Towards Real-time, Reliable and Efficient Service in Wireless Cyber-Physical Systems

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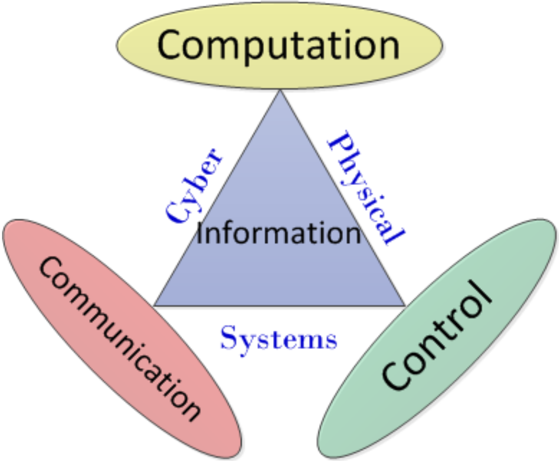
Outline

Introduction

Wireless Cyber-Physial Systems (WCPS)



Introduction

Our focus

- Design real-time, reliable and efficient WCPS

Our methodology

- Light-weight algorithm and protocol design
- Theoretical analysis of different algorithms
- Extensive experimental and simulation evaluation

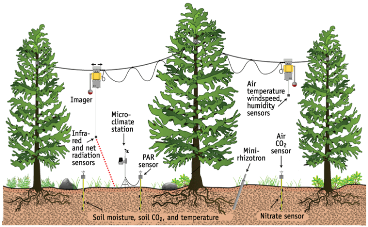
Case Studies

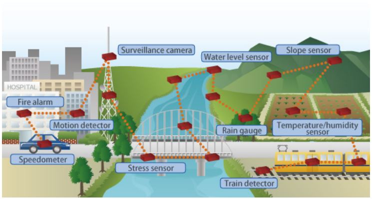
1. Wireless Networked Sensing and Control
2. Intelligent Transportation Systems
3. Electric-Vehicle-Integrated Smart Grid

Outline

Wireless Networked Sensing and Control (WNSC)

- Wireless sensor networks + Close-loop control
- Various mission-critical applications





Wireless Networked Sensing and Control

Wireless Sensor Networks

- Communication infrastructure of WNSC
- Highly resource-constrained

In-Network Processing (INP)

- Reduce traffic flow $\rightarrow$ resource efficient
- End-to-end QoS are usually not considered

Wireless Networked Sensing and Control

Challenges for INP in WNSC

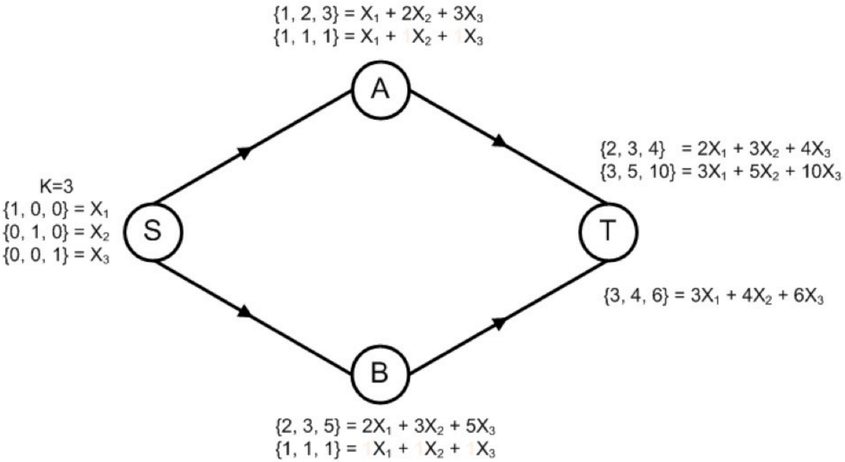
- Stringent end-to-end QoS requirements, e.g., latency, reliability and efficiency, in WNSC
- Dynamic communication environments

To cope with these challenges, we investigate

- Joint optimization between INP and QoS
  - Real-time packet packing scheduling [7][9]
  - Optimal network-coding routing [8][3]

NetEye Testbed

Optimal Network-Coding-Based Routing



System Model

- A directed graph $G = (V, E)$ with one source S and one destination T
- Edge $(i, j) \in E$ with link reliability $P_{ij} = \frac{1}{ETX_{ij}}$
- Node i has a forwarder candidate set FCS_i, i.e., one-hop neighbors of i

MIN-NC Problem

- Determine the forwarder set FS_i for each node i
- **Minimize** the total transmission cost to deliver K linear independent packets from S to T

Minimize the cost of NC-based routing

A greedy approach

1. Sort forwarder candidates in non-descending order of their transmission cost;
2. Select the best candidate remaining into forwarder set;
3. Keep it in the set if the total transmission cost can be reduced, go back to last step;
4. Stop if the total transmission cost cannot be reduced.

Theorem of optimality

Theorem

Given a node S and its forwarder candidate set $D_S = \{A_1, A_2, \ldots, A_M\}$, our greedy algorithm yields the minimal transmission cost to the destination node of NC-based routing and the corresponding forwarder set.

We proved this theorem by contradiction.

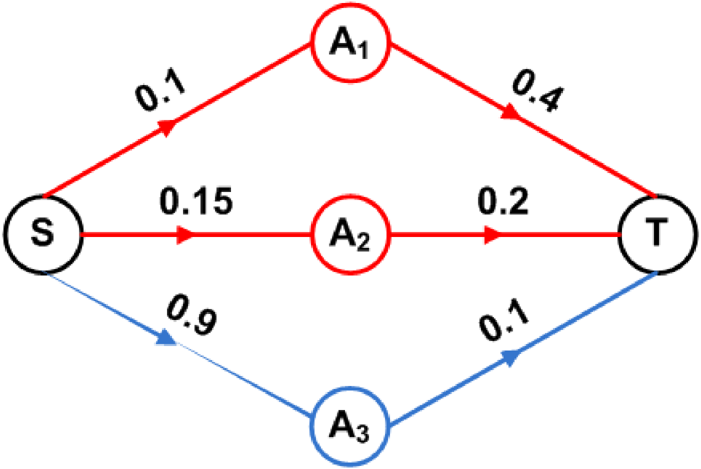
Properties of the optimal routing braid

Theorem

Given a node S with a candidate set FCS_S of M forwarders, the optimal forwarder set FS_S computed in our greedy algorithm does not always contain node A^* where $A^* \in FCS_S$ and $\frac{1}{P_{SA^*}} + C_{A^*} \leq \frac{1}{P_{SA_i}} + C_{A_i}$ for any $i \in FCS_S/\{A^*\}$.

Shortest single path routing is not always in the optimal braid.

Properties of the optimal routing braid



The optimal routing braid is $\{A_1, A_2\}$

$$\begin{aligned}
C_{\{A_1,A_2\}} &= \frac{1}{1-(1-0.1)(1-0.15)} \cdot [1 + \frac{0.1}{0.4} + \frac{0.15(1-0.1)}{0.2}] \\
&= \frac{1}{0.235} \cdot (1 + \frac{1}{4} + \frac{0.135}{0.2}) \\
&= 8.1915 \\
C_{\{A_1,A_2,A_3\}} &= \frac{1}{1-(1-0.1)(1-0.15)(1-0.9)} \\
&\quad \cdot [1 + \frac{0.1}{0.4} + \frac{0.15(1-0.1)}{0.2} + \frac{0.9(1-0.1)(1-0.15)}{0.1}] \\
&= \frac{1}{0.9235} \cdot (1 + \frac{1}{4} + \frac{0.135}{0.2} + \frac{0.6885}{0.1}) \\
&= 9.5398 > C_{\{A_1,A_2\}}
\end{aligned}$$

Properties of the optimal routing braid

Theorem

Given a node S with a candidate set FCS_S of M forwarders, the optimal transmission cost C_S^* computed in our greedy algorithm is always lower than or equal to $\frac{1}{P_{SA^*}+C_{A^*}}$ where $A^* \in FCS_S$ and $\frac{1}{P_{SA^*}} + C_{A^*} \leq \frac{1}{P_{SA_i}} + C_{A_i}$ for any $i \in FCS_S/\{A^*\}$.

Cost of optimal NC-based routing is upper bounded by shortest single path routing.

ONCR: an Optimal Network-Coding-based Routing Protocol

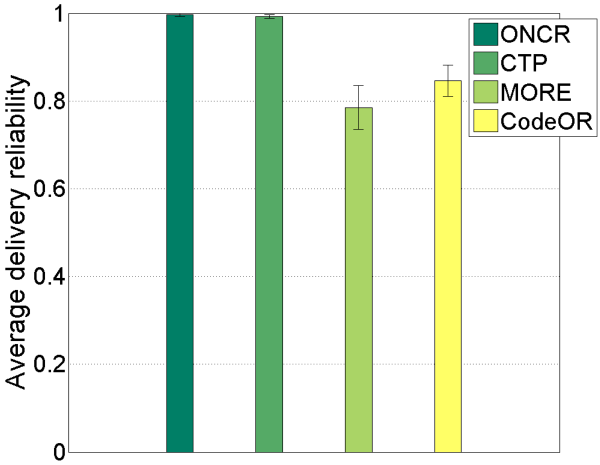
- Routing engine: a distributed implementation of our greedy algorithm
- M-NSB: a coded ACK scheme to solve the collective space problem with lower implementation complexity than CCACK
- Rate control: nodes forward a flow after receiving a load-dependent threshold of packets to 1) reduce contention and 2) avoid potential linear dependence between forwarded packets

Performance evaluation

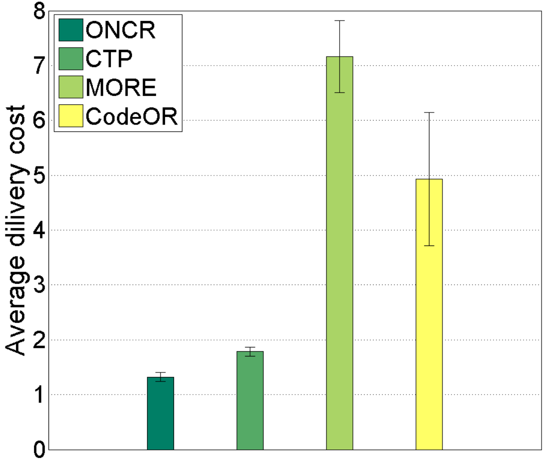
Experiment setting up

- Testbed: NetEye, a 130-sensor testbed at Wayne State University
- Topology: 40 nodes, 10/20 are source nodes, 1 sink node
- Protocols compared: *ONCR*, CTP, MORE, CodeOR
- Traffic pattern: 3-second periodic traffic
- Metrics: delivery reliability, delivery cost, goodput and routing diversity

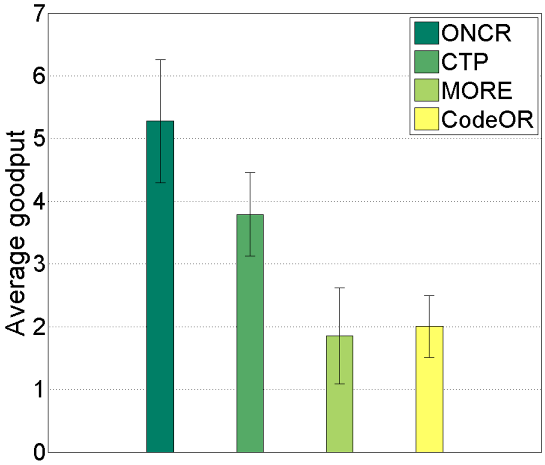
10-source: delivery reliability



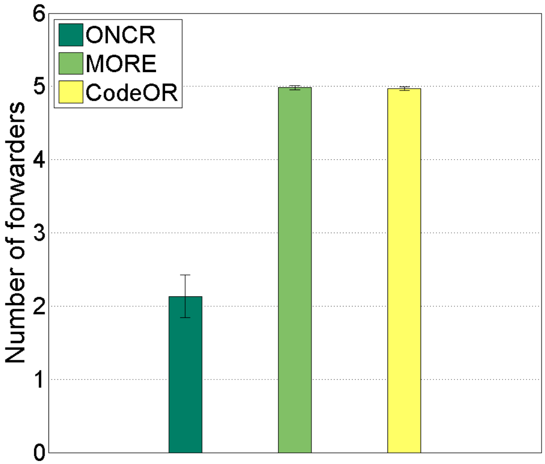
10-source: delivery cost



10-source: goodput



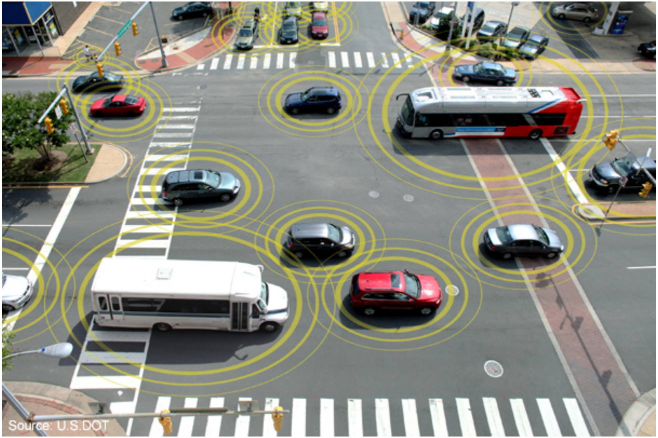
10-source: routing diversity



Outline

Intelligent Transportation Systems

A smarter and safer transport networks



Intelligent Transportation Systems

Vehicle-to-Vehicle(V2V) Communication

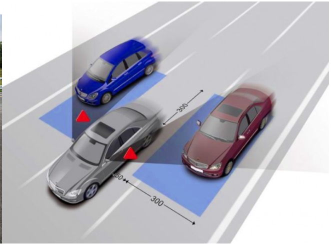
- Communication infrastructure for Intelligent Transportation Systems (ITS)

Intelligent Transportation Systems

V2V Safety Data Dissemination

- Crucial for vehicle safety
- Contain periodic routine data and event-driven emergency data
- Emphasis on small delay and high coverage

(c) Collision Avoidance



(d) Lane Change

Sources: *www.gm.com* and *www.Mercedes-Benz.com*

Intelligent Transportation Systems

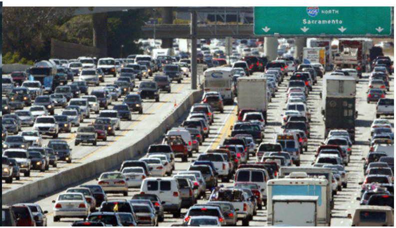
Dedicated Short Range Communication(DSRC)

- In February 2014, the U.S. DoT announced to commit to the use of DSRC technologies on new light-duty vehicles.

Intelligent Transportation Systems

Challenges for DSRC

- Unstable communication quality between vehicles due to high mobility
- Severe “broadcast storm” during rush hours



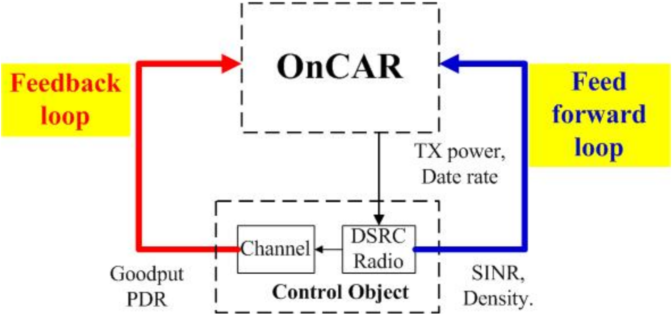
Intelligent Transportation Systems

To cope with these challenges, we explore

- the correlation between transmission power and data rate during broadcast [1]
- vehicle's data preference when collecting safety-data [4]

Online Control Approach of Power and Rate (OnCAR)

- Adaptively controls transmission power and data rate to improve the performance of DSRC
- Leverages a feed forward loop and a feedback control loop to produce the optimal choices of power and rate

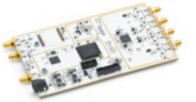


VSmart: DSRC-enabled smart vehicle testbed

VSmart: DSRC-enabled smart vehicle testbed

Laptops or tablets as in-vehicle CPU

iRobot Create as vehicles



USRP B210 boards as DSRC radios

OnCAR in VSmart: Adaptive Cruise Control

Existing ACC systems:

- Based on radar and cameras
- Perform poorly under bad weather and at night

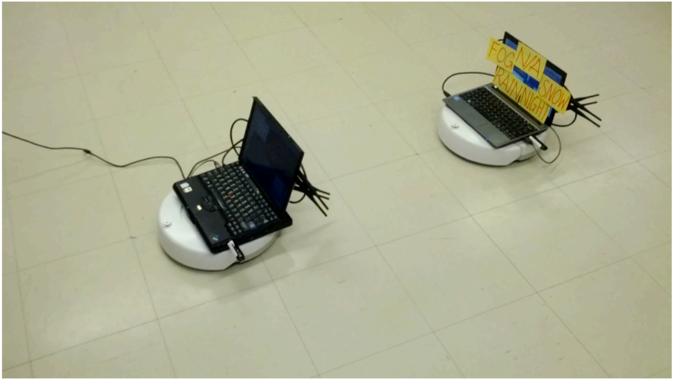
OnCAR in VSmart: Adaptive Cruise Control

To simulate these weather conditions:

- Block the webcam of the laptop

OnCAR in VSmart: Adaptive Cruise Control

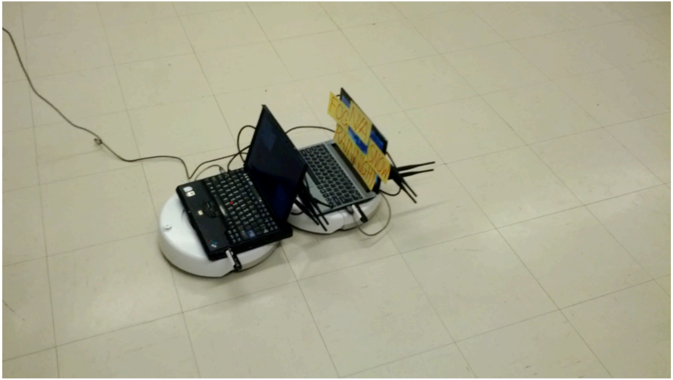
- One vehicle follows the movements of the other



OnCAR in VSmart: Adaptive Cruise Control

Existing ACC under bad weather

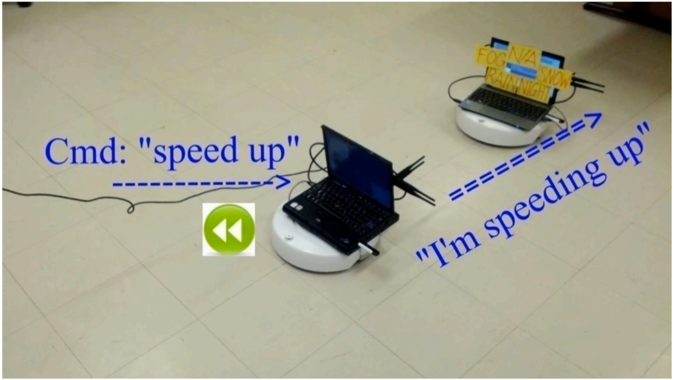
- Two vehicles crashed



OnCAR in VSmart: Adaptive Cruise Control

ACC with baseline DSRC

- The leader sends movement commands to the follower via DSRC



OnCAR in VSmart: Adaptive Cruise Control

ACC with baseline DSRC

- The follower repeats the same movements when receiving commands via DSRC

OnCAR in VSmart:: Adaptive Cruise Control

ACC with baseline DSRC

- Only **four out of ten** commands were received.

OnCAR in VSmart: Adaptive Cruise Control

ACC with OnCAR

- All ten movement commands were received successfully

Data Preference: A New Perspective of Safety Data Dissemination

- Vehicles show the following preferences when collecting safety data:
  - **Spatial preference**: the closer, the better;
  - **Temporal preference**: the newer, the better;
  - **Type preference**: the more important, the better.

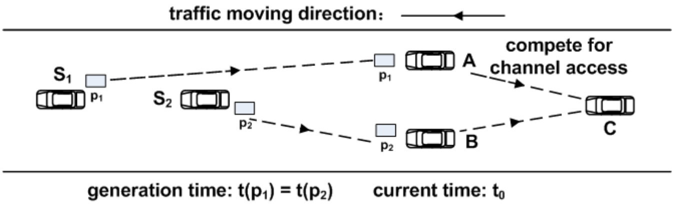


Figure: Spatial Preference

Data Preference: A New Perspective of Safety Data Dissemination

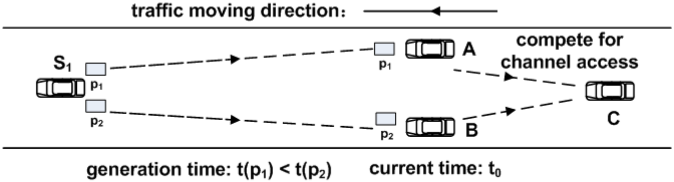


Figure: Temporal Preference

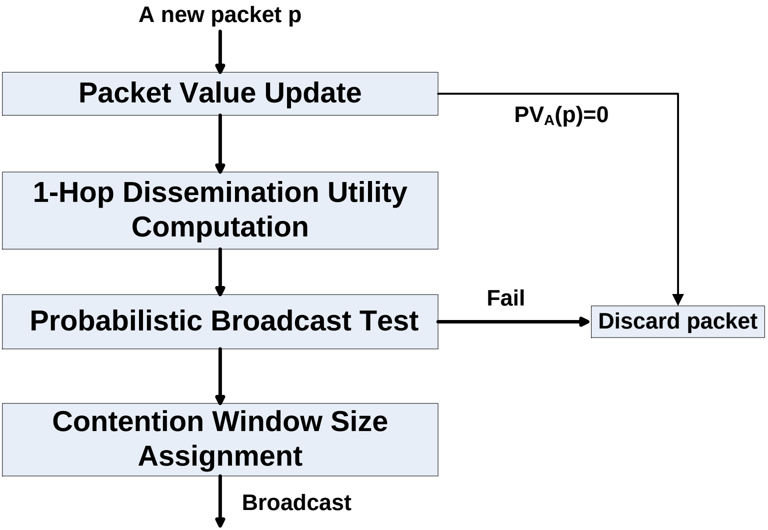
- Quantify these preferences on a per-packet level

  Packet Value = Spatial Value × Temporal Value × Type Value.

- Given a packet p, its **packet-value** for vehicle v:

$$PV_v(p) = S_v(p) \cdot T_v(p) \cdot W_p.$$

PVCast: a Packet-Value-Based Dissemination Protocol



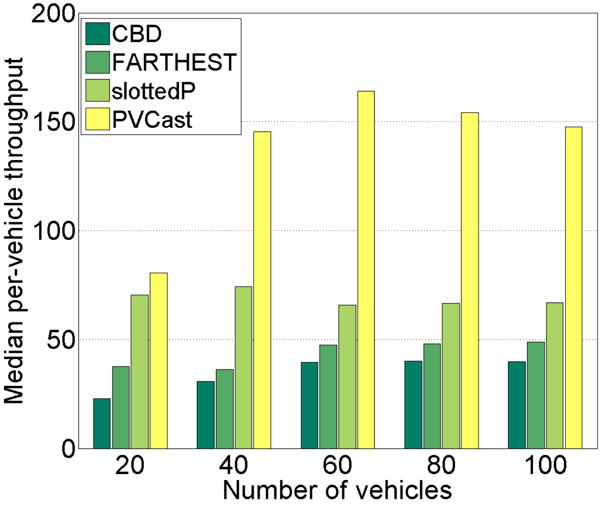
Simulation on Highway Scenario

Performance Metrics

- Per-Vehicle Throughput
- Broadcast Rate
- Broadcast Efficiency
- Per-Packet Delivery Delay
- Per-Packet Vehicle Coverage
- Per-Vehicle Emergency Throughput

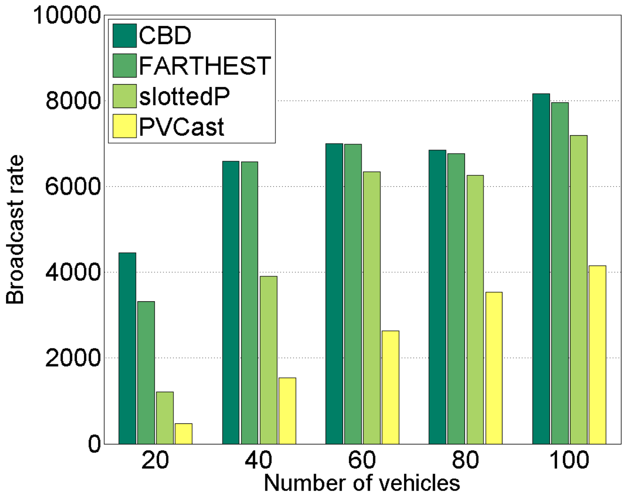
Simulation Results

Per-Vehicle Throughput



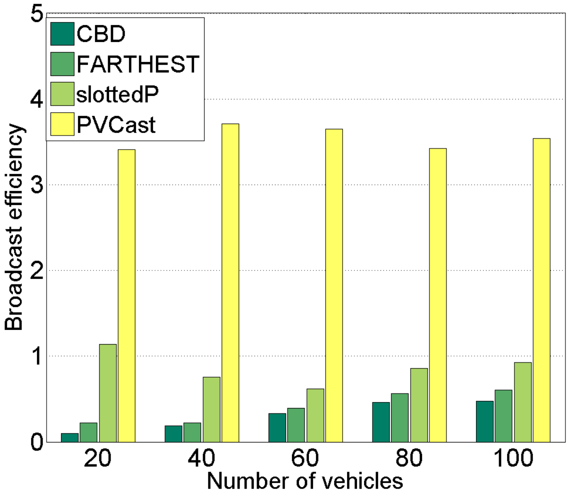
Simulation Results

Broadcast Rate



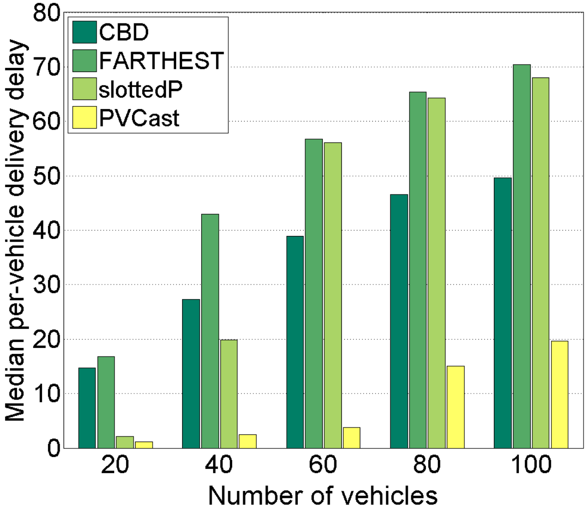
Simulation Results

Broadcast Efficiency



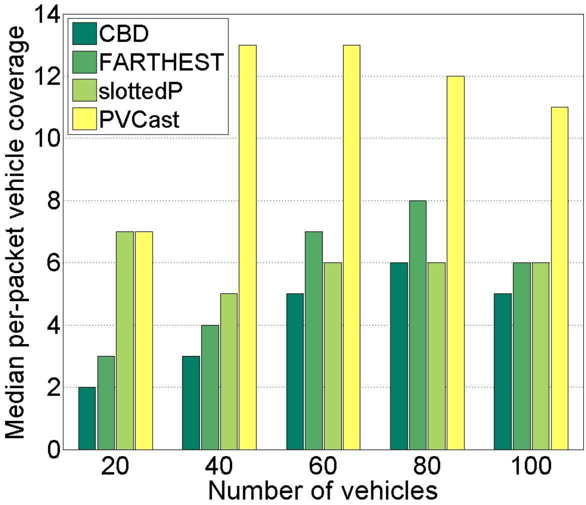
Simulation Results

Per-Packet Delivery Delay



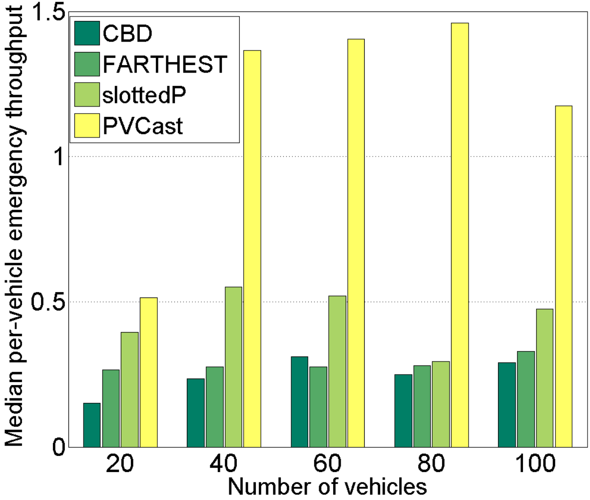
Simulation Results

Per-Packet Vehicle Coverage



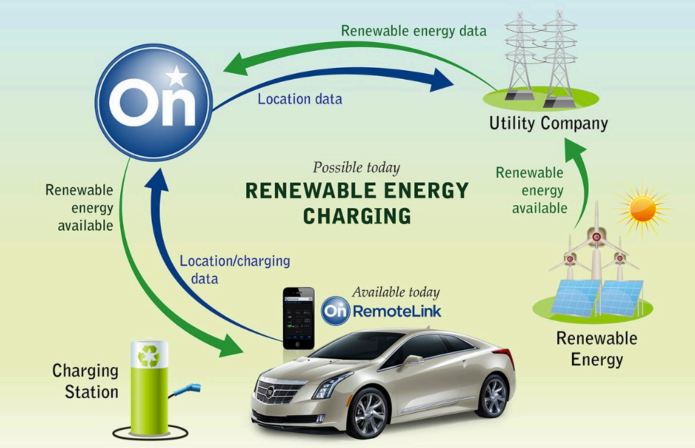
Simulation Results

Per-Vehicle Emergency Throughput



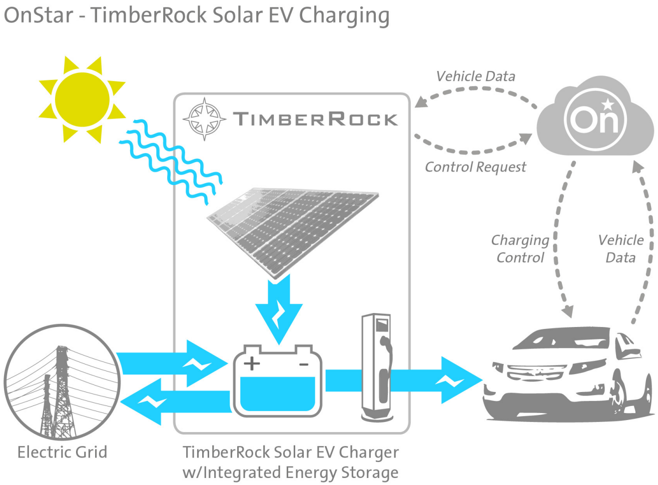
Outline

Electric-Vehicle-Integrated Smart Grid



Source: *www.gm.com*

Electric-Vehicle-Integrated Smart Grid



Source: *www.timberrockes.com*

Electric-Vehicle-Integrated Smart Grid

Challenges for EV-integrated Smart Grid

- Unpredictable supply and demand
- Limited information exchange between supplier and consumer
- Lack of efficient market mechanism

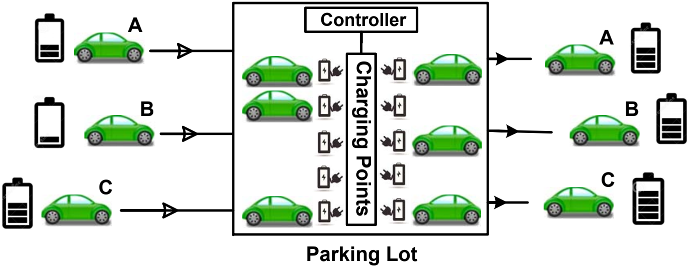
Electric-Vehicle-Integrated Smart Grid

To cope with these challenges, we leverage a reliable vehicle-to-infrastructure communication system, e.g., OnStar, and

- design an online auction mechanism for EV park-and-charge [5]
- develop distributed charging scheduling algorithm for EV park-and-charge [2]
- design demand-response-based optimal operation strategy for commercial EV charging stations [6]

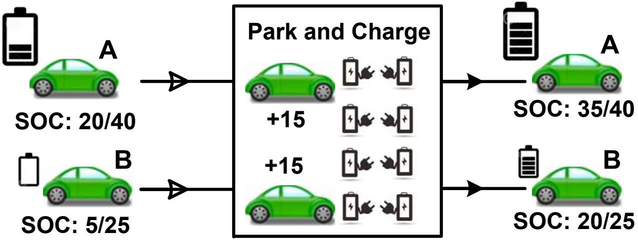
An Online Auction Framework for EV Park-and-Charge

Park-and-Charge



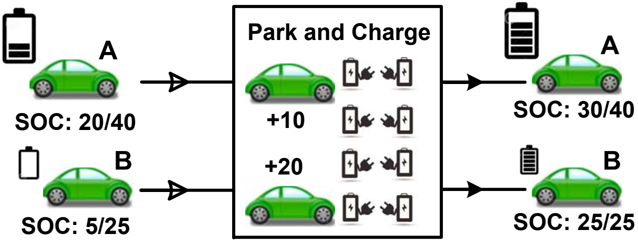
An Online Auction Framework for EV Park-and-Charge

Inefficient Electricity Allocation



An Online Auction Framework for EV Park-and-Charge

Efficient Electricity Allocation



An Online Auction Framework for EV Park-and-Charge

Auc2Charge Framework

- Customers send their bids, i.e., how much money to charge how much electricity, to charging station via smart phone/tablet
- Charging station decides how to allocate the electricity and how to charge customer using approximated algorithm of binary integer programming

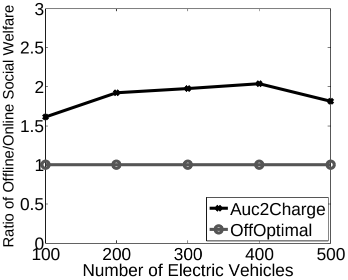
An Online Auction Framework for EV Park-and-Charge

Properties of Auc2Charge

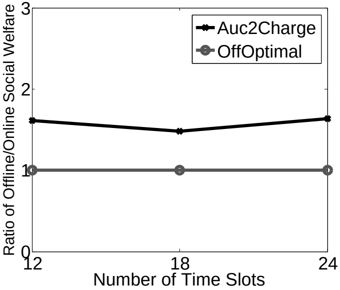
- Truthful: customers' dominant strategy is to bid truthfully
- Individual Rational: every customer gets a non-negative utility
- Computational Efficient: auction runs in polynomial time
- Social Welfare Guarantee: explicit approximation ratio

An Online Auction Framework for EV Park-and-Charge

Simulation Result: Social Welfare



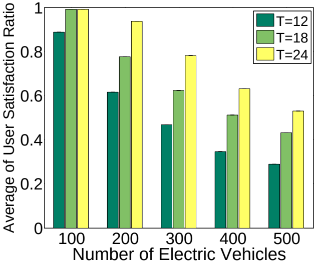
(a) $T = 12$



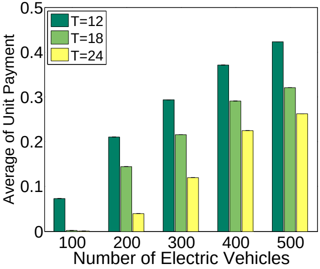
(b) 100 Electric Vehicles

An Online Auction Framework for EV Park-and-Charge

Simulation Result: User Satisfaction



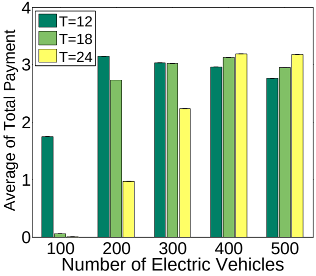
(c) User Satisfaction Ratio



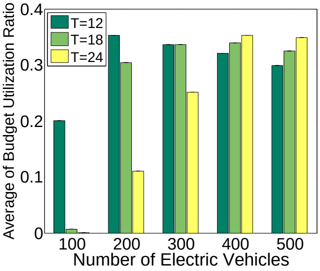
(d) Unit Charing Payment

An Online Auction Framework for EV Park-and-Charge

Simulation Result: User Satisfaction



(e) Total Charging Payment



(f) Budget Utilization Ratio

Outline

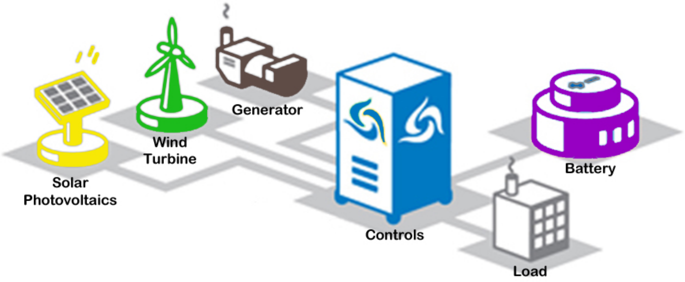
Future CPS Research and College Education

What is the Future of Cyber-Physical Systems?

Research Opportunities CPS Research

Exploration of larger physical space in CPS design,

- Example: joint scheduling of generation and deferrable load in micro grid

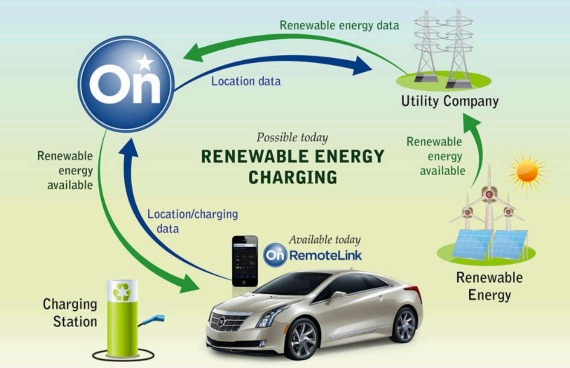


Source: *www.civicsolar.com*

Research Opportunities CPS Research

Interaction between different CPS

- Example: connecting ITS and Smart Grid through EV



Source: *www.gm.com*

Research Opportunities CPS Research

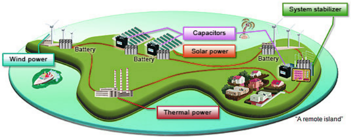
Data Security and Privacy

- Example: develop unified differential privacy solution for data management in CPS

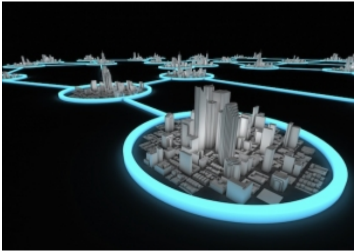
Research Opportunities CPS Research

Efficient Market Mechanism

- Example: mechanism design for microgrid-based electricity market



(g) Single Microgrid

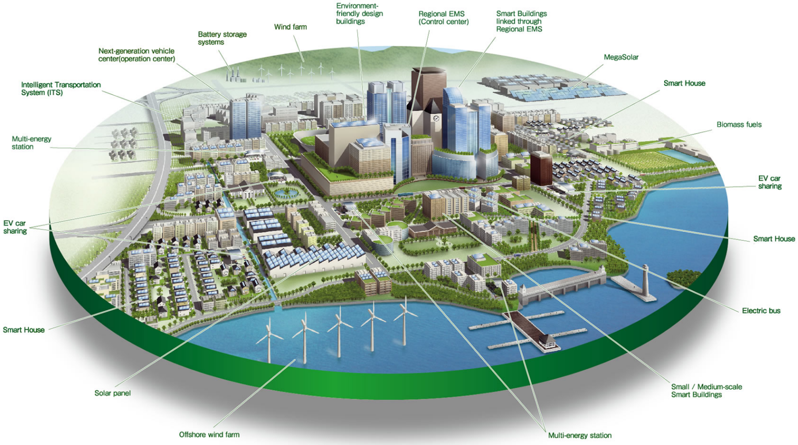


(h) Many Microgrids

Source: *ourenergypolicy.org*

Next Milestone of CPS

Smart City



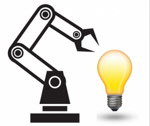
Source: *holyroodconnect.com*

CPS-Related Curriculum Developing

Core CPS Courses

- Computer Networks
- Wireless (Sensor) Networks
- Control Theory
- Real-Time Systems






Sources: *galwaycartridge.ie*, *osu.edu*, *nielsentechnologies.com*, *umass.edu*

CPS-Related Curriculum Developing

Future CPS education requires a curriculum with multi-disciplinary courses

- Data Science
  - Machine Learning, Data Security and Privacy and etc
- Mathematic
  - Convex Optimization, Stochastic Optimization and etc
- Economics
  - Algorithmic Game Theory, Behavior Economics and etc
- Social Science
  - Social Psychology and etc

Outline

Concluding Remarks

- Review our recent findings in enabling real-time, reliable and efficient service for WCPS
  - Wireless Networked Sensing and Control
  - Intelligent Transportation Systems
  - EV-integrated Smart Grid
- Future Research on CPS → Smart City
- A multi-disciplinary curriculum for CPS education

Thank you!

Outline

List of Publications I

Xi Chen, Linghe Kong, Xue Liu, Lei Rao, Fan Bai, and Qiao Xiang.
Oncar: Online adaptive control of transmission power and data rate for vehicular communications, under review.
2015.

Fanxin Kong, Qiao Xiang, Linghe Kong, Jing Chen, and Xue Liu.
On-line scheduling for electric vehicle charging in park and charge systems, under review.
2015.

Qiao Xiang.
In-network processing for mission-critical wireless networked sensing and control: A real-time, efficiency, and resiliency perspective.
PhD Dissertation, Wayne State University.

Qiao Xiang, Xi Chen, Linghe Kong, Lei Rao, and Xue Liu.
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In *ACM sixth International Conference on Future Energy Systems, e-Energy 2015, Bangalore, India, July 14th - 17th, 2015*, 2015.

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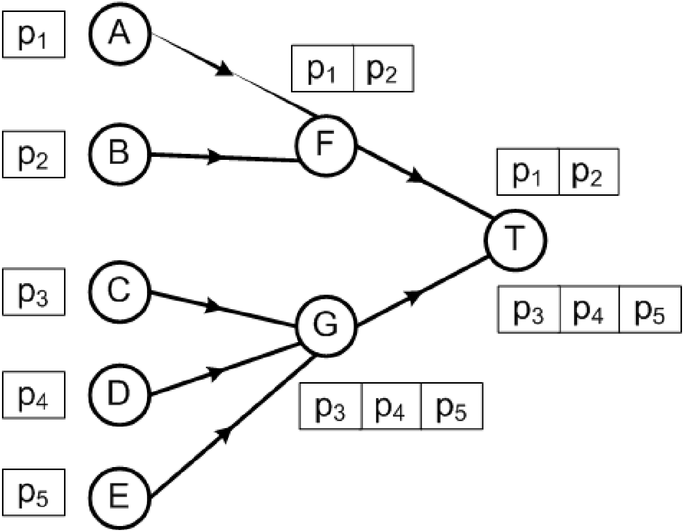
List of Publications III

Qiao Xiang, Hongwei Zhang, Jinhong Xu, Xiaohui Liu, and L.J. Rittle.
When in-network processing meets time: Complexity and effects of joint optimization in wireless sensor networks.
Mobile Computing, IEEE Transactions on, 10(10):1488 –1502, oct. 2011.

Real-time packet packing scheduling



Real-time packet packing scheduling

System Model

- A directed collection tree $T = (V, E)$
- Edge $(v_i, v_j) \in E$ with weight $ETX_{v_i,v_j}(l)$
- A set of information elements $X = \{x\}$
- Each element $x : (v_x, l_x, r_x, d_x)$

Problem (P)

- Schedule the transmission of X to R
- Minimize the total number of transmissions
- Satisfy the latency constraints of each $x \in X$

Computational Complexity

Problem P_0

- Elements are of equal length
- Each node has at most one element

Problem P_1

- Elements are of equal length
- Each node generates elements periodically

Problem P_2

- Elements are of equal length
- Arbitrary data generating pattern

Computational Complexity

P_0, P_1, P_2, P	$K \geq 3$	$K = 2$	
		re-aggregation is not prohibited	re-aggregation is prohibited
Complexity	strongly NP-hard	strongly NP-hard	$O(N^3)$
NP-hard to achieve approximation ratio	$1 + \frac{1}{200N}(1 - \frac{1}{\epsilon})$	$1 + \frac{1}{120N}(1 - \frac{1}{\epsilon})$	

$K =$ Maximal packet length $N = |X|$

Re-aggregation: a packed packet can be dispatched for further packing

tPack: A Utility-Based Online Scheduling Algorithm

When a node receives a packet *pkt* with length s_f

- Decisions: to hold or to transmit immediately
- Utility of action: Reduced Amortized Cost
- One-hop locality

$$AC = \frac{\text{\# of TX}}{\text{length of data}}$$

Decision Rule

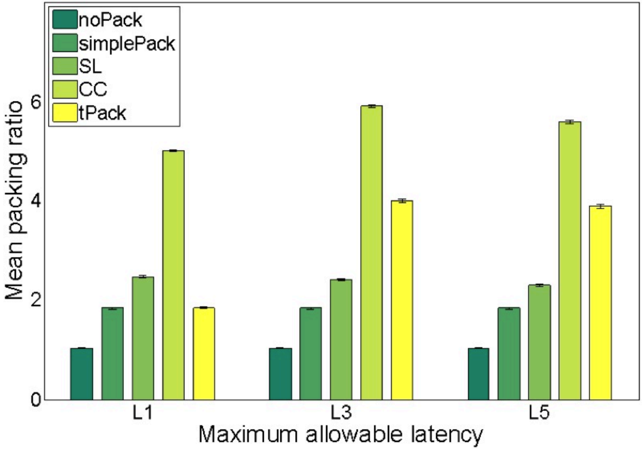
- The packet should be immediately transmitted if $U_p > U_l$
- The packet should be held if $U_p \leq U_l$

Performance evaluation

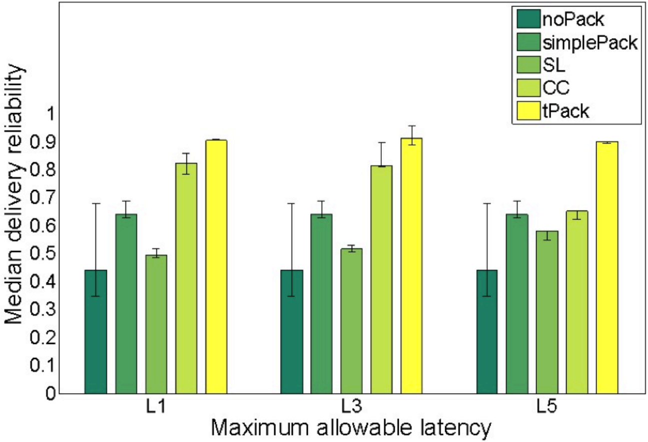
Experiment setting up

- Testbed: NetEye, a 130-sensor testbed at Wayne State University
- Topology: 120 nodes, half are source nodes, 1 sink node
- Protocols compared: noPacking, simplePacking, spreaded latency, common clock, *tPack*
- Traffic patterns: periodic traffic and event traffic
- Metrics: packing ratio, delivery reliability, delivery cost, deadline catching ratio and latency jitter

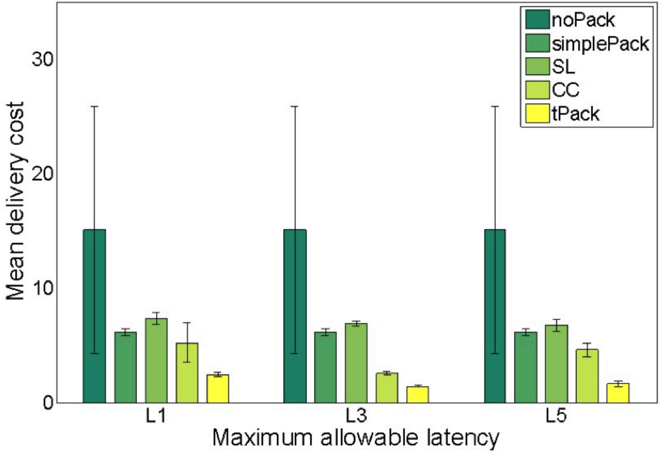
3-second periodic traffic: packing ratio



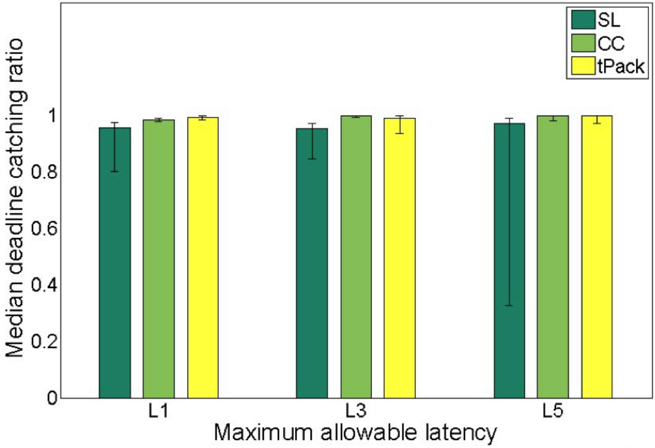
3-second periodic traffic: delivery reliability



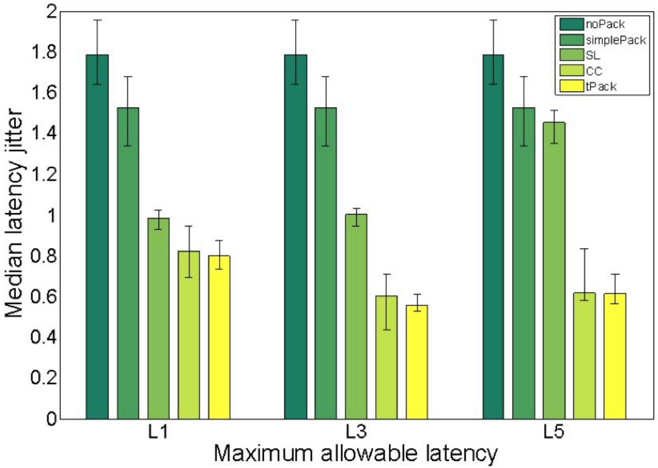
3-second periodic traffic: delivery cost



3-second periodic traffic: deadline catching ratio



3-second periodic traffic: latency jitter



Computational Complexity

When $K \geq 3$ and T is a tree, regardless of re-aggregation

- P_0 is NP-hard $\rightarrow$ P_1 is NP-hard $\rightarrow$ P_2 is NP-hard $\rightarrow$ P is NP-hard

When $K \geq 3$ and T is a chain, regardless of re-aggregation

- The reduction from SAT problem still holds*

When $K = 2$ and re-aggregation is not prohibited

- The reduction from SAT problem still holds in both tree and chain structures

When $K = 2$ and re-aggregation is prohibited

- Problem P is equivalent to the maximum weighted matching problem in an interval graph
- Solvable in $O(N^3)$ by Edmond's Algorithm

*: This solves an open problem in batch process

Competitive Ratio of tPack

- Problem P'
  - T is a complete tree
  - Leaf nodes generate elements at a common rate
- Theorem: For problem P', *tPack* is $min\{K, max_{v_j \in V_{>1}} \frac{2ETX_{v_jR}}{2ETX_{v_jR} - ETX_{p_jR}}\}$-competitive, where K is the maximum number of information elements that can be packed into a single packet, $V_{>1}$ is the set of nodes that are at least two hops away from the sink R.
- Example: When ETX is the same for each link, *tPack* is 2-competitive.

A mathematical framework for cost of NC-based routing

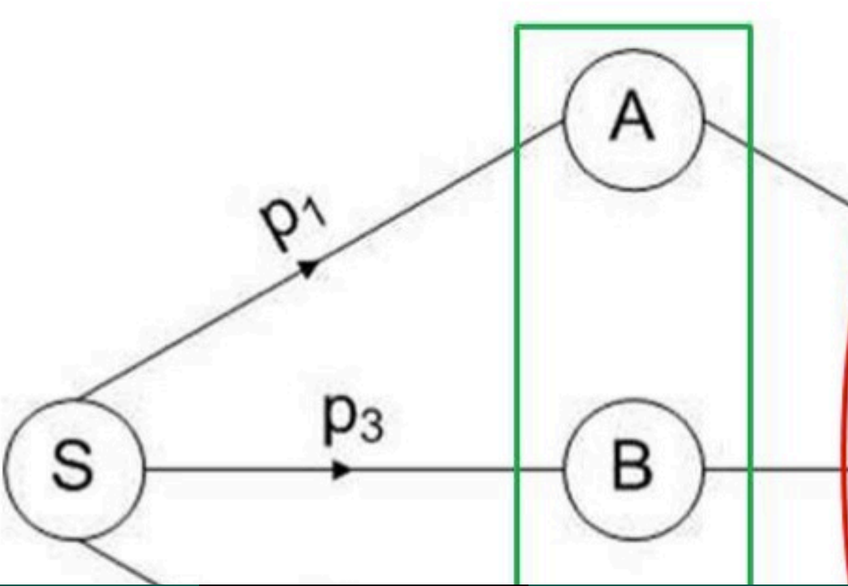
Definition

For a node j in the forwarder candidate set FCS_i, the **effective load** L_j is defined as the number of linear independent packets received by j but none of the nodes in FCS_i that has lower transmission cost to the destination.

How does the framework work?

1. Define the whole forwarder set as a virtual node V_S
2. Compute the transmission cost from the S to V_S
3. Sort forwarders in non-descending order of their transmission cost
4. Each forwarder only forwards its effective load with corresponding cost
5. Sum up all transmission cost

An example



$$C_{SD_S}(K) = \frac{K}{P_{SV_{D_S}}} = \frac{K}{1-(1-P_1)(1-P_3)(1-P_5)}$$

$$K_A^S = \frac{KP_1}{1-(1-P_1)(1-P_3)(1-P_5)}$$

$$K_B^S = \frac{KP_3}{1-(1-P_1)(1-P_3)(1-P_5)}$$

$$K_C^S = \frac{KP_5}{1-(1-P_1)(1-P_3)(1-P_5)}$$

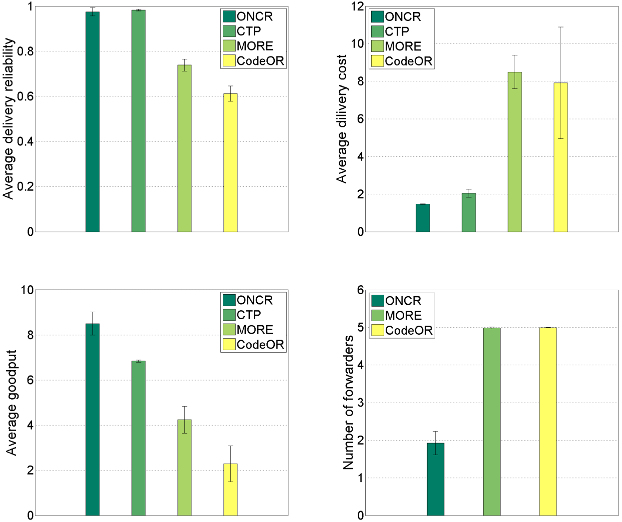
$$L_A = K_A^S$$

$$L_B = K_B^{S'} = K\frac{K_B^S}{K}(1-P_1) = K_B^S(1-P_1)$$

$$L_C = K_C^{S'} = K_C^S(1-P_1)(1-P_3)$$

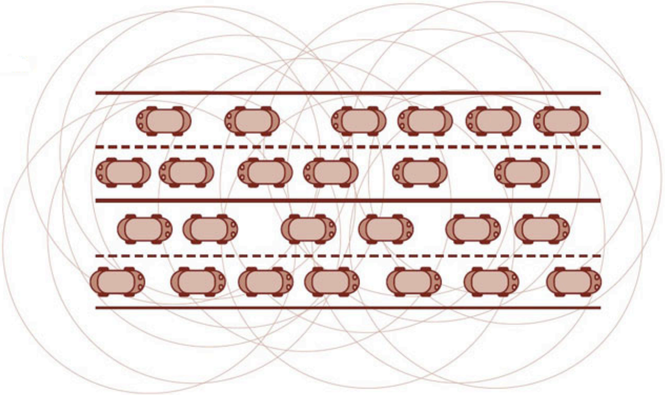
$$
\begin{aligned}
C_S(K) &= C_{SD_S}(K) + C_{AT}(L_A) + C_{BT}(L_B) + C_{CT}(L_C) \\
&= \frac{K}{1-(1-P_1)(1-P_3)(1-P_5)} \\
&\quad + \frac{L_A}{P_2} + \frac{L_B}{P_4} + \frac{L_C}{P_6} \\
&= \frac{K}{1-(1-P_1)(1-P_3)(1-P_5)} \\
&\quad \cdot [1 + \frac{P_1}{P_2} + \frac{P_3(1-P_1)}{P_4} + \frac{P_5(1-P_1)(1-P_3)}{P_6}]
\end{aligned}
$$

20-source


Average delivery reliability
1
0.8
0.6
0.4
0.2
0
ONCR
CTP
MORE
CodeOR
Average dilivery cost
12
10
8
6
4
2
0
ONCR
CTP
MORE
CodeOR
Average goodput
10
8
6
4
2
0
ONCR
CTP
MORE
CodeOR
Number of forwarders
6
5
4
3
2
1
0
ONCR
MORE
CodeOR

Broadcast Storm

Severe “broadcast storm” would jeopardize the QoS of

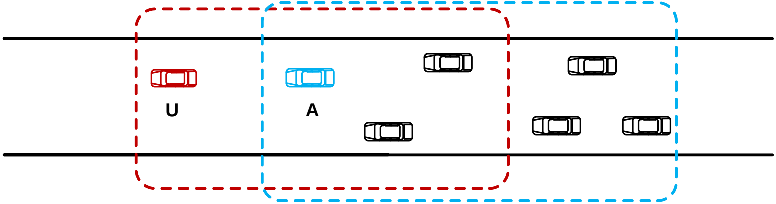


source: *accessmagazine.org*

1-Hop Dissemination Utility

$$\text{Utility} = \text{Packet Value} \times \text{Effective Dissemination Coverage.}$$

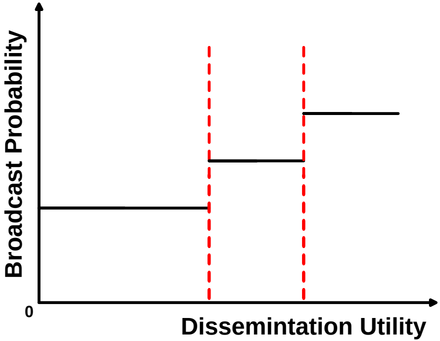
Effective Dissemination Coverage



$$edc_A(p) = 5 - 2 = 3$$

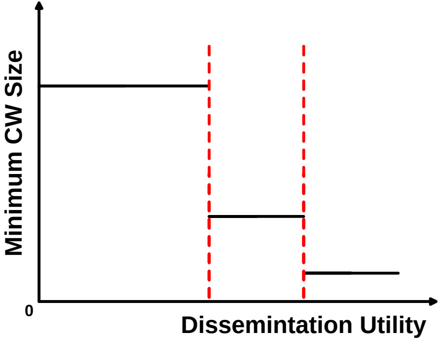
Probabilistic Broadcast Test

- Piecewise function of dissemination utility
- Higher dissemination utility
  → Higher chance for broadcasting

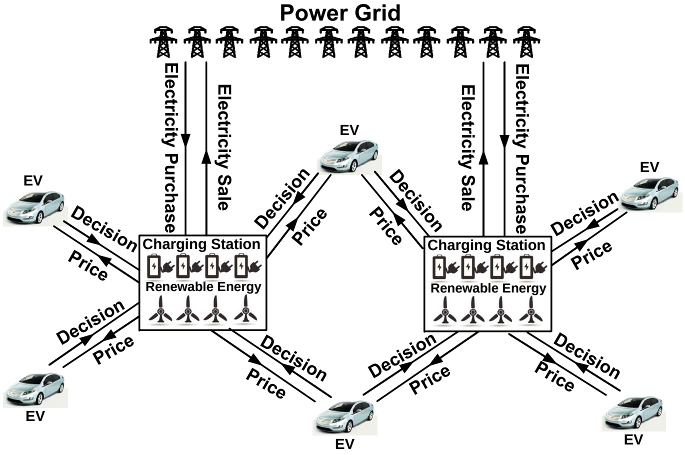


Contention Window Size Assignment

- Piecewise function of dissemination utility
- Higher dissemination utility
  $\rightarrow$ Smaller minimum CW size
  $\rightarrow$ Higher priority to get channel access



Green Revenue: Demand-Response-Based Charging Station



Event-Driven Scheduling for EV Park-and-Charge