Towards Connected Vehicles for Smarter & Greener Transportation

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Smart Cities
Smart Cities

- Services offered by Smart Cities should be:
  - Smart
  - Cheap
  - Secure
  - Safe and reliable
  - Aligned with societal trends
Smart Cities

- Infrastructure management
- Knowledge management

Intelligence is in the Software
Objective: leverage advanced technologies to develop multidisciplinary solutions to reduce traffic congestion and mitigate its undesirable impact

Make the mobility of people and goods worldwide:
- Faster
- Cheaper
- Eco-friendly
- and safer
Smart Transportation (2/3)

- Evolution
  - Cities evolve
  - Traffic pattern, volumes, complexity and data sources evolve
    - 2.9 billion vehicles by 2050
  - Technology evolves, what to monitor evolves
Critical impact

- Congestion costs billions to world economy
- According to a study conducted by INRIX, a leading traffic investigation service
  - 2013–2030: the economic loss due to traffic congestion in UK alone is expected to be a staggering £307 billion
    - => an increased congestion per-household cost from £1,426 in 2013 to £2,057 in 2030
Efficient Data Collection

- Wireless Sensing technologies, energy efficiency, efficient & secure multi-hop transmissions, VaaR

Traffic Congestion

- Prediction and mitigation techniques, Adaptive TMS, emergency services, etc.

Smart Cities Lab

CAVs

- Secure and reliable communication protocols, Safety & traffic efficiency applications, bandwidth scarcity

Mobility as a Service (MaaS)
Road traffic data life cycle

Data Sensing and Gathering

Service Delivery - diverse end-users

Policy Companies

Data Fusion, Processing & Aggregation

(SUMO, veins, vissim, ns-3)

Data Exploitation

Some applications

- Leveraging the wealth of traffic data gathered from road monitoring equipment or shared by road users
- Creating **new business models** for existing travel means
  - Waze
  - UBER
  - RESROBOT
  - ...


Autonomous Vehicles
Autonomous (Self-driving) Vehicles (1/3)

- Localization: where am I?
- Sensing the surroundings: what’s happening around me?
- Perception (fusion of sensor data)
- Reasoning and decision making
- Motion control
Autonomous (Self-driving) Vehicles (2/3)

Autonomous vehicle demonstration by CATAPULT Transport System, UK
Autonomous (Self-driving) Vehicles (3/3)

- GPS
- DSRC (760 MHz, 5.9 GHz)
- Cellular technology (LTE, 5G, etc.)
  - Electronic Toll Collection
- Radar
- Bluetooth
- Wi-Fi
- Wireless Battery Charging
- Visible Light Communications (VLC)
Connected & Autonomous Vehicles (CAVs)
Vehicular Networks

- Wireless communication between
  - Vehicles (V2V)
  - Vehicles and the road infrastructure (V2I)
  - Vehicles and X?

- Promise to solve many of today’s road traffic problems by
  - Improving road users’ safety
  - Shortening their trip times
  - Enhancing their travel experience
  - Reducing air pollution
Vehicle to X communication patterns

- Vehicle-to-X (V2X)
  - X: pedestrian, RSU, IoT device etc.

- Inter-Vehicle Communication (IVC),

- Vehicular ad-hoc network (VANET),

- ...

C. Sommer and F. Dressler, Vehicular Networking, Cambridge University Press, 2014
Taxonomy of use cases

Vehicle–to–X

Non–Safety
- Comfort
- Traffic Information Systems

Safety
- Situation Awareness
- Warning Messages

- Contextual Information
- Entertainment
- Optimal Speed Advisory
- Congestion, Accident Information
- Adaptive Cruise Control
- Blind Spot Warning
- Traffic Light Violation
- Electronic Brake Light

C. Sommer and F. Dressler, Vehicular Networking, Cambridge University Press, 2014
Cooperative Adaptive Cruise Control

- Cars share info on speed changes in real-time
  - More efficient Adaptive cruise control system
  - Reduced carbon emissions
Taxonomy of use cases

Vehicle-to-X

Non-Safety
- Many messages
- High data rate
- Low latency demands
- Low reliability demands

Safety
- Few messages
- Small packet size
- High latency demands
- High reliability demands

C. Sommer and F. Dressler, Vehicular Networking, Cambridge University Press, 2014
IEEE802.11p WAVE/DSRC

- IEEE 802.11p
  - PHY layer mostly identical to IEEE 802.11a
  - Variant with OFDM and 16 QAM
  - 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 (theoretically), speed up to 200 km/h
IEEE802.11p WAVE/DSRC

- MAC layer of IEEE 802.11a plus extensions
  - QoS (EDCA priority access, cf. IEEE 802.11e, ...)
  - Multi-Frequency and Multi-Radio capabilities
  - New Ad Hoc mode
  - ...
IEEE802.11p WAVE/DSRC

- Channel management
  - Dedicated frequency band at 5.9 GHz allocated to WAVE
  - Exclusive for V2V and V2I communication
  - 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

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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
IEEE802.11p WAVE/DSRC

- 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

IEEE Vehicular Technology Society, "IEEE 1609.4 (Multi-channel Operation)," IEEE Std, November, 2006
IEEE802.11p WAVE/DSRC

- Time slots
  - Synchronization envisioned via GPS receiver clock
  - Standard value: 100ms sync interval (with 50ms on CCH)
  - Short Guard Interval (GI) at start of time slot (radio switching delay)
  - During GI, the medium is considered busy
Congestion control in Urban Vehicular Networks
Cities generate an enormous amount of data
- 4 million terabytes of traffic in 2022
- 630K terabytes from connected cars

A large portion to be carried by vehicular networks

Wireless congestion problem

Research problem: Scope

- Safety and critical information. *(periodically broadcasted)*
- Urban scenarios
- Two types of messages
  - Safety and event driven warning messages
  - Control messages (beacons, CAMs, etc)
Congestion control for safety information

- Critical information, multi hop transmission, high periodicity, limited timeframe, short to medium length messages
- Goal, limit the amount of data inserted in the network
  - Get rid of unnecessary retransmissions after failures
  - Channel conditions (Shadowing, Doppler Effect, …)

Congestion control for safety information

Road–Casting Protocol (RCP)

- **Distance factor (D)**
  - a function of the distance between the sender & the potential next forwarder, the next junction and the potential next forwarder, and the next junction to the transmission range of the sender

- **Link Quality factor (LQ)**
  - is a function of the signal quality (SQ), the channel quality (CQ) and the collision probability (CP)
    - CQ is intended to estimate the state of the channel around the receiver before and at the time of the reception of the emergency message
Congestion control for safety information

Road–Casting Protocol (RCP)

- Retransmission Probability
  \[ P = (1 - \omega_p)D + \omega_p LQ \]
  \( 0.5 \leq \omega_p \leq 1 \)
  \( D: \) Distance Factor
  \( LQ: \) Link Quality Factor

- Retransmission Waiting Time (Backoff)
  \[ WT = CW \times (1 - P) + \delta \]
  \( \delta: \) Random value in \( \mu s \)
  so that \( 2\mu s < \delta < 9\mu s \)
  \( CW: \) Contention Window
Impact of vehicles density on **Packet Delivery Ratio** and **End-to-End Delay**: RCP vs. distance based forwarding, link based forwarding and flooding
Congestion control for safety information

- **Microscopic congestion control ✓**
  ◦ Amount of data inserted in the network on a point-to-point level

- **Macroscopic congestion control**
  ◦ The extent of data inserted in the network (end-to-end)

- Determine the Region of Interest (RoI) for multi-hop safety messages
- Keep the amount of data inserted in the network minimal
Congestion control for safety information

The set of critical junctions (red ticks) delimitating the zone where vehicles are already blocked due to an incident
Congestion control for safety information

Road map connectivity check performed by each receiver of an emergency message: using simplified A* algorithm
The ratio, under different vehicle densities, of vehicles located inside and outside the RoI which did not receive the emergency message (Algiers map)
Impact of vehicles density on the accuracy of the RoI definition: RCP scheme RoI vs. circular RoI (Algiers map)
Congestion control for periodic beacons
Critical information, single hop transmission, high periodicity, continuously transmitted, short length messages

Goal, limit beacons collisions to negligible levels in all channel conditions

Channel capacity

- 10 Hz / 48 ms / 60% \(\Rightarrow\) 28.8 ms
- 1 ms/beacon \(\Rightarrow\) 28 beacons per CCHI \(\Rightarrow\) 28 vehicles

Congestion control for periodic beacons

Adaptation mechanism:
Successive Rate and Power Adaptation (SuRPA)

- Successively adapt transmit Rate, then Power according to the observed local density

- Binary search
  - Fastest way to locate a value in a sorted set
  - The optimal channel load that produces marginal collision rate (lower than 5%)
Congestion control for periodic beacons

Adaptation mechanism:

LD: local density

CCHI 1

\[
\begin{align*}
LD_{\text{Min}} & \quad \text{TR} = 10 \text{ Hz} \\ 
& \quad TP = 1 \text{ dBm} \\
\end{align*}
\]

CCHI 2

\[
\begin{align*}
LD_{\text{Min}} & \quad \text{TR} = 10 \text{ Hz} \\ 
& \quad TP = 2 \text{ dBm} \\
\end{align*}
\]

CCHI 3

\[
\begin{align*}
LD_{\text{Min}} & \quad \text{TR} = 10 \text{ Hz} \\ 
& \quad TP = 4 \text{ dBm} \\
\end{align*}
\]

LD\(_1\)

\[
\begin{align*}
& \quad \text{TR} = 10 \text{ Hz} \\ 
& \quad TP = 10 \text{ dBm} \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{Collision rate } = 10\% \\
& \quad \text{Busy ratio } = 45\% \\
\end{align*}
\]

LD\(_2\)

\[
\begin{align*}
& \quad \text{TR} = 10 \text{ Hz} \\ 
& \quad TP = 2 \text{ dBm} \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{Collision rate } = 3\% \\
& \quad \text{Busy ratio } = 25\% \\
\end{align*}
\]

LD\(_3\)

\[
\begin{align*}
& \quad \text{TR} = 10 \text{ Hz} \\ 
& \quad TP = 4 \text{ dBm} \\
\end{align*}
\]

\[
\begin{align*}
& \quad \text{Collision rate } = 5\% \\
& \quad \text{Busy ratio } = 35\% \\
\end{align*}
\]

LD\(_{\text{Max}}\)
Congestion control for periodic beacons

- Adaptation mechanisms:
  - Spatial and temporal adaptation of transmission parameters

- Further enhance this adaptation
  - Anticipate channel load peaks

- Predict near-future channel fluctuations
- Apply the transmit parameters adaptation to the predicted local density
Altruistic prediction mechanism

Prediction & Adaptation – Algorithms (P&A–A)

The percentage of deviation from the effective (real) case under different vehicle densities: P&A–A vs. plain prediction and ETSI schemes.
Congestion control for periodic beacons

Impact of the distance to the intersection on the observed density: P&A–A vs. plain prediction and ETSI schemes
Summary

- Road–Casting Protocol (RCP)
  - Next forwarder selection (*microscopic* congestion control)
  - Region of Interest definition (*macroscopic* congestion control)

- Prediction & Adaptation – Algorithms (P&A–A)
  - *Altruistic* prediction mechanism
  - *Successive* transmission Rate and Power adaptation
Next Road Re-routing

Main ideas: Two-Step Re-routing

- First, in order to avoid the blocked road, vehicles are diverted to their optimal turns according to the local traffic conditions.
- Then, vehicles leverage the on-board navigation system to complete the remaining of their journeys.

Objective

- Reducing the average trip time of all the vehicles in the road network.
Next Road Re-routing (NRR)

- Consider **three factors** on all the next turn choices
  - Geographic Closeness, Travel Time (*selfish* routing/individual benefit)
  - Traffic Load (*altruism* routing / global benefit)
  - The lane which has the **least cost value** will be suggested
Next Road Re-routing (NRR): deployment

SCATS: Sydney Coordinated Adaptive Traffic System
MAS Architecture

- **Agent**
  - The traffic light and the set of outgoing lanes that it controls.
  - Easier and more efficient than vehicle-based MAS

- **Coordination**
  - Global traffic load balancing can be done through “Lane 1”
Simulation Setting

- Trip generation time: 30min
  - Close one lane of the road in the center area for 20min (5th min – 25th min)
  - Simulation runs until all the trips are finished
- All the vehicles are identical
  - same length, same minimum gap etc.
- Grid maps:
  - 3X2, 4X3, 5X4, 6X5, 7X6, 8X7, 9X8
  - Road type: two bidirectional lanes; Length: 150 m
- Realistic map (TAPAS Cologne):
  - City center (18.15 km2)
  - Traffic demand: 6:00am – 6:30am
Blocked Road

Closed Road

Diagram showing blocked road.
Performance Improvement

- NRR wins in both scenarios
Summary

Novelties of NRR
- Two steps re-routing
  - Optimal next-turn
  - Current navigation system
- Make full use of the existing infrastructures
  - Traffic lights + Induction loops
  - Current navigation system

Benefits of NRR
- Substantial average trip time reduction
- Keep the global traffic load balanced
Emerging Challenges
Emerging challenges in Smart Transportation

- Bandwidth scarcity of DSRC spectrum
- Congestion and awareness control
- Electric and hybrid vehicles
  - Route planning and re-routing
- Security, privacy, liability, and dependability
- ...

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Bandwidth scarcity of DSRC spectrum

- Cognitive radio technology
  - Opportunistic usage of spectrum holes in other bands
  - Software Defined Radio (SDR)
- Using LTE/5G networks to carry specific types of vehicular traffic
- Internet of Vehicles (IoV)
- ...
Electric vehicles

- Efficient route planning and re-routing
- How to efficiently overcome their specific constraints?
  - Limited battery capacity
  - Limited number of charging stations
  - Long waiting time at stations
  - Significantly long battery recharge time
  - Range anxiety
Security, privacy and liability

- Cyber attacks
  - Severe consequences in case of a successful attack

- Privacy
  - Location, interests, social networks

- Liability
  - In case of a car crash
    - The car manufacturer or the driver?
Conclusion

- Smart transportation is an emerging research field facing many challenges and offering many opportunities.
- Successfully overcoming these challenges promises a significant societal and economic impact.
- Most experts foresee that vehicular networks will be a key enabler of smart & green transportation, thus addressing its major technical challenges is essential.
Example of a recent research contribution

CRITIC : Main idea

Apply **Cognitive Radio** principle used in wireless networks in road networks

- The **reserved lanes policy**
- **&**
- **Connected Vehicles system**
CRITIC: A Cognitive Radio Inspired Road Traffic Congestion Reduction Solution

Wireless Networks Spectrum

- Frequency band 1: Under utilized spectrum
- Frequency band 2: Highly congested spectrum
- Frequency band 3: Normally used spectrum

Road Network

- Lane 1
- Lane 2
- Priority (bus) lane

- Regular car temporarily using an under-utilized priority lane
- Spectrum users opportunistically use spectrum 1 holes
CRITIC: Demo

Link on Youtube:
https://www.youtube.com/watch?v=7ap-Nk1uoKo
CRITIC: Performance evaluation results

10x10 Grid network

10x10 Grid network
References

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ETSI EN 302 663 V 1.2.1 Intelligent Transport Systems (ITS). Intelligent transport systems (its); access layer specification for intelligent transport systems operating in the 5 ghz frequency band, 2013


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  - ns−3
    - https://www.nsnam.org/
  - Vissim