Attacker Independent Stability Guarantees for Peer-2-Peer-Live-Streaming Topologies

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This work was in part supported by the
Deutsche Forschungsgemeinschaft under grant
numbers KU658/10-1 and SCHA1533/1-1.

P2P-Live-Streaming - What & Why?

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Realtime distribution of continously generated multimedia-stream to varying and potentially large set of viewers.

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Key Idea

Incorporate viewers' resources for distribution to overcome problems of classical Client-Server approach:

- restricted bandwidth resources at server
- high hardware costs
- inefficient traffic patterns (all paths lead to server)

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- enter the system at source node s

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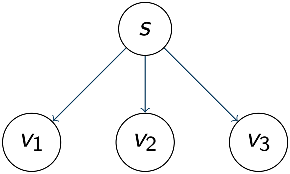

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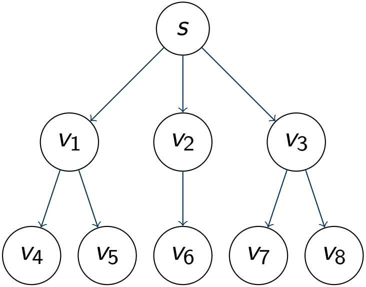

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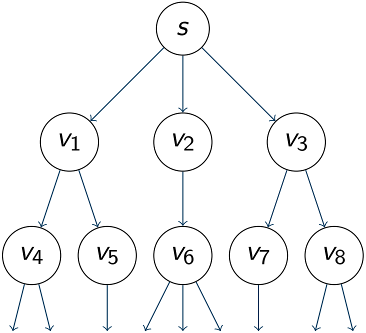
Packet distribution over *Spanning Trees*!



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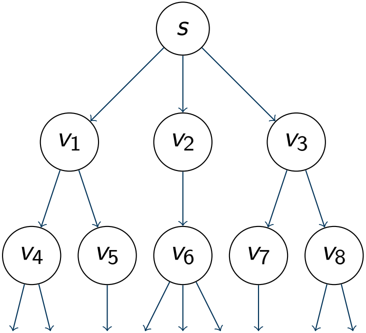

Service quality of peers in low levels of the tree depends on *cooperation* and *health* of *all* nodes in its path to the source.

Problems of P2P-Live-Streaming systems

But peers...

- constantly join and leave the system
- have small resources
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A key idea

Using multiple distribution trees with varying inner nodes decreases dependency on single nodes.

Model of push-based P2P-Streaming systems (1)

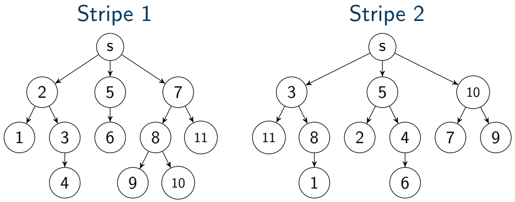
Basic model

- Stream is divided into k substreams called *stripes*
- Participants $V = \{s, v_1, \ldots, v_n\}$ are nodes of a graph G
- Stripe i is distributed using a directed spanning tree T_i over V
- *Streaming Topology* $\mathcal{T} = \{T_1, \ldots, T_k\}$ is set of these k distribution trees

Model of push-based P2P-Streaming systems (2)

More definitions...

- Assumption: source has a maximum degree of $C \cdot k$, for $C \in \mathbb{N}^+$
- Nodes receiving packets directly from s are called *heads* of $\mathcal{T}$
- The *successors* $succ_i(v)$ *of a node* $v \in V$ *in* $T_i \in \mathcal{T}$ are all nodes of the maximal subtree of T_i that is rooted in v



$C = 3$

Heads $H = \{2, 3, 5, 7, 10\}$

$\text{succ}_1(2) = \{1, 2, 3, 4\}$

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What do we aim for?

Goal

1. *Identify* the class of all streaming topologies that are *optimally stable* against node failures due to malicious DoS attacks.
2. Provide rules for their *efficient* construction.
3. Design and implement *distributed* topology management mechanisms realizing stable topologies in P2P-streaming systems.

Attackers, damage and stability (1)

Abstract attacker

A map from $\mathcal{T}$ and $x \in \mathbb{N}$ to a set $X \subseteq V \setminus \{s\}$ of x failing peers.

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- Source attack would always be optimal.
- Would disregard influence of distribution topology
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Damage function $a_{\mathcal{T}}(X)$

The *damage function* $a_{\mathcal{T}} : 2^V \rightarrow \mathbb{R}$ quantifies the damage incured on $\mathcal{T}$ by the failure of nodes.

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Attackers, damage and stability (2)

In this work, we chose on the *packet loss* damage function, summing up the number of successors of nodes in X over all stripes.

$$a_{\mathcal{T}}(X) = \sum_{i=1}^{k} \left| \bigcup_{v \in X} \mathrm{succ}_i(v) \right|$$

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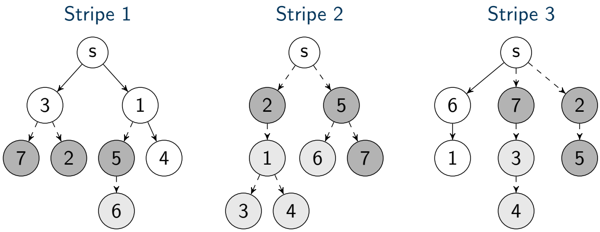

$a_{T_1}(X) = 4$

$a_{T_2}(X) = 7$

$a_{T_3}(X) = 5$

$a_{\mathcal{T}}(X) = 16$

The complete class of optimally stable streaming topologies (1).

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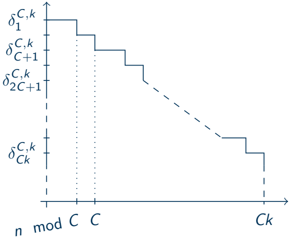
For $l = (i \text{ div } C)$ and $h = (i \mod C)$, define

$$\delta_i^{C,k} = \begin{cases} \left\lceil \frac{n}{C} \right\rceil + (k - 2l - 1) & \text{if } h \leq (n \mod C) \\ \left\lfloor \frac{n}{C} \right\rfloor + (k - 2l - 1) & \text{otherwise} \end{cases}$$



The complete class of optimally stable streaming topologies (2).

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Optimally stable topologies [1]

A topology $\mathcal{T}$ with parameters C, k, n is optimally stable if and only if $a_{\mathcal{T}}(\mathcal{O}(\mathcal{T}, m)) = \sum_{i=1}^{m} \delta_i^{C,k}$ for $1 \leq m \leq C \cdot k$.

[1] Brinkmeier et. al., "Optimally DoS Resistant P2P Topologies for Live Multimedia Streaming", *IEEE Transactions on Parallel and Distributed Computing*, 2009

The bad news.

Decision problem

Decide whether any given streaming topology $\mathcal{T}$ is optimally stable.

We have shown that this problem is co-NP-complete.
Hence, without P=NP, it is *not solvable in polynomial time*.

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All is not lost

We can identify a large and easy-to-check subclass of optimally stable topologies!

Necessary properties of stable topologies (1)

Stable topologies must follow a number of necessary rules.

Not-Too-Many-Successors Rule

Every peer has at most $\delta_1^{C,k} = \lceil \frac{n}{C} \rceil + (k-1)$ successors.

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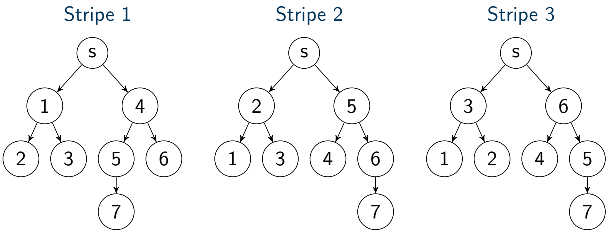
Necessary properties of stable topologies (2)

Head Rules

1. In each stripe each head adjacent to the source has exactly one head from each other stripe as a successor.
2. If $u, v \in V$ are heads and $u \in \mathrm{succ}(v)$, then $|\mathrm{succ}(u)| = |\mathrm{succ}(v)|$.



Necessary properties of stable topologies (3)

Head topology of $\mathcal{T}$

The *head topology* $\mathcal{H}(\mathcal{T})$ of a topology $\mathcal{T}$ is a streaming topology over node set $V_{\mathcal{H}(\mathcal{T})} = \{v \in V \mid v \text{ is head in } \mathcal{T}\} \cup \{s\}$ and in tree T_i, an edge (u, v) exists if $v \in \mathrm{succ}_i(u)$ in $\mathcal{T}$.

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Heads-Are-Optimally-Stable Rule

For topology $\mathcal{T}$ to be stable, $\mathcal{H}(\mathcal{T})$ has to be optimally stable.

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Heads-Are-Optimally-Stable Rule

For topology $\mathcal{T}$ to be stable, $\mathcal{H}(\mathcal{T})$ has to be optimally stable.

- Untrivial requirement.
- Large class of stable head topologies has been identified since paper submission.

A large and easily checkable subclass of optimally stable topologies

Shown requirements are not sufficient to guarantee optimal topology stability.

But: complexity of decision problem traced back to existence of non-heads with head-like successor number.

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Strictly-Not-Too-Many-Successors Rule

Every head has at most $\delta_1^{C,k} = \lceil \frac{n}{C} \rceil + (k-1)$ successors and every non-head has at most $\delta_{Ck}^{C,k} = \lfloor \frac{n}{C} \rfloor - k - 1$ successors.

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Theorem

A streaming topology $\mathcal{T}$ satisfying

- Head Rules 1
- Head Rules 2
- Heads-Are-Optimally-Stable Rule
- Strictly-Not-Too-Many-Successors Rule

is optimally stable.

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Theorem

A streaming topology $\mathcal{T}$ satisfying

- Head Rules 1
- Head Rules 2
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is optimally stable.

- Easy to construct.
- Membership checkable in polynomial time.

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Current Implementation

Cost functions based on

- stripe-specific successor numbers of children
- nodes prefer forwarding single stripe: one-stripe-only rule

Simulations [2]: topology properties near optimum

Conclusion & Outlook

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Outlook

- Distributed construction still challenging problem.
- Assuming Multiple Description Coding or Forward Error Correction, more complex damage measures regarding indivual service loss of nodes can be introduced.
  - Hardness of attacker problems already studied in [3]
  - Optimal topologies are topic of ongoing research.

Thank you for your attention!

Do you have questions?

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