Vehicular Communications and Networks

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Outline

• Technology trends and applications scenarios

• Characteristics, challenges and architectures for IVC (high mobility broadband wireless access on the road)

• Characteristics and challenges of vehicular adhoc networks (safety and ITS applications)

• Vehicular mobility modelling

• ITS case studies
  – Information dissemination in highly dynamic, intermittently connected VANET
  – Traffic congestion reduction using V2V communications
  – V2V-based rear-end collision avoidance
  – Parallel simulations of large V2V networks
  – Cyber-attacks on VANET

• Emerging technologies: dynamic spectrum access, cognitive radios, smart and directional antennas

• Summary

• Bibliography
Technology trends

- BMW, Mercedes, Fiat, Ford, Toyota, Nissan, … are prototyping vehicles equipped with Wi-Fi (802.11a/b/g) and DSRC (802.11p)

- Wi-Fi enabled vehicles are expected to be on the road within the next 3-5 years

- In the US, FCC allocated 75 MHz of spectrum for dedicated short-range vehicular communications (total UK 3G spectrum is ~ 140 MHz)
- In the UK and across the EU 30 MHz of spectrum has been put aside for vehicular networks.

- Assuming 10% market penetration, this amounts to ~3-4 million Wi-Fi enabled vehicles carrying people in the UK, and ~15 million in the US

- Vehicles equipped with wireless technology can communicate directly with each other (V2V), and with the fixed infrastructure (V2I). They can form Vehicular Adhoc Networks (VANET)

- New opportunities in:
  - High mobility broadband wireless access
  - Intelligent Transport Systems (ITS)
  - Sensor networks on the road
High mobility broadband wireless access

- Extending broadband access to high mobility users in cars, buses, coaches in cities, highways, roads
  - Mobile office (Internet, email, file transfers ..)
  - Entertainment (video-on-demand, games ..)
  - Location based services and charging (parking, road usage, local restaurants, local traffic info, dynamic map updates, ..)
  - Voice over IP (VoiP)

Not exclusively WiFi but a hybrid of 3G/LTE, WiFi and mobile WiMAX

Ko, Sim, Nekovee, 2006
Safety and Intelligent Transport Systems

- Improve road safety, increase efficiency of road usage, reduce congestion and traffic jams
  - Early warning of road hazards
  - Driver assistance and collision avoidance
  - Real-time traffic monitoring and control on a much finer scale than is possible now (with loop detectors)
  - Real-time route guidance and journey planning
  - Cooperative driving: lane merger, high-speed platoons
  - Real-time traffic control and re-shaping/smoothing

Final Report, Traffimatics Project, 2006
Sensor networks on the road

- Position sensors
  - GPS, accelerometer, compass, tilt sensor

- Environment sensors
  - CO₂, cameras, thermometer, barometer, humidity sensor

- Vehicle sensors
  - ignition, speed, engine speed, engine temperature, …

- Vehicle interior sensors
  - camera, ID card reader

- Wireless communication
  - 802.11{a,b,g}, GPRS, 3G

Timelines

Figure 1: Necessary vehicle and infrastructure penetration rates for different kinds of applications

T. Kosch, BMW R&D, 2005.
High Mobility Broadband Wireless Access (BWA)
### BWA - Wireless technologies

<table>
<thead>
<tr>
<th></th>
<th>3G</th>
<th>DSRC 802.11p (WAVE)</th>
<th>Wi-Fi 802.11a/b/g</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td>up to 12 km</td>
<td>up to 1 km</td>
<td>up to 1 km</td>
</tr>
<tr>
<td><strong>data rate</strong></td>
<td>384 Kbps – 2Mbps, 5.76/14.4Mbps (HSUPA/ HSDPA)</td>
<td>up to 27 Mbps</td>
<td>up to 54 Mbps</td>
</tr>
<tr>
<td><strong>Spectrum / GHz</strong></td>
<td>1.8, 1.9 and 2.1</td>
<td>5.9 (USA), 5.8 (Japan, Europe)</td>
<td>2.4 (b/g), 5.2, 5.8 (a)</td>
</tr>
<tr>
<td><strong>licence</strong></td>
<td>licensed</td>
<td>dedicated spectrum (USA)</td>
<td>licence-exempt*</td>
</tr>
<tr>
<td><strong>access mechanism</strong></td>
<td>centrally scheduled</td>
<td>contention based</td>
<td>contention based</td>
</tr>
<tr>
<td><strong>limitations</strong></td>
<td>• Very high deployment costs</td>
<td>• short to medium range</td>
<td>• short to medium range</td>
</tr>
<tr>
<td></td>
<td>• low transmission rates, scalability (backhaul)</td>
<td></td>
<td>• Interference issues due to shared spectrum</td>
</tr>
<tr>
<td><strong>advantage</strong></td>
<td>• already available, large coverage</td>
<td>• low deployment costs</td>
<td>• low deployment cost, distributed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• distributed</td>
<td></td>
</tr>
</tbody>
</table>
# BWA - Wireless technologies

<table>
<thead>
<tr>
<th></th>
<th>WiMAX 802.16e (Nomadic)</th>
<th>WiBro (Mobile, &lt;= 60km/h)</th>
<th>LTE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td>up to 5 Km</td>
<td>up to 5 Km</td>
<td>up to 12 km</td>
</tr>
<tr>
<td><strong>data rate</strong></td>
<td>maximum 70 Mbps; 10 Mbps @ 10km</td>
<td>maximum 50 Mbps</td>
<td>20-100 Mbps</td>
</tr>
<tr>
<td><strong>spectrum</strong></td>
<td>2.3/2.5, 3.5, 5 GHz</td>
<td>2.3 ~ 2.4 GHz</td>
<td>?? (digital dividend, 800 MHz band, e.g. Germany)</td>
</tr>
<tr>
<td><strong>licence</strong></td>
<td>licensed &amp; licence-exempt</td>
<td>licensed</td>
<td>licensed</td>
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</tr>
<tr>
<td></td>
<td>• large coverage</td>
<td>• large coverage</td>
<td>• large coverage</td>
</tr>
</tbody>
</table>

- **WiMAX 802.16e (Nomadic)**: Supports high data rates and large coverage. Suitable for nomadic use with a range up to 5 km.
- **WiBro (Mobile, <= 60km/h)**: Also offers high data rates and large coverage, but the range is up to 5 km, making it more suitable for mobile applications up to 60 km/h.
- **LTE**: Known for its high data rates and large coverage, with a range up to 12 km. However, it faces high deployment costs and scalability limitations in the backhaul infrastructure.
System Architecture

Legend:
- Road site AP/BS (omnidirectional antenna)
- Backhaul wireless mesh router (directional antenna)
WiFi vs cellular based architecture

Ko, Sim, Nekovee, 2006.
Performance of Wi-Fi-based BWA

- Vehicle-to-vehicle communications
  - new channel model and performance study
- Single vehicle / single roadside AP
  - 802.11 performance at vehicular speeds (urban and highway)
- Single vehicle / multiple roadside APs
  - Co-channel interference and optimal channel allocation
  - Handoff at speeds
- Many vehicles /multiple roadside APs
  - (Rapid) temporal (day/night/rush hour) and spatio-temporal (traffic jams) change in user density → Requires *highly adaptive* protocols
Vehicle-to-vehicle communications

- Measured power spectrum of V2V channel showed significant differences from that of the conventional I2V channel
  - The Jake’s fading channel model will not be suitable

Measurement result showed that there is significant performance degradation when 2 vehicles move at high relative velocity

- In the I2V communication channel model: there are only scatterers near the vehicle
- In V2V communications, there are scatterers around both the transmitter and receiver.
- Correlated double ring scattering channel mathematical model has been proposed for V2V
- Sum of sinusoids approximation simulation model for V2V

More performance analysis is required.


Single vehicle/single AP (highway)

Total throughput:

\[ T_{total} = \int_{x_o-R}^{x_o+R} T_i(x(t), v) dt \approx \frac{1}{v} \int_{x_o-R}^{x_o+R} T_i(x) dx \]

\[ T_{total} \approx \frac{2R}{v} \overline{T_i}, \overline{T_i} = \frac{1}{2R} \int_{x_o-R}^{x_o+R} T_i(x) dx \]
802.11b at speeds I

The AP was powered by batteries and located roadside with the antenna at 2m above ground level. The vehicle was equipped with a roof mounted 6 dBi omni-directional 2.4GHz antenna and a GPS receiver was used to measure location and speed. All data parameters were logged and then later combined to create a complete view of the test runs.

TCP results at 60 mph

802.11b at speeds II: connectivity phases

- Experiments performed in highway conditions
- Roof-mounted external antenna
- UDP and TCP measurements for both V2I and I2V scenarios
- Bell-shaped throughput curves (entry, production, exit phases)
- Velocity-dependence is mainly due to the total residence time

802.11b at speeds II: speed dependence

- Experiments performed under no-interference conditions (desert)
- External antenna on the roof
- UDP, TCP, HTTP
- Observed some velocity-dependent packet loss

802.11a at low speeds: Suburban

- Drive past an access point
- Highly variable performance
- Low speeds impacted by time spent in nulls of radio coverage
- Impacts data rates for slow moving traffic

Single vehicle/ multiple access points I

Co-channel interference:
- Optimal channel assignment is required to minimize interference while maximizing coverage
- For 802.11.b/g there are only 3 non-overlapping channels
- Relatively simple in 1D geometries (i.e. stretch of highway)
- Hard problem in 2D (graph colouring) → heuristics
Single vehicle/ multiple access points II

802.11 Handoff at speeds

- Autonomous handoff initiated by client itself (unlike the centralised approach in cellular systems):
  - SNR/packet loss monitoring
  - Channel scanning for new AP
  - Authentication/Association
- Handoff can take up to 500 ms, mainly due to the scanning phase
- Main effect is on real-time applications (VoiP)
- Fast layer 2 handover

Source: Ramani and Savage, 2005.
Components of L2 handoff time

Layer 2 handoff components:

<table>
<thead>
<tr>
<th>HANDOFF PHASE</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection*</td>
<td>About 1000 ms</td>
</tr>
<tr>
<td>Search/Scanning</td>
<td>350-500 ms</td>
</tr>
<tr>
<td>Authentication &amp; Association</td>
<td>&lt;20 ms</td>
</tr>
<tr>
<td>Infrastructure update</td>
<td>&lt;20 ms</td>
</tr>
</tbody>
</table>

AP beacon frequency ~ 100 ms (default)

* Some implementations skip the detection phase

• Major phases of handover process:
  – Detection
  – Searching
  – Execution
L2 handoff time improvement

- **Detection**
  - Reduce beacon interval to 60ms
  - Reduce no. of retransmission trials

- **Search**
  - Scan only subset of channels
  - Fast scanning (reduce beacon frequency)
  - Continuous scanning (before the need arose)
  - In VCNs road topology information and mobility prediction can be utilized to reduce scanning times

Source: Héctor Velayos and Gunnar Karlsson (http://web.it.kth.se/~hvelayos/papers/TRITA-IMIT-LCN%20R%2003-02%20Handover%20in%20IEEE%20802.pdf)

Improvement can be achieved by modifying wireless card driver!
Many vehicles/ multiple access points

- Average throughput per user depends strongly on traffic conditions

- Requires adaptive resource management on a much finer time and length scale than 2G/3G

FIG. 2. Empirical velocity-density relations for different definitions of the average velocity. Symbols represent averages of 1-minute data determined via the harmonic velocity formula \( V = 1/(1/v_\alpha) \), while the solid line is a fit function to the velocity averages determined via the conventionally applied arithmetic formula \( V = \langle v_\alpha \rangle \). (After Helbing, 1997a.)
Smart / directional antenna

- Vishnu Navda, et. al., ACM MobiSys’07, June 11~14, 2007, San Juan, Puerto Rico, USA.

In the MobiSteer project, Vishnu Navda, et. al. show that beam steering can improve the connectivity duration as well as PHY-layer data rate due to better SNR provisioning.

Directional antenna
- reducing the transmission collisions, as well as increasing the channel reuse possibility.
- Suitable for VANET with parallel neighboring vehicular traffic
Characteristics and Challenges of Vehicular Adhoc Networks
(Safety and ITS Applications)
Rapidly changing network topologies

- Vehicles continuously move in and out of each other’s range
  - short link lifetimes
  - No continuous end-to-end connectivity
  - Frequent network fragmentations into isolated clusters

\[ t_{\text{link}} \sim \frac{2r}{|V_i - V_j|} \text{ same direction} \]
\[ t_{\text{link}} \sim \frac{2r}{(V_i + V_j)} \text{ opposite direction} \]

Results are for average traffic in a highway (CA, US), simulations studies by Blum and Eskandarian, 2004.
Large node density variations

- Node density variations are governed by traffic conditions:
  - day/night/rush hour variations
  - Free flow vs. congestion
  - Traffic jam waves (time and space)

network fragments into isolated clusters

$V_{critical}$

end-to-end connectivity as function of mean velocity, Nekovee, VTC 2006
Inter-vehicle communications at speeds

• Unlike I2V only very few (published) measurements.
  - Singh et al. discuss experimental test for 802.11b with two vehicles driving in urban, suburban and highway (roof top external antennas)
  - Yin et al. discuss simulation studies using a detailed radio model of DSRC, finding some speed-dependence in the relation between SNR and BER
  - Speed-dependence especially important in opposite-lane communication scenarios

Sim, Nekovee, Ko, 2005
MAC layer and scalability

• To avoid interference caused by nearby devices using the same channel, access to medium is regulated by the 802.11 MAC protocol.

• 802.11 uses a contention-based access mechanism.

• Devices refrain from transmission and backoff for a random time when they sense a busy medium. This can greatly limit network throughput:

\[ T_{\text{max}} \sim \frac{B_r L}{2r_i} \]

• Potential solutions
  ▪ More channels, more spectrum (cognitive radio).
  ▪ TDMA-based MAC protocols and scheduling algorithms (require synchronization).

Potential solutions include:

- More channels, more spectrum (cognitive radio).
- TDMA-based MAC protocols and scheduling algorithms (require synchronization).
Vehicular adhoc communications for ITS

- Point-to-point routing

- Single-hop communications
  - Collision avoidance
  - Platoon formation

- Multihop communications
  - Information dissemination (traffic conditions, road hazards)
  - Traffic data collection
Point-to-point routing

- Rapidly changing topology:
  - Proactive routing problematic due to many invalid routes
  - Reactive routing attempt to discover routes when needed but route discovery could take longer than route lifetime!
  - Location-based routing delivers only to a zone of relevance (shorter hops) but requires location information (Briesmeister et al, 2000)
  - **Alternatives:** Infrastructure-assisted routing and epidemic/opportunistic routing (effectively point-to-multipoint)

Single hop communications I

- Fog conditions. Car 2 is driving behind car 1.
- Car 1 suddenly breaks and broadcasts a warning message.
- To avoid a collision we must have:

\[
t_{\text{comm}} + t_{\text{reaction}} < \frac{|x_2 - x_1|}{v_2} - c \frac{v_2}{f}
\]

message communication latency, driver’s reaction time (~750 ms), road’s grip coefficient

Single-hop communications II

- Simulation studies of single-hop communication for delay-critical safety applications by Yin et al (2004).
- DSRC standard (PHY/MAC protocol stack) at 5.9 GHz is used.
- VANET created by 100 vehicles moving on a city roadmap, each having ~1000 m transmission range, using a single 10 MHz common channel.
- 1-10 safety message/second/vehicle (100-200 B).

- Performance metrics used:
  - Single-hop latency
  - Single-hop throughput (fraction of single-hop neighbours receiving the message).

A 100 ms latency limit is proposed by Vehicular Safety Communications Consortium (VSCC)
Modelling vehicular movements

- Vehicular movements in traffic are highly correlated and are constrained by road topology and traffic lights etc.
- Conventional MANET mobility models, random walk and random waypoint are highly inadequate.
- Fortunately there is much research (physicists, transport engineers) on traffic and vehicular mobility models.
- Broadly speaking, there are three levels of modelling:
  - Fluid models (macro scale)
  - Cellular automata models (meso scale)
  - Car-following models (micro scale)

Traffic jam waves in a highway corridor from car-following simulations, Vazquez-Prada and Nekovee, 2005.
• Fluid models
  • Vehicular traffic is described as an incompressible fluid (view from an airplane)
  • Characterised by: $\rho(x,t)$, $V(x,t)$, $Q(x,t)$
  • Navier-Stokes-type equations describe time-evolution
  • In steady-state we have (highway):

\[
\bar{V}_e(x) \approx V_f \left( 1 - \frac{\bar{\rho}_e(x)}{\rho_{jam}} \right)^\beta
\]

\[
\bar{d} = l + \frac{1}{\bar{\rho}_e(x)}
\]
• Car-following models
  
  - Track the movements of individual cars in time and space.
  - Cars accelerate/decelerate due to a force which depends on their distance and velocity relative to the car ahead of them.
  - Additional rules for multiple-lane scenarios.
  - Each car can have its own individual attributes (length, driver behaviour, car/truck …)
  - Can accurately reproduce real traffic behaviour in highways and urban scenarios.

\[ F_i(t) \sim 1 - \left( \frac{\Delta v_i(t)}{v_i^0} \right)^4 - \left( \frac{x_i^0}{\Delta x_i(t)} \right)^2 \]

- $v_i^0$: desired speed (speed limit)
- $\Delta v_i(t) = v_{i+1}(t) - v_i(t)$
- $\Delta x_i(t) = x_{i+1}(t) - x_i(t) - l$
Coupled simulation approach
(Large scale experimental evaluation is not an option)

- Microscopic vehicular traffic simulator (IDM, Dracula, TranSim)
- Wireless network simulator (Trafficom, NS2, NS3)
- Grid Computing Platforms (Legend, Hector, NGS)
Information dissemination in VANET I
Information dissemination in VANET II

• Applications:
  – Local traffic conditions for ITS.
  – Warning messages (road hazards, accidents, congestion)
  – Sensor data alerts.
  – Epidemic routing.

• Challenges
  – Intermittent network connectivity (reliability issues).
  – Excessive network traffic and MAC latency caused by highly correlated transmissions (scalability issues).

• Proposed approaches.
  – Infrastructure-assisted: roadside info-stations/accesspoints/cellular assist VANET to bridge the gaps.
  – Purely ad-hoc: store and forward/opportunistic mechanisms similar to those used delay-tolerant networks.
  – Selective broadcasting schemes (deterministic, probabilistic).
Information dissemination in VANET III

• Limitations
  – Infrastructure-assisted: Infrastructure may not be always available, single point of failure
  – Adhoc: often requires control data exchange (e.g. to maintain clusters), or additional information (e.g. road topology information and location)
  – Selective broadcasting schemes address scalability but cannot cope with intermittent connectivity and network fragmentations
Edge-aware epidemic

- Persistent flooding achieves 100% reliability but generates excessive traffic.
- In epidemic protocols nodes re-transmit messages with a probability $P$.
- This reduces traffic but reliability is probabilistic (even in static networks).
- Edge-aware epidemic: Only nodes at the edge of a cluster keep the message alive.
- How does a node know it is on the edge?

Source: Nekovee, IET Intelligent Transport, 2009
Algorithms

- After receiving a new message a node selects a backoff time from \([0, T_{\text{max}}]\) and waits.

- When the waiting time expires it counts the received messages from vehicles in the front, \(N_f\), and from the back, \(N_b\).

- It then makes a probabilistic forwarding decision based on the imbalance.

- Only nodes at the edge “survive”.

- They periodically broadcast the message until there is a cluster merger.

- Directional messaging can be handled in the same way (cluster head and tails).

\[
T_{\text{max}} = \min \left\{ T_0 \exp \left( \frac{|x_{\text{req}} - x_{\text{req}}|}{L} \right), \frac{T_0}{U} \right\},
\]

where \(U\) is a parameter which can be used to indicate the “urgency” of the message and \(L\) and \(T_0\) are protocol parameters.

\[
P = \begin{cases} 
1 & \text{if } N_f \text{ or } N_b = 0 \\
1 - \exp \left( -\alpha \frac{|N_f - N_b|}{N_f + N_b} \right) & \text{otherwise.} 
\end{cases}
\]
IDM -VANET simulator

http://nekovee.info/VANET1.htm
http://vwisb7.vkw.tu-dresden.de/~treiber/MicroApplet/
Scalability

- Road with one lane in each direction
- High vehicle density/lane → continuous e2e connectivity
- Transmission range: 120 m
- We inject a message in a randomly chosen vehicle and follow its propagation
- Results averaged over a large number of simulation runs

Fig. 1. Total number of transmitted messages is shown as a function of vehicle density for flooding and edge-aware epidemic protocol.
Reliability

- Road with one lane in each direction
- Vehicles move at a specific flow into the road
- Flow rates was adjusted to obtain intermittently connected networks
- Message injected at $t=30$ s
- Transmission ranges: 60, 120 m
- Both omni-directional and directional propagation scenarios
Congestion reduction using V2V messaging

100% WiFi-equipped vehicles
V2V communication for rear-end collision avoidance

- Better than conventional break light (visibility, LOS → chain collisions)
- Better than cellular (distributed → faster and cheaper). **cellular delivery latency ~ 1-4 seconds**
- Suffers from **communication delay** (802.11p’s MAC contention mechanism)
- Suffers from **packet loss** (hidden node + MAC contention + wireless V2V channel)
Performance modelling of V2V-based rear-end collision avoidance protocols

- V1 is moving ahead of V2.
- V1 suddenly brakes to avoid a hazard.
- Upon braking a warning message is triggered, and is broadcasted using V2V adhoc communication.
- In principle superior to brake lights signalling (low visibility, driver’s slow reaction).
- Reduces the chance of chain collision due to increased “visibility” range.
- In practice V2V communication is subject to delivery latency and packet loss → repeated retransmission.
- A precise formulation of QoS requirements for collision avoidance not available in literature.
- We provide analytical results to guide V2V protocol design.

\[
x_1(t) = x_0 + v_1 t - \frac{1}{2} a t^2
\]

\[
x_2(t) = \begin{cases} 
    x_2^0 + v_2^0 t \\
    x_2^0 + (v_2^0 + a t_{cr}) t - \frac{1}{2} a (t^2 + t_{cr}^2)
\end{cases}
\]
Maximum delivery latency and minimum retransmit frequency

\[ t_{c}^{\text{max}} = \min \left\{ \left( \frac{2S}{a} \right)^{1/2}, \frac{V}{a} \left( \sqrt{1 + \frac{2Sa}{V^2}} - 1 \right) \right\} - t_r \]

\[ f_{r}^{\text{min}} = \frac{1}{t_{c}^{\text{max}} - t_c} \left( \frac{\log \epsilon_{CA}}{\log(p_{v2v})} \right); \quad 0 \leq t_c \leq t_c^{\text{max}} \]

- Inter-vehicle gap
- Driver reaction time
- Emergency deceleration
- Single hop delivery latency
- Single hop packet loss rate
Modelling ingredients

- **Realistic car-following model (IDM) for vehicular movement:**
  Random walk and random waypoint mobility models cannot describe the highly correlated motion of cars (Treiber et al, Phys. Rev. E, 2000).

\[
S(V) = (S_0 + VT) \left[ 1 - \left( \frac{V}{V_0} \right)^{\delta} \right]^{-1/2}
\]

- **Velocity-dependent wireless channel model:**
  In highways relative velocity difference between two communicating cars can reach 200-300 Km/h (in opposite lanes).

\[
p_{ij} = p_{ij}(r_{ij}, v_{ij}) = \frac{1}{2} + \frac{1}{2} \text{erf} \left( \frac{\beta_{th} - \beta(r_{ij}, v_{ij})}{\sqrt{2}\sigma} \right)
\]

average velocity per lane

average distance between adjacent cars

average density per lane

signal attenuation threshold

signal attenuation: distance + velocity+ log normal shadow fading (Sim, Nekovee, Ko, 2005)
Maximum acceptable latency (no loss)

![Graph showing the relationship between mean vehicle velocity and maximum V2V delivery latency under different road conditions. The graph includes lines for ice road, mud road, wet asphalt road, and dry asphalt road, with labels for free flow and traffic jam.]
Minimum message retransmission frequency

without shadowing & fading

with shadowing & fading
Next steps - M25 London

M25 London Orbital

121.5 miles long

Longest and one of the most congested ring roads in the world

31 junctions

9 motorway interchanges

Junction 15 to 14 carries 165000 cars per day

Simulating just Junction 15 to 14 for 24 hours would take over a year to achieve on a single processor machine
Parallel simulations of V2V networks

• Run many (10,000) independent simulations of small networks on parallel machines with different parameter combinations:
  • vehicle density
  • packet size,
  • transmit rate,
  • transmit power
• The aim is to map out V2V network performance metrics (latency, packet drop rate etc) as multi-variable functions of system parameters.
• Design traffic- adaptive V2V protocols
Cyber-attacks on VANET

Securing vehicular networks against cyber-attacks is a major issue due to the criticality of many of their applications in ITS.
A plethora of potential cyber-attacks

Raya and Hubaux, 2005.

Wireless worm attacks

Modelling worm attacks on VANET

- Worms are self-replicating computer viruses that can spread in networks without any human intervention.

- The last few years has seen the emergence of new types of worms that specifically target wireless networks.

- Unlike conventional worms, they can propagate wirelessly, using a radio communication technology, such as WiFi or Bluetooth.

Nekovee, 2006
Worm spreading model

- A worm spreads in the network by multi-hop forwarding, instead of using IP scanning which could be highly inefficient for VANET.
- Each car can be in one of three states: susceptible, infected, patched.
- Infected cars broadcast the worm at any possible opportunity.
- Susceptible cars become infected at a rate $\lambda$ when they receive a transmission from an infected car.
- Infected cars can get patched at a rate $\delta$.
- The time it takes to process a worm by each car is a constant value of one clock tick. Worm transmission is assumed to be instantaneous.
Simulation studies

- We consider worm propagation in a 10 km highway corridor consisting of 1 lane in each direction.

- Effective transmission range per vehicle is fixed at 250m.

- Traffic conditions are characterized by mean velocity in each lane, e.g. $V=0,20,40,60,80,100,120$ Km/h and the IDM model is used to compute the mean vehicle density.

- For a given density we create an instant of the vehicular network by distributing vehicles randomly and uniformly in each lane, and linking two vehicles (i and j) with a probability given by our velocity-dependent shadow fading model.

- A randomly chosen vehicle is infected by the worm at the beginning of each simulation.
Propagation dynamics of an unknown worm in VANET

Standard Worm Propagation Model

network fragments
Impact of interactive patching

![Graph showing the impact of interactive patching on the fraction of infected vehicles over time and the maximum fraction of infected vehicles with different patching rates.](image)
Emerging trends/technologies for spectrum access

- Radio Spectrum is a key resource for wireless networks
- In the past spectrum was rigidly regulated and managed
- But this is changing to a much more dynamic management of and access to spectrum (phenomenal increase in spectrum + inefficiency of command & control + technology advances)
- Emerging technologies:
  - Software-defined radio (SDR)
  - Dynamic Spectrum Access (DSA)
  - Cognitive radio (CR)

The FCC Frequency Allocation Table at 3GHz.

A mobile phone conversation using a cognitive radio link

Scientific American, March 2006.
Dynamic Spectrum Access

- Dynamic Spectrum Access (DSA) techniques allow devices (just-in-time) selection of the most appropriate spectrum
- Early forms of DSA already exist
- BT Fusion phone is an example:
  - Indoor: Wi-Fi (licence-exempt)
  - Outdoor Cellular (licensed)
Cognitive radio

• Smart devices built on software-defined radio:
  – scan their environment.
  – identify unused (licensed) spectrum bands (learning).
  – move into one of these bands (frequency-agile/reasoning).
  – move out to another band when necessary (predictive).

The Trajectory of a cognitive radio in time-frequency space, Nekovee 2006.
Summary

• VCNs hold promises for a plethora of important applications:
  – High Mobility Broadband Wireless Access
  – Future Intelligent Transport Systems
  – Pervasive Sensor Networks on the Road
• A tough but exciting area of research at the intersection of a number of disciplines and technologies
• Important advances have been made in research but many open research challenges:
  – Handoff at speeds
  – Traffic-adaptive protocols
  – Scalability
  – Security
  – Spectrum demand and interference management
• Advanced simulations and modelling coupled to measurements are essential in order to address research challenges in the realistic context of large scale systems
• They can also give us a glimpse of the future
Further readings

- Kosch T, Technical concepts and prerequisites of car-to-car communications, 5th European Congress and Exhibition on ITS, 2005


• Thanks and acknowledgements
  – David Cottingham, The University of Cambridge
  – Stephen Eubank, Georgia Tech
  – Keith Briggs, BT Research

  – Video: Courtesy of Synthetic Data Products for Societal Infrastructures and Proto-Populations: Data Set 3.0, NDSSL-TR-07-010, Network Dynamics and Simulation Science Laboratory, Virginia Polytechnic Institute and State University, 1880 Pratt Dr, Building XV, Blacksburg, VA, 24061, ndssl.vbi.vt.edu/Publications/ndssl-tr-07-010.pdf
Performance of VLC receivers

- Vary over the day
  - Due to variation in background light/global irradiance
- Newly proposed receiver perform much better
Visible light communications (VLC) for VANET

- Advantages:
  - No radio interference
  - No radio spectrum required
  - Utilization of existing infrastructure
  - Safe
  - Low cost

- Disadvantages:
  - LOS, Short-distance transmission
  - A lot of optical noises in outdoor, i.e., background light
  - Changes in the relative position between transmitter and receiver
Receiver structure for VLC

- Background light is the major source of noise in VLC receiver.
- A conventional receiver may have optical filter with relatively large bandwidth to receive the 3 traffic light colours:
  - Collect higher noise level as well.
- An improved structure is to have separate optical filters for green light and red and yellow lights:
  - Each filter collect lesser noise.

Conventional Selective combining
L3 handoff time improvement

Two of the main L3 handoff delays:
- detection of a subnet change
- address acquisition time via DHCP

An example of L3 handoff delay improvement is to reduce the DHCP acquisition time as in the work by Andrea G Forte, et al, ACM Proceeding on Wireless Internet, 2006

- Scenario 1: The MN enters in a new subnet for the first time ever.
- Scenario 2: The MN enters in a new subnet it has been before and it has an expired lease for that subnet.
- Scenario 3: The MN enters in a new subnet it has been before and it still has a valid lease for that subnet.