Wireless Sensor Networks
6. WSN Routing

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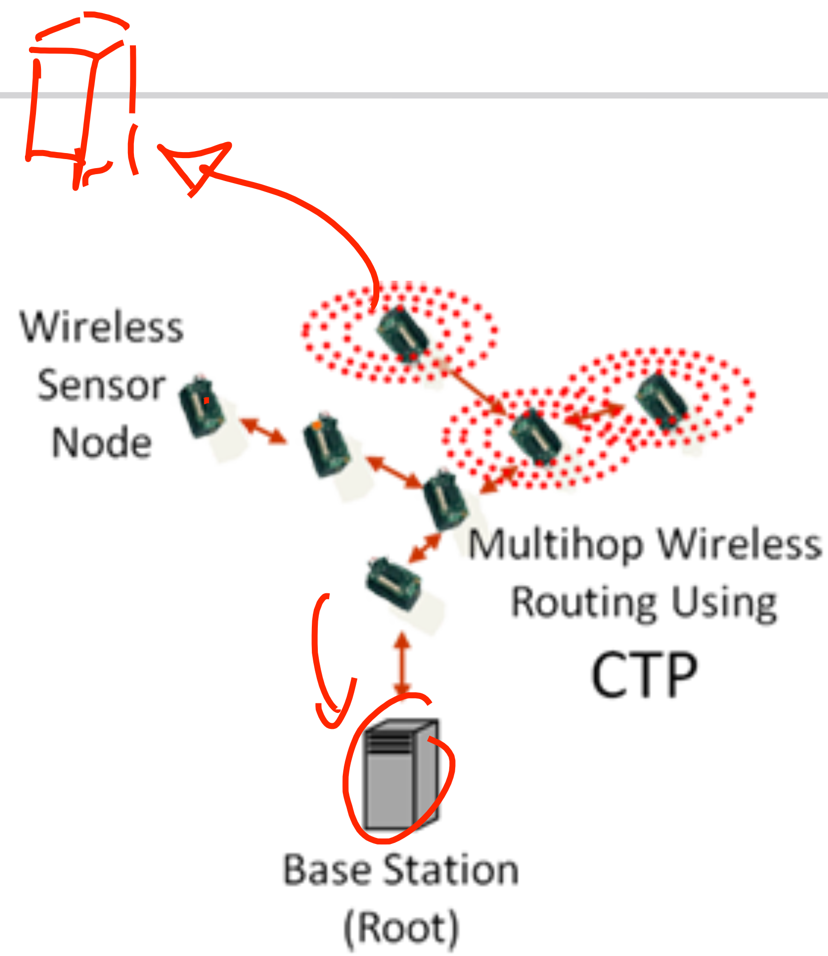
Collective Tree Protocol

- Literature
  - CTP: An Efficient, Robust, and Reliable Collection Tree Protocol for Wireless Sensor Networks, O. Gnawali, R. Fonseca, K. Jamieson, D. Moss, P. Levis, ACM Transactions on Sensor Networks, Vol. 10, No. 1, Article 16, November 2013.
    - preliminary version appeared at SenSys 09
  - https://sing.stanford.edu/gnawali/ctp/

Collective Tree Protocol (CTP) Overview

- Tree topology based collection
  - Anycast route to the sink(s)
  - To collect data
  - Distance Vector Protocol
- Components
  - Link quality estimation
  - Datapath validation
  - Adaptive beaconing
- CTP become a benchmark protocol
- Many deployments, applications and implementations
- Related to
  - IPv6 Routing Protocol for Low power and Lossy Networks (RPL)
  - RFC 6206 Trickle algorithm



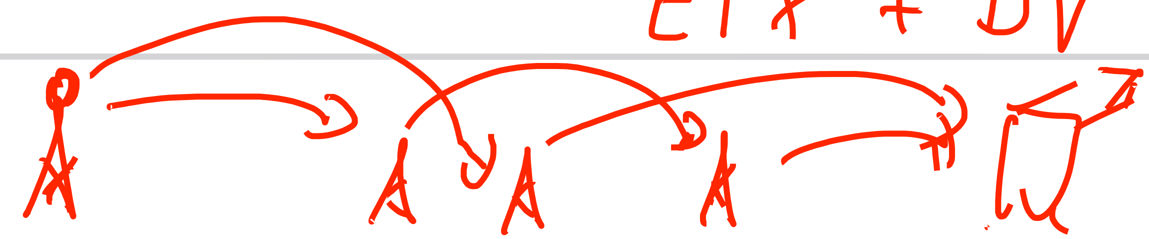
https://sing.stanford.edu/gnawali/ctp/

Unicast 1-1
broadcast 1 → all
multicast 1 → group
convergecast all → 1
anycast 1 → 1 out of a group

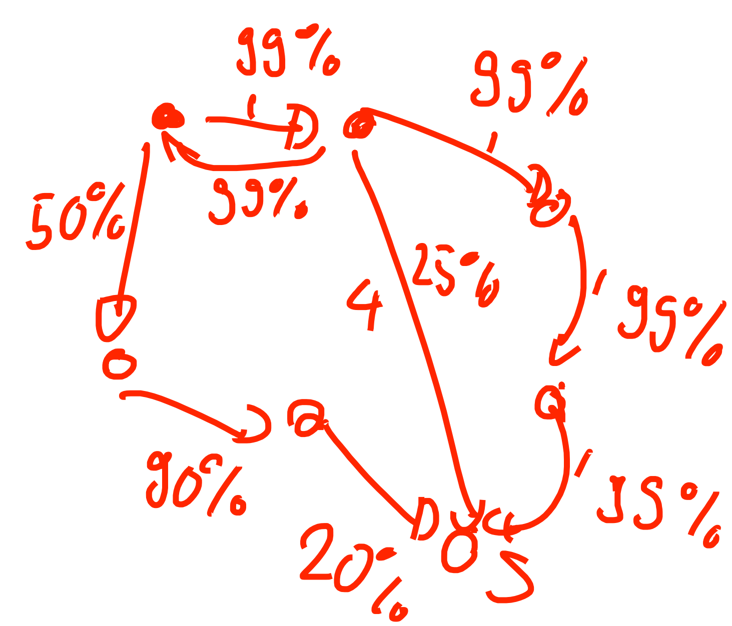
Collective Tree Protocol (CTP)
Goals

- Reliability
  - ≥ 90-99% delivery rate of end-to-end packets
- Robustness
  - Operate without tuning or configuration
  - wide range of network conditions, topologies, workloads, environments
- Efficiency
  - Deliver packets with minimum amount of transmissions
- Hardware independence
  - no assumption of specific radio transceivers

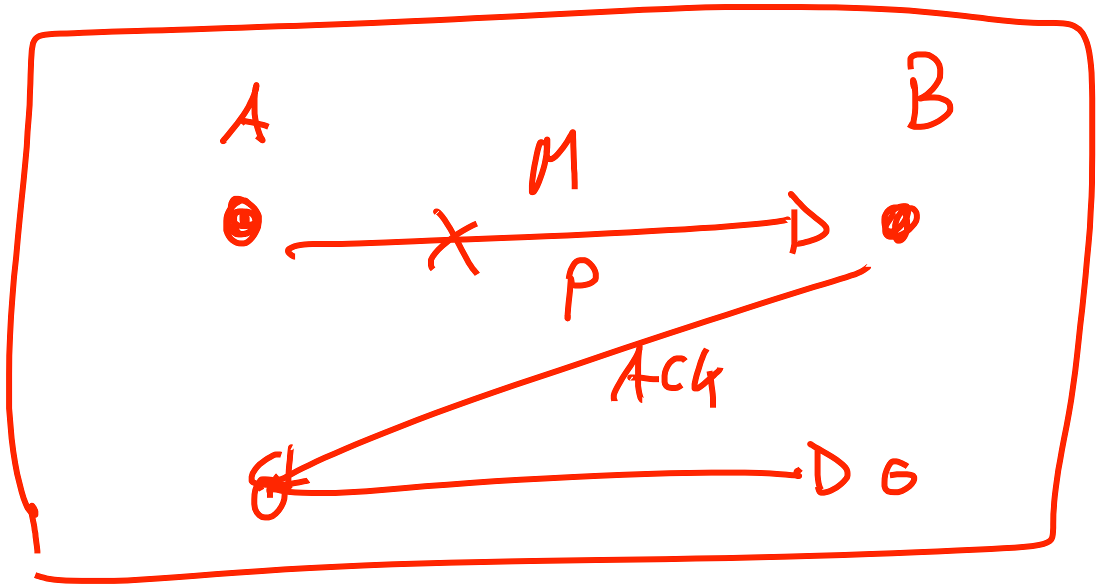
ETX Cost Metric



- Literature
  - A High-Throughput Path Metric for Multi-Hop Wireless Routing, D.S.J. De Couto D. Aguayo, J. Bicket, R. Morris, MobiCom ’03, September 14–19, 2003, San Diego, California, USA.
- Goal
  - Improve throughput of wireless networks by a better metric for routing protocols
- Idea
  - Take link-loss ratios and compute a distance
- ETX: Expected transmission count metric
  - $d_f(e)$: forward delivery ratio of a link e
  - $d_r(e)$: reverse delivery ratio of a link e



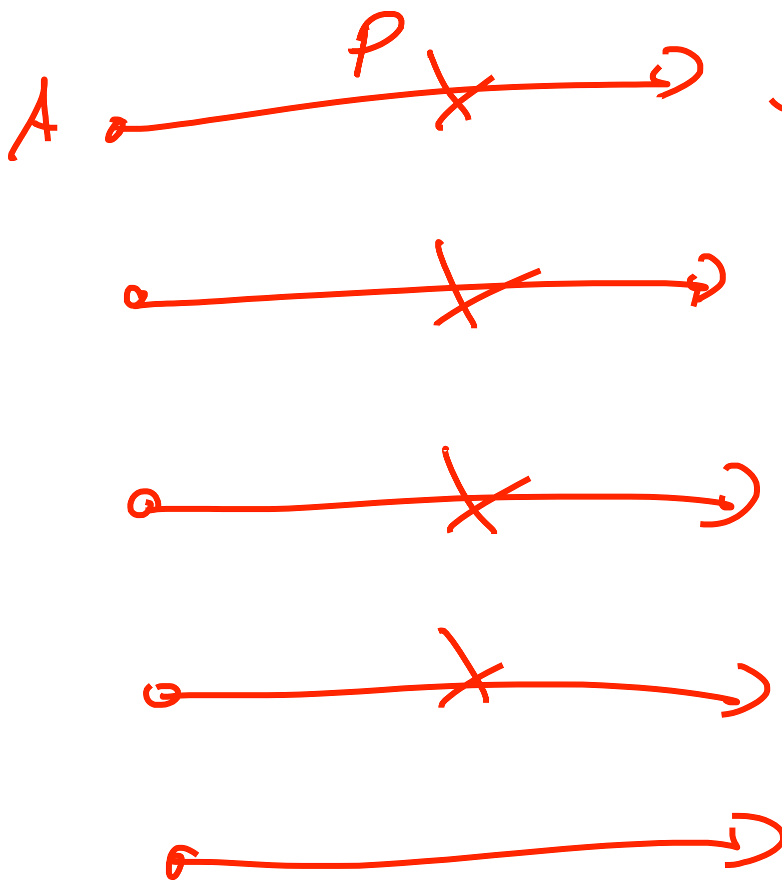
$$\mathrm{ETX}(e) = \frac{1}{d_r(e) \cdot d_f(e)}$$



$$p_f = \frac{1}{2}$$

$$p_r = \frac{1}{2}$$

$$p = p_f \cdot p_r = \frac{1}{4}$$

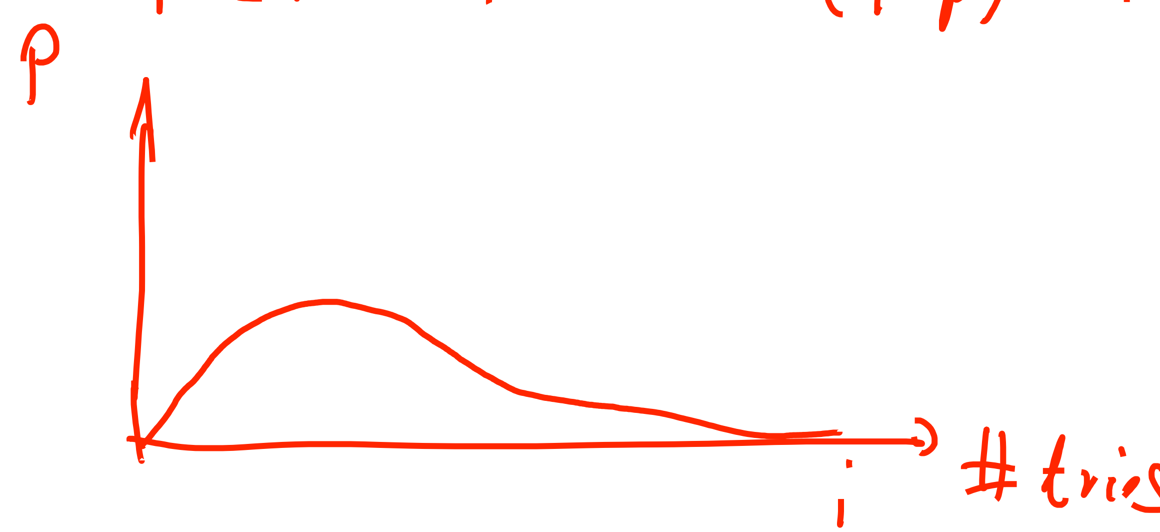


$$P[\text{1. try works}] = p$$

$$P[\text{2. try works}] = (1-p)p$$

$$P[\text{3. try works}] = (1-p)^2 \cdot p$$

$$P[\text{ith try works}] = (1-p)^{i-1} \cdot p$$



$$E[X] = \sum_{i=1}^{\infty} i \cdot P[X=i]$$

$$= \sum_{i=1}^{\infty} i\,(1-p)^{i-1} \cdot p$$

$$E[X] = 1 \cdot p + 2p \cdot (1-p) + 3 \cdot p(1-p)^2 + 4 \cdot p(1-p)^3 \ldots\ldots$$

$$= p \cdot \Big(1 + (1-p) + (1-p)^2 + (1-p)^3 \ldots\ldots \quad \frac{1}{p}$$

$$q = (1-p)$$

$$+ (1-p) + (1-p)^2 + (1-p)^3 \ldots\ldots \quad \frac{1}{p} \cdot (1-p)$$

$$+ (1-p)^2 + (1-p)^3 \ldots \quad \frac{1}{p}(1-p)^2$$

$$+ (1-p)^3 \ldots \quad \frac{1}{p}(1-p)^3$$

$$\ddots \quad \vdots \Big)$$

$$= 1 + (1-p) + (1-p)^2 + (1-p)^3 \ldots = \frac{1}{p}$$

$$\left(1 + q + q^2 + q^3 + q^4 \ldots\ldots\right) \cdot (1-q) = 1$$

$$= 1 + q + q^2 + q^3 + q^4 \ldots$$

$$- q - q^2 - q^3 - q^4 \ldots$$

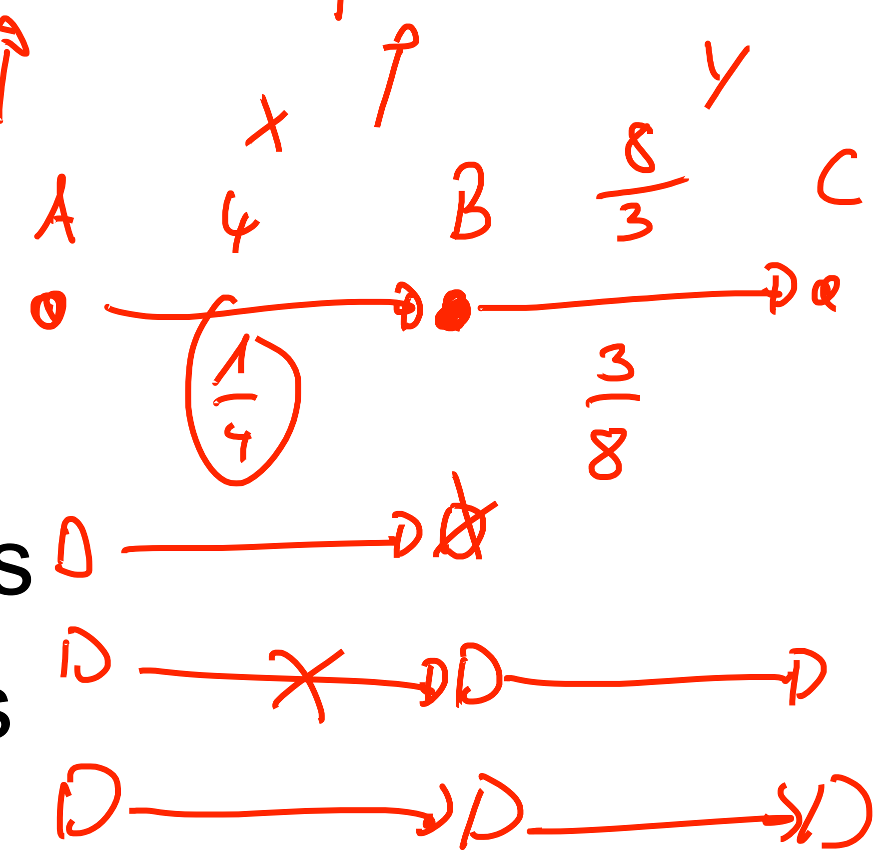
$$0 \quad 0 \quad 0 \quad 0$$

$$1 + (1-p) + (1-p)^2 + \ldots = \frac{1}{1-q} = \frac{1}{p}$$

ETX Characteristics

- ETX(P) of a path P= (e_1, e_2, … e_m)

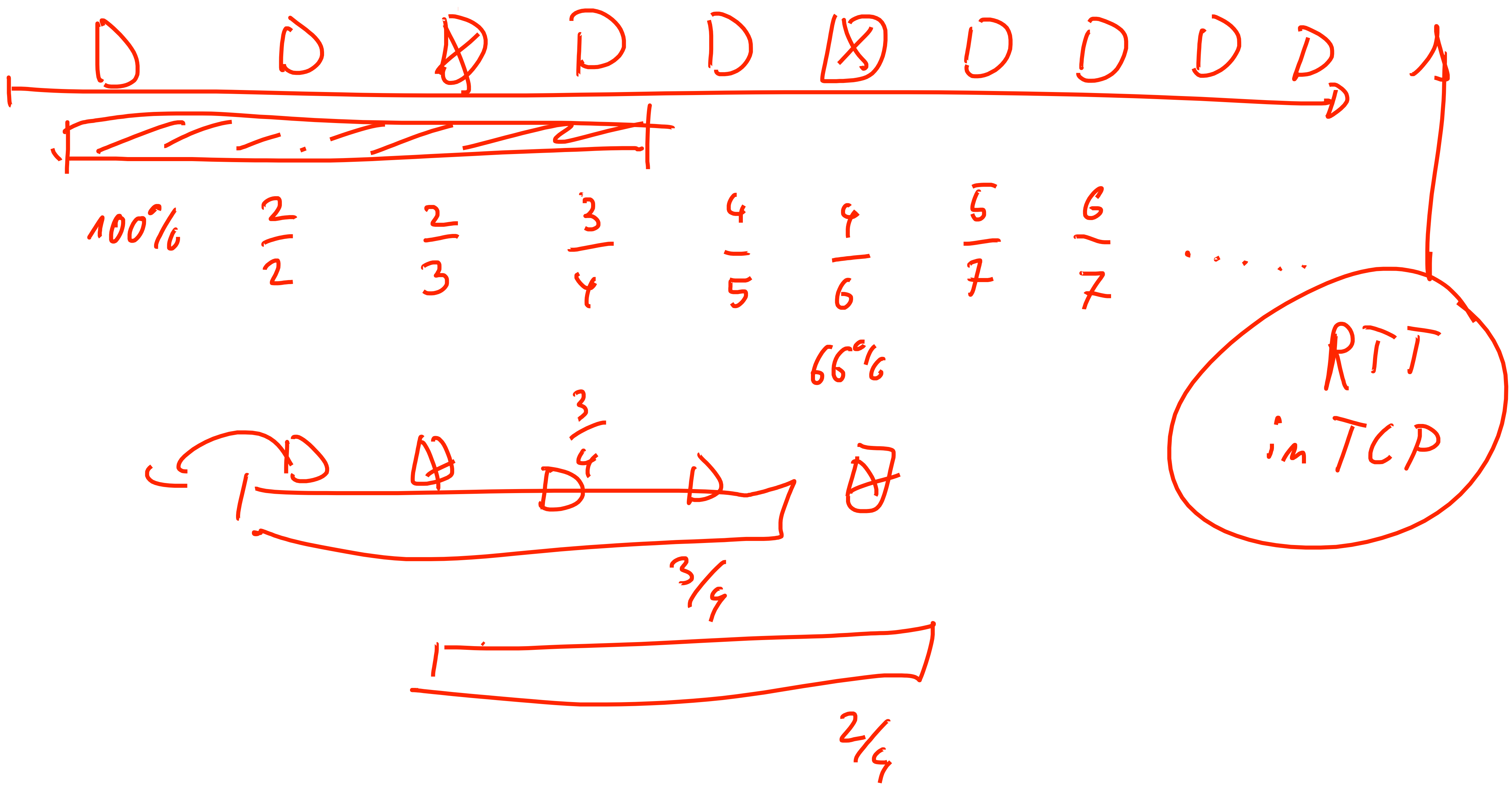
$$\mathrm{ETX}(u_1,\ldots,n) = \sum_{i=1}^{n-1} \mathrm{ETX}(u_i,u_{i+1}) = \sum_{i=1}^{n-1} \frac{1}{d_r(u_i,u_{i+1}) \cdot d_f(u_i,u_{i+1})}$$



- ETX
  - based on delivery ratios
  - detects asymmetry
  - use link loss ratio measurements
  - penalizes routes with more hops
  - tends to minimum spectrum use

A → B

$$\#Ack \cdot \underbrace{\frac{1}{10}}_{\alpha} + \underbrace{\frac{9}{10}}_{(1-\alpha)} \cdot \text{oldestimat} = \text{Exponential moving average}$$



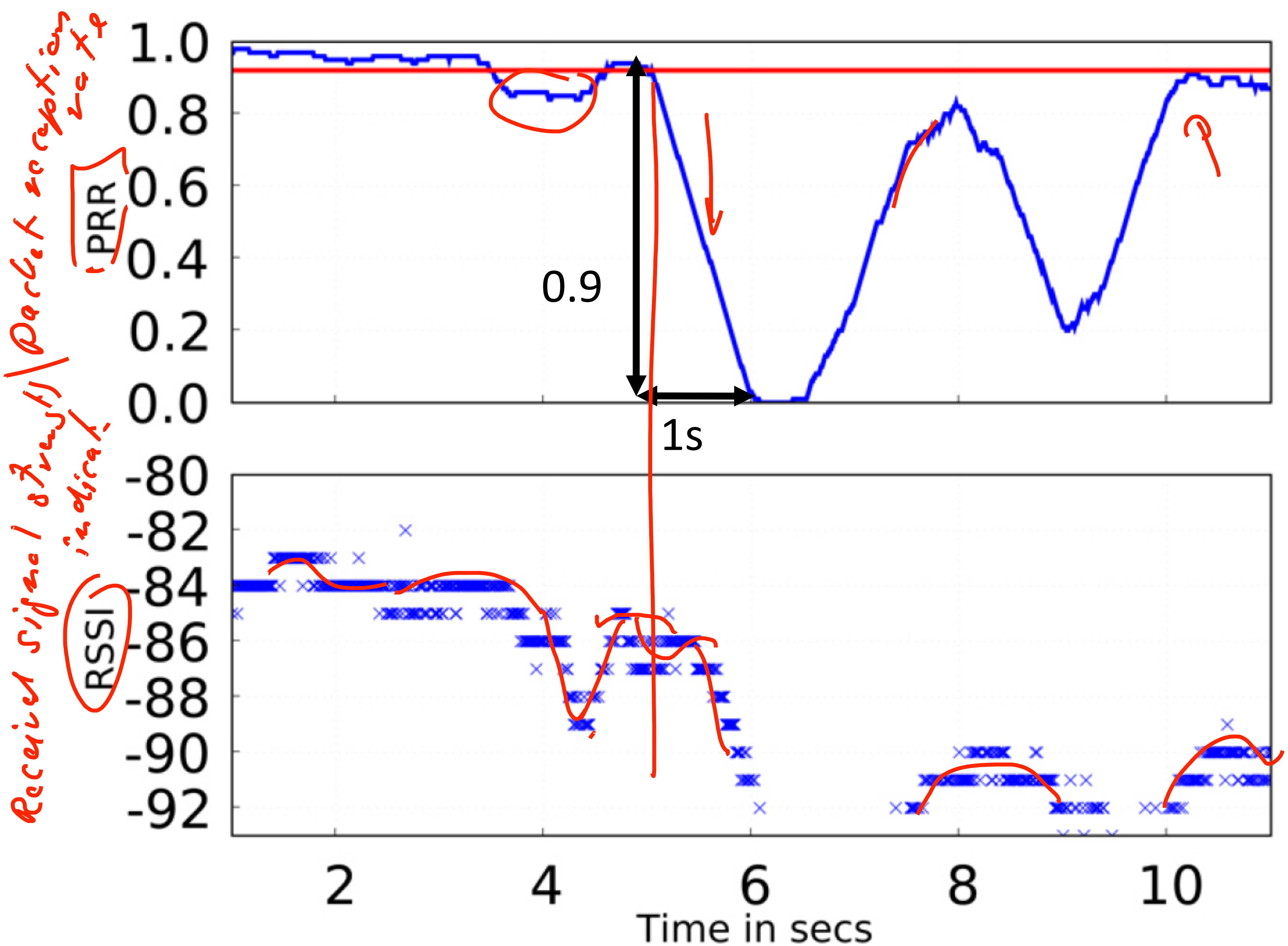
ETX: Computing Delivery Ratios

- Each node broadcasts link probes
  - of fixed size
  - at period τ
- count(t-w,t): number of probes received at window w

$$r(t) = \frac{\text{count}(t-w,t)}{w/\tau}$$

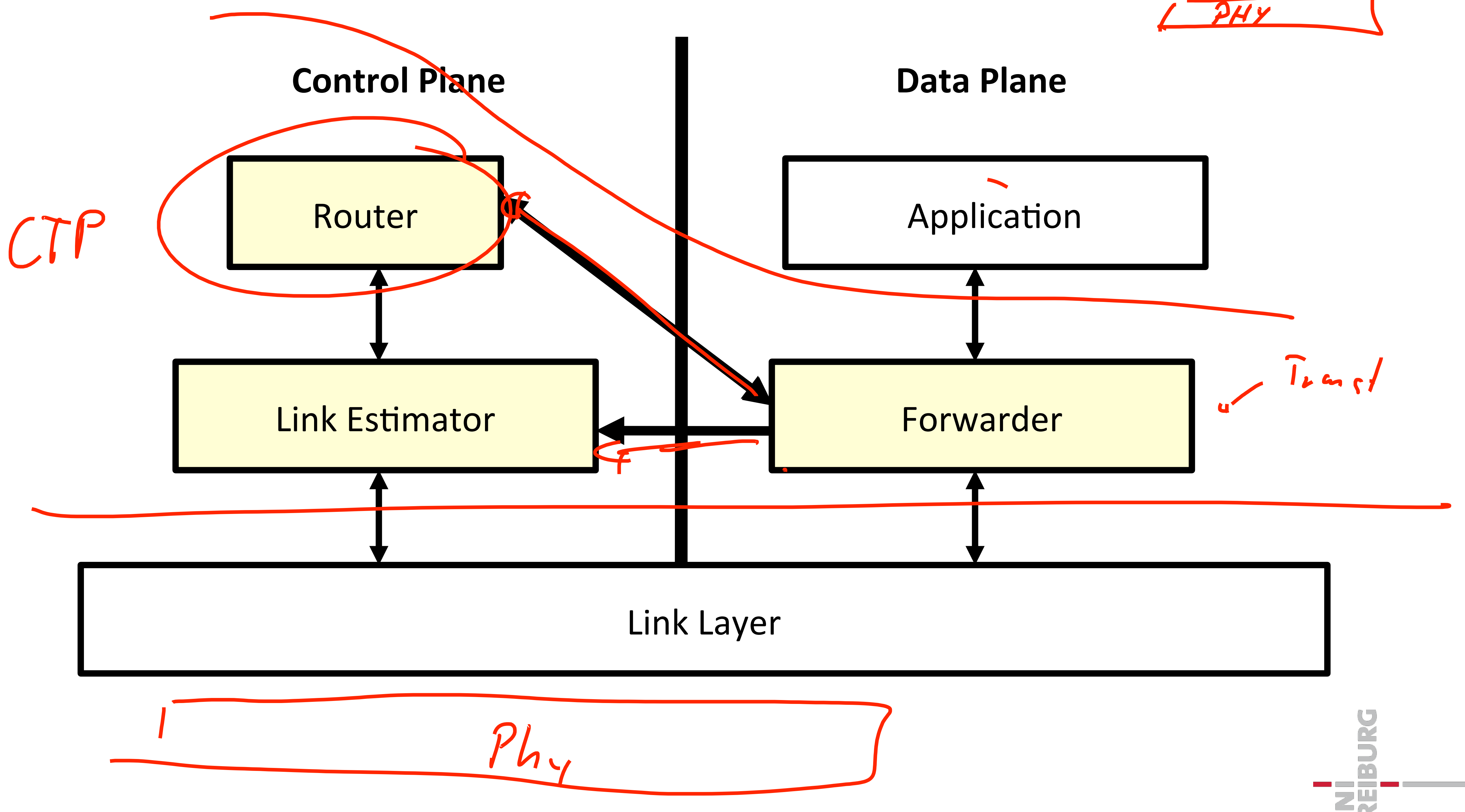
- ETX has been also applied to DSDV, DSR
- ETX is the basis of CTP

CTP Wireless Link Dynamics



CTP: Interplay between Control and Data Plane

- Enable control and data plane interaction

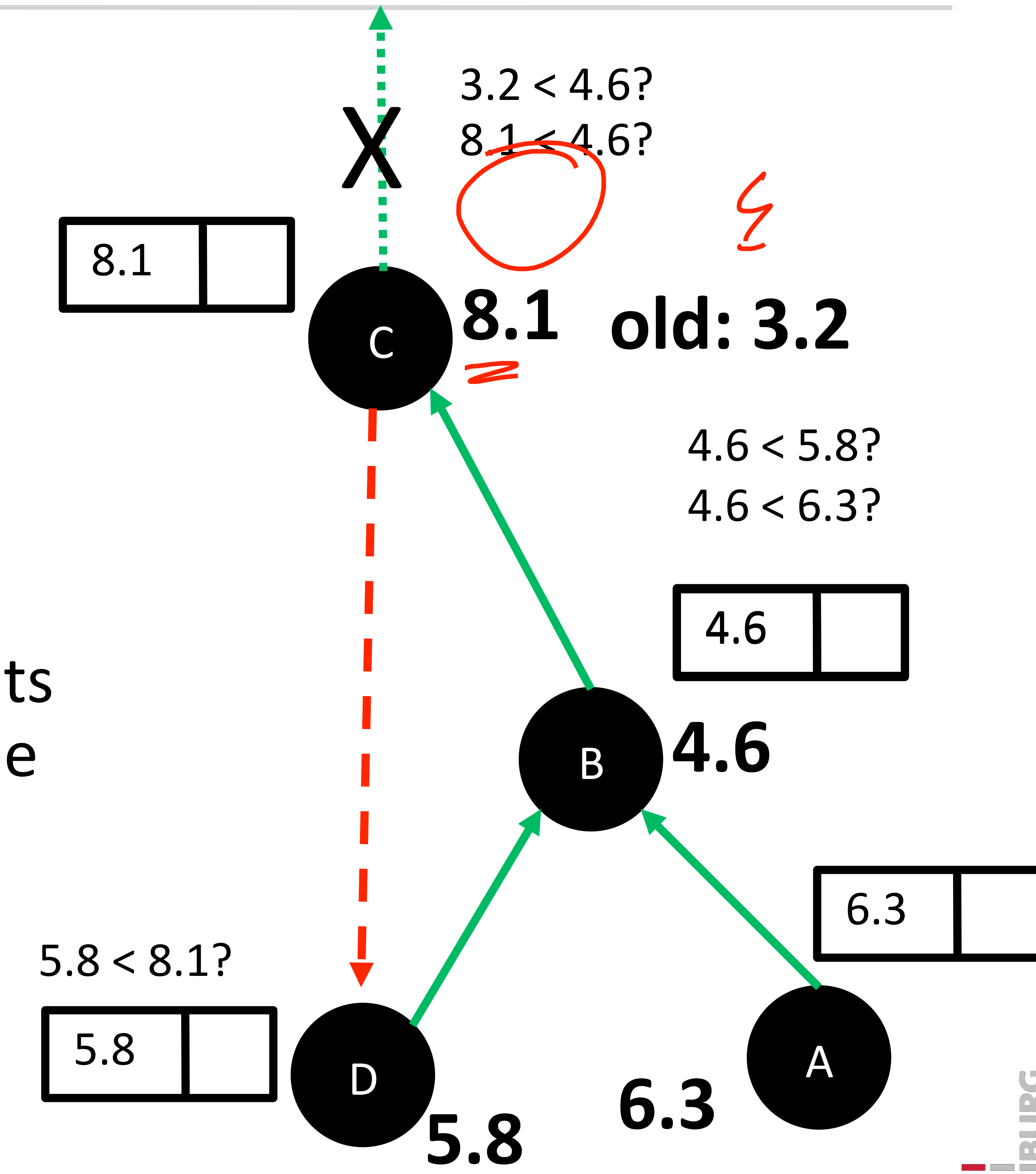


CTP Datapath validation

- Use data packets to validate the topology
  - Inconsistencies
  - Loops
- Receiver checks for consistency on each hop
  - Transmitter's cost is in the header
- Same time-scale as data packets
  - Validate only when necessary

CTP Detecting Routing Loops

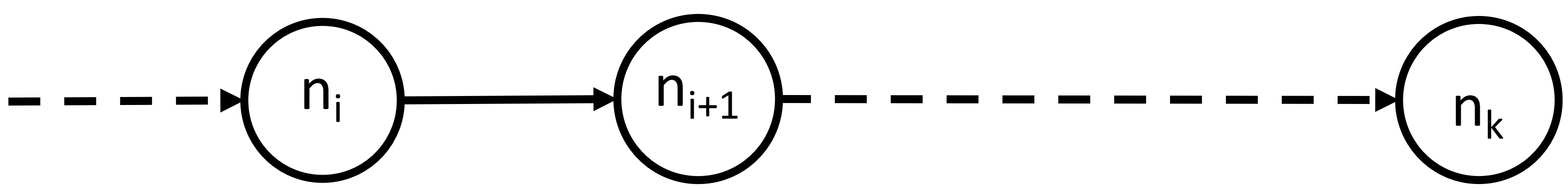
- Datapath validation
  - Cost in the packet
  - Receiver checks
- Inconsistency
  - Larger cost than on the packet
- On Inconsistency
  - Do not drop the packets
  - Signal the control plane



Routing Consistency

- *Next hop* should be closer to the destination
- Maintain this consistency criteria on a path

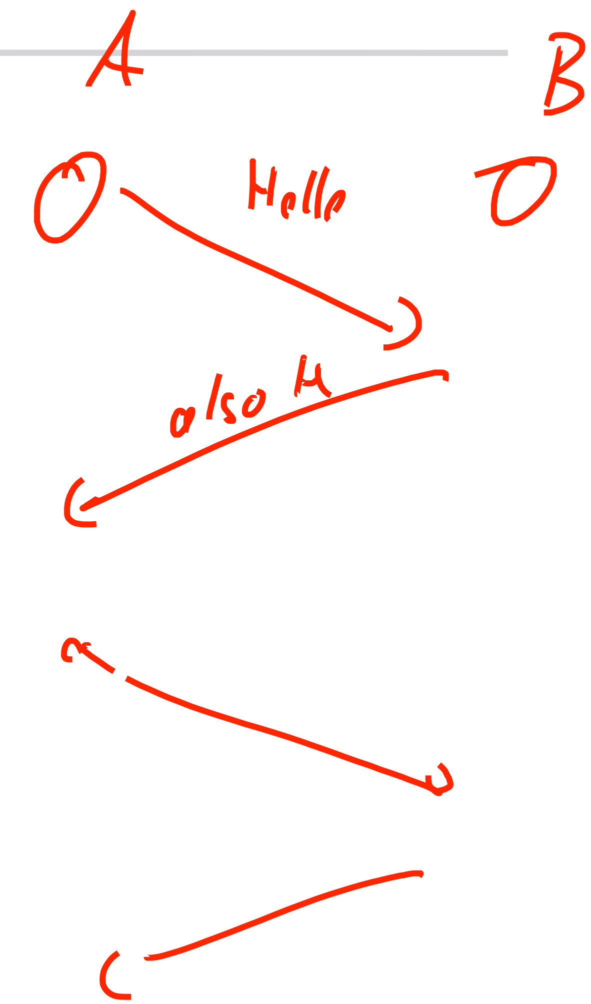
$$\forall i \in \{0, k-1\},\ ETX(n_i) > ETX(n_{i+1})$$



- Inconsistency due to stale state

CTP: Adaptive Beaconing

- Fixed beacon intervals never fit
  - too many beacons, if no changes appear
  - too few beacons, if drastic changes appear
- Agility-efficiency tradeoff
- Solution: Use Trickle algorithm
- Trickle
  - WSN update mechanism for software updates
  - Code propagation: Version number mismatch
  - Literature
    - Trickle: A Self-Regulating Algorithm for Code Propagation and Maintenance in Wireless Sensor Networks, Philip Levis, Neil Patel, David Culler, Scott Shenker, NSDI'04 Proceedings of the 1st conference on Symposium on Networked Systems Design and Implementation - Vol. 1, 2-2
    - RFC6206



Trickle: Idea

- An algorithm for establishing eventual consistency in a wireless network
- Establishes consistency quickly
- low overhead when consistent
- Cost scales logarithmically with density
- Requires very little RAM or code
  - 4-7 bytes of RAM
  - 30-100 lines of code
- Motivation: don't waste messages (energy and channel) if all nodes agrees
- Uses
  - Routing topology
  - Reliable broadcasts
  - Neighbor discovery

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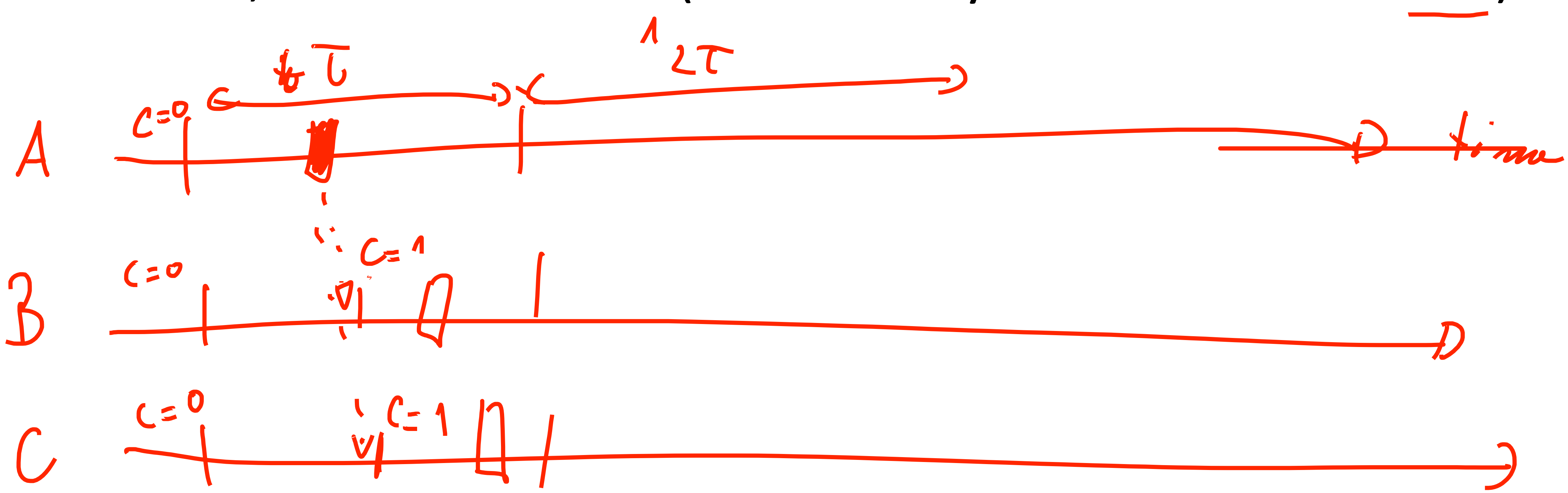
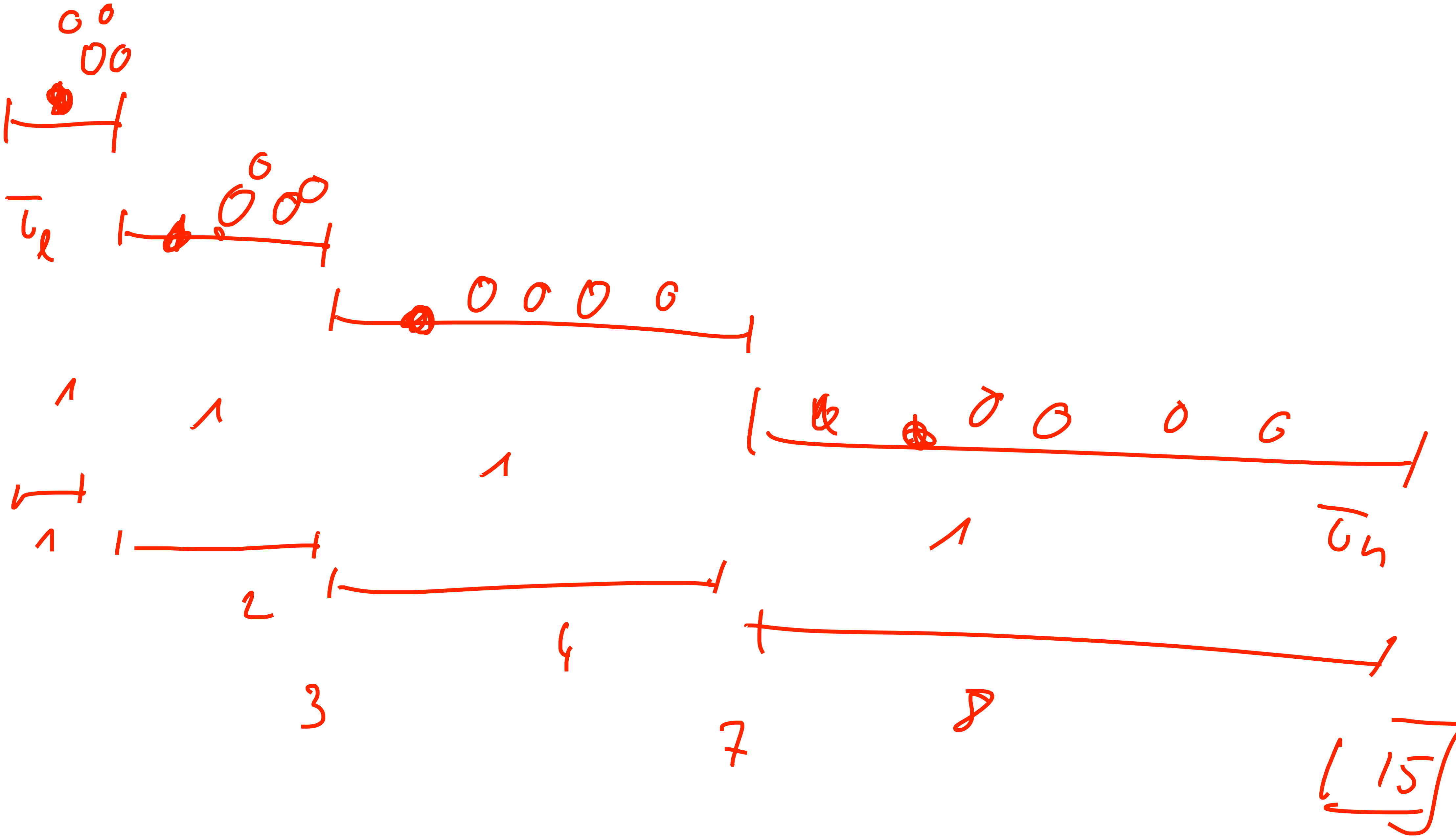
Trickle: Suppression

- At beginning of interval of length τ
  - counter c=0
  - On consistent transmission, c++
- Node picks a time t in range [τ/2,τ]
  - At t, transmit if c < k (redundancy constant k=1 or k=2)



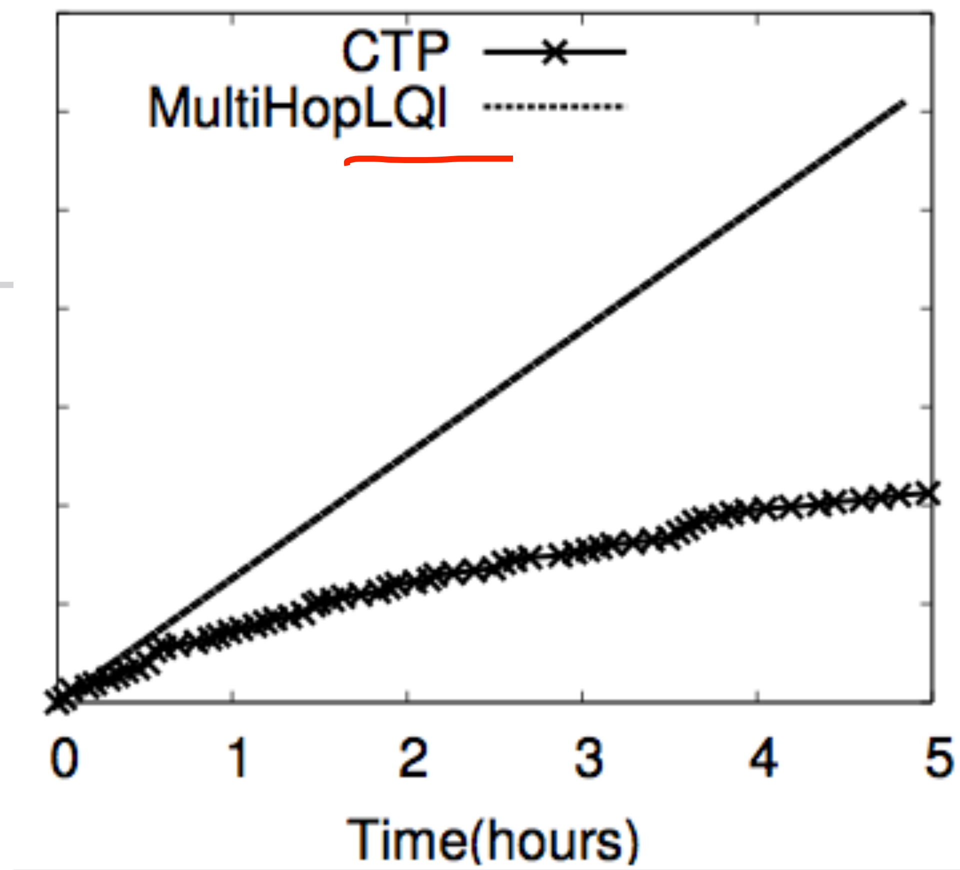


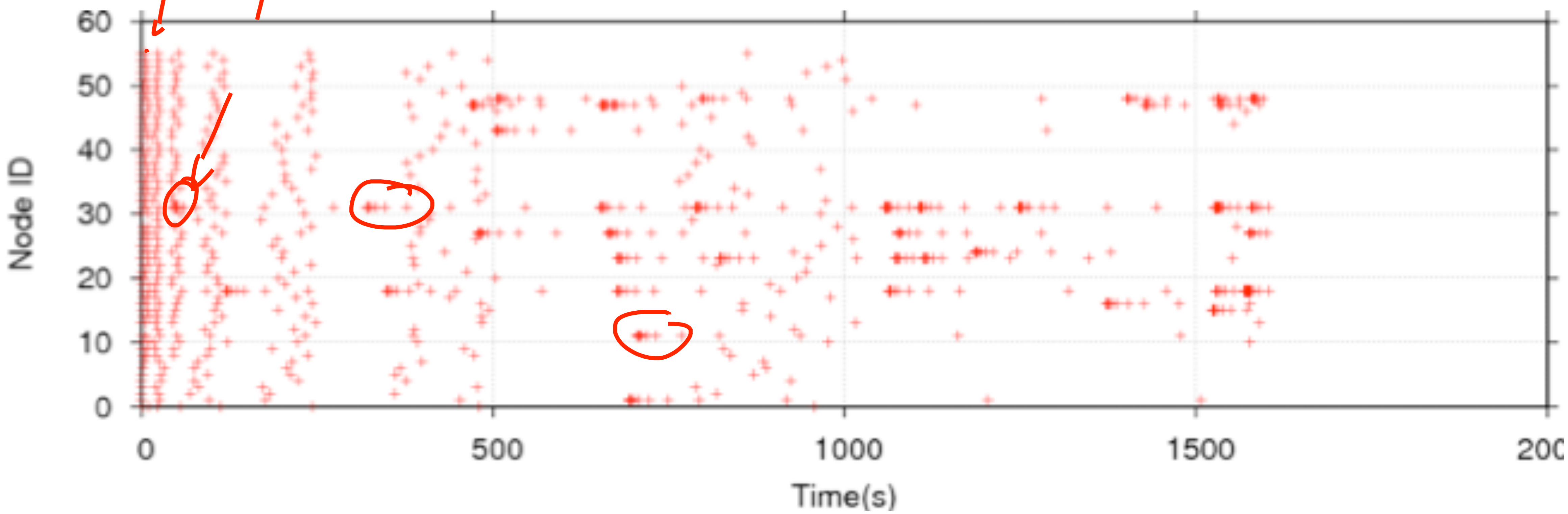
t_1
1
1
1
1
1
2
4
8
3
7
15
t_n

Trickle: Variable Interval Length

- Interval varies between
  - τ_l:minimum interval length
  - τ_h: maximum interval length
- Start with intervals of length $\tau = \tau_l$
  - At end of interval τ, double τ up to τ_h
  - On detecting an inconsistency, set τ to τ_l
- Consistency leads to logarithmic number of beacons
- Inconsistency leads to fast updates

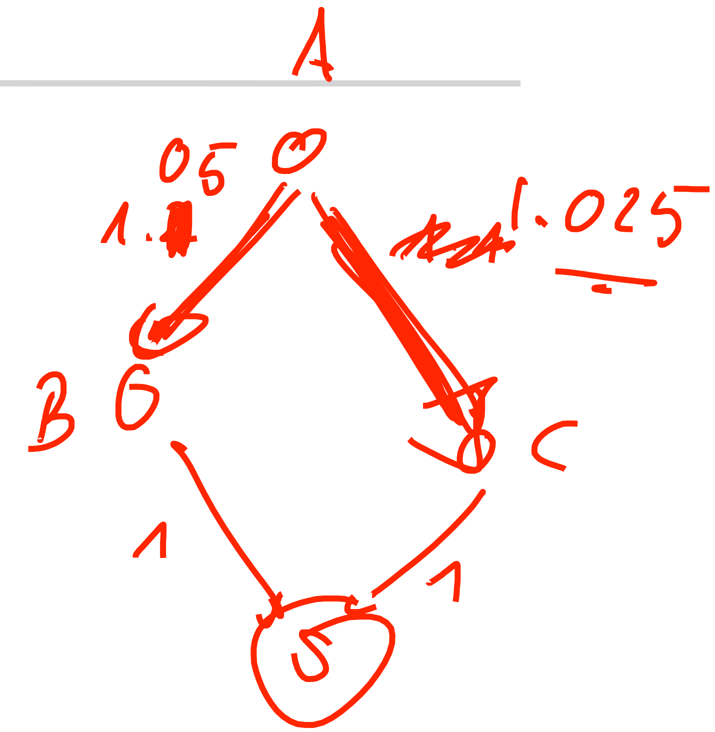
Trickle: Beacons





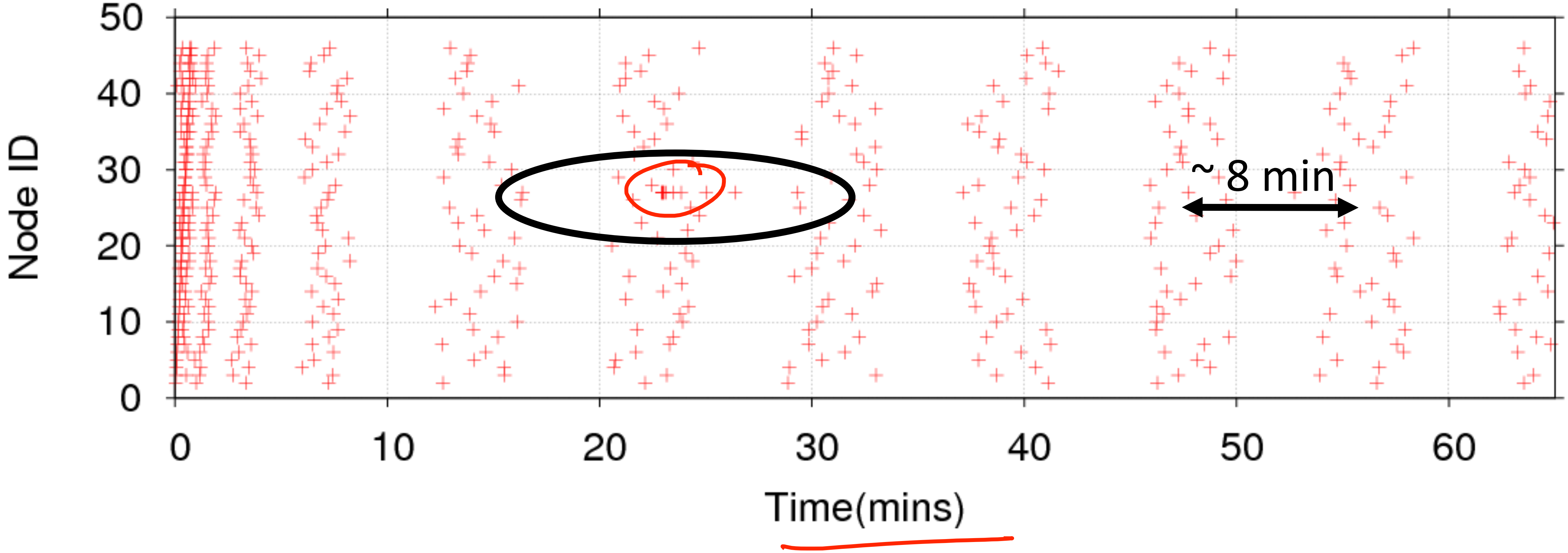
Philip Lewis, The Trickle Algorithm

CTP: Control Traffic Timing

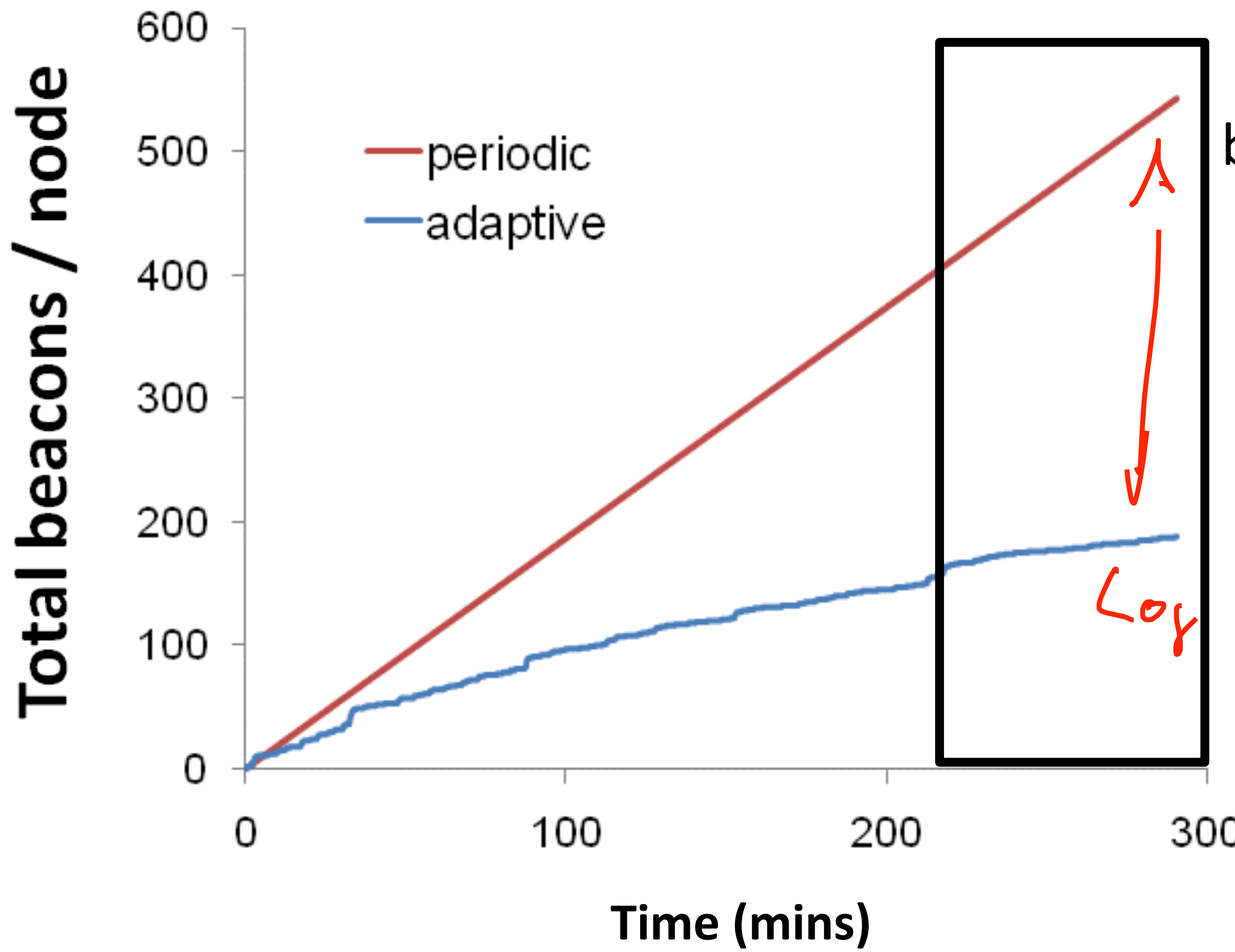


- Extend Trickle to time routing beacons
- Reset the interval
    - ETX(receiver) ≥ ETX(sender)
    - Significant decrease in gradient
        - improvement of ≥ 1.5
    - "Pull" bit
        - new node wants to hear beacons from neighbors
  - Optional: automatic reset after some time (e.g. 5 min.)
- Beaconing interval between 64ms and 1h

CTP Adaptive Beacon Timing (without automatic reset)



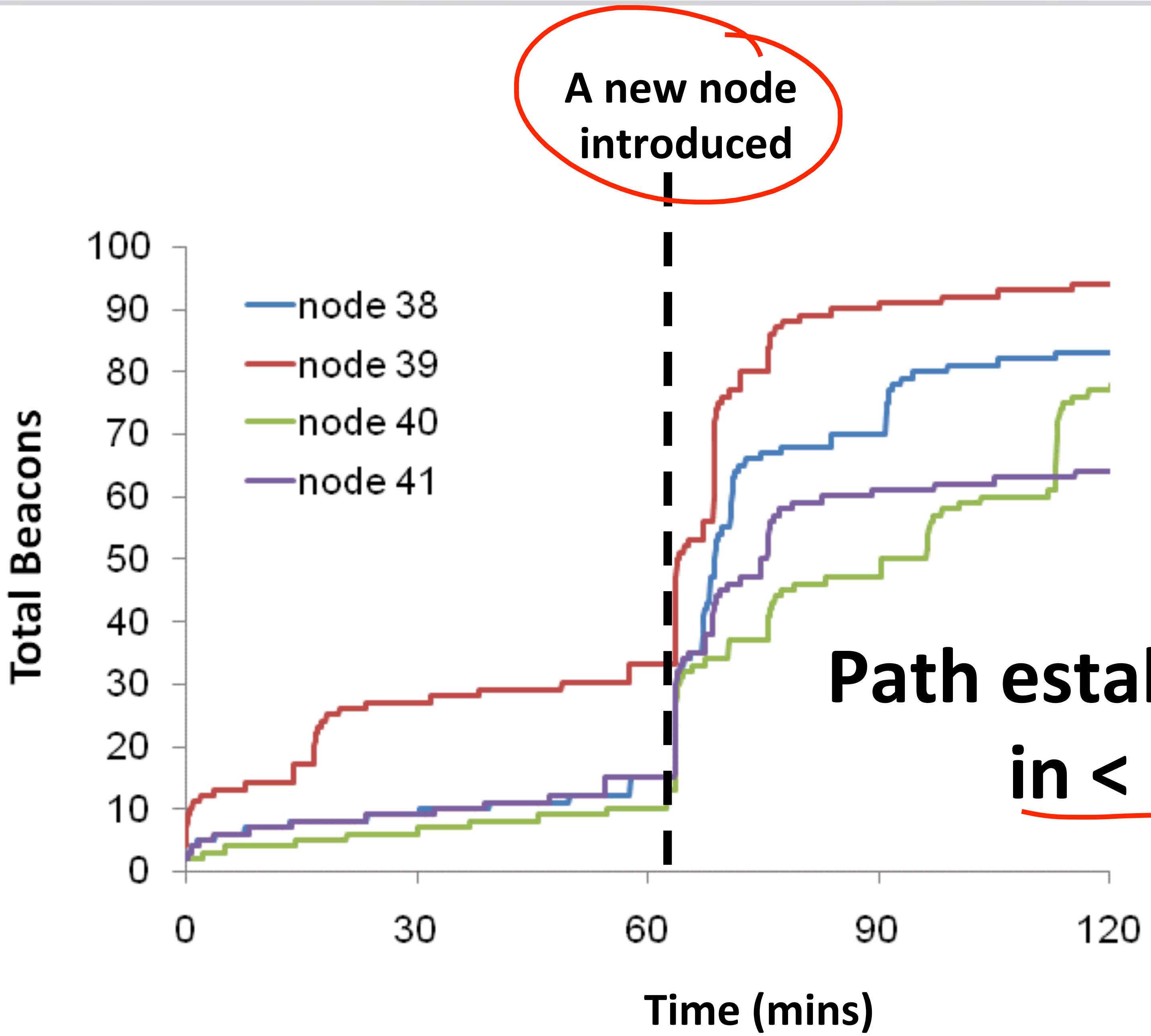
Adaptive vs Periodic Beacons



1.87 beacon/s

0.65 beacon/s

Node Discovery

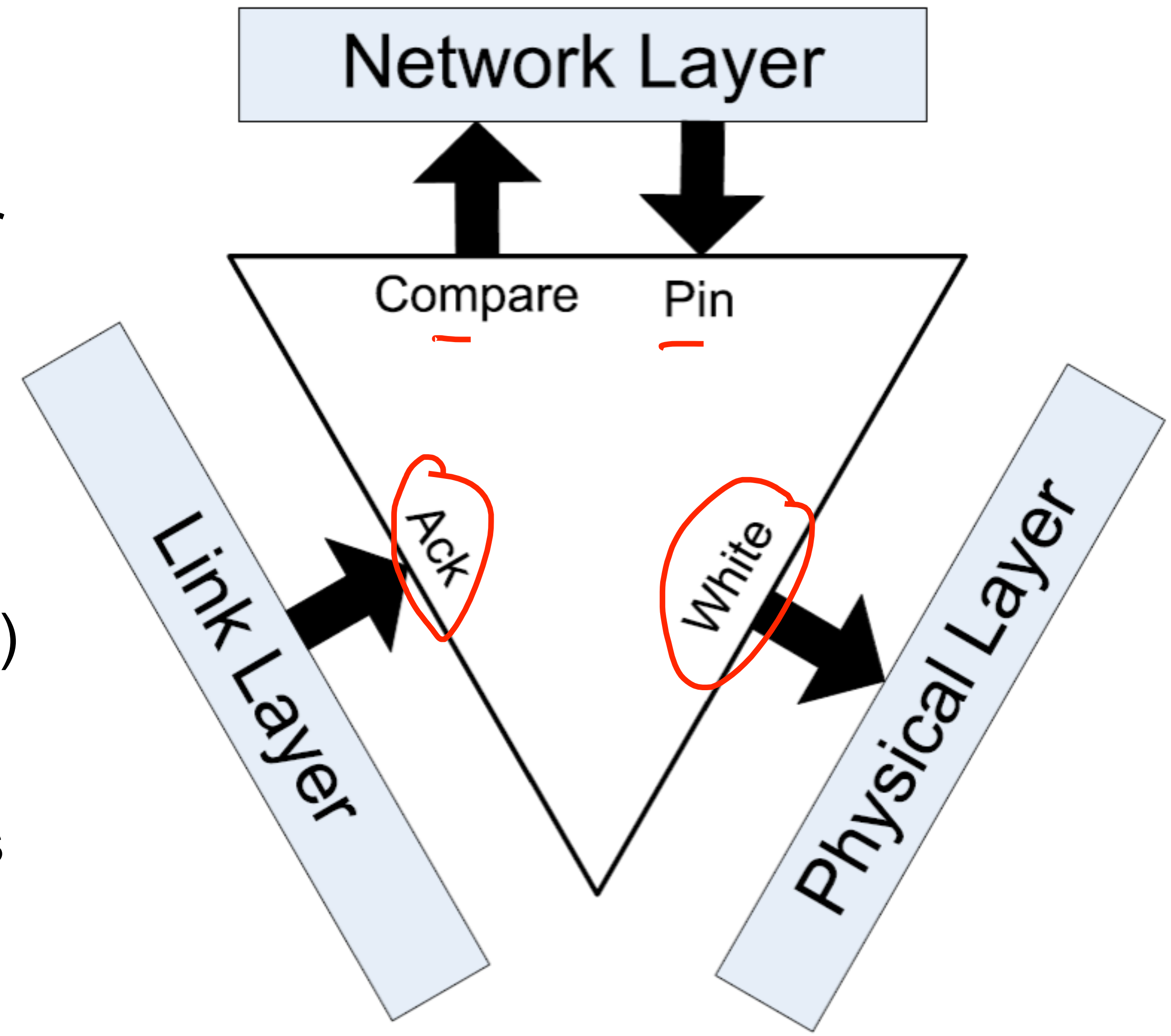


Path established in < 1s

Tutornet

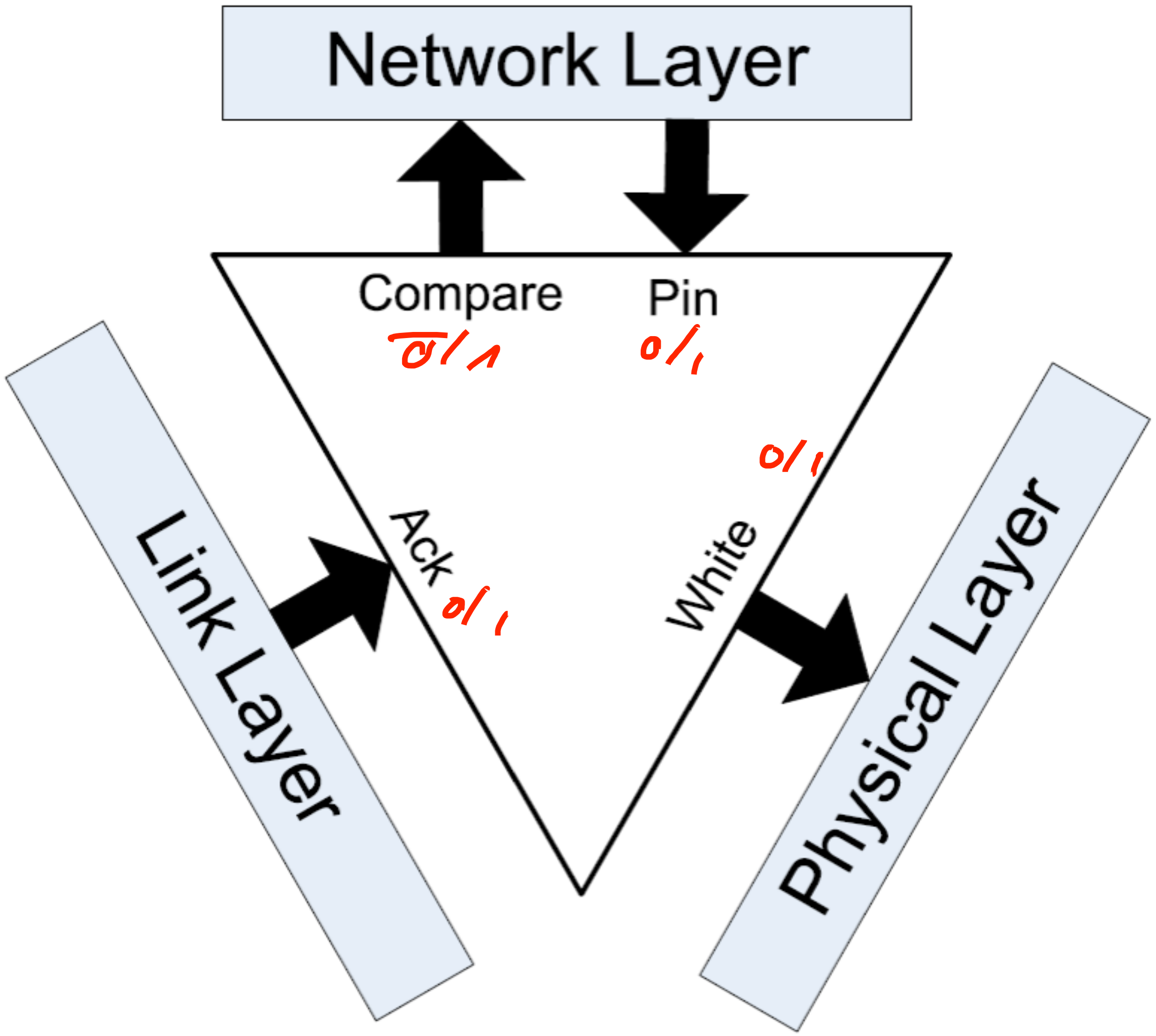
CTP: Link Estimation Layer Information

- Physical Layer
  - LQI: estimate of how easily a received signal can be demodulated by accumulating the magnitude of the error between ideal constellations and the received signal
  - RSSI: Received Signal Strength Indicator (not used)
  - PRR: Packet Reception Ratio (not used)
- Link Layer
  - Number of received Acknowledgements
  - Periodic beaconing (for ETX)
- Network Layer
  - Link on the shortest hop route to sink
  - Geometric information

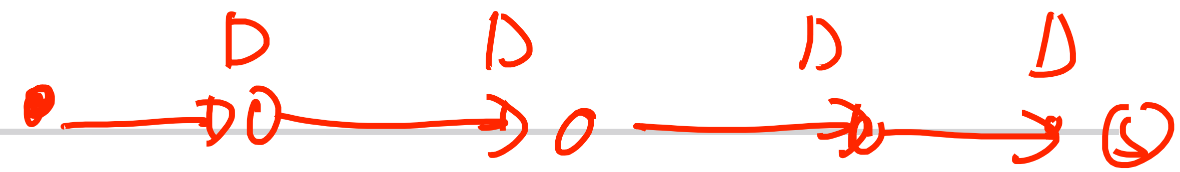


Link Estimation by Four Bits

- COMPARE
  - Is this a useful link?
- PIN
  - Network layer wants to keep this link in the table
- ACK=1
  - A packet transmission on this link was acknowledged
- WHITE=1:
  - each symbol in the packet has a very low probability of decoding error



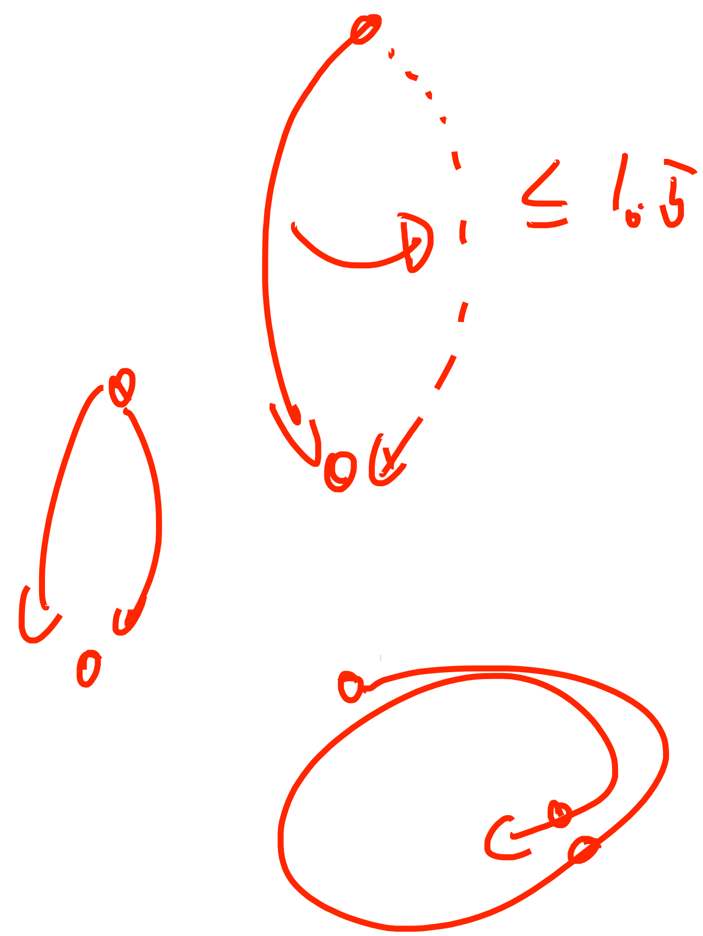
Link Estimation Details



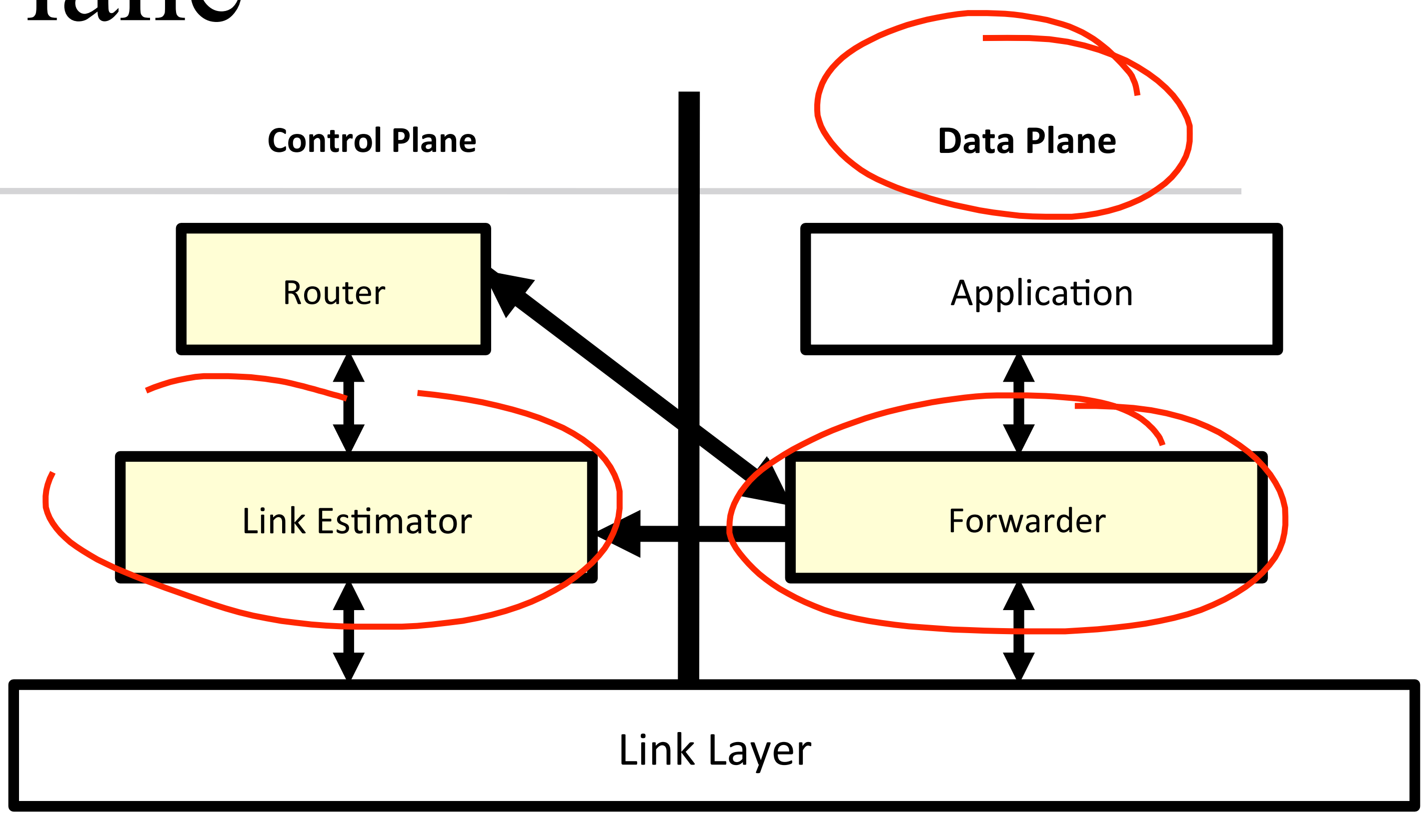
- Network layer
  - receives packet from new link
- Estimator checks
  - white bit is set?
  - asks network layer whether link improves routing -> set compare bit
  - If both bits are set
    - remove an unpinned entry from routing table and replace it with packet
- Use ack bit to compute ETX
  - separately compute ETX for unicast and broadcast value every k_u or k_b (~5) packets by k_u/a
    - a: number of acknowledgements
  - Average by windowed exponentially weighted moving average over reception probabilities (EWMA)
  - ETX = 1/average
  - Combine unicast and broadcast ETX by a second EWMA

CTP: Routing

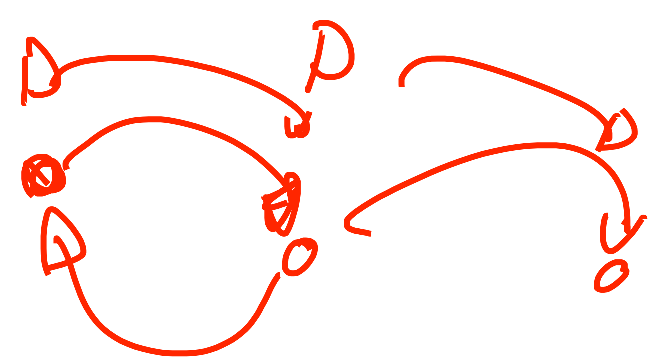
- Prevent fast route changes
  - by hysteresis in path selection
  - switch only routes if other route is significantly better
    - i.e. ETX is at least 1.5 lower
- Looping packets
  - are not dropped
  - but paused
  - recognized by the Transmit Cache
  - and resent



CTP: Data Plane



- Concepts
  - THL: time has lived field (instead of TTL)
  - Aggressive retransmission strategy
    - 32 tries per packet
- Per-Client Queueing
  - client = application or service
  - one outstanding packet per client
- Hybrid Send Queue
  - lower level FIFO queue of route-through and generated packets
  - size = #clients + forward-buffer-size
- Transmit Timer
  - Prevent self-interference by waiting on the expectation two packet times between transmissions
  - i.e. choose random time in waits in the range of (1.5*p*,2.5*p*)
    - where p is the packet time
- Transmit Cache
  - False (negative/positive) acknowledgments
  - Distinguish duplicate packets from loop packets (using THL)
  - Looping packets are forward to repair routing tables
  - Remembering is important to identify duplicates (size: 4 packets)



CTP: Experiments at Stanford

Testbed	Platform	Nodes	Size m^2 or m^3	Degree Min	Degree Max	PL	Cost	Cost PL	Churn node·hr
Tutornet (16)	Tmote	91	50×25×10	10	60	3.12	5.91	1.90	31.37
Wymanpark	Tmote	47	80×10	4	30	3.23	4.62	1.43	8.47
Motelab	Tmote	131	40×20×15	9	63	3.05	5.53	1.81	4.24
Kansei[a]	TelosB	310	40×20	214	305	1.45	–	–	4.34
Mirage	Mica2dot	35	50×20	9	32	2.92	3.83	1.31	2.05
NetEye	Tmote	125	6×4	114	120	1.34	1.40	1.04	1.94
Mirage	MicaZ	86	50×20	20	65	1.70	1.85	1.09	1.92
Quanto (15)	Quanto	49	35×30	8	47	2.93	3.35	1.14	1.11
Twist	Tmote	100	30×13×17	38	81	1.69	2.01	1.19	1.01
Twist	eyesIFXv2	102	30×13×17	22	100	2.58	2.64	1.02	0.69
Vinelab	Tmote	48	60×30	6	23	2.79	3.49	1.25	0.63
Indriya	TelosB	126	66×37×10	1	36	2.82	3.12	1.11	0.05
Tutornet	Tmote	91	50×25×10	14	72	2.02	2.07	1.02	0.04
Blaze[b]	Blaze	20	30×30	9	19	1.30	–	–	–

[a] Packet cost logging failed on ten nodes.
[b] Blaze instrumentation does not provide cost and churn information.
Note: Cost is transmissions per delivery and PL is path length, the average number of hops a data packet takes. Cost/PL is the average transmissions per link. All experiments are on 802.15.4 channel 26 except for the Quanto testbed (channel 15) and one of the Tutornet experiments (channel 16).

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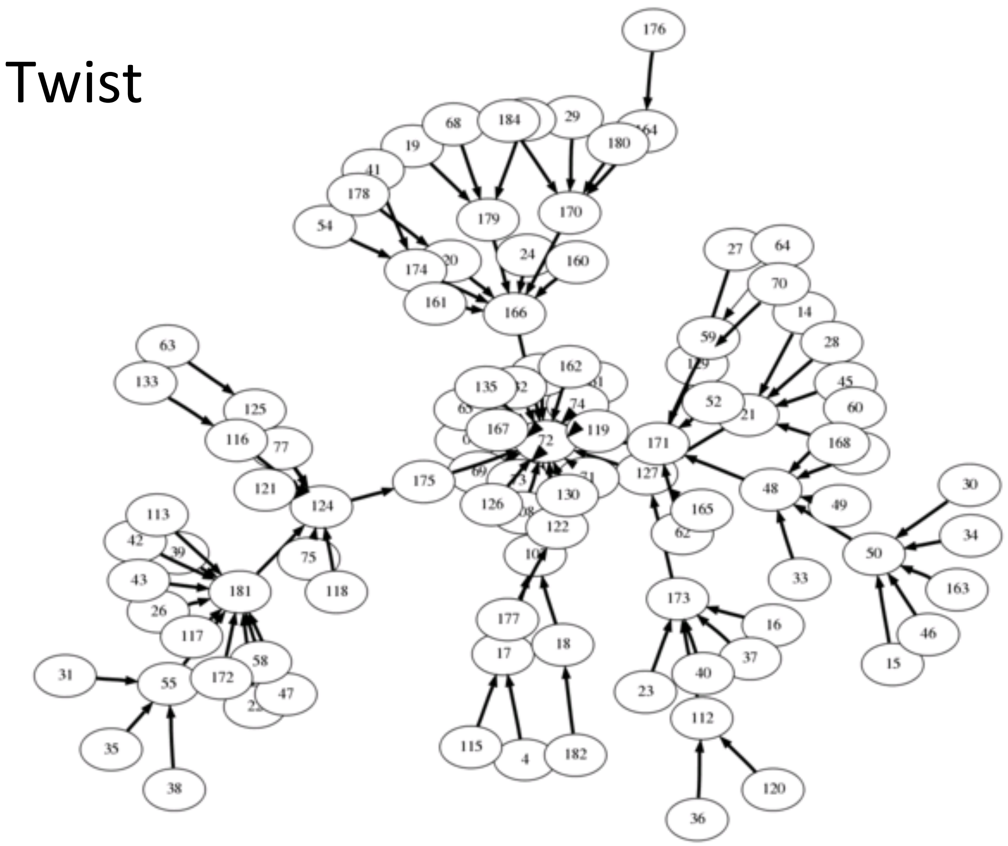
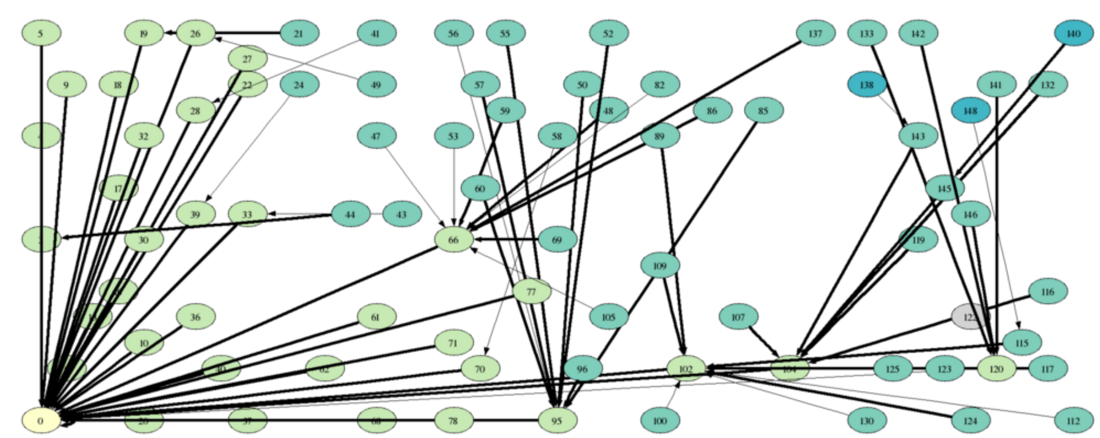
CTP: High end-to-end delivery ratio

Testbed	Delivery Ratio
Wymanpark	0.9999
Vinelab	0.9999
Tutornet	0.9999
NetEye	0.9999
Kansei	0.9998
Mirage-MicaZ	0.9998
Quanto	0.9995
Blaze	0.9990
Twist-Tmote	0.9929
Mirage-Mica2dot	0.9895
Twist-eyesIFXv2	0.9836
Motelab	0.9607

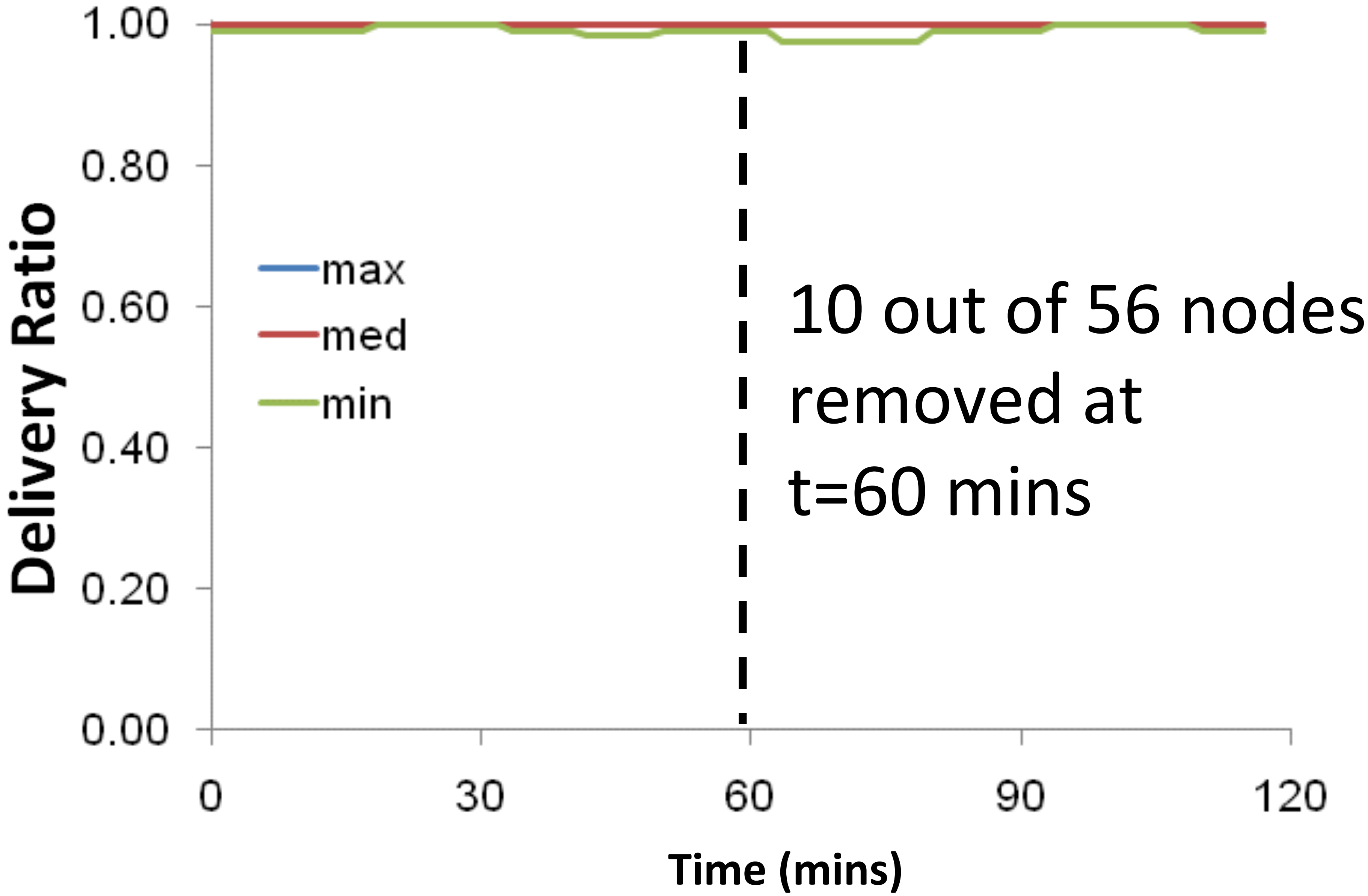
Twist



Mirage

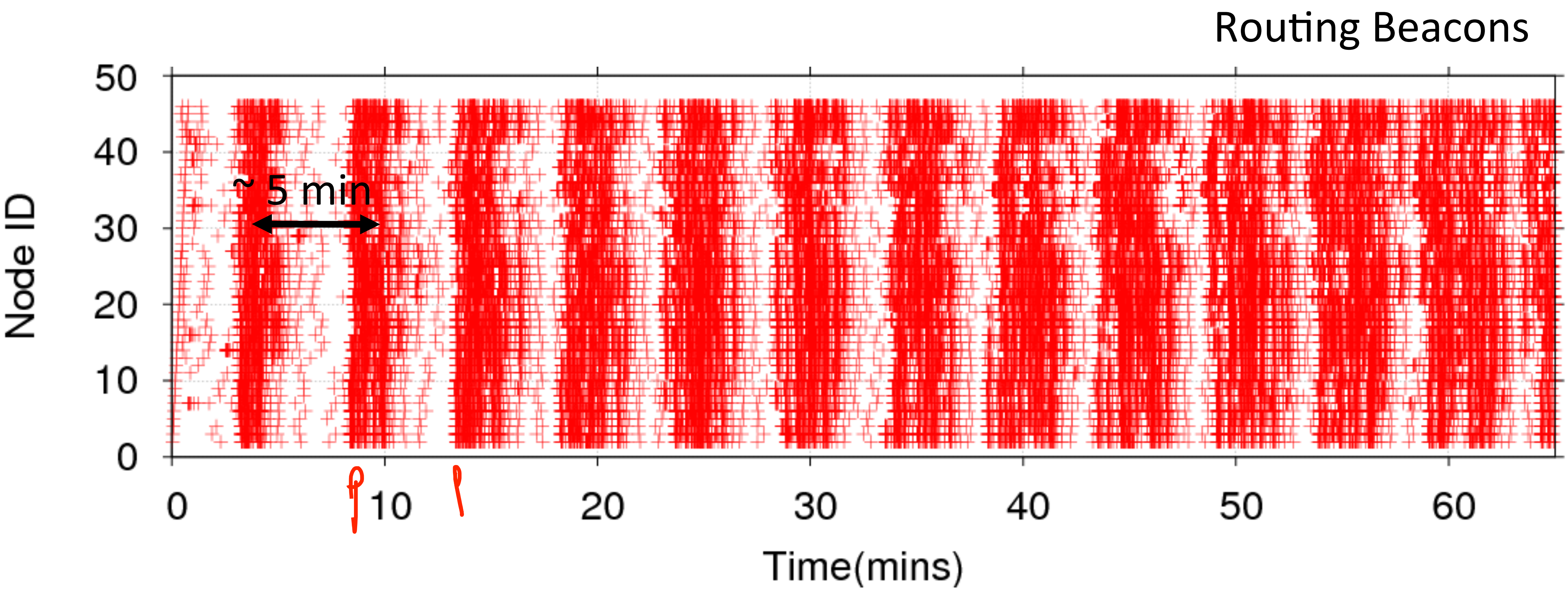


CTP: No disruption in packet delivery



Gnawali, Collection Tree Problem – SenSys 2009 presentation

CTP: Nodes reboot every 5 mins



CTP Performance

- Reliability
  - Delivery ratio > 90% in all cases
- Efficiency
  - Low cost and 5% duty cycle
- Robustness
  - Functional despite network disruptions

LPL

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