Cooperative Vehicle-to-Vehicle Communications: From Mobile Sensing to Data Dissemination

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• V2X Research Challenges

• Mobile Sensing: V2V-based Road Traffic Congestion Detection

• Data Dissemination: Multi-Hop Road Connectivity Estimation
V2X Research Challenges
Vehicular Communications

• Cooperative V2X Systems: advanced ITS technology for traffic safety, management and infotainment services
  – Next step in active safety
  – Rapid distributed detection and reaction capability for road traffic management

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Vehicular Communications

- **WAVE, IEEE 802.11p, ITS G5A: evolution of IEEE 802.11a**
  - MAC: basic CSMA/CA access method
  - PHY: OFDM, same modulation/coding but 10MHz channel

- **5.9GHz band: 7 channels (USA) / 3 channels (Europe)**
  - One Control Channel: reference channel to detect surrounding vehicles and establish communication links (ad hoc broadcast tx mode)
  - Service Channels: public safety and private services
Many challenges ahead for the full and effective deployable of cooperative V2X communication systems

- Still need a consistent benefits demonstration
  - Driver assistance
    - Efficient HMI
    - Highly dynamic networks
  - Large-scale deployments
- Integration within the car: from electronics to antenna design
- Privacy and security
- Location accuracy
- Challenging propagation conditions, particularly for V2V
  - Selected 5.9GHz frequency band
  - Communications reliability
- Multi-channel transmissions
Vehicular Communications

- Communications/network-centric design vs applications design

\[ D_w = \frac{1}{2} \left( \frac{v_B - v_A}{a_A - a_B} \right)^2 + L + D_s \]

Vehicular Communications

- Congestion vs awareness control
  - Congestion control: limit/control channel load to ensure stable operation
  - Awareness control: aimed at efficiently ensuring each vehicle’s capacity to detect as well as to communicate to the relevant vehicles in their local neighborhood

Vehicular Communications

- Link quality metrics
- Multi-applications scenario
  - Communications Adaptation Layer

- Miguel Sepulcre, Jens Mittag, Paolo Santi, Hannes Hartenstein, Javier Gozalvez
  “Congestion and Awareness Control in Cooperative Vehicular Systems”, Submitted to Proceedings of IEEE

- Is energy really not a constraint?
- Looking for more complexity…what about V2P?
Mobile Sensing: V2V-based Road Traffic Congestion Detection
Setting the Scene…

• V2X promising technology…

• Need to demonstrate long term benefits: safety and traffic management
  – Traffic management: large-scale and relatively large emulation times
  – Different perspectives
    ▪ Improve traffic flows vs prioritising multimodal public transport
    ▪ Centralised vs distributed traffic management

• iTETRIS project
  – iTETRIS is an open source integrated wireless and traffic simulation platform for the assessment of real-time road traffic management solutions making use of cooperative ITS Systems over large scales scenarios
Setting the Scene…

- Traffic Condition Estimation: Use dynamic V2X communications to monitor traffic situations and detect anomalous cases in a more reactive, precise and efficient way.
- Traffic management: Reaction policies aimed at completing the detection phase by traffic information dissemination over the radio.

<table>
<thead>
<tr>
<th>Traffic Condition Estimation</th>
<th>Traffic Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1: Traffic Jam detection</td>
<td>S3: Bus Lane Management</td>
</tr>
<tr>
<td>S2: Travel Time Estimation</td>
<td>S4: Limited Access Warning</td>
</tr>
<tr>
<td>S3: Bus Lane Management</td>
<td>S5: Request Based Personalized Navigation</td>
</tr>
<tr>
<td>S4: Limited Access Warning</td>
<td>S6: Regulatory and Contextual Speed Information</td>
</tr>
<tr>
<td></td>
<td>S7: Emergency Vehicle</td>
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<tr>
<td></td>
<td>S8: Event Based Traffic Condition Notification</td>
</tr>
</tbody>
</table>
Setting the Scene…

- Reducing road traffic congestion can be achieved through effective management strategies
  - Mechanisms needed for the rapid and accurate detection of road traffic conditions
  - Current ITS technologies usually require the deployment of infrastructure sensors
    - Trade-off between traffic estimates accuracy and the number of deployed infrastructure sensors

- V2X: ¿capacity to complement/substitute ITS sensors?
  - Periodic beacons/CAMs (Cooperative Awareness Messages)
    - Possibility to continuously monitor local road traffic conditions
State of the Art

• COC (Contents Oriented Communications)
  – Vehicles estimate the road traffic density from received beacons or CAMs
    ▪ Periodically transmit this information to other vehicles
  – Congestion detection through comparison of road traffic density estimates with average traffic density values
  – Traffic congestion detection at the expense of communications overhead

State of the Art

- Possibilities to limit the communications overhead
- TrafficView: aggregation method to combine data from neighbouring vehicles
- SOTIS
- Combine the information generated by multiple vehicles using digital road maps
- Vehicles generate and exchange traffic information about the road segment they are currently located in, and other road segments for which they have traffic information
- Variant: only a single vehicle in each road segment is in charge of collecting and aggregating road traffic data
- Once aggregated, the information is transmitted to adjacent road segments
- Selection of the cluster head usually generates additional signaling overhead
State of the Art

- Other proposals limit the exchange of traffic information to only those situations of unexpected or abnormal traffic conditions
  - StreetSmart
  - General trade-off: overhead vs estimation reliability
    - Local estimates and decisions: low overhead but low estimation reliability
    - Correlated estimates and decisions: good estimate but large overhead
Problem Statement

• Cooperative V2X vehicles: mobile sensors

• Some limitations from previous proposals
  – CAMs and specific packets
    ▪ Exchanged even under non-congested conditions
    ▪ Communications overhead
  – Detection reliability: no cooperation among vehicles
  – No information about the characteristics of the traffic congestion

• CoTEC: COperative Traffic congestion detECtion
  – Capable to accurately detect the traffic congestion intensity and length
  – Control of the communications overhead

CoTEC

- CoTEC: local and cooperative detection
  - CAMs/beacons: locally monitor road traffic conditions
    - Fuzzy logic to detect congestion conditions
  - Congestion detected: cooperative process to correlate individual decisions
    - Improves detection accuracy
    - Capacity to characterise congestion condition: location, length and intensity

![Diagram of CoTEC](image)
CoTEC - Local Traffic Congestion Detection

- Traffic congestion estimation
  - Skycomp: US cities analysis through aerial surveys of different freeways
  - Six different Level-Of-Service (LOS) based on the US Highway Capacity Manual (HCM)
    - HCM LOS system does not distinguish between different levels of traffic congestion for the LOS F category
    - Skycomp’s system extends the HCM LOS F rating to differentiate distinct levels of traffic congestion

<table>
<thead>
<tr>
<th>CONGESTION LEVEL</th>
<th>TRAFFIC DENSITY</th>
<th>VEHICLE’S SPEED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight</td>
<td>[46-60] veh/mi/ln or [29-37] veh/km/ln</td>
<td>[30-50] mi/h or [48-81] km/h</td>
</tr>
<tr>
<td>Moderate</td>
<td>[60-80] veh/mi/ln or [37-50] veh/km/ln</td>
<td>[15-40] mi/h or [24-64] km/h</td>
</tr>
<tr>
<td>Severe</td>
<td>Above 80 veh/mi/ln or 50 veh/km/ln</td>
<td>Below 25 mi/h or 40 km/h</td>
</tr>
</tbody>
</table>
CoTEC - Local Traffic Congestion Detection

- Fuzzy-based local congestion detection
  - Inputs, sets and membership functions: speed and density
  - Output: congestion level
  - Fuzzy rules

### Fuzzy Rules

<table>
<thead>
<tr>
<th>Traffic density</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>VeryHigh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very Slow</td>
<td>Slight</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Severe</td>
</tr>
<tr>
<td>Slow</td>
<td>Free</td>
<td>Slight</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Medium</td>
<td>Free</td>
<td>Slight</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>Fast</td>
<td>Free</td>
<td>Free</td>
<td>Free</td>
<td>Slight</td>
</tr>
</tbody>
</table>

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• **Objective:** to achieve a consensus decision by evaluating individual estimations

• How is the information exchanged between the vehicles?
  – CTE messages used to collect local traffic estimations
  – Each vehicle forwarding the CTEM updates the traffic information in the packet based on its local estimation
  – Vehicles located at rear-end obtain a global vision of the traffic jam
CoTEC - Cooperative Traffic Congestion Detection

• Forwarding mechanism
  – Information-centric multi-hop forwarding protocol
  – **Contention-based forwarding** (CBF) at application layer
  – Only vehicles estimating traffic congestion **participate** in the forwarding process (rear-end detection and false alarms avoidance)
    – Forwarding finalized when reaching not congested area
    – Forwarding stops if a false or inaccurate traffic congestion situation is detected
    – Vehicles located outside traffic jam in charge of disseminating the traffic congestion information
CoTEC - Cooperative Traffic Congestion Detection

• How the information is processed to achieve a coherent decision?
  
  – **Mean-based**: the mean of the individual estimations is calculated in every hop
    \[ Mean_n = \frac{VehicleEstimation + (n-1) \cdot Mean_{n-1}}{n} \]
  
  – **Median-based**: forwarders include their estimations in the packet and last vehicle calculate the median
  
  – **Frequency intervals**: median based on grouped frequency distributions
    
    | Congestion intervals | Frequencies |
    |----------------------|-------------|
    | [0.4-0.5)            | 1           |
    | [0.5-0.6)            | 1           |
    | [0.6-0.7)            | 2           |
    | [0.7-0.8)            | 3           |
    | [0.8-0.9)            | 4           |
    | [0.9-1]              | 2           |

  – **Frequency intervals and neighbors**: frequency intervals increased by the number of neighbors that the vehicle detects
CoTEC - Detection Capability Evaluation

• Simulation settings
  – Movement traces generated in SUMO
  – 3.5km freeway segment with 2 lanes per direction
  – Communication range of 300m and CAM rate of 1Hz

• Simulated highway scenario
• Local traffic congestion detection
  – Traffic information gathered through V2V communications
CoTEC - Detection Capability Evaluation

- Cooperative traffic congestion detection
  - Median intervals neighbors closely follows the centralized approach whereas it offers the lowest error

![Congestion estimation by CoTEC](chart.png)
CoTEC - Detection Capability Evaluation

- Cooperative traffic congestion detection
  - Lower relaying distance implies higher number of forwarders (higher number of estimates) -> Higher detection accuracy
  - CTE message size increases with number of forwarders for the Median technique

![RMSE for increasing relaying distance](image)

- Median intervals neighbors
- Median
- Mean
- Number of vehicles

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• Transmission range
Further Activities

• Yet, we still need to do some optimisation
  – Front-end detection process
  – Rear-end detection vs false alarms
  – Local estimation under packet collisions and low V2V penetration rates
  – Effect of lower communications range on detection reliability
  – Local estimation in urban environments considering traffic flow interruptions by traffic lights

• Test under a more realistic communications modelling setting and larger scale
iTETRIS combines the simulator SUMO and the network simulator ns-3
- Applications for Road Traffic Management are implementable on the top of it

Peripheral blocks integrated by a third block called iTETRIS Control System (iCS)
- Architecture adopted to ensure standard compliancy (ETSI), modularity, interoperability and maintainability

Autonomous and programming language-independent development of each architecture block is allowed
The iCS and the peripheral blocks are connected through internet sockets
- A client/server relationship between iCS and the other blocks is used

The iCS is always the controlling actor pushing commands and/or information to- and pulling results from the peripheral blocks
- Each interconnection iCS <-> peripheral block, a client entity in iCS and a server entity in the peripheral block are implemented
The ETSI ITS Communications Architecture is implemented in iTETRIS over the union of the blocks APPLICATIONS, iCS and ns-3.

ETSİ ITS Facilities Layer's functionalities split over iCS and ns-3:
- Application-related facilities in iCS
  - Storing, updating and managing of the information needed by the applications on the top of the iCS
- Communications-related facilities in ns-3
  - Support the message transmission over the underlying radio interfaces
- Split needed to reduce the number of interactions between iCS and ns-3
  - Both iCS and ns-3 hold the specific information that they use for their autonomous operation, without being obliged to contact each other too frequently to retrieve it
  - Advantage in computational resource expenditure and simulation time
iTETRIS Heterogeneous V2V and V2I communications

- Heterogeneous wireless communication platform
  - Different communication modalities required by iTETRIS applications (traffic efficiency)
  - V2V and V2I combined strategies -> ITS-G5/802.11p, WiMAX, UMTS and DVB-H

- Access technology selection mechanisms
  - Most suitable option in time and space
    - User preferences
    - Application requirements
    - Technology status and availability
  - Use of dedicated networks for ITS services
    - Based on technical and financial aspects
  - Split of ITS communication traffic over more than one technology
iTETRIS includes the ITS-G5A European profile defined by ETSI
- Based on 802.11p
- Mode of operation for road safety and traffic efficiency applications in the [5,875-5,905] GHz band
- Support for distributed congestion control -> Per-packet control of radio parameters (Data rate and transmission power)

ITS-G5A/802.11p model
- System-level ITS-G5A/802.11p implementation in ns-3
- System-level V2V and V2I propagation models implementation in ns-3
- Link-level ITS-G5A/802.11p PHY implementation in Matlab Simulink
CoTEC Implementation and Integration in iTETRIS

APP
1) SUB>Returns_Cars_In_Zone
2) SUB_Set_Cam_Area
3) SUB_RECEIVED_Cam_Info
4) Density and speed estimates based on info from CAMs (speed and position)
5) Obtain fuzzy detection value from fuzzy-based system
6) Decide which vehicles must generate the CTE msg (based on fuzzy value, jam threshold and position)
7) Generate CTE messages and pass their payload down to the ICS
8) Process payload of received CTE msg,
9) Check if packet must be disseminated (vehicle outside the jam) or forwarded (vehicle is in jam),
10) Continue from step 5)

ICS
4) Activate CAM txon in ns-3 (vehicles located in a given edge)
5) Retrieve CAM messages from ns-3
6) CMD_RECEIVED_CAM_INFO → Inform App about received CAMs
7) CMD_CARS_IN_ZONE → Pos and speed of vehicles in zone
8) CMD_NOTIFY_APP_EXECUTE
9) Store of CTE-message payload
10) Trigger CTE msg txon in ns-3
11) Track received CTE messages
12) CMD_NOTIFY_APP_MESSAGE_STATUS
13) Provide App with CTE msg payload
14) Topobroadcast Txon (NodeId, ServiceId, SchdTxonTime)

SUMO
- Generate traffic jam
- Provide vehicles’ speed and position in every time step

ns-3
16) Simulate topobroadcast transmission/reception
17) Pass received CTE msg up to the ICS

Fuzzy detection estimates, CTE msg generation and forwarding decisions are made in APP.

CTE msg payload
- Sender’s position
- Timestamp
- Traffic congestion information (i.e., fuzzy values)
Data Dissemination: Multi-Hop Road Connectivity Estimation
Exchange of data among vehicles that are not within their communications range: multi-hop communications

- Example of the use of VANETs would be the notification of a traffic jam to vehicles approaching the congested area

Efficiency of dissemination process dependant on routing protocols and adequate selection of relaying nodes

- Most protocols exploit geographical information
- Selection based on current road traffic conditions, and hence the potential presence of relaying nodes
- Proposals to estimate road traffic conditions usually imply a high communications overhead
V2V Distributed and Real Time Road Connectivity Discovery

- Vehicle-Assisted Data Delivery (VADD): long time road traffic statistics
- Landmark Overlays for Urban Vehicular Routing Environments (LOUVRE)
  - Select forwarding routes based on real time vehicular traffic estimations
- Improved Greedy Traffic Aware Routing protocol (GyTAR): dynamic path computation at intersections and real time road traffic density assessment
  - Infrastructure-Free Traffic Information System (IFTIS)
- DiRCoD: a novel Distributed and Real Time Communications Road Connectivity Discovery mechanism
  - Selects next forwarding road segment by directly detecting its multi-hop connectivity: capacity to transmit packets from end-to-end

**Multi-hop connectivity vs traffic density estimation**

M. Rondinone and J. Gozalvez, "Distributed and Real Time Communications Road Connectivity Discovery through Vehicular Ad-hoc Networks", Proc. of the 13th IEEE Conference on Intelligent Transportation Systems (ITSC 10), Sept. 2010
DiRCoD provides road connectivity information in I1 where a routing decision about the next intersection to address has to be taken.

Road connectivity information corresponds to the virtual distance (in terms of hops) that separate I1 from adjacent intersections (I2).

If a road segment is fully connected (provides end to end multi-hop connectivity – Figure left), then the virtual distance is 0.

Otherwise, if the road only offers partial connectivity (Figure right), the virtual distance is > 0 (2 in the figure).
DiRCoD exploits standard beacon/CAM messages

Connectivity fields (few bits) representing the virtual distance are appended to CAM message
- Added to normal beacons only by specific nodes selected by the protocol in a smart and distributed way

Connectivity field “propagated” towards I1 by its subsequent inclusion in the beacon of the vehicles that receive it along the road segment

Algorithm adopts measures ensuring stability and scalability issues
- Vehicles in the same segment retransmitting CAM messages with the same connectivity field: redundant
  - Only a subset of vehicles will include such connectivity
- Different vehicles at I2 generating connectivity fields in a short time
• IFTIS
  – Road segments divided into equally distributed cells of radius equal to the vehicles’ communications range
  – Vehicles arriving at I2 generate and tx a cell density packet (CDP)
    ▪ CDP is transmitted towards I1 using subsequent geounicast multi-hop transmissions from cell center to cell center
  – Vehicles that receive CDP at the cell centers count the number of their current neighbors and store this value in the CDP
    ▪ Only vehicles that have previously updated a CDP at one of the cell centers generate a new CDP when arriving at I2
V2V Distributed and Real Time Road Connectivity Discovery

- Probability that vehicles at I1 receive at least one connectivity message before leaving the intersection

- Average communications overhead
Thank you for your attention

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*Ubiquitous Wireless Communications Research Laboratory*
• ITS-G5A/802.11p implementation based on current ns-3 WiFi module
• New functionalities/modules implemented for ITS-G5A/802.11p operation

<table>
<thead>
<tr>
<th>802.11p functionality</th>
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<tbody>
<tr>
<td>10Mhz channel spacing</td>
</tr>
<tr>
<td>Control of transmission parameters by upper layers/management block</td>
</tr>
<tr>
<td>Routing packets to 802.11p channel</td>
</tr>
<tr>
<td>Channel switching</td>
</tr>
<tr>
<td>V2V and V2I propagation models</td>
</tr>
<tr>
<td>Optimized PHY model</td>
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</tbody>
</table>

- 802.11p NetDevice Router -> Routing of packets to the correct NetDevice
- 802.11p Switching Manager -> Cancellation/storing/resuming of packets
- Support for congestion control -> Per-packet control of power and data rate
- V2V and V2I propagation models
  - Path-loss, shadowing and multi-path
- Two different propagation environments: highway and urban

  - LOS/NLOS differentiation in urban scenarios (off-line visibility map)
  - Path-loss dependent on distance to the intersection
• Implementation of ITS-G5A/802.11p PHY layer in Simulink
  – Different channel estimators and feedback-decision equalizers (Ideal, mapper and Viterbi)

• Georgia Tech vehicular channels modes

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Distance between Tx and Rx (m)</th>
<th>Average PER result (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2V Expressway Oncoming</td>
<td>300-400</td>
<td>5.6</td>
</tr>
<tr>
<td>V2V Expressway Same Direction with Wall</td>
<td>300-400</td>
<td>1.9</td>
</tr>
<tr>
<td>V2V Urban Canyon Oncoming</td>
<td>100</td>
<td>4.4</td>
</tr>
<tr>
<td>V2I Suburban Street</td>
<td>100</td>
<td>3.0</td>
</tr>
<tr>
<td>V2I Expressway</td>
<td>300-400</td>
<td>2.7</td>
</tr>
<tr>
<td>V2I Urban Canyon</td>
<td>100</td>
<td>0.8</td>
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