# When In-Network Processing Meets Time: Complexity and Effects of Joint Optimization in Wireless Sensor Networks

**Master Thesis**

**by**

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# Introduction

- Wireless Sensor Networks
  - Highly resource-constrained
- In-Network Processing
  - Reduce traffic flow → resource efficient
  - End-to-end QoS are usually not considered
- Mission-Critical Real-Time CPS:
  - Close-loop control
  - More emphasis on end-to-end QoS, especially latency and reliability

# Introduction

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

- Our focus:
  - Understanding problem complexity
  - Designing simple distributed online algorithm
  - Understanding systems benefits

# Outline

- System Model and Problem Formulation
- Complexity Analysis
- A Utility Based Online Algorithm
- Performance Evaluation
- Conclusion

# System Model and Problem Formulation

- System Model
  - A directed collection tree $T = (V,E)$
  - Edge $(v_i, v_j) \in E$ with weight $ETX_{vi, vj}\ (l)$
  - 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 $x \in X$

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# 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

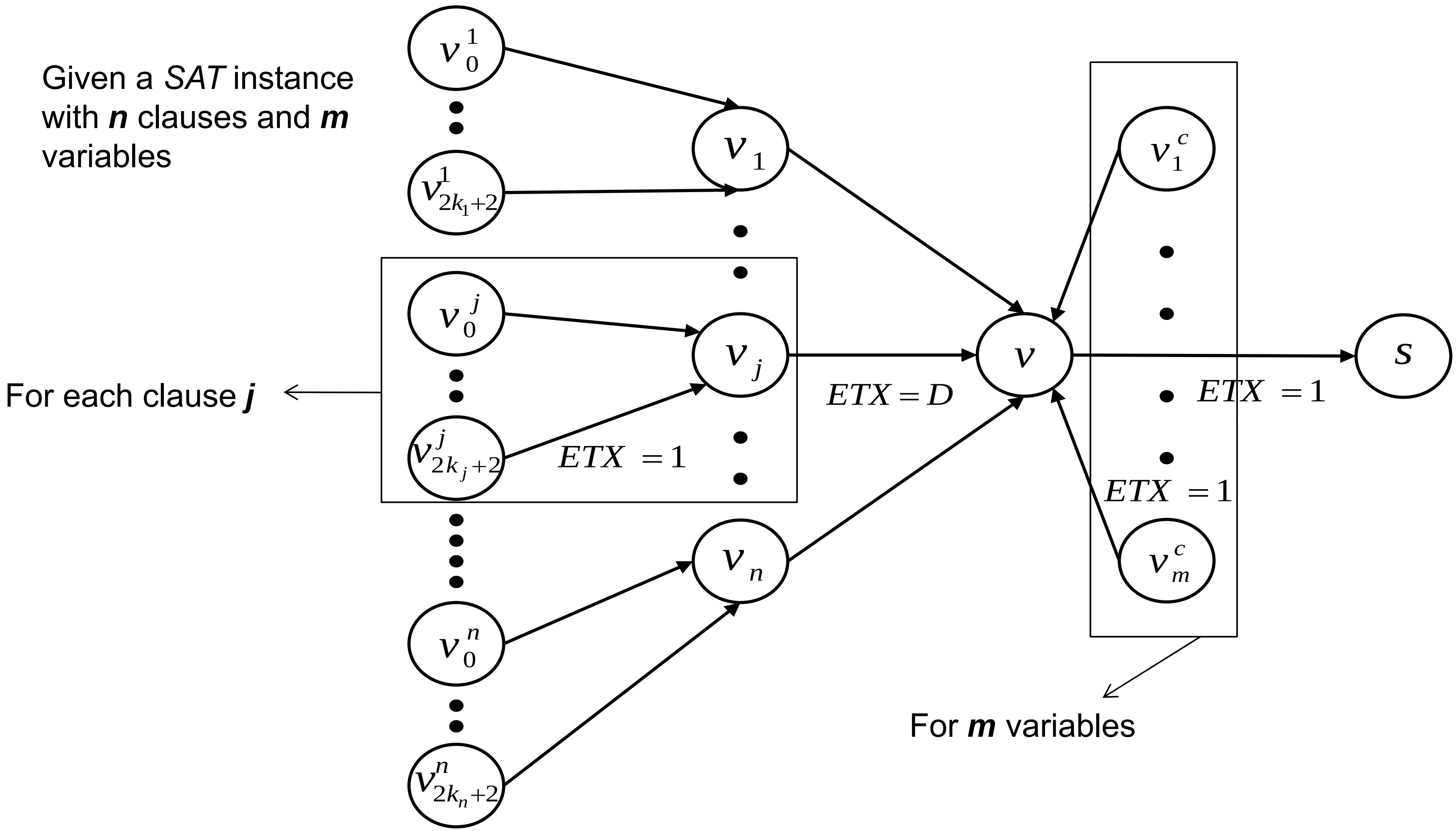
| $P_0, P_1, P_2, P$ | $K \geq 3$ | K = 2 | |
|---|---|---|---|
| | | re-aggregation is not prohibited | re-aggregation is prohibited |
| Complexity | strong NP-hard | strong NP-hard | $O(N^3)$ |
| NP-hard to achieve approximation ratio | $1+\frac{1}{200N}(1-\frac{1}{\varepsilon})$ | $1+\frac{1}{120N}(1-\frac{1}{\varepsilon})$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

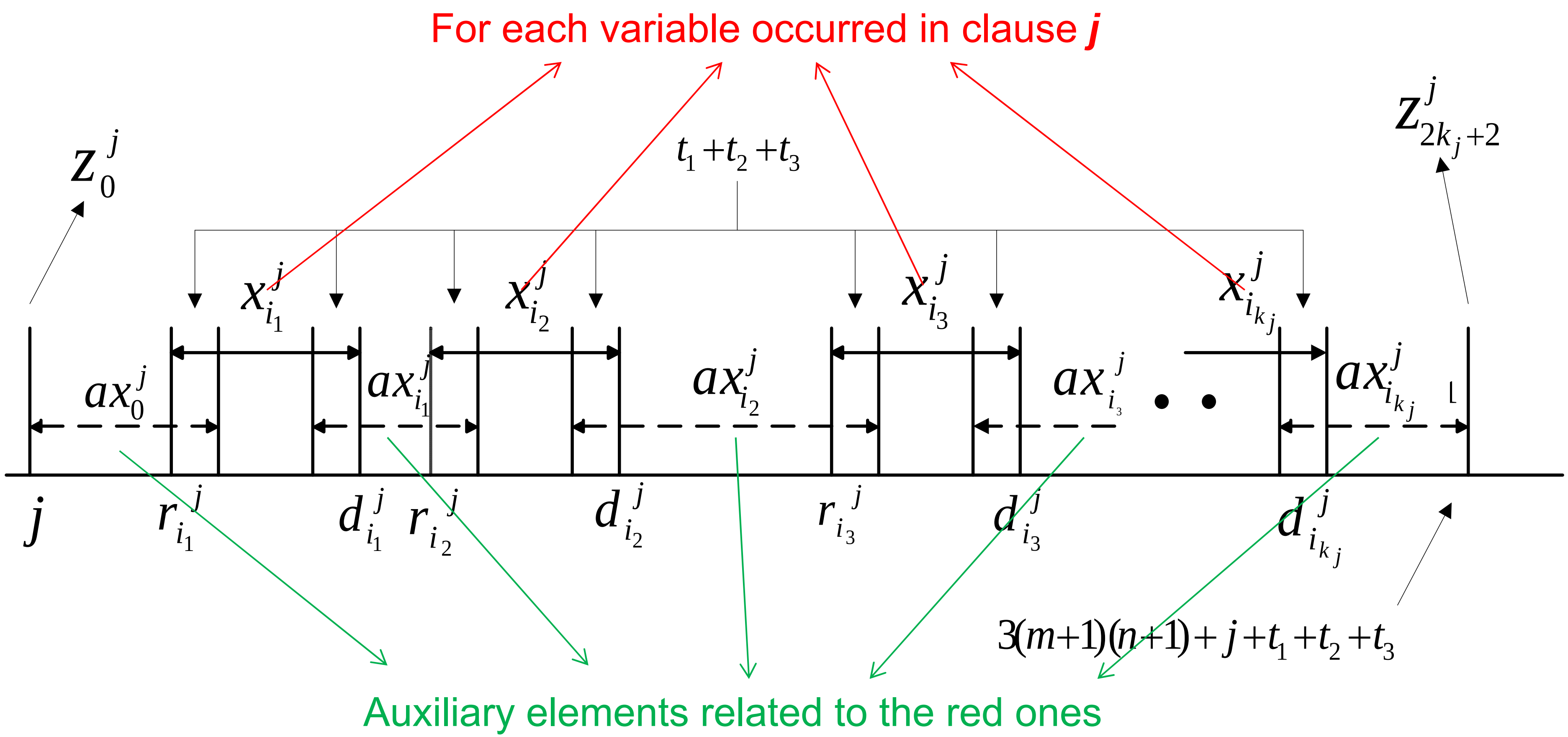
K = Maximal packet length $N = |X|$

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

# Complexity Analysis

- K ≥ 3, $P_0$ is NP-hard in tree structures -- Reduction from *SAT*





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 ≥ 3, and T is a chain, regardless of re-aggregation
  - The reduction from *SAT* still holds*
- When K = 2 and re-aggregation is not prohibited
  - The reduction from SAT 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 Edmonds' Algorithm

* This solves an open problem in batch processing

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# 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

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

Cost without packing

$$U_l = AC'_l - AC_l$$

- Utility of transmitting a packet:

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

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

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

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 $U_p \le U_l$
- Competitive Ratio
  - Problem *P'*
    - T is a complete tree
    - Leaf nodes generate elements at a common rate
  - Theorem: For problem *P′*, tPack is $\min\{K, \max_{v_j \in V_{>1}} \frac{2ETX_{v_jR}}{2ETX_{v_jR} - ETX_{p_jR}}\}$ -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-comptetive

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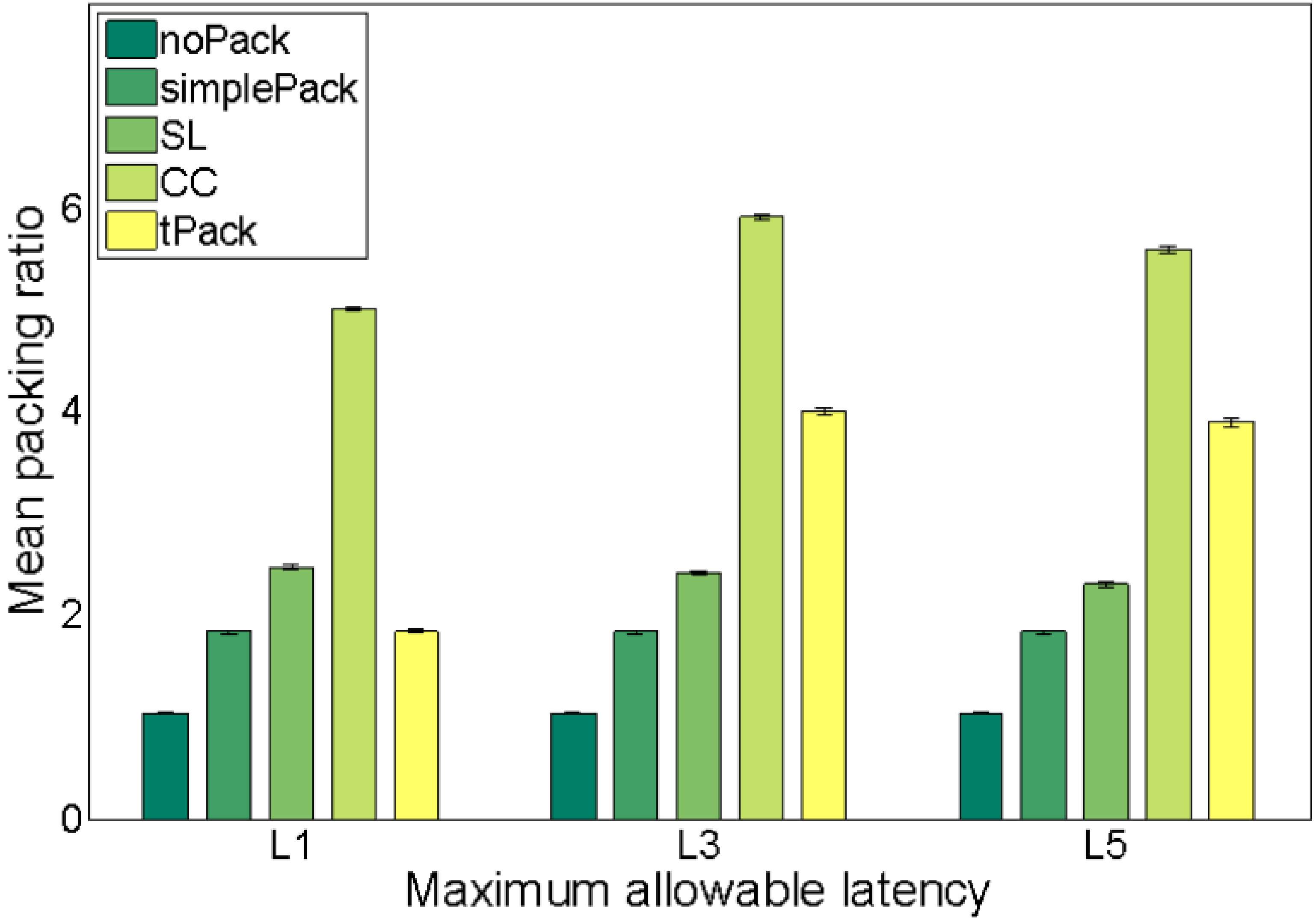
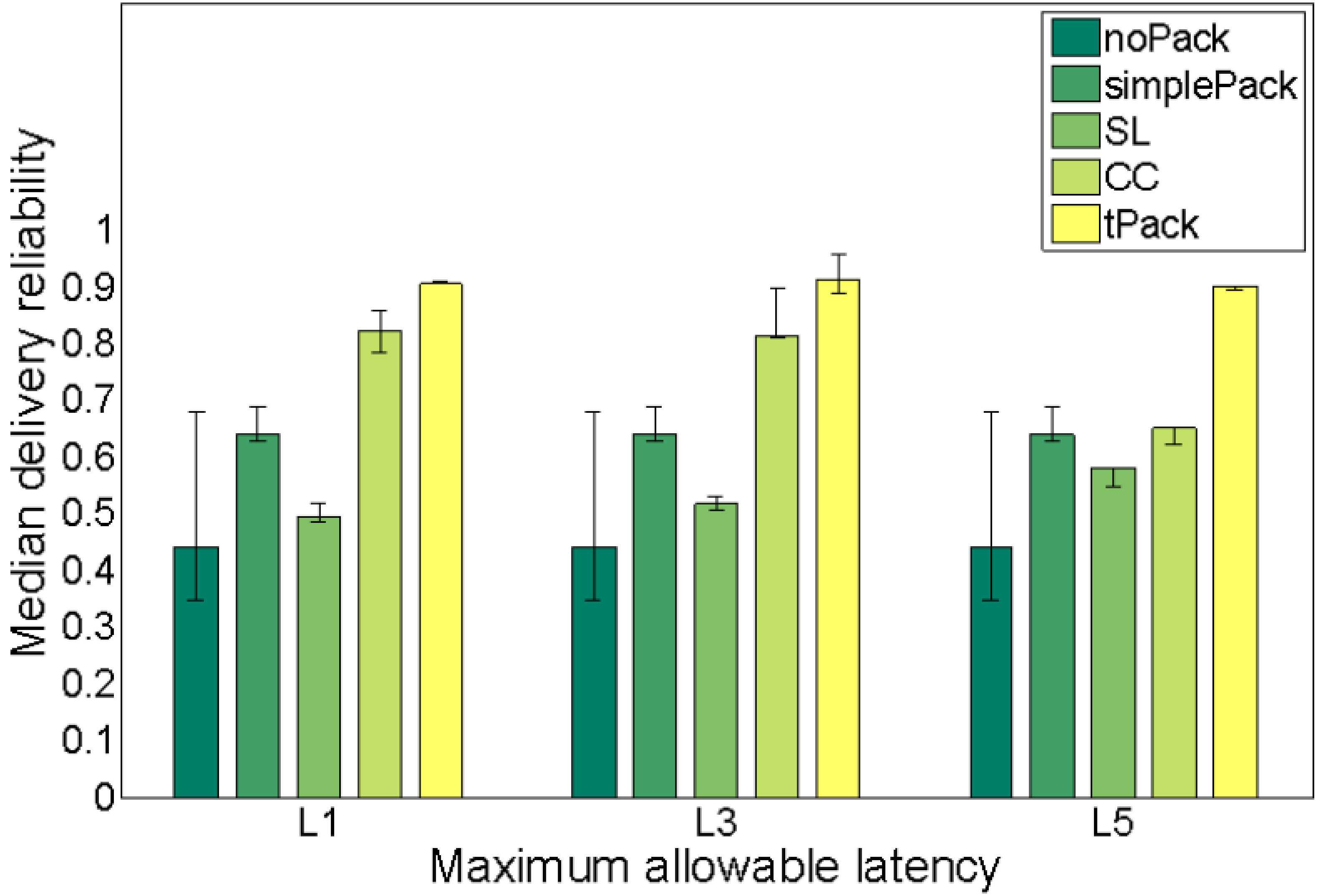
# Performance Evaluation

- Experiment Setting Up
  - Testbed: NetEye, a 130-sensor testbed
  - Topology: 120 nodes, half are source nodes
  - 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
    - latency jitter

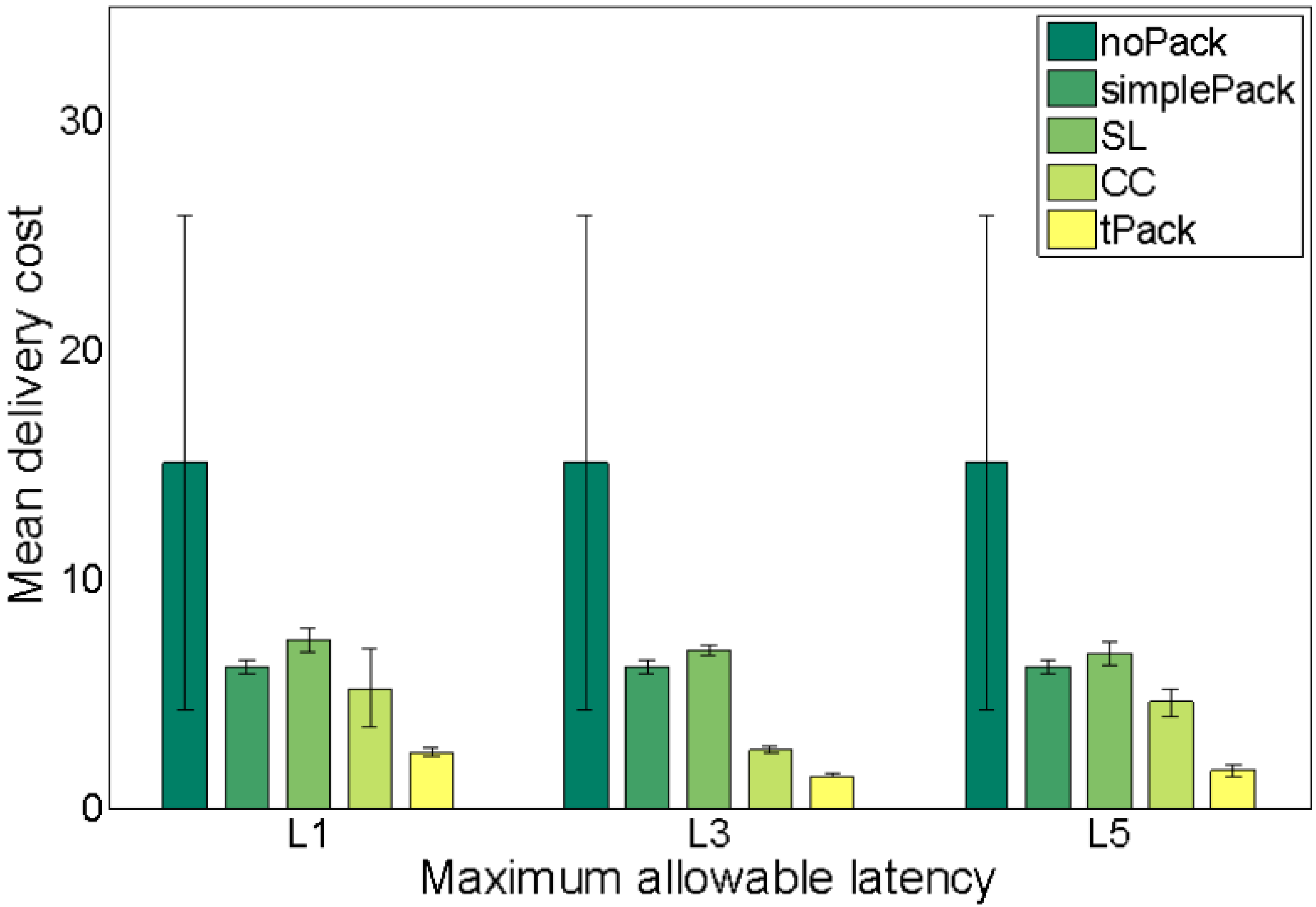
# 3 second packing ratio



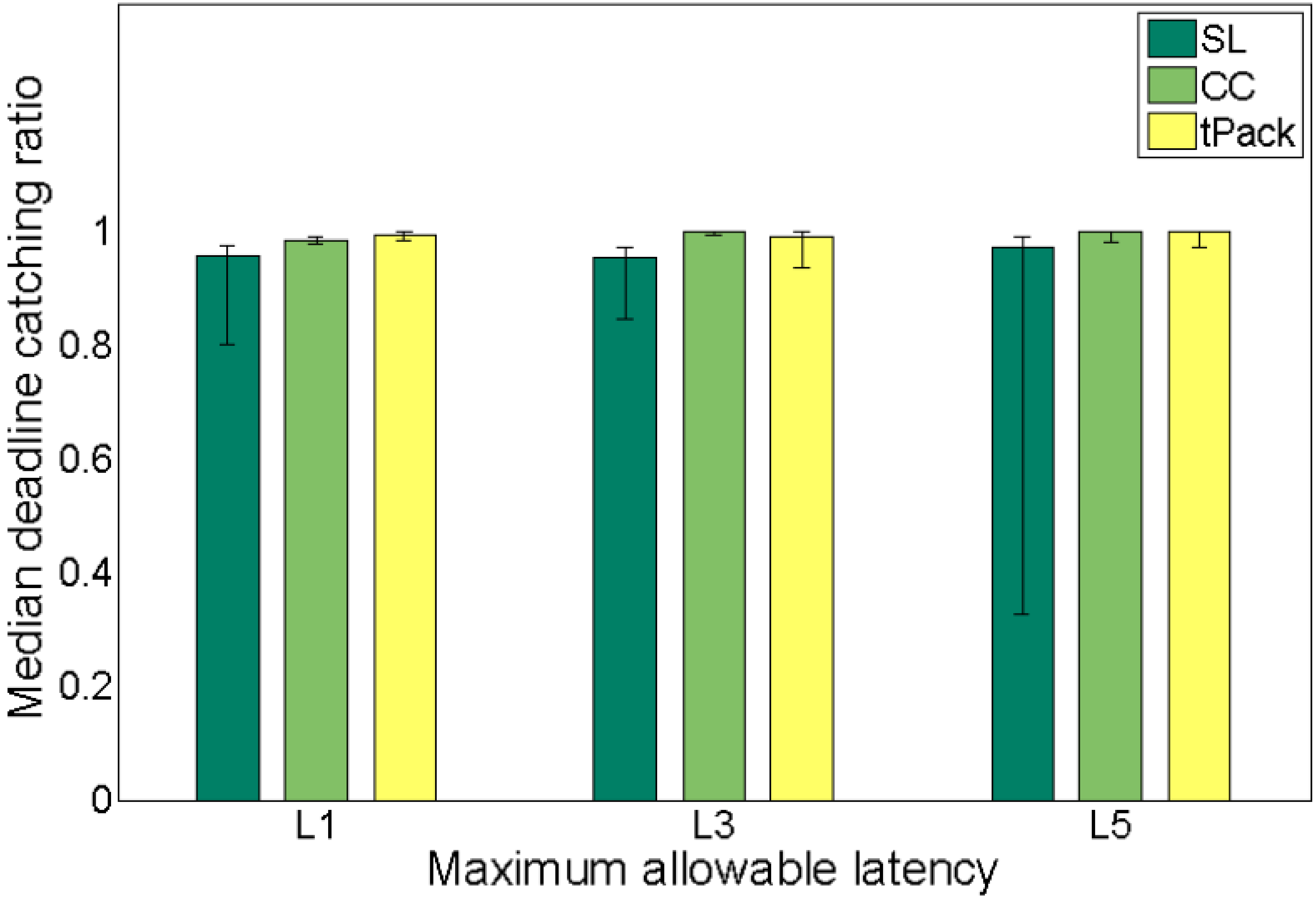
# 3 second delivery reliability



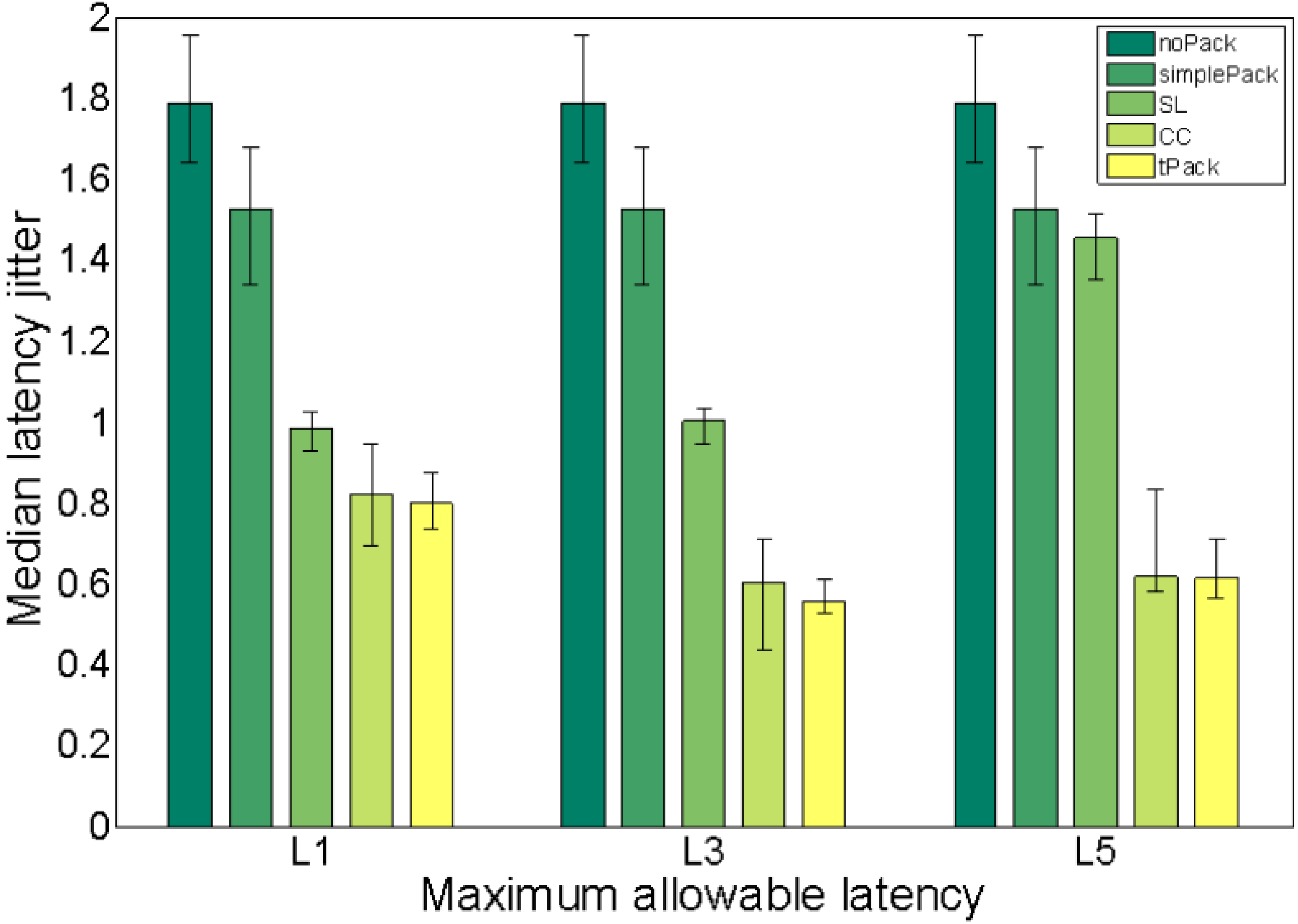
# 3 second delivery cost



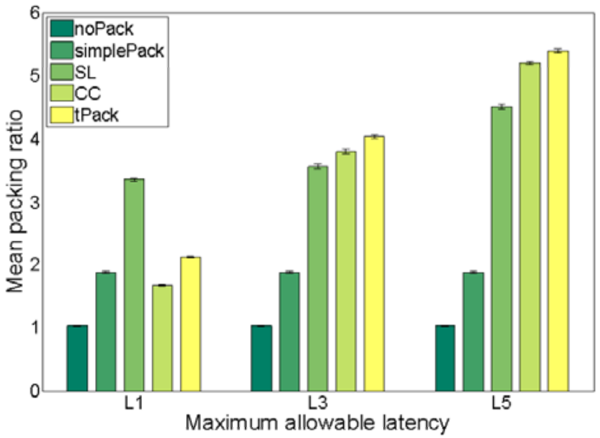
# 3 second deadline cathcing ratio

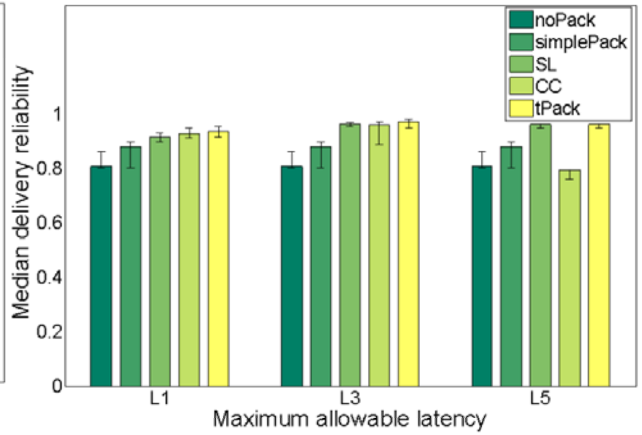


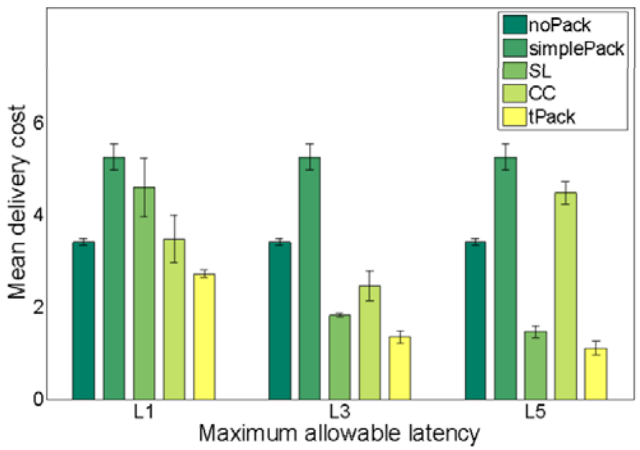
# 3 second latency jitter

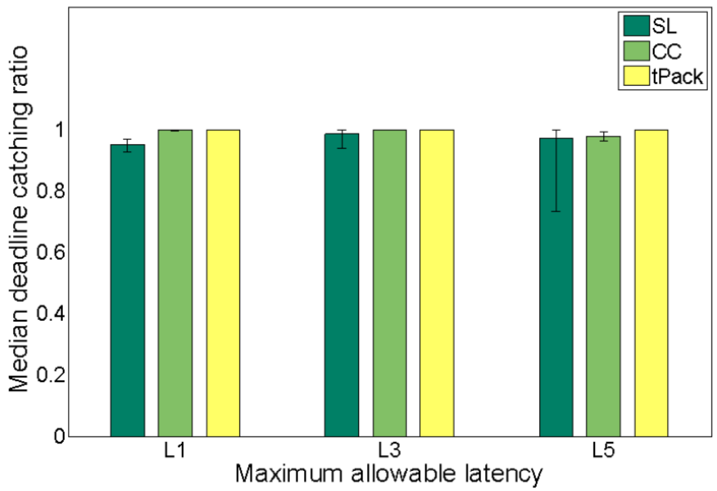


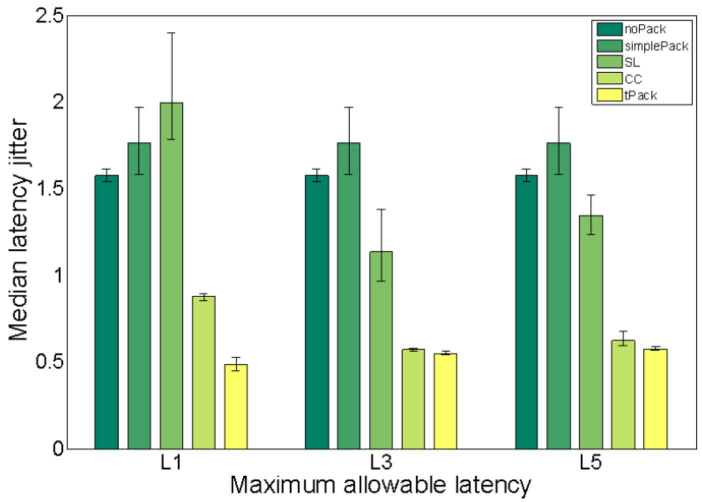
# 6 second


noPack
simplePack
SL
CC
tPack
Mean packing ratio
0
1
2
3
4
5
6
L1
L3
L5
Maximum allowable latency

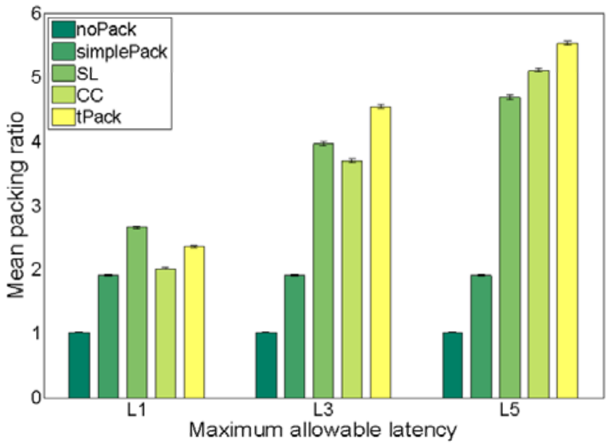

noPack
simplePack
SL
CC
tPack
Median delivery reliability
0
0.2
0.4
0.6
0.8
1
L1
L3
L5
Maximum allowable latency

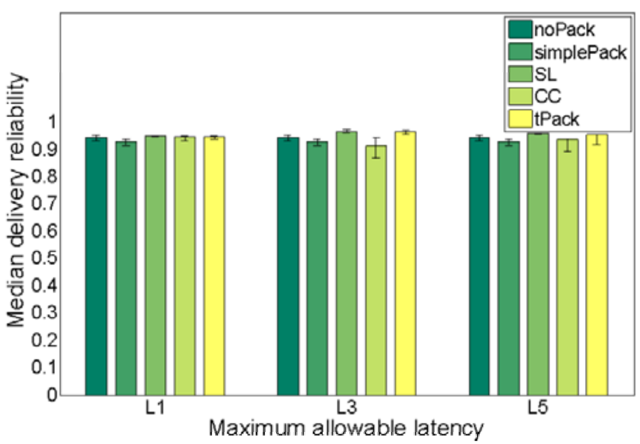

noPack
simplePack
SL
CC
tPack
Mean delivery cost
0
2
4
6
L1
L3
L5
Maximum allowable latency

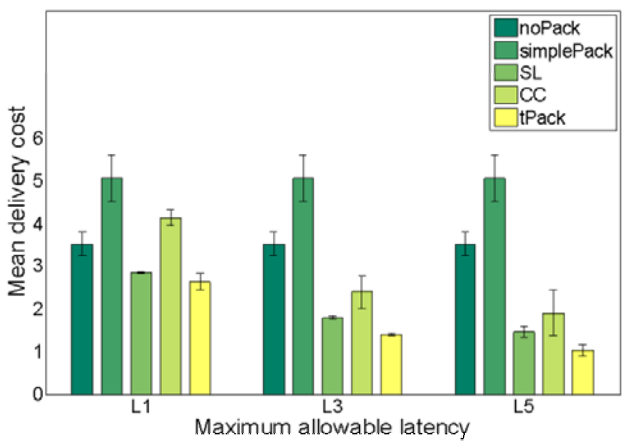

SL
CC
tPack
Median deadline catching ratio
0
0.2
0.4
0.6
0.8
1
L1
L3
L5
Maximum allowable latency

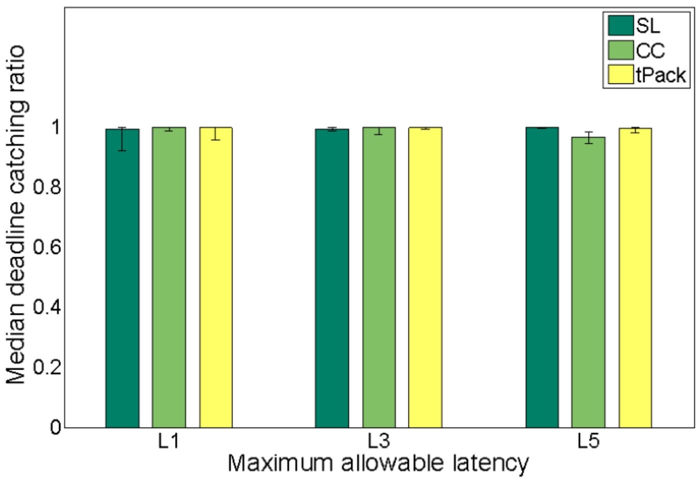

noPack
simplePack
SL
CC
tPack
Median latency jitter
0
0.5
1
1.5
2
2.5
L1
L3
L5
Maximum allowable latency

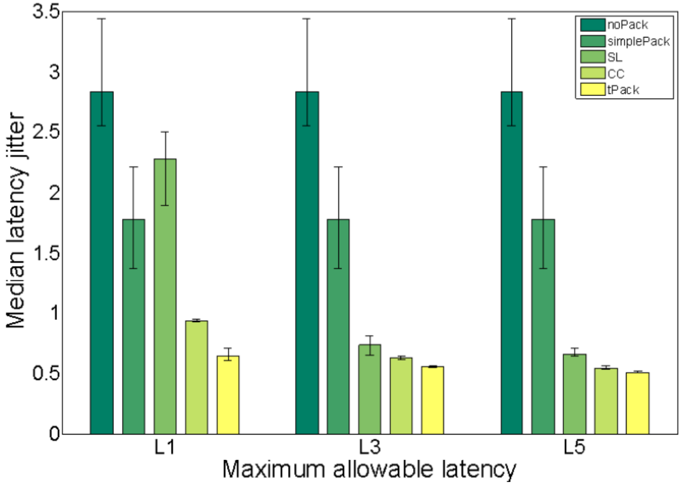
# 9 second


noPack
simplePack
SL
CC
tPack
Mean packing ratio
L1
L3
L5
Maximum allowable latency

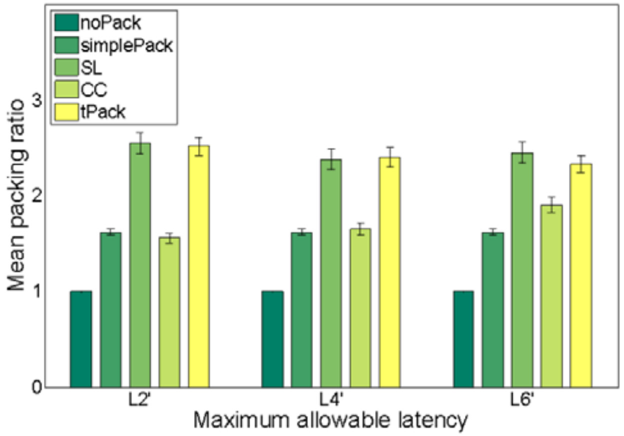

noPack
simplePack
SL
CC
tPack
Median delivery reliability
L1
L3
L5
Maximum allowable latency

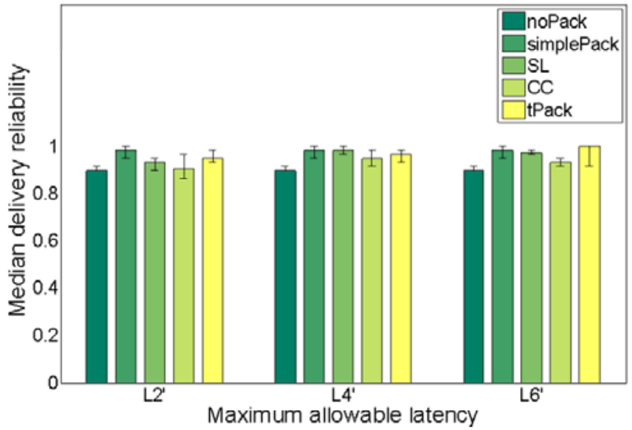

noPack
simplePack
SL
CC
tPack
Mean delivery cost
L1
L3
L5
Maximum allowable latency

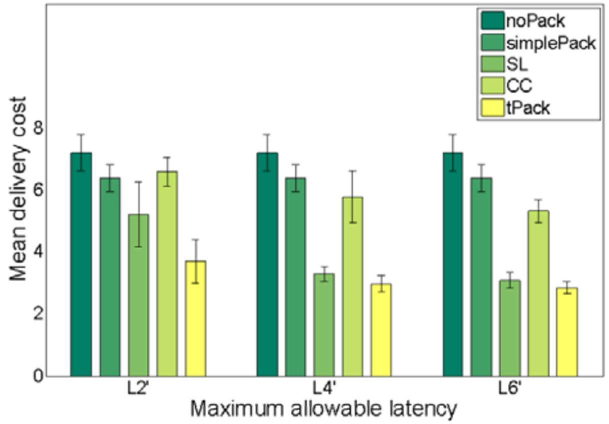

SL
CC
tPack
Median deadline catching ratio
L1
L3
L5
Maximum allowable latency

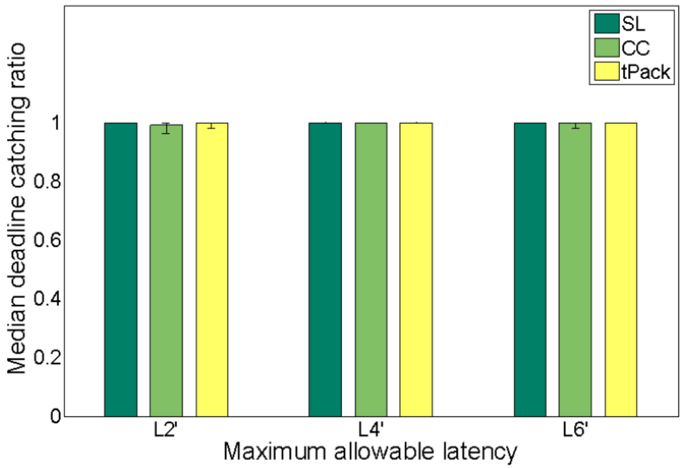

noPack
simplePack
SL
CC
tPack
Median latency jitter
L1
L3
L5
Maximum allowable latency

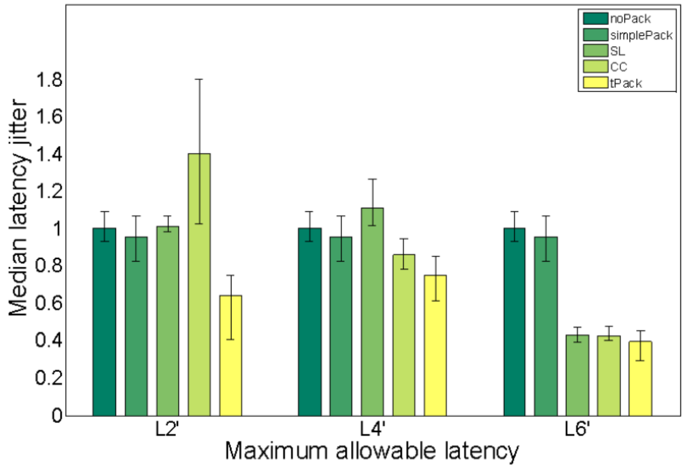
# Event traffic



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# Conclusion and Future Work

- Conclusion
  - Impact of INP constraints on problem complexity
  - Feasibility of a simple, distributed online algorithm
  - Systems benefits in terms of efficiency and predictable latency

- Future Work
  - Complete competitive analysis on the utility based algorithm
  - Joint optimization of other INP and QoS constraints in WCPS