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

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Outline

1. Introduction
2. Wireless Networked Sensing and Control
3. Intelligent Transportation Systems
4. Electric-Vehicle-Integrated Smart Grid
5. Future CPS Research and College Education
6. Concluding Remarks
7. List of Publications
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
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Wireless sensor networks + Close-loop control

Various mission-critical applications
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
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

\[ \{1, 2, 3\} = X_1 + 2X_2 + 3X_3 \]
\[ \{1, 1, 1\} = X_1 + X_2 + X_3 \]

\[ K=3 \]
\[ \{1, 0, 0\} = X_1 \]
\[ \{0, 1, 0\} = X_2 \]
\[ \{0, 0, 1\} = X_3 \]

\[ \{2, 3, 4\} = 2X_1 + 3X_2 + 4X_3 \]
\[ \{3, 5, 10\} = 3X_1 + 5X_2 + 10X_3 \]

\[ \{3, 4, 6\} = 3X_1 + 4X_2 + 6X_3 \]

\[ \{2, 3, 5\} = 2X_1 + 3X_2 + 5X_3 \]
\[ \{1, 1, 1\} = X_1 + X_2 + X_3 \]
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 \( \{A_1, A_2\} \)

\[
C_{\{A_1, A_2\}} = \frac{1}{1 - (1 - 0.1)(1 - 0.15)} \cdot [1 + \frac{0.1}{0.4} + \frac{0.15(1 - 0.1)}{0.2}]
\]

\[
= \frac{1}{0.235} \cdot (1 + \frac{1}{4} + \frac{0.135}{0.2})
\]

\[
= 8.1915
\]

\[
C_{\{A_1, A_2, A_3\}} = \frac{1}{1 - (1 - 0.1)(1 - 0.15)(1 - 0.9)} \cdot [1 + \frac{0.1}{0.4} + \frac{0.15(1 - 0.1)}{0.2} + \frac{0.9(1 - 0.1)(1 - 0.15)}{0.1}]
\]

\[
= \frac{1}{0.9235} \cdot (1 + \frac{1}{4} + \frac{0.135}{0.2} + \frac{0.6885}{0.1})
\]

\[
= 9.5398 > C_{\{A_1, A_2\}}
\]
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.
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

![Average delivery reliability chart]

- ONCR
- CTP
- MORE
- CodeOR
10-source: delivery cost

![Bar chart showing delivery cost comparison for different methods: ONCR, CTP, MORE, and CodeOR. The chart displays the average delivery cost across different methods, with MORE significantly outperforming the others.]
10-source: goodput
10-source: routing diversity

Number of forwarders

- ONCR
- MORE
- CodeOR
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A smarter and safer transport networks

Source: U.S.DOT
Vehicle-to-Vehicle (V2V) Communication

- Communication infrastructure for Intelligent Transportation Systems (ITS)
V2V Safety Data Dissemination

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

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

(c) Collision Avoidance  
(d) Lane Change
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.
Challenges for DSRC

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

- Based on radar and cameras
- Perform poorly under bad weather and at night
To simulate these weather conditions:

- Block the webcam of the laptop
• One vehicle follows the movements of the other
Existing ACC under bad weather

- Two vehicles crashed
ACC with baseline DSRC

- The leader sends movement commands to the follower via DSRC
ACC with baseline DSRC

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

- Only four out of ten commands were received.
ACC with OnCAR

- All ten movement commands were received successfully

No crash! Reliable!
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
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 $v$:

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

Packet Value Update

1-Hop Dissemination Utility Computation

Probabilistic Broadcast Test

Contention Window Size Assignment

Broadcast

$PVA(p) = 0$

Fail

Discard packet
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

- CBD
- FARTHEST
- slottedP
- PVCast

Median per-vehicle throughput vs. Number of vehicles:
- 20 vehicles: CBD ~ 15, FARTHEST ~ 65, slottedP ~ 50, PVCast ~ 70
- 40 vehicles: CBD ~ 30, FARTHEST ~ 110, slottedP ~ 80, PVCast ~ 100
- 60 vehicles: CBD ~ 45, FARTHEST ~ 150, slottedP ~ 95, PVCast ~ 120
- 80 vehicles: CBD ~ 60, FARTHEST ~ 180, slottedP ~ 105, PVCast ~ 130
- 100 vehicles: CBD ~ 75, FARTHEST ~ 200, slottedP ~ 110, PVCast ~ 140
Simulation Results

Broadcast Rate

- CBD
- FARTHEST
- slottedP
- PVCast

Broadcast rate vs. Number of vehicles for different broadcast rates.
Simulation Results

Broadcast Efficiency

![Bar Chart]

- **CBD**
- **FARTHEST**
- **slottedP**
- **PVCast**

**Y-axis:** Broadcast efficiency

**X-axis:** Number of vehicles

Values:
- 20 vehicles: CBD = 0.5, FARTHEST = 1.5, slottedP = 2.0, PVCast = 3.0
- 40 vehicles: CBD = 1.0, FARTHEST = 2.0, slottedP = 2.5, PVCast = 3.5
- 60 vehicles: CBD = 1.5, FARTHEST = 2.5, slottedP = 3.0, PVCast = 4.0
- 80 vehicles: CBD = 2.0, FARTHEST = 3.0, slottedP = 3.5, PVCast = 4.5
- 100 vehicles: CBD = 2.5, FARTHEST = 3.5, slottedP = 4.0, PVCast = 5.0
Simulation Results

Per-Packet Delivery Delay

- CBD
- FARTHEST
- slottedP
- PVCast

- Median per-vehicle delivery delay
- Number of vehicles: 20, 40, 60, 80, 100

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Per-Packet Vehicle Coverage

- CBD
- FARTHEST
- slottedP
- PVCast

Median per-packet vehicle coverage vs. Number of vehicles:
- 20 vehicles: CBD < FARTHEST < slottedP < PVCast
- 40 vehicles: CBD < FARTHEST < slottedP < PVCast
- 60 vehicles: CBD < FARTHEST < slottedP < PVCast
- 80 vehicles: CBD < FARTHEST < slottedP < PVCast
- 100 vehicles: CBD < FARTHEST < slottedP < PVCast
Simulation Results

Per-Vehicle Emergency Throughput

![Simulation Results Chart]

- CBD
- FARTHEST
- slottedP
- PVCast

**Graph Details:**
- **Y-axis:** Median per-vehicle emergency throughput
- **X-axis:** Number of vehicles (20, 40, 60, 80, 100)

**Legend:**
- CBD: Green
- FARTHEST: Yellow
- slottedP: Light Green
- PVCast: Dark Green

**Insights:**
- PVCast consistently shows the highest throughput across all vehicle numbers.
- CBD has the lowest throughput compared to other methods.
- The throughput increases with the number of vehicles.
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Electric-Vehicle-Integrated Smart Grid

Source: www.gm.com
OnStar - TimberRock Solar EV Charging

Electric Grid

TimberRock Solar EV Charger w/Integrated Energy Storage

Vehicle Data

Control Request

Charging Control

Vehicle Data

Source: www.timberrockes.com
Challenges for EV-integrated Smart Grid

- Unpredictable supply and demand
- Limited information exchange between supplier and consumer
- Lack of efficient market mechanism
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]
Park-and-Charge
Inefficient Electricity Allocation

SOC: 20/40
SOC: 5/25
SOC: 20/40
SOC: 35/40
SOC: 20/25
+15
+15
Park and Charge

A
B
A
B
Efficient Electricity Allocation

- SOC: 20/40
- SOC: 5/25
- SOC: 30/40
- SOC: 25/25

Park and Charge

- +10
- +20

A

B

A

B
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
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
Simulation Result: Social Welfare

(a) $T = 12$

(b) 100 Electric Vehicles
Simulation Result: User Satisfaction

(c) User Satisfaction Ratio

(d) Unit Charging Payment
Simulation Result: User Satisfaction

(e) Total Charging Payment

(f) Budget Utilization Ratio
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What is the Future of Cyber-Physical Systems?
Exploration of larger physical space in CPS design,

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

Source: www.civicsolar.com
Interaction between different CPS

- Example: connecting ITS and Smart Grid through EV

Source: www.gm.com

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Data Security and Privacy

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

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Core CPS Courses

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

Sources: galwaycartridge.ie, osu.edu, nielsentechnologies.com, umass.edu
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
Concluding Remarks

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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!
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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, Fanxin Kong, Xi Chen, Lei Rao, and Xue Liu. Green revenue from green energy: A brokers perspective of electric vehicle charging stations, under review. 2015.


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 \( x \in X \)
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
<table>
<thead>
<tr>
<th>$P_0, P_1, P_2, P$</th>
<th>$K \geq 3$</th>
<th>$K = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>strongly NP-hard</td>
<td>strongly NP-hard</td>
</tr>
<tr>
<td></td>
<td>$1 + \frac{1}{200N} (1 - \frac{1}{\epsilon})$</td>
<td>$1 + \frac{1}{120N} (1 - \frac{1}{\epsilon})$</td>
</tr>
</tbody>
</table>

$K = \text{Maximal packet length}$

$N = |X|$

Re-aggregation: a packed packet can be dispatched for further packing
When a node receives a packet $\text{pkt}$ with length $s_f$

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

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

**Decision Rule**

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

![Graph showing packing ratio vs maximum allowable latency]

- noPack
- simplePack
- SL
- CC
- tPack

Mean packing ratio

Maximum allowable latency:
- L1
- L3
- L5
3-second periodic traffic: delivery reliability

![Bar chart showing median delivery reliability for different maximum allowable latencies (L1, L3, L5). The chart compares different packing methods: noPack, simplePack, SL, CC, tPack.]{:width=1000}
3-second periodic traffic: delivery cost

![Graph showing mean delivery cost vs. maximum allowable latency]

- **noPack**
- **simplePack**
- **SL**
- **CC**
- **tPack**

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3-second periodic traffic: deadline catching ratio

![Bar graph showing median deadline catching ratio for SL, CC, and tPack across L1, L3, and L5 latency levels.](image)
3-second periodic traffic: latency jitter

![Graph showing latency jitter](graph.png)
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
Problem $P'$

- $T$ is a complete tree
- Leaf nodes generate elements at a common rate

Theorem: For problem $P'$, $tPack$ is $\min\{K, \max_{v_j \in V_{>1}} \frac{2\text{ETX}_{v_jR}}{2\text{ETX}_{v_jR} - \text{ETX}_{p_jR}}\}$-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 $\text{ETX}$ 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
\[ C_{SD_S}(K) = \frac{K}{P_{SV_{DS}}} = \frac{K}{1 - (1 - P_1)(1 - P_3)(1 - P_5)} \]

\[ K_S^A = \frac{KP_1}{1 - (1 - P_1)(1 - P_3)(1 - P_5)} \]
\[ K_S^B = \frac{KP_3}{1 - (1 - P_1)(1 - P_3)(1 - P_5)} \]
\[ K_S^C = \frac{KP_5}{1 - (1 - P_1)(1 - P_3)(1 - P_5)} \]

\[ L_A = K_S^A \]
\[ L_B = K_{B}^S' = K \frac{K_S^B}{K} (1 - P_1) = K_S^B (1 - P_1) \]
\[ L_C = K_{C}^S' = K_C^S (1 - P_1)(1 - P_3) \]
\[ C_S(K) = C_{SDS}(K) + C_{AT}(L_A) + C_{BT}(L_B) + C_{CT}(L_C) \]

\[ = \frac{K}{1 - (1 - P_1)(1 - P_3)(1 - P_5)} \]

\[ + \frac{L_A}{P_2} + \frac{L_B}{P_4} + \frac{L_C}{P_6} \]

\[ = \frac{K}{1 - (1 - P_1)(1 - P_3)(1 - P_5)} \]

\[ \cdot [1 + \frac{P_1}{P_2} + \frac{P_3(1 - P_1)}{P_4} + \frac{P_5(1 - P_1)(1 - P_3)}{P_6}] \]
Severe “broadcast storm” would jeopardize the QoS of
Utility = Packet Value × 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
  - Smaller minimum CW size
  - Higher priority to get channel access

![Dissemination Utility vs Minimum CW Size Diagram]
Green Revenue: Demand-Response-Based Charging Station

Charging Station

Renewable Energy

Power Grid

Electricity Purchase

Electricity Sale

Decision

Price

EV

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Event-Driven Scheduling for EV Park-and-Charge

(a) A combined zone

(b) Separate zones