Routing Without Routes
The Backpressure Collection Protocol

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Introduction

Why do we need a new routing protocol for sensor networks?

- There exist real-world sensing applications requiring high data rate[a]
- 802.15.4 Radios are highly susceptible to external interference
- Link variability even in the absence of external interference
- Sink mobility, particularly in new participatory sensing paradigms

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[a] Volcano, construction and cane toad monitoring. Multi-hop capacity < 4 KBps.

This work in a nutshell:

We present the Backpressure Collection Protocol, a novel routing approach that does hop-by-hop per-packet forwarding rather than computing end-to-end paths.

BCP is joint work with Avinash Sridharan, Bhaskar Krishnamachari and Omprakash Gnawali

Basics of Backpressure Routing

Routing and forwarding based on distributed weight computations:

$$w_{i,j}(t) = (\quad [Q_i(t) - Q_j(t)] \quad - \quad V \cdot ETX_{i,j}(t) \quad) \cdot R_{i,j}(t)$$

Routing Control Decision:

Node i identifies the outbound link with greatest weight w_{i,j^*}

Forwarding Control Decision:

If $w_{i,j^*} > 0$ then forward the packet, else wait time T.

How do packets find their way to the sink?

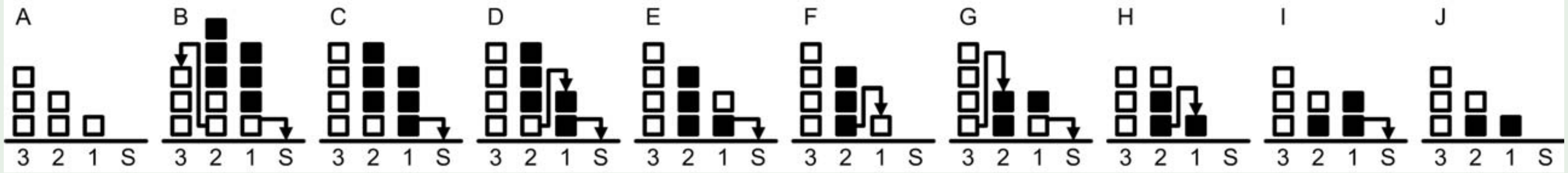
$$w_{i,j}(t) = \left(\quad [Q_i(t) - Q_j(t)] \quad - \quad V \cdot ETX_{i,j}(t) \quad \right) \cdot R_{i,j}(t)$$

The sink is the only node that can pull the packets from the network

- The sink has zero queue backlog
- Link weight computations generate gradients toward the sink
- Per-hop queue differentials are impacted by link cost

A simple linear example

$$V \cdot ETX_{i,j} = 1 \quad R_{i,j} = 1$$



Theory Background

Theoretical Relationship

- Backpressure routing of BCP is a distributed approximation to the centralized queue backpressure scheduling

Theoretical Origins: Lyapunov Drift-Based Stochastic Optimization

- Based on work by Tassiulas and Ephremides '92
- Extended by Neely '03, Georgiadis *et al.* '05, to include utility optimization

Objective

Minimize time average expected system transmissions while maintaining strongly stable queues:

$$\begin{aligned} \min \quad & f(\bar{x}) \\ \text{s.t.} \quad & \limsup_{t \to \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}[Q_i(\tau)] < \infty \text{ for all } i \end{aligned}$$

Translating from Theory to Practice

BCP is the First Ever Systems Implementation of Backpressure Routing

- We have implemented the first ever backpressure routing protocol for many-to-one wireless sensor networks.
- Written for TinyOS 2.x, a large market share embedded operating system
- Implemented over IEEE 802.15.4 compliant radios

Packet Looping

Addressed by using ETX as a link penalty

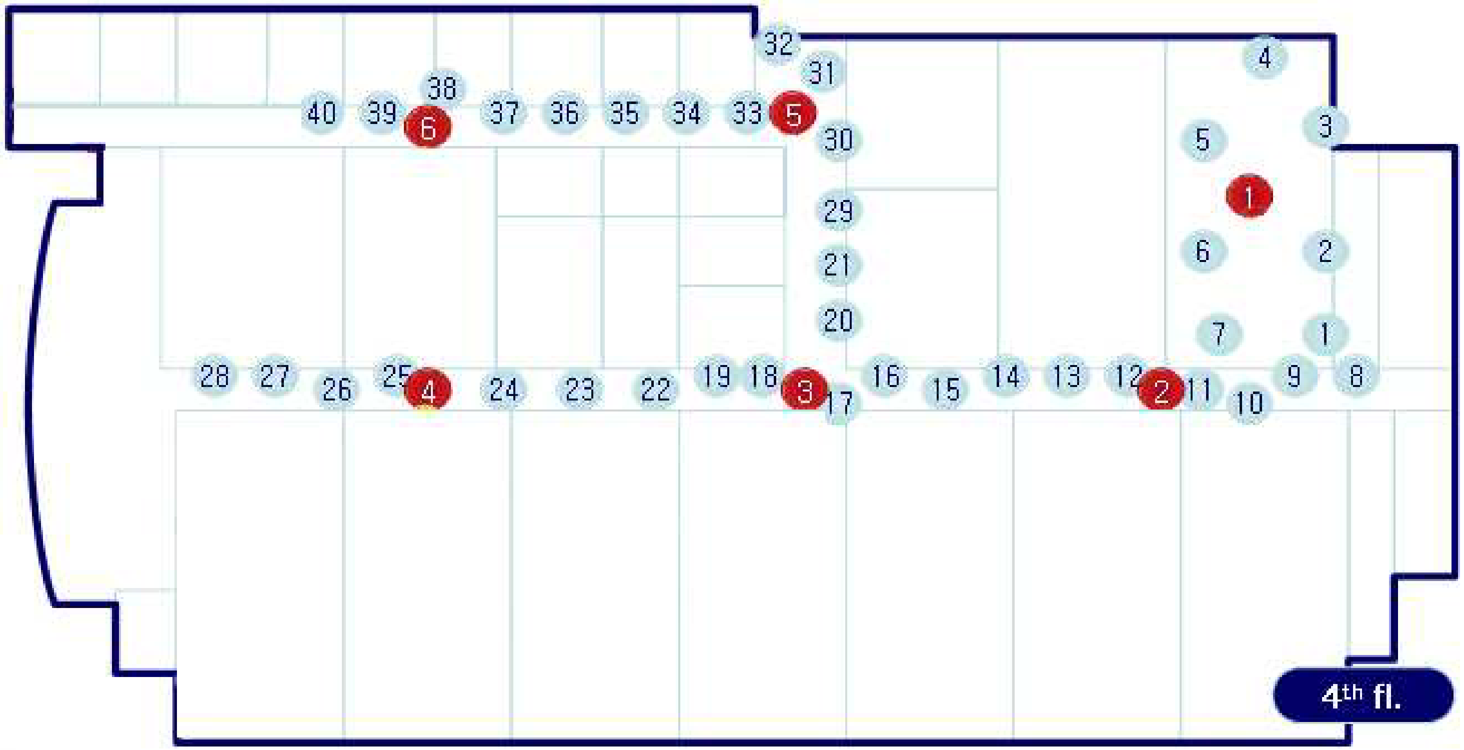
Packet Delivery Delay

Addressed by use of LIFO service priority

Scalability

Support for queue scaling through Floating Queues

Static Network Testbed Configuration



Network Parameters

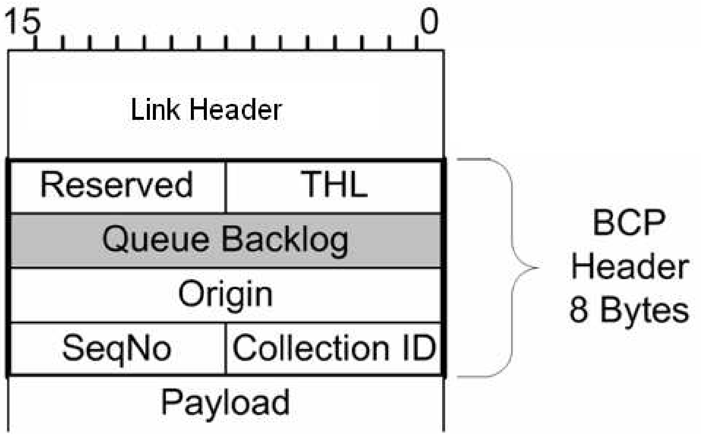
- Motes 1-40 on Tutornet
- 802.15.4 channel 26
- Transmit power -18 dBm
- Sink mote 1
- Source motes 2-40
- Poisson arrivals

Comparison with the Collection Tree Protocol

We benchmark BCP against the state-of-the-art Collection Tree Protocol [Gnawali *et al.*, Sensys 2009] (CTP) for TinyOS 2.x.

Packet Overhead

The header added by BCP is 8 bytes, the same size as that used by CTP. BCP Does not use periodic beacon mechanisms, and therefore has no beacon control overhead.



Max-Min Achievable Goodput

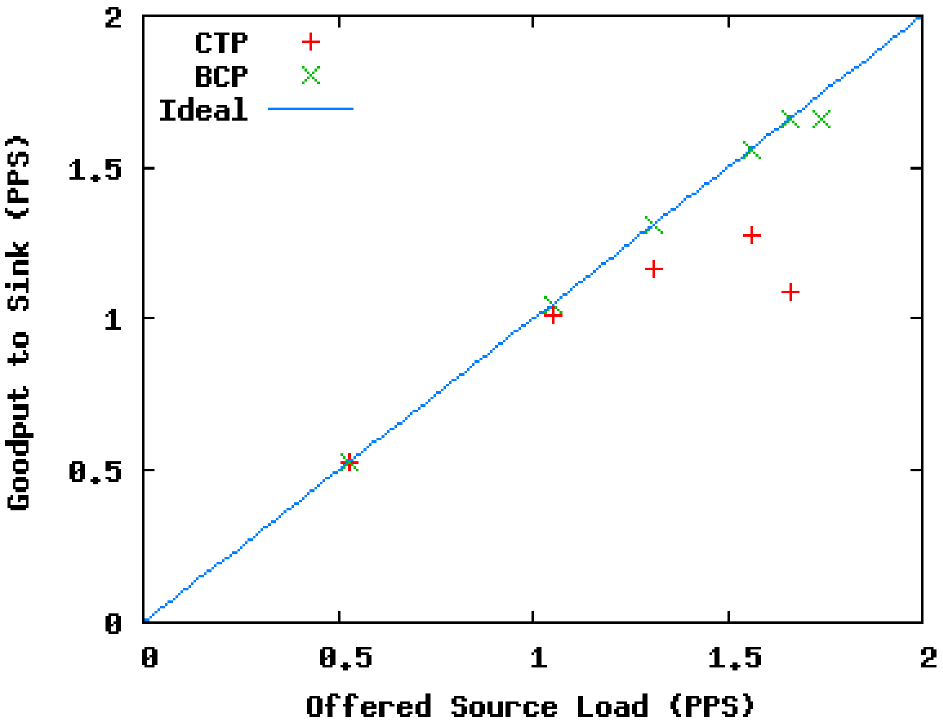
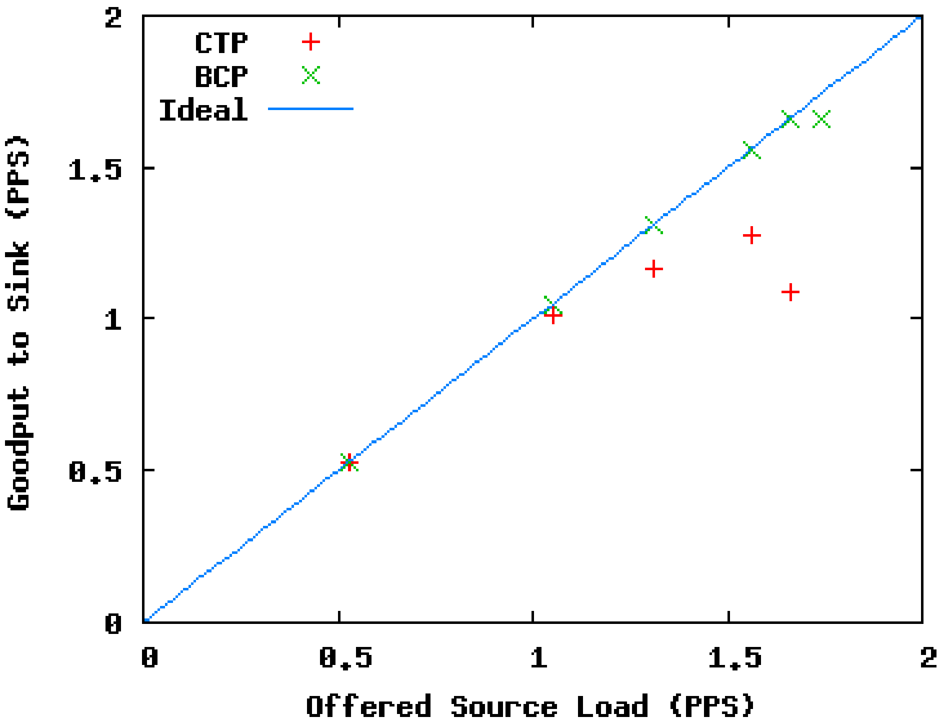


Figure: Per source Goodput versus source rate.

Max-Min Achievable Goodput



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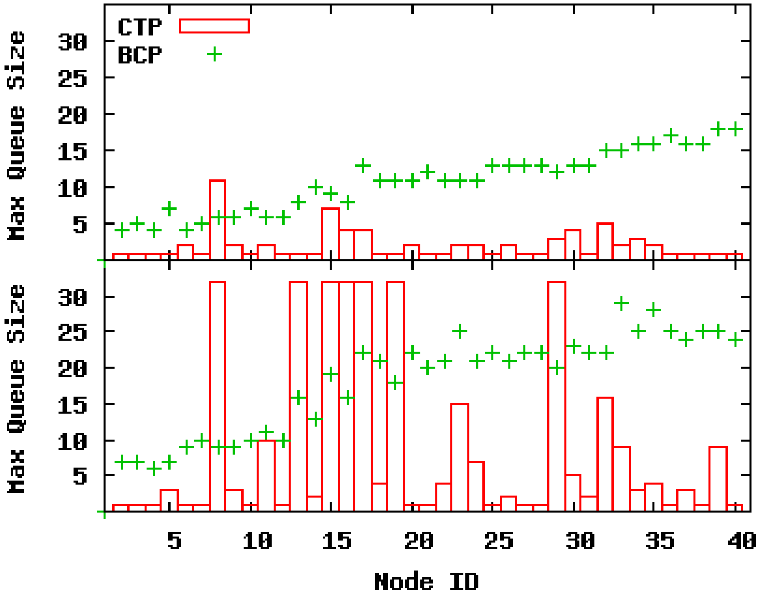
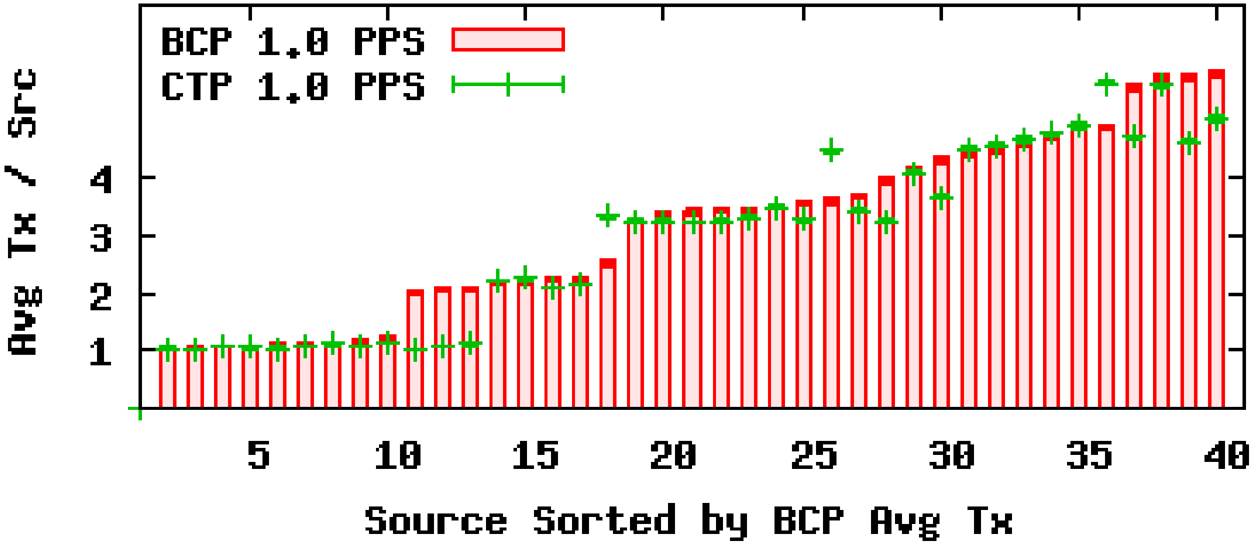


Figure: Maximum queue size over 35 minute experiment at 0.5 and 1.5 packets per second per source.

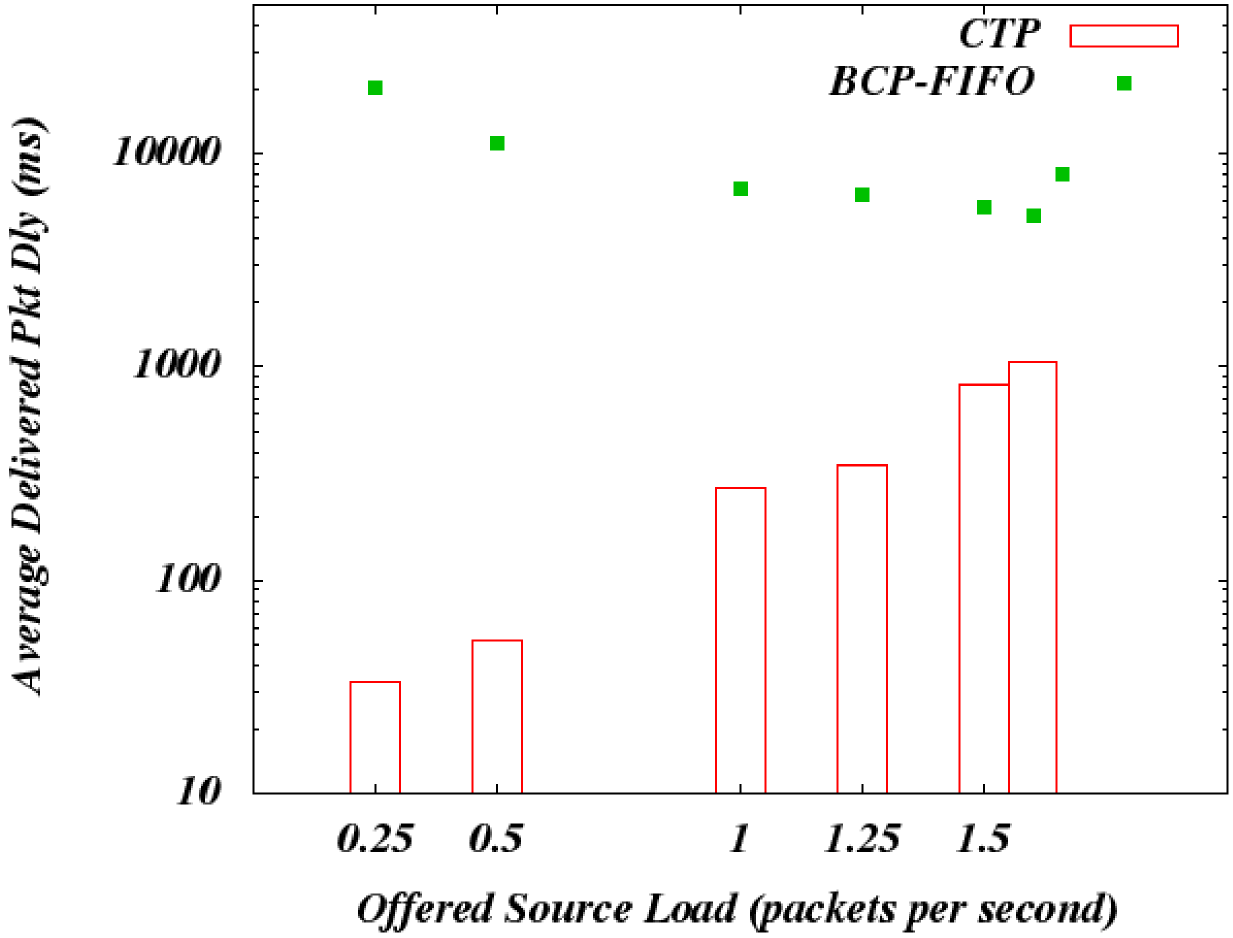
A Comparison of Packet Delivery Efficiency



Source-to-Sink transmissions per packet delivered

- Using only data-driven link estimation, BCP performs competitively with CTP
- Static network packet transmission efficiency is not a factor in improved network capacity

Empirical FIFO Delay Results



Delivered Packet Delay

Persistent minimum backlogs and FIFO service priority impacts delivered packet delay tremendously.

Closure of the Low Rate Delay Gap Using LIFO

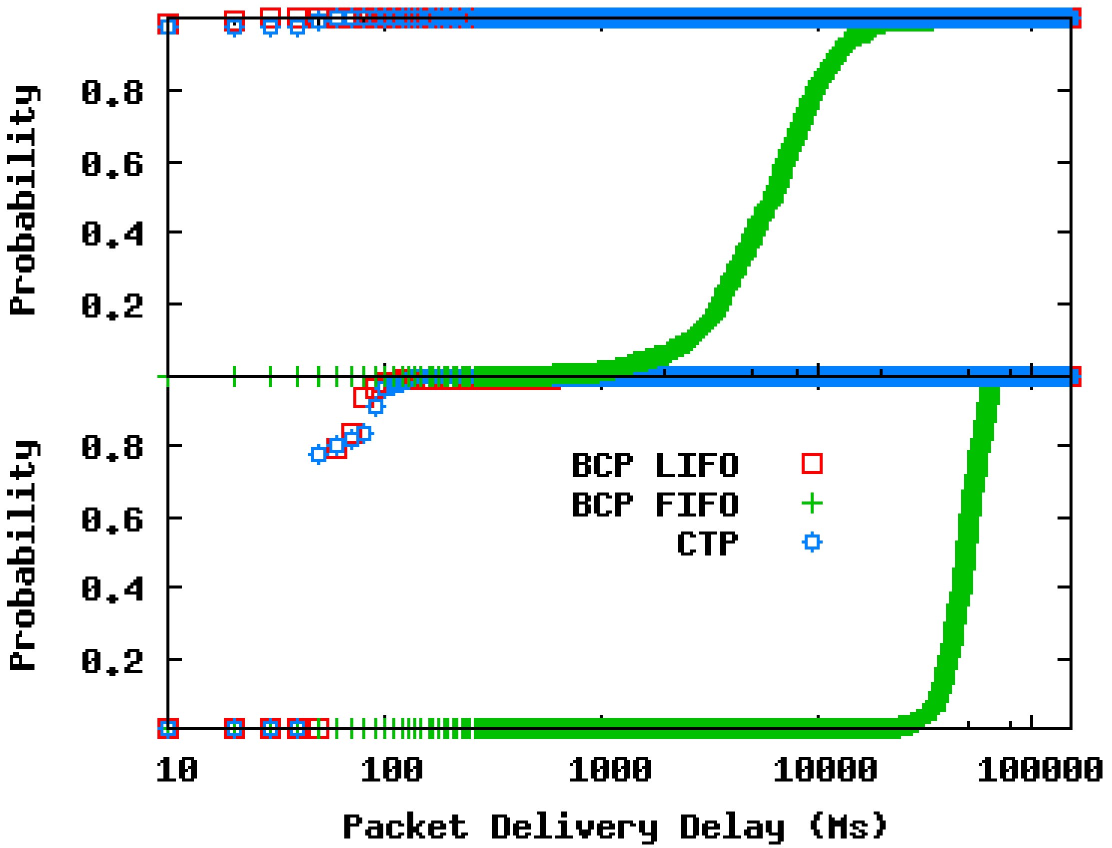


Figure: Delivered packet delay CDF for node 4 (1 hop, top) and 40 (4 hops, bottom) at 0.25 PPS/Source. System average delivered packet delay is reduced by more than 98% through LIFO usage.

An Intuitive Motivation for Our LIFO Innovation

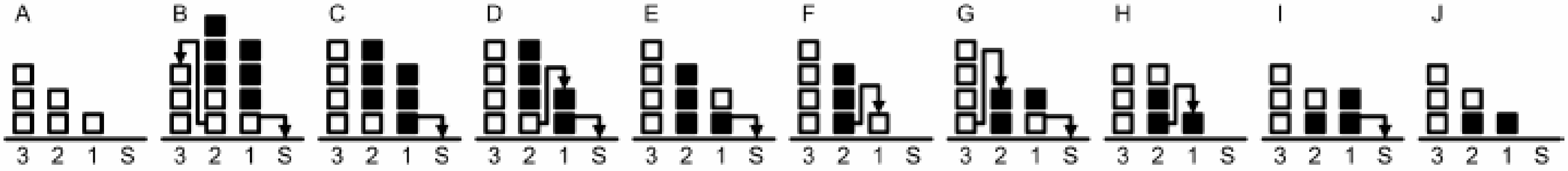


Figure 1: An intuitive example of backpressure routing on a four-node line network with FIFO queueing service. Three packets (in black) are injected at nodes 1 and 2 at time B, intended for the destination sink S.

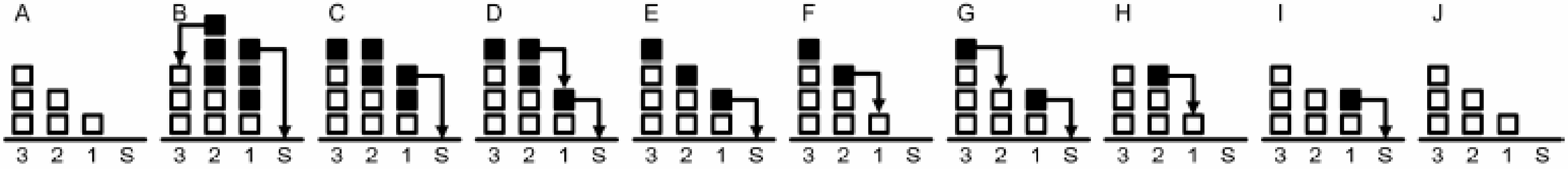
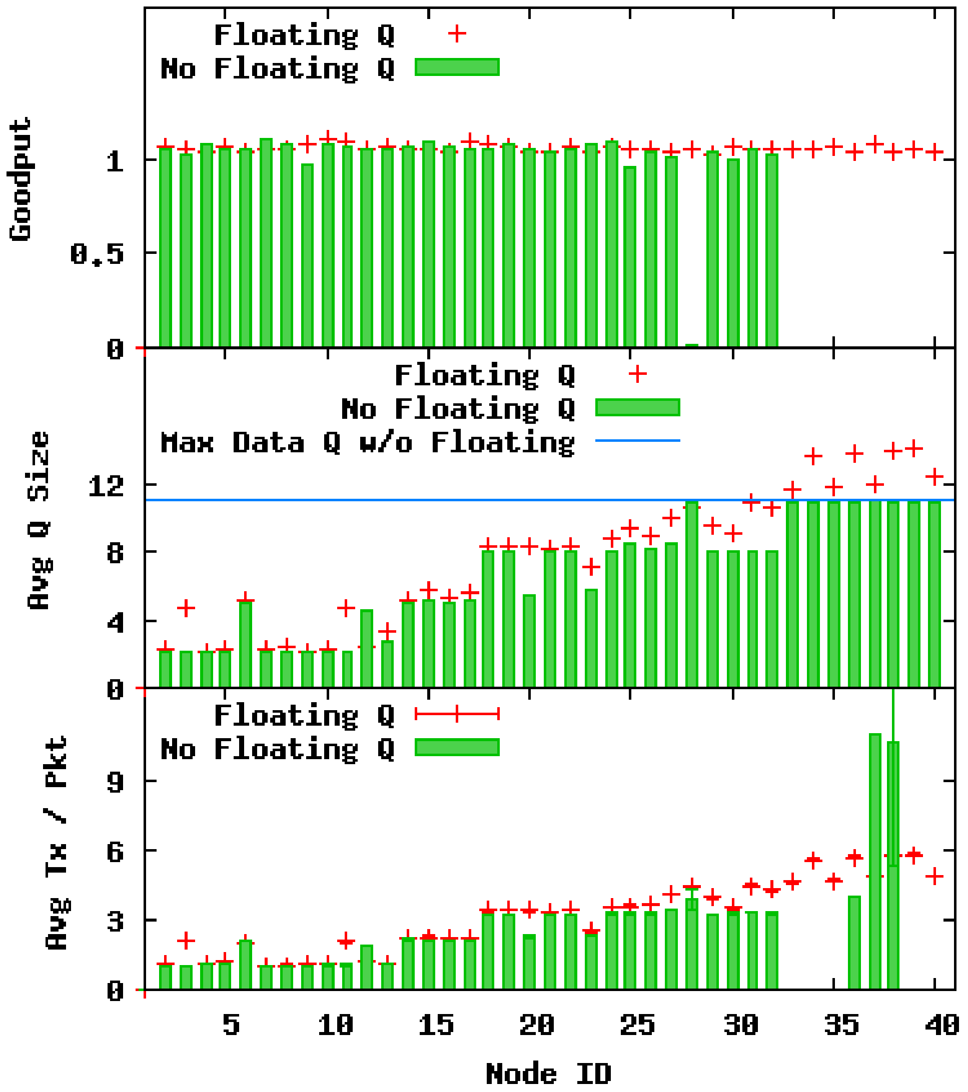


Figure 3: The four-node network of Figure 1, now with LIFO service priority. New additions to the queues flow over the existing gradient to the sink.

The Floating Queue: Our Support for Scalability



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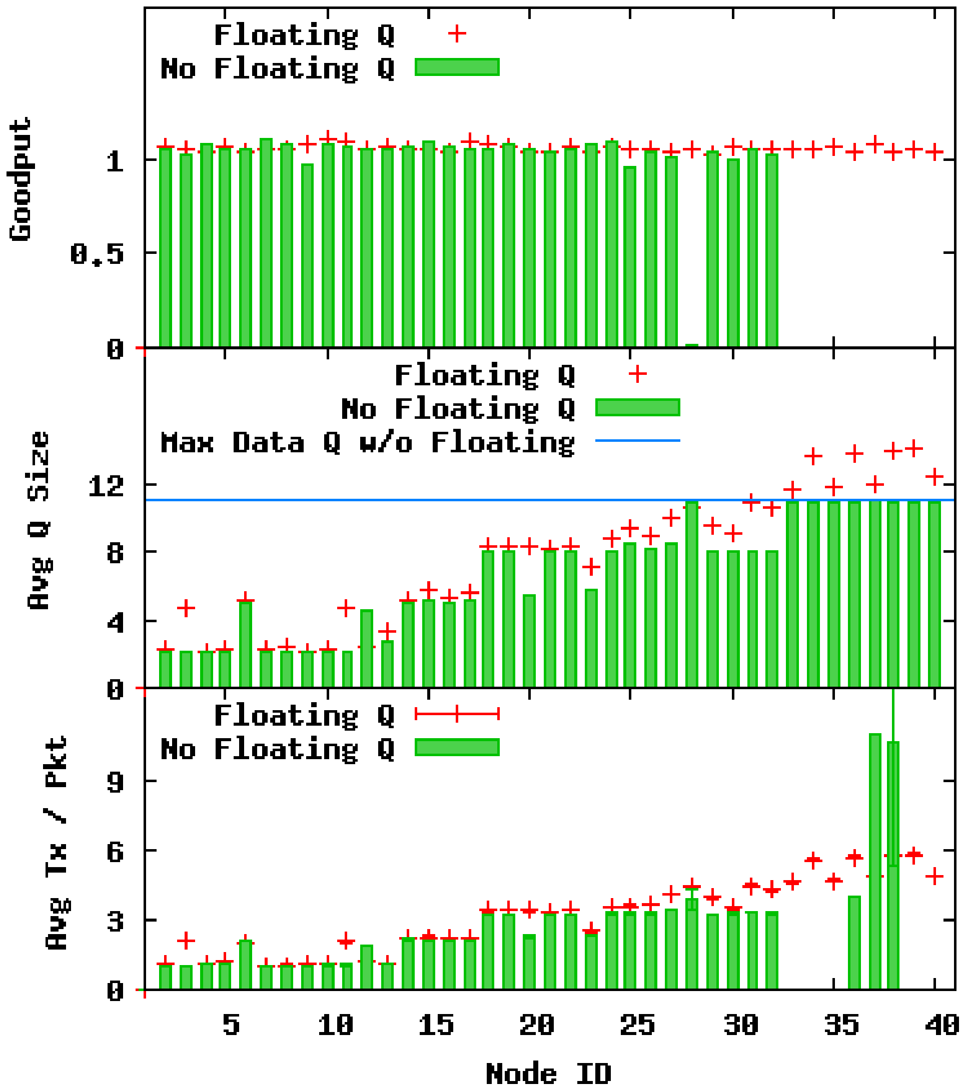
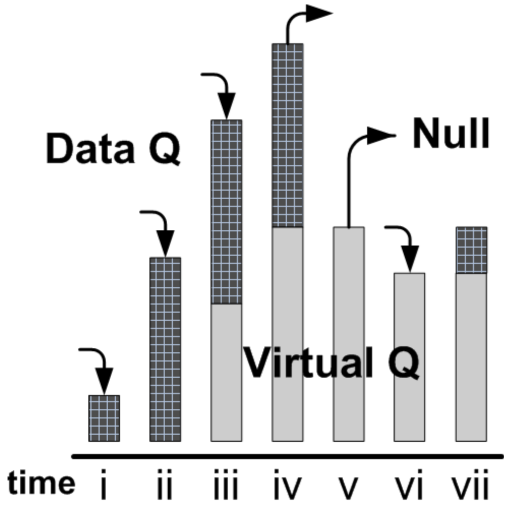
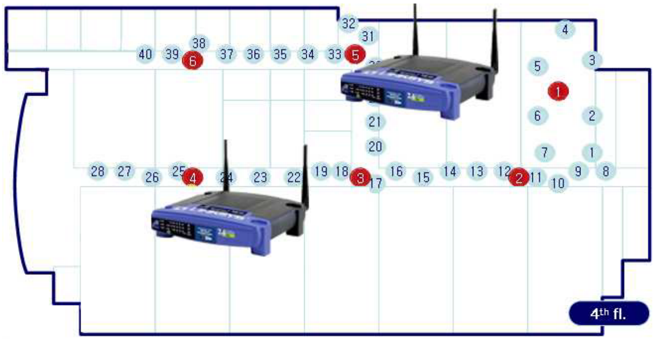




Floating Queue Operation

- Finite data queue
- Data Q overflows discard to virtual Q
- Data Q underflows service virtual Q

External Interference Performance



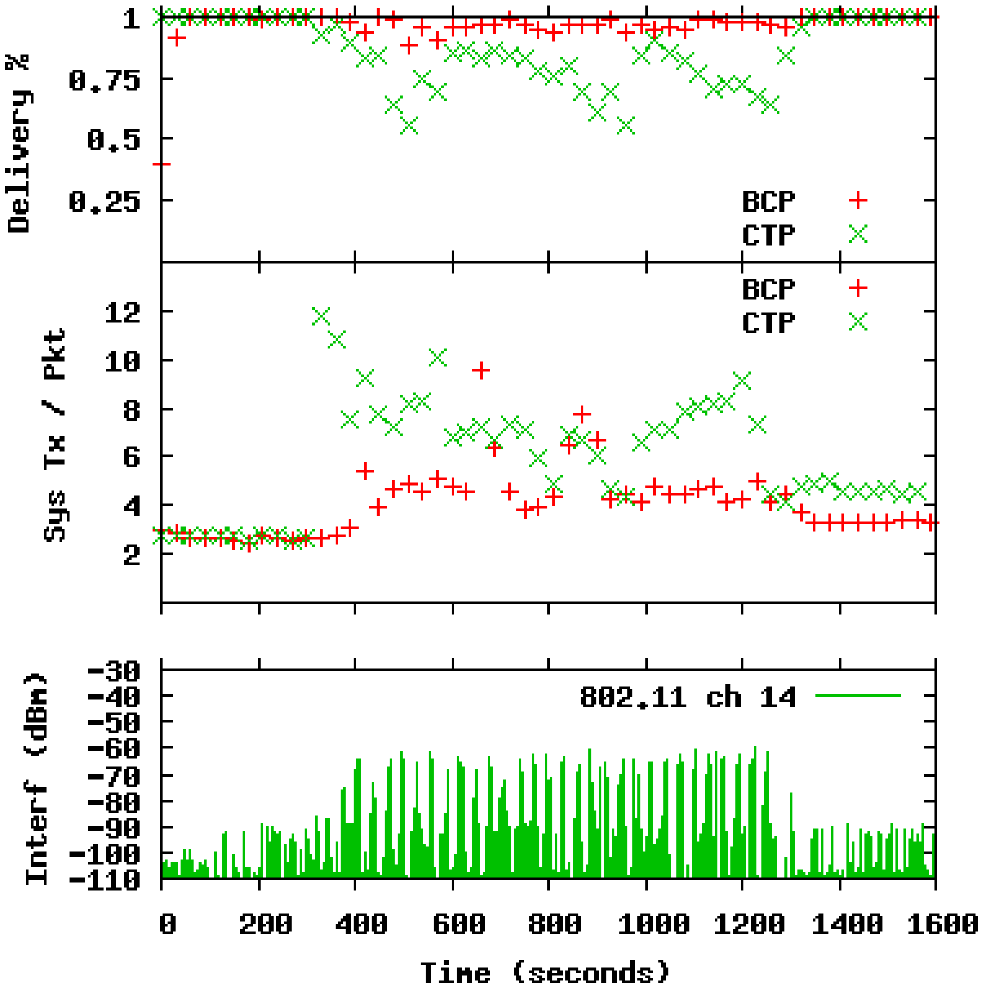
Experiment Setup

External interference

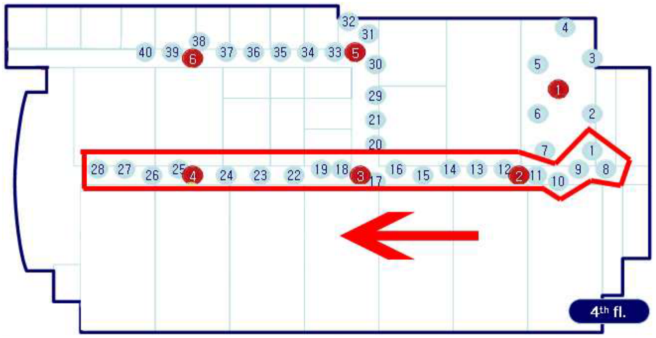
- 2 Devices
- 802.11 channel 14
- 20 sec on / 10 sec off
- 890 Bytes x 200 PPS Each

Sources and Timeline

- 0.25 PPS / source
- Interference on @ 300 Sec
- Interference off @ 1200 Sec



High Sink Mobility Performance



Sink Mobility

- 20 mote sink sequence
- 1,000 ms / sink
- 0.25 PPS / source

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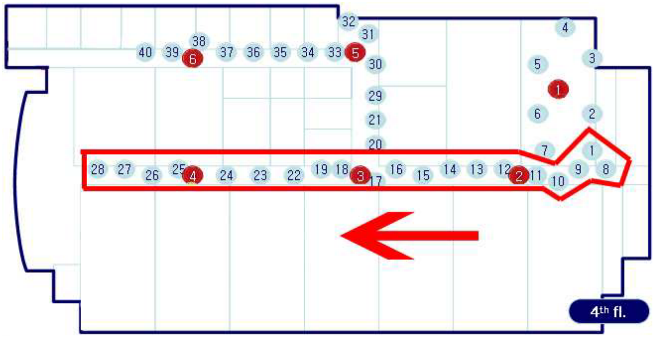

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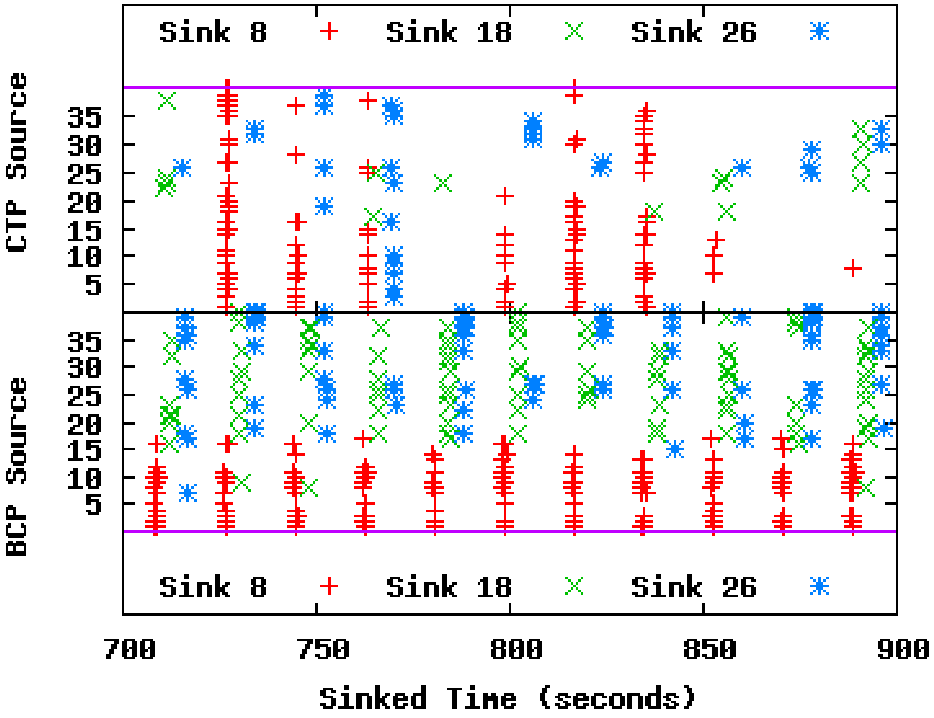

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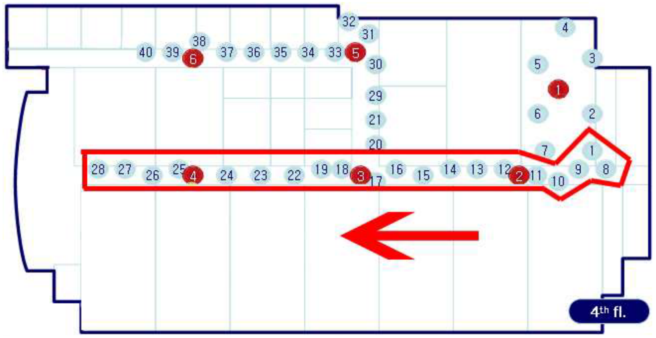

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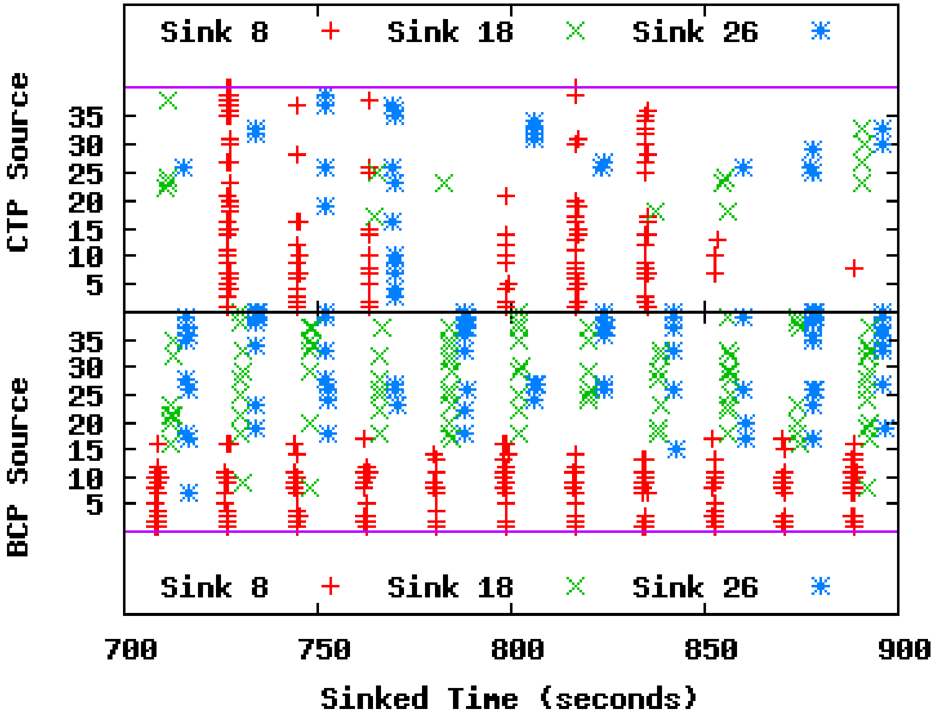

	Mobility		Static	
	BCP	CTP	BCP	CTP
Delivery Ratio	0.996	0.590	0.969	.999
Average Tx/Packet	1.73	9.5	2.39	2.65

Wrapping it Up

A Free Lunch?

There remain some important areas in need of future investigation:

- Learning time
- Out-of-order packet delivery
- Low power operation under asynchronous sleep cycling

BCP is Available

- Source Code is in TinyOS Contrib (usc/bcp)
- See our paper: S Moeller, A Sridharan, B Krishnamachari, O Gnawali. *Routing Without Routes: The Backpressure Collection Protocol*. IPSN 2010.
- `http://anrg.usc.edu/~scott/`