In-Network Processing for Mission-Critical Wireless Networked Sensing and Control: A Real-Time, Efficiency, and Resiliency Perspective

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Outline

Outline

Introduction

Wireless Sensor Networks

- Highly resource-constrained

In-Network Processing

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

Mission-Critical Wireless Networked Sensing and Control (WNSC)

- Close-loop control
- More emphasis on end-to-end QoS, especially latency, reliability and resiliency

Introduction

Packet packing

- Application independent INP
- Simple yet useful in practice
    - UWB intra-vehicle control
    - IETF 6LowPAN: high header overhead

Network coding (NC)

- First proposed in wired networks
- Provide benefits on throughput and robustness
- Naturally extended into wireless environment
- Integrated with opportunistic routing, e.g., MORE

Introduction

Our focus

- Explore system benefits of different INP methods
- Joint optimization between INP and QoS
- Temporal and spatial data flow control in WNSC

Our methodology

- Computational complexity study on different optimization problems
- Light-weight algorithm and protocol design
- Theoretical analysis of different algorithms
- Extensive testbed-based experimental evaluation

Introduction

Roadmap

1. Real-time packet packing scheduling
2. Energy-efficient NC-based routing
3. Proactive NC-based protection

Outline

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 $x \in X$

Complexity analysis

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

Complexity analysis

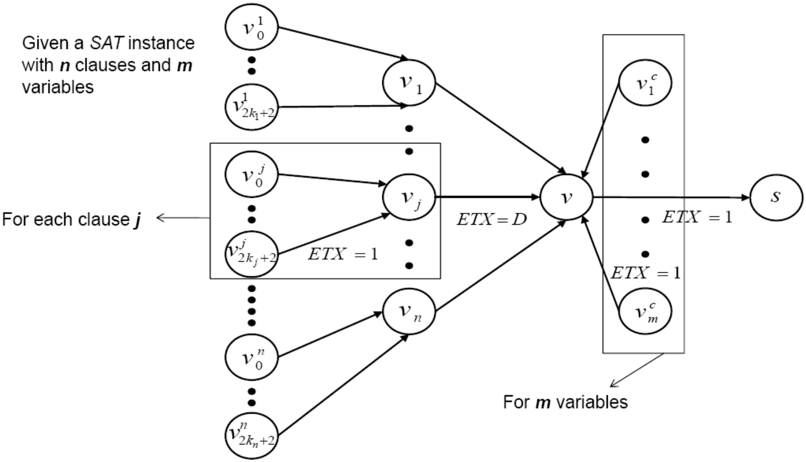
P_0, P_1, P_2, P	$K \geq 3$	$K = 2$	
		re-aggregation is not prohibited	re-aggregation is prohibited
Complexity	strongly NP-hard	strongly NP-hard	$O(N^3)$
NP-hard to achieve approximation ratio	$1+\frac{1}{200N}(1-\frac{1}{\epsilon})$	$1+\frac{1}{120N}(1-\frac{1}{\epsilon})$	

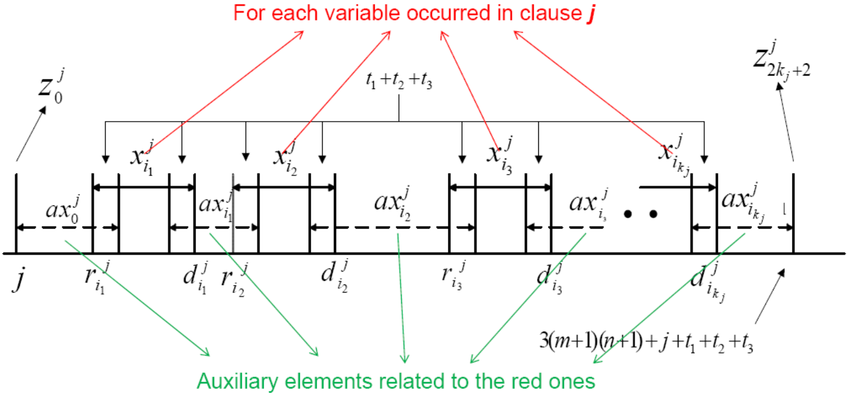
$K =$ Maximal packet length $N = |X|$

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

Complexity analysis

$K \geq 3$, P_0 is NP-hard in tree structures – a reduction from SAT problem




For each variable occurred in clause j
$t_1+t_2+t_3$
z_0^j
$z_{2k_j+2}^j$
$x_{i_1}^j$
$x_{i_2}^j$
$x_{i_3}^j$
$x_{i_{k_j}}^j$
ax_0^j
$ax_{i_1}^j$
$ax_{i_2}^j$
$ax_{i_3}^j$
$ax_{i_{k_j}}^j$
j
$r_{i_1}^j$
$d_{i_1}^j$
$r_{i_2}^j$
$d_{i_2}^j$
$r_{i_3}^j$
$d_{i_3}^j$
$d_{i_{k_j}}^j$
$3(m+1)(n+1)+j+t_1+t_2+t_3$
Auxiliary elements related to the red ones

Complexity analysis

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

A utility based online 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

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

A utility based online algorithm

Utility of holding a packet:

Cost with packing

$$AC'_l = \frac{1}{L - s'_f} ETX_{jR}(L - s'_f) \qquad AC_l = \frac{1}{L - s'_f + S_l} ETX_{jR}(L - s'_f + S_l)$$

Cost without packing

$$U_l = AC'_l - AC_l$$

Utility of transmitting a packet:

$$U'_p = \frac{\frac{t'_f}{t_p} ETX_{p_jR}(s_p)}{\frac{t'_f}{t_p} s_p} - \frac{\frac{t'_f}{t_p} ETX_{p_jR}(L)}{\frac{t'_f}{t_p} L} = \frac{ETX_{p_jR}(s_p)}{s_p} - \frac{ETX_{p_jR}(L)}{L}$$

$$U''_p = \frac{\lceil \frac{L-s'_f}{L-s_p} \rceil ETX_{p_jR}(s_p)}{\lceil \frac{L-s'_f}{L-s_p} \rceil s_p} - \frac{\lfloor \frac{L-s'_f}{L-s_p} \rfloor ETX_{p_jR}(L) + I_{mod} ETX_{p_jR}(s_p + l_{mod})}{\lceil \frac{L-s'_f}{L-s_p} \rceil s_p + L - s'_f}$$

$$U_p = \begin{cases} U'_p & \text{if } \frac{t'_f}{t_p}(L - s_p) \le L - s'_f \\ U''_p & \text{otherwise} \end{cases}$$

Every packet received by parent can get fully packed via ***pkt***

A utility based online algorithm

Decision Rule

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

Competitive Ratio

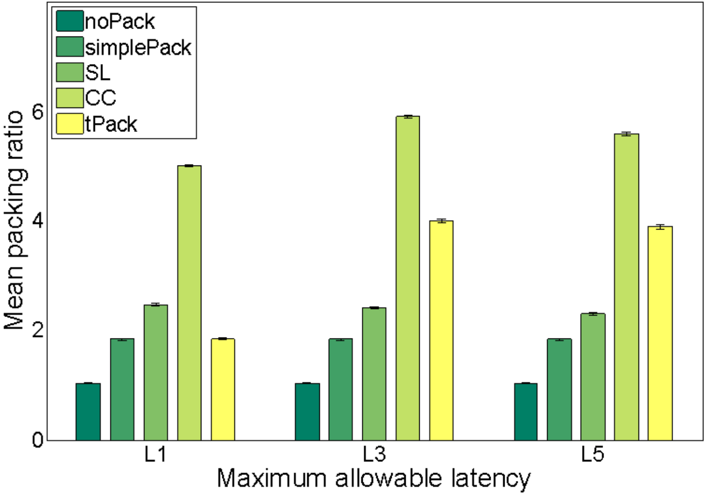
- Problem P'
  - T is a complete tree
  - Leaf nodes generate elements at a common rate
- Theorem: For problem P', *tPack* is $min\{K, max_{v_j \in V_{>1}} \frac{2ETX_{v_j R}}{2ETX_{v_j R} - ETX_{p_j R}}\}$-competitive, where K is the maximum number of information elements that can be packed into a single 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.

Performance evaluation

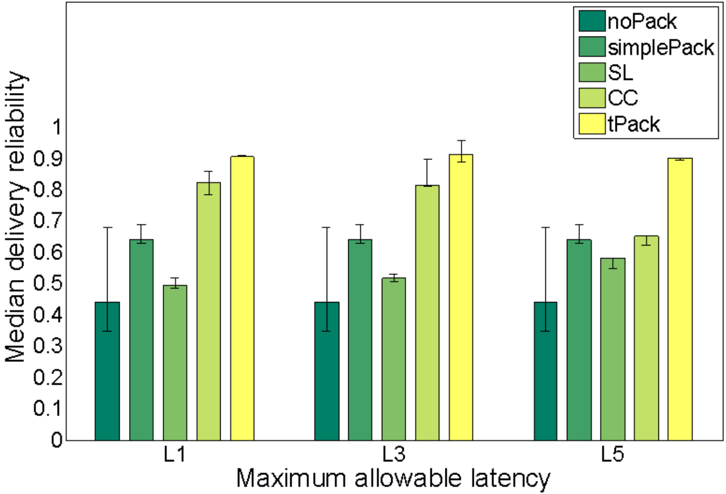
Experiment setting up

- Testbed: NetEye, a 130-sensor testbed (State Hall)
- 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

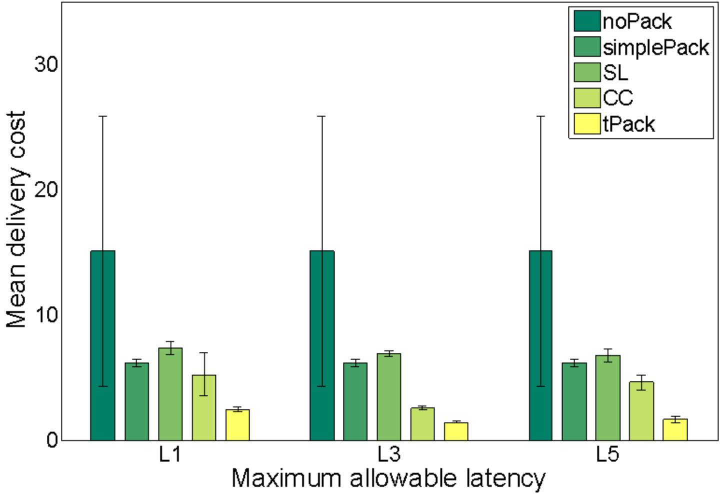
3-second periodic traffic: packing ratio



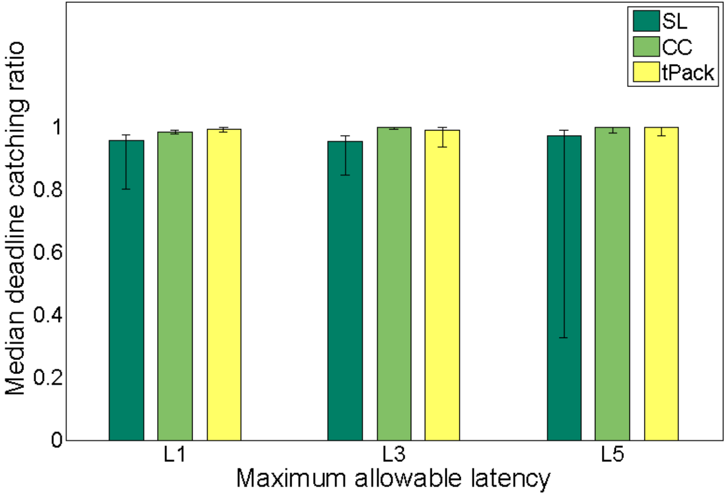
3-second periodic traffic: delivery reliability



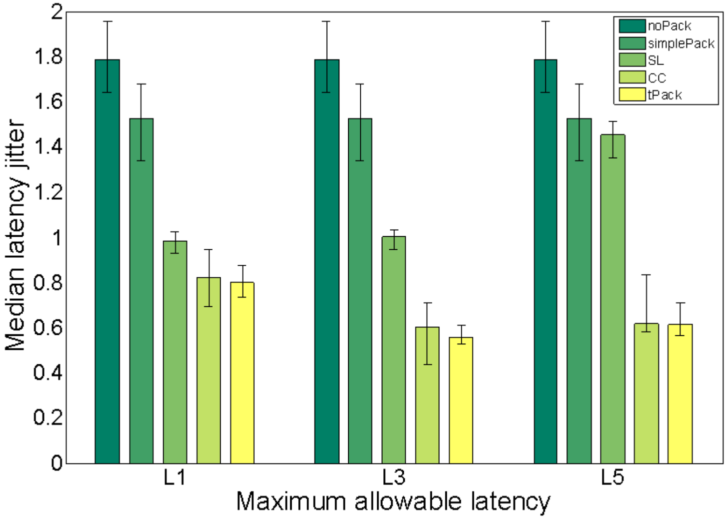
3-second periodic traffic: delivery cost



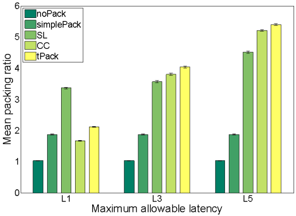
3-second periodic traffic: deadline catching ratio

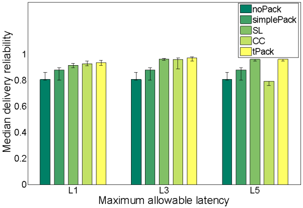


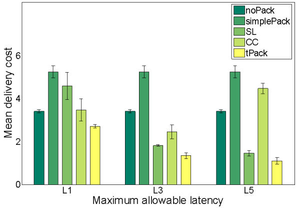
3-second periodic traffic: latency jitter

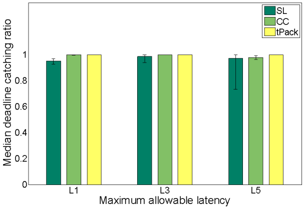


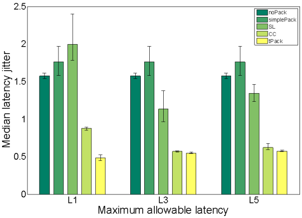
6-second periodic traffic



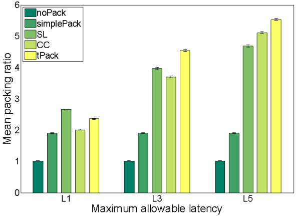


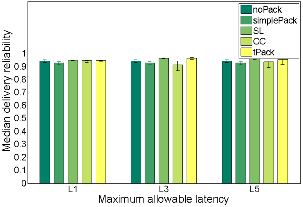


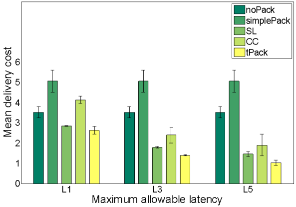


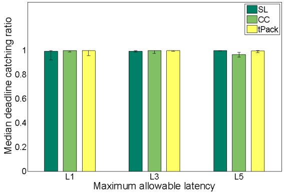


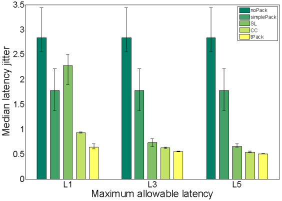
9-second periodic traffic



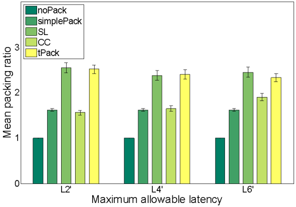


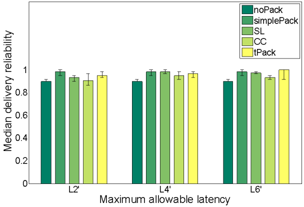


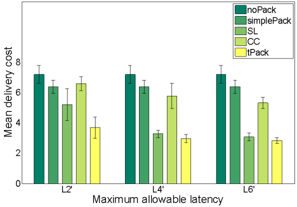


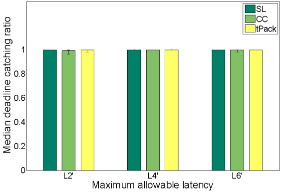


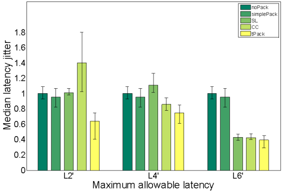
Event traffic











Remarks

- Impact of INP constraints on problem complexity
- Feasibility of a simple, distributed online algorithm
- System benefits in terms of efficiency and predictable latency
- **Temporal data flow control in mission-critical WNSC**

Outline

Inter-flow coding vs. intra-flow coding

Inter-flow coding

- Designed for multiple source-destination pairs, i.e., multi-unicast traffic

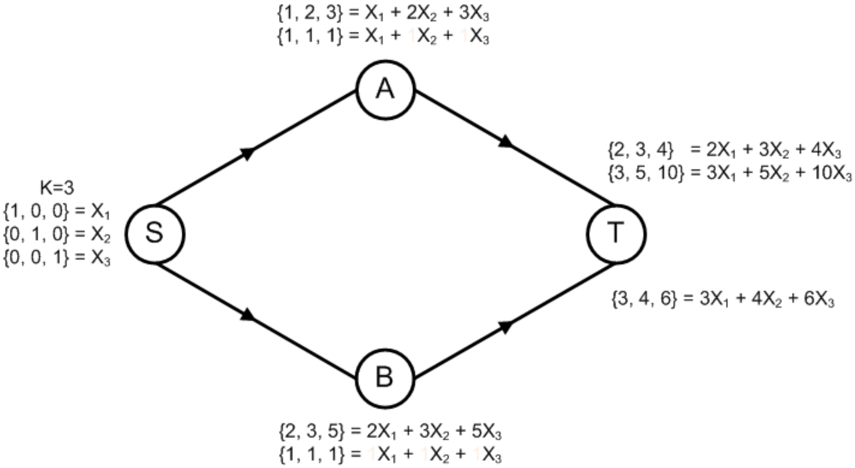
Intra-flow coding

- Designed for single source-destination pair traffic

In WNSC:

- We focus on multi-hop convergecast traffic, i.e., multiple sources to one destination
- Inter-flow coding
    - Absence of perfect feedback channel
    - Transform convergecast to multi-unicast traffic is complex
- Intra-flow coding
    - Easier to transplant to convergecast

Intra-flow network coding: an example



Energy-efficient 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 with transmission cost C_{iT} and a forwarder candidate set FCS_i

Problem Q_0

- Decide the forwarder set FS_i for each node i
- Decide the effective load of each node in FS_i for each node i
- Minimize the total transmission cost from S to T

A mathematical framework for cost of NC-based routing

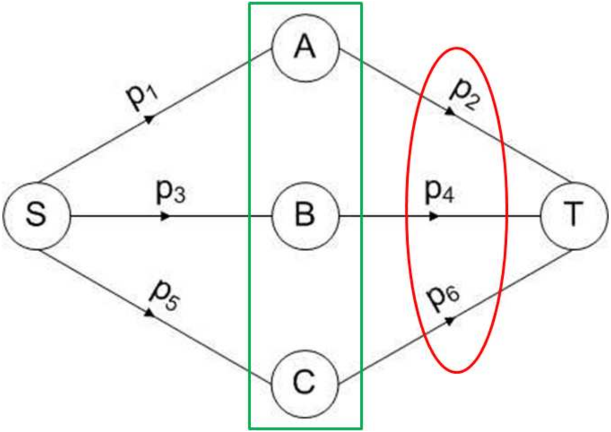
Definition

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-increasing order of their transmission cost
4. Each forwarder only forwards its effective load with corresponding cost
5. Sum up all transmission cost

An example



$$P_2 \geq P_4 \geq P_6$$

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

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

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

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

$$L_A = K_A^S$$

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

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

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

Algorithm 1 Compute the transmission cost of NC-based routing for the current node S with M forwarder candidates

Input: current node S, $D_S = \{A_1, A_2, \ldots, A_M\}$

Output: $C_S(1)$: the expected number of transmissions to deliver 1 packet from S to T

Sort nodes in D_S by a non-descending order of $C_{A_i}(1)$, where $i = 1, 2, \ldots, M$.

Sorted nodes are labeled as $\{A'_1, A'_2, \ldots, A'_M\}$

$C_{SD_S}(1) = \frac{1}{1-\prod_{i=1}^{M}(1-P_{SA'_i})}$

$L_{A'_1} = C_{SD_S}(1)P_{SA'_1}$

$F = 1 - P_{SA'_1}$

for $i \to 2, 3, \ldots, M$ **do**

$\quad L_{A'_i} = C_{SD_S}(1)P_{SA'_i}F$

$\quad C_{A'_i}(L_{A'_i}) = L_{A'_i}C_{A'_i}(1)$

$\quad F = F(1 - P_{SA'_i})$

end for

$C_S(1) = C_{SD_S}(1) + \sum_{i=1}^{M} C_{A'_i}(L_{A'_i})$

Minimize the cost of NC-based routing

A greedy approach

1. Sort forwarder candidates in non-increasing 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.

Minimize the cost of NC-based routing

Algorithm 2 Compute the minimal transmission cost of NC-based routing and the corresponding FS for the input node S with M forwarders

Input: node S, $D_S = \{A_1, A_2, \ldots, A_M\}$, $FS_S = \emptyset$
Output: $C_S^*(1)$: the minimal transmission cost to deliver 1 packet from S to T
Sort nodes in D_S by a non-descending order of $C_{A_i}(1)$, where $i = 1, 2, \ldots, M$.
Sorted nodes are labeled as $\{A_1', A_2', \ldots, A_M'\}$
$FS_S = \{A_1'\}$
$C_S^*(1) = \frac{1}{P_{SA_1'}} + C_{A_1'}(1)$
for $i \rightarrow 2, 3, \ldots, M$ **do**
    Run Algorithm 1 with input S and $D_S = \{A_1', \ldots, A_i'\}$
    Get the result as $C_S^{new}(1)$
    if $C_S^{new}(1) > C_S(1)$ **then**
        break
    else
        $FS_S = FS_S \cup A_i'$
        $C_S^*(1) = C_S^{new}(1)$
    end if
end for

Theorem of optimality

Theorem

Given a node S and its forwarder candidate set $D_S = \{A_1, A_2, \ldots, A_M\}$, Algorithm 2 yields the minimal transmission cost to the destination node of NC-based routing and the corresponding forwarder set.

We proved this theorem by contradiction.

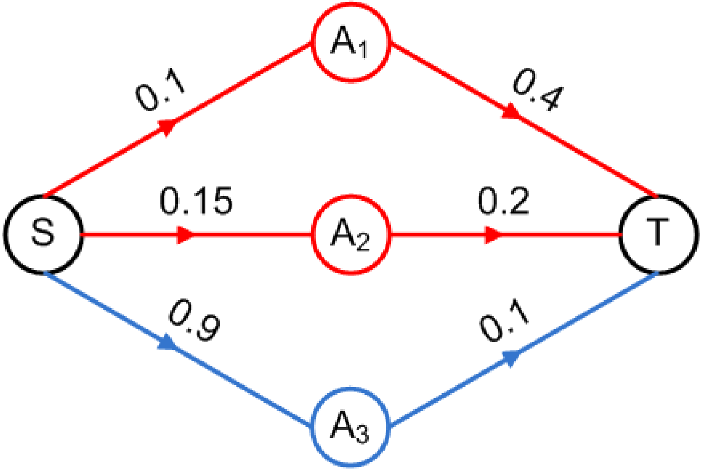
Properties of the optimal routing braid

Theorem

Given a node S with a candidate set FCS_S of M forwarders, the optimal forwarder set FS_S computed in Algorithm 2 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 Algorithm 2 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.

Protocol design and implementation

EENCR: an energy-efficient NC-based routing protocol

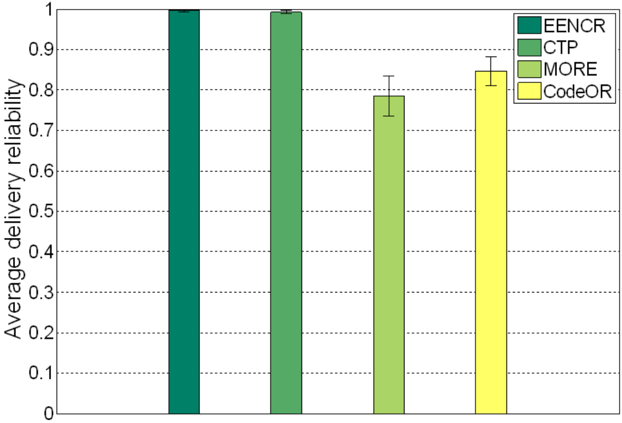
- Routing engine: a distributed implementation of Algorithm 2
- M-NSB: a coded ACK scheme to solve the collective space problem with lower implementation complexity than CCACK
- Rate control: nodes forward a flow after receiving a load-dependent threshold of packets to 1) reduce contention and 2) avoid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

Performance evaluation

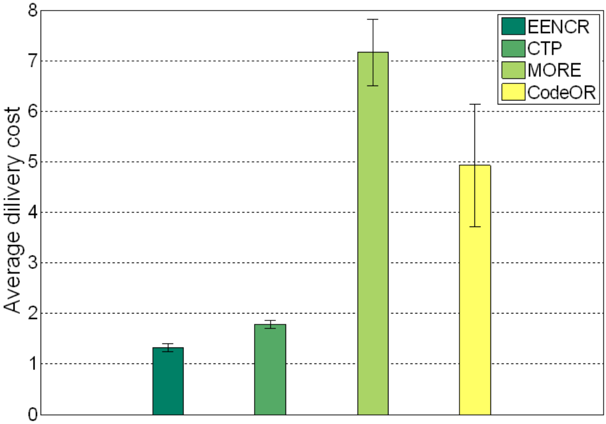
Experiment setting up

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

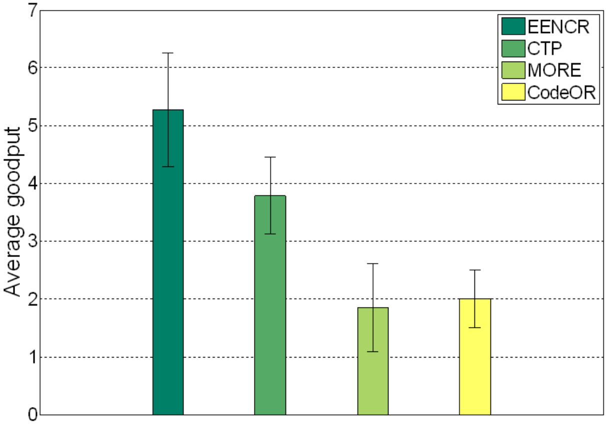
10-source: delivery reliability



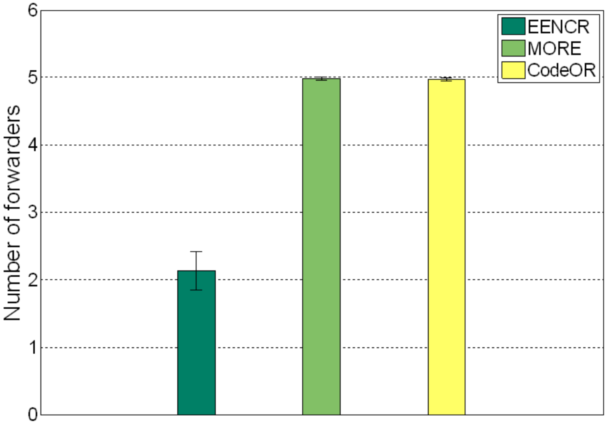
10-source: delivery cost



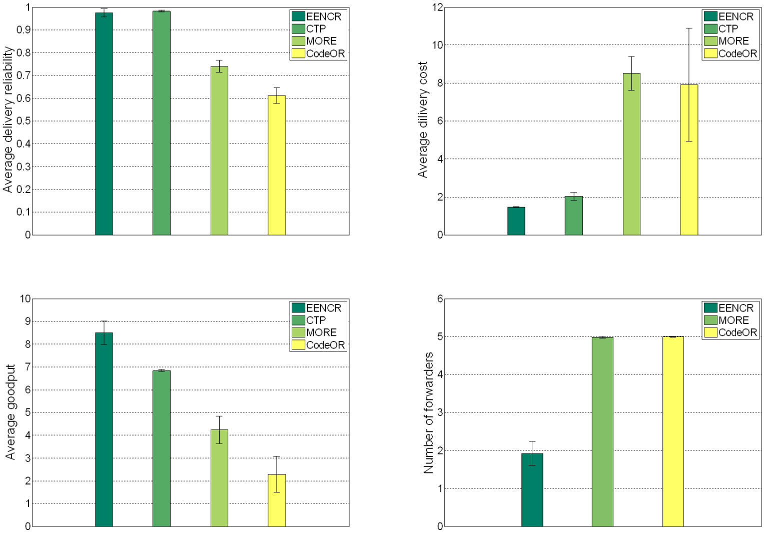
10-source: goodput



10-source: routing diversity



20-source



Average delivery reliability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
EENCR
CTP
MORE
CodeOR
Average dilivery cost
0
2
4
6
8
10
12
EENCR
CTP
MORE
CodeOR
Average goodput
0
1
2
3
4
5
6
7
8
9
10
EENCR
CTP
MORE
CodeOR
Number of forwarders
0
1
2
3
4
5
6
EENCR
MORE
CodeOR

Remarks

- The first mathematical framework on cost measurement of NC-based routing
- A greedy optimal cost minimization and forwarder set selection algorithm
- System benefits in terms of efficiency and reliability
- **Spatial data flow control in mission-critical WNSC**

Outline

Proactive network coding based protection

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 with transmission cost C_{iT} and a forwarder candidate set FCS_i

Problem $\mathbf{Q}$

- Decide the forwarder set FS_i for each node i
- Decide the effective load of each node in FS_i for each node i
- Construct 2 node-disjoint routing braids
  - 1+1 protection against transient node failure
- Minimize the total transmission cost from S to T

Problem $\mathbf{Q}'$

- The same as $\mathbf{Q}$ except that in the input graph, all the paths from S to T are node-disjoint to each other

Complexity analysis

A 0-1 programming formulation of $\mathbf{Q}'$

Minimize: $$C_1 + C_2 = \frac{1}{1-\prod_{i=1}^{m}(1-x_i \cdot P_{2i-1})} \cdot \sum_{i=1}^{m} \frac{x_i \cdot P_{2i-1} \prod_{j=1}^{i-1}(1-x_j \cdot P_{2j-1})}{P_{2i}}$$
$$+\frac{1}{1-\prod_{i=1}^{m}(1-y_i \cdot P_{2i-1})} \cdot \sum_{i=1}^{m} \frac{y_i \cdot P_{2i-1} \prod_{j=1}^{i-1}(1-y_j \cdot P_{2j-1})}{P_{2i}}$$
$$+\max\{\frac{1}{1-\prod_{i=1}^{m}(1-x_i \cdot P_{2i-1})}, \frac{1}{1-\prod_{i=1}^{m}(1-y_i \cdot P_{2i-1})}\}$$

such that

$$x_i \in \{0,1\}$$
$$y_i \in \{0,1\}$$
$$x_i + y_i \leq 1$$
$$P_{2i} \geq P_{2(i+1)}$$
$$0 \leq P_{2i} \leq 1$$
$$0 \leq P_{2i-1} \leq 1$$
$$\text{for } i = 1, 2, \ldots, m,$$

Complexity analysis

Lemma

Problem $\mathbf{Q}'$ *is NP-hard.*

We prove this lemma via a reduction from the 2-PARTITION problem.

Theorem

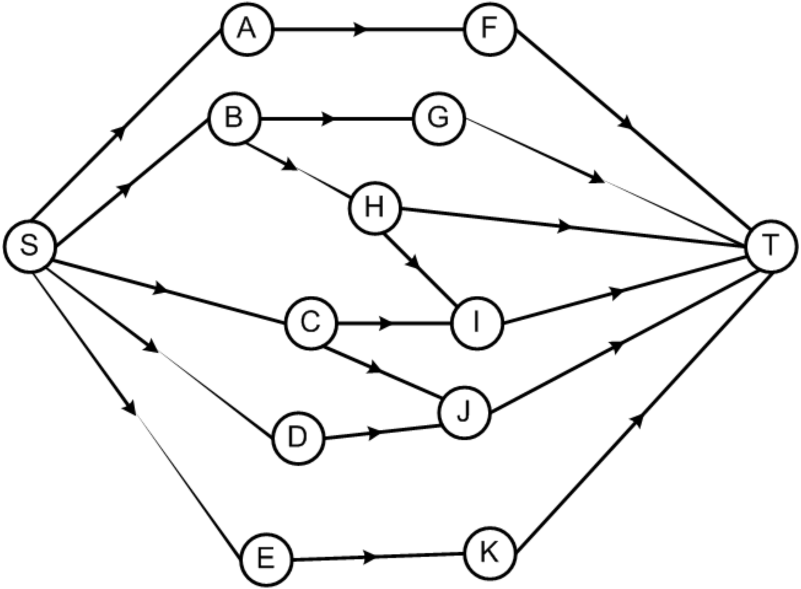
Problem $\mathbf{Q}$ *is NP-hard.*

An immediate result from the NP-hardness of $\mathbf{Q}'$.

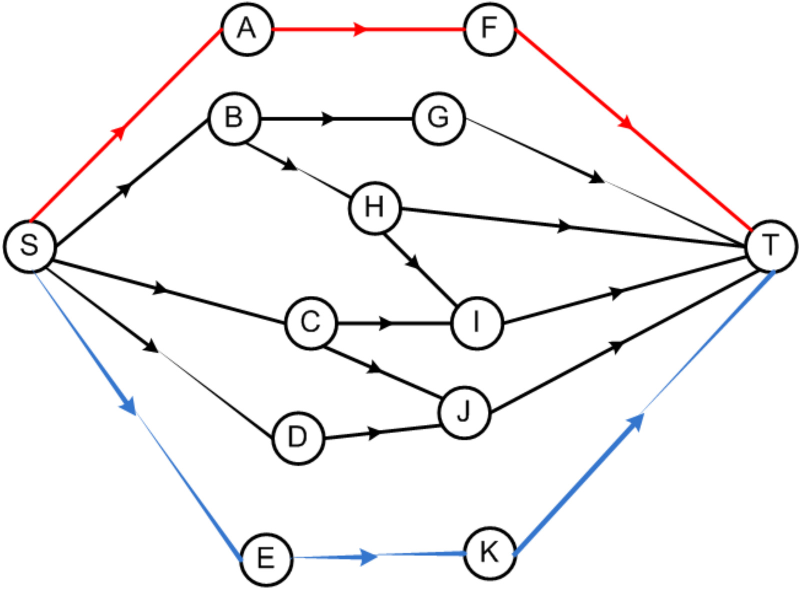
A heuristic algorithm for Problem Q

1. Compute 2 node-disjoint paths R_1 and R_2 with minimal total cost on G ($C_{R_1} \geq C_{R_2}$)
2. Build an auxiliary graph G_1 excluding all intermediate nodes of R_2 and links connected to these nodes from G
3. Compute the first braid B_1 as the optimal single braid on G_1
4. Build an auxiliary graph G_2 excluding all intermediate nodes of B_1 and links connected to these nodes from G
5. Compute the second braid B_2 as the optimal single braid on G_2

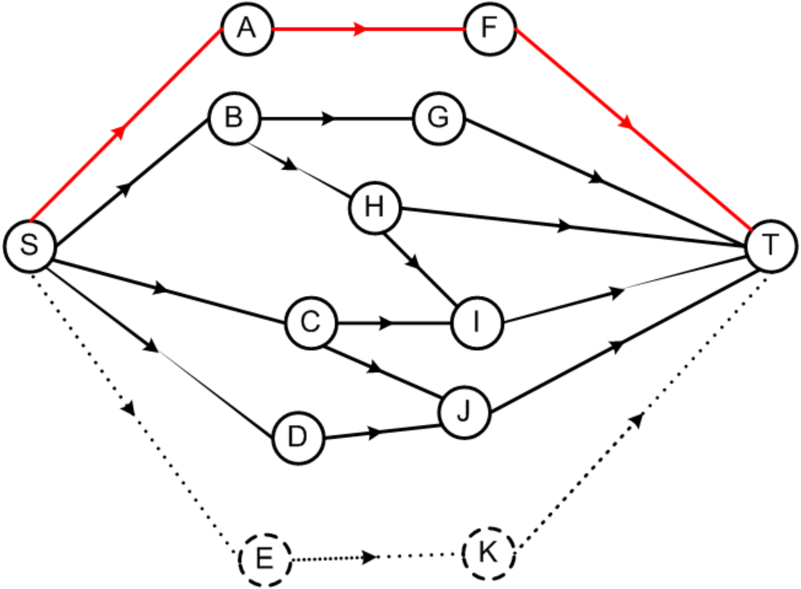
Finding node-disjoint braids - an example



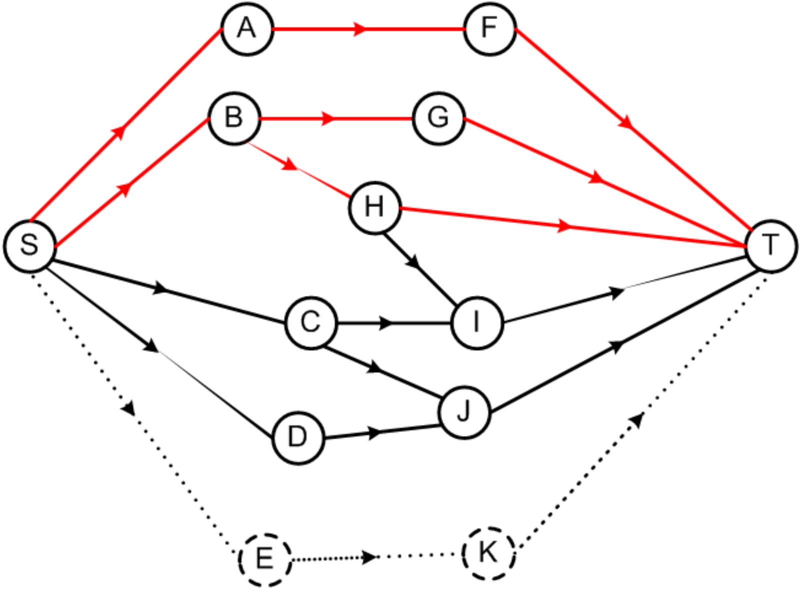
Finding node-disjoint braids - an example



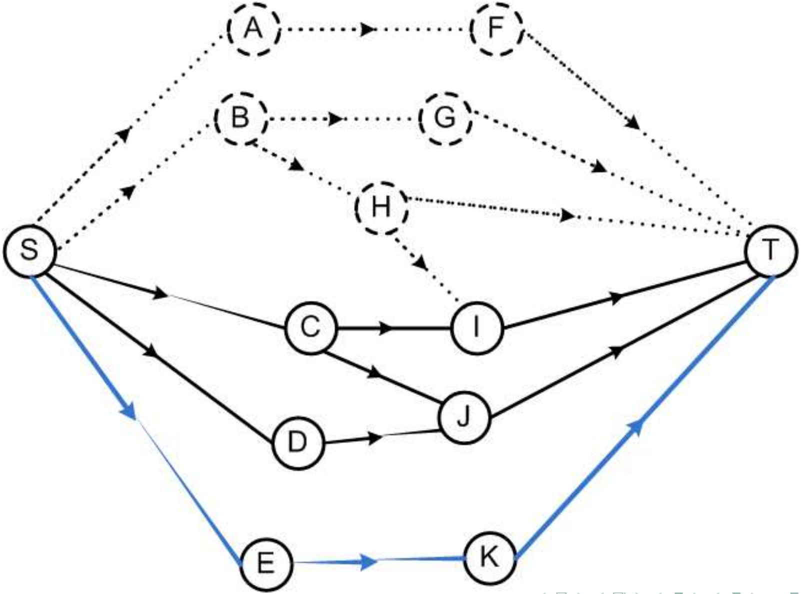
Finding node-disjoint braids - an example



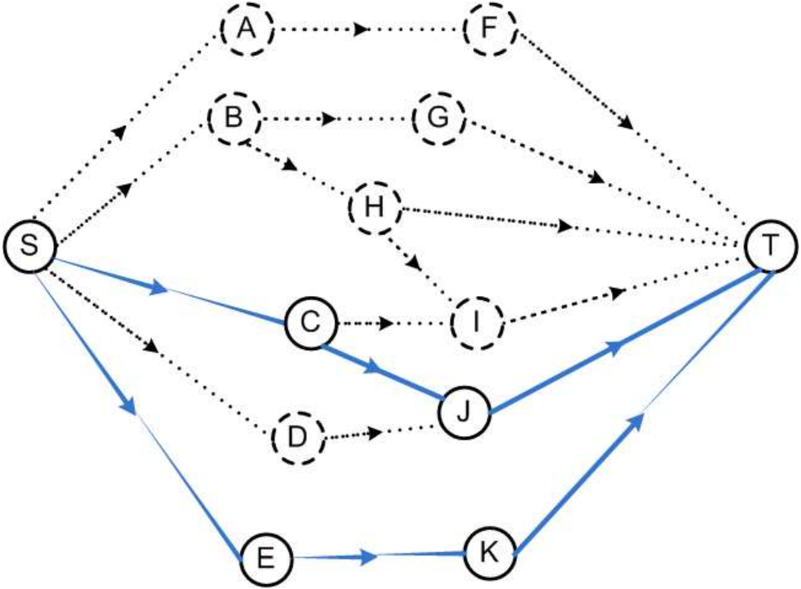
Finding node-disjoint braids - an example



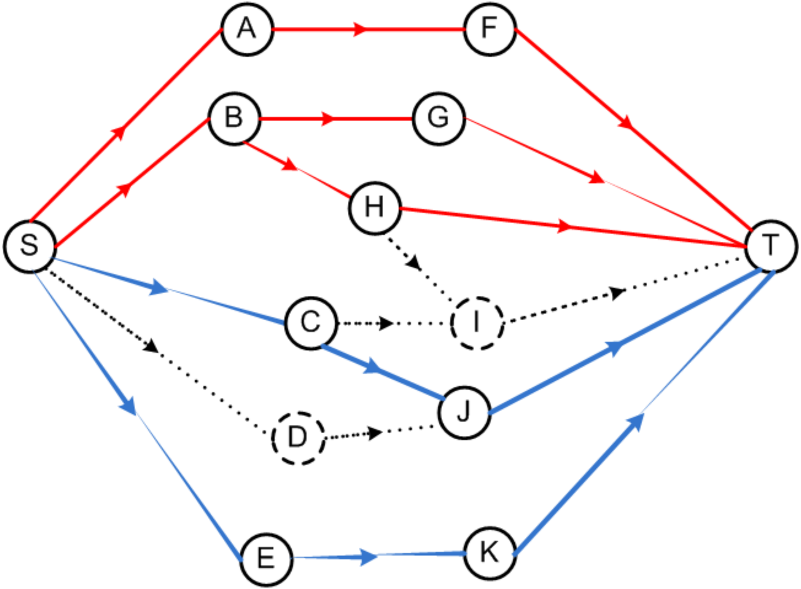
Finding node-disjoint braids - an example



Finding node-disjoint braids - an example



Finding node-disjoint braids - an example



Algorithm 3 A heuristic algorithm for two node-disjoint braids construction

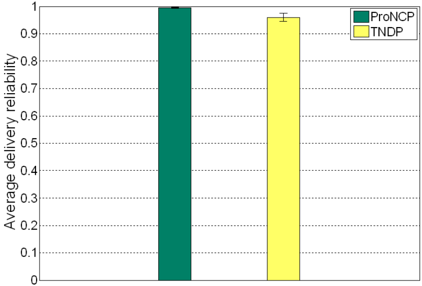
Input: a DAG $G = (V, E)$ with source S and destination T
Construct 2 minimal cost node-disjoint paths $\{R_1, R_2\}$ from S and T, where $C_{R_1} \geq C_{R_2}$
$B_1 = R_1, B_2 = R_2$
$G_1 = G$
for every node V_i in G_1 **do**
    if $V_i \in B_2$ **then**
        Remove V_i and all links attached to V_i from G_1
    end if
end for
Run Algorithm 2 on G_1 and denote the resulting braid as B^1_{single}
$B_1 = B^1_{single}$
$G_2 = G$
for every node V_i in G_2 **do**
    if $V_i \in B_1$ **then**
        Remove V_i and all links attached to V_i from G_2
    end if
end for
Run Algorithm 2 on G_2 and denote the resulting braid as B^2_{single}
$B_2 = B^2_{single}$
Stop and return $\{B_1, B_2\}$

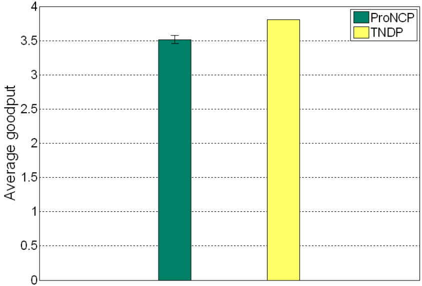
Performance evaluation

Experiment setting up

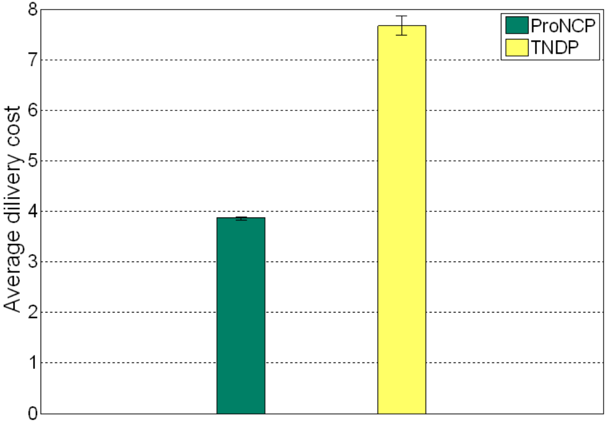
- Testbed: NetEye, a 130-sensor testbed (Maccabees Building)
- Topology: 60 nodes, 10 are source nodes, 1 sink node
- Protocols compared: *ProNCP*, TNDP (two node-disjoint path protection)
  Note: braids and routes are computed offline via sampling results.
- Traffic pattern: 3-second periodic traffic
- Failure model: probabilistic transient failure on intermediate nodes
- Metrics: delivery reliability, delivery cost and goodput

No failure: delivery reliability and goodput

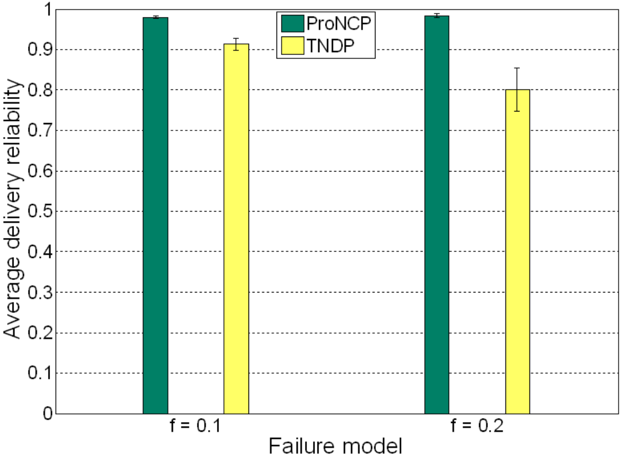




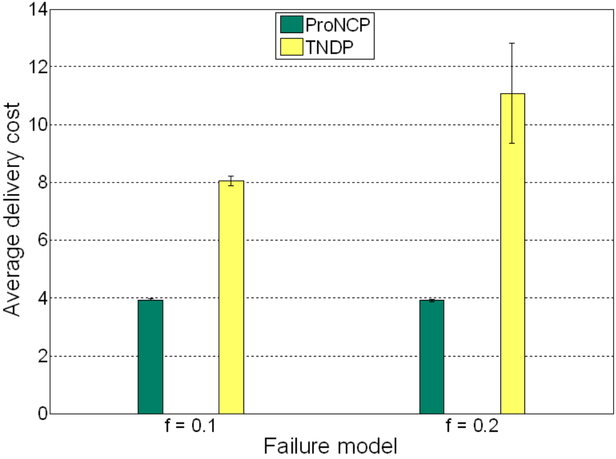
No failure: delivery cost



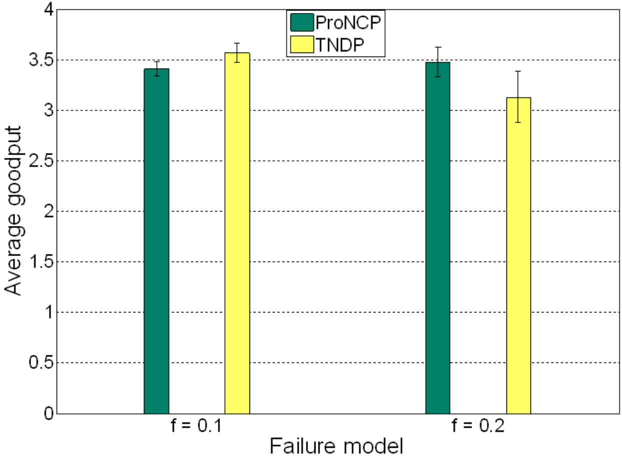
Transient failure: delivery reliability



Transient failure: delivery cost



Transient failure: goodput



Remarks

- Complexity study on 1+1 proactive NC-based protection problem
- A heuristic node-disjoint-braids construction algorithm
- System benefits in terms of reliability, delivery cost and stability under transient failures
- **Spatial data flow control and protection in mission-critical WNSC**
- Future work:
  design of low-overhead distributed algorithm for node-disjoint braids construction

Outline

Conclusion

- Explore optimization of different INP in mission-critical WNSC
- Demonstrate system benefits in terms of reliability, delay, efficiency and resiliency theoretically and experimentally
- Achieve temporal and spatial data flow control

Outline

1. Introduction
2. Real-time packet packing scheduling
3. Energy-efficient network coding based routing
4. Proactive network coding based protection
5. Conclusion
6. **Acknowledgments**

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