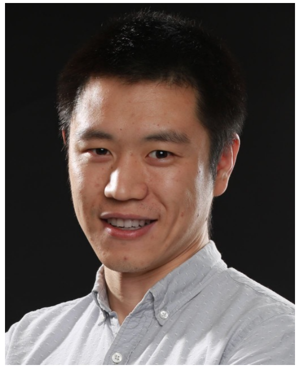
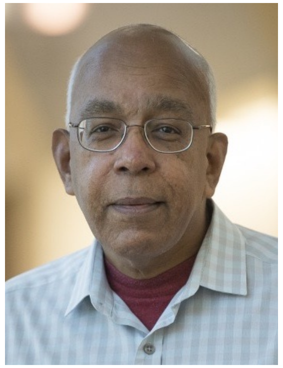
RICE UNIVERSITY

DEVCOM ARMY RESEARCH LABORATORY

Improve Latency of Backpressure Routing with Wireless Link Features



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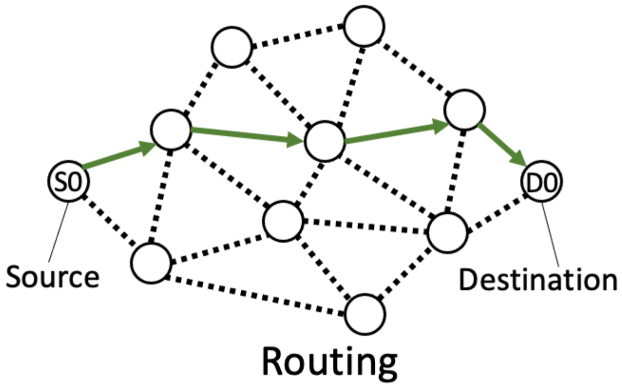
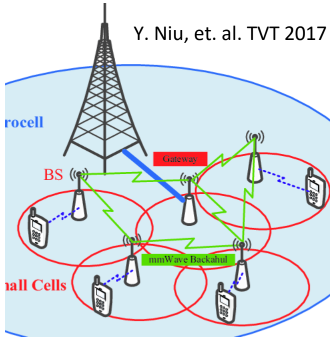
IEEE workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP)

Los Sueños, Costa Rica, December 10-13, 2023

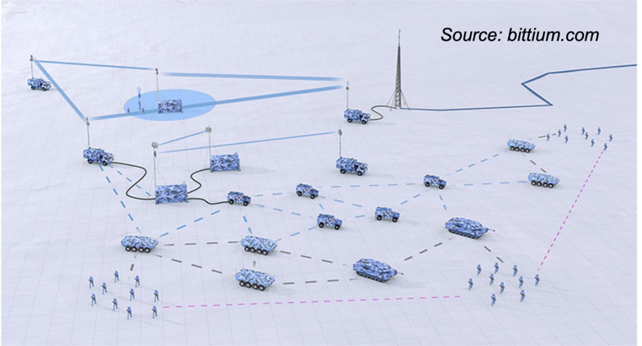
Backpressure (BP) Routing for Multihop Wireless Networks





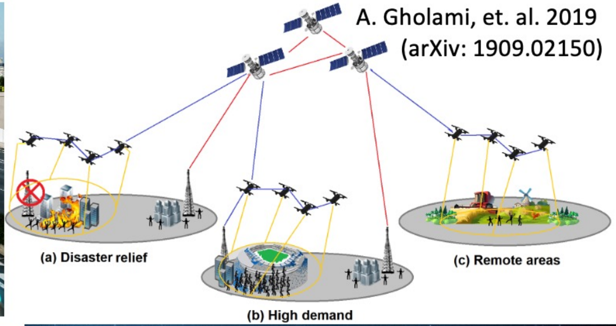
Y. Niu, et. al. TVT 2017

- Wireless Ad-hoc Networks
  - Military
  - Disaster relief
- Wireless Sensor Networks

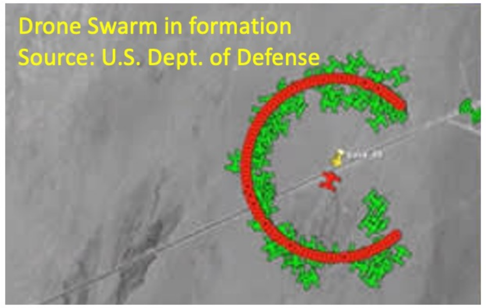

Source: bittium.com

- Wireless Backhaul Networks
  - Small cell backhaul
  - Drone/CubSat-assisted 5G/6G
  - Starlink
  - Rural/Agriculture broadband
- Machine-to-Machine Comm.
  - Internet-of-Things (IoT)
  - Connected vehicles
  - Drone fleet / Robotic Swarm
  - Smart factory


Graphic: Business Wire



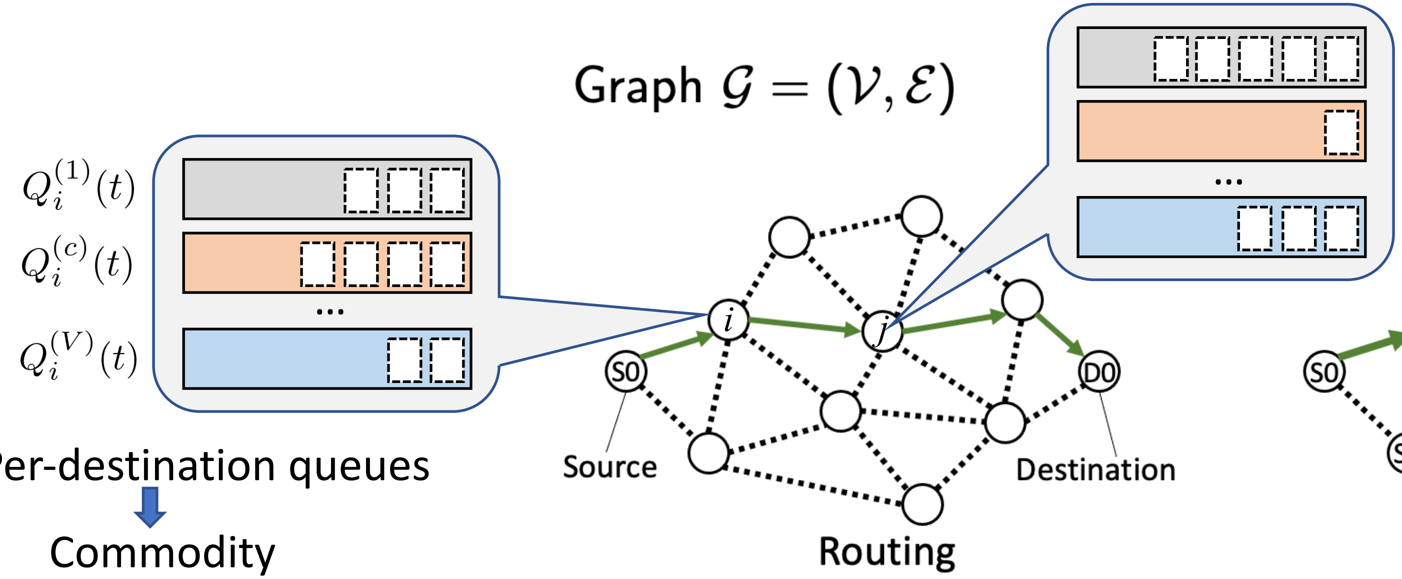
A. Gholami, et. al. 2019 (arXiv: 1909.02150)

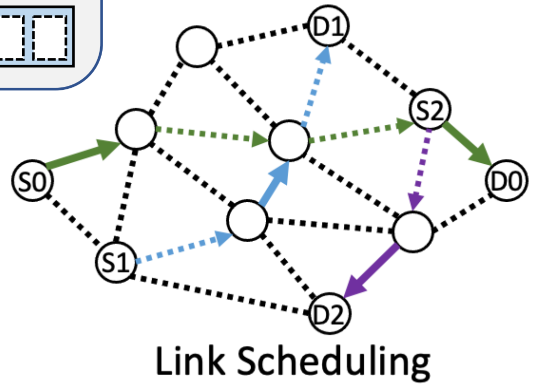

Drone Swarm in formation
Source: U.S. Dept. of Defense

Starlink, source: CyberHoot.com

Backpressure Routing*

✓Distributed Routing
✓Congestion prevention
✓Throughput optimality
✗Poor latency performance
- ✗Slow start
- ✗Loop
- ✗Last-packet problem





Source: zhongyuanzhao.com

1. Select optimal commodity $c^*_{ij}(t) = \underset{c \in \mathcal{V}}{\text{argmax}}\{U_i^{(c)}(t) - U_j^{(c)}(t)\}$

$U_i^{(c)}(t) = Q_i^{(c)}(t)$ Vanilla BP

$U_i^{(c)}(t) = Q_i^{(c)}(t) + B_i^{(c)}$ Biased BP

Shortest path-aware bias

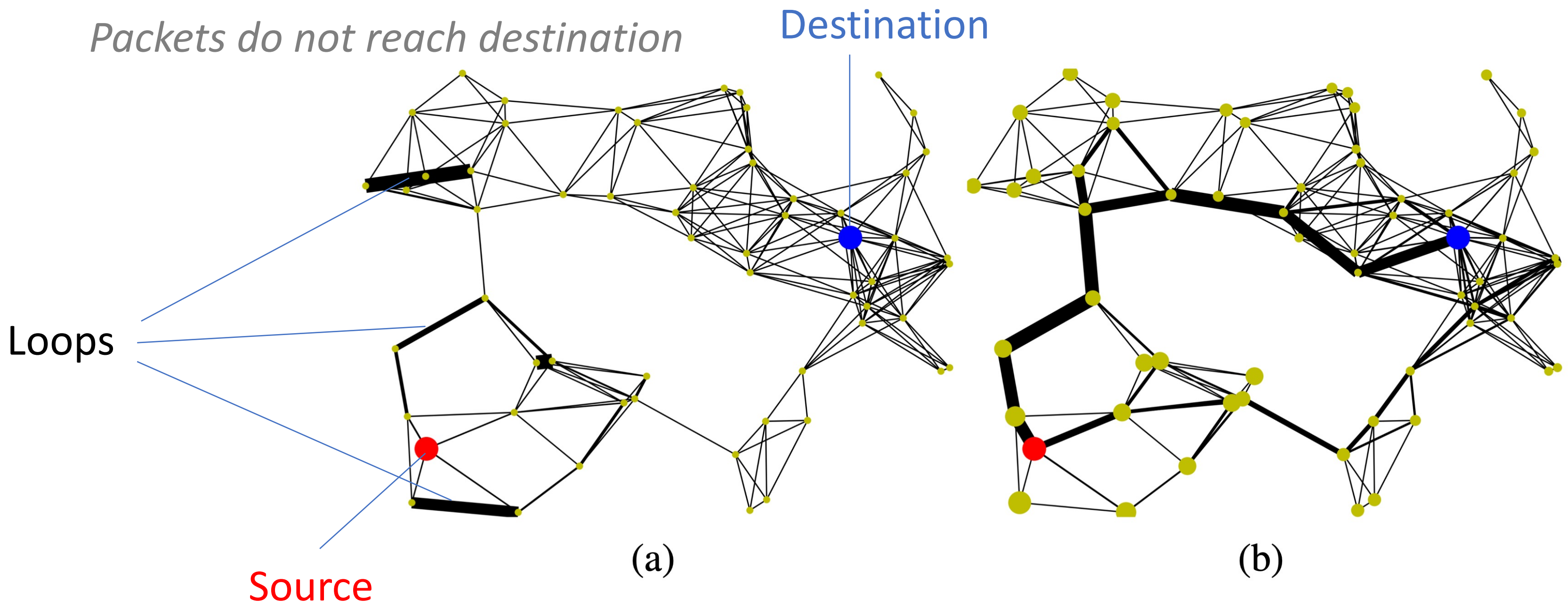
2. Find link gradient $w_{ij}(t) = \max\{U_i^{(c^*_{ij}(t))}(t) - U_j^{(c^*_{ij}(t))}(t), 0\}$

3. MaxWeight scheduling $\mathbf{l}^{BP}(t) = \underset{\mathbf{l}(t) \in \{0,1\}^{|\mathcal{E}|}}{\text{argmax}} \; \mathbf{l}(t)^\top \cdot [\mathbf{r}(t) \odot \mathbf{w}(t)]$

4. Assign link capacity $\mu_{ij}^{(c)}(t) = \begin{cases} r_{ij}(t), & \text{if } c = c^*_{ij}, w_{ij} > 0 \\ 0, & \text{otherwise} \end{cases}$

* L. Tassiulas, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," IEEE Trans. on Automatic Control, vol. 31, no. 12, 1992.

Vanilla v.s. biased BP routing



- ✓Distributed Routing
- ✓Path finding
- ✓Throughput optimality
- ✓~~Poor~~ latency performance
  - ✓ ~~Slow start~~
  - ✓ ~~Loop~~
  - ✓ ~~Last packet problem~~

Vanilla BP
Congestion gradient

Biased BP: shortest hop distance*
Congestion gradient + hop distance gradient

Route visualization: Normalized number of packets over links in 500 steps

Can we do better than shortest hop distance bias?

* M. Neely, E. Modiano, and C. Rohrs, "Dynamic power allocation and routing for time-varying wireless networks," IEEE J. Sel. Areas Commun., vol. 23, no. 1, pp. 89–103, 2005

Delay-aware shortest path bias based on link duty cycle*

How likely a link is scheduled under current network topology and traffics

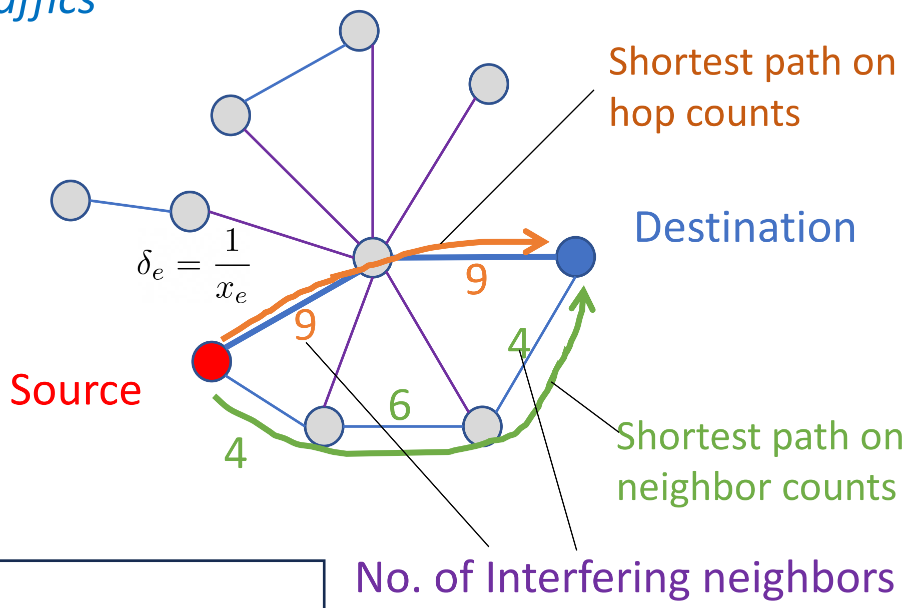
Link duty cycle $0 < x_e \leq 1 \quad e \in \mathcal{E}$

Per hop distance (edge weight)

Link duty cycle $\delta_e = \frac{1}{x_e}$

or

Link duty cycle and long-term link rate $\delta_e = \frac{\bar{r}}{x_e r_e}$



Link duty cycle predicted by a 5-layer graph convolutional neural network (GCNN)

$$\mathbf{x} = \Psi_{\mathcal{G}^c}(\mathbf{1}; \boldsymbol{\omega})$$

Fully distributed execution (layer l)

$$\mathbf{X}^l_{e*} = \sigma_l \left(\mathbf{X}^{l-1}_{e*} \mathbf{\Theta}^l_0 + \left[\mathbf{X}^{l-1}_{e*} - \sum_{u \in \mathcal{N}_{\mathcal{G}^c}(e)} \frac{\mathbf{X}^{l-1}_{u*}}{\sqrt{d(e)d(u)}} \right] \mathbf{\Theta}^l_1 \right)$$

Trainable weights; Output features; Non-linear activation; Input features; Set of neighbors; Node degree

* Zhao et. al., ”Delay-aware Backpressure Routing using Graph Neural Networks”, IEEE ICASSP 2023

Bias Scaling: A Closer Look at the Last Packet Problem

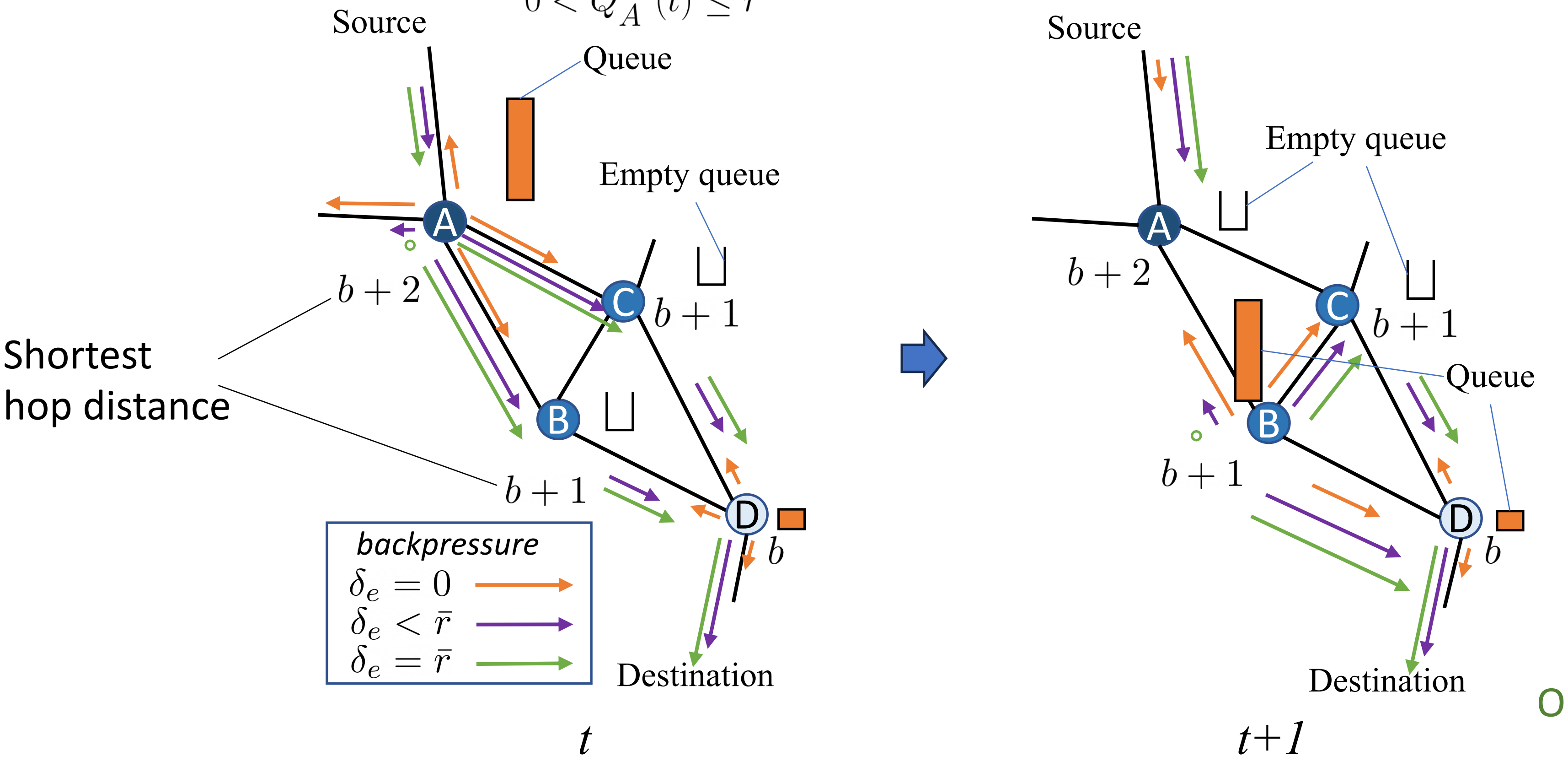
backpressure $w_{AB}(t) = \max\left\{Q_A^{(c^*)}(t) - Q_B^{(c^*)}(t) + B_A^{(c^*)} - B_B^{(c^*)}, 0\right\}$

How to determine K?

bias as K times shortest hop distance* $\delta_e = K$

the last packets

$0 < Q_A^{(c)}(t) \leq \bar{r}$



$\delta_e \geq \bar{r}$

Minimize the reversal of backpressure directions as the last packets traverse the network

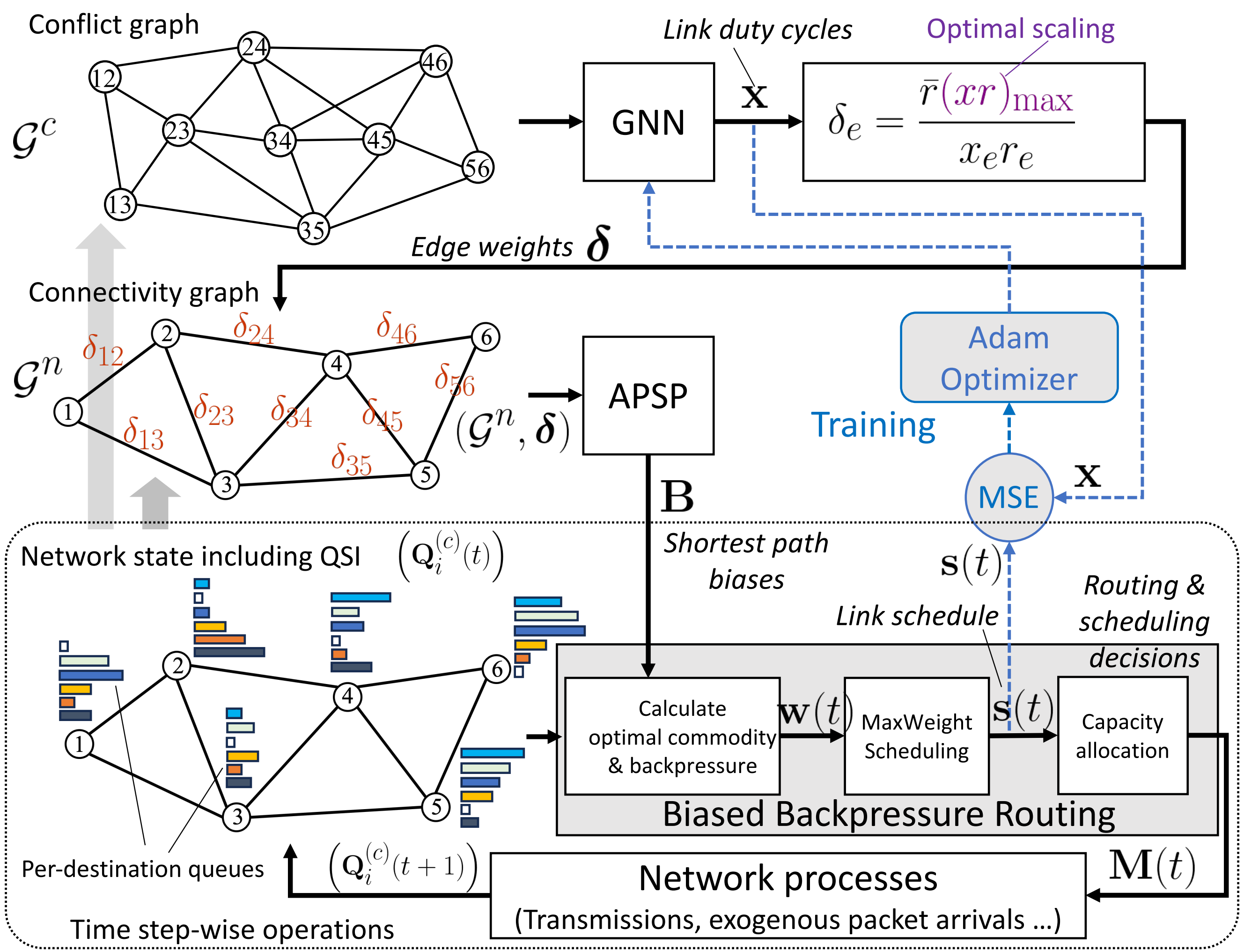
$$\min_{e \in \mathcal{E}} \delta_e := \bar{r}$$

Maximize the role of congestion gradient in path finding, while minimizing backpressure reversal

Optimal scaling of bias (or edge weights)

* M. Neely, E. Modiano, and C. Rohrs, "Dynamic power allocation and routing for time-varying wireless networks," IEEE J. Sel. Areas Commun., vol. 23, no. 1, pp. 89–103, 2005

Overall Architecture of SP-BP



Throughput optimality:
BP algorithm can stabilize the queues in the network as long as the arrival rates of flows are within the network capacity region

*Queue-agnostic shortest path bias (non-negative) retains the throughput optimality of vanilla BP**

* M. Neely, E. Modiano, and C. Rohrs, "Dynamic power allocation and routing for time-varying wireless networks," IEEE J. Sel. Areas Commun., vol. 23, no. 1, pp. 89–103, 2005

Bias Maintenance

(rounds of message exchanges)

- Additional Complexity of SP-BP
  - GCNN $\mathcal{O}(L)$
  - Single source shortest path (SSSP)
  - All pairs shortest path (APSP)

Distributed weighted SSSP and APSP

$$\mathcal{O}(V)$$

GCNN and SP algorithms only need to run once a while, when topology changes

- Bias Maintenance
  - nodes move around
  - nodes join or leave the network
- Neighborhood Update

$$B_i^{(c)}(t+1) = \begin{cases} \min_{j \in \mathcal{N}(i)} \left[B_j^{(c)}(t) + \delta_{ij}(t) \right], & i \neq c \\ 0, & i = c \end{cases}$$

No additional communication rounds, increased message size in regular signaling required by vanilla BP scheme

* M. Neely, E. Modiano, and C. Rohrs, "Dynamic power allocation and routing for time-varying wireless networks," IEEE J. Sel. Areas Commun., vol. 23, no. 1, pp. 89–103, 2005

Exponential Queue (*expQ*)

Queue State Information (QSI)

No. of packets transmitted by node i

No. of external packets arrive at node i

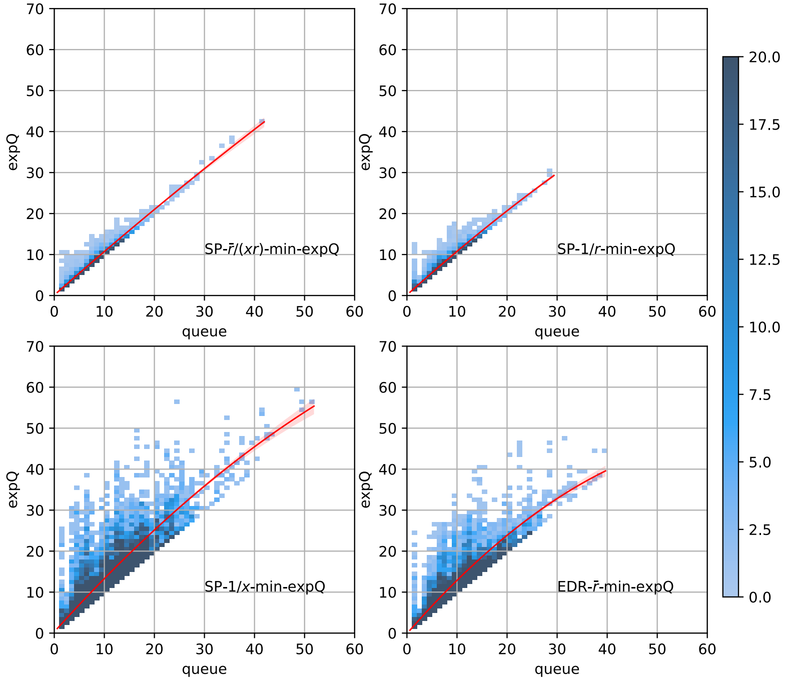
$$g\left(\mathbf{Q}_i^{(c)}(t+1)\right) = (1+\epsilon)\, g\left(\mathbf{Q}_i^{(c)}(t)\right) \max\left[1 - \frac{M_{i-}^{(c)}(t)}{Q_i^{(c)}(t)}, 0\right] + M_{i+}^{(c)}(t) + A_i^{(c)}(t)$$

Compounding parameter

Queue length

No. of packets received by node i

$$0 < \epsilon \ll 1$$



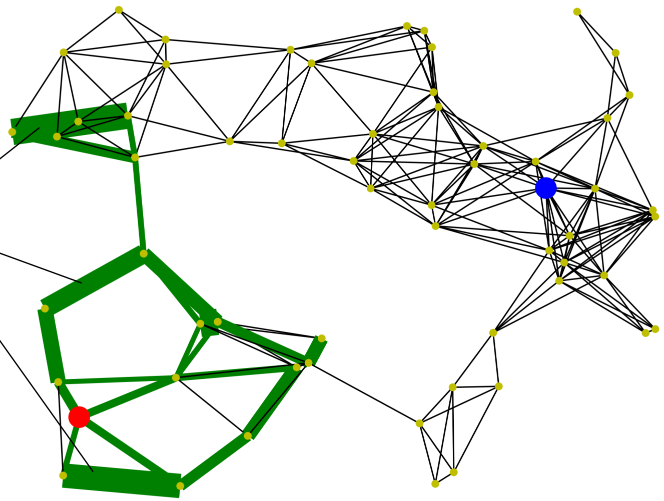
Routes Visualization

number of packets transmitted in both directions

Nodes distribution:
2D Poisson process model

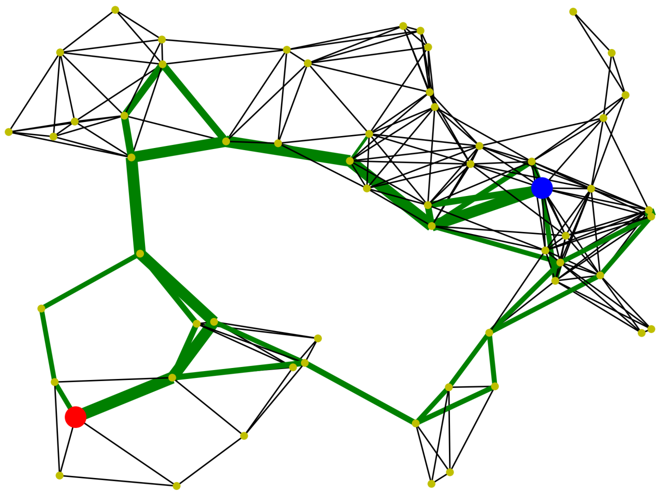
60 nodes, 19 flows, 500 time steps, edge width $1 + \sqrt[3]{n}$

Trapped in loops



Routes not established in 500 steps, no packet delivery!

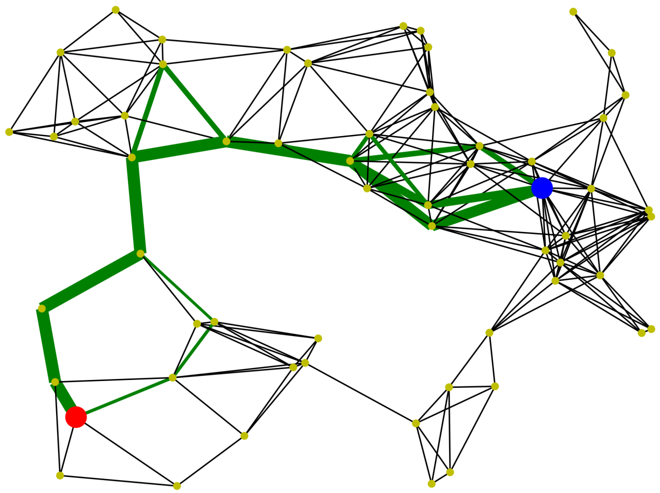
Basic BP scheme



Routes established quickly, packets delivered, less loops

Enhanced Dynamic Routing*
(with optimal bias scaling)

$$\delta_e = \bar{r}$$



Routes are more concentrated, but not just shortest path routing (single path)

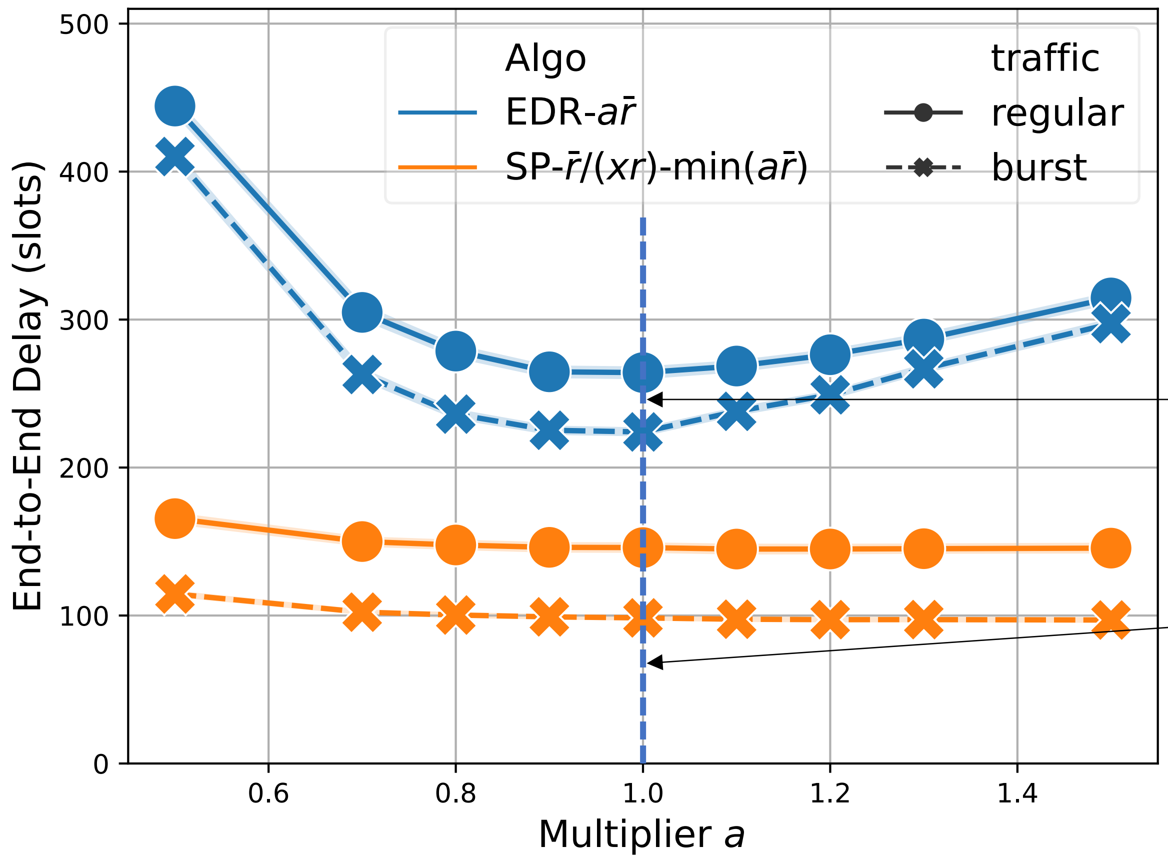
GCNN-enhanced SP-BP

$$\delta_e = \frac{\bar{r}}{x_e r_e}$$

* M. Neely, E. Modiano, and C. Rohrs, "Dynamic power allocation and routing for time-varying wireless networks," IEEE J. Sel. Areas Commun., vol. 23, no. 1, pp. 89–103, 2005

Optimal Bias Scaling

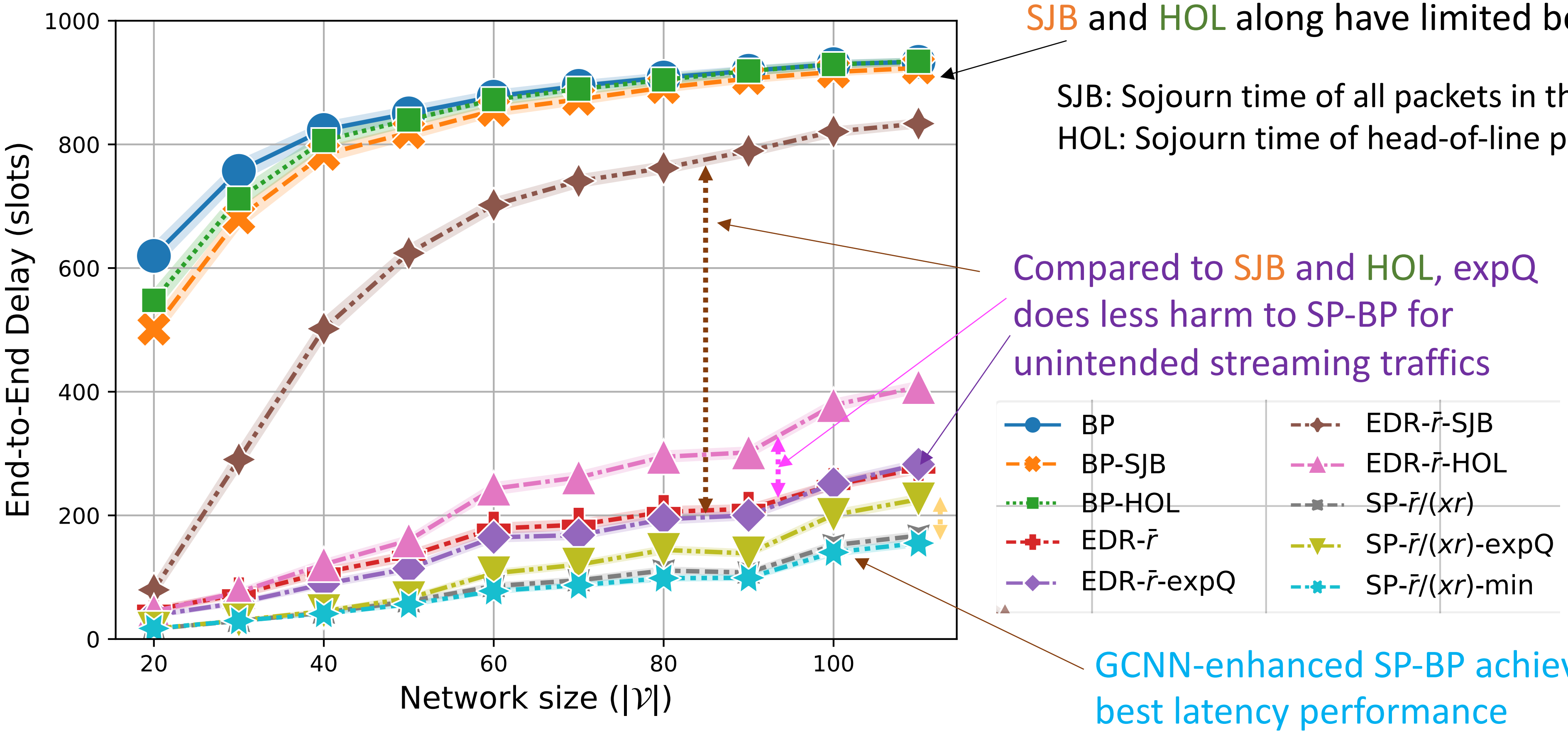
$$\min_{e\in\mathcal{E}} \delta_e := a\bar{r}$$



$$\delta_e = \bar{r}$$

$$\delta_e = \frac{\bar{r}(xr)_{\max}}{x_e r_e}$$

End-to-End Delay for Streaming Traffics $\lambda(f) \in \mathbb{U}(0.2, 1.0)$



SJB and HOL along have limited benefit

SJB: Sojourn time of all packets in the queue *

HOL: Sojourn time of head-of-line packet in the queue **

Compared to SJB and HOL, expQ does less harm to SP-BP for unintended streaming traffics

GCNN-enhanced SP-BP achieves best latency performance

On 100 random graphs from **2D Poisson model,** T=1000 Unit-disk interference model (wireless sensor/ad-hoc networks)

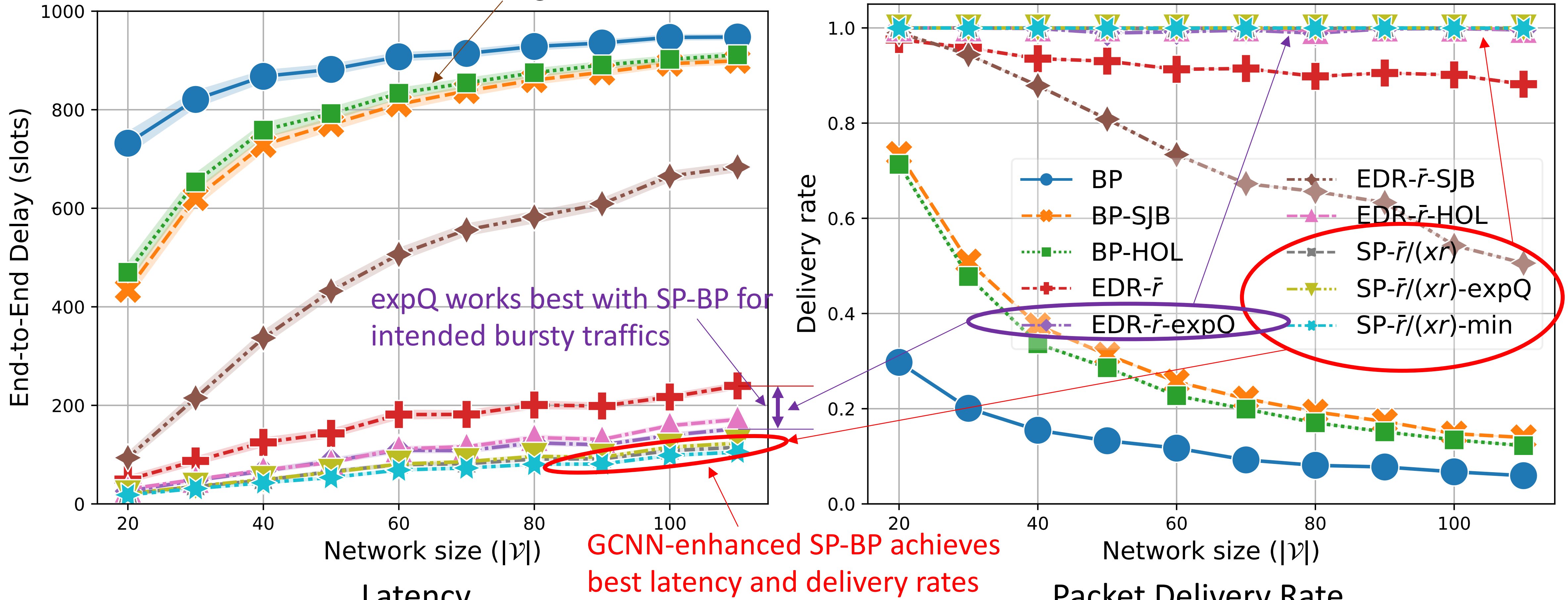
* L. Hai, Q. Gao, J. Wang, H. Zhuang, and P. Wang, "Delay-optimal back-pressure routing algorithm for multihop wireless networks," IEEE Trans. Vehicular Tech., vol. 67, no. 3, pp. 2617–2630, 2018

** . Ji, C. Joo, and N. B. Shroff, "Delay-based back-pressure scheduling in multihop wireless networks," IEEE/ACM Trans. Netw., vol. 21, no. 5, pp. 1539–1552, 2012.

Performance under Bursty Traffics

$$\lambda(f) \in \mathbb{U}(2.0, 10.0), t < 30$$
$$\lambda(f) = 0, t \geq 30$$

SJB and HOL along have limited benefit



Latency

Packet Delivery Rate

On 100 random graphs from **2D Poisson model,** T=1000

Unit-disk interference model (wireless sensor/ad-hoc networks)

Performance under Network Mobility

Mobility setting: every 100-time steps, 10 nodes take a small random step while keeping the network connected.

Instantaneous ASAP (Impractical) → Ideal

Neighborhood update (practical) → Neighbor

	EDR-$\bar{r}$		SP-$\bar{r}/(xr)$	
Bias update	Delay (std.)	Delivery (std.)	Delay (std.)	Delivery (std.)
Ideal	278.3 (106.1)	81.2% (8.7%)	**155.2** (80.9)	**90.8%** (6.1%)
Neighbor	331.8 (103.8)	75.7% (9.1%)	**282.5** (87.5)	**78.5%** (7.8%)

On 10 random graphs of 100 nodes from **2D Poisson model,** T=1000

Unit-disk interference model (wireless sensor/ad-hoc networks)

Streaming Traffics $\lambda(f) \in \mathbb{U}(0.2, 1.0)$

Conclusion & Future directions

- Advancements for shortest path-biased backpressure (SP-BP)
  - Link duty cycle + Long-term link rate → delay-aware edge weight
  - Optimal bias scaling
  - Network mobility: Low-overhead bias maintenance
  - Prioritize older packets: expQ + SP-BP
- Advantages of SP-BP schemes
  - Significantly improve end-to-end delay & delivery rate
  - Fully distributed execution
  - Minimal increase in complexity & overhead (update only once a while)
- Address uncertainties in link features
- Address varying levels of network mobility