



Hybrid Unicast and Multicast Flow Control:

A Linear Optimization Approach

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Flow Control Motivation

- Content delivery over multicast networks is challenging
 - Real-Time Delay Constraints
 - Receiver Heterogeneity
 - Intra-Session Fairness
 - Quality of Service
 - **Inter-Session (Flow) Fairness**
 - Network Resource Sharing
- Flow fairness for mixed UDP and TCP sessions is complicated. Unlike TCP, UDP lacks built-in flow fairness support.
- A generic solution is required.

Background Work

- Fairness Issues
 - Ammar, Georgia Tech
 - Rubenstein, Columbia
 - Kurose, UMass
- Feedback Aggregation Implosion
 - Garcia, UCSC
 - DeLucia, USC
- Flow Control
 - Srikant, UIUC
 - Kelly, Cambridge
 - Low, Caltech
 - Jaffe, MIT
 - Towsley, UMass
- Congestion Control
 - Jacobson, UCB
 - Floyd, UCB
 - Vicisano, UC London

Flow Fairness Utility

- The utility is defined as

$$U_i(x_i) = \min\left(\frac{x_i}{X_i}, 1\right) = \begin{cases} \frac{x_i}{X_i}, & x_i \leq X_i \\ 1, & x_i > X_i \end{cases}$$

where X_i is the requested bandwidth of flow i with $X_1 \leq X_2 \leq \dots \leq X_f$

- **Max-Min Fairness Definition:** A bandwidth allocation scheme among a number of competing flows is max-min fair if no flow can be allocated a higher bandwidth without reducing the allocation of another flow with an equal or a lower rate.

Centralized Flow Control: Global Topology

- Problem Formulation

$$\max_{x_1, \dots, x_f} \sum_{i=1}^f W_i \left(\frac{x_i}{X_i} \right)$$

$$\text{Subject To: } \sum_{i=1}^f w_{ji} x_i \leq C_j \quad \forall j \in \{1, \dots, l\}$$

$$x_i \leq X_i \quad \forall i \in \{1, \dots, f\}$$

$$x_i \leq x_{i+1} \quad \forall i \in \{1, \dots, f-1\}$$

$\{W_1, \dots, W_f\}$ weighting functions

$\{C_1, \dots, C_l\}$ link capacities

$$X_1 \leq X_2 \leq \dots \leq X_f$$

Further, $w_{ji} = \begin{cases} 1, & \text{if flow } i \text{ utilizes link } j \\ 0, & \text{otherwise} \end{cases}$

- LP can be solved with complexity $O((l+2f)^2)$

- **Theorem:** The solution is max-min fair by if

$$\frac{W_1}{X_1} > \dots > \frac{W_f}{X_f}$$

- Multicast reward by setting

$$W_i = \frac{h_i}{\sum_{j \in L} w_{ji}}$$

$$W_i = h_i$$

where $\{h_1, \dots, h_f\}$ are the number of flow end nodes.

Decentralized Flow Control: Local Link

- Problem Formulation

$$\max_{x_1, \dots, x_f} \sum_{i=1}^f \frac{x_i}{X_i}$$

$$\text{Subject To: } \sum_{i=1}^f x_i \leq C$$

$$x_1 \leq x_2 \leq \dots \leq x_f$$

C link capacity

$$X_1 \leq X_2 \leq \dots \leq X_f$$

- Theorem: The LP can be solved with linear $O(f)$ complexity utilizing the water-filling approach

- Water-Filling Solution

$$\text{Case 1: } C \geq \sum_{j=1}^f X_j \quad ,$$

$$\text{then } x_i = X_i \quad , \quad 1 \leq i \leq f$$

$$\text{Case 2: } C < \sum_{j=1}^f X_j \quad ,$$

then

$$x_i = \begin{cases} X_i, & 1 \leq i \leq h \\ \frac{C - \sum_{j=1}^h X_j}{f-h}, & h+1 \leq i \leq f \end{cases}$$

integer h satisfies

$$X_h \leq \frac{C - \sum_{i=0}^h X_i}{f-h} \leq X_{h+1}$$

$$0 \leq h \leq f-1$$

$$X_0 \stackrel{\Delta}{=} 0$$

Quasi-Centralized Flow Control: Zone

- Comparison of FC Schemes
 - Global solution may be overhead prohibitive
 - Local Solution is max-min fair but sub-optimal for the overall topology
- Solution
 - Hybrid Flow Control
 - Tradeoff between accuracy and complexity
 - Exchange state information within the local zones
 - Minimum fair share of a flow spanning over multiple zones is considered
- Description
 - Define local zones with associated Designated Nodes (DNs)
 - Zone Discovery Process
DN sends broadcast pilot packets with a given TTL
 - Effective for sparse topologies with few populated areas
 - Hybrid complexity of $O((l_z + 2f_z)^2)$ with l_z links and f_z flows in the largest zone

ECN Marking

- Utilize Binary Marking
- Given an ordered list of per link fair shares

$$l_k^1 \leq l_k^2 \leq \dots \leq l_k^{n_k}$$

- Identify bottleneck link by conveying

$$\Phi_k = [(l_k^1)^N + (l_k^{n_k})^N]^{\frac{1}{N}} = (l_k^1) [1 + (\frac{l_k^2}{l_k^1})^N + \dots + (\frac{l_k^{n_k}}{l_k^1})^N]^{\frac{1}{N}} \approx l_k^1$$

to end nodes, where $l_k^i = \frac{1}{l_i}$

- Mark with probability $1 - \exp(-(\Phi_k^i)^N)$
- Measure the receiving rate of unmarked packets $\Xi_k = \exp(-\Phi_k^N)$
- Estimate minimum fair share as $(-\ln \Xi_k)^{\frac{-1}{N}}$
- Requires numerical stabilization

ECN-Based Implementation: Unicast

Intermediate Node

- Calculate minimum fair share of the link from one of the decentralized or quasi-centralized FC algorithms

- Determine the values of

$$I_k^i = 1/l_k^i, \quad b_k^i = \left[\frac{l_{k,max}^i}{l_{k,min}^i} \right]^{\frac{1}{2e}}, \quad \text{and}$$
$$C_k^i = l_{k,max}^i \left[\frac{l_{k,max}^i}{l_{k,min}^i} \right]^{\frac{1-e}{2e}}$$

- Calculate $j_k^i = \log_{b_k^i} (C_k^i I_k^i)$
- Mark a packet with probability $1 - \exp(-j_k^i)^N$ for some large N

End Node

- Calculate the rate of receiving unmarked packets for the previous time interval as

$$\Xi_k = \exp(-\Phi_k^N)$$

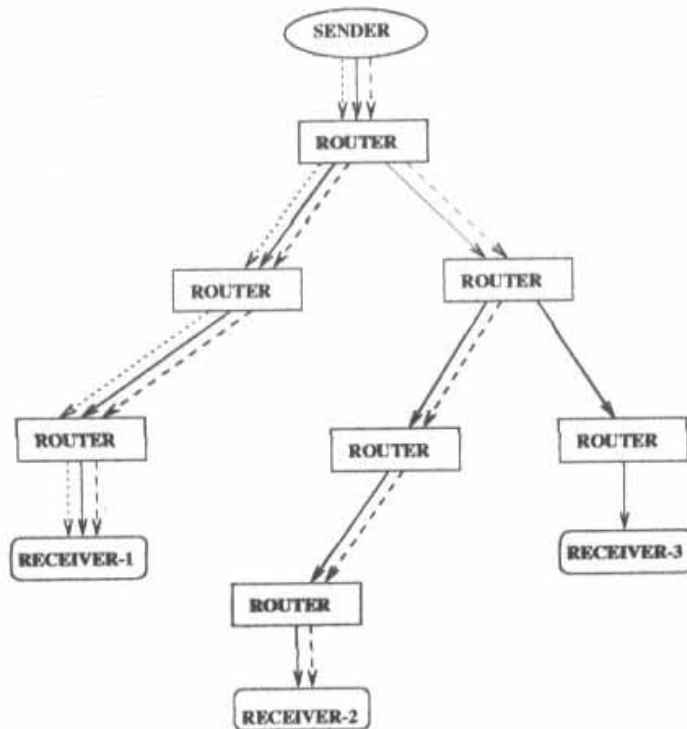
- Approximate minimum fair share of the path from the source as $(C_k^i / (b_k^i)^{J_k})$

$$\text{where } J_k = [-\ln \Xi_k]^{1/N}$$

Multicasting Implications

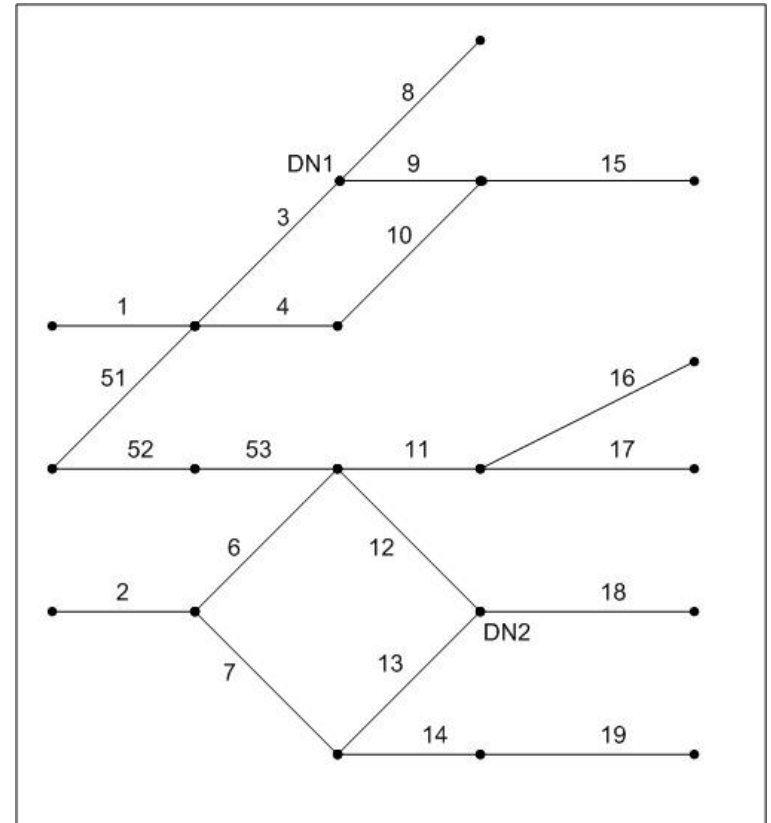
- Consider one-to-many multicast trees
- Expand a multicast session as a set of virtual unicast sessions with the multicast source and an individual receiver.
- Address feedback implosion in the discovery process
 - Feedback aggregation for detecting individual fair shares in a group of nodes.
 - Timer-based feedback suppression for detecting the overall minimum fair share of a group of receivers.

Layered Media Flow Control

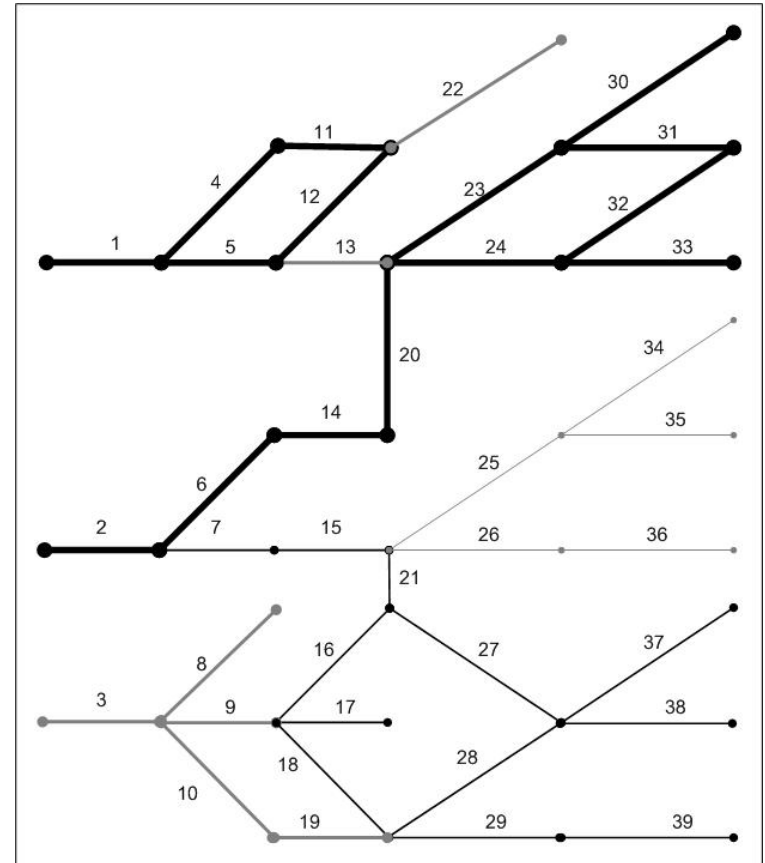


- Treat each layer as an independent flow.
- Since, $W_1 \geq \dots \geq W_f$ and $X_1 \leq \dots \leq X_f$, low-bandwidth high-priority flows are accommodated first under both global and local algorithms.
- Under partial fulfillment due to bandwidth limitation, the bandwidth assigned to low-priority groups is given to high-priority groups.

Topology (1): Flow Control



Topology (2): Layered Media





Thank You

<http://newport.eecs.uci.edu/~hyousefi>