MAC for Vehicular Communications Networks

Xuemin (Sherman) Shen
Broadband Communication Research Group (BBCR)
Dept. of ECE, University of Waterloo
200 University Avenue West
Waterloo, Ontario, Canada N2L 3G1
Outline

- Introduction to vehicular networks
  - What are vehicular networks?
  - Why vehicular networks?
  - Design issues
- MAC for highly mobile drive-thru Internet
- MAC for safety applications
- Conclusion
Modern Transportation

- Modern society depends on modern transportation
  - Faster, safer, lower cost

### Roads, Passengers carried
(million passenger-km)

<table>
<thead>
<tr>
<th>Country</th>
<th>Passengers carried</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>6,798,346</td>
</tr>
<tr>
<td>China</td>
<td>1,676,024</td>
</tr>
<tr>
<td>Germany</td>
<td>994,312</td>
</tr>
<tr>
<td>France</td>
<td>864,100</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>708,000</td>
</tr>
<tr>
<td>Italy</td>
<td>665,818</td>
</tr>
<tr>
<td>Mexico</td>
<td>465,600</td>
</tr>
<tr>
<td>Spain</td>
<td>391,711</td>
</tr>
<tr>
<td>Australia</td>
<td>323,660</td>
</tr>
<tr>
<td>Pakistan</td>
<td>322,765</td>
</tr>
</tbody>
</table>

### Vehicles per 1000 people

Transportation Challenge

- **Safety**: Global road traffic crashes accounts for
  - 1.2 million deaths/year since 2007
  - Top the causes of death for ages 15-29
  - 3% of GDP loss for low/middle-income countries

- **Mobility**: In 2015, US
  - Commuters wasted 8 billion hours in traffic
  - $160 billion cost of urban congestion

- **Environment**: In 2014, US
  - Wasted fuel topped 3 billion gallons
  - 56 billion lbs. of additional CO₂
What are Vehicular Networks?

- A vehicle in the near future will be an intelligent unit with on-board sensors, computers and communication devices (like “Knight Rider”)
- Vehicular Network is an emerging technology to enable vehicles to communicate wirelessly and form a network on road

**Smart Car Model:** © J. P. Hubaux, S. Capkun, and J. Luo, “The Security and Privacy of Smart Vehicles“.
In 1999, FCC has allocated a specific spectrum band (5.850 – 5.925GHz) to Dedicated Short Range Communication (DSRC) for the exclusive use of vehicular communications.

In 2010, IEEE 802.11p - Wireless Access in Vehicular Environments (WAVE)
Connected Vehicles

- **Key elements:**
  - Vehicle to vehicle (V2V) communications based on dedicated short-range communications (DSRC)
  - Vehicle to infrastructure (V2I) communications using road-side unit (RSU) or cellular networks
  - V2X: the umbrella term include V2V, V2I, vehicle to pedestrian (V2P), vehicle to cloud (V2C), vehicle to sensor (V2S), ……

V2X Applications (1)

- **Safety applications:**
  - Vehicle collision avoidance with V2V, e.g., blind spot, lane change, left turn, forward collision warning
  - Vehicle/pedestrian collision avoidance with V2P

- **Enhance efficiency with V2I:**
  - Traffic light control
  - Street light management
  - Intersection movement assist
V2X Applications (2)

- Enable services with vehicle-to-cloud (V2C)
  - Smart parking
  - EV charging management
  - Location-related advertisement
Initiatives Worldwide

• In U.S., Dept. of Transportation issued advance notice of proposed rulemaking on Aug. 2014 to mandating the implementation of V2V technology. OEMs will begin including DSRC and V2V applications in 2020 model year vehicles.

• In Japan, Driving Safety Support Systems uses V2I communications to provide real-time road traffic information services. Alert on congestion or accidents are sent via wireless beacon using DSRC.

• In Europe, the roll out of Cooperative ITS (c-ITS) based on both V2V and V2I is underway, e.g., the ITS Corridor connecting German, Dutch, and Austria.
Industry Deployment Actions

- Car manufacturers, communication device and software vendors, network operators and service providers
  - GM will sell vehicles equipped with DSRC and V2V applications beginning with the 2017 model year.
  - Qualcomm, NXP and others have announced DSRC capable chip.
  - DSRC OBE Market Penetration Projection: 1% in 2016 and 75% in 2030.
  - By Nov. 2016, AT&T connects a million cars, topping signups for phones.
  - CarPlay (Apple) and Android Auto (Google)
Vehicular communications make our urban lives more interesting and efficient with social relations, and localized applications in the future cities.

Why Vehicular Networks?

We already have cellular networks, and many WiFi hotspots around us.

Why vehicular networks?
Efficiency

- Fast, direct and efficient communications in proximity (Desirable for urgent safety communications)

- Traditional cellular networks are indirectly, slow and costly to attain the same usage
Low Cost Data Service

- Cost-effective approach for infotainment applications
- Cellular Networks

<table>
<thead>
<tr>
<th>Bell Canada Mobile Internet Plan[^5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5.00 /mo.</td>
</tr>
<tr>
<td>10mB</td>
</tr>
</tbody>
</table>

- 5GB = 27.8 hr video playback at 400kbps
- Guaranteed data volume but **not** guaranteed download speed and user experience!

- Vehicular networks: cheap services by
  - Enabling vehicles to exchange contents stored in buffers
  - Cooperative communication to download Internet contents

[^5]: http://www.bell.ca, retrieved on 5th Sept from
Utilizing Mobility of Vehicles

- Extended coverage of broadband services

Ship contents to different locations by commute bus
(Used in rural and village areas where Internet infrastructure rarely exists)
Challenges

- **Wireless resources**
  - Limited and expensive, e.g., by 2019, US will need 350+ MHz of licensed spectrum
  - Time-varying, location-dependent, fast fading, shadowing, interference limited

- **Network topology and density**
  - Random topology due to high mobility (up-to 35 m/s of vehicle speed, and 70 m/s of relative speed)
  - Fast-change density in time/spatial domains, e.g., due to road congestion in rush hour, at main streets/highways, non-predictable accidents, etc.
There are many research activities related to Vehicular Communications Networks:

1) Direct and reliable short range connection;
2) Access delay;
3) Capacity analysis;
4) Medium access control;
5) Data traffic offloading;
6) Mobility model;
7) Security and privacy;
8) DSRC/WhiteFi interworking;
9) LTE-V, etc.
MAC for Highly Mobile Drive-thru Internet

- What is the drive-thru Internet?
- Research motivations and goals
- Analytical model and results
- Simulation verifications

Drive-Thru Internet

- Drive-thru Internet [7]
  - Vehicle to roadside unit (RSU) communication
  - Using off-the-shelf 802.11b hardware, a vehicle could maintain a connection to a roadside AP for 500m and transfer 9MB of data at 80km/h using either TCP or UDP

- CarTel [8]:
  - Extend drive-thru Internet in city-wide situ Wi-Fi networks (in Boston)
  - Vehicle has intermittent and short-lived connectivity yet high throughput while available

Previous works confirm the effectiveness of drive-thru Internet, but are largely based on small scale experiments.

Focus on the link quality of single vehicle to RSU communication.

Do not consider the MAC issue when a large group of vehicles contend to transmit simultaneously.
MAC in Motion:

Impact of Mobility on the MAC Throughput of Drive-Thru Internet
Drive-thru Internet for One Vehicle

- **Adaptive transmission rates** according to the channel condition (distance to the roadside unit (RSU))

![Diagram showing data rates and distance to RSU](image)

- 2 Mbps
- 5.5 Mbps
- 11 Mbps
- 5.5 Mbps
- 2 Mbps
Performance Anomaly: Drive-thru Internet for Multiple Vehicles

- IEEE 802.11p (WAVE for vehicular communications) adopts the fundamental (Distributed Coordination Function) DCF for MAC (CSMA/CA)
- With multi-rate connections, DCF presents performance anomaly: system throughput is bottlenecked by the minimal-rate transmission
  - Channel is always used for low-rate transmissions, as once they grab the channel, it takes a long time for them to release channel

Vehicular network is crowded, and vehicles need to share the channel

Queue is bottlenecked by the slow customer (No matter how many items you have, you may always have to wait for a long time)
Questions

- With multiple highly mobile vehicles sharing the channel, what is the **achievable throughput of individual vehicles**?
- How to address the performance anomaly in vehicular communications?
System Model

- Vehicles traverse consecutive RSUs at the mean velocity $\nu$.
- Saturated case, i.e., vehicles always have packets to transmit.
- Focus on one RSU with its radio coverage divided into $N$ zones denoted as $\mathbb{Z} = \{1, 2, \ldots, N\}$, where each zone $z \in \mathbb{Z}$ has
  - different data transmission rate, $r_z$
  - different minimum contention window, $W_z$
  - different length, $d_z$
Mobility Model

- Each state represents one spatial zone in $Z = \{1, 2, \ldots, N\}$
- Mobility of vehicles is represented by zone transitions
- The mean sojourn time of vehicles in each zone $t_z = d_z / v$

- In a slot time $\Delta$, a vehicle moves to the next zone with prob. $\Delta / t_z$ and stays in the current zone with the rest probability
3D Markov Chain Model of DCF

- **State space** \((z, s, b)\)
  - \(z\) : zone currently in
  - \(s\) : backoff stage
  - \(b\) : backoff time

- Backoff time, \(b\), continuously deducts during the channel free period.
- When \(b\) is to be 0, start one transmission and reset \(b\) in the range of \([0, 2^s W_z]\)
- If transmission fails, increase backoff stage \(s\) by one, otherwise set \(s\) to 0.
Numerical Solution

- Solving the 3D Markov chain, we can obtain
  - steady state probability of each vehicle at any zones with any backoff stage and backoff time
  - transmission probability of each vehicle at any zones
    - probabilities of successful transmission and collision
  - impacts of velocity, DCF parameters (backoff stage and time) on the resultant throughput

- Nodal throughput in zone $z$

  $$s_z = \frac{\tau_z (1 - p_{col}) L}{\text{Average Time of Each Transmission}}$$

  average time for backoffs + average time spent in collision + average time for successful transmission

- Integrated node throughput

  $$S' = \sum_{z \in Z/{0}} X_z s_z$$

  Node population in zone $z$
Simulation

- Discrete-event simulator coded in C++
- Road segment length = 270 m (250m in RSU + 20m inter-RSU)
- By default: velocity = 80km/h, population = 130 vehicles, pkt length = 1500 Bytes, 4 street lanes
  - Equal contention window as in legacy DCF
  - Differentiated contention window in different zones
- 30 runs on each simulation, 95% confidence interval

Traffic jam density $k_{jam}$ | 120 veh/km/lane
---|---
Free-way speed $v_f$ | 160 km/h

(a) Spatial zones in the RSU radio coverage
Equal Contention Window (CW) in Zones (CW = 32)

- Legacy DCF sets equal CW in all zones

Nodal throughput in zones unrelated to the data rate (performance anomaly)
- Increasing velocity results in degraded overall throughput
Differentiated CW in Zones

- Bell-shape curve (nodes with high transmission rate have smaller contention windows)
- Increasing velocity results in degraded throughput
- This is because that increasing velocity results in intended backoffs

<table>
<thead>
<tr>
<th>Zone z</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_z$ (m)</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>40</td>
<td>60</td>
<td>40</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>$r_z$ (Mbps)</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>5.5</td>
<td>11</td>
<td>5.5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$CW_{\text{min},z}$</td>
<td>Inf</td>
<td>128</td>
<td>64</td>
<td>32</td>
<td>16</td>
<td>32</td>
<td>64</td>
<td>128</td>
</tr>
</tbody>
</table>
VeMAC: Supporting Reliable Broadcast

TDMA-based MAC to support reliable broadcast for road safety applications
High Priority Safety Applications

- **A list of road safety applications**
  - Traffic signal violation warning
  - Green light optimal speed advisory
  - Emergency electronic brake light
  - Pre-crash sensing
  - Stop sign movement assistance
  - Intersection collision warning
  - Blind merge warning
  - Curve speed warning
  - Highway merge assistance
  - Lane change warning
  - Visibility enhancer
  - Cooperative forward collision warning
  - Approaching emergency vehicle
  - Many others...

One-hop broadcast service
IEEE WAVE and Limitations

- WAVE: Wireless Access in Vehicular Environment

- IEEE 802.11p: amendment to IEEE Std 802.11 (CSMA/CA)

- **Unreliable one-hop broadcast service**
  
  No RTS/CTS frames --> hidden terminal problem
  No ACK frame --> unreliability
Hidden Terminal Problem

- **Problem**
  - *C is transmitting* a frame to *B*.
  - *A is unaware of C’s Tx.*
  - *Now, if A transmits, A’s Tx will collide with C’s at B*

- The above problem is due to *C being hidden* from *A.*
  - *Hidden means* being “far away” …
No collision detection

- **Fact: **Collision at receiver is more serious than collision at transmitter.

- In a wired LAN
  - Collision is *indirectly* detected after some delay by the sender.
  - In a WLAN, collision detection by sender is not possible, which leads the hidden terminal problem.

- Collision is avoided (CA), rather than detected ...
VeMAC

- Reliable broadcast of safety messages by employing time division multiple access

![Diagram showing time slot indices and distributed time slot assignment](image)

- Designed to detect transmission collisions
- Designed to eliminate the hidden terminals
Technical Challenges

- Transmission collision detection, distributed time slot assignment, vehicle mobility
VeMAC Prototyping
Governmental Mandatory

- **European Union**
  - The European Commission adopted two proposals to ensure that cars will automatically call emergency services in case of a serious crash (starting 2016).

- **United States**
  - The U.S. DOT has announced that steps toward enabling V2V communications for light vehicles will start by 2017.
Industry Efforts

- Solutions for connected cars

**GM OnStar**
- Convenience: Vehicle Management, Travel & Itinerary
- Infotainment: Video on Demand, Emergency Call
- Safety: OnStar Guardian

**Sony MirrorLink**
- Entertainment, Navigation

**BMW ConnectedDrive**
- Parking, Informative, Direct Assistance

**Toyata Entune**
- Remote Control with Windows Phone
Summary

- A modern vehicle will be a network of sensors, computers and communication facilities.

- Vehicular networks connect vehicles to make our trips more safe, more efficient and more interesting.