Interference-Aware Fair Rate Control in Wireless Sensor Networks (IFRC)

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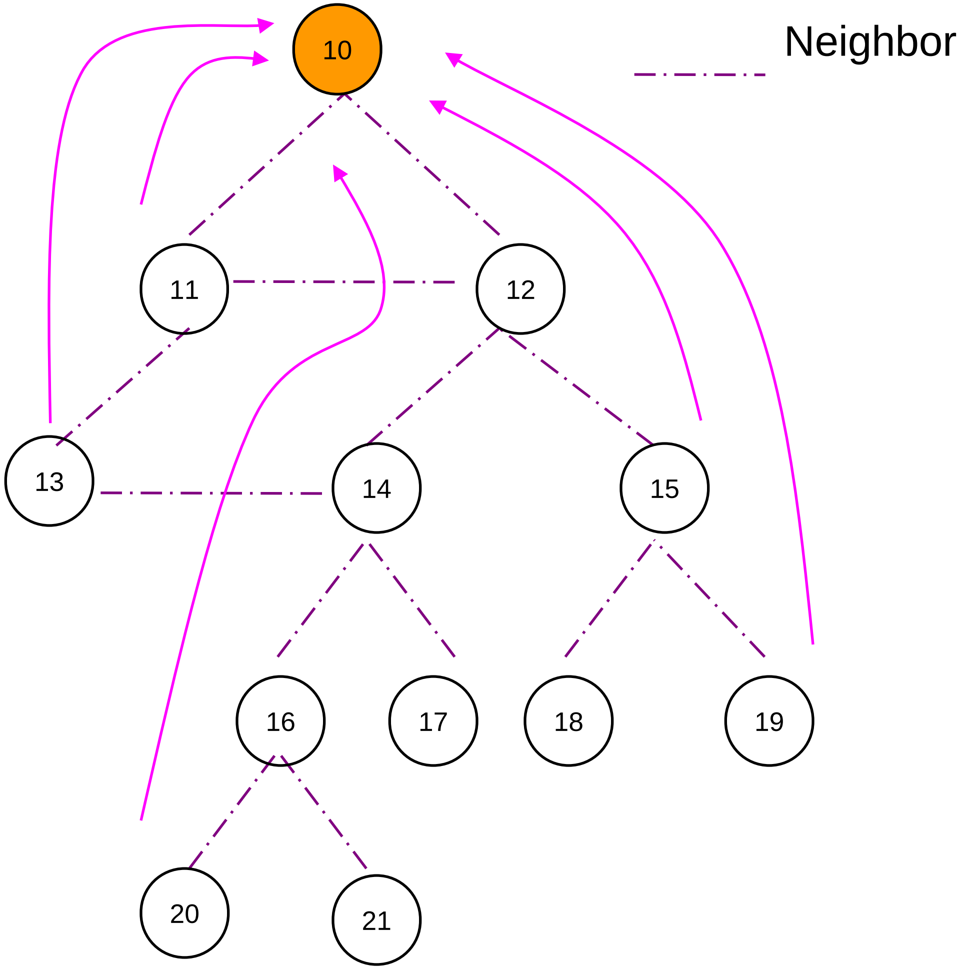
Introduction

What is it about?

- Given a sensor network of N nodes, each transmitting data over multiple hops to a base station

- How to employ congestion control to prevent congestion collapse caused by nodes sending data at the same time

Tree-based traffic pattern



Motivation: A Wireless Sensor Network for Collecting Structural Vibrations

- Nodes continuously measure structural vibrations

- When a significant response is detected, each node sends a large amount of data to the base station

- In the absence of rate control mechanism the sensor network can suffer congestion collapse

IFRC is:

- Distributed and adaptive mechanism for fair and efficient rate control in wireless sensor network
- The proposed solution is built upon standard MAC layer (CSMA) and Routing layer (link quality based path selection)
- Usage of tree-based traffic pattern

Main Challenges:

- Design a mechanism by which each node can locally detect all flows that can compete for channel capacity
- Fairly adapt its own rate such that the capacity is not exceeded
- Signal all relevant flows to do so as well

How it works?

- Monitors average queue length to detect incipient congestion
- When detected:
- Uses AIMD control law to ensure convergence to fairness
- And low overhead congestion sharing mechanism to notify all flows that pass through congested node to adjust their sending rates

How it works? (2)

- This means identifying both flows that pass through a congested node as well as those which do not traverse the congested node at all but still may affect its sending rate by means of interference

Related Work

- Falls into two areas:
- Congestion Mitigation – regulate transmission rate so that network goodput and fairness degrade gracefully

- Congestion Control – seeks to find optimal rate which is fully efficient so that network is fully utilized and node's goodput is close to its sending rate

Related Work on Congestion Mitigation

- Fusion
- Uses queue lengths to measure network congestion
- Applies hop-by-hop backpressure for congestion sharing
- Does not implement AIMD control law used to converge to a fair and efficient rate
- IFRC employs AIMD control law and distributedly converge to fair and efficient rate

Related Work on Congestion Control

- Early work (Woo and Culler)
- Examines AIMD adjustment strategy in which:
- the addictive increase is proportional to the number of the descendants of a node
- multiplicative decrease is performed whenever a node detects that its parent is unable to forward its traffic
- Congestion sharing: signal from a parent to its children

Related Work on Congestion Control 2

- ESRT: Event to Sink Reliable Transport

- Base station centrally computes rate allocation
- Periodically re-task the nodes by broadcasting a new transmission rate

Motivation and Definitions

Explaining the motivation (Design)

- Sensor Net with node ids : [1….N]

- Traffic **sourced** by node i : f(i)

- Goal : assign adaptively rate r(i) to i based on f(i)

Assumptions (Design)

- Nodes run on a contention based MAC layer
    - * IFRC not checked in TDMA systems

- Nodes run a routing protocol over tree scheme -> performance depends on it!

- Link layer retransmissions -> otherwise, end-2-end feedback needed!

Goals : Fairness & Efficiency

- Environment -> Multiple Wireless Contention Domains

- Domain specific Fairness goal -> assign *at least* most congested fair share rate!

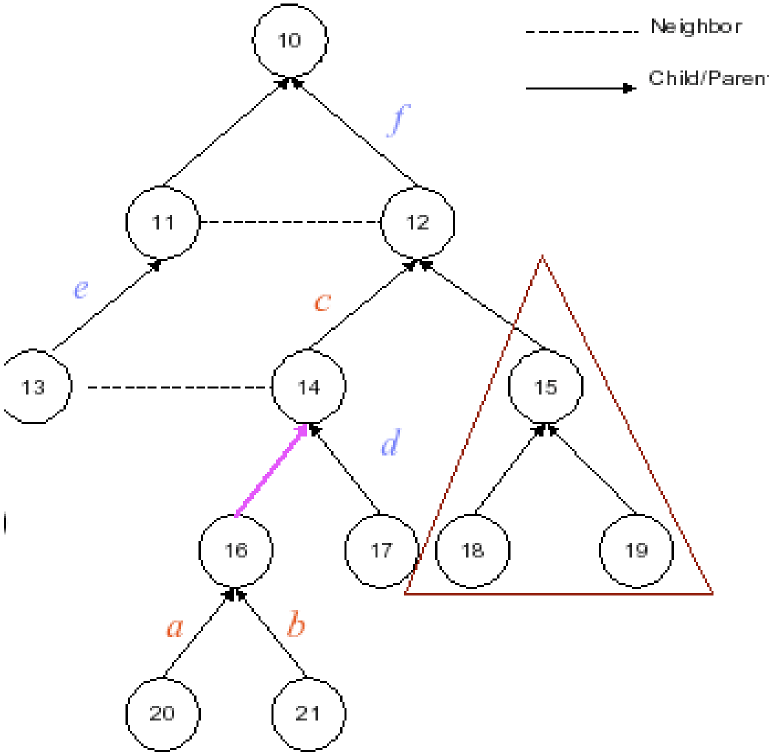
- Efficiency achieved by allowing higher rates for flows in less restrictive contention domains

Challenges (Example)

Interfering links

L1 interferes L2 when it
blocks initiation OR reception of L2

Potential interferer
n1 potential interferer of n2
if n1 uses a link that can potentially
interfere with the link n2 -> parent(n2)



Technical Goal of IFRC :

Set Φ(i) : F(i) U F(j), where j neighbour of I

-> Goal is to allocate fair and efficient share of bandwidth B in Φ(i)

- In Previous example:

if node 16 is the most congested -> other nodes should have rate at most r(16)

Design

Design : 3 inter-related parts

(I) Measuring Congestion Levels

(II) Congestion Sharing Mechanism

(III) Rate Adaptation Mechanism

DESIGN (I) : Measuring Congestion levels

Congestion level @ node (i) measured according to queue length -> OK for tree based structure with traffic to single sink

$avg\_q = (1 - wq) \times avg\_q + wq \times inst\_q$

IF $avg\_q > U$, THEN congestion

IF congestion, THEN $r = r/2$

After that additive increase BUT node in congestion state as long as $avg\_q > L$

DESIGN(II): Congestion Sharing Mechanism

- Goal is node i to share its congestion state with all potential interferes
- Node i includes in its packet :
  - Its own rate r(i) and its congestion state
  - Rate and congestion state of its most *congested* child
- Still some potential interferes might not be signalled ->

2 rules : (a) -> if i == parent(j) THEN r(j) < r(i)

(b) -> if j == neighbor(i) AND j "congested"

THEN r(i) = min(r(i), r(j))

DESIGN(III) : Rate Adaptation

- IFRC employs the AIMD principle :

  - $\delta/r(i)$ = rate of additive increase, every 1/r(i) secs
  - If i congested when threshold U(k) is crossed, THEN node halves current r(i) : happens at most once every congestion epoch
  - If i overhears parent j and r(i) > r(j) THEN r(i) = r(j)
  - If i overhears neighbour l and p one of l's children THEN r(i) = r(l) or r(p)

DESIGN : base station & extensions ..

- IFRC base station provides rate adaptation assistance

-> maintains a rate r(b) which constraints children according to rule 1

- IFRC extensions :
  1. **Multiple base stations** -> need to adapt base station behaviour
  2. **Weighted fairness** -> node i assigned w(i), so need to achieve w(i)/f(i)
  3. **Only subset of nodes transmit**

Parameter Selection in IRFC

Why Parameter Selection?

IRFC converges to a fair rate using AIMD

Parameter selection controls:

- Long term stability
- Efficiency
- Convergence properties

IRFC is an open-loop system

TCP receives acknowledgements after one round trip time (RTT).

This RTT is a natural timescale at which many rate adaptation functions are invoked.

IRFC does not have an end to end feedback mechanism

Instead IRFC needs to use carefully selected parameters to ensure stability and efficiency.

Intensity of AIMD

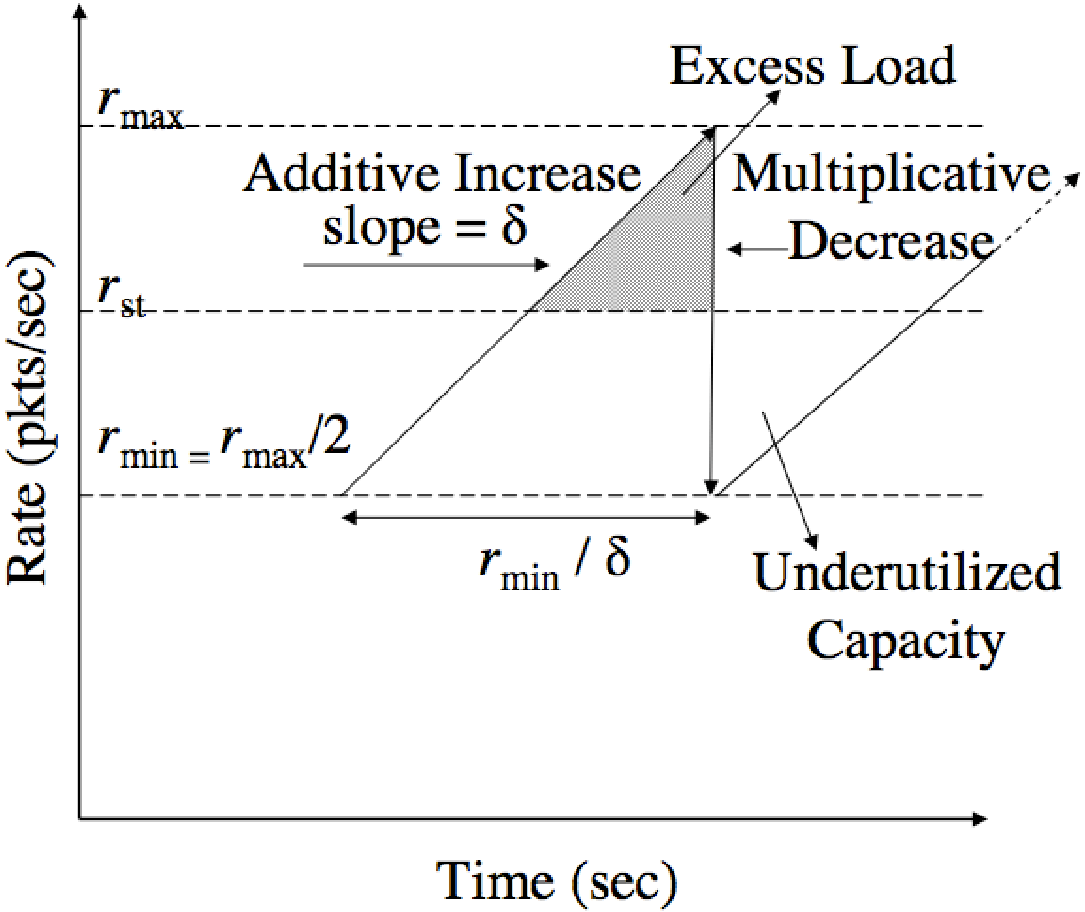
Rate (r_i) increased by δ/r_i every $1/r_i$ seconds

$1/r_i$ is the interpacket transmission time

$$r_i\left(t+\frac{1}{r_i(t)}\right)=r_i(t)+\frac{\delta}{r_i(t)}$$

$$r_i(t)=\delta t$$

AIMD behavior



Finding the best step size

To avoid reaching r_{max} too quickly

$$\delta / r_{min,i} \ll r_{min,i}$$

The value of ε governs the step size

$$\delta = \varepsilon r_{min,i}^2 \qquad 0 < \varepsilon < 1$$

Requirements for Stability

- Excess load is the amount of additional packets transmitted when r_i is above r_{st}
  - This causes queues to build up
- Underutilized capacity is the unexploited transmission opportunity when r_i is below r_{st}
  - This allows queues to disperse
- For stability excess load must be less than underutilized capacity

Requirements for Stability

Sustainable rate must be more than halfway between min rate and max rate

$$r_{st,i} > \frac{r_{min,i}+r_{max,i}}{2}$$

Max rate is double min rate because of multiplicative decrease

$$r_{max} = 2 \times r_{min}$$

Therefore

$$r_{st,i} > \frac{3r_{max,i}}{4}$$

Excess load

The excess load produced by one node

$$(r_{max,i} - r_{st,i})^2/(2\delta)$$

Taking all nodes into account

$$\sum_i \frac{(r_{max,i} - r_{st,i})^2 f_{ij}}{2\delta}$$

f_{ij} takes contention between nodes into account

Boundaries for excess load

So that a congestion signal is triggered excess load must exceed the first queue threshold U_o

$$\sum_i \frac{(r_{max,i} - r_{st,i})^2 f_{ij}}{2\delta} > U_0$$

To avoid more than one multiplicative decrease excess load must be less than the second queue threshold U_1

$$\sum_i \frac{(r_{max,i} - r_{st,i})^2 f_{ij}}{2\delta} < U_1$$

Considering Latency

- Considering the time it takes for a congestion signal to get to a node
- The node could have increased its rate s_i times

$$r_{max,i} > r_{st,i} + \frac{s_i \delta}{r_{st,i}}$$

Leap of Faith

Let $F_j = \Sigma f_{ij}$ and set $r_{st}/r_{min} = 1.5$

For small F_j

$$\varepsilon < \frac{F_j}{8U_0}$$

For large F_j

$$\varepsilon < \frac{9U_1}{2\bar{s}^2 F_j}$$

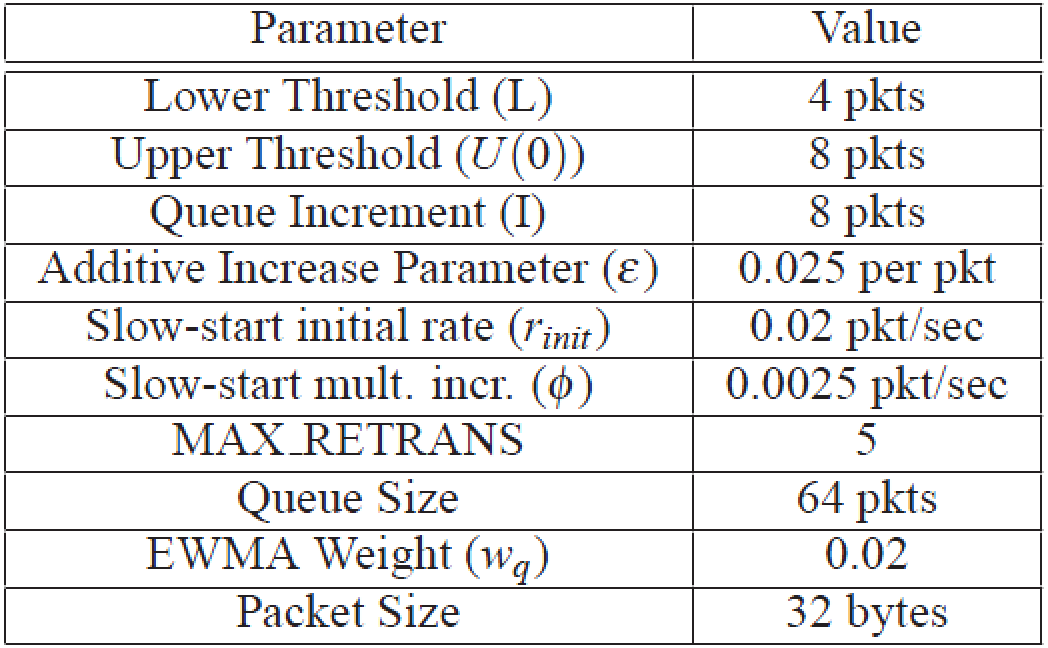
F_j dependant on network size and topology

Other Parameters

Other parameters were chosen using intuition rather than rigorous analysis

More work needs to be done on the analysis of all other parameters

Parameters of IFRC experiment



Parameter	Value
Lower Threshold (L)	4 pkts
Upper Threshold ($U(0)$)	8 pkts
Queue Increment (I)	8 pkts
Additive Increase Parameter (ε)	0.025 per pkt
Slow-start initial rate (r_{init})	0.02 pkt/sec
Slow-start mult. incr. (ϕ)	0.0025 pkt/sec
MAX_RETRANS	5
Queue Size	64 pkts
EWMA Weight (w_q)	0.02
Packet Size	32 bytes

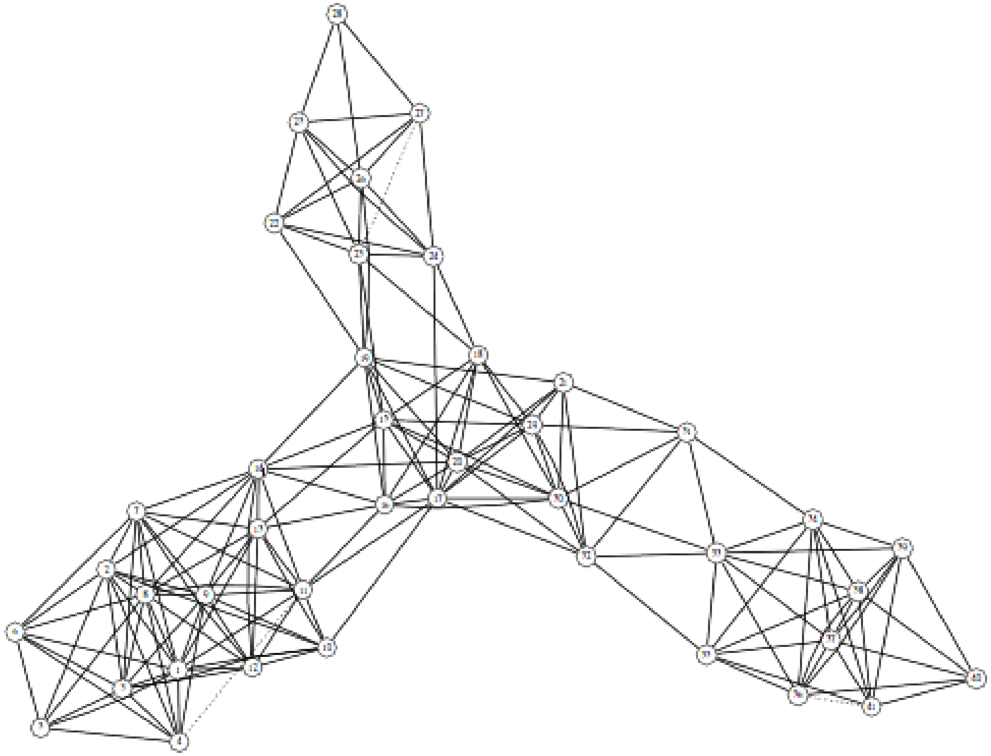
Evaluation

Implementation and Methodology

- TinyOS 1.1 with IFRC plugged in
- 40-node indoor wireless testbed
- Moteiv Tmote nodes
  - 8MHz processor
  - 10KB RAM
  - 250Kbps wireless
  - USB back-channel for logging
- Loss rate of < 40%

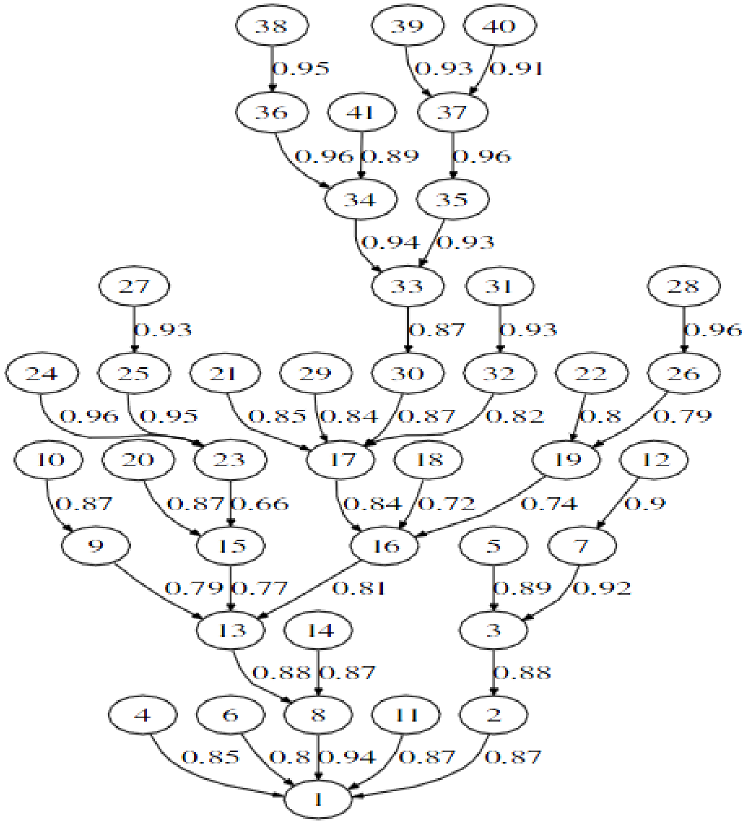
Testbed connectivity graph

- 1125 square meters

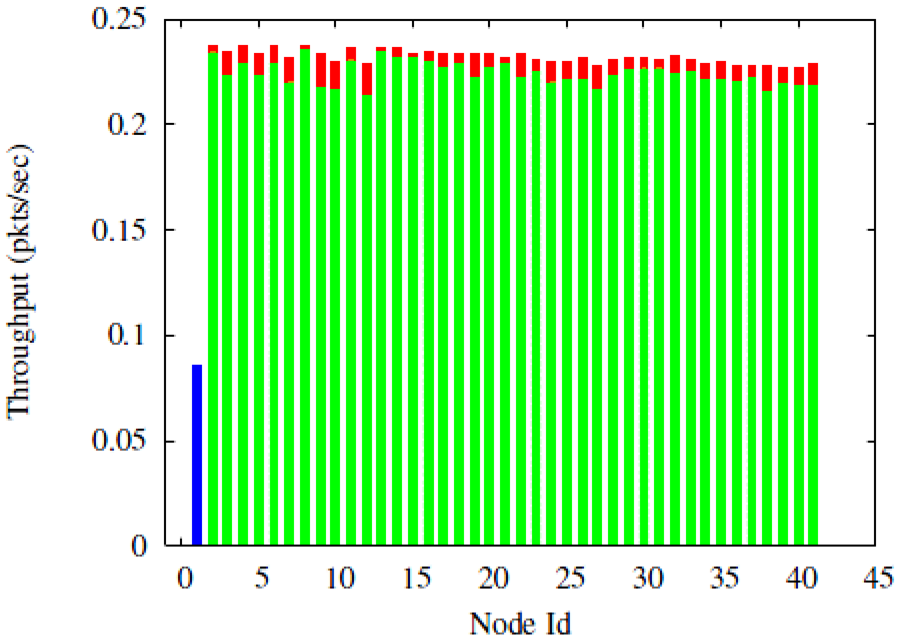


Routing tree

- All nodes transmit
- One base station
- Flows treated equally
- 66%-96% reception
- 9 hops deep



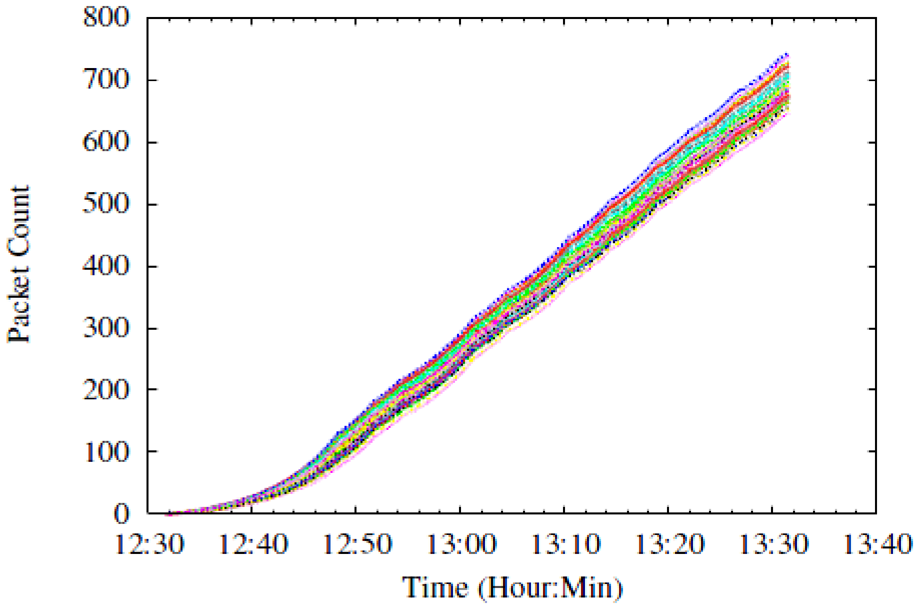
Fair rates and goodput



- 🟩 packet received
- 🟥 packet lost
- 🟦 base station control traffic

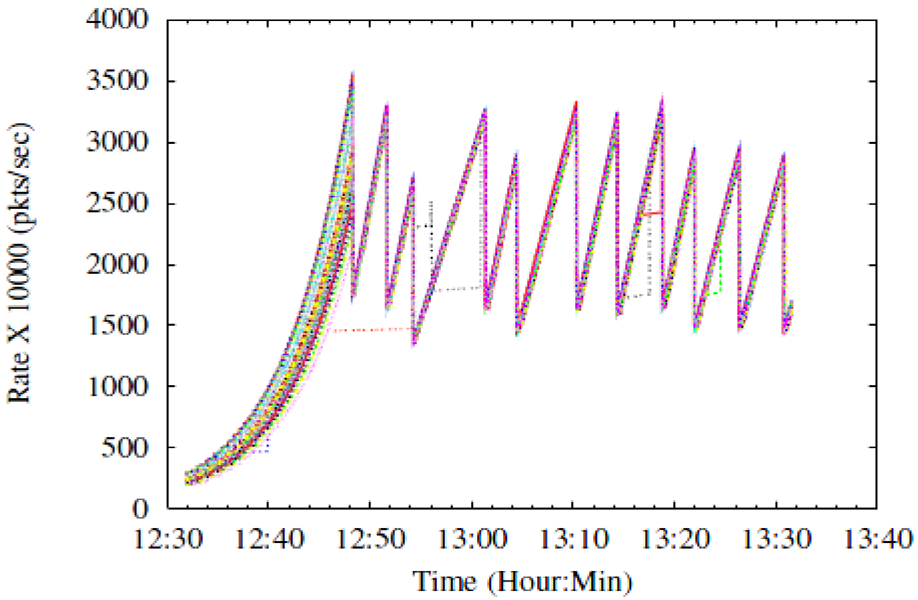
- < 8% packet loss

Stable instantaneous throughput



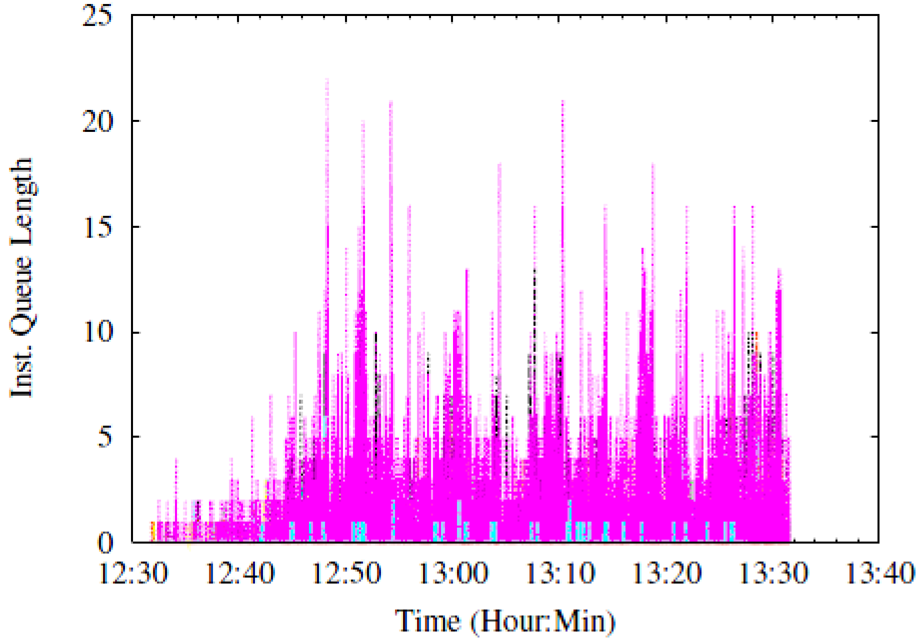
- Minor variation due to AIMD

Node rate adaptation nearly synchronous



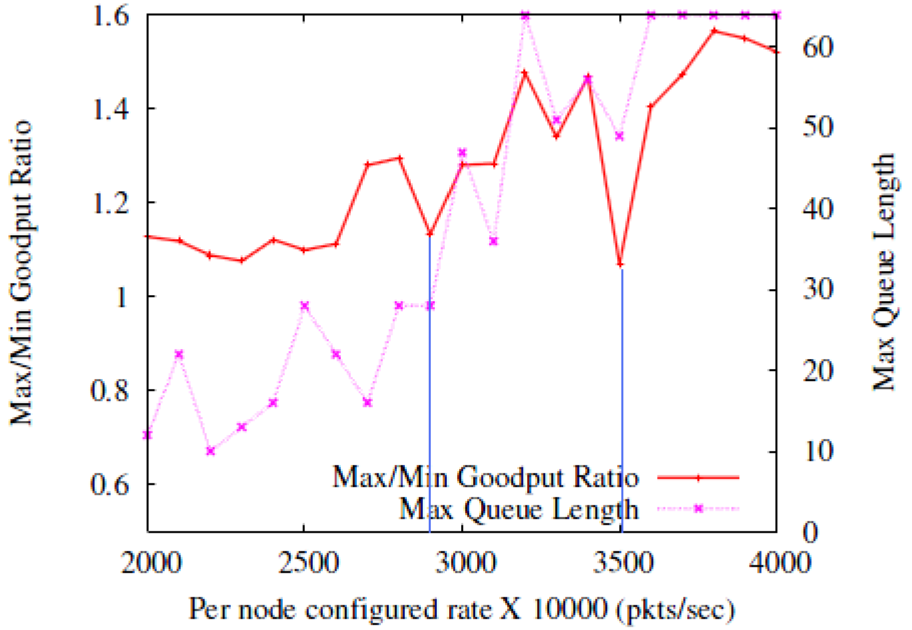
- Slow start and AIMD
- Horizontal lines due to experiment data loss

No packet loss



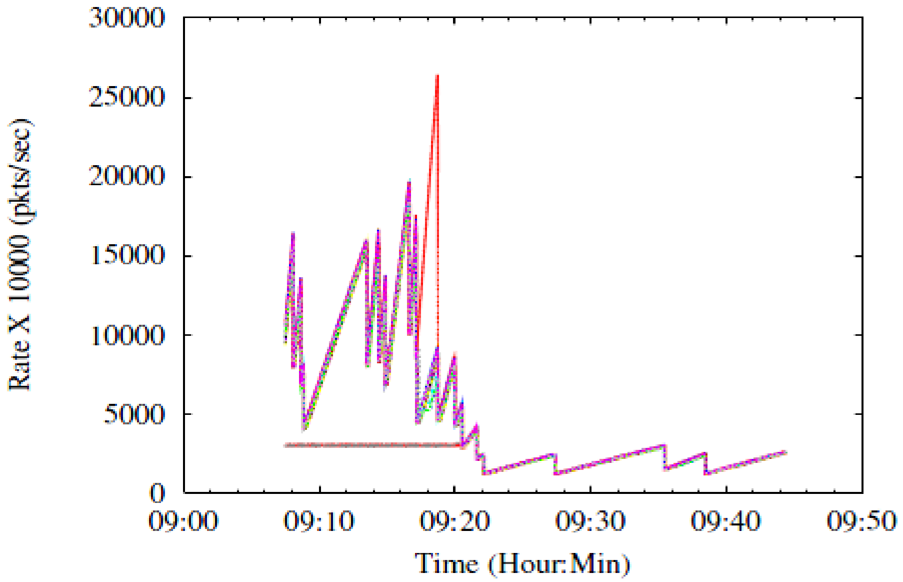
- Instantaneous queue size always < 20

60%-80% of the optimal rate is achieved



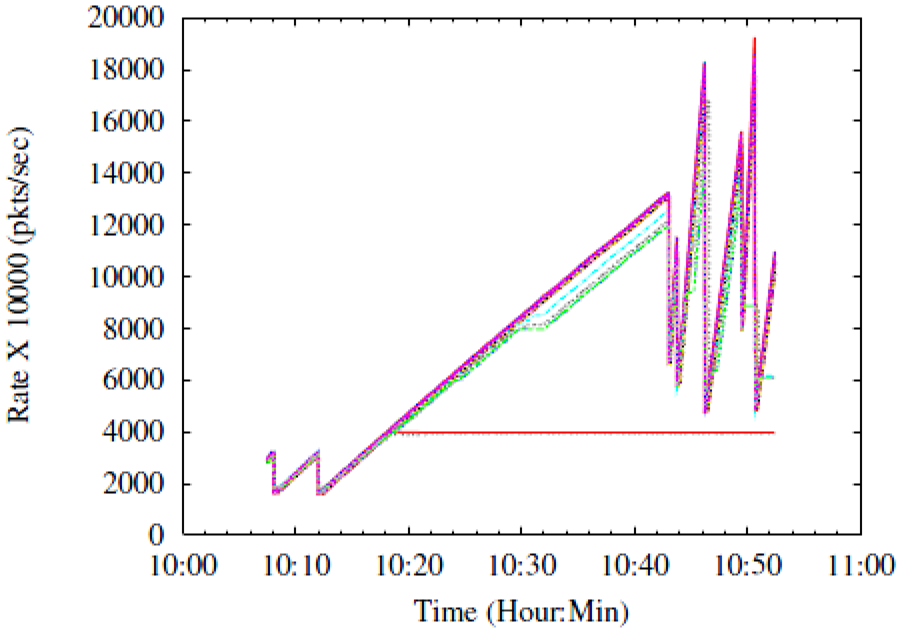
- At 0.26 packets/sec 80% optimal rate
- At 0.36 packets/sec 60% optimal rate

IFRC adapts when adding nodes



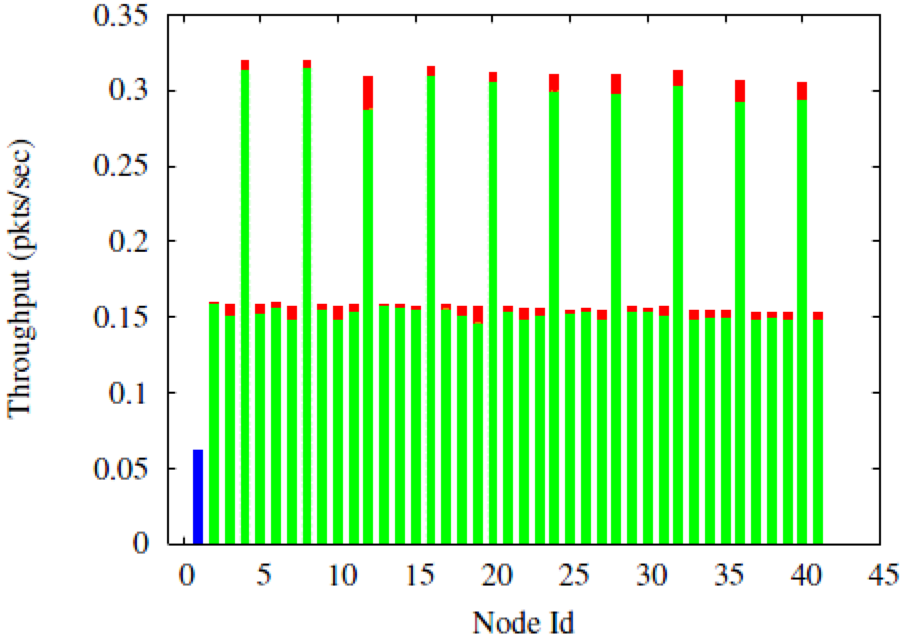
- Two successive decreases near 9:09 due to parent and child congestion state

IFRC adapts when removing nodes



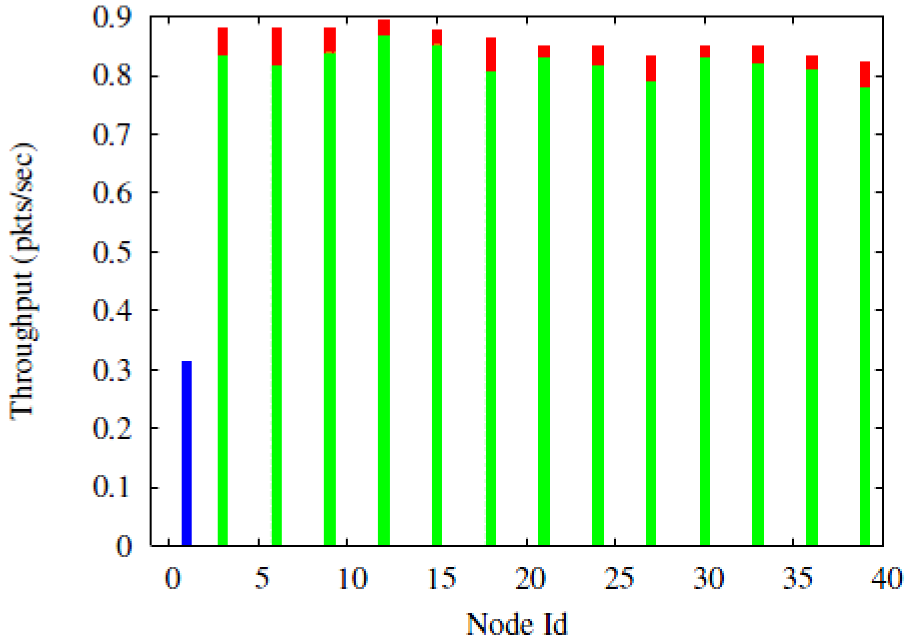
- At 10:30 slight de-synchronization due to packet loss

Weighted Fairness



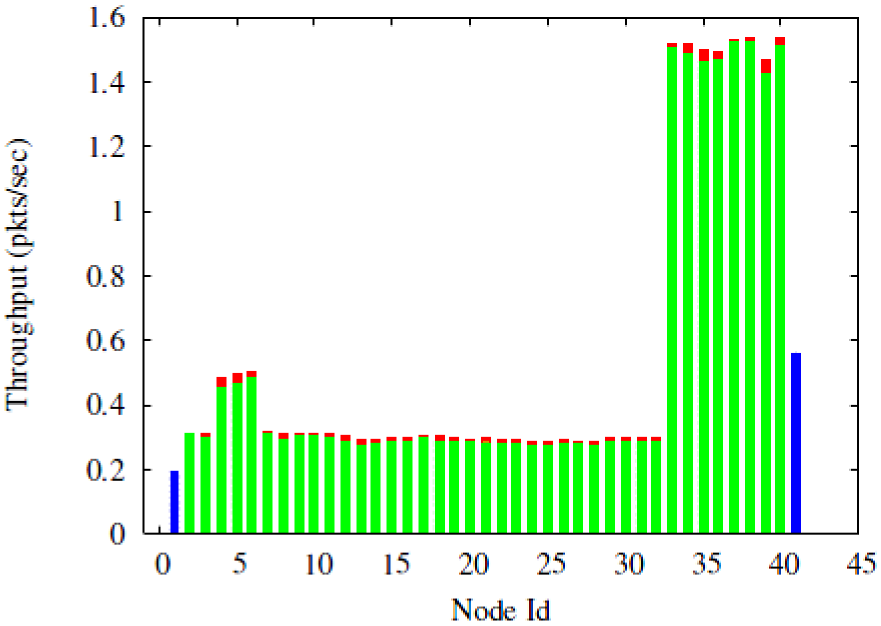
- Weight 2 if node id divisible by four
- Weight 1 all other nodes

IFRC adapts to the available capacity and allocates it fairly



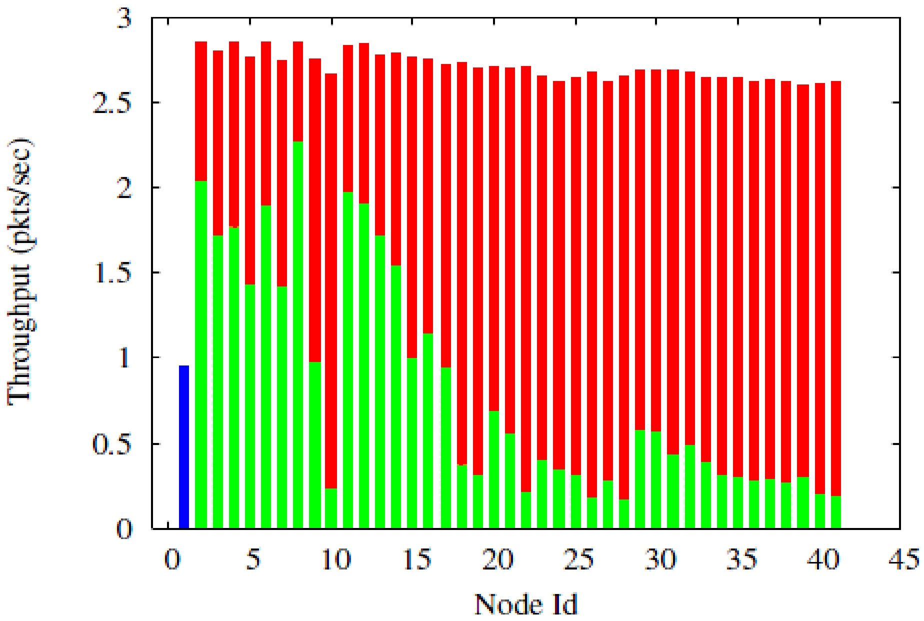
- Transmit if node id divisible by three

IFRC efficient with multiple sinks



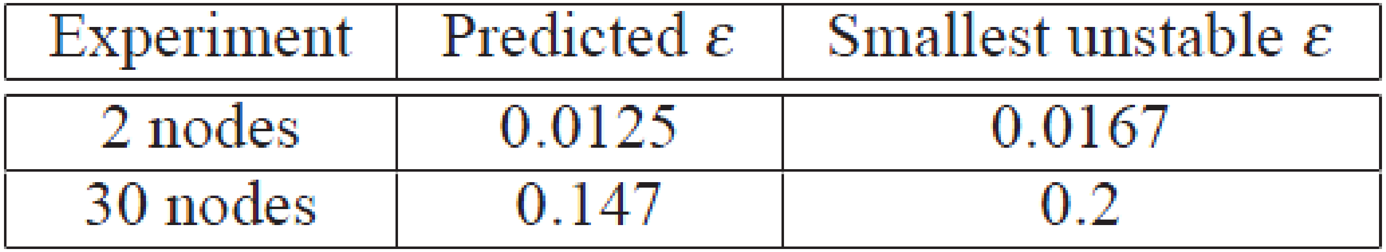
- Two base stations 1 and 41
- Nodes rate fair among trees

Link layer retransmissions are essential



- Per flow goodput without link layer retransmissions

Validating the choice of ε



Experiment	Predicted ε	Smallest unstable ε
2 nodes	0.0125	0.0167
30 nodes	0.147	0.2

Appraisal of IFRC

IFRC is a new technology (2006)

It is the first practical interference aware rate control mechanism for wireless sensor networks

Appraisal of IFRC

Initial results seem promising

However experiments made with the assumption that nodes are constantly sending packets

It has not been tested if IFRC can recover from a node failing completely

More tests should be carried out with different topologies and with data sent in bursts to see if IFRC still performs well