Real-Time Path Planning for Optimized Spatial Utilization and Travel Cost in VANET-Enhanced Transportation System

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Problems

• The 2007 Urban Mobility Report stated that traffic congestion causes 4.2 billion hours of extra travel every year in US, which almost accounts for 2.9 billion extra gallons of gas.

One particular research challenge to our interest is to obtain real-time traffic information and to use real-time traffic information for path planning and traffic congestion avoidance.
Contributions

• First, we propose a **VANET-assisted ITS framework** with the enhanced functionalities of real-time path planning, in which VANETs enable efficient communications between vehicles and RSUs to deliver the useful traffic information for the real-time path planning;

• *Second, we design a real-time path planning strategy* to improve **global** road network spatial utilization while reducing **travel cost** for individual vehicles. With our proposed path planning strategy, a vehicle intelligently follows a replanned path to bypass the gridlock area; and

• *Third, we carry out extensive simulations to validate the effectiveness and efficiency of our proposed path planning strategy.* Simulation results confirm that our proposed path planning algorithm is able to find alternative vehicle path bypassing the congestion area in a timely, efficient and globally coordinated way.
VANET-enhanced ITS

1) Wired communication
2) Wireless communication

Vehicle-Traffic Server
Wired Network
V2I Communication
RSU

V2V/V2I Communication
Static sensor
car Bus car
Network Architecture

1) DSRC
2) Public transportation system
System Model

Infrastructure
- RSUs
- Static sensors
- Vehicle-traffic server

Mobile Node (with GPS devices)
- Private cars (DSRC: V2V/V2R): $n_p$
- Taxis (GSM): $n_t$
- Buses (GSM): $n_b$

$w_j = 1$
$w_j = 0$

$w_j$ is the capability of a vehicle $j$ to change its path.
System Model

Communication Link

• After sensing the gridlock, a vehicle broadcasts the warning message to any super-node or any RSU directly by V2V/V2I communication;

• if one super-node receives the warning message, it will be in charge of broadcasting the message to other super-nodes through the public commu. system
System Model

Message Required (why?)

• 1) the warning messages with gridlock indicators and a global message lifetime which are generated by the vehicles near the accidents/gridlocks, and transmitted mainly based on V2V communications;

• 2) the information for vehicle-traffic inflow and outflow of the roads, collected by the deployed static sensors at the intersections; and

• 3) the information of the vehicles’ current paths, stored in the vehicle-traffic server, and used to update the real-time path information.
Objective

• When an unexpected situation happens, how re-plan the path for each vehicle to fully utilize the traffic capacity with maximizing the overall vehicle-traffic throughput and minimizing the path cost (e.g., travel time / gas cost).
Definition

Let $\mathcal{I}$ denote the set of intersections in the network

- **Vehicle-traffic capacity**
  
  Let $c_{mn}(t), (m, n \in \mathcal{I})$ denote the maximum available traffic flow at the time slot $t$ of road segment $(m, n)$ where $m$ and $n$ are adjacent intersections, called vehicle-traffic capacity, which may be related by the speed limitation on that road segment.

- **Vehicle-traffic throughput**
  
  Let $\lambda_{mn}(t)$ denote the realistic traffic inflow of road segment $(m, n)$, called vehicle-traffic throughput, which is determined by the number of vehicles flowing into that road segment.
Methodology

• Step1: collect sensing data (traffic information);
• Step2: broadcast/rebroadcast the traffic environment information to the other vehicles/RSUs ;(MD-based)
• Step3: path planning to fully utilize the network traffic capacity, based on the received traffic information and the available paths.
Traffic Flow

• Consider a Queue $Q_i^d(t)$ at one intersection $i$, buffering vehicles destined to destination $d$.

• The queueing law on the size of queue

$$Q_i^d(t+1) = \max\{Q_i^d(t) - \sum_{j \in J_i} \lambda_{ij}^d(t), 0\} + \sum_{u \in J_i} \mu_{ui}^d(t) + x_i^d(t);$$

satisfying

$$\mu_{ij}(t) \leq \alpha_{ij}(t) \cdot c_{ij}(t) \quad \text{(gridlock indicator)}$$

$$\sum_{j \in IN_i} \lambda_{ij}(t) = \sum_{j \in OU_i} \mu_{ji}(t), \forall i \in \mathbb{I} \quad \text{(flow balance equ.)}$$
The travel cost

- Selfish direction factor $p_{r_{ji}m_d}$ to measure the cost of the planned path, for vehicle $m$, where $r_{ji}$ is the turning decision.

$$p_{r_{ji}m_d} = \eta \cdot \rho(\left| S_{r_{ji}m_d} \right| - \left| S_{S_i m_d} \right|)$$

(compared to the shortest path)

e.g., extra travel time; gas cost...
• Thus,

\[ p_{ij}(t) = \begin{cases} 
\frac{1}{\sum_{m \in \mathcal{V}} w_m} \cdot \sum_{m \in \mathcal{V}, d \in D} w_m \cdot p_{r_{ji}m_d}, & \text{if } \alpha_{ij} = 1, \sum_{m \in \mathcal{V}} w_m \neq 0; \\
\infty, & \text{otherwise.} 
\end{cases} \]

\[ p_{iJ_i}(t) = \begin{cases} 
\frac{1}{\sum_j \alpha_{ij}(t)} \cdot \sum_j \alpha_{ij}(t) \cdot p_{ij}(t), & \text{if } \sum_j \alpha_{ij}(t) \neq 0; \\
0, & \text{otherwise.} 
\end{cases} \]
Objective

• Utility-minus-cost Maximization Prob.

$$\max \sum_{i \in \mathbb{I}} \chi \left( \sum_{j \in J_i} \lambda_{ij} \right) - \sum_{i \in \mathbb{I}} p_{iJ_i},$$

s.t.

$$0 \leq \mu_{ij}(t) \leq \alpha_{ij}(t) \cdot c_{ij}(t),$$

$$\sum_{j \in IN_i} \lambda_{ij}(t) = \sum_{j \in OU_i} \mu_{ji}(t),$$

$$\lim sup_{T_0 \to \infty} \frac{1}{T_0} \sum_{0}^{T_0} E[Q_i(t)] < \infty, \forall i \in \mathbb{I}.$$
Path Planning Algorithm

• Lyapunov Optimization:
  1) the weight of intersection $i$

$$W_{ij_i}(t) = \sum_{j \in J_i} \alpha_{ij}(t) \cdot \min\{c_{ij}(t), \sum_{d \in D} \{Q_i^d(t) - Q_j^d(t)\}\}$$

$$-V \cdot p_{ij_i}(t)$$

2) assigned vehicles to the queue $Q_j^d(t)$

$$j_d^* = \max_{j \in J_i} \{Q_i^d(t) - Q_j^d(t)\}$$
Performance Evaluation

Average-moving-delay (AMD) reduction by path planning

Bar graph showing the average moving delay (second) with and without path planning under different group conditions for various numbers of accidents.
Performance Evaluation

AMD comparison based on different accident active time-duration
Performance Evaluation

AMD comparison with different number of slow vehicles
Performance Evaluation

Average path length increment due to path planning
Conclusion

• Develop a VANET-enhanced real-time path planning strategy for vehicles to avoid the gridlock in ITS;
• To maximize the utilization-minus-cost problem improving the overall spatial utilization and reducing the average vehicle travel cost, by means of Lyapunov optimization.
THANK YOU!