One-to-Many TCP
Scalability and End-to-End Reliability

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Summary

- Non Scalability of Reliable Native IP Multicast
- Multicast Overlays
- Reliability of Multicast Overlays by Back-Pressure
- Scalability of Overlay-Multicast
- The Infinite Memory Case

■ joint work with F. Baccelli (INRIA-ENS), A. Chaintreau (INRIA-ENS), S. Sahu (IBM Research) and A. Riabov (Columbia), INFOCOM 04, MTNS 04.

Reliable Group Communication over the Internet

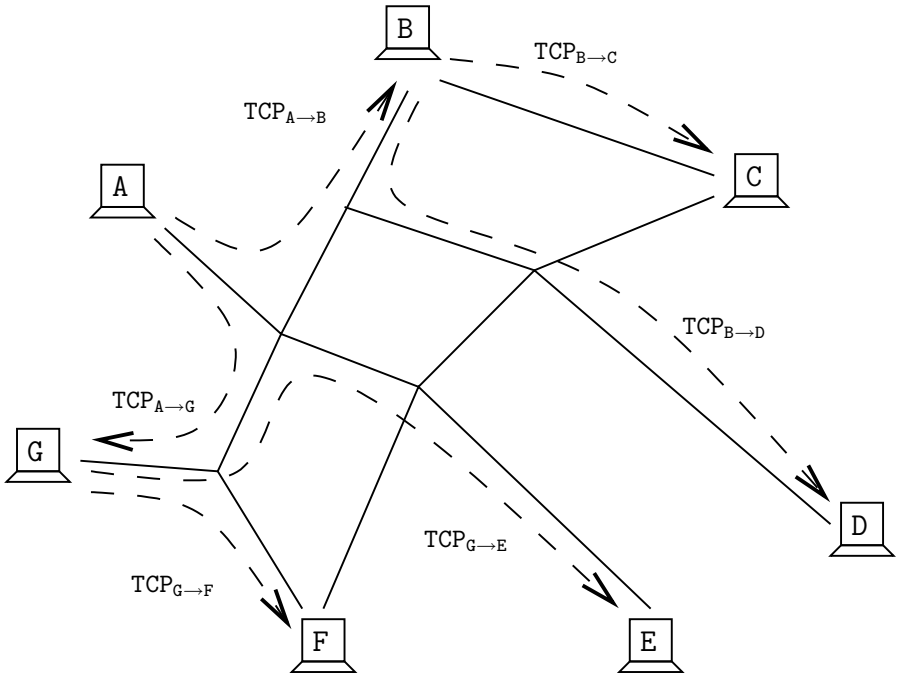
- Group communication: the same large data has to be transported in an efficient and reliable way from a source to a large set of users
- Multicast tree: the broadcasting is made via a tree where each node duplicates the packets it receives from its mother node and sends them to all its daughter nodes
  - Native IP multicast
  - Overlay based multicast (or application-level multicast)

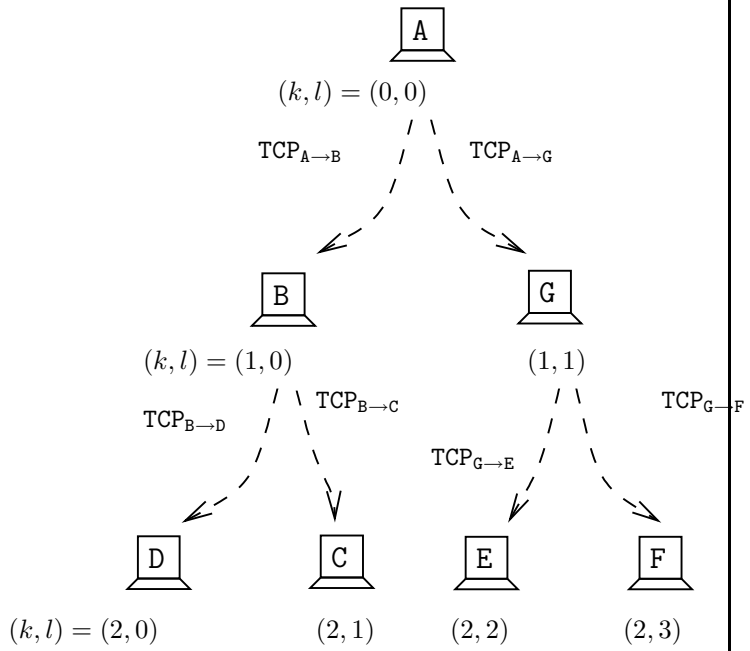
Native IP Multicast

- Native reliable IP multicast: the nodes of the tree are Internet routers;
- IP-supported multicast has deployment obstacles: new functions (routing, replication) are needed in routers.
- Reliable IP-supported multicast has scalability problems: in the presence of random fluctuations, when a window congestion control mechanism is used for ensuring reliability, the group throughput tends to 0 when the group size gets large
  - S. Bhattacharyya, D. Towsley, J. Kurose INFOCOM 1999
    The Loss Path Multiplicity Problem in Multicast Congestion Control
  - A. Chaintreau, F. Baccelli, C. Diot INFOCOM 2001
    Impact of Network Delay Variation on Multicast Session Performance with TCP-like Congestion Control

Multicast Overlays

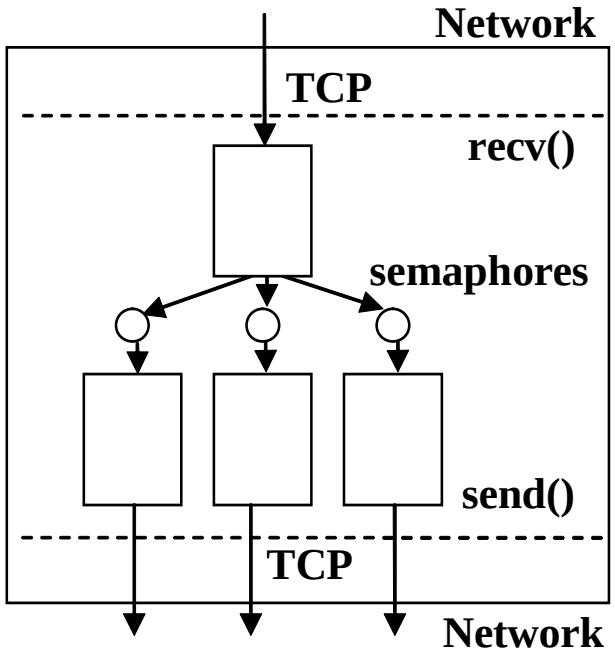
- IP overlays: application–layer structures that are built upon the existing transport protocols of the Internet
- Multicast Overlay
  - the nodes of the tree are end-systems
  - the edges of the tree are point-to-point TCP connections
  - the end-systems are in charge of multicast routing and replication: after receiving data from its mother node, a node replicates the data on each of its outgoing links and forwards it in sequence to each of its daughter nodes in the overlay tree.


B
$\text{TCP}_{\text{B}\to\text{C}}$
$\text{TCP}_{\text{A}\to\text{B}}$
A
C
$\text{TCP}_{\text{B}\to\text{D}}$
$\text{TCP}_{\text{A}\to\text{G}}$
G
D
$\text{TCP}_{\text{G}\to\text{E}}$
$\text{TCP}_{\text{G}\to\text{F}}$
F
E


A
$(k,l)=(0,0)$
$\text{TCP}_{\text{A}\to\text{B}}$
$\text{TCP}_{\text{A}\to\text{G}}$
B
G
$(k,l)=(1,0)$
$(1,1)$
$\text{TCP}_{\text{B}\to\text{D}}$
$\text{TCP}_{\text{B}\to\text{C}}$
$\text{TCP}_{\text{G}\to\text{F}}$
$\text{TCP}_{\text{G}\to\text{E}}$
D
C
E
F
$(k,l)=(2,0)$
$(2,1)$
$(2,2)$
$(2,3)$

Zoom on End-Systems

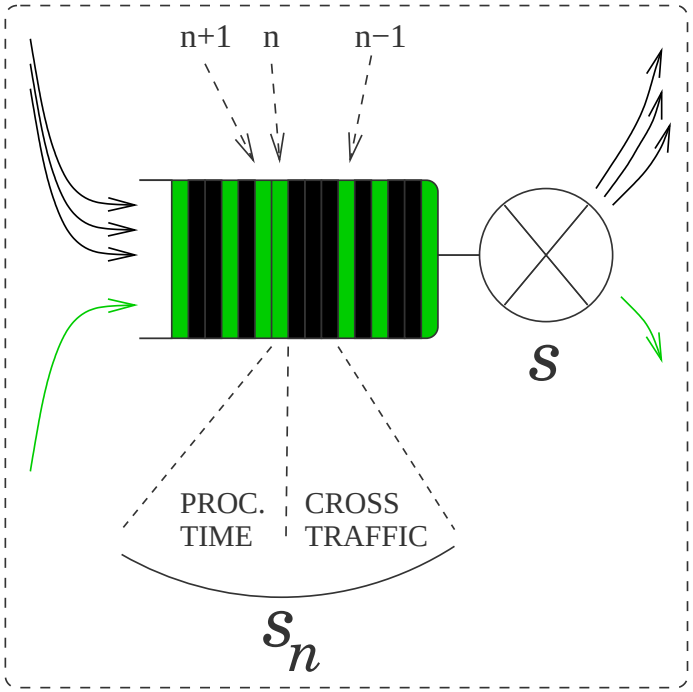
- End-system input and output buffer interaction during overlay multicast.



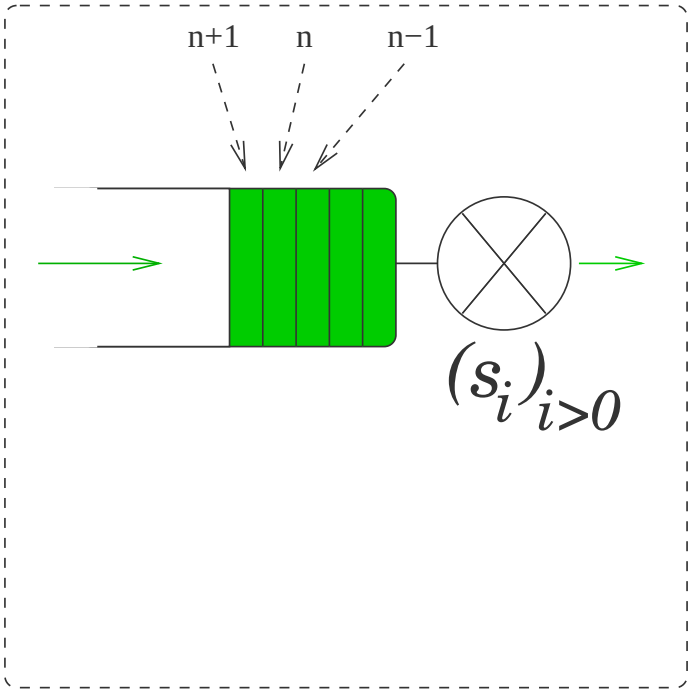
Zoom on a Point to Point TCP Connection

- Each TCP connection
  - has a route that consists of a sequence of Internet routers in series
  - is affected by random fluctuations (slow downs) and random packet losses/marking (AQM, RED) due to its competition with (Internet) cross traffic
  - reacts to slow downs using the TCP adaptive window congestion control mechanism
  - recovers from packet losses using the retransmission mechanism of TCP.

TCP Connection: Random Fluctuations in Routers



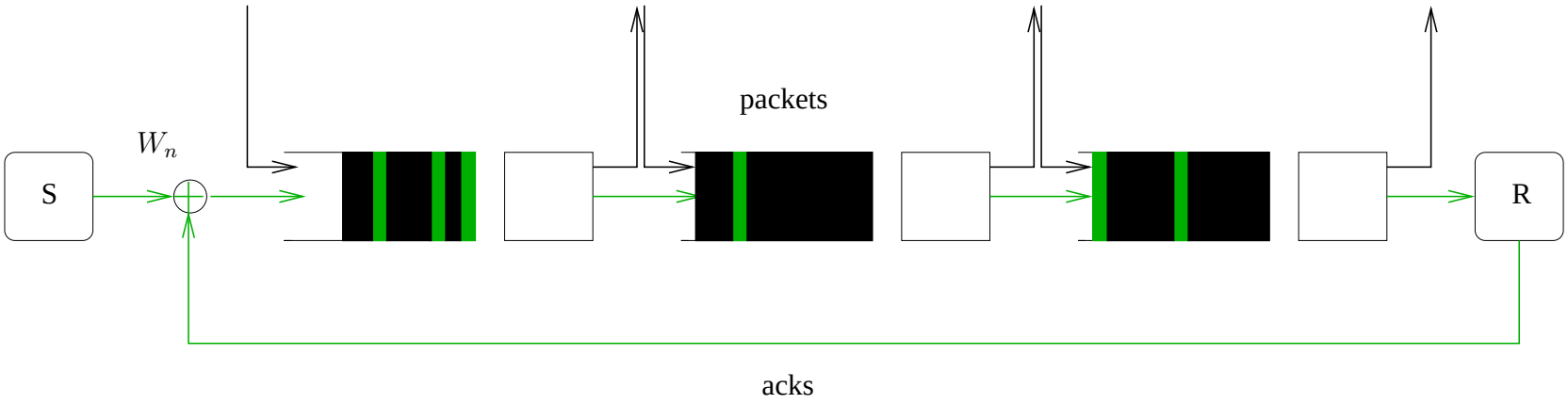
A Router



Our Model

TCP Connection: End to End Adaptive Window Flow Control

- Each received packet is acknowledged by the receiver back to the source via an ack. that contains the sequence number of the packet.
- Window flow Control: if the window size is W, the source can only send packet $n + W$ after packet n has been acknowledged.



TCP Connection: End to End Adaptive Window Flow Control (*continued*)

- TCP window size adaptation

$$w_0 = 1, \qquad w_{n+1} = f(w_n, F(n)),$$

$F(n)$: feedback signal on the state of congestion, function of losses (TD) or marking (MK)

- General principle of TCP Reno's congestion avoidance (CA) phase: AIMD dynamics

$$f(w_n, \text{OK}) = w_n + \frac{1}{w_n}, \quad f(w_n, \text{TD or MK}) = \left\lfloor \frac{w_n}{2} \right\rfloor$$

- Maximal window advertised by the receiver depending on the size of its input buffer.

TCP Connection with Losses: Retransmissions

- If packet m is lost whereas packets $m+1$, $m+2\ldots$ are received, these packets trigger duplicate acks
- When packet $m+3$ is received, its duplicate ack (TD) triggers the Fast Retransmit Fast Recovery procedure
  - the sender sends a duplicate of packet m,
  - the sender halves its window and inflates it of 3 units, which usually blocks the sending of new packets
  - each time a new packet $m+4$, $m+5$,... is received, a new duplicate ack is sent back to the source, and each such duplicate ack inflates the window: constant number of in flight packets
  - when the duplicate of packet m arrives, all packets from m to $m+W_m$ are simultaneously acknowledged and the window then starts a new CA phase from $W_m/2$.

Reliability of Multicast Overlays via Back-Pressure

- Three different types of packet losses in the overlay network:
  1. Losses in the path in-between the nodes:
     recovered by the TCP acknowledgment and retransmit mechanisms
  2. Losses due to input buffer overflow:
     will not occur thanks to the back-pressure mechanism of TCP
  3. Losses due to output buffer overflow:
     will not occur thanks to the overlay back-pressure: a packet will be removed from the input buffer only when it is copied to all of the output buffers. The copy process is blocked when one output buffer is full.
- These two back-pressure mechanisms guarantee that there will be no loss at the overlay nodes even if they have finite-size buffers.

Main Conclusion on Reliability of Multicast Overlays

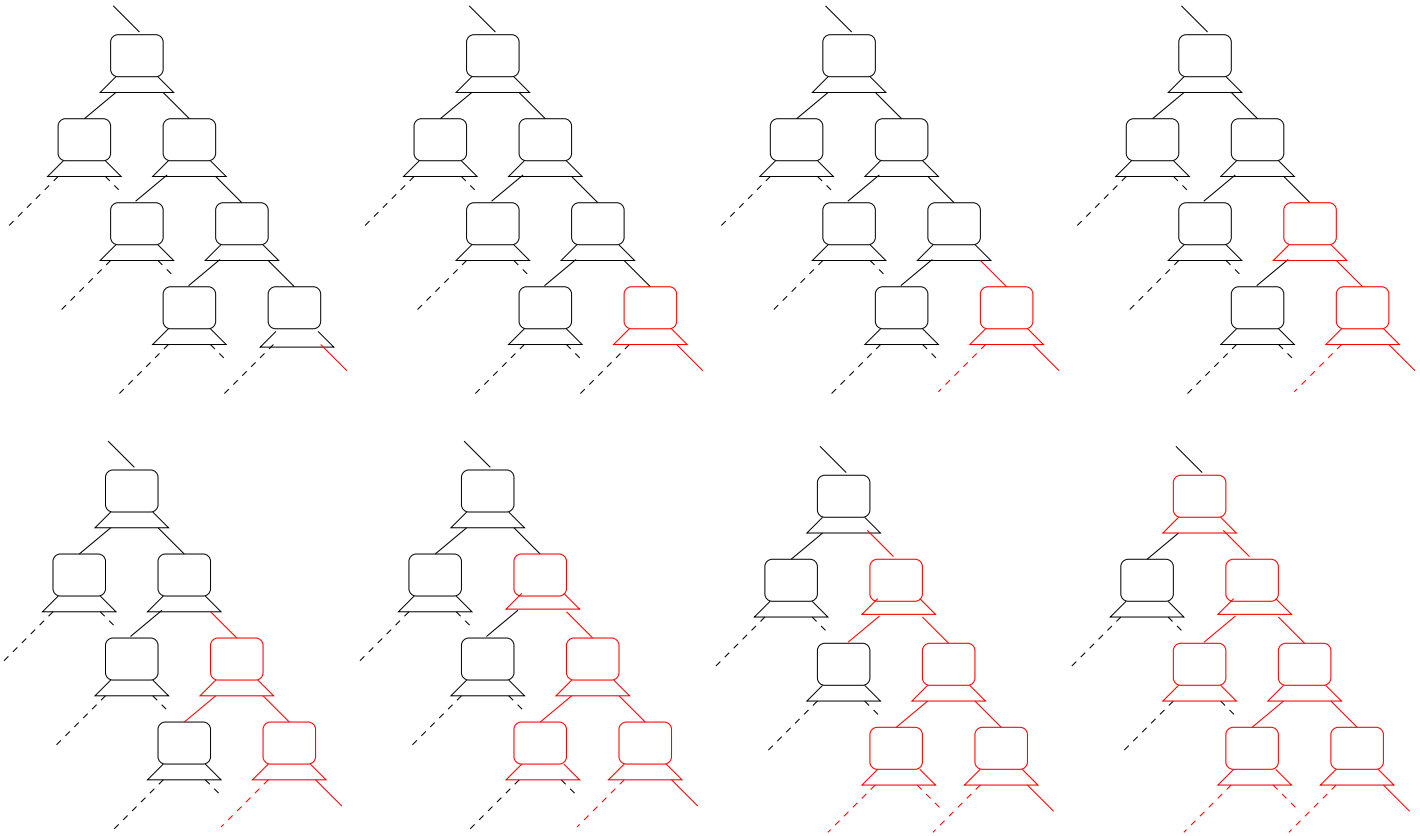
- Backpressured multicast overlays offer a reliable point to multipoint transport mechanism that adapts to congestion in the network in the same spirit as TCP does point to point.

Main Question about Scalability of Multicast Overlays

- There are two key new blocking phenomena proper to multicast overlays:
  1. In any multicast overlay, the mechanisms ensuring in-sequence relaying at each end-system that follows a TCP connection with losses
  2. In any back-pressured multicast overlay, the overflow prevention mechanism in each end-system with finite memory.
- How much will these chained blocking mechanisms reduce the throughput of the group communication when the group size grows large?

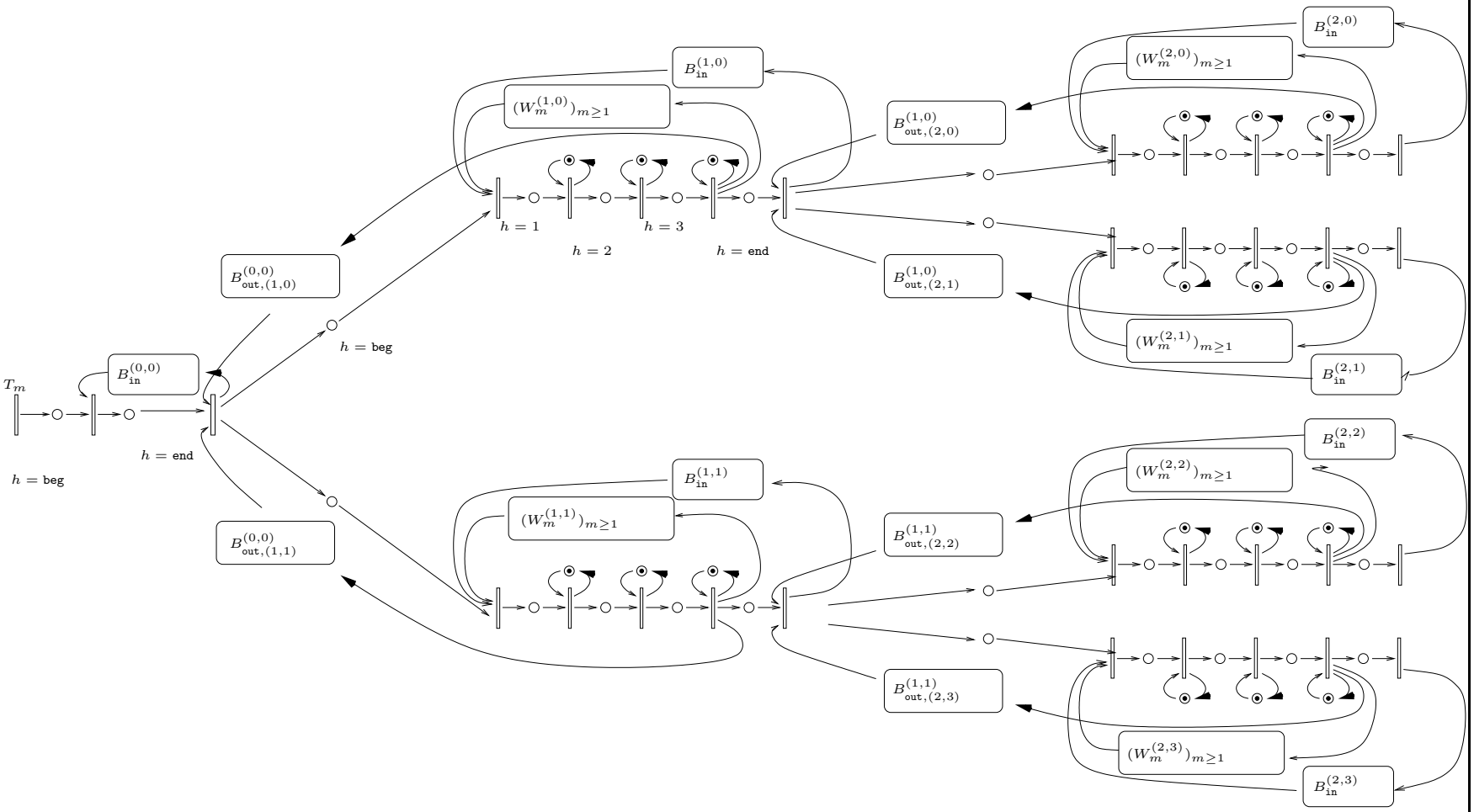
Urvoy-Keller and Biersack NGC, October 2002

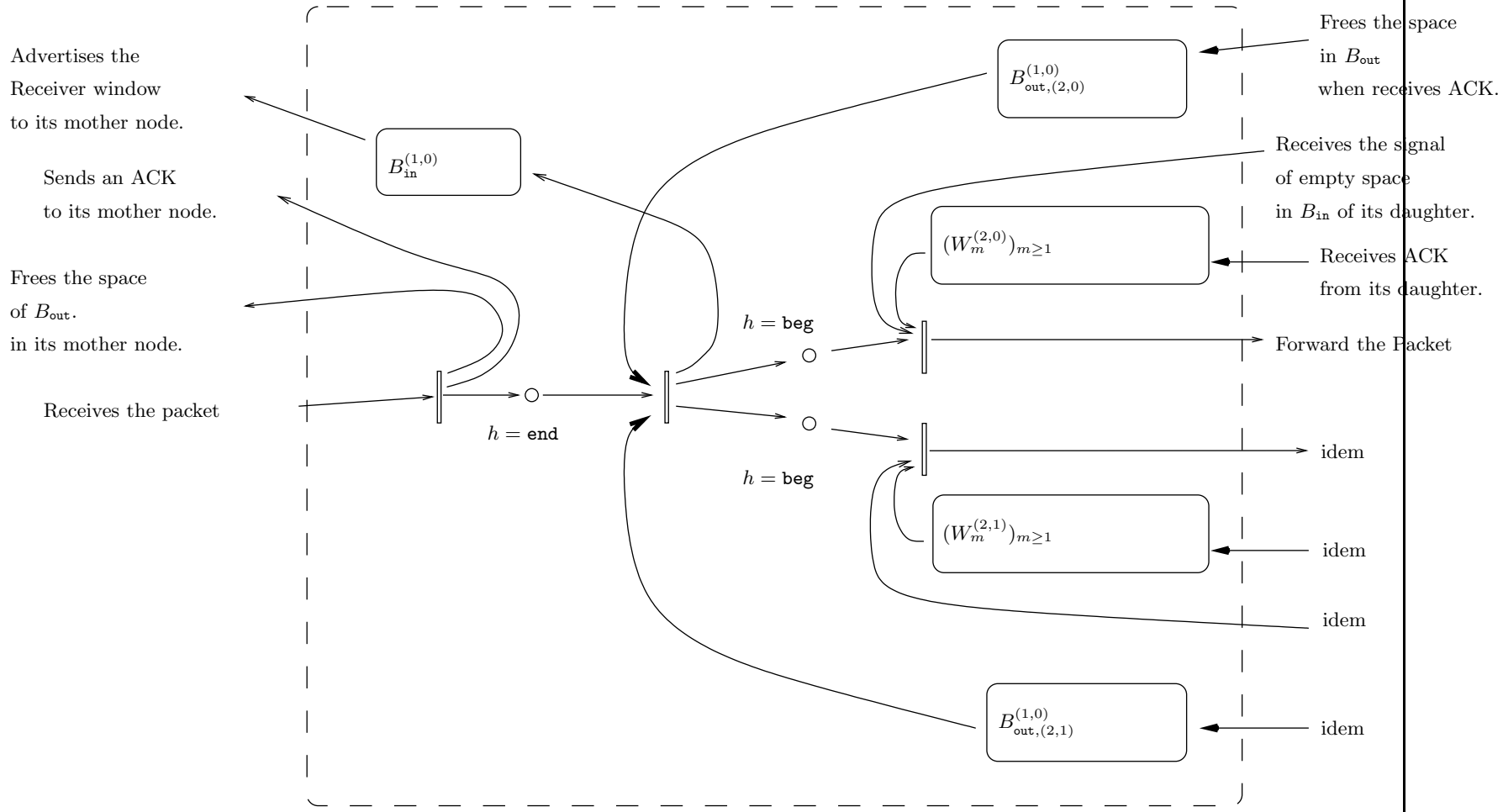
Backward and Forward Propagation of Fluctuations due to Back-Pressure



Petri Net–like Model

- Description of an end-system in the marking case
  - $W_m^{(k,l)}$ the window sequence in TCP connection k, l
  - $H_{(k,l)}$ # routers in TCP connection k, l


T_m
h = beg
h = end
$B^{(0,0)}_{\text{in}}$
$B^{(0,0)}_{\text{out},(1,0)}$
$B^{(0,0)}_{\text{out},(1,1)}$
h = beg
h = end
$B^{(1,0)}_{\text{in}}$
$(W^{(1,0)}_m)_{m\geq 1}$
$h = 1$
$h = 2$
$h = 3$
h = end
$B^{(1,0)}_{\text{out},(2,0)}$
$B^{(1,0)}_{\text{out},(2,1)}$
$B^{(1,1)}_{\text{in}}$
$(W^{(1,1)}_m)_{m\geq 1}$
$B^{(1,1)}_{\text{out},(2,2)}$
$B^{(1,1)}_{\text{out},(2,3)}$
$B^{(2,0)}_{\text{in}}$
$(W^{(2,0)}_m)_{m\geq 1}$
$(W^{(2,1)}_m)_{m\geq 1}$
$B^{(2,1)}_{\text{in}}$
$B^{(2,2)}_{\text{in}}$
$(W^{(2,2)}_m)_{m\geq 1}$
$(W^{(2,3)}_m)_{m\geq 1}$
$B^{(2,3)}_{\text{in}}$


Advertises the
Receiver window
to its mother node.
Sends an ACK
to its mother node.
Frees the space
of $B_{\mathtt{out}}$.
in its mother node.
Receives the packet
$B^{(1,0)}_{\mathtt{in}}$
$h = \mathtt{end}$
$h = \mathtt{beg}$
$h = \mathtt{beg}$
$B^{(1,0)}_{\mathtt{out},(2,0)}$
$(W^{(2,0)}_m)_{m\geq 1}$
$(W^{(2,1)}_m)_{m\geq 1}$
$B^{(1,0)}_{\mathtt{out},(2,1)}$
Frees the space
in $B_{\mathtt{out}}$
when receives ACK.
Receives the signal
of empty space
in $B_{\mathtt{in}}$ of its daughter.
Receives ACK
from its daughter.
Forward the Packet
idem
idem
idem
idem

Evolution Equations for Fast Simulation

- $x_m^{(k,l,h)}$ time when (k,l,h) completes the transmission of packet m
- Equation for root (with $\mathtt{d}(k,l)$ the daughter nodes of k,l):

$$x_m^{(0,0,\mathtt{beg})} = T_m \vee x_{m-B_{\mathtt{in}}^{(0,0)}}^{(0,0,\mathtt{end})}$$

$$x_m^{(0,0,\mathtt{end})} = x_m^{(0,0,\mathtt{beg})} \vee \left(\bigvee_{l \in \mathtt{d}(0,0)} x_{m-B_{\mathtt{out},(1,l)}^{(0,0)}}^{(1,l,H_{(1,l)})} \right)$$

- $T_m \equiv 0$: saturated input case.

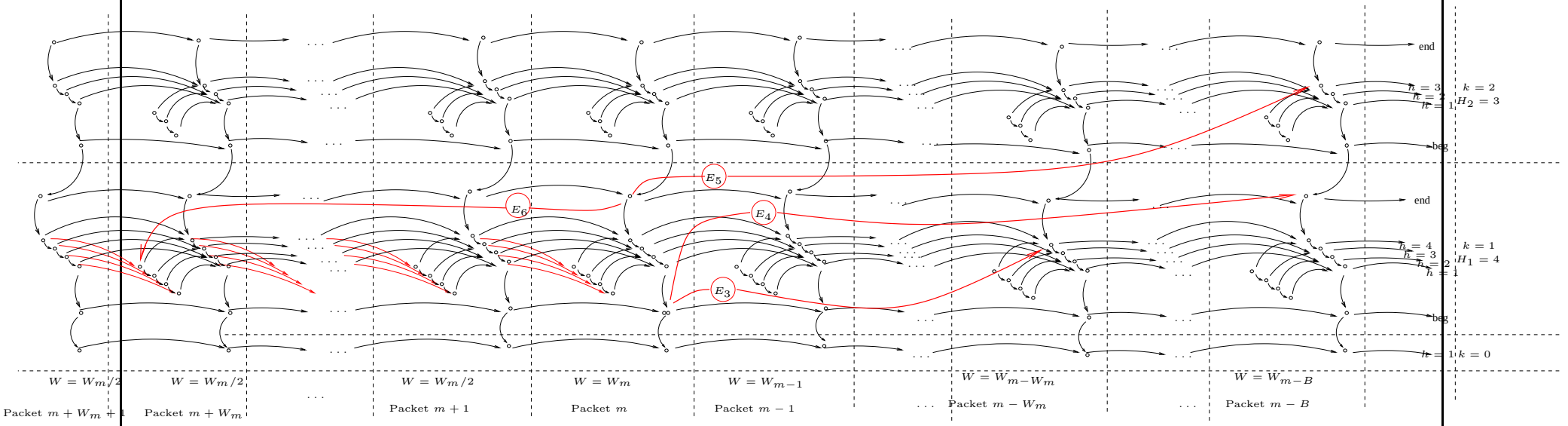
Evolution Equations for Fast Simulation (*continued*)

- Internal nodes: for $k \geq 1,\ l \geq 0$, (with $\mathtt{m}(k,l)$ the mother node of k,l):

$$
\begin{aligned}
x_m^{(k,l,\mathtt{beg})} &= x_m^{(k-1,\mathtt{m}(k,l),\mathtt{end})} \vee x_{m-B_{\mathtt{in}}^{(k,l)}}^{(k,l,\mathtt{end})} \vee x_{m-W_m^{(k,l)}}^{(k,l,H_{(k,l)})} \\
x_m^{(k,l,1)} &= \left(x_m^{(k,l,\mathtt{beg})} \vee x_{m-1}^{(k,l,1)} \right) + s_m^{(k,l,1)} \\
x_m^{(k,l,H_{(k,l)})} &= \left(x_m^{(k,l,H_{(k,l)}-1)} \vee x_{m-1}^{(k,l,H_{(k,l)})} \right) + s_m^{(k,l,H_{(k,l)})} \\
x_m^{(k,l,\mathtt{end})} &= \left(x_m^{(k,l,H_{(k,l)})} \vee \left(\bigvee_{l' \in \mathtt{d}(k,l)} x_{m-B_{\mathtt{out},(k+1,l')}^{(k,l)}}^{(k+1,l',H_{(k+1,l')})} \right) \right)
\end{aligned}
$$

Interpretation as Longest Path in a Random Graph

- Case of two TCP connections in series with losses and resequencing



- E_3: window control; E_4, E_5: backpressure; E_6: resequencing.
- In the saturated root case, $x_m^{(k,l,\mathtt{end})}$ is the weight of the maximum weight path from $(k, l, \mathtt{end}, m)$ to $(-1, 0, 1, 0)$ in this random graph.

Topology – Statistical Assumptions

- Homogeneous model
  - The tree has a fixed degree D (math + first mile effect)
  - All TCP connections are structurally and statistically equivalent
  - All back-pressure parameters are the same everywhere in the tree.
  - The packet marking or loss process is independent and identically distributed (i.i.d.) in each TCP connection: W_m's are Markov Chains.
  - Aggregated service times are independent and identically distributed in all routers, with law σ with finite mean.

Topology – Statistical Assumptions (*continued*)

- Non-homogeneous model
  - The fan out degree in the tree is bounded from above by D
  - The number of hops of each route is bounded from above by H
  - The packet losses/markings are i.i.d. with loss/marking probability bounded from above by $p < 1$
  - The input and output buffers are bounded from below and from above by constants
  - The aggregated service times are independent and upper bounded by a random variable σ with finite mean.
- Both cases guarantee a positive throughput for each TCP connection when saturated

Main Result

Theorem Consider an overlay multicast tree with infinite height $k = 0, 1, 2, \ldots$. If the random variable σ is light tailed, i.e. there exists a real number $\tau > 0$ such that $\mathbb{E}[e^{t\sigma}] \leq A(t) < +\infty$ for all $0 \leq t \leq \tau$, then under both the homogeneous and the non-homogeneous assumptions,

$$\theta^{-1} = \limsup_{m \to \infty} \frac{x_m^{(k,l,\mathtt{end})}}{m} \leq \mathtt{Const}(H, D) < \infty \quad a.s. .$$

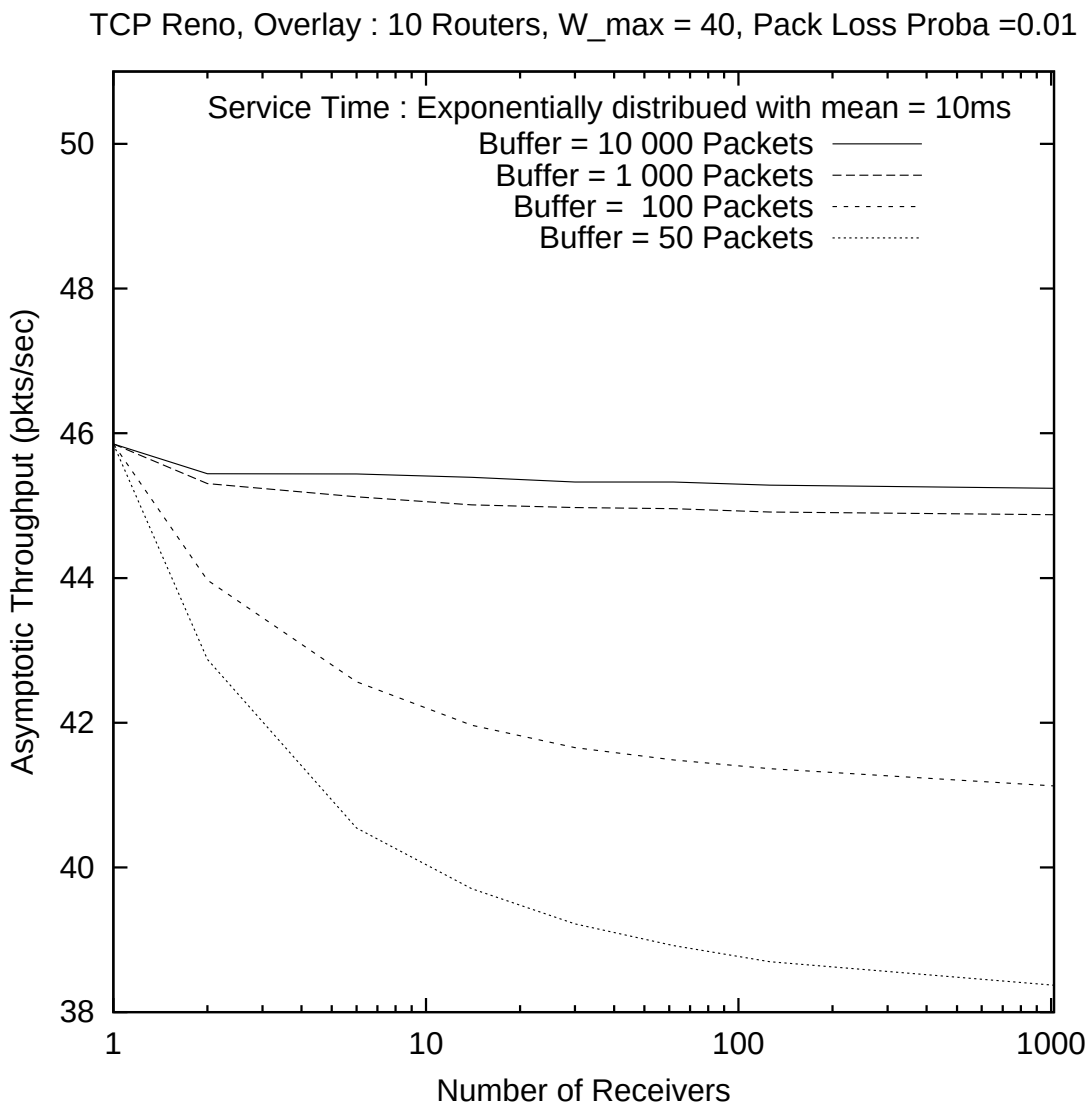
uniformly in (k, l), both for the marking and the loss–resequencing cases. In the light tailed i.i.d. case, the group communication is strictly positive even in an infinite tree.

Extensions

- Heavy tailed case with moment condition in the case of an infinite series of TCP connections
- The tree case with heavy tails is an open questions

Simulations: Buffer Size

- Based on the (max plus) equations
- Can handle up to 1000 nodes
- Focus on asymptotic group throughput
- Default option:
  - $p = 0.01$, 10 routers in series, exponential and Pareto random aggregated service times with mean equal to 10ms
  - B=50,100,1000 and 10 000 Pkts
  - transfer of 2GB of data

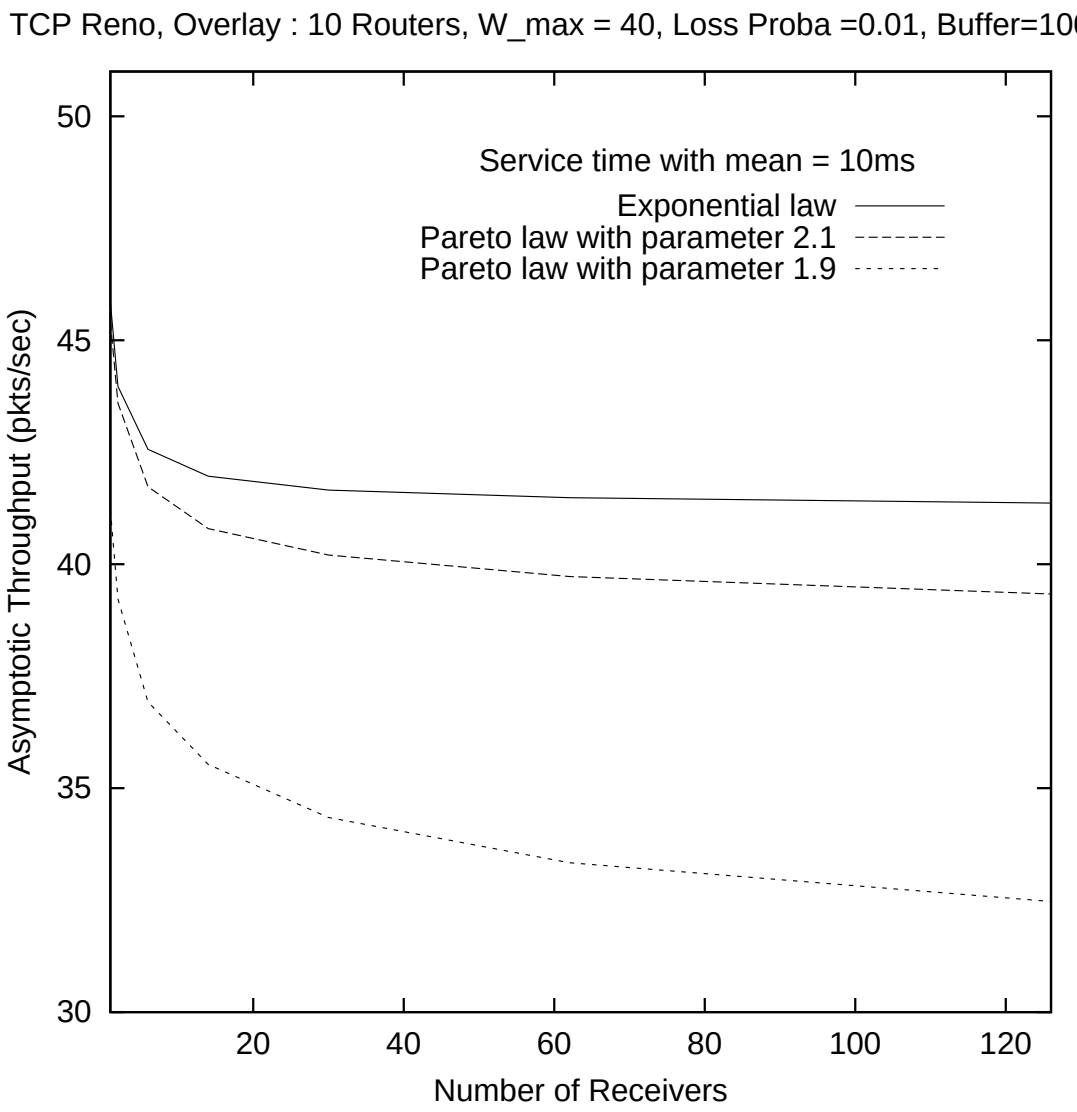

TCP Reno, Overlay : 10 Routers, W_max = 40, Pack Loss Proba =0.01
Service Time : Exponentially distribued with mean = 10ms
Buffer = 10 000 Packets
Buffer = 1 000 Packets
Buffer = 100 Packets
Buffer = 50 Packets
Asymptotic Throughput (pkts/sec)
50
48
46
44
42
40
38
1
10
100
1000
Number of Receivers

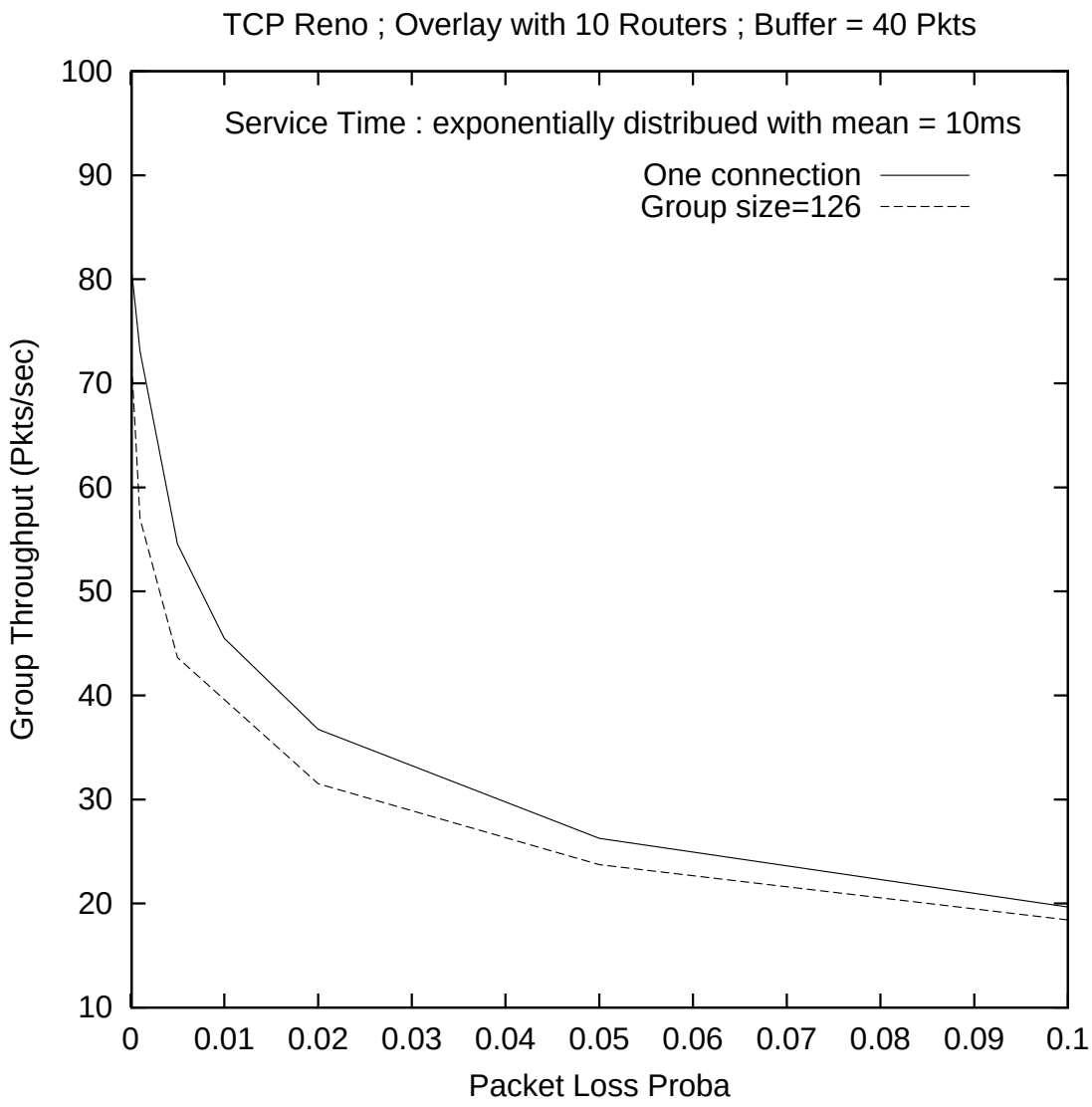
Simulation: Ratio of Asymptotic Throughput / One-Connection Throughput

Buffer (Pkts)	10,000	1,000	100	50
TCP RENO	.99	.98	.90	.83
TCP ECN	.99	.99	.92	.87

Simulation: Influence of Fluctuations

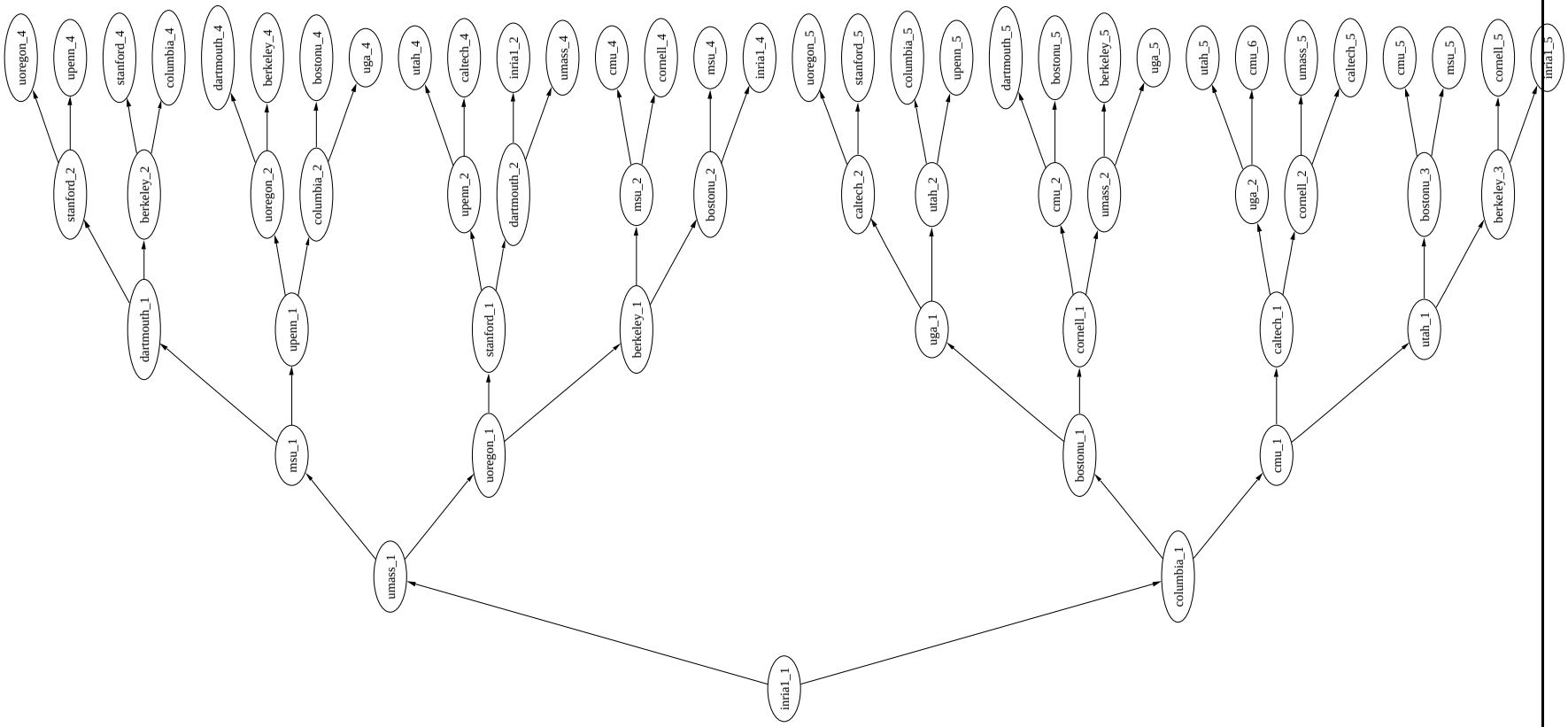
- Law of cross traffic
- Packet loss probability


TCP Reno, Overlay : 10 Routers, W_max = 40, Loss Proba =0.01, Buffer=100Pkts
Service time with mean = 10ms
Exponential law
Pareto law with parameter 2.1
Pareto law with parameter 1.9
Asymptotic Throughput (pkts/sec)
50
45
40
35
30
20
40
60
80
100
120
Number of Receivers


TCP Reno ; Overlay with 10 Routers ; Buffer = 40 Pkts
Service Time : exponentially distribued with mean = 10ms
One connection
Group size=126
Group Throughput (Pkts/sec)
Packet Loss Proba
100
90
80
70
60
50
40
30
20
10
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

Planet-Lab Experiments

- Multicast tree consisting of 64 PlanetLab nodes



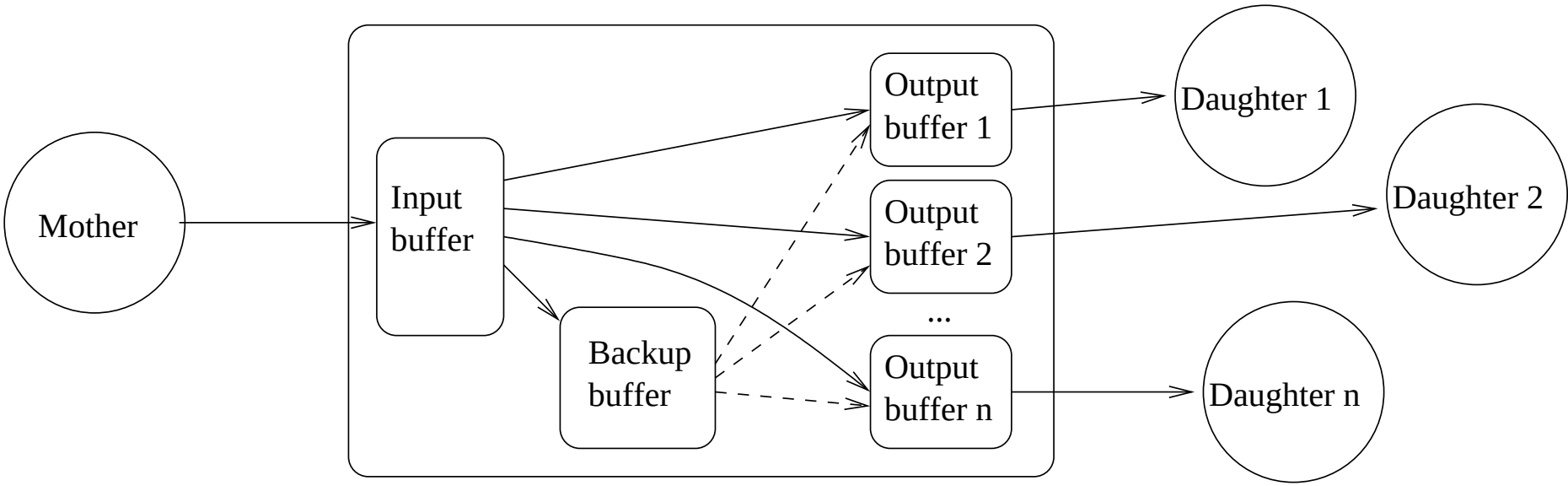
Planet-Lab Experiments

- Size of each packet is 200 bytes

Group size:	15	31	63
Buffer=50 Pkts	95	86	88
Buffer=100 Pkts	82	88	77
Buffer=1000 Pkts	87	95	93

- The absolute numbers are different but again the group throughput changes very little with the group size.

Handling Node Failures: backup buffer



End-to-end relibility

Theorem 2: An overlay multicast system with backup buffer of size $(m \cdot (B_{OUT}^{\max} + B_{IN}^{\max}) + B_{OUT}^{\max})$ *is end-to-end reliable with tolerance to m failures.*

TABLE III

END-TO-END RELIABILITY EXPERIMENTS IN PLANET-LAB

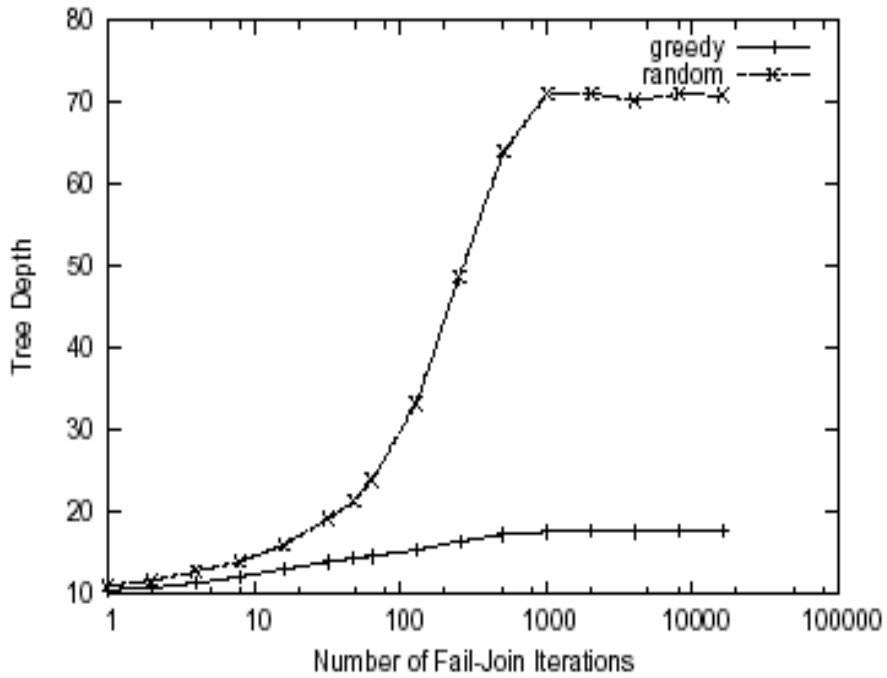
	min	average	max
Throughput (Pkts/sec)	49.05	55.24	57.65
# of Retransmitted Packets	34	80.5	122
Reconnection time (D)	0.12	3.53	5.2
Reconnection time (M)	0.27	3.81	5.37

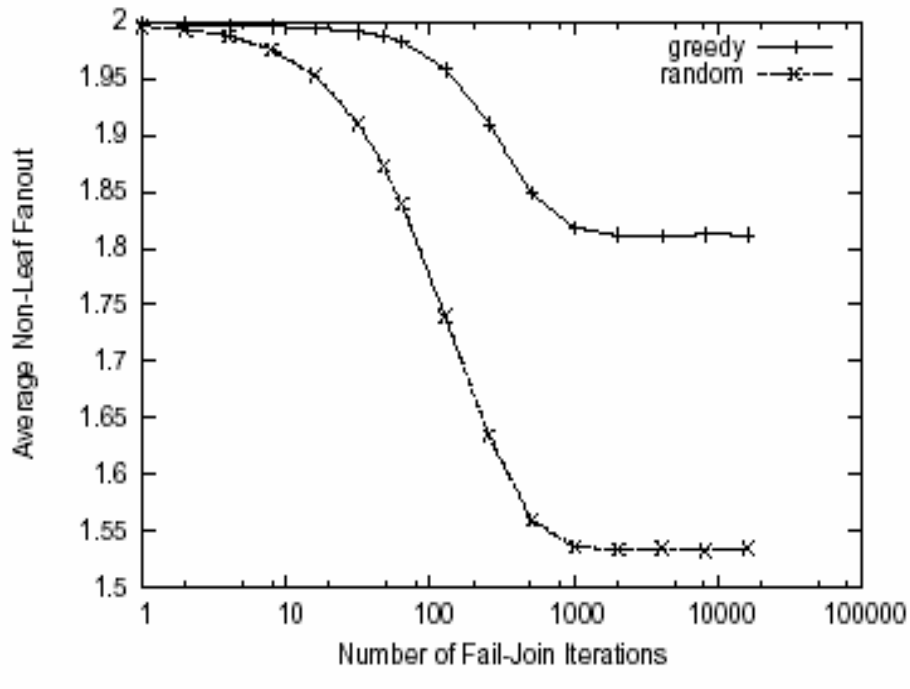
Handling Leave/Join/Node Failures

Algorithm GREEDY_RECONNECT

1. Suppose node (k, l) fails. Let $\mathcal{S}$ be the set of orphaned subtrees, rooted at daughters of (k, l). Let $\mathcal{A}$ be the set of active nodes in subtree of $(k-1, \mathfrak{m}(k, l))$, but not in the subtree of (k, l).
2. Choose a node $(k+1, l') \in \mathcal{S}$ that has subtree of largest depth.
3. Choose a node $(p, q) \in \mathcal{A}$ that is closest to the source.
4. Connect $(k+1, l')$ to (p, q).
5. Update $\mathcal{S} \leftarrow \mathcal{S} \setminus \{(k-1, l')\}$ and add active nodes from subtree of $(k+1, l')$ to A.
6. If $\mathcal{S}$ is not empty, go to Step 2.

Solution Features: balanced tree with bounded degree





The Infinite Buffer Case: Scalability of Throughput

- The infinite buffer case can be studied on a line rather than a tree without loss of generality.
  - θ_k: local saturated throughput of TCP connection k.
  - The throughput in the line at node K is given by the minimum of the saturated local throughputs : $\Theta^{\lambda}_{1,K} = \min(\lambda, \theta_1, \cdots, \theta_K)$

The throughput is positive for groups of any size, if the local saturated throughputs are all lower bounded by θ.

Infinite Buffer Case: Need for a Source Rate Control

– In order to avoid buffer occupancy explosion, it is necessary to control the rate at which the source sends data.

– For $\lambda < \theta$, for all K, the latency $L_m^{(K)}$ of packet m from end-system K to $K+1$ converges to a stationary law when m tends to ∞

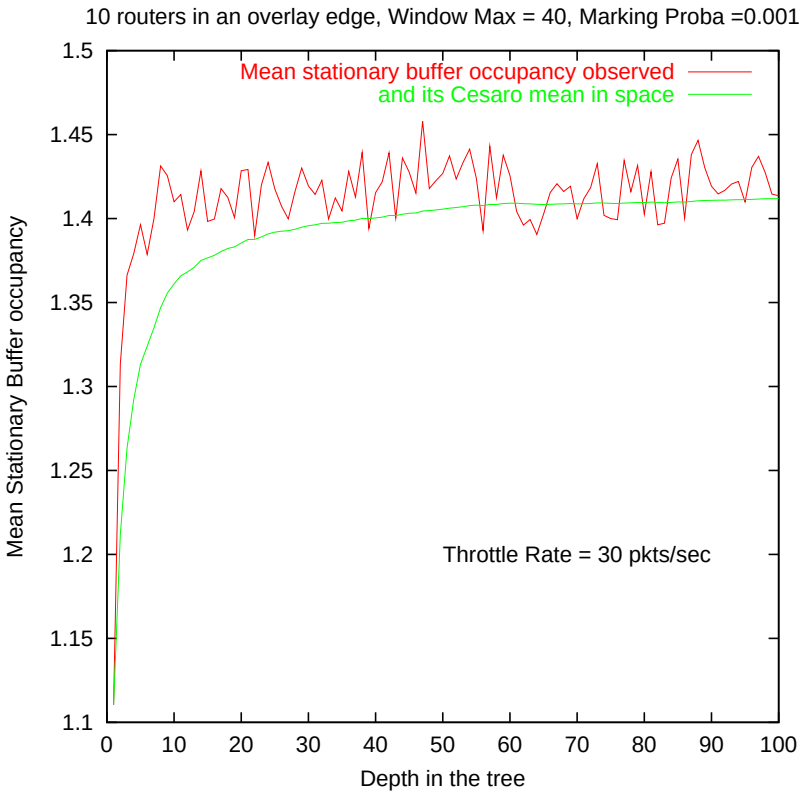
- Question How does this stationary law evolve when K is growing?
- We focus on
  – the marking case
  – the homogeneous case: $H_k = H$, $p_k = p$, $s_m^{(k,h)} \stackrel{d}{=} s$

Mean Buffer Occupancy : Empirical Study

– Numerical computation of the (max,plus) equation.

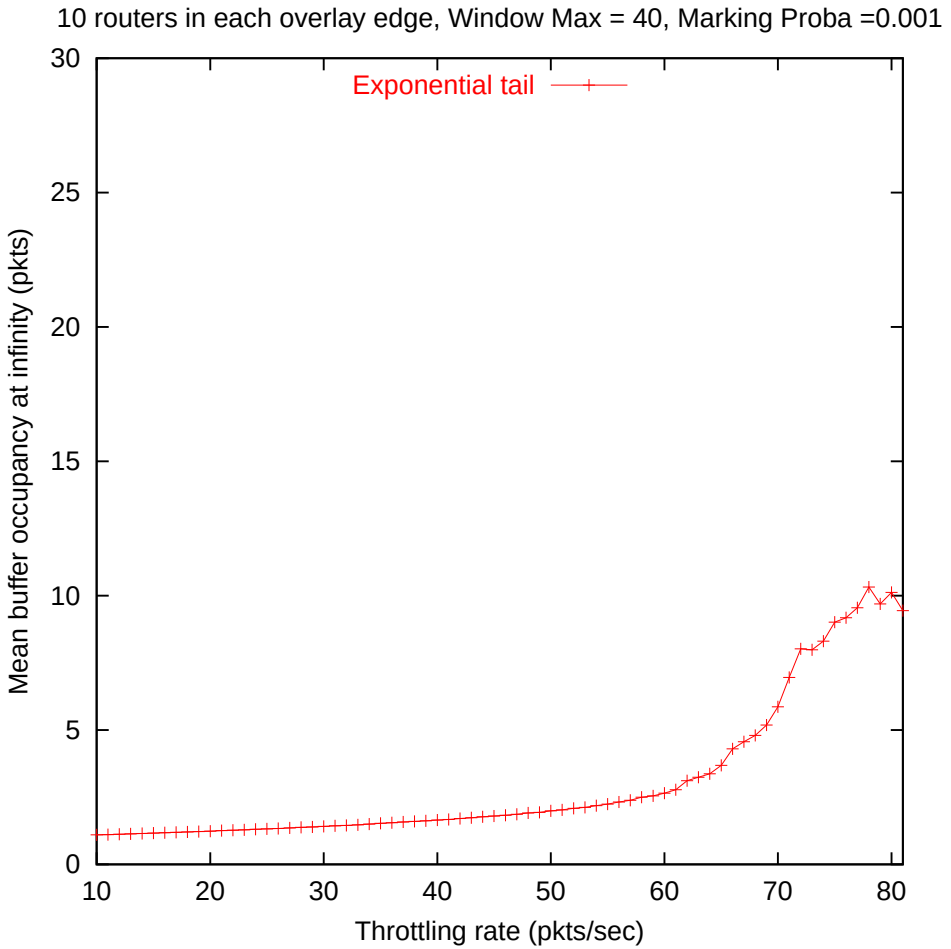
– Stationary mean buffer occupancy w.r.t. the distance from the source.

– Convergence when the distance tends to infinity.



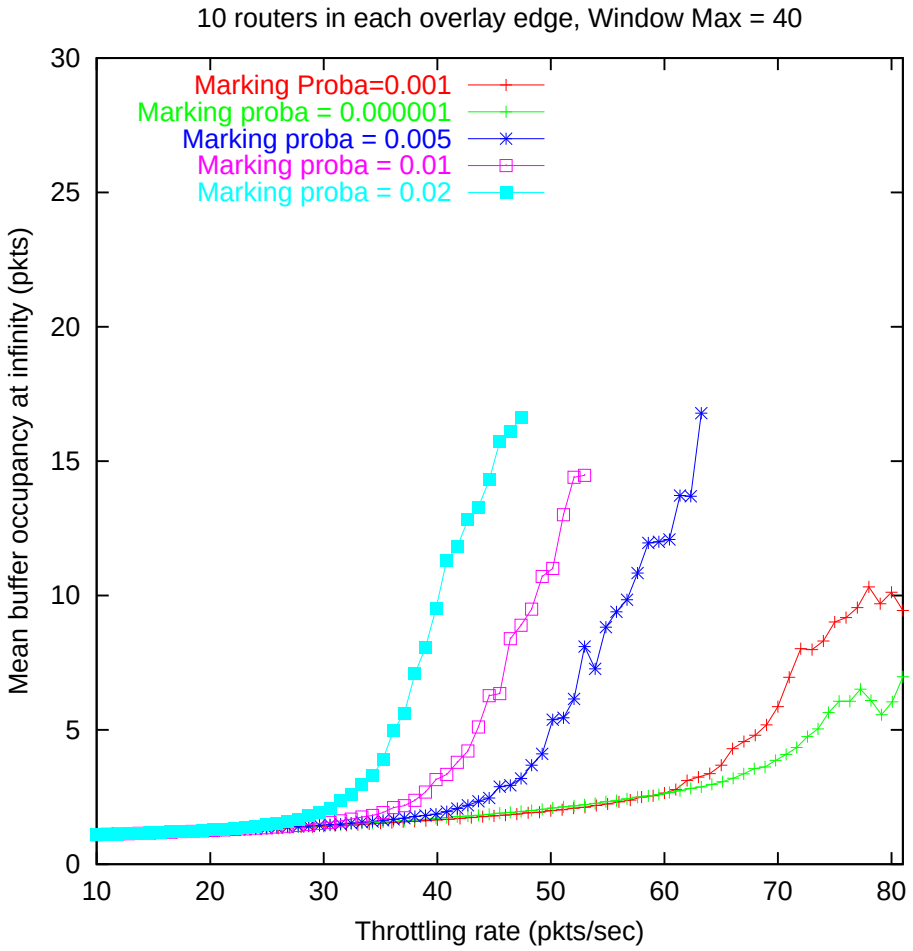
Mean Buffer Occupancy : Empirical Study (cont'd)

– "Infinite time" - "Infinite space" limit mean buffer occupancy, w.r.t. throttling rate.



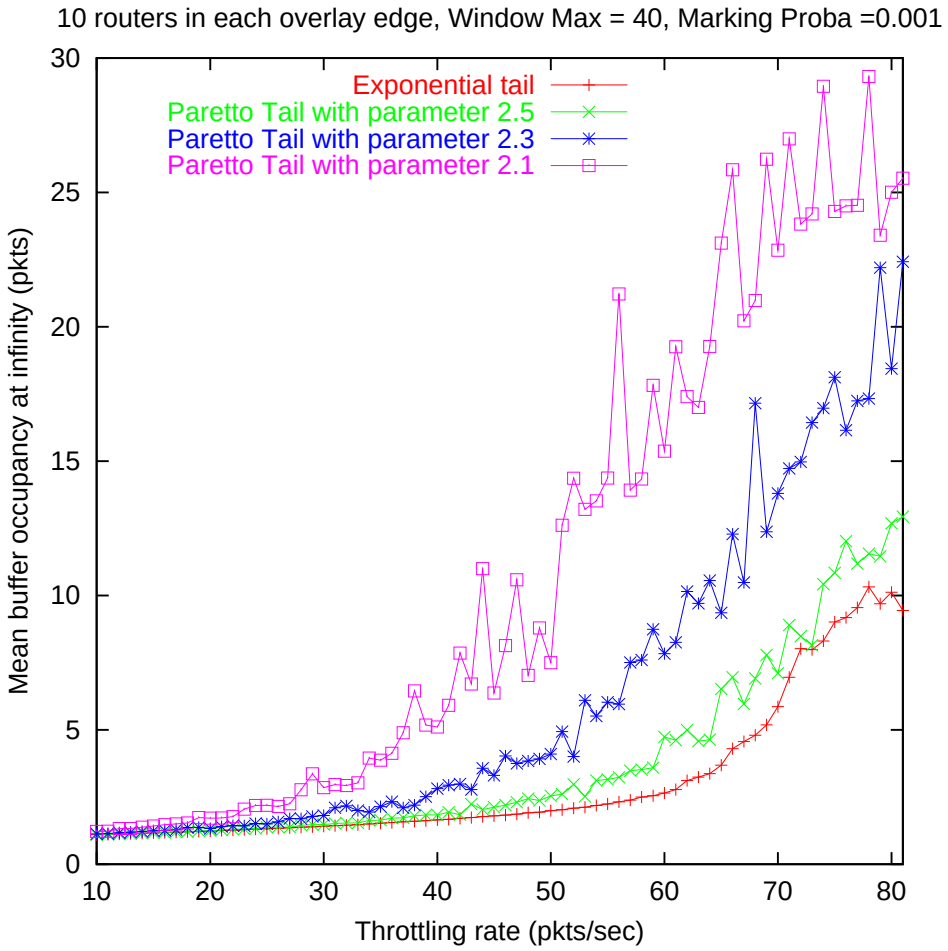
Mean Buffer Occupancy : Empirical Study (cont'd)

– Several packet marking probability cases.



Mean Buffer Occupancy : Empirical Study (cont'd)

– Several cross traffic distribution cases.



Mean Buffer Occupancy : Condition on law s

– For $\mathbb{E}[s^2] = \infty$, the stationary law of buffer occupancy (as well as latency) never admit a finite mean.

– For $\mathbb{E}[s^2] < \infty$, the mean buffer occupancy in end-system K and the expected latency from the source to end-system K is finite ... but nothing can be said for $K \to \infty$.

– From now, we assume : $\int_0^{+\infty} P(s \geq u)^{1/2} du < \infty$.

(It is implied by $\mathbb{E}[s^2 \, (\log(s))^{2+a}] < \infty$, for $a > 0$ and by $\mathbb{E}[s^b] < \infty$, for $b > 2$).

Mean Buffer Occupancy : Mathematical Justification

– Define $\gamma(u) = \lim_{k\to\infty} \frac{x^{(k,l,end)}_{\lfloor xk \rfloor}}{k}$.

– The Legendre transform of γ gives the limit with K (in Cesaro sense) of the stationary latency $L^{(K)}$ of level K when the source rate is throttled to λ:

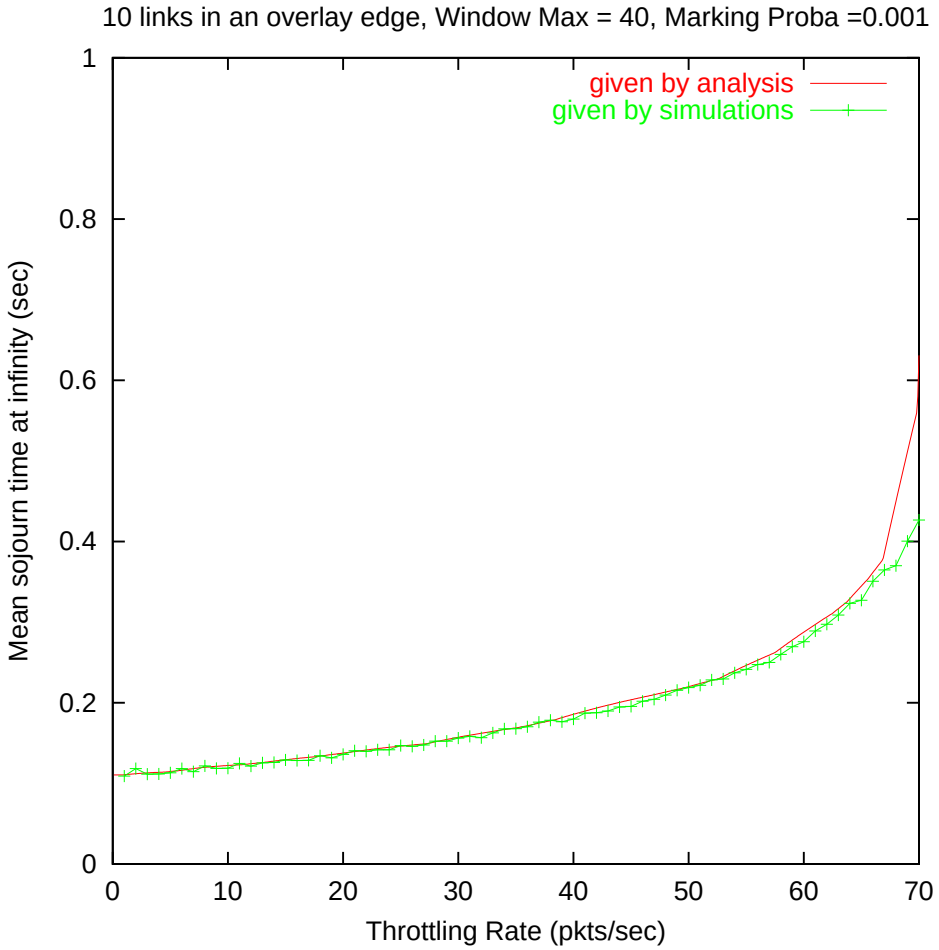
$$\lim_{K\to\infty} \frac{L^{(K)}}{K} = d(\lambda) = \sup_{x>0} \left(\gamma(x) - \frac{1}{\lambda} x \right) .$$

– Multiplied by λ, one gets a bound on the limit with K (in Cesaro sense) of the mean stationary buffer B_K used in an end-system with level K.

$$\lim_{K\to\infty} \frac{B^{(k)}}{K} \leq \lambda . d(\lambda)$$

Mean Buffer Occupancy : Numerical Validation

- Two methods are used to evaluate $d(\lambda)$.
- Legendre transform gives an efficient way to estimate $d(\lambda)$.



Optimal Tree Construction

- Complete graph $G = (V, E)$
  - Nodes = end-systems; numbered from 1 to n, where node 1 is the root.
  - Edges: each pair of nodes $i, j \in V$ is connected via a route in the Internet with local saturation throughput θ_{ij}
- Question (infinite buffer - rate control case): Find a tree from the root with maximum group throughput, where group throughput is the minimum of all path throughputs in the tree.

Optimal Tree Construction (*continued*)

- Model I: Access Link not the Bottleneck
- Algorithm to construct a tree with optimal group throughput:
  - Sort all $n(n-1)/2$ edges in increasing (local maximal) throughput order
  - Discard edges starting with those with the smallest throughput until the set of remaining edges on the n nodes makes a connected graph;
  - Build a spanning tree rooted in the source using the remaining edges of the sorted list.

The resulting spanning tree is optimal.

Optimal Tree Construction (*continued*)

- Model II: Accounting for Bottleneck at Access Link
- The constraints on node throughput for each node i can be treated as degree constraints
- The decision problem under this setting is a generalization of the minimum degree spanning tree
- The problem is provably NP-hard.
- Approximation algorithm with polynomial running time also proposed.

Conclusions

- Reliable multicast overlays can be deployed on top of the current TCP/IP
- Throughput scales provided all point to point connections that are used within the overlay offer minimal quality guarantees
- This conclusion holds true even in the case of moderate input and output buffers
- Need of a rate control in case of infinite buffers for guaranteeing scalable latency.
- General methodology (based on links between large overlay networks and statistical physics) applicable to other overlay networks.