FBR: Dynamic Memory-Aware Fast Rerouting

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IEEE Global Internet 2022

Network Failure Protection

- Increasingly strict reliability requirements for modern computer networks
- In case of network failures, instantly reroute packages around failures
- However, fast rerouting requires additional forwarding rules (memory!)

We initiate the study of **memory-aware fast rerouting** techniques. Our aim is to develop a fast rerouting algorithm that explicitly models the memory limit on the routers.

Control Plane vs. Data Plane

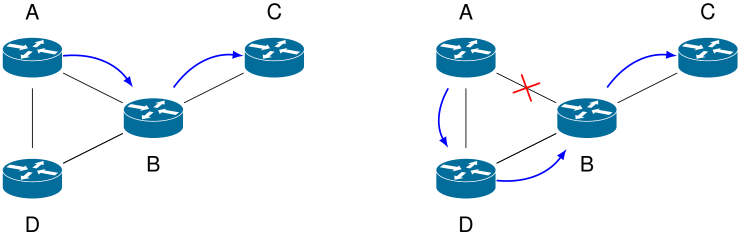
Control plane

- Determines how packets are forwarded
- Encodes the forwarding in data plane

Data plane

- Handles the packet-level forwarding using forwarding tables created by control plane logic

Motivation for Fast Rerouting



- Router and link failures are inevitable
- Convergence (in control plane) to new routing is slow
- Meanwhile, reroute based only on local failure information
  - Maintains connectivity until new routing is installed in data plane

Fast Rerouting in MPLS

- Multi-Protocol Label Switching: forwarding only by packet label
- Routers can mutate the packet label during forwarding
- Proactively compute data plane with protection paths
- Store information in label to aid routers in choosing intact protection paths

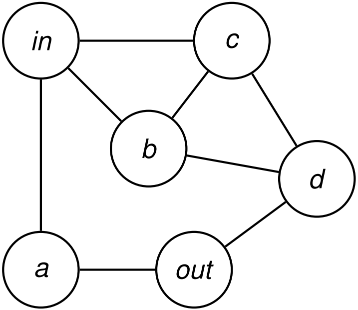
Our Contribution

We present Forward-Backward Routing (FBR) that generates highly failure resilient fast rerouting, while never exceeding the given memory limits of the routers.

Network Model

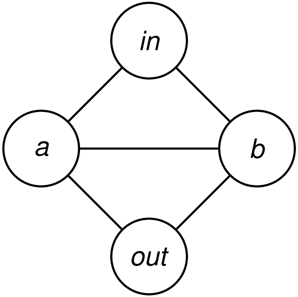
Definition

A *network topology* is an undirected graph $G = (V, E)$, where V is a set of *routers* and $E \subseteq V \times V$ is a set *links* between *routers*.



Demand: flow from *in* with label ℓ_0 to *out*

Packet Forwarding Using Label Switching



τ : forwarding table

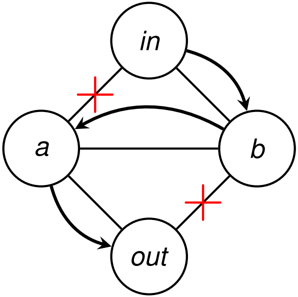
Router	Label	Priority	Router	Label
in	ℓ_1	1	*a*	ℓ_1
		2	*b*	ℓ_2
	ℓ_2	1	*b*	ℓ_2
a	ℓ_1	1	*out*	ℓ_1
		2	*b*	ℓ_1
		3	*in*	ℓ_2
b	ℓ_1	1	*out*	ℓ_1
	ℓ_2	1	*out*	ℓ_2
		2	*a*	ℓ_1

Memory usage = number of rules

$$M(\tau, in) = M(\tau, a) = M(\tau, b) = 3$$

Packet Forwarding Using Label Switching

Demand: (in, out, ℓ_1)



$F = \{(in, a), (b, out)\}$

τ_F : active forwarding table

Router	Label	Priority	Router	Label
in	ℓ_1	~~1~~	~~*a*~~	~~ℓ_1~~
		2	*b*	ℓ_2
	ℓ_2	1	*b*	ℓ_2
a	ℓ_1	1	*out*	ℓ_1
		~~2~~	~~*b*~~	~~ℓ_1~~
		~~3~~	~~*in*~~	~~ℓ_2~~
b	ℓ_1	~~1~~	~~*out*~~	~~ℓ_1~~
	ℓ_2	~~1~~	~~*out*~~	~~ℓ_2~~
		2	*a*	ℓ_1

Step	Router	Label	Forwarding rules
1	*in*	ℓ_1	$\cancel{(1, a, \ell_1)}, (2, b, \ell_2)$
2	*b*	ℓ_2	$\cancel{(1, out, \ell_2)}, (2, a, \ell_1)$
3	*a*	ℓ_1	$(1, out, \ell_1)$
4	*out*	ℓ_1	

Objective for Memory-Aware Fast Rerouting

Goal: High resilience to failures without exceeding any router's memory

Measure for failure resilience:

$$connectedness(\tau, D) = \sum_{F \subseteq E} p_F \cdot connectivity(\tau_F, D),$$

where

$connectivity(\tau_F, D) = \textit{ratio of successful deliveries to achievable deliveries}$

$connectivity, connectedness \in [0, 1]$

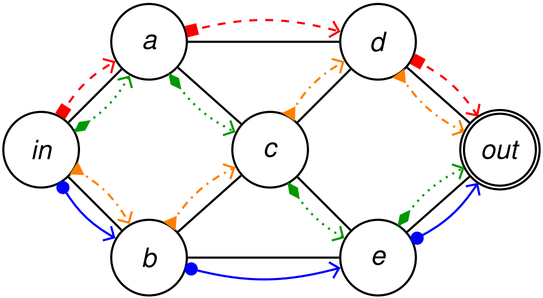
Forward-Backward Routing (FBR)

Intuition

- Find a list of alternative paths from ingress to egress
- In case of failure: route along the first path
- If that path fails, backtrack towards ingress
- When the next path is reached, switch to that path
- Repeat

FBR Example

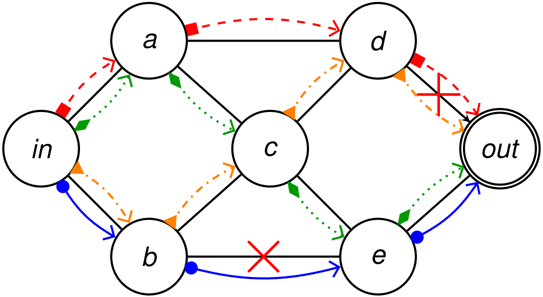
Demand: *in* to *out* with initial label ●



Path order: ● ■ ⧫ ▲

FBR Example

Demand: *in* to *out* with initial label ●



Path order: ● ■ ⧫ ▲

$$F = \{(b, e), (d, out)\}$$

Trace: *in* – *b* – *b* – *in* – *a* – *d* – *d* – *a* – *c* – *e* – *out*

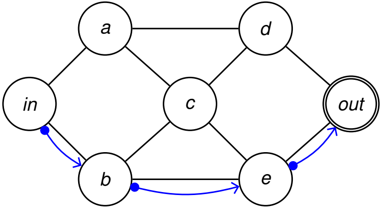
Encoding the Paths

1 unique label for every path encoded

For each path:

- Skip encoding if it exceeds memory!
- Encode forwarding with a unique label ℓ_i
- (If not last path) For each router in the path:
  - Add a local lookup to upgrade to the next label ℓ_{i+1}
  - Add backtracking rules with label ℓ_{i+1}

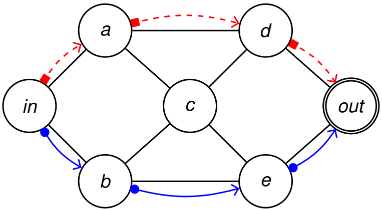
FBR Example: Encoding



τ : forwarding table

Router	Label	Priority	Router	Label
in	ℓ_1	1	*b*	ℓ_1
a				
b	ℓ_1	1	*e*	ℓ_1
c				
d				
e	ℓ_1	1	*out*	ℓ_1

FBR Example: Encoding



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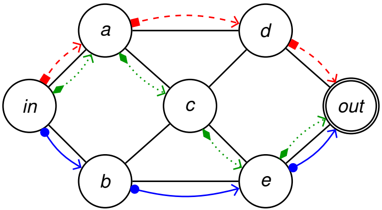
		2	*in*	ℓ_2
	ℓ_2	1	*a*	ℓ_2
a	ℓ_2	1	*d*	ℓ_2
b	ℓ_1	1	*e*	ℓ_1
		2	*b*	ℓ_2
	ℓ_2	1	*in*	ℓ_2
c				
d	ℓ_2	1	*out*	ℓ_2
e	ℓ_1	1	*out*	ℓ_1
		2	*e*	ℓ_2
	ℓ_2	1	*b*	ℓ_2

FBR Example: Encoding



If $m(v) = 5$ for *in* then no more paths can be added.

τ : forwarding table

Router	Label	Priority	Router	Label
in	ℓ_1	1	*b*	ℓ_1
		2	*in*	ℓ_2
	ℓ_2	1	*a*	ℓ_2
		2	*in*	ℓ_3
	ℓ_3	1	*a*	ℓ_3
a	ℓ_2	1	*d*	ℓ_2
		2	*a*	ℓ_3
	ℓ_3	1	*c*	ℓ_3
b	ℓ_1	1	*e*	ℓ_1
		2	*b*	ℓ_2
	ℓ_2	1	*in*	ℓ_2
c	ℓ_3	1	*e*	ℓ_3
d	ℓ_2	1	*out*	ℓ_2
		2	*d*	ℓ_3
	ℓ_3	1	*a*	ℓ_3
e	ℓ_1	1	*out*	ℓ_1
		2	*e*	ℓ_2
	ℓ_2	1	*b*	ℓ_2
	ℓ_3	1	*out*	ℓ_3

Theoretical Properties

Theorem

Forward-Backward Routing is loop-free.

Proof sketch: Paths are loop-free and are only used once.

Theorem

For a k-connected network topology, FBR can achieve $(k-1)$-resilience using $3k-2$ rules per demand per router.

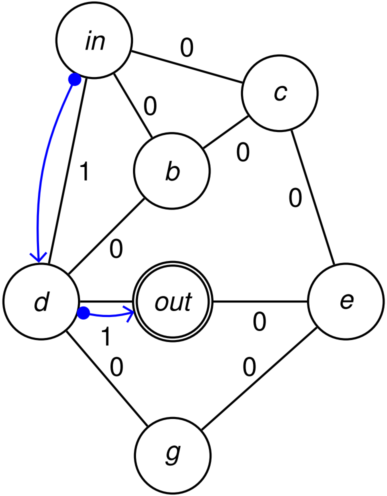
Proof sketch: In a k-connected graph, at least k edges must be removed to disconnected the graph. FBR creates k edge-disjoint paths to attempt.

Simple Path Generation Approach

Idea: Increase weight of used edges to increase disjointedness of paths.

For each iteration do:

- Pick next demand d
- Find shortest path p in G
- Update weights $W(d, e) := W(d, e) \cdot 2 + 1$ for each $e \in p$



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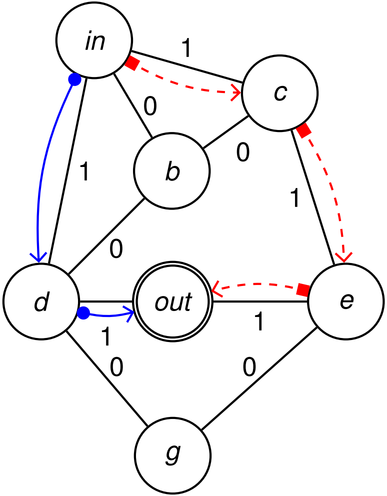

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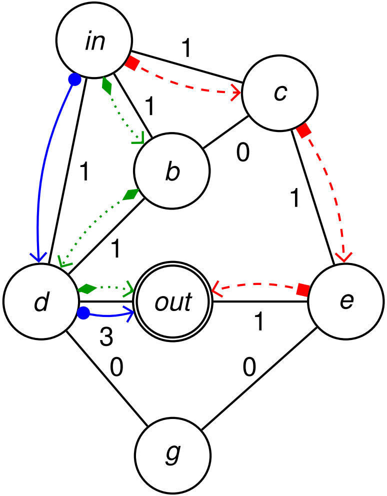

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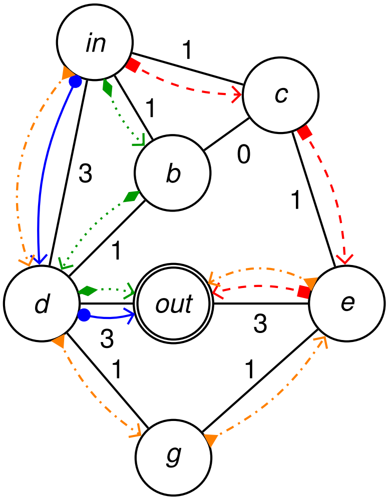


Methodology

Evaluation specifications

- 259 real-world networks from Topology Zoo
- Failure scenarios of size 0 to 4
- 1000 failure scenario limit for each size of F
- We assume link failures are independent, with probability 0.001 for a single link failure
- All routers are assumed to have the same memory limit

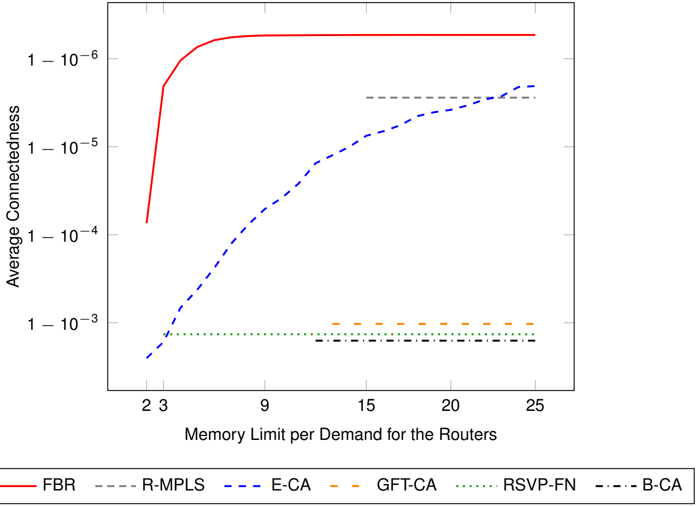
All experiments were conducted using the data plane simulation toolkit MPLS-Kit [2022] on a compute-cluster.

Related Work

Fast rerouting algorithms

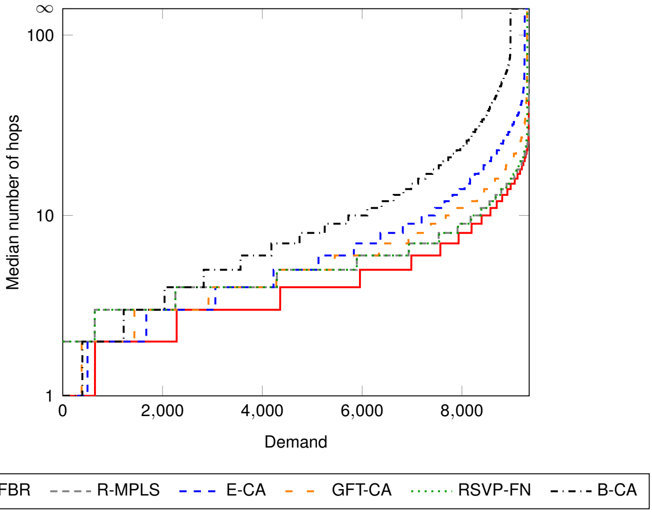
- RSVP-FN: industry standard [RFC 4090, 2005]
- R-MPLS: recent work that augments RSVP-FN [CoNEXT, 2022]
- B-CA: static arborescence approach [Trans. on Netw., 2017]
- GFT-CA: static DAG approach [INFOCOM, 2021]
- E-CA: dynamic memory-aware arborescence approach

Results: Connectedness and Memory Usage



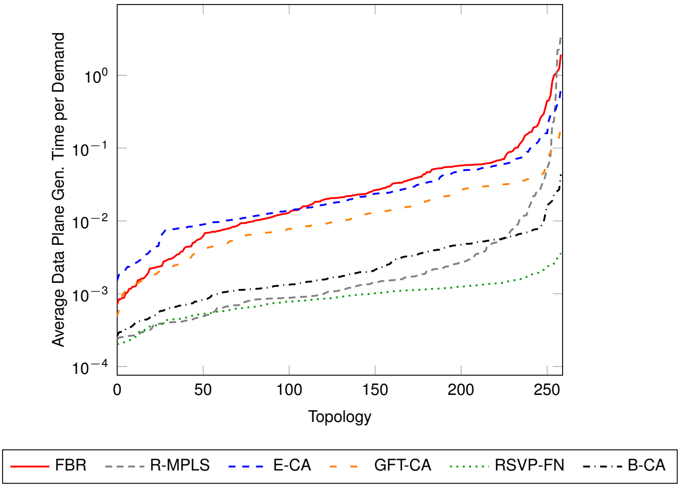
FBR achieves highest connectedness at any memory limitation!

Results: Number of Hops



FBR uses the fewest number of hops.

Results: Data Plane Generation Time



FBR is generally slower than the others, but still always under 2 seconds.

Conclusion

Forward-Backward Routing

- Memory-aware fast rerouting
- Outperforms previous work w.r.t. failure resilience and memory usage
- Uses the fewest number of hops
- Maximum generation time per demand is 2 seconds

Future Work

Improved path generation algorithm.