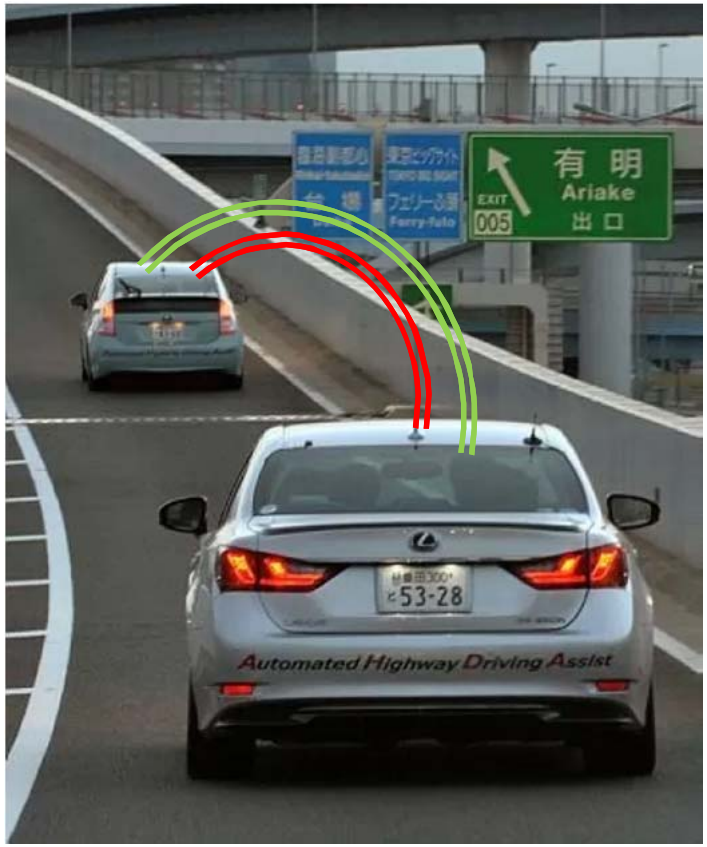
- V2V communications face significant challenges
  - Network scalability
  - High reliability levels required by cooperative driving
  - High bandwidth for cooperative perception or sensing
- Possibility to apply heterogeneous networking to V2V
  - IEEE 802.11p
  - Cellular V2X
  - Visible Light Communications
  - Mm-Wave
  - TV white space

Heterogeneous V2V for Cooperative Driving

UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V: cooperative driving

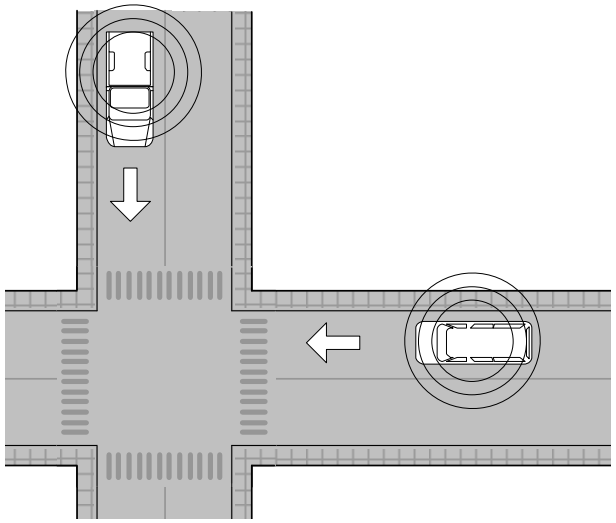
- Cooperative driving requires high reliability

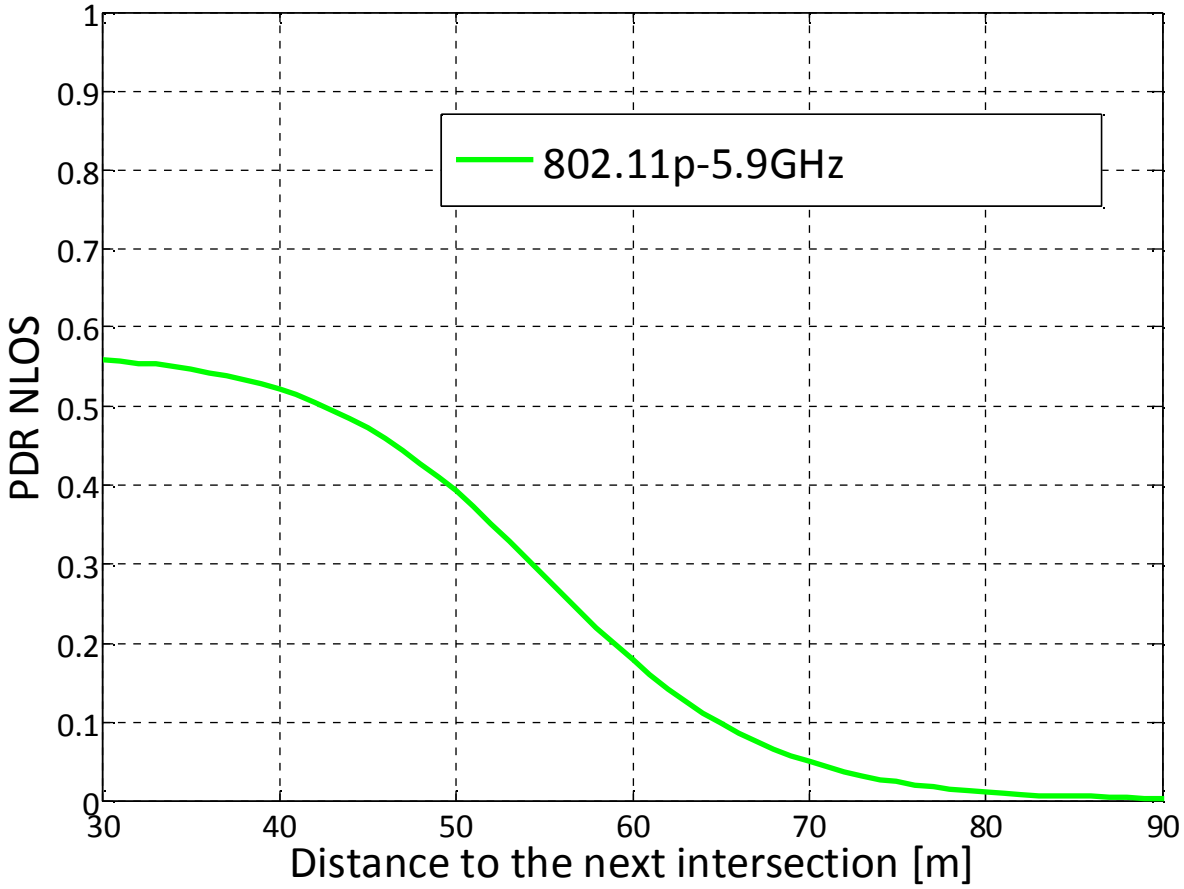


"Volvo's Self-Driving Program Will Have Redundancy For Everything"
IEEE Spectrum, May 2016

UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V: cooperative driving



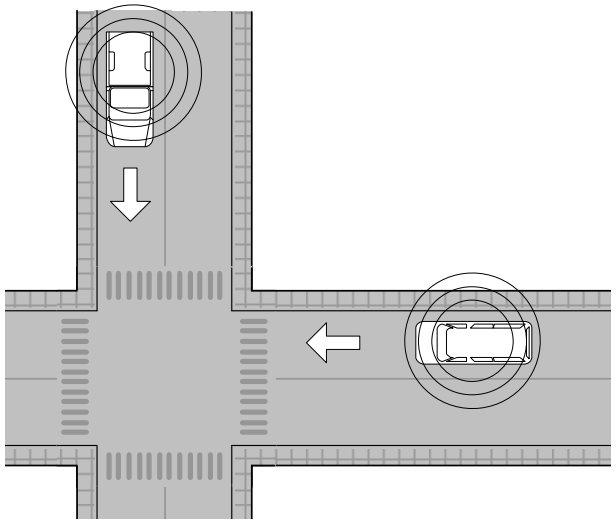


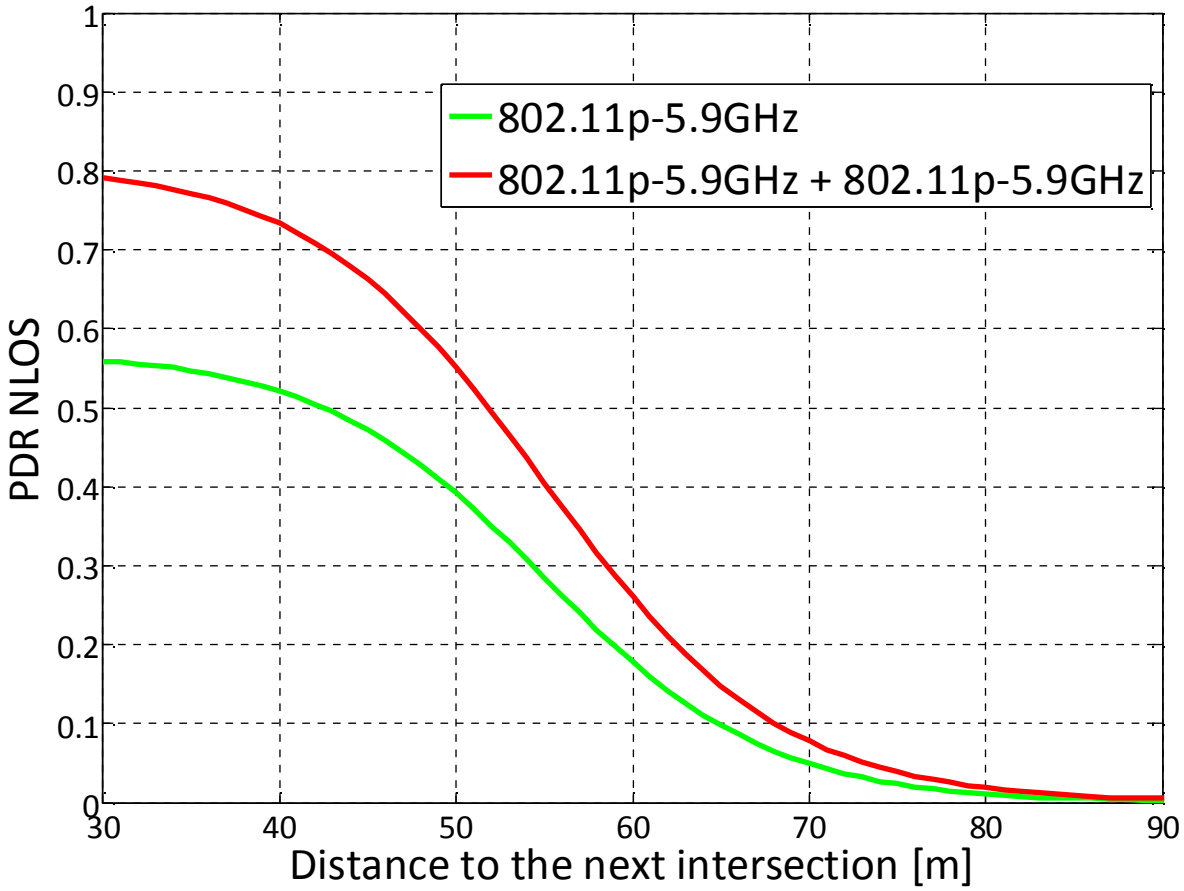
Manhattan scenario. 20 packets per second

UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V: cooperative driving

- Redundancy



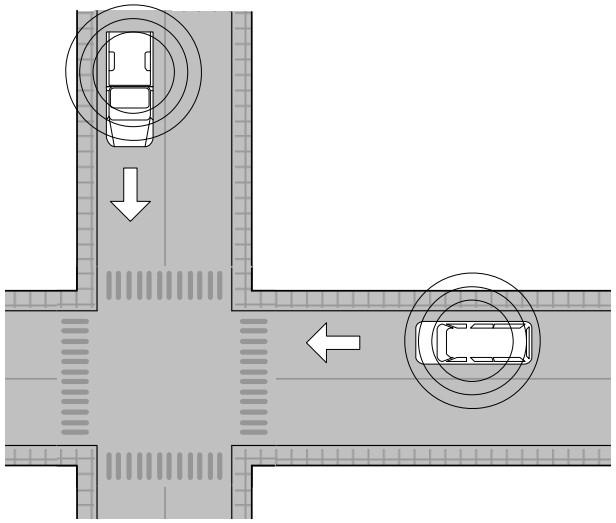


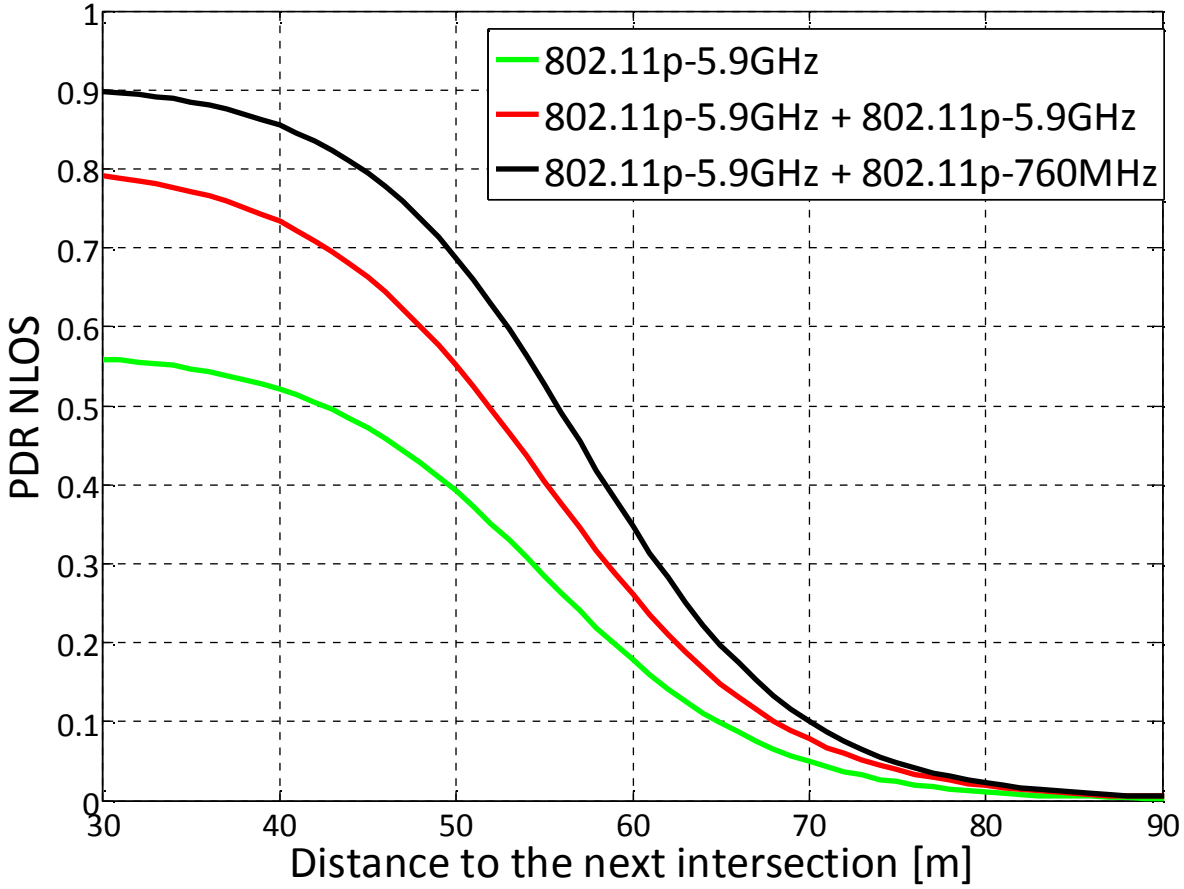
Manhattan scenario. 20 packets per second

UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V: cooperative driving

- Het. V2V for redundant tx: exploit different characteristics
  - Propagation



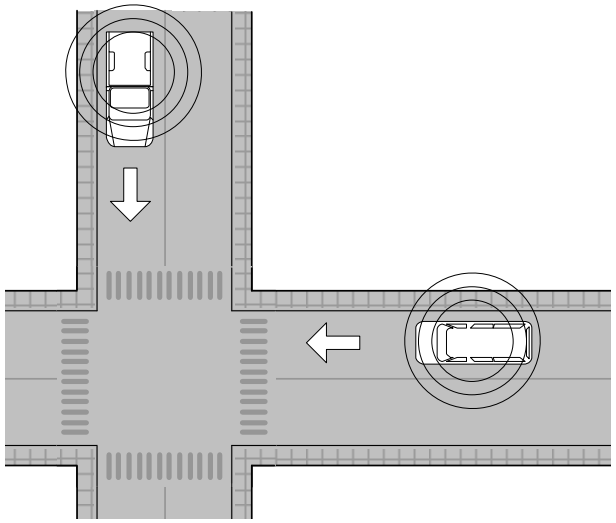


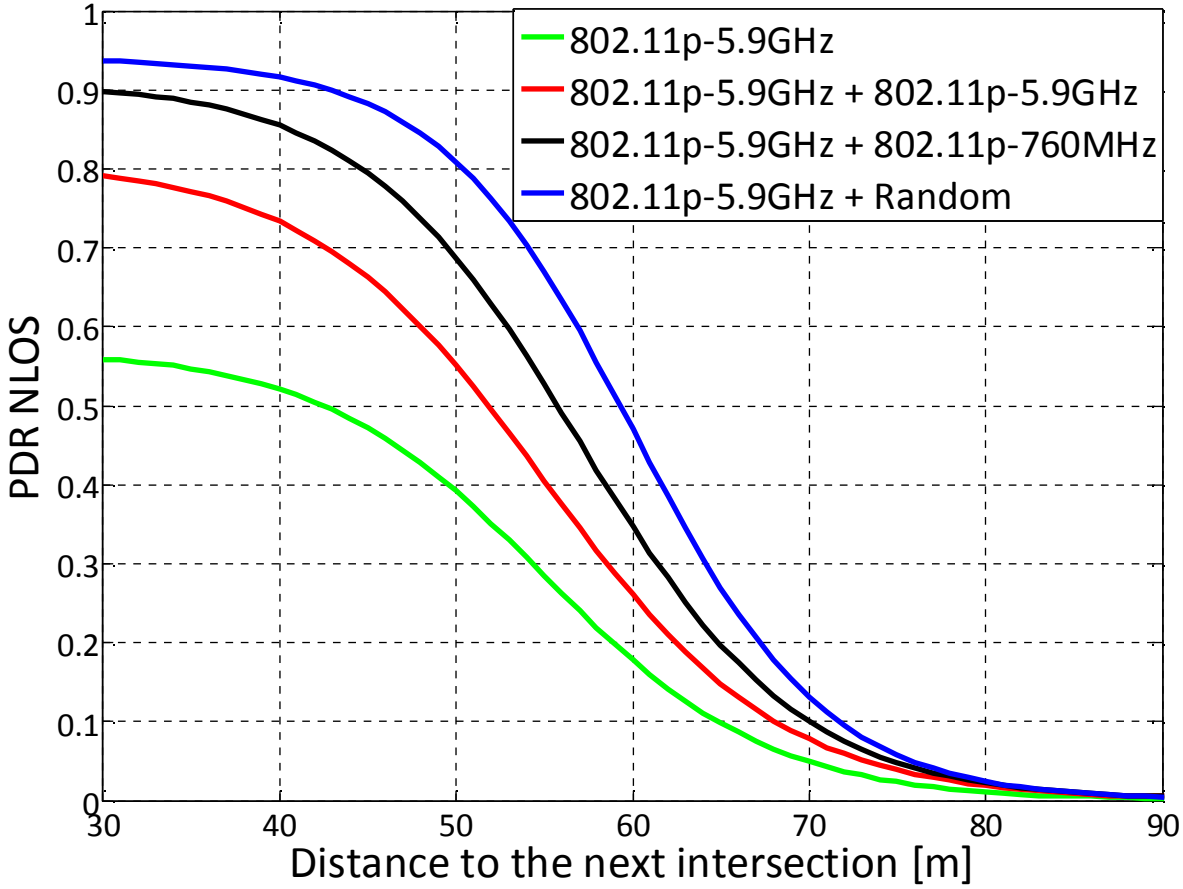
Manhattan scenario. 20 packets per second

UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V: cooperative driving

- Het. V2V for redundant tx: exploit different characteristics
  - Congestion & packet collisions



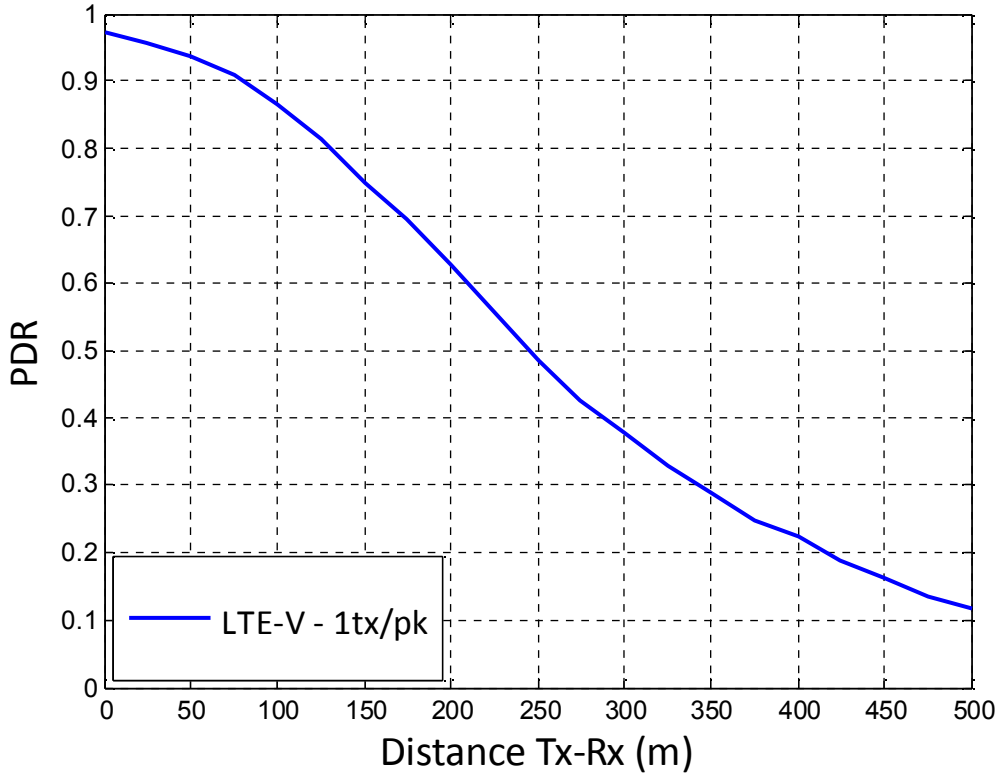


Random: IEEE802.11p@5.9GHz, IEEE802.11p@760MHz or WiFi @2.4GHz

UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V: cooperative driving

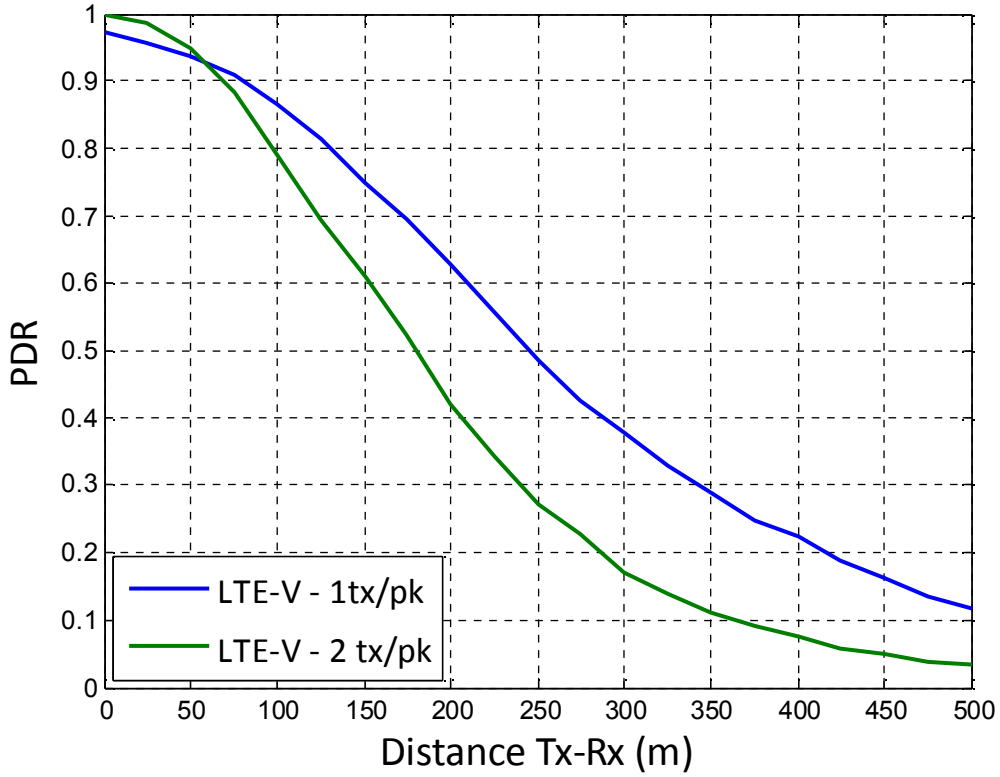
- Het. V2V for redundant tx
  - ‘Diversity’ in medium access: LTE-V for Cellular V2X



UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V: cooperative driving

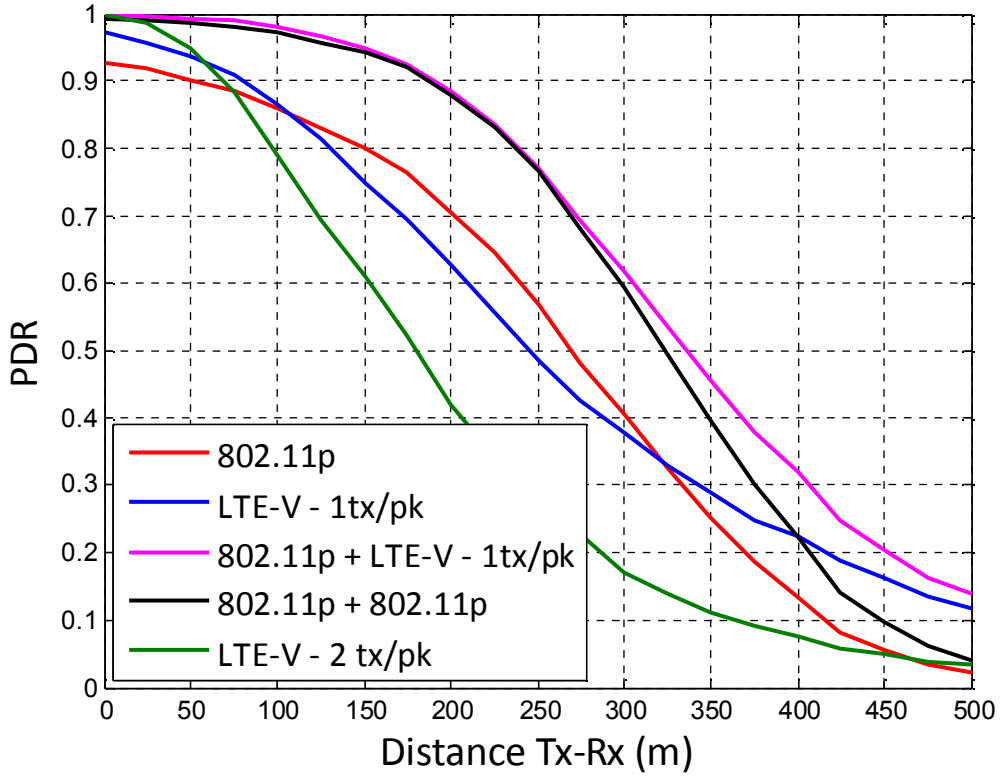
- Het. V2V for redundant tx
  - ‘Diversity’ in medium access: LTE-V for Cellular V2X



UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V: cooperative driving

- Het. V2V for redundant tx
  - ‘Diversity’ in medium access: LTE-V for Cellular V2X
    - ‘Uncorrelated interference patterns’



UNIVERSITAS Miguel Hernández de Elche

Heterogeneous V2V for Cooperative Sensing

UNIVERSITAS Miguel Hernández de Elche

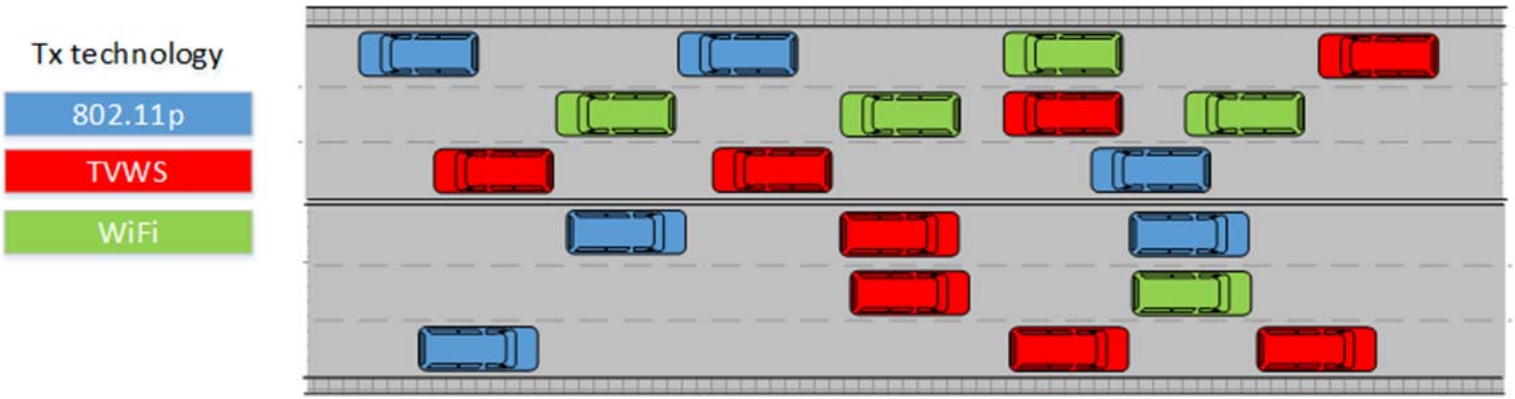
Heterogeneous V2V: cooperative sensing

- Cooperative perception or sensing: exchange of sensor data
  - Requires higher bandwidth than provided by 802.11p
  - Scenario: vehicles equipped with different technologies

	802.11p 760MHz	802.11p 5.9GHz	WiFi 2.4GHz	WiFi 5.6GHz	TVWS
Band-width	10MHz	10MHz	20MHz	20MHz	6MHz
Power	20dBm 100mW	23dBm 200mW	20dBm 100mW	17dBm 50mW	20dBm 100mW
Data rate	18Mbps	27Mbps	54Mbps	54Mbps	7.2Mbps
MCS	16QAM 3/4	64QAM 3/4	64QAM 3/4	64-QAM 3/4	64-QAM 3/4
Freq.	0.76GHz	5.9GHz	2.4GHz	5.6GHz	0.46GHz

Heterogeneous V2V: cooperative sensing

- Cooperative perception or sensing: exchange of sensor data
  - Requires higher bandwidth than provided by 802.11p
  - Scenario: vehicles equipped with different technologies
    - Can transmit using one, but can receive on all



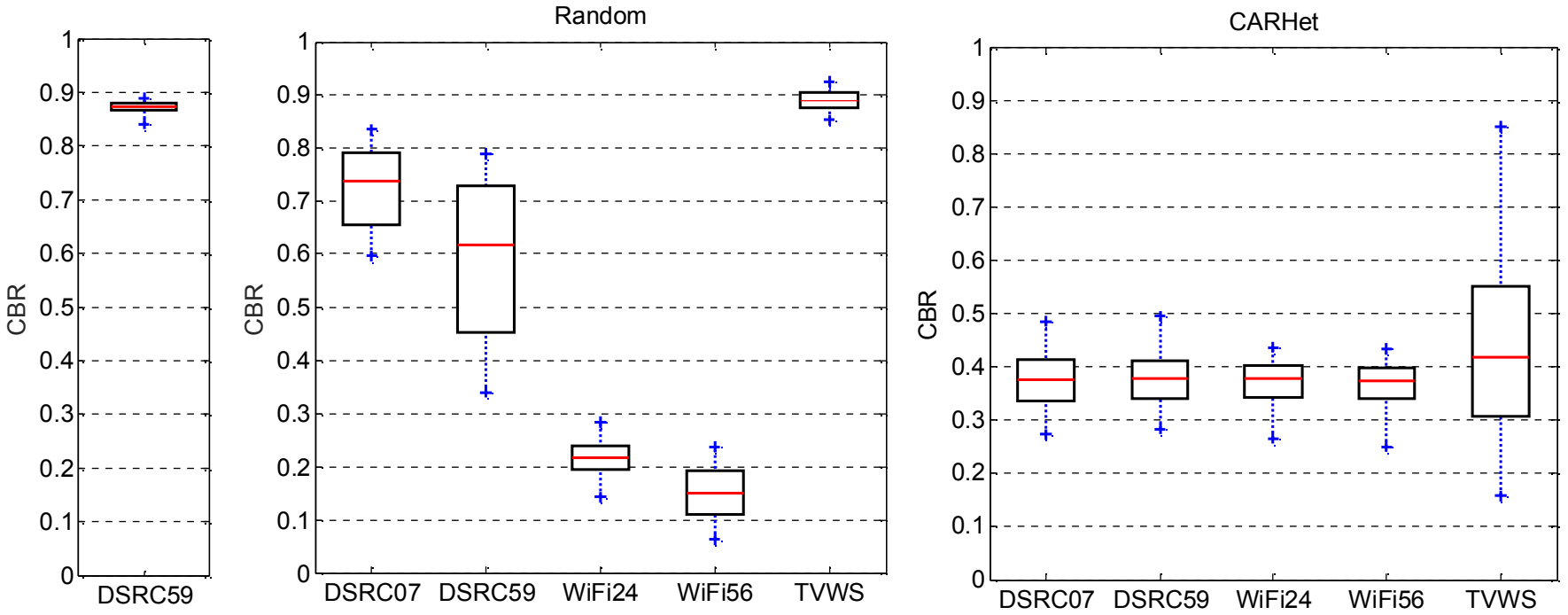
Which technology should each vehicle use to transmit?

Heterogeneous V2V: cooperative sensing

- CARHet: Heterogeneous V2V alg. for cooperative perception
  - Local decisions at each vehicle
    - Identifies comms. technologies that satisfy application requirements
    - Selects the one that minimizes the maximum channel load experienced by any neighbor
  - Proposal to extend the Collective Observation Service
    - Vehicles periodically share information about their communications context conditions
  - Risk of instability (constant changes of selected technologies)

Heterogeneous V2V: cooperative sensing

- CARHet: Heterogeneous V2V alg. for cooperative perception
  - Highway with traffic density of 20 veh/km/lane (80 veh/km)
  - Application requirements: 1Mbps, 40m

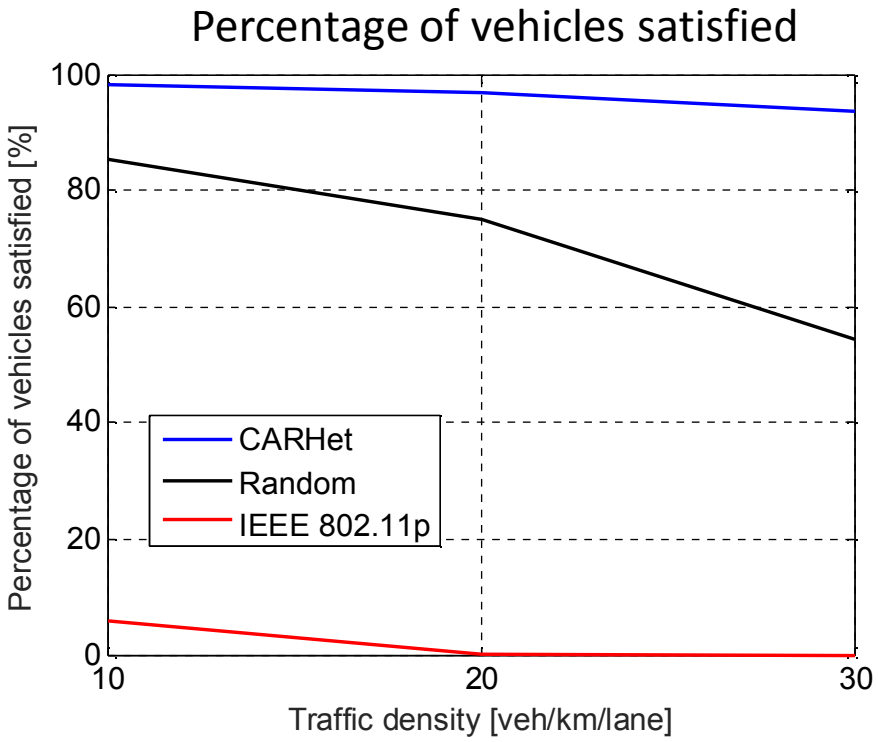


CBR (Channel Busy Ratio): metric for channel load

UNIVERSITAS Miguel Hernández de Elche

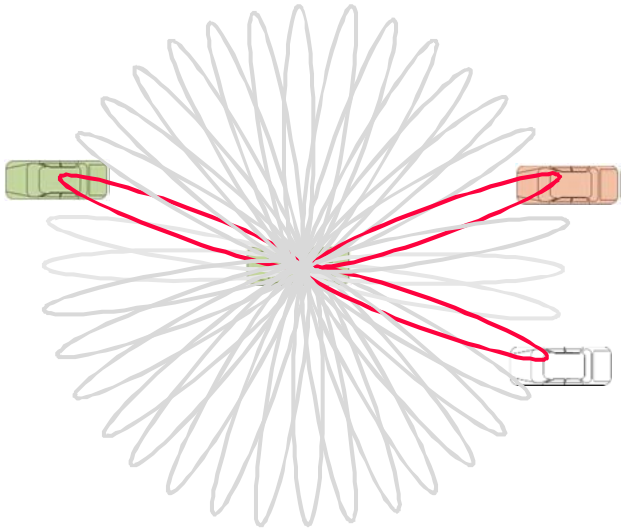
Heterogeneous V2V: cooperative sensing

- CARHet: Heterogeneous V2V alg. for cooperative perception
  - Highway with traffic density of 20 veh/km/lane (80 veh/km)
  - Application requirements: 1Mbps, 40m



Heterogeneous V2V: cooperative sensing

- Tx. of raw sensor data (autonomous driving): high bandwidth
  - mmWave technologies above 30GHz
  - Challenge 1: mmWave beam alignment & tracking in high mobility
    - Brute force: test all possible transmit and receive beams sequentially
      ⇨ high overhead

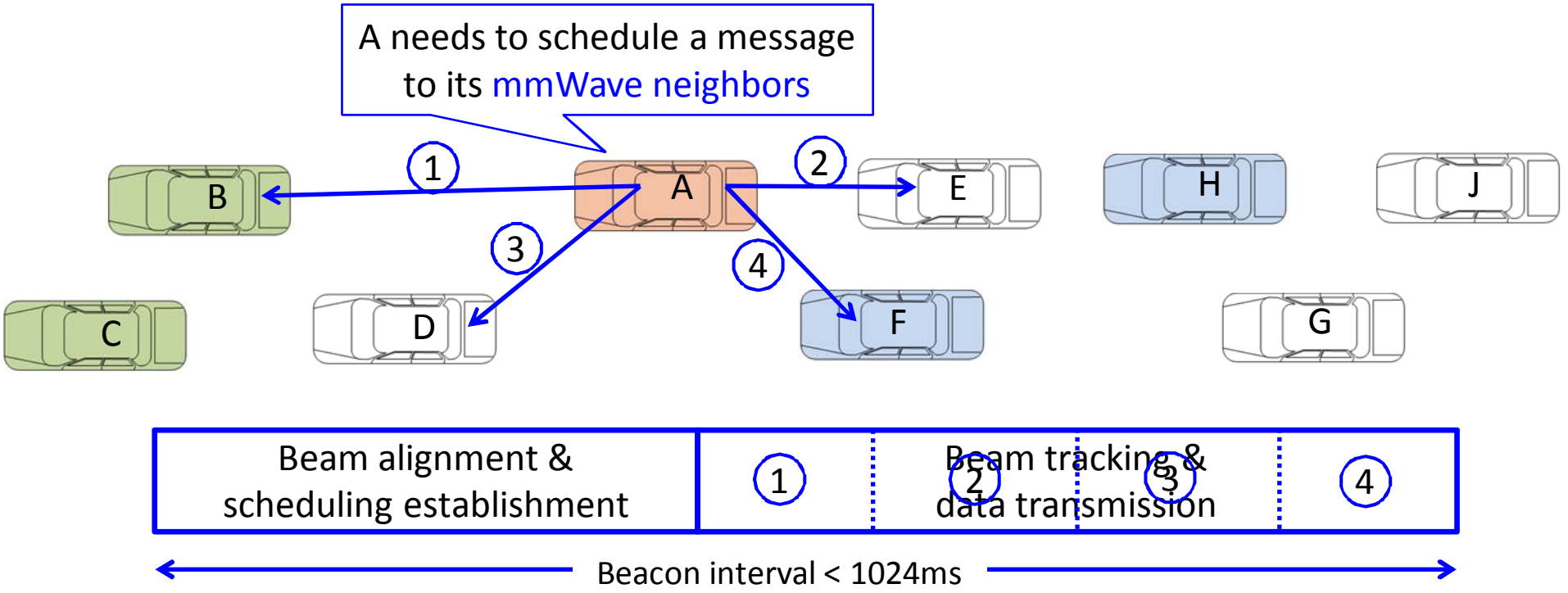


  - Use 802.11p data for mmWave communication link configuration
    - Obtain relative position of neighboring vehicles

J., Choi et al., "Millimeter Wave Vehicular Communication to Support Massive Automotive Sensing", IEEE Communications Magazine, Dec. 2016

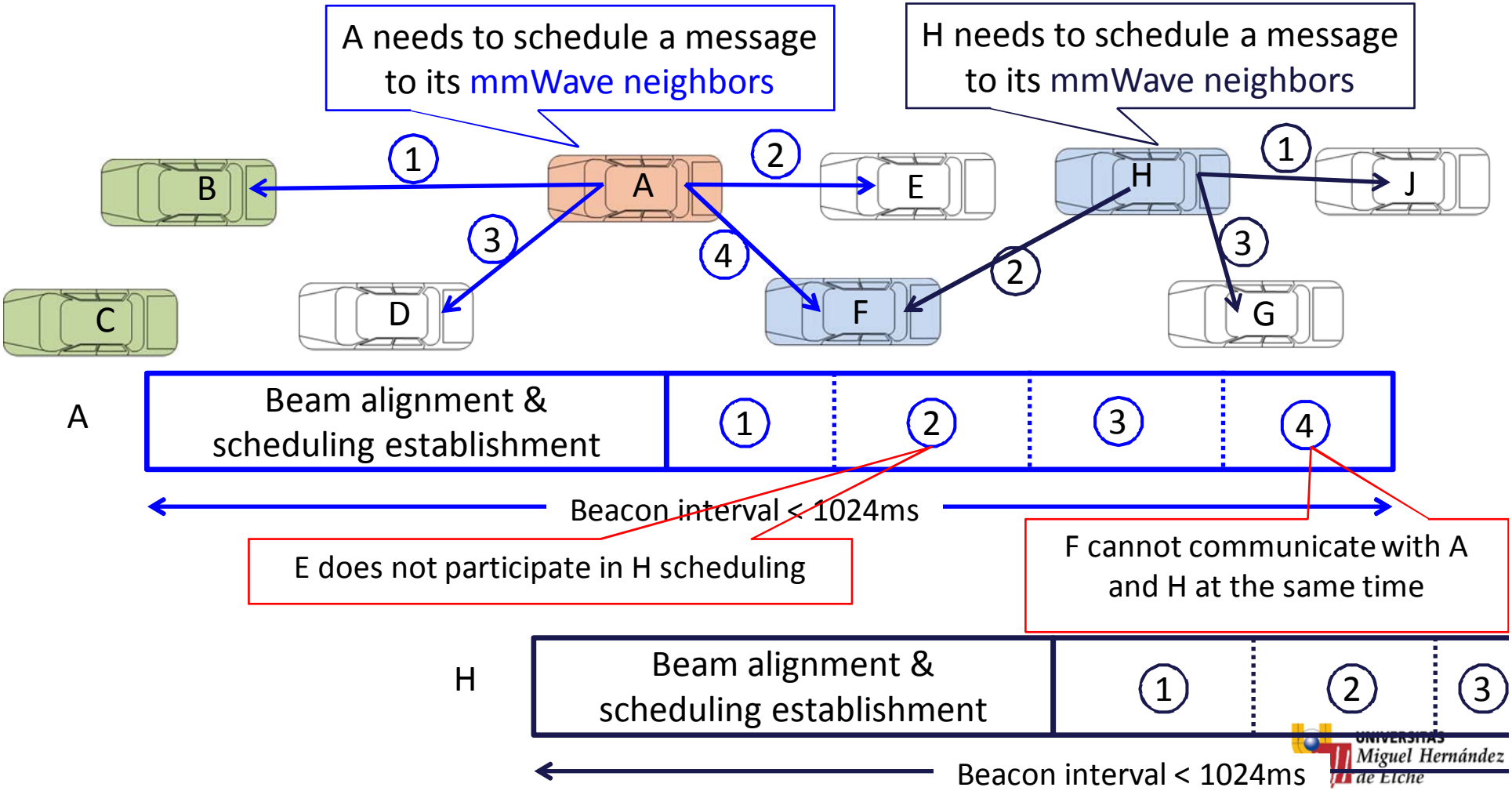
Heterogeneous V2V: cooperative sensing

- Tx. of raw sensor data (autonomous driving): high bandwidth
  - mmWave technologies above 30GHz
  - Challenge 2: scheduling of transmissions



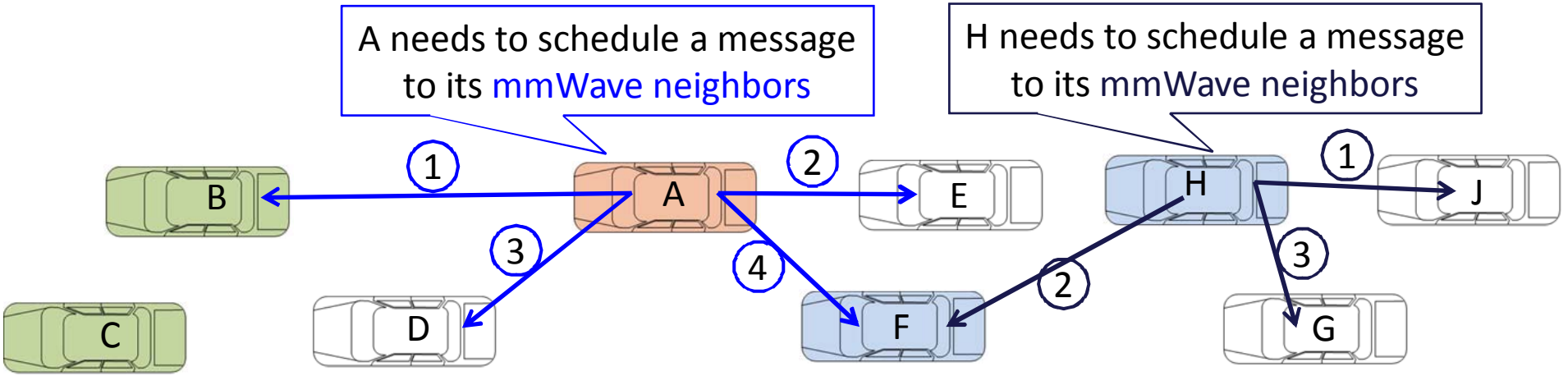
Heterogeneous V2V: cooperative sensing

- Tx. of raw sensor data (autonomous driving): high bandwidth
  - mmWave technologies above 30GHz
  - Challenge 2: scheduling of transmissions



Heterogeneous V2V: cooperative sensing

- Tx. of raw sensor data (autonomous driving): high bandwidth
  - mmWave technologies above 30GHz
  - Challenge 2: scheduling of transmissions



Use 802.11p to support scheduling: low frequency control plane with omnidirectional transmissions

UNIVERSITAS
Miguel Hernández
de Elche

IEEE Connected Vehicles

www.ieee-connected-vehicles.org

Thank you for your attention!

j.gozalvez@umh.es

UNIVERSITAS Miguel Hernández de Elche