Content-Based Routing

Routing Schemes and Space Complexity

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Applications

- System monitoring and management
  - e.g., management of a large data center
- Stream processing
  - e.g., analysis of financial data
- Service discovery
  - e.g., in a "cloud" computing infrastructure
  - e.g., in service-oriented computing
- Distributed simulation
  - e.g., multi-player games

Applications: Not Only Data Centers

- RSS News feeds
- Facebook notifications
- Twitter
- Google Alerts
- eBay Alerts
- . . .
- Facebook "Beacon"
  - Art.com, Blockbuster, Bluefly, CBS Interactive, eBay, ExpoTV, Fandango, Gamefly.com, Kiva, Kongregate, LiveNation, Mercantila, NY Times, Overstock.com, Redlight Mgmt, Seamless Web, Six Apart, STA Travel, TheKnot, Travelocity, Viagogo
- Many other "aggregators"

They want to be the content-based network!

Content-Based Communication

a.k.a. Publish/Subscribe Communication

- Receivers decide what they want to receive—they *subscribe*
  - "what they want" is predicated upon *the content of messages*
- Senders simply send information out—they *publish*
  - no need to address specific addresses or groups
- The system ("broker" or "dispatcher") does the rest
  - it delivers published messages to all interested subscribers

Messages: Example 1

- *A set of attributes* (plus possibly some opaque content)

channel = BBC News | News Front Page | World Edition
link = http://news.bbc.co.uk/go/rss/-/2/hi/default.stm
language = en-gb
title = Berliners celebrate fall of Wall
description = World leaders past and present join thousands of Berliners marking the 20th anniversary of the fall of the Berlin Wall.
link = http://news.bbc.co.uk/2/hi/europe/8349742.stm
pubDate = Mon, 09 Nov 2009 15:52:04 GMT
category = Europe

...

Messages: Example 2

- *A set of "tags"* (plus possibly some opaque content)

art, **design**, **culture**, **gallery**, **museum**, **new york**

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Predicates: Example 1

- *An expression of attribute constraints*

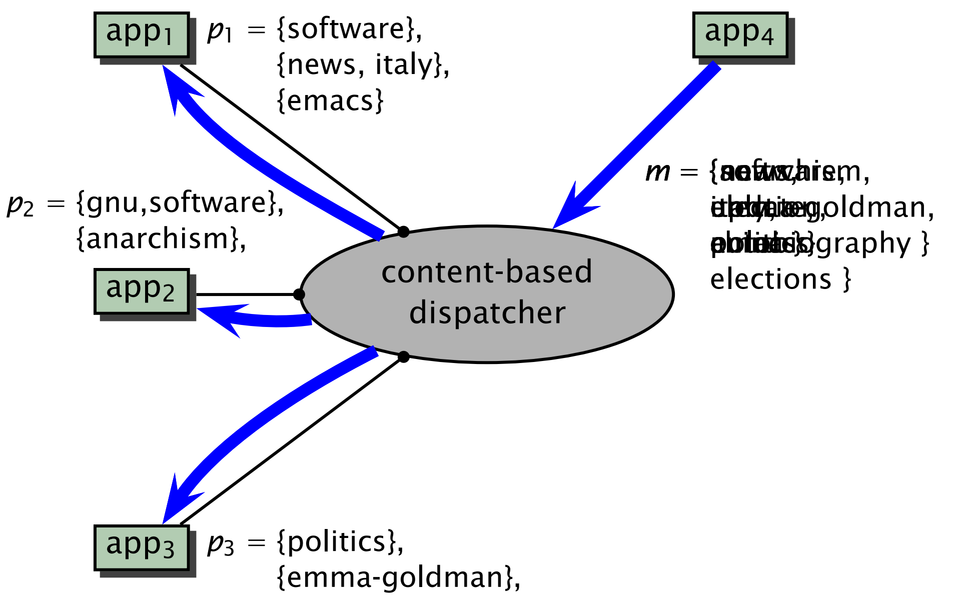
p = **author** = "Glenn Greenwald"
  $\vee$ **channel** = "BBC News"
    $\wedge$ **category** = "Europe"
    $\wedge$ **title** $=^{\text{regex}}$ ".$*$Italy.$*$"
  $\vee$ **management-event** = "disk-failure"
    $\wedge$ **host** = "research.inf.usi.ch"
  $\vee$ **management-event** = "disk-usage"
    $\wedge$ **host** = "research.inf.usi.ch"
    $\wedge$ **space-available** $<$ 1Gb

Predicates: Example 2

- *Sets of "tags"*

p = { **development**, **free-software**, **gnu/linux** },
  { **programming**, **c++** },
  { **tools**, **gnu/linux** },
  { **emacs** },
  { **philosophy**, **anarchism** },
  { **politics**, **emma-goldman** },
  { **chomsky**, **interview** },
  { **lugano**, **grotto** },
  { **lugano**, **pizzeria** }
  { **lugano**, **music**, **live** }

Example: Centralized Architecture



Content-Based Networking

- Content-based communication (a.k.a., publish/subscribe) *designed and implemented as a network service*
  - architecture
  - routing
  - forwarding
  - ...
- Host interface
  - *send-message(m)*
  - *set-predicate(p)*
- Type of service
  - datagram service (i.e., “best effort”)

Outline

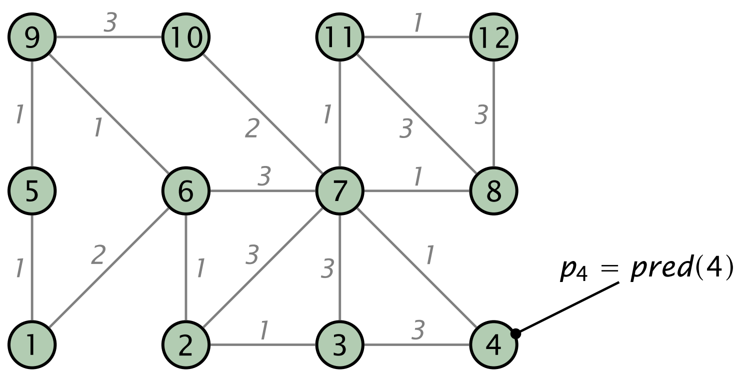
PART I: Routing Schemes

- Routing on a tree cover
- Routing on the whole graph
  - routing with per-receiver unicast information
  - routing with per-sender trees

PART II: Space Complexity

- Analysis for three routing schemes
- Reducing the space complexity
  - encoding (compressing) predicates
  - grouping sources and destinations, folding predicate tables

Content-Based Network Model



- $CBN = (V, E, weight, \mathcal{M}, \mathcal{P}, pred)$
  - $v \in V$ is a processor (host or router)
  - $e \in E$ is a reliable bidirectional communication link
  - $weight : E \to \mathbb{R}$ is a link-weight function
  - $\mathcal{M}$ is a set of *messages*
  - $\mathcal{P}$ is a set of *predicates*; $p \in \mathcal{P}$ is a function $p : \mathcal{M} \to \{0, 1\}$
  - $pred : V \to \mathcal{P}$ associates a processor $v \in V$ to a predicate $p \in \mathcal{P}$

Content-Based Routing *Scheme*

Extension of a standard model by Peleg and Upfal [JACM'89]

- Messages travel in *packets*

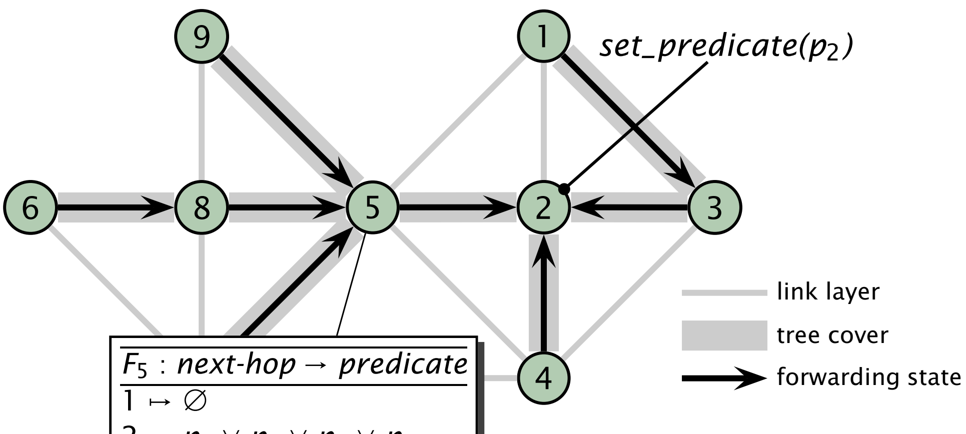
$$c = \langle m, h \rangle$$

  - $m = msg(c)$ is a message; $m \in \mathcal{M}$
  - $h = hdr(c)$ is a *header*; $h \in \mathcal{H}$
  - a scheme defines $\mathcal{H}$, the set of allowable message headers

- Packets are forwarded hop-by-hop from source to destinations

- A routing scheme is a *distributed algorithm* consisting of *per-processor, processor-local routing functions*
  - (re)writing packet headers
  - deciding where to forward a packet

Routing on a Tree Cover



- Routing protocol propagates predicates along the tree cover

- Forwarding state *attracts* messages towards matching predicates

Tree-Cover Scheme

- Headers are used to store the last hop of a packet

$$\mathcal{H} = V$$

$$\textbf{Init}_v(\cdot) = v$$

$$\textbf{Hdr}_u(v) = v$$

- Processor u forwards $c = \langle u, m \rangle$ using F_u

ProcessPacket$_u(c = \langle v, m \rangle)$
1 $\triangleright$ we are at processor u
2 **for** $w \in \{w \neq v | m \in F_u(w)\}$
3 **do** forward $\langle u, m \rangle$ to w

Per-Processor Routing Functions

For each processor v

- *Initial header function*

$$\textbf{Init}_v : \mathcal{M} \to \mathcal{H}$$

given a message m originating at v, $\textbf{Init}_v(m)$ is m's initial header, so v starts by forwarding a packet $c = \langle \textbf{Init}_v(m), m \rangle$

- *Header (rewriting) function*

$$\textbf{Hdr}_v : \mathcal{H} \to \mathcal{H}$$

given a packet $c = \langle h, m \rangle$, v forwards $c' = \langle \textbf{Hdr}_v(h), m \rangle$

- *Forwarding function*

$$\textbf{Fwd}_v : \mathcal{H} \times \mathcal{M} \to \mathbb{P}(\mathit{neighbors}(v))$$

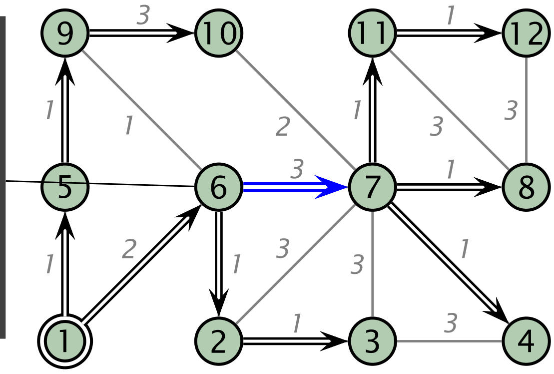
v forwards $\langle h, m \rangle$ to the subset of its neighbors $\textbf{Fwd}_v(h, m)$

Basic Per-Source Forwarding (PSF)

- Idea
  - a per-source spanning tree T_v for each source v
  - annotate edges $e = (u, w)$ in T_v with the disjunction of the predicates of processor w and all its descendents in T_v
  - processor-local functions F store edge annotations

F_6: annotations for processor 6

source,next-hop $\to$ *predicate*
...
$1, 1 \mapsto \varnothing$
$1, 2 \mapsto p_2 \vee p_3$
$\boxed{1, 7 \mapsto p_4 \vee p_7 \vee p_8 \vee p_{11} \vee p_{12}}$
$1, 9 \mapsto \varnothing$
...



PSF Scheme

- Headers are used to store the source of a message

$$\mathcal{H} = V$$

$$\mathbf{Init}_v(\cdot) = v$$

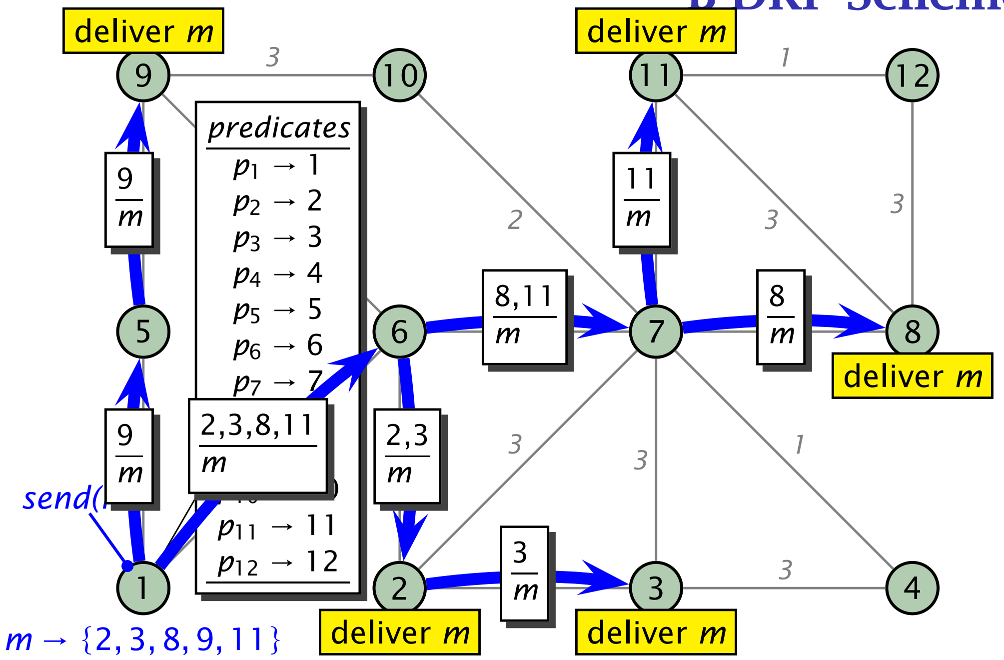
$$\mathbf{Hdr}_u(v) = v$$

- Processor u forwards $c = \langle v, m \rangle$ using F_u

$$\mathbf{Fwd}_u(v, m) = \{w | m \in F_u(v, w)\}$$

notation: if p is a predicate, $m \in p$ means $p(m) = 1$

B-DRP Scheme



(router-level topology)

Basic Steps

1. Perform a content-based matching of a message *once* at the source
   - compile a complete list of receivers
2. Use *unicast* routing information to forward to all receivers
   - using *dynamic receiver partitioning* (DRP)

B-DRP: Basic Ingredients

- Unicast routing information

unicast : *router-id* → *neighbor-link*

- Predicates from all routers in the network

predicates : *router-id* → *predicate*

Memory Requirements of a Scheme

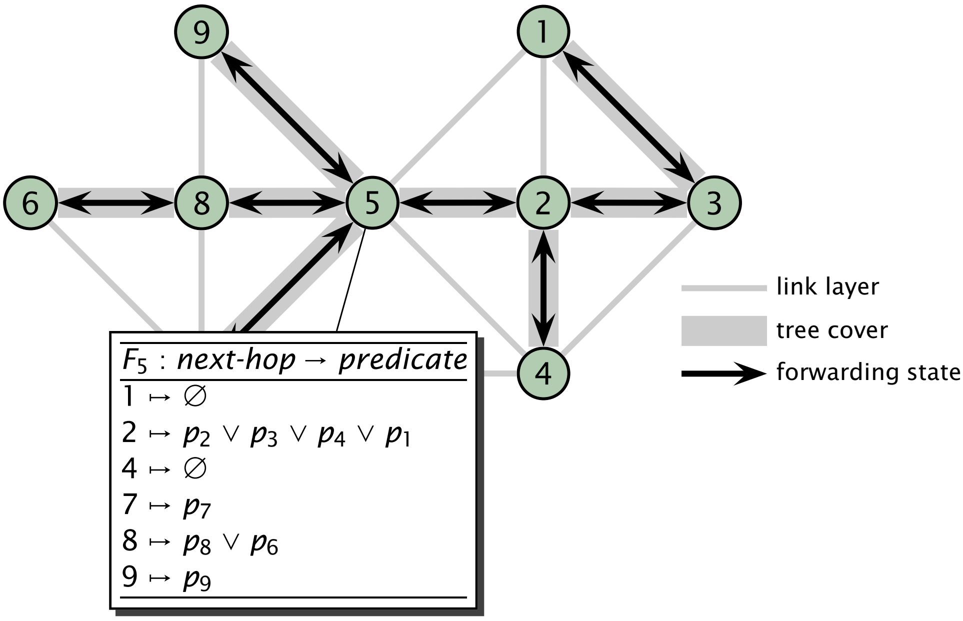
- How much memory do we need to implement a scheme?
  - over the entire network
  - average, max for each processor/router

- *Notation*

  Let $M(\cdot)$ to denote the memory requirements for a generic component or function

  - literally, the number of *bits*

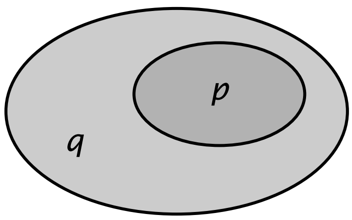
Tree-Cover Complexity



Covering Relation

- Covering relation $p \prec q$: *q covers p* when every message matching p also matches q

$$p \prec q \stackrel{\text{def}}{=} \forall m : p(m) \Rightarrow q(m)$$



- Represents the *content-based* *subnet* *address* relation

Reduced Table Sizes

F_5 : *next-hop* $\to$ *predicate*
$1 \mapsto \emptyset$
$2 \mapsto p_2 \vee p_3 \vee p_4 \vee p_1$
$4 \mapsto \emptyset$
$7 \mapsto p_7$
$8 \mapsto p_8 \vee p_6$
$9 \mapsto p_9$

$\wedge$

$$p_1 \prec p_2, p_4 \prec p_2$$

$\Longrightarrow$

F_5 : *next-hop* $\to$ *predicate*
$1 \mapsto \emptyset$
$2 \mapsto p_2 \vee p_3$
$4 \mapsto \emptyset$
$7 \mapsto p_7$
$8 \mapsto p_8 \vee p_6$
$9 \mapsto p_9$

Disjunction Advantage

- Given a set of predicates $P = \{p_1, p_2, \ldots, p_n\}$, we define the *disjunction advantage*

$$\alpha(P) = \frac{M(p_1 \vee p_2 \vee \ldots \vee p_n)}{M(p_1) + M(p_2) \cdots + M(p_n)}$$

- In the case $M(p_1) \approx M(p_2) \approx \ldots \approx M(p_n) \approx M_p$, we define

$$\alpha(k) = \frac{M(p_1 \vee p_2 \vee \ldots \vee p_k)}{kM_p}$$

- How does α affect the space complexity of a given scheme?
- Can we quantify α?

α in a Generic Predicate Model

- A predicate $p \in \mathcal{P}$ is a subset of a finite universe of messages $\mathcal{M}$, therefore $M(p) = p \log |\mathcal{M}|$
- Assuming a uniform distribution of predicates p of size $|p| = h$

$$\mathrm{E}(\alpha) = \frac{\mathrm{E}(|P|)}{nh}$$

$\mathrm{E}(|P|)$ is the expected size of the union of n random sets of size h

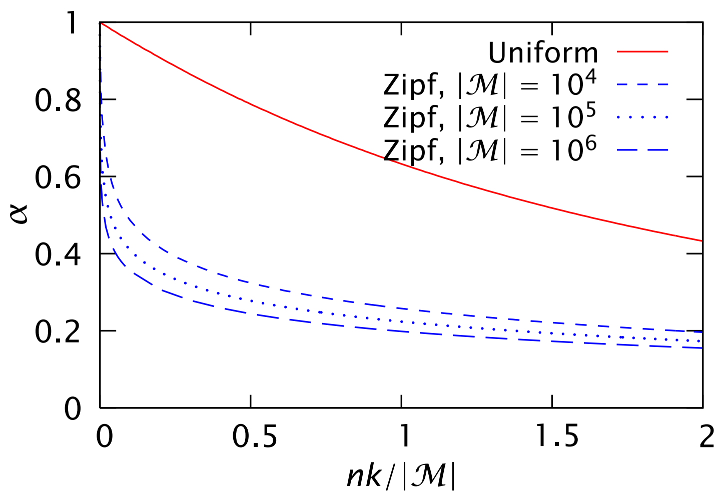
$$\Pr[m \in P] = 1 - \left(1 - \frac{h}{|\mathcal{M}|}\right)^n \approx 1 - e^{-\frac{nh}{|\mathcal{M}|}}$$

expected size of P and then the expected disjunction advantage

$$\mathrm{E}(\alpha) = \frac{|\mathcal{M}|}{nh}\left(1 - \left(1 - \frac{h}{|\mathcal{M}|}\right)^n\right) \approx \frac{|\mathcal{M}|}{nh}\left(1 - e^{-\frac{nh}{|\mathcal{M}|}}\right)$$

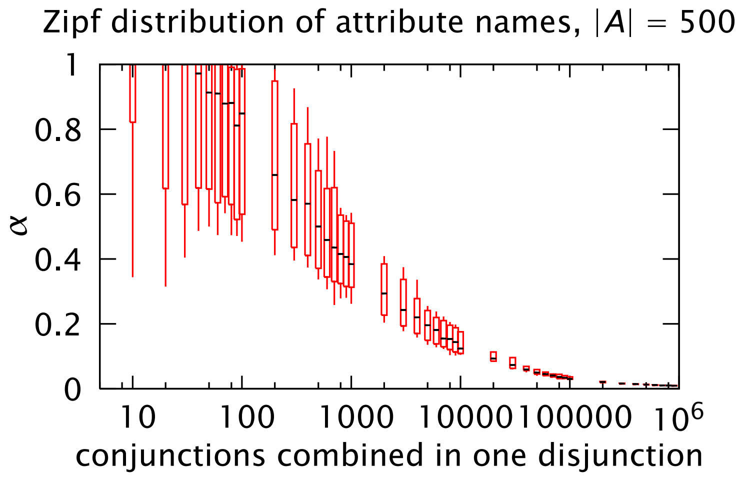
α in a Generic Predicate Model (2)

- Monte Carlo simulation
- Uniform vs. Zipf distribution for messages



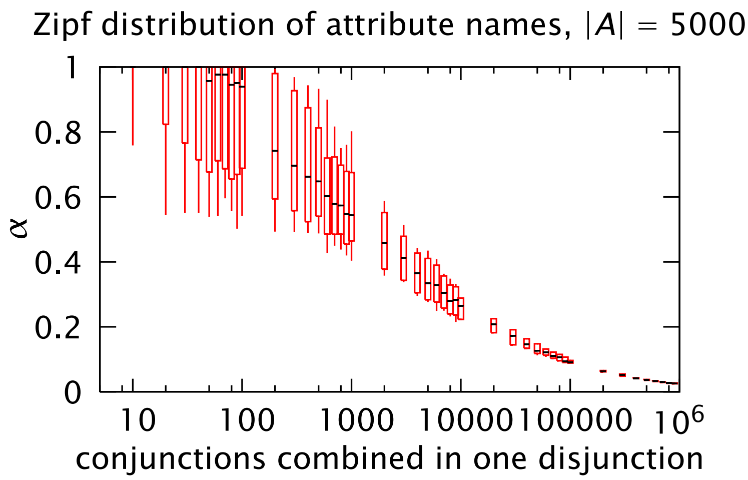
α in a Specific Predicate Model (1)

- Monte Carlo simulation
- Disjunctive normal form of attribute constraints



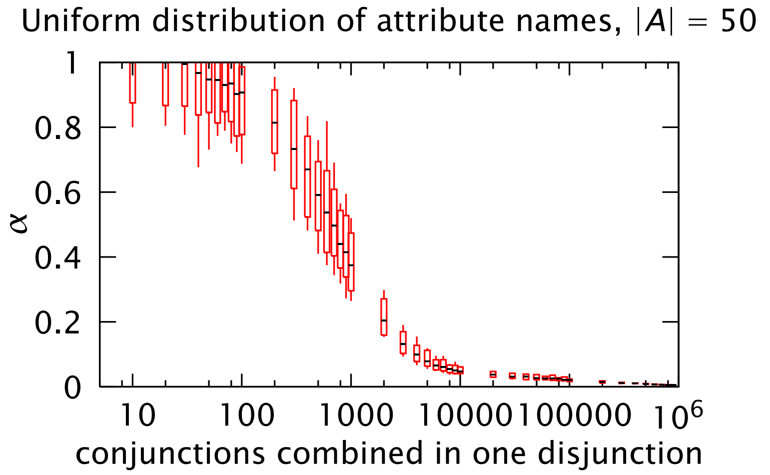
α in a Specific Predicate Model (2)

- Monte Carlo simulation
- Disjunctive normal form of attribute constraints



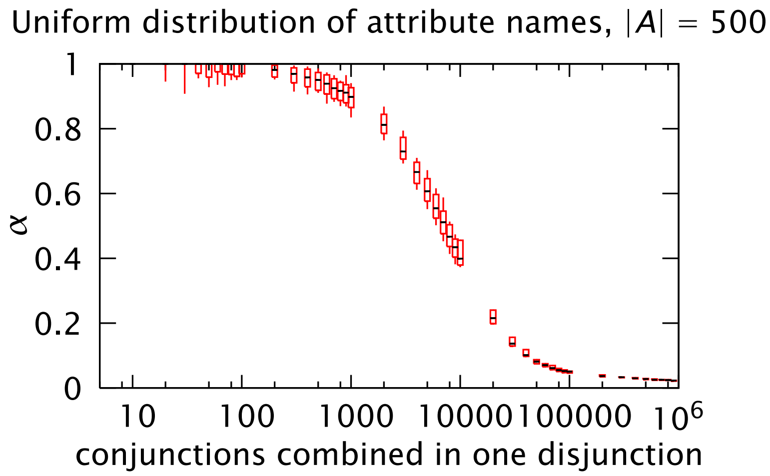
α in a Specific Predicate Model (3)

- Monte Carlo simulation
- Disjunctive normal form of attribute constraints



α in a Specific Predicate Model (4)

- Monte Carlo simulation
- Disjunctive normal form of attribute constraints



Memory Requirements of PSF

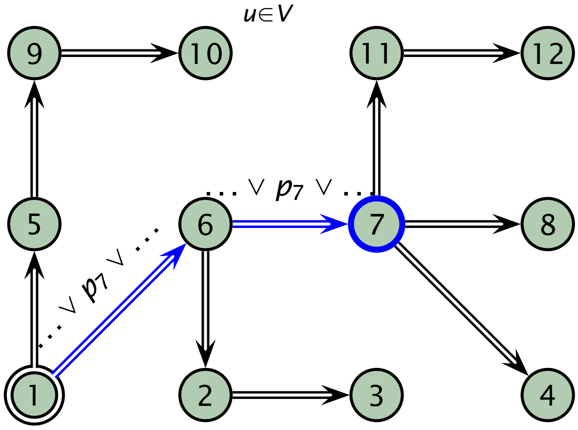
- Let $M(PSF)$ represent the memory requirements of PSF (over the entire network)
  - let V be the set of *routers*
  - let $R \subseteq V$ be the set of routers that have active *receivers*
  - let $S \subseteq V$ be the set of routers that have active *senders*
- Therefore,

$$M(PSF) = \sum_{u \in V} M(F_u) = \sum_{v \in S} M(T_v)$$

Memory Requirements of PSF (2)

- Memory requirement of a source-rooted tree T_v

$$M(T_v) = \sum_{u \in V} M(F_u(v, \cdot))$$



$$M(T_v) = \sum_{x \in R} M(p_x) distance(v, x)$$

Memory Requirements of PSF (3)

- Total memory requirement for PSF

$$M(PSF) = \sum_{v \in S} \sum_{x \in R} M(p_x) distance(v, x)$$

- A couple of uniformity assumptions
  - $\forall u \in R : M(pred(u)) = M_p$
  - senders and receivers are uniformly distributed
  - Let d be the average distance between two processors

$$M(PSF) = |S||R|M_p d$$

- Obviously $d = O(n)$
  - but in power-law random graphs $d = O(\log \log n)$ is very likely

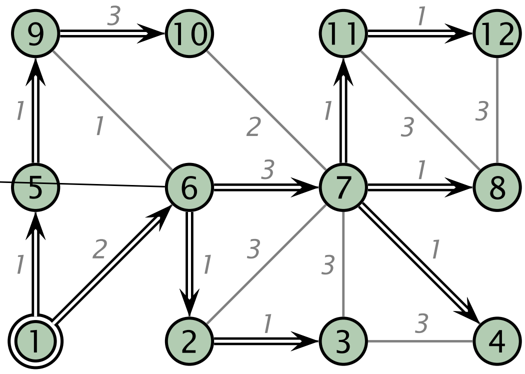
$$M(PSF) = O(n^2 \log \log n)$$

PSF Distinguishes Every Receiver

F_6: annotations for proc. 6

source,next-hop → *predicate*

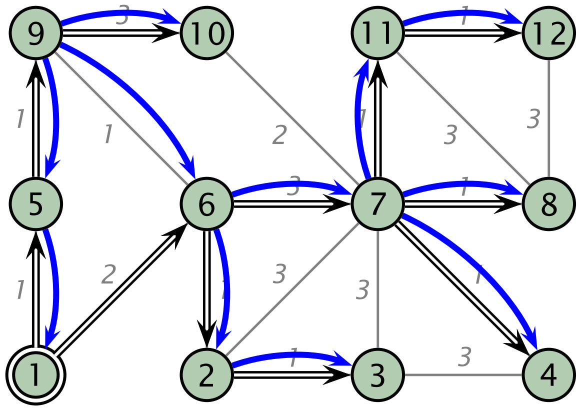
...
$1, 1 \mapsto \emptyset$
$1, 2 \mapsto p_2 \vee p_3$
$1, 7 \mapsto p_4 \vee p_7 \vee p_8 \vee p_{11} \vee p_{12}$
$1, 9 \mapsto \emptyset$
...



- The previous analysis assumes that, e.g., $M(p_2 \vee p_3) = M(p_2) + M(p_3)$

- In general, $M(p_2 \vee p_3) \leq M(p_2) + M(p_3)$
  - e.g., $p_2 =$ (port > 1000) $\wedge$ (port < 3000) and $p_3 =$ (port > 2000) $\wedge$ (port < 4000) can be combined in the disjunction $p_2 \vee p_3 =$ (port > 1000) $\wedge$ (port < 4000)

PSF Distinguishes Every Sender



- The previous analysis assumes that, e.g., processor 6 sees $T_1 \neq T_9$
- In general, from the viewpoint of u, $F_u(v_1, \cdot)$ may be identical to $F_u(v_2, \cdot)$ for some v_1 and v_2
  - e.g., $F_6(1, \cdot) = F_6(5, \cdot) = F_6(9, \cdot)$

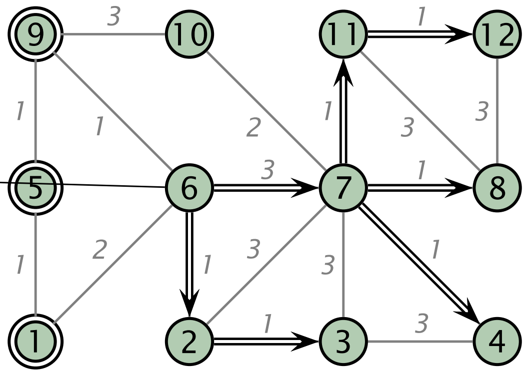
Improved Per-Source Forwarding

- *Destination grouping*
  - old idea: compression of predicates (used also on a tree-cover)
- *Source indistinguishability*
  - one forwarding entry per *equivalence class of indistinguishable sources*
- *Table folding*

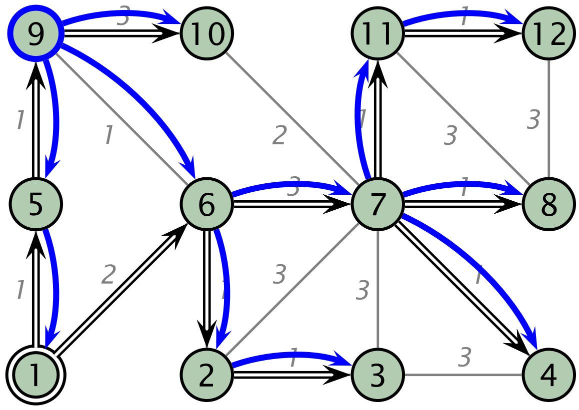
F_6: annotations for proc. 6

source,next-hop → *predicate*

. . .
$\{1,5,9\}, 1 \mapsto \emptyset$
$\{1,5,9\}, 2 \mapsto p_2 \vee p_3$
$\{1,5,9\}, 7 \mapsto p_4 \vee p_7 \vee p_8 \vee \ldots$
$\{1,5,9\}, 9 \mapsto \emptyset$
. . .



Rewriting Sources



- if a and b are indistinguishable by u, then they are also indistinguishable by all the descendants of u on T_a and T_b
  - those two sets of descendants are identical
- So, we can further compress forwarding state by rewriting the source with the most recent *indistinguishable* representative

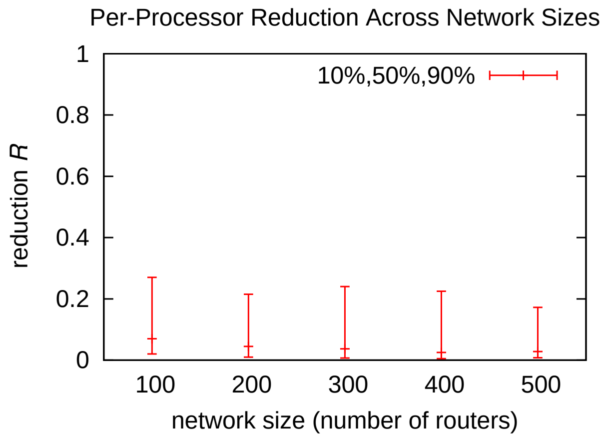
Evaluation

- Analysis of the compression of predicates
- Analysis of the indistinguishability relation
- Actual memory usage in practice
  - simple method to treat sources as content
  - concrete implementation of a forwarding table

Indistinguishability of Sources

- 25 networks for each size; BRITE; Waxman model of autonomous systems; for each processor u we compute

$$R_u = \frac{\text{number of equivalence classes}}{\text{total number of processors}}$$

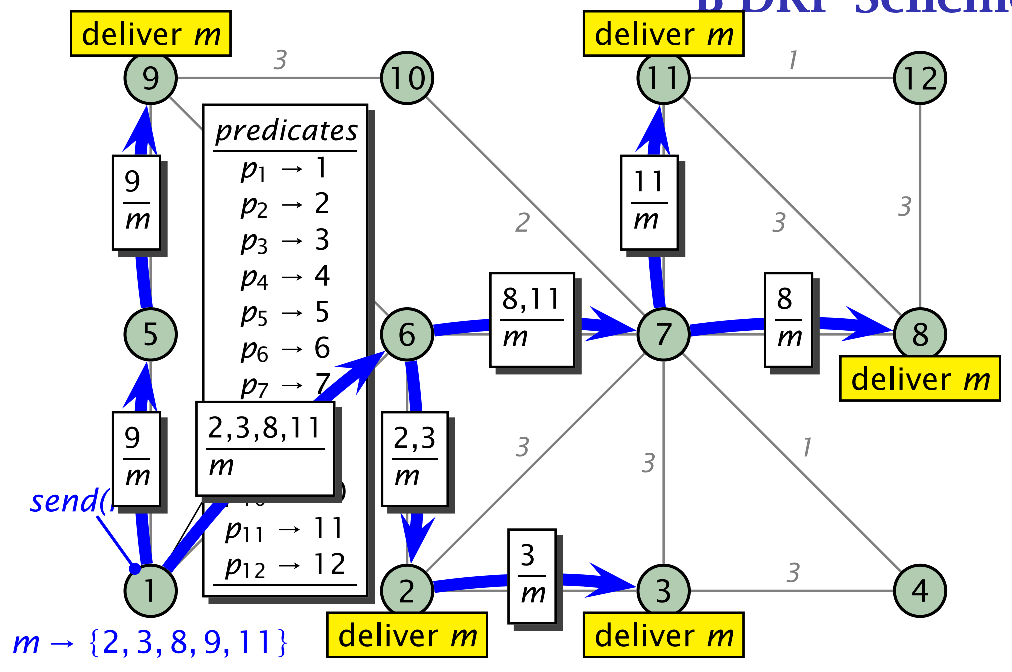


Folding Sources into Predicates

source	*next-hop*	→ *predicate*
1	1	$\mapsto \emptyset$
1	2	$\mapsto p_2 \vee p_3$
1	7	$\mapsto p_4 \vee p_7 \vee p_8 \vee p_{11} \vee p_{12}$
1	9	$\mapsto \emptyset$
1	10	$\mapsto \emptyset$
10	1	$\mapsto p_1$
10	2	$\mapsto p_2 \vee p_3$
10	7	$\mapsto \emptyset$
10	9	$\mapsto \emptyset$
10	10	$\mapsto \emptyset$
...		

next-hop	→ *predicate*
1	$\mapsto$ *source* $= 10 \wedge p_1$ $\vee \ldots$
2	$\mapsto$ *source* $= 10 \wedge (p_2 \vee p_3) \vee$ *source* $= 1 \wedge (p_2 \vee p_3)$ $\vee \ldots$
7	$\mapsto$ *source* $= 1 \wedge (p_4 \vee p_7 \vee p_8 \vee p_{11} \vee p_{12})$ $\vee \ldots$
9	$\mapsto \ldots$
10	$\mapsto \ldots$

B-DRP Scheme



Encoding Idea

$$\begin{tikzcd}[column sep=huge]
m \arrow[r, leftrightarrow, "p(m)"] \arrow[d, "X_S"'] & p \arrow[d, "X_P"] \\
S_m \arrow[r, leftrightarrow, "S_m \supseteq S_p^i \text{ for some } i"] \arrow[d, "B"'] & S_p^1, S_p^2, \ldots \arrow[d, "B"] \\
B_m \arrow[r, leftrightarrow, "B_m \supseteq B_p^i \text{ for some } i"] & B_p^1, B_p^2, \ldots
\end{tikzcd}$$

1. Map m and p into sets of tags S_m and $S_p^1, S_p^2, \ldots$, such that

$$p(m) \Rightarrow \left(\exists S_p^i \in \{S_p^1, S_p^2, \ldots\} : S_m \supseteq S_p^i\right)$$

2. Represent S_m and $S_p^1, S_p^2, \ldots$ with Bloom filters B_m and $B_p^1, B_p^2, \ldots$

Bloom Filters

- $U = \{x_1, x_2, \ldots\}$ is the universe of values we intend to represent
- A Bloom set over U is defined by
  - a bit vector B of size m
  - k distinct hash functions $h_1, h_2, \ldots, h_k$ with signature $H : U \to \{0, 1, \ldots, m-1\}$
- $B(x)$ is computed as follows

Input: x, an element of the universe U
Output: $B(x)$, Bloom filter representing the singleton $\{x\}$

$B \leftarrow \emptyset$ // all zeros
foreach $i \in \{1, \ldots, k\}$
  $B[h_i(x)] \leftarrow 1$
return B

Bloom Filters (2)

- Given a set of n elements $S = \{x_1, x_2, \ldots x_n\}$

$B(S) \leftarrow B(x_1) \cup B(x_2) \cup \cdots \cup B(x_n)$

Input: S, a set elements from the universe U
Output: $B(S)$, Bloom filter representing S

$B \leftarrow \emptyset$
foreach $x \in S$
  foreach $i \in \{1, \ldots, k\}$
    $B[h_i(x)] \leftarrow 1$
return B

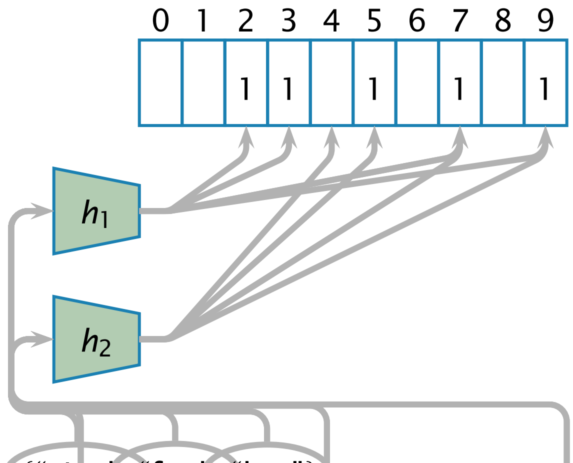
- Testing $x \in S$ amounts to testing $B(x) \subseteq B(S)$

i.e., (assuming B is implemented as an integer)

$x \in S \Leftrightarrow$ (Bx & BS) == Bx

Bloom Filters: Example

U is the universe of character strings; $k = 2$; $m = 10$



$S = \{$"ciao", "foo", "bar"$\}$

Test: "foo": *yes*, "abc": *no*, "xyz": *yes* (false positive)

Encoding with Tags

$$
\begin{tikzcd}
m = \{\text{software, update, emacs}\} \arrow[rr, leftrightarrow, "p(m)"] \arrow[d, "X_S"'] & & p = \{\text{gnu,software}\}, \{\text{emacs}\}, \{\text{anarchism}\} \arrow[d, "X_P"] \\
S_m = \{\text{software, update, emacs}\} \arrow[rr, leftrightarrow, "S_m \supseteq S_p^i \text{ for some } i"] \arrow[d, "B"'] & & S_p = \{\text{gnu,software}\}, \{\text{emacs}\}, \{\text{anarchism}\} \arrow[d, "B"] \\
B_m = [0110010101] \arrow[rr, leftrightarrow, "B_m \supseteq B_p^i \text{ for some } i"] & & B_p = [0101010010]\ [0010000100]\ [0001000001]
\end{tikzcd}
$$

From Constraints to Tags

1. Constraint encoding

encoding rule			*type*
c	$\rightarrow$	$s(c)$	
name $=$ *value*	$\rightarrow$	"***name***=*value*"	equality
name $\langle$*other-operator*$\rangle$ *value*	$\rightarrow$	"$\exists$***name***"	existence

Example:

- **disk-space** $< 1Gb$ $\longrightarrow$ "∃disk-space"
- **disk-space** $= 2Gb$ $\longrightarrow$ "disk-space=2"

2. A *conjunction* $f = c_1 \wedge c_2 \wedge \cdots \wedge c_k$ is encoded with the union of the encodings of its constraints $S_f = \{s(c_1), s(c_2), \ldots, s(c_k)\}$

3. A predicate $P = f_1 \vee f_2 \vee \ldots \vee f_F$ P is encoded with a set of sets $S_P = \{S_1, S_2, \ldots, S_F\}$

Message Encoding

1. Every attribute **name** $=$ *value* is encoded with two strings

encoding rule		
a	$\rightarrow$	$s(a) = \{s^{=}(a), s^{\exists}(a)\}$
name $=$ *value*	$\rightarrow$	{"***name***=*value*", "$\exists$***name***"}

disk-space $= 2Gb \rightarrow$ {"disk-space=2Gb", "∃disk-space"}

2. A message $m = \{a_1, a_2, \ldots, a_n\}$ is therefore encoded with a set $S_m = s(a_1) \cup s(a_2) \cup \cdots \cup s(a_n)$

B-DRP State

- *Local predicates*

  local-predicates : *host-id* → *predicate*

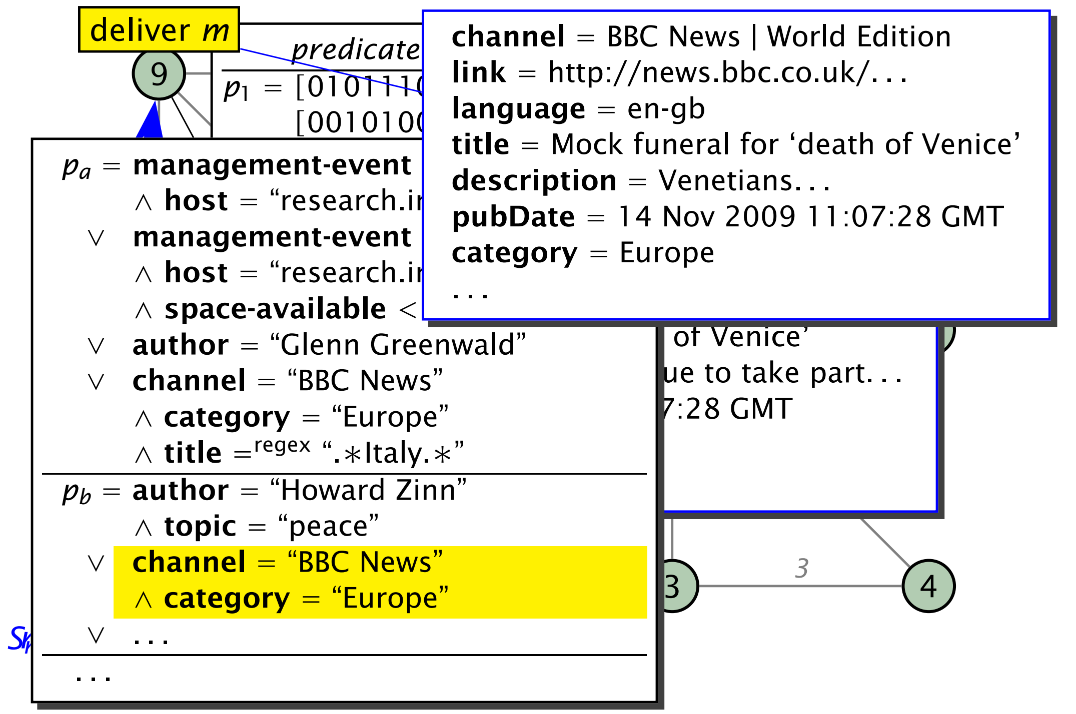
- *Predicates* from all other routers

  predicates : *router-id* → *encoded-predicate*

- *Unicast* routing information

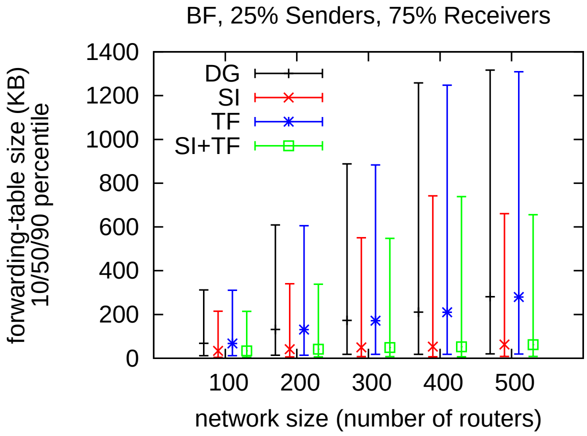
  unicast : *router-id* → *neighbor-link*

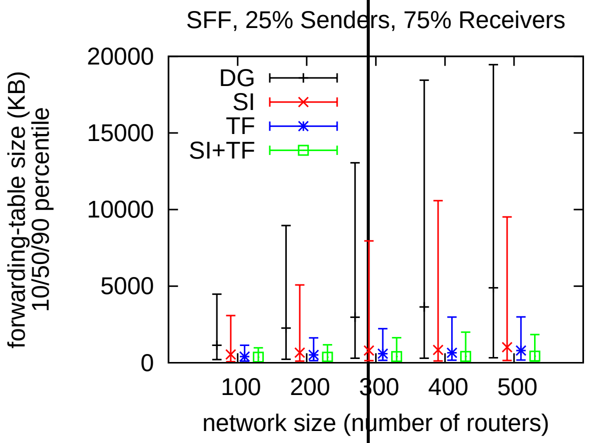
B-DRP: Two Matching Processes



Emulation with SFF

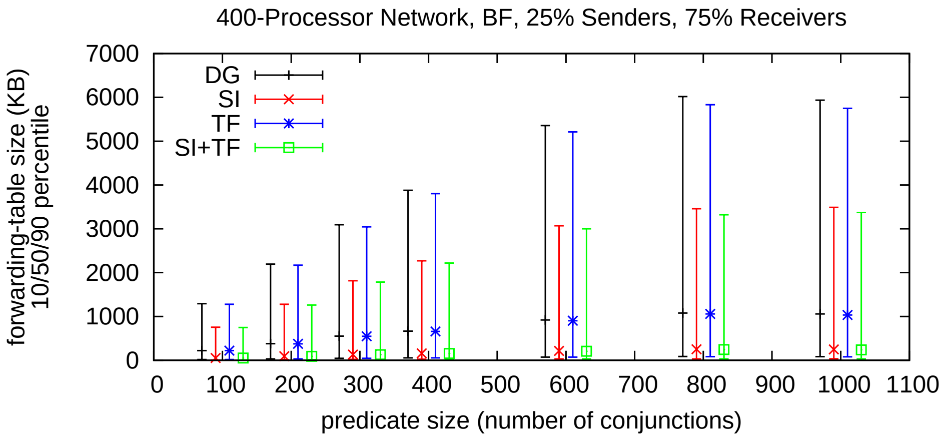
- Siena Fast Forwarding algorithm; for each processor we measure the *actual memory usage*

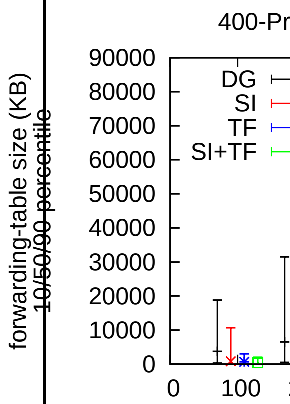




Emulation with SFF (2)

- Siena Fast Forwarding algorithm; for each processor we measure the *actual memory usage*





Emulation with SFF (3)

- Siena Fast Forwarding algorithm; for each processor we measure the *actual memory usage*