Implementing a Cognitive Routing Method for High-Rate Delay Tolerant Networking

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IEEE 2023 Cognitive Communications for Aerospace Applications Workshop - Cleveland, OH - NASA GRC (online) - June 20–22, 2023

Introduction

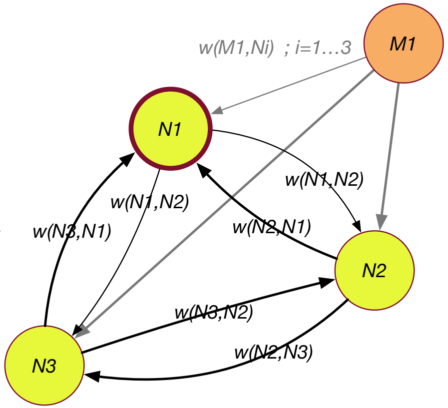
- Space Communications and Delay-Tolerant Networking (DTN)
- Contact Graph Routing (CGR)
  - Standard DTN protocol
  - Limitations:
    - Network-wide congestion
    - Packet losses along the path
    - Metrics other than the bundle delivery time
- Cognitive Networking
  - Artificial intelligence and machine learning
  - Learning and prediction to optimize network performance

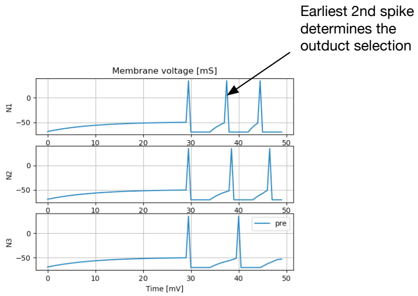
Cognitive Space Gateway (CSG)

- Reinforcement learning approach to the space bundle routing problem
- Spiking neural networks
- Design goals:
  - Dynamic
  - Distributed (autonomous operation)
  - (Near) real-time routing decisions
  - Multi-objective routing
- This study questions:
  - How to support multi-objective routing?
  - What is the realistic routing performance of the method?
  - Can the CSG method be improved?

CSG Approach: Optimal Routing Action

Spiking Neural Network (SNN) architecture defining the Cognitive Network Controller (CNC) for the CSG agent



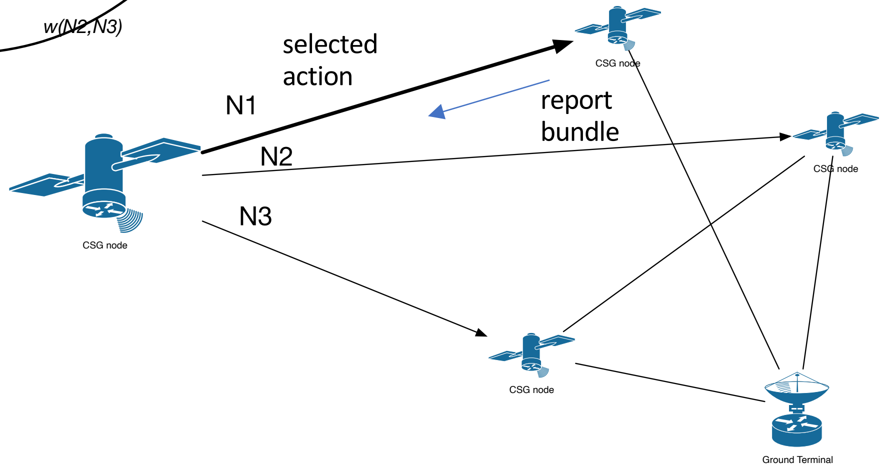


leaky integrate-and-fire neuron model

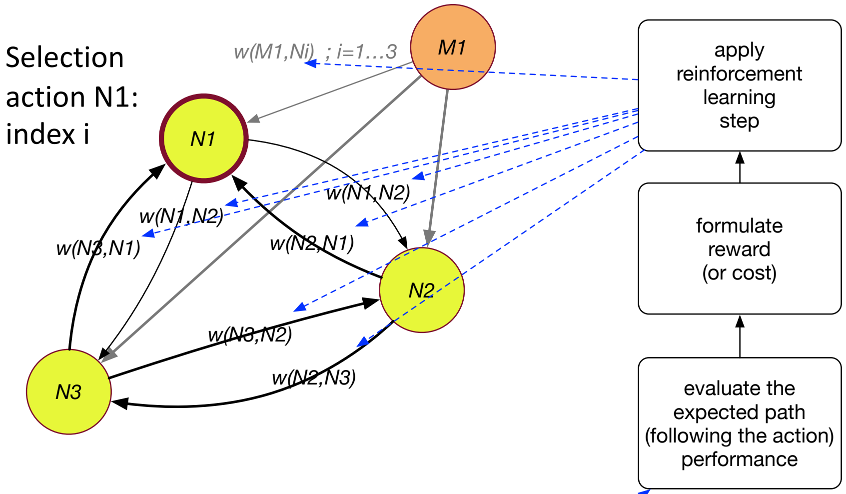
$$\tau \frac{d}{dt} u(t) = -u(t) + RI(t)$$

$$I(t) = i_e(t) + \sum_f \sum_j \sum_k w_{jk} \, i_{jk}^{(f)}(t)$$

CSG agent

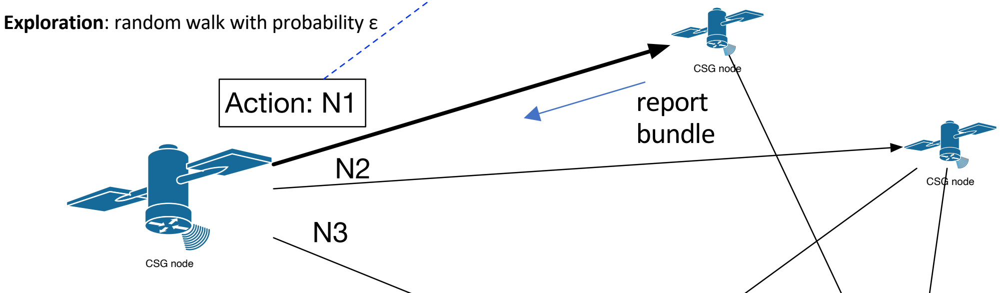


CSG Approach: Learning & Exploration



$$w(c_j, c_i) \leftarrow w(c_j, c_i) + \eta\delta \quad ; j = 1, \ldots, n; i \neq j$$
$$w^k(g, c_i) \leftarrow w^k(g, c_i) - \eta\delta \quad ; k = 1, \ldots, n$$

- *i* is the index of the selected action
- *η>0* is the learning rate
- *δ* is the cost advantage of the action
- Parallel inhibitory synapses *k*
- Cost = predicted path delay in the original CSG



CSG Method Improvements

1. Cost advantage based on the minimum cost for all actions
2. Cap on synapse strength updates
3. CNC pre-training
4. Multi-objective routing

Notes:

- Routing based on loss becomes relevant when best-effort CLAs are used
- Minimum delay and minimum loss may be contradictory routing optimization objectives

Multi-Objective Routing

Agent i, action j, destination d, cost C is given by:

- Delay

$$T_{i,d} = T_{i,j} + T_{j,d} + D_{i,d}$$
$$C = T_{i,d} \qquad (1)$$

- Loss

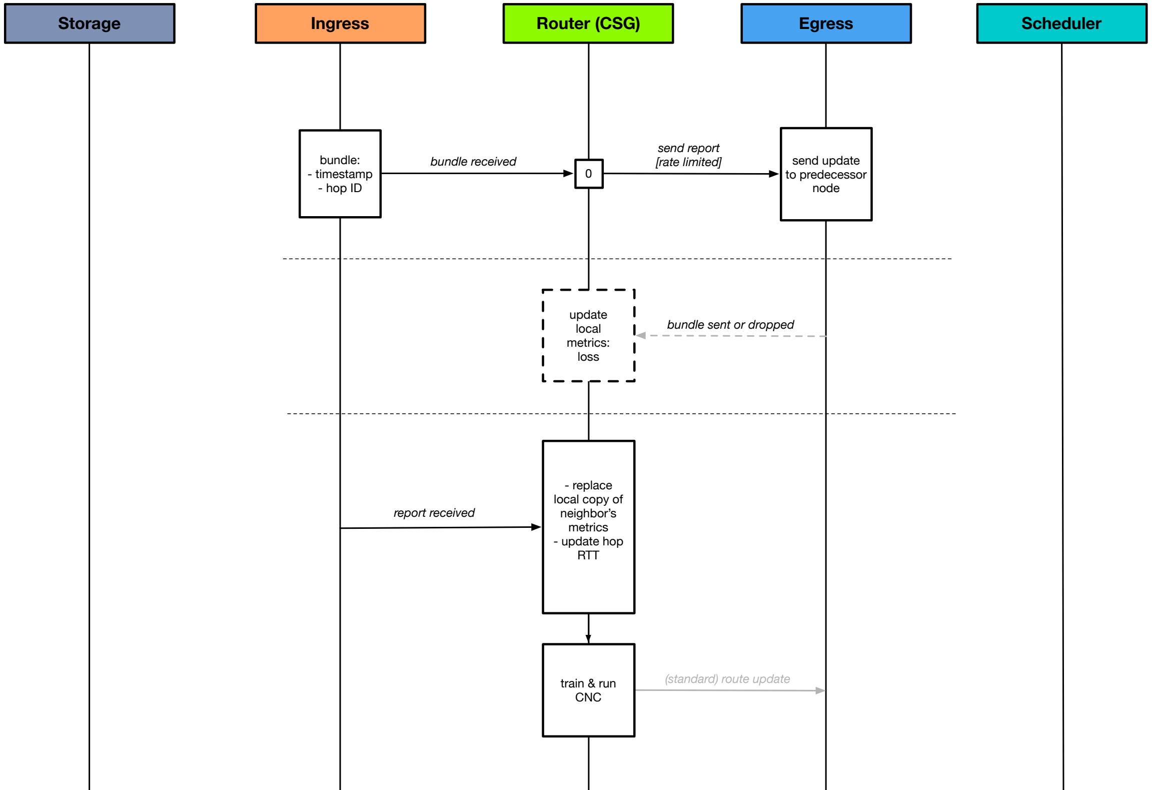
$$P_{i,d} = 1 - (1 - P_{i,j})(1 - P_{j,d})$$
$$C = \frac{1}{1 - P_{i,d}} \qquad (2)$$

- Delay-loss

$$C = \frac{T_{i,d}}{1 - P_{i,d}} \qquad (3)$$

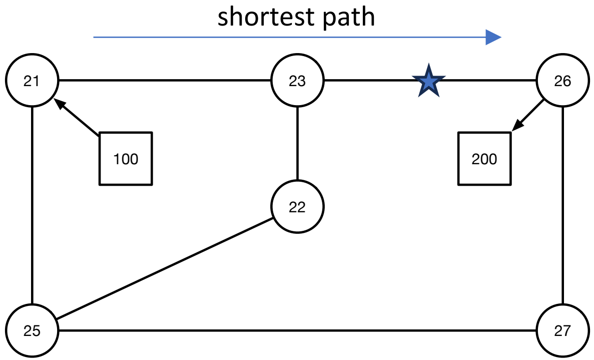
CSG Implementation for HDTN

- High-Rate DTN (HDTN) provides an implementation of DTN protocols for modern hardware platforms
- C++ and open-source libraries (Boost, 0MQ, OpenSSL, etc.)
- Modular design
- CSG router module implemented



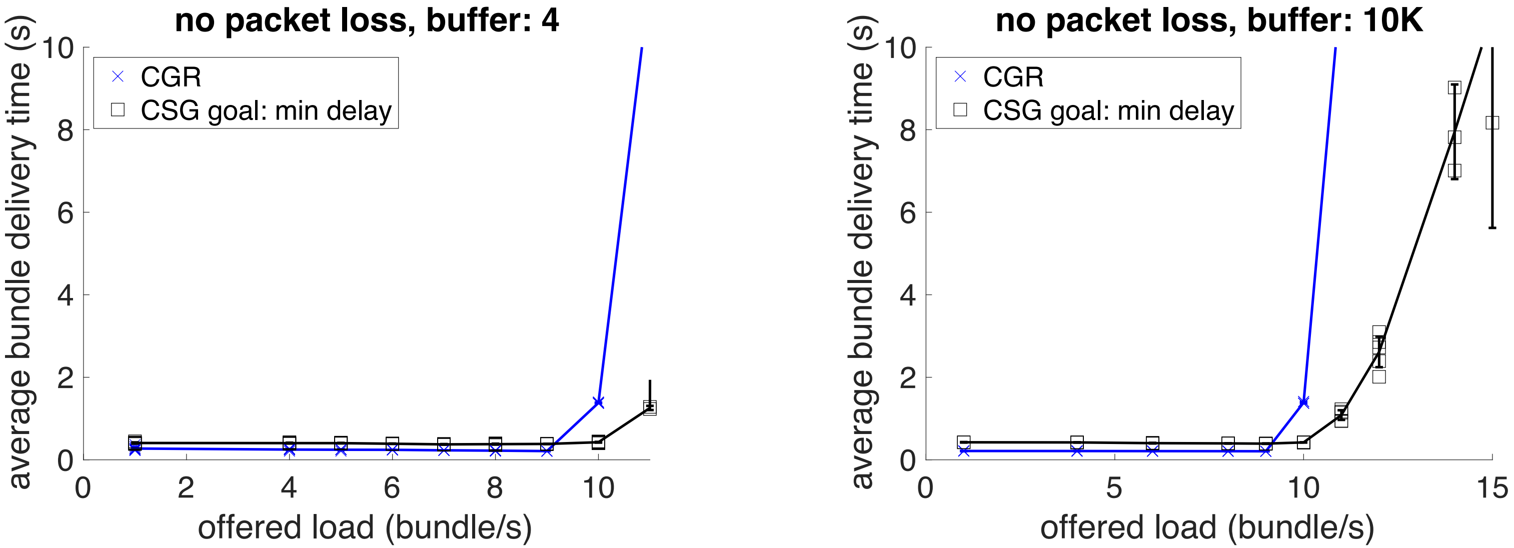
Experimental Evaluation

- Six R220 servers each equipped with six Ethernet ports
- Test flow:
  - *bpgen-async*: node 100 (running on node 21)
  - *bpsink-async*: node 200 (running on node 26)
- Links:
  - CAT-5 twister pair
  - 100 ms OWLT (propagation delay)
- Shortest path
  - 4 hops
  - 23-26 affected by loss



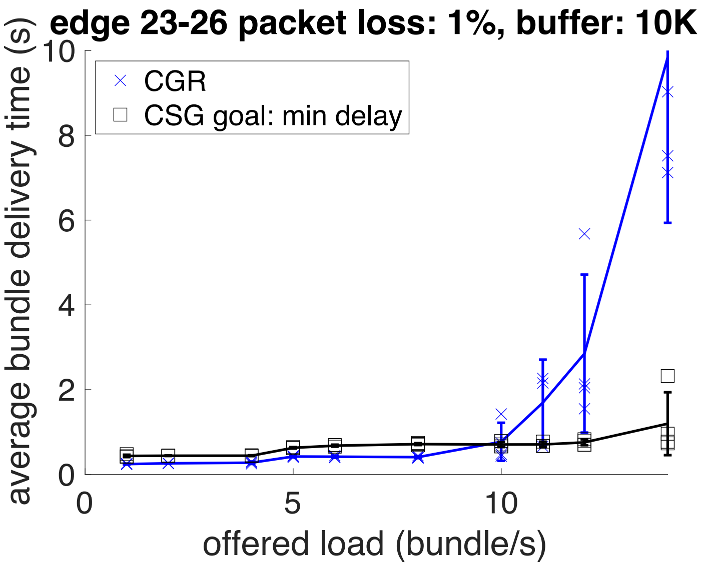
HDTN parameters	
udpRateBps	8×10^5 bps
maxNumberOfBundlesInPipeline	10^4
maxSumOfBundleBytesInPipeline	10^8 bytes
numRxCircularBufferBytesPerElement	65535 bytes
maxIngressBundleWaitOnEgressMilliseconds	100 ms
CSG parameters	
Exponential Moving Average factor (α)	0.1
Random walk probability (ϵ)	0.1
Learning factor (η)	0.01
CNC execution rate limit per destination (τ^{-1})	1
Max. path length	16

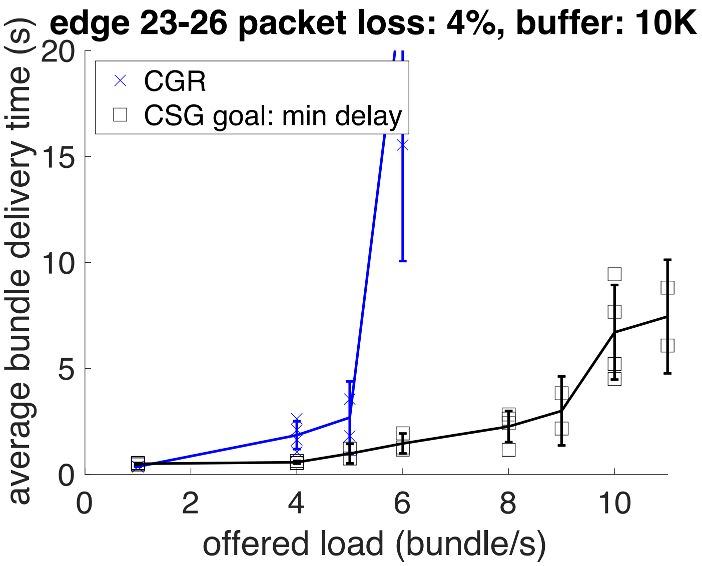
Min. Delay as Routing Goal (1)



- Impact of (UDP) CLA's buffer sizes (HDTN parameter)
- CSG performs slightly worse of low loads because exploration may involve the use of suboptimal routes

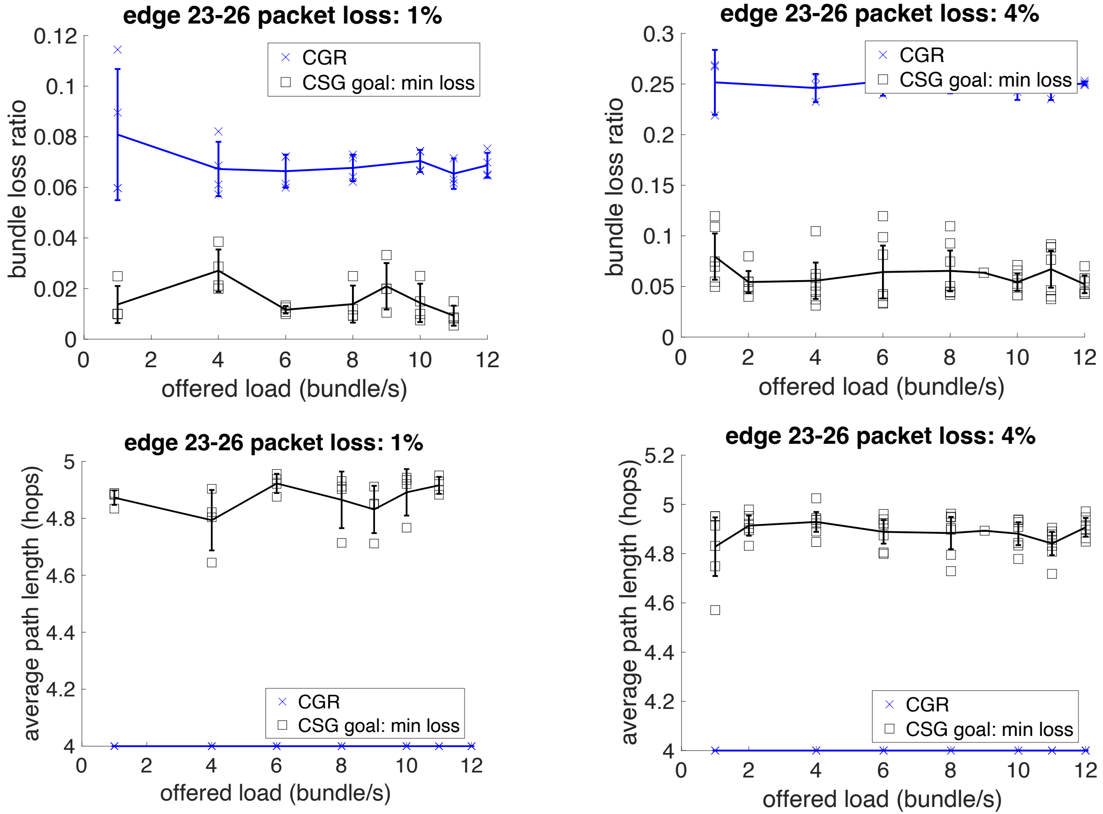
Min. Delay as Routing Goal (2)





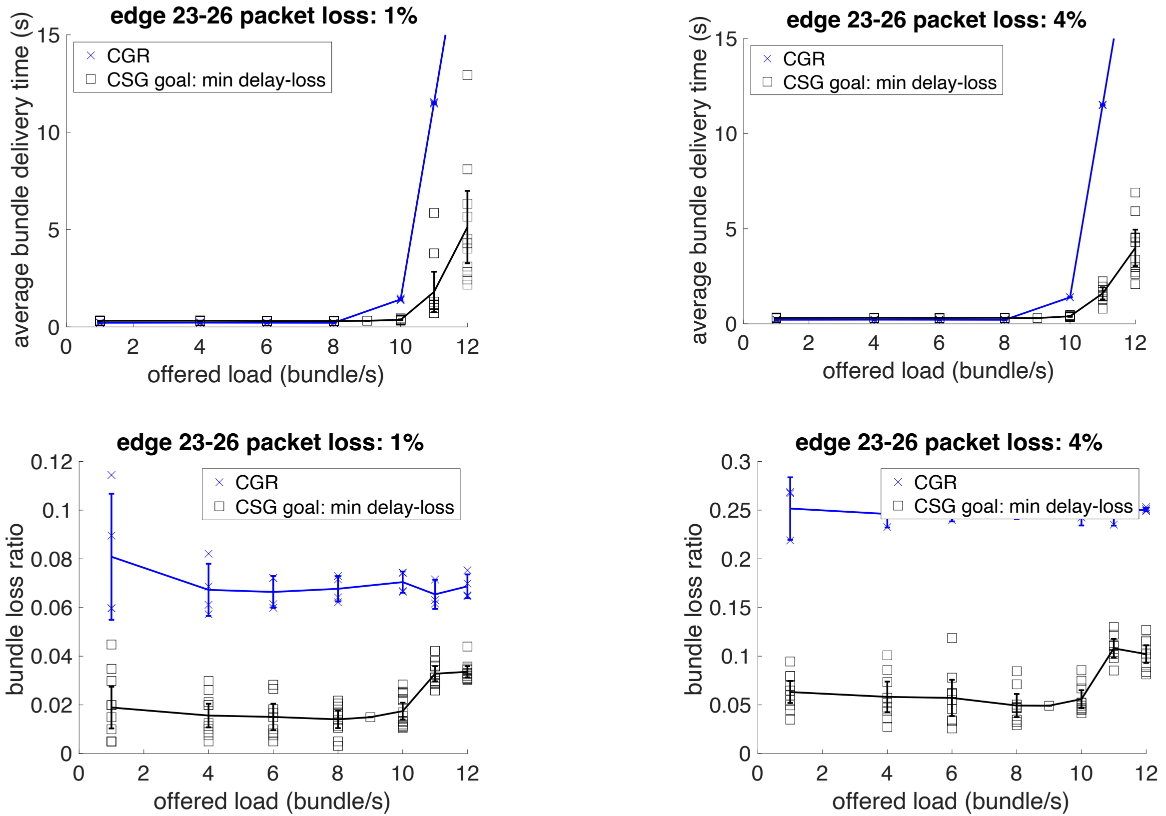
- CLA: *tcpcl_v3*
- Packet losses extend the average 23-26 hop bundle delivery time

Min. Loss as Routing Goal



- Best-effort CLA (UDP)
- Min. loss routing is approximately equivalent to max throughput routing

Delay-Loss as Routing Goal



Conclusion

- Enhanced the CSG algorithm for faster convergence and improved optimality
- Developed a dedicated CSG routing module for HDTN implementation
- Empirical experiments confirmed the efficacy of adaptive routing with the CSG, showing better performance than CGR for heavy traffic loads
- This work opens up future advancements and practical applications