SafeGuard: Safe Forwarding during Route Changes

Ang Li
Dept. of Computer Science
Duke University
angl@cs.duke.edu

Xiaowei Yang
Dept. of Computer Science
Duke University
xwy@cs.duke.edu

David Wetherall
Intel Research Seattle &
University of Washington
djw@cs.washington.edu

ABSTRACT

This paper presents the design and evaluation of SafeGuard, an intra-domain routing system that can safely forward packets to their destinations even when routes are changing. SafeGuard is based on the simple idea that packets carry a destination address plus a local estimate of the remaining path cost. We show that this simple design enables routers to detect path inconsistencies during route changes and resolve on a working path for anticipated failure and restoration scenarios. This in turn means that route changes do not disrupt connectivity even though routing tables are inconsistent over the network. We evaluate the router performance of SafeGuard using a prototype based on NetFPGA and Quagga. We show that SafeGuard is amenable to high-speed hardware implementation with low overhead. We evaluate the network performance of SafeGuard via simulation. The results show that SafeGuard converges faster than a state-of-the-art IP fast restoration mechanism and reduces periods of disruption to a minimal duration, *i.e.*, the failure detection time.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.2.2 [**Computer-Communication Networks**]: Network Protocols—*Routing Protocols*

General Terms

Algorithms, Design, Performance, Reliability.

Keywords

Routing, convergence, protocols.

1. INTRODUCTION

One of the well-known problems in networking is to reduce forwarding disruptions while routes are changing. When a network change occurs (*e.g.*, a link goes down), routers will be informed and recompute their forwarding tables to adapt to the change, a process known as routing convergence. During convergence, routers adjacent to failures may not have valid routes, or routers may have inconsistent next hop sequences that form temporary loops called micro-loops. Micro-loops can cause packet loss due to TTL expiration. They can also amplify traffic that is trapped in a loop and congest the network links, causing collateral damage to other traffic not affected by the topology change.

Unfortunately, network changes happen frequently and are part of daily operations [20, 28], while real-time applications such as VoIP, online gaming, video conferencing, and IPTV need network services that are free of interruption [5, 9]. Even sub-second periods of packet loss or delay may adversely impact the users of these applications [9, 29], but the present Internet routing system can easily produce noticeable periods of disruption following a change in the network, *e.g.*, a failure or restoration of equipment, an ISP policy change, or a traffic engineering route adaptation.

This long-standing networking problem has brought forth a plethora of solutions both from academia and industry: [8, 13, 14, 15, 16, 17, 21, 23, 25, 31, 37]. However, all of the effective solutions [14, 16, 21, 25] that can minimize the disruption period to its theoretical minimal (*i.e.*, the failure detection time) require a burdensome change of the underlying routing protocol; some also require on-demand route computation and variable packet header length. Consensus routing replaces routing convergence with distributed consensus protocol that synchronizes route updates among routers [21]. Other approaches introduce a strict update order [14, 17] that prevents routers from independently updating their routing tables in parallel. The convergence-free routing [25] approach abandons routing convergence, but requires packets to carry all failed components they encounter and routers to compute paths on demand; it also requires an additional centralized protocol to disseminate and update static network maps at routers.

A simple, effective, and efficient solution that minimizes forwarding disruptions while routes are changing remains elusive. By simple, we mean a solution that does not increase the complexity of routing convergence. Link state routing protocols such as OSPF introduce no state dependency among routers and allow each router to dynamically update their routing tables *independently* and *in parallel*. It has been shown to have the least complexity and converge faster than other alternative convergence proposals [12]. By effective, we mean to minimize periods of disruption to the failure detection time, a minimal period that cannot be shortened without physical layer improvement. By efficient, we mean a solution that is amenable for high-speed hardware implementation and retains much of the IP forwarding design: simple table lookups with fixed packet header length. We recognize that satisfying all three goals may not align well with commercial market constraints such as immalleable router hardware, but we believe an intellectual endeavor to explore this unique design point is worthwhile and may influence future network designs.

CoNEXT'09, December 1–4, 2009, Rome, Italy.

As a first step, this paper presents a new approach called SafeGuard that is simple, effective, and efficient at minimizing network service interruptions for intra-domain route changes. In SafeGuard, a packet carries the cost of the remaining path to its destination. Routers use this cost to detect route changes and resolve on a valid alternative path. The routing system can rapidly disseminate the news of a failure (or a restoration) to quickly return to its optimal state. It can do this in any update order without the concern of breaking connectivity. We believe that this work is the first design to achieve the effective and efficient goals without increasing the complexity of routing convergence.

A key observation underlying this design is that the remaining path cost succinctly encodes valuable path information that we can leverage. On one hand, it can be embedded into a fixed-length field, similar to a forwarding label [34]; on the other hand, it sheds light on what links lie on the remaining path, approximating the effect of a full source route. When a router's local path cost differs from that carried by a packet, it indicates route changes; the cost difference informs a router whether its local path is valid or not, as outdated paths using failed components would have lower costs than a working one. A router can use this information to select a working path from a set of pre-computed alternatives and forward packets to their destinations along the working path. Of course, pre-computation limits protection to anticipated failure or restoration scenarios (such as single links, nodes, or shared risk link groups), but the trade-off is favorable: multiple independent events rarely occur in complete synchrony, and events that are off by a few hundreds of milliseconds (*i.e.*, the routing converge periods) are fully protected as consecutive anticipated events.

We evaluate SafeGuard in terms of both router and network performance. To assess router performance, we implement SafeGuard in hardware using the NetFPGA platform [18] and in software using the Quagga routing suite [4]. Our experiment results show that SafeGuard is amenable to high-speed hardware implementation and introduces memory and computational overhead comparable to other practical solutions that use pre-computed paths to suppress failures [10].

We use simulations over a range of real, inferred, and randomly generated topologies to assess network performance. We find that no packets are trapped in loops with SafeGuard even when two independent links fail simultaneously, versus micro-loops that can amplify traffic up to 50 folds and occur on average for 16% of the routing transitions we test. After single component failures, SafeGuard fully restores connectivity after the failure detection time. Further, SafeGuard achieves the same convergence time as vanilla OSPF, which is up to 15% shorter than the convergence time of a state-of-the-art loop-avoidance mechanism.

The rest of the paper is organized as follows. § 2 introduces the problem we address. § 3 and § 4 describe SafeGuard and its properties. § 5 evaluates the router and network performance of the SafeGuard design. We compare SafeGuard with related work in § 6 and conclude in § 7.

2. COST AS A SAFEGUARD

The SafeGuard design aims to provide a simple and efficient solution that reduces forwarding disruption during route changes to the failure detection time without altering or increasing the complexity of the routing convergence process. To achieve this goal, we make each packet carry the remaining path cost to its destination and routers pre-compute alternative paths for anticipated network changes. In this section, we first use a simple example to illustrate how SafeGuard works. We present the detailed design in the following section.

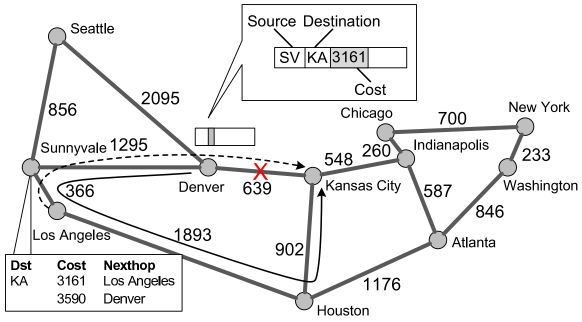


Figure 1: Forwarding using cost-carrying packets on the Abilene network.

2.1 Using Cost to Resolve Inconsistencies

Figure 1 shows an example using the Abilene network topology. All link weights are taken from the Abilene network configuration [1]. Suppose the link between Denver and Kansas City fails, and the Denver node has updated its forwarding table to use the Sunnyvale node to reach Kansas City. The Sunnyvale node has not learned of the failure nor updated its forwarding table. Without carrying a path cost, packets will loop temporarily between Sunnyvale and Denver, as the Sunnyvale node is still using the outdated next hop Denver to reach Kansas City.

If instead, packets carry the remaining path cost and routers update this cost at each hop using their local estimates, the Sunnyvale node will stamp the remaining path cost to Kansas City (639) into the packets it forwards to Denver. As the Denver node has updated its forwarding table to bypass the failed link to Kansas City, its local path cost (4456) is larger than the packet cost (639). This difference indicates that routes are changing and some node may have incorrect forwarding paths. More importantly, it suggests that Denver's path bypasses a failure that has not been seen by its upstream router Sunnyvale. This is because the updated topology that does not contain a failed component must have "longer" shortest paths. Therefore, the Denver node can infer that its path is working. It then forwards the packet to its default next hop Sunnyvale and updates the packet cost to the remaining path cost (3161).

Here we emphasize again that what distinguishes path cost from a path identifier (*e.g.*, an MPLS label) is the ability to resolve which path may have included a failed (or a newly restored) component. This in turn assists a router to choose a working path. In contrast, if a packet simply carries a path identifier, a router may detect a path inconsistency, but cannot tell which path, its default path or an upstream router's default path, is a working path.

When the Sunnyvale node receives the packet with a path cost 3161 from the Denver node, it can infer that its default path has a failure of which it has not learned. This is because its local cost (1934) is lower than the packet cost (3161). Instead of using its default path, the Sunnyvale node will try to find an alternative path that matches the packet cost. By pre-computing all alternative paths that bypass a single component on its default shortest paths, the Sunnyvale node is able to map the path cost (3161) to an alternative path: Sunnyvale→Los Angeles→Houston→Kansas City, and forwards the packet to the correct next hop (Los Angeles) without forming a loop.

2.2 Distinguishing Equal-Cost Paths

As shown in the above example, after detecting a path inconsistency, a router may also use the path cost carried by a packet to select a working path that matches the cost. This would work well

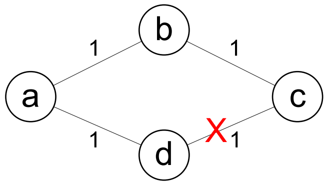


Figure 2: In this simple topology each link has the cost of one. There are two equal cost paths from a to c: $a \rightarrow b \rightarrow c$ and $a \rightarrow d \rightarrow c$.

if different paths to the same destination have different costs. However, practical network configurations may have equal cost paths for load balancing and backup reasons. When this occurs, a path cost may not reliably identify a working path as shown in Figure 2. There are two equal-cost paths from a to c: $a \rightarrow b \rightarrow c$ and $a \rightarrow d \rightarrow c$. Suppose the node d that detects the link failure to c reroutes the packet to a with a remaining path cost 2. When node a receives this packet, the packet cost matches both paths: one valid and one failed. The node a may erroneously forward the packet along the invalid path $a \rightarrow d \rightarrow c$.

To address this issue, the SafeGuard design adds a random noise to a regular link cost to help distinguish equal-cost paths. With this design, a node is able to select a valid alternative path with high probability. We describe this design in more detail.

3. DESIGN

The SafeGuard design has four main components: enhanced link and path costs, packets that carry enhanced path costs, a pre-computed alternative path database (APD) maintained by routers, and a forwarding algorithm that is provably safe and can forward packets to their destinations without forming loops during anticipated route changes. We describe each design component in turn.

3.1 Enhanced Link and Path Costs

The SafeGuard design embeds a noise into the lower k-bit of a link's cost metric to help distinguish multiple equal cost paths to the same destination. We refer to this metric as the enhanced link cost metric, and denote it as $\overline{cost}$. An enhanced link cost can be viewed as a pair of two values: $(cost, noise)$, where the higher-order bits $cost$ is the regular link cost configured by a network operator without considering failure recovery issues, and the lower order k-bit $noise$ is a random value within $[0, 2^k - 1]$.

We further define the addition and comparison functions over the enhanced link cost metric to enable shortest path computation using enhanced costs. If two enhanced link costs: $l_1.\overline{cost} = (l_1.cost, l_1.noise)$ and $l_2.\overline{cost} = (l_2.cost, l_2.noise)$, are added together, each part is added separately: $l_1.\overline{cost} + l_2.\overline{cost} = (l_1.cost + l_2.cost,\ l_1.noise + l_2.noise)$. Two enhanced link costs are compared lexicographically: $l_1.\overline{cost} > l_2.\overline{cost}$, if $l_1.cost > l_2.cost$, or $l_1.cost \equiv l_2.cost$ and $l_1.noise > l_2.noise$.

An enhanced path cost is the sum of all enhanced link costs on the path p: $p.\overline{cost} = (\sum_{l_i \in p} l_i.cost\ ,\ \sum_{l_i \in p} l_i.noise)$. We refer to the first term as the regular path cost $p.cost$, and the second as the path noise $p.noise$. When a router stores an enhanced path cost, it only stores the last k-bits of the path noise: $p.\overline{cost} \leftarrow (p.cost, p.noise \bmod 2^k)$ to ensure that an enhanced path cost can be encoded in a fixed-length label.

3.2 Packets that Carry Costs

In the SafeGuard design, a packet carries a fixed-length label $pkt.\overline{cost}$ that encodes the enhanced path cost of its remaining path to the destination. Routers use the regular path cost field $pkt.cost$ to detect path inconsistencies and to resolve whether its default path or an upstream router's default path is a working path. In the latter case, the router uses the entire packet cost $pkt.\overline{cost}$ to select a working path.

We also use 1-bit in a packet header to indicate whether a packet has been detoured before due to path inconsistency. When this bit is off, a packet is called in the *normal* mode; otherwise, it is called in the *escort* mode. Routers can use this bit to detect non-anticipated topology events and abort the effort of searching for a working path. This is because for anticipated events, a packet only needs to be detoured at most once before it reaches its destination (§ 4).

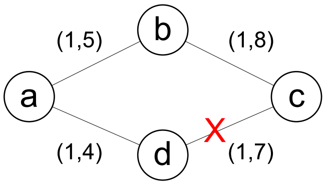


Figure 3: In this simple topology each link has the cost of one and a link noise. The enhanced cost of each link is marked in the format $(cost, noise)$. There are two paths with equal regular cost from a to c: $a \rightarrow b \rightarrow c$ and $a \rightarrow d \rightarrow c$.

3.3 Alternative Path Database

The SafeGuard design uses an alternative path database (APD) to store alternative paths to reach a destination if a failure occurs on a router's current network map. Conceptually, an APD is a table that maps the destination and enhanced path cost pair: $(dst, \overline{cost})$, to a valid next hop: $(dst, \overline{cost}) \rightarrow nexthop$.

To avoid on-demand computation, SafeGuard makes a router pre-compute alternative paths by anticipating a future failure on its current network map G. If a router anticipates a network element e (a link, node, or shared risk link group (SRLG) [33]) may fail in the future, it computes an alternative shortest path to reach a destination by removing the element e from the network map G. This computation uses the enhanced link cost metric. The router stores the enhanced path cost and the next hop in its APD. If the same alternative path can bypass multiple elements, the router only stores the path once.

As we will discuss in § 3.5, with randomly chosen link noises, different alternative paths will have different enhanced path costs with high probability. This would warrant that a router selects a working path with high probability. As shown in Figure 3, the enhanced path cost for the path $a \rightarrow b \rightarrow c$ is now (2,13), different from the enhanced path cost (2,11) of $a \rightarrow d \rightarrow c$ (had $d \rightarrow c$ not failed). When the node d reroutes a packet to a, it will carry the enhanced path cost (2,13), which unambiguously identifies the alternative path $a \rightarrow b \rightarrow c$ that bypasses the failed link. If in the unlikely case that a router has different alternative paths with the same enhanced path costs, the router will store the path that bypasses the largest number of failed elements on its default paths to maximize the utility of this path.

A router may re-compute its APD whenever it receives a routing update that changes its current network map. In the case of a failure event, the updated APD is only used when the next topology change occurs. Thus the computation is not urgent and could be done in low priority after a router has updated its forwarding tables. In the case that a topology update results in a better connected topology, *e.g.*, a link up, a router can save computation by swapping the next hops and path costs in its previous forwarding tables to its APD before updating its forwarding tables. As we will soon describe in the next subsection, paths in a router's previous forwarding tables would be the alternative paths computed without the newly added topology element.

3.4 Forwarding

We now describe how a SafeGuard router forwards packets without loops during routing transitions. We first describe how a router sets up its forwarding tables and then the forwarding algorithm.

3.4.1 Forwarding Table Entries

As in the current intra-domain routing system, an entry in a router n_i's forwarding table contains the mapping between a destination prefix to a set of next hops n_{i+1}. These next hops are computed using the regular link costs without considering link noises. This design ensures that packets are always forwarded along their regular shortest paths, *i.e.*, any of the equal cost multiple paths, when routing is not in transition.

The SafeGuard design also adds path cost information to a router's forwarding tables. Each forwarding table entry includes not only the next hops n_{i+1}, but also the enhanced path cost from each of the next hop n_{i+1} to the destination: $n_{i+1}.\overline{cost}$. Moreover, it also includes the enhanced path cost from the current router n_i to the destination: $n_i.\overline{cost}$. These path costs are used by the forwarding algorithm to detect route changes and choose a working path.

A router n_i may efficiently compute the enhanced path costs after it computes its regular shortest paths. Let T denote the shortest path graph generated by the regular shortest path computation. The router can compute the enhanced path cost $n_i.\overline{cost}$ for each destination by running a shortest path computation on T (rather than the full network map) using the enhanced link cost metric. This algorithm is correct because enhanced costs are compared lexicographically, so the shortest path defined over the enhanced cost metric must be one of the shortest paths defined over the regular link costs. Similarly, the enhanced path cost associated with each next hop ($n_{i+1}.\overline{cost}$) can be computed efficiently using the shortest path graph T with each next hop node being the root node of the shortest path computation.

3.4.2 Packets in the Normal Mode

When a packet arrives at a router n_i, the router first checks its forwarding mode. If the packet is in the normal mode, the router ignores the path noise and only compares its local regular cost $n_i.cost$ with the packet cost $pkt.cost$. It uses this comparison to detect and resolve any inconsistency, and turns on the escort mode if necessary. If the packet is already in the escort mode, the router uses the enhanced packet cost $pkt.\overline{cost}$ to identify a working path and forwards the packet along the path.

A packet enters the network in the normal mode. When a router n_i receives an incoming packet in the normal mode, it compares the regular costs only. There are three possible outcomes:

Matching Costs ($n_i.cost \equiv pkt.cost$): This indicates that the router n_i and its upstream router have consistent forwarding paths. The router n_i selects a next hop n_{i+1} from its forwarding table, updates the packet's cost label using the enhanced path cost associated with the next hop n_{i+1}: $n_{i+1}.\overline{cost}$, and forwards the packet to the next hop n_{i+1}.

Higher Local Cost ($n_i.cost > pkt.cost$): This inconsistency shows that a router's local cost is higher than its upstream router's cost. The network must be in a routing transition, as the router n_i has computed different paths from other routers. As the packet is in the normal mode, this is the first cost inconsistency the packet encounters. The router will attempt to resolve the dispute.

Given the local cost is higher, the router n_i resolves the inconsistency by forwarding the packet along its default paths. Its default paths must be valid because n_i must have a less connected topology than other routers, as it has a higher path cost. If it is a failure event, n_i must have already updated its forwarding table according to the event, and its path will bypass the failed component. If it is a restoration event, n_i must have not updated its forwarding table, and its path will not use the newly restored or added component, but can still reach the destination. Therefore, same as in the matching costs case, the router selects one of its next hops, updates the packet's cost label using its local cost, and forwards the packet to the next hop. The router will also turn on the escort bit to notify the downstream routers that a path inconsistency has been encountered.

A special case of higher local cost inconsistency occurs when a packet reaches a router adjacent to a failure. The router has detected the failure but has not updated its forwarding table yet. Therefore, the router's next hop is invalid and its local cost $n_i.cost$ is infinite. In this case, a router n_i will immediately start using the alternative path pre-computed to bypass its next hop to forward and update the packet cost. The router will first try to use the alternative path that bypasses its next hop node. If such a path is unavailable, *e.g.*, the next hop is the destination, the router uses the alternative path computed by removing the link to reach the next hop. Let the enhanced cost of the alternative path be $n_i.\overline{cost'}$, and the next hop of it be n'_{i+1}. The router n_i turns on the escort bit, updates the packet's cost to be the remaining enhanced path cost of the alternative path by subtracting the next hop link cost: $pkt.\overline{cost} \leftarrow n_i.\overline{cost'} - l_{n_i \rightarrow n'_{i+1}}.\overline{cost}$. The subtraction is done separately for regular cost and noise and the subtraction of noises is modulo 2^k based as described in § 3.1.

Lower Local Cost ($n_i.cost < pkt.cost$): This inconsistency shows that a router's local cost is lower than its upstream router. Again, the network must be in a transition. As the router has a lower local cost, it must have a network topology with more components. It is no longer safe to forward along the router's default next hops, because it may include a failed component.

To resolve a lower local cost inconsistency, a router uses the packet's enhanced cost $pkt.\overline{cost}$ to look up an alternative path in its APD, because its APD is computed using smaller topologies than its current one, and a path with higher cost may be found in the APD. Suppose this lookup returns a next hop n'_{i+1}. The router n_i updates the packet's cost label using the alternative path's cost, turns on the escort bit, and forwards the packet to n'_{i+1}.

3.4.3 Packets in the Escort Mode

If an incoming packet is in the escort mode, the router will try to forward the packet along the working path chosen by the upstream router who detects the cost inconsistency. It is not enough to only consider the regular costs because they may not uniquely identify the valid path among equal cost paths. In this case, the router n_i will try to find a path whose enhanced cost matches exactly with the incoming packet's enhanced cost. To do this, the router first compares its local enhanced path cost $n_i.\overline{cost}$ with the packet's cost $pkt.\overline{cost}$. There are two outcomes:

Matching Costs ($n_i.\overline{cost} \equiv pkt.\overline{cost}$): This indicates that the router's shortest path with cost $n_i.\overline{cost}$ is consistent with the chosen working path. In this case n_i will forward the packet using the next hop associated with the enhanced path cost, and update the packet's cost label accordingly.

Non-matching Costs ($n_i.\overline{cost} \neq pkt.\overline{cost}$): In this case, the upstream router that detects a route inconsistency has chosen a working path that is different from the router's current shortest path defined over the enhanced costs. The router uses the packet's cost

k	Collision Probability
10	0.0097
16	0.00015
24	6.0×10^{-7}
32	2.3×10^{-9}

Table 1: The probability of having two equal enhanced cost paths between two nodes when there are $c = 5$ regular equal cost paths, given different noise length k.

label $pkt.\overline{cost}$ to look up an alternative path in its APD. If an alternative path is returned, it updates the packet's cost and forwards the packet to the corresponding next hop.

If there is an APD look-up failure, it indicates unexpected topology changes such as multiple independent failures or different alternative paths having the same enhanced cost. In this case, not all routers would have a working path. Any further forwarding may risk forming a loop. When this occurs, a router may either demote the packet to lower priority or discard it. Our design chooses to discard for simplicity.

3.5 Cost Collision Analysis

The link noises are introduced to distinguish equal cost paths. We assign random values to link noises to distinguish any two equal cost paths with high probability. We analyze this probability, and also discuss an alternative mechanism that deterministically generates collision-free link noises for a given network topology.

A link noise is chosen randomly within $[0, 2^k - 1]$. A path noise that is the sum of link noises modulo 2^k is also randomly distributed. If a node has c paths to the same destination with the same regular path cost, the probability that no two such paths have the same enhanced path cost is:

$$1 \cdot (1 - \frac{1}{2^k})...(1 - \frac{c-1}{2^k}) = \frac{2^k!}{2^{ck}(2^k - c)!}$$

Table 1 shows the probability of collision when $c = 5$ for various values of k. In practice, c is typically small (< 5) [1], because two backup paths usually suffice.

As can be seen, with practical values of c and k, the probability of collision is low. Our simulations use a 10-bit noise value, and we do not run into any collisions on all simulated topologies, including an inferred tier-1 topology. Therefore, we think that the probability of collision can be practically ignored if we use a 32-bit or longer noise label.

Alternatively, we have also designed an algorithm that deterministically generates a collision-free noise configuration for a given network topology. The algorithm runs in polynomial time in terms of the number of equal cost paths (see details in [26]). One caveat about this algorithm is that the collision-free noise configuration is generated for a given network topology; a future topology change may require a new noise configuration to be collision-free (although this occurs with low probability). For simplicity, we opt to use random noises.

3.6 Practical Considerations

Atomic Update: One practical issue worth mentioning is partial router updates. A topology change involving multiple links (such as a node or SRLG failure) will trigger multiple routing updates in a link-state routing protocol such as OSPF or IS-IS. If a router partially updates its forwarding tables according to a subset of the routing messages, its local cost may not match the alternative paths' costs in other routers' APDs, as an APD only includes paths that bypass a whole component (*e.g.*, a node with all its links removed). The issue does not only happen for SafeGuard: other loop-avoidance techniques such as [14] would also work incorrectly if partial updates occur.

Fortunately, there already exist several practical techniques to enable atomic router updates, as partial updates churn up routers' CPU power and are harmful for routing convergence. These techniques include OSPF and IS-IS's delay timers that batch route update processing, throttling techniques [3] that automatically adjust the delay timer according to the incoming rate of route updates, and the recent proposed LSA correlation technique [19] that identifies concurrent multiple link updates by correlating the information in different LSAs. Therefore, in the SafeGuard design, we assume that routers use atomic updates for an anticipated topology update.

Deployment: The SafeGuard design can be deployed by individual ISPs on the Internet without introducing new protocols. Routers need to upgrade to pre-compute alternative paths (§ 3.3), add the enhanced path costs in its forwarding tables (§ 3.4.1), and support the new forwarding algorithm (§ 3.4).

One possible way of deploying SafeGuard on today's hardware routers is to exploit the MPLS infrastructure. A path cost label may be embedded into an MPLS label upon a packet's entrance to an ISP's network and swapped at each hop during forwarding. We defer a complete deployment study of SafeGuard as future work.

4. PROPERTIES

We now briefly describe the forwarding properties of the SafeGuard design. We omit formal proofs due to the lack of space, and refer interested readers to our technical report [26]. When stating those properties, we do not consider congestion loss, because it is not caused by violations of forwarding consistency. We also ignore the failure detection time during which routers may forward packets to a failed link without noticing the failure, and the router initialization period during which a newly added router has not obtained any topology information.

Property 1 *Packets will follow regular shortest paths, including equal cost paths, to reach their destinations in the normal mode when the network is in steady state.*

This property holds because routers compute the next hops in their forwarding tables using only the regular link costs. The SafeGuard forwarding algorithm compares only the regular path cost in a packet with a router's local estimate for normal-mode packets. In steady state when routes are not changing, these two costs will always match and packets will reach their destinations without encountering any inconsistency.

Property 2 *If enhanced path costs are distinct, during the routing transition period in which only one network element changes its status and the network is not partitioned, a packet will be forwarded to its destination in either the normal or the escort mode.*

This property holds because when there is only one element changing its status, a router always has a working path in either its forwarding tables or its APD, dependent on whether the router has learned of the change and updated its forwarding tables. Therefore, if any router on a packet's path detects a cost inconsistency, it is able to either use its default path or a valid alternative path in its APD to forward the packet.

---

[1] This observation is based on five proprietary ISP topologies with real link costs.

Topology	# of Forwarding Table Entries	# of NotVia Entries		# of APD Entries		APD Computation Time (ms)		NotVia Computation Time (ms)	
Abilene	11	Avg	15.4	Avg	17.3	Avg	0.165	Avg	0.093
Node:11		Max	17	Max	26	Max	0.176	Max	0.112
Link:28		Min	14	Min	12	Min	0.157	Min	0.073
Sprint	315	Avg	368.8	Avg	777	Avg	79.4	Avg	49.7
Node:315		Max	449	Max	1769	Max	89.2	Max	84.2
Link:1944		Min	278	Min	534	Min	71.9	Min	36.8
Random	100	Avg	116.6	Avg	276.1	Avg	6.2	Avg	2.7
Node:100		Max	140	Max	376	Max	11.9	Max	10.6
Link:394		Min	102	Min	149	Min	5.8	Min	2.0

Table 2: Summary of the memory and computational overhead introduced by SafeGuard. For memory overhead the normal forwarding table size and the number of NotVia entries are shown for comparison. For computational overhead the NotVia computation time is shown for comparison.

Property 3 *A packet will not be trapped in a micro-loop without being discarded.*

By trapped in a micro-loop, we mean that if all routers stop updating their forwarding tables after forming a loop, a packet will not escape the loop until its TTL expires. This property holds because a packet cannot traverse a node twice without a cost inconsistency. After one inconsistency is detected, the packet is marked as in the escort mode, and it will either follow a working path to reach the destination, or be discarded by a router that detects another cost inconsistency and cannot find a cost-matching path in its APD.

5. EVALUATION

In this section, we describe the evaluation of SafeGuard. We have evaluated both the router performance and network performance of SafeGuard.

5.1 Router Performance

The SafeGuard design adds computational and memory overhead to a router. A router does an additional cost comparison and a possible APD lookup during packet forwarding time. It also needs to compute the enhanced path costs in a router's forwarding tables, pre-compute alternative paths that bypass anticipated network failures, and store the alternative paths in its APD. To quantify the overhead, we implement our design using NetFPGA [18] and the Quagga routing suite [4].

NetFPGA provides a hardware-accelerated data plane that emulates the real hardware-based forwarding engine in commodity routers. It comes with a reference implementation of an IPv4 router that leverages TCAMs (Ternary Content-Addressable Memories) built from on-chip registers. Quagga comes with a full-fledged OSPFv2 daemon (`ospfd`), which we use as the underlying routing protocol. We implement the alternative path database using TCAM, and modify the NetFPGA reference router to support our forwarding algorithm described in § 3.4. We extend `ospfd` to compute the enhanced path costs and the alternative paths needed for SafeGuard after each routing update. The total modification includes ∼800 lines of Verilog code and ∼3000 lines of C/C++ code.

To evaluate the forwarding overhead of SafeGuard, we benchmark its forwarding performance using the NetFPGA implementation. We send small packets with 64 bytes to the NetFPGA data plane using a PC machine, and measure the packet throughput and the per-packet processing time. Our experiments show that SafeGuard increases the per-packet forwarding time by 48ns (equivalent to 6 clock cycles as the development board runs at 125Mhz by default), and has a total per-packet forwarding overhead of 120ns. This would translate into 4.3Gbps throughput if per-packet processing is the bottleneck on a SafeGuard router's forwarding plane. Moreover, since the extra cycles are mostly spent at accessing the new APD table, the forwarding performance of SafeGuard can be further optimized by parallelizing the lookups in both the forwarding table and the APD.

We then evaluate the computational and memory overhead of SafeGuard. We first feed the modified `ospfd` daemon with different network topologies. To evaluate the overhead of computing shortest paths with the enhanced path costs (§ 3.4.1), we measure the time to compute all forwarding entries with the enhanced path costs, and compare it with the regular shortest path computation time. The results show that the modified shortest path computation with the enhanced costs only increases the computation time by 1%∼3% compared to a router's regular shortest path computation. As we describe in § 3.4.1, this is because the extra computations based on the enhanced link costs can be optimized by using only the links on the regular shortest paths, which typically are a small portion among all links in the network.

We also measure the time it takes to compute the alternative paths and the size of the APDs. In comparison, we also implement the algorithms to compute the backup paths for NotVia [10], a practical IP fast reroute technique that uses pre-computed backup paths to bypass temporary failures, but does not prevent micro-loops during routing convergence. For both mechanisms, we compute the alternative paths for all single link and node failures. Our experiments run on a Pentium D 2.4GHz machine with 2GB memory.

Table 2 shows the time it takes to finish computing the alternative paths, and the number of additional entries a router keeps for SafeGuard and NotVia on various topologies. As can been seen, alternative path computation in SafeGuard takes less than 100ms on the largest Sprint topology, and this time is comparable to NotVia. The number of entries in a router's APD may be 2-8 times larger than a router's intra-domain forwarding table, but is comparable to that of NotVia's, suggesting that SafeGuard's memory overhead is practically affordable. If the memory overhead becomes a practical concern, we can further reduce it by applying optimization. We omit the details for ease of exposition, but a detailed description about the optimization technique can be found in [26].

5.2 Network Performance

We use simulations to further study the network performance of SafeGuard. We have implemented SafeGuard in SSFNet [6], an event-driven simulator that has a complete OSPFv2 implementation. We use the simulator to evaluate whether SafeGuard can en-

Topology	Type	# of Nodes	# of Links
Abilene	Real	11	28
Telstra	Inferred	108	306
Exodus	Inferred	79	294
Sprint	Inferred	315	1944
Random	Random	100	394

Table 3: Summary of the topologies used in our simulations.

Parameter	Value
HelloInterval	50ms
RouterDeadInterval	250ms
SPF Delay	200ms
SPF Computation Time	($0.00247n^2$+0.978)ms
FIB/RIB Update Time	$rand([0.1, 0.11])p$ms

Table 4: Summary of the simulation settings. n is the number of routers in the network. p is the number of entries in the forwarding table.

able safe forwarding during route changes without altering the routing convergence process. To do so, we compare SafeGuard with both the vanilla IP forwarding and a state-of-the-art IP fast restoration mechanism. For each of the mechanisms, we simulate routing convergence caused by various types of topology updates, and measure packet forwarding performance during the convergence periods. Next we describe the simulation details and the results.

5.2.1 Metrics

Flow Amplifying Factor: We measure how many times a packet passes the same unidirectional link during route changes. We refer to this metric as the flow amplifying factor, because if a traffic flow of t Mb/s passes the same link for K times, then the flow's peak rate on that link would become $K \times t$ Mb/s. This metric helps answer the question whether SafeGuard prevents forwarding loops during route changes.

Packet Loss Rate: We measure the packet loss rate of the flows that are affected by the updated component. This metric shows whether SafeGuard is effective in minimizing periods of disruption during route changes.

Path Stretch: A path stretch is defined as the ratio of the cost of a path taken by a packet to the shortest path cost in the network. Path stretch shows the forwarding sub-optimality during route changes. This metric measures the quality of the alternative path SafeGuard chooses to resolve a cost inconsistency. The lower the path stretch is, the better the path.

Convergence Time: We also measure the time it takes for the network to converge after a topology change. The convergence time is measured from the change happens to the last router update finishes. This metric shows whether SafeGuard delays convergence.

5.2.2 Simulation Setup

Mechanisms: We simulate SafeGuard as described in § 3.4 with the OSPF implementation of SSFNet. We configure SafeGuard to pre-compute alternative paths for all single link and node failures. The various timers and delays of the OSPF implementation are summarized in Table 4. These parameters are set according to the values recommended by various fast convergence techniques [8, 22] and the values observed in commercial production routers [7, 15, 36]. We simulate fast convergence because SafeGuard's benefits are even more prominent during slow convergence during which micro-loops last longer, but we desire to emphasize only the benefits not replaceable by fast convergence techniques.

For comparison, we also simulate vanilla IP forwarding with OSPF and a state-of-the-art IP fast restoration mechanism, which includes a fast rerouting technique called NotVia Addresses [10] and a loop-avoidance convergence mechanism called Ordered FIB Update (oFIB) [14]. NotVia fast reroutes packets through a precomputed backup path when they encounter a failed component. It does not by itself prevents micro-loops, and thus needs to be combined with a loop-avoidance mechanism such as oFIB. oFIB prevents micro-loops during convergence by enforcing a strict order of routing updates across different routers. We simulate the "fast mode" of oFIB which uses signaling messages to impose the update order. The two mechanisms are chosen because they together can reduce the disruption after route changes to the failure detection time after single failure, and are now under standardization at IETF. SafeGuard can also reduce the disruption to the failure detection time, but without modifying the routing convergence protocol or enforcing any router update order.

Network Topologies: We simulate on real, inferred, and randomly generated topologies summarized in Table 3. The inferred topologies are from the Rocketfuel project [38], and the random topology is generated using the BRITE topology generator [2]. Real and inferred topologies contain precise or inferred link weights [27]. We use the random topology to test how SafeGuard works on asymmetric networks. The link weight in each direction is set independently, each using a random integer between 1 and 50.

Link delays of each topology are set according to the geographic proximity of their end nodes. If two routers are in different Points-of-Presence (PoPs), we infer the link delay between them from the geographical distance, and in the generated topology the nodes are randomly spread on a plane as large as the US continent. If two routers are in the same PoP, we assume the link delay is 0.1ms.

Topology updates: We simulate routing transitions for both single element update and multiple independent update events. For single element update, we test single link up/down events and node up/down events. For multiple independent updates, we test two concurrent link failures. For each type of update we run 100 experiments with randomly chosen element updates.

After each update event, we send probing packets every 5ms between each pair of nodes. We use the probing packet traces to compute various metrics such as the traffic amplifying factor and packet loss rate. The probing packets' TTLs are initialized to 128, the default TTL value of the Windows XP operating system. We do not simulate real traffic patterns because it is extremely time-consuming to simulate, and the simulations would not finish in a reasonable time, *i.e.*, a few days.

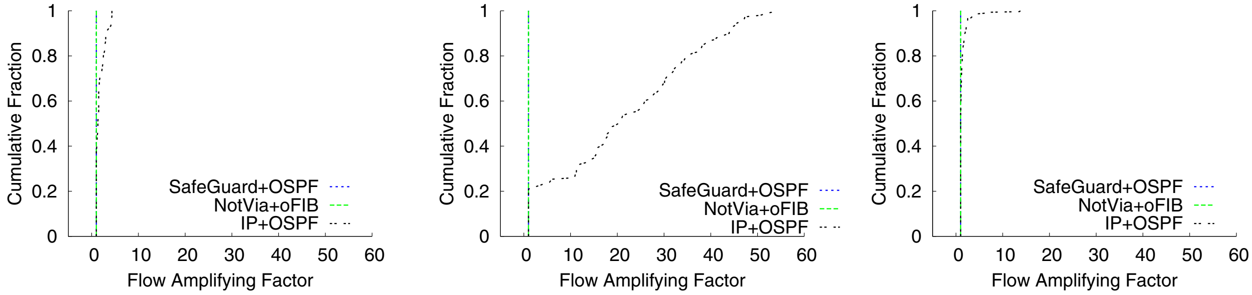
5.2.3 Avoiding Forwarding Loops

Figure 4 and 5 compare the distributions of the flow amplifying factors of vanilla IP forwarding with OSPF, NotVia with oFIB, and SafeGuard with OSPF in a real network topology (Abilene), an inferred tier-1 network topology (Sprint), and a randomly generated network topology (Random). Results from other topologies are similar and omitted. The distributions are drawn from all micro-loops we have observed in the tests. As shown in the figure, SafeGuard's flow amplifying factor is ≤ 2. This result shows that SafeGuard prevents packets from being trapped in micro-loops, as packets at most take one detour to reach their destinations.

In contrast, the vanilla IP forwarding with OSPF can have amplifying factors greater than 50. The trapped flows will be amplified

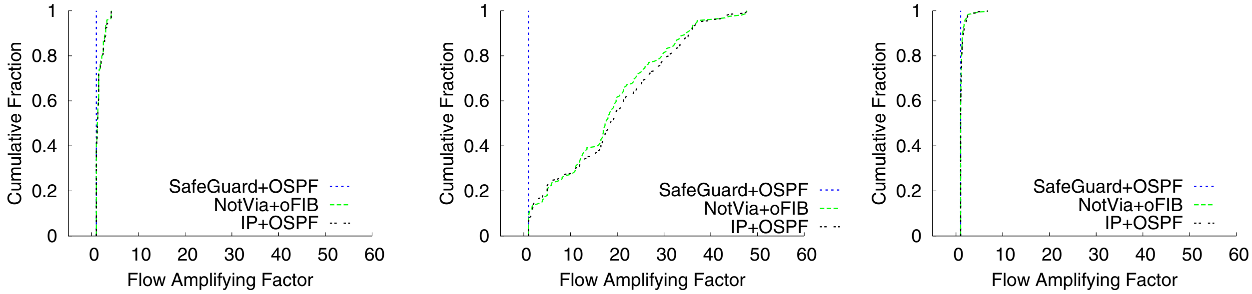
Update Type	# of Tests Containing Loops	Total # of Micro-loops	Total # of Links Involved	Loop Duration (ms)			
				Avg	Max	Min	Stddev
OSPF							
Link Failure	19	81	132	12.5	44.6	0.32	15.4
Node Failure	17	125	154	11.5	26.3	0.10	26.7
Link Up	4	7	14	11.9	40.7	0.80	21.8
Node Up	11	20	38	6.32	24.8	0.19	6.45
Two Link Failures	38	144	182	9.0	39.7	0.39	11.2
oFIB							
Two Link Failures	36	138	178	8.8	41.2	0.18	10.8

Table 5: Summary of loops during convergence in the Sprint topology. For each update type we run 100 experiments with randomly chosen topology updates.



(a) Abilene (b) Sprint (c) Random

Figure 4: The cumulative distribution of the loops' flow amplifying factor on three topologies for single link failure case. The lines of SafeGuard+OSPF and NotVia+oFIB overlap with each other at the left side of the figures, because both of them can prevent loops after single topology changes.



(a) Abilene (b) Sprint (c) Random

Figure 5: The cumulative distribution of the loops' flow amplifying factor for two link failures case.

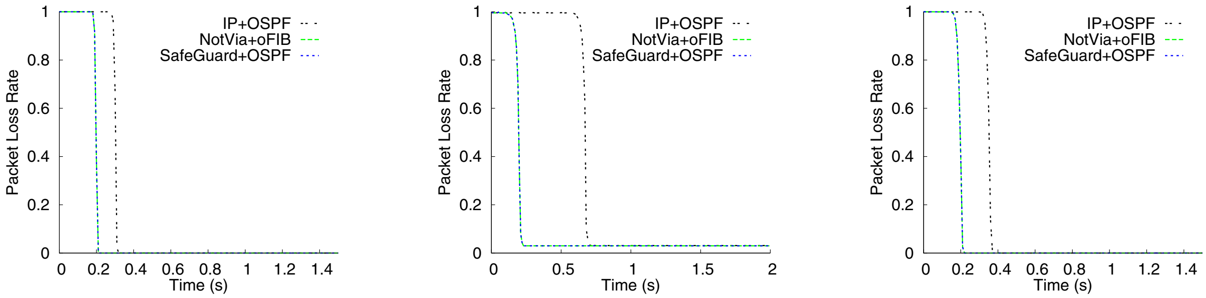
for 50 times, which is likely to congest a link and cause congestion loss. One can also note that the Sprint topology suffers from loops with much larger amplifying factors than the other two. This is because routers in Sprint are aggregated in different Points-of-Presence (PoPs), and the latencies between routers in the same PoP are small, as they are usually co-located in the same facility. Hence the forwarding loops occurred inside a PoP usually have high amplifying factors.

NotVia with oFIB also has a flow amplifying factor ≤ 2 after single link failures, which is consistent with previous studies [14]. However, when two links fail simultaneously, NotVia with oFIB has flow amplifying factors comparable with vanilla IP with OSPF, suggesting micro-loops can still occur. This is because oFIB falls back to fast convergence when multiple topology changes occur. In contrast, SafeGuard can prevent micro-loops even under two simultaneous link failures, because it discards packets in escort mode if a cost matching alternative path cannot be found in a router's APD.

Table 5 summarizes the characteristics of micro-loops observed under the Sprint topology in our simulations. As can be seen, in case of a failure, more than 15% of the simulations contain forwarding loops, and the loops can involve many links ($\sim$ 10% of the total number of links in the topology) and cause congestion on them. Although with fast convergence the loops only last for less than 50ms, given the large amplifying factors shown above they may still cause voluminous flow amplification.

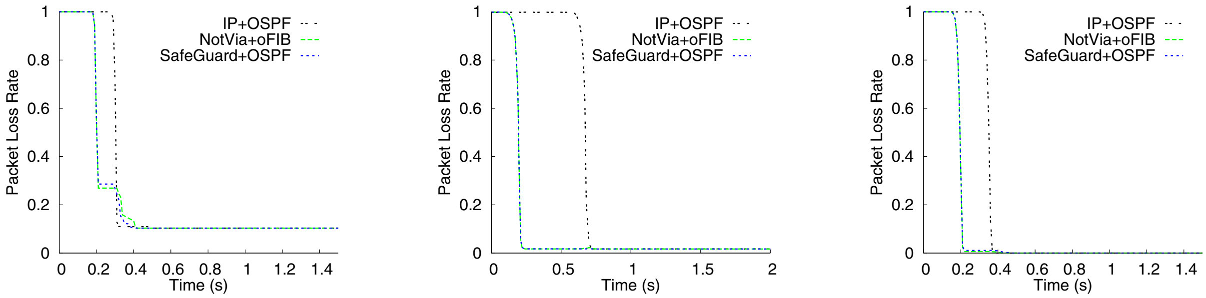
5.2.4 *Reducing Packet Loss*

Figure 6 and 7 show the average packet loss rates after a link failure and two link failures for each mechanism in three topologies. Note that the packet loss rates do not include congestion loss caused by micro-loops, because we do not simulate real traffic load. Therefore, the packet loss rates we measure are those caused by failed routes. For vanilla IP forwarding, the packet loss rate could be much higher in practice, because micro-loops would lead to con-



(a) Abilene (b) Sprint (c) Random

Figure 6: The average packet loss rate after a single link failure. X-axis is the time-line. The failure happens at time 0, and is detected after 200 $\sim$ 250ms. Y-axis is the packet loss rate for all probing flows that use the failed link. The line of SafeGuard+OSPF overlaps with that of NotVia+oFIB.



(a) Abilene (b) Sprint (c) Random

Figure 7: The average packet loss rate after two link failures. Other configurations are the same as in Figure 6.

gestion loss. We measure the packet loss rate at time t by counting how many probe packets sent during the period $[t, t + 10ms]$ are lost. We average the loss rates over all experiments for each type of update event.

Figure 6 and 7 show that SafeGuard successfully reduces packet loss rates, while vanilla IP forwarding has much higher packet loss rate. Packets may encounter failed routes until the network has converged, and the forwarding disruption times may last about 600ms. In a single failure case, after the failure is detected (after $\sim$ 200ms), SafeGuard is able to rapidly bypass failures through the alternative paths. The time is independent of the size of the network, as SafeGuard only needs the routers adjacent to the failure to detect the failure and does not need the failure to be disseminated over the network. In some of the figures, the packet loss rates do not reach zero because the network is disconnected. In the two link failure case, SafeGuard may also experience packet loss during routing convergence as routers have not pre-computed the alternative paths to bypass them.

NotVia with oFIB also reduces the packet loss rates, and achieves similar performance to SafeGuard. This is because NotVia can fast reroute packets along pre-computed alternative paths once they encounter a failure. However, because oFIB cannot prevent micro-loops when multiple components fail simultaneously, in practice NotVia with oFIB may have higher packet loss rate due to link congestion under the case of two links failure.

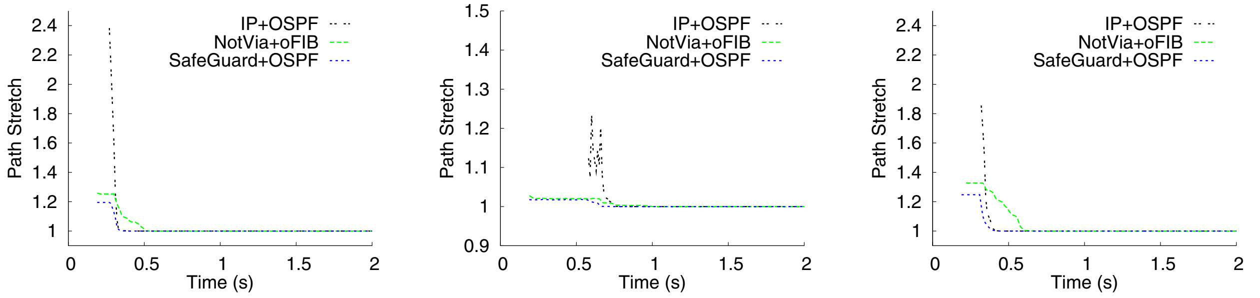
5.2.5 Path Stretch

Figure 8 shows the average path stretch during routing convergence for a single link failure case. The path stretch is averaged over all source and destination pairs whose default forwarding paths include the failed link. As can be seen, with SafeGuard the path stretch smoothly reduces to 1 during convergence, indicating that the forwarding paths gradually shift to the new shortest paths as routers update their states independently. However, under vanilla IP forwarding, one can observe path stretch surges during routing convergence because of micro-loops: some packets reach their destinations after a micro-loop is resolved but have looped for dozens of times. NotVia with oFIB can also prevent micro-loops after single topology changes. However, the path stretch takes longer time before it drops to 1, suggesting that traffic stays longer on the sub-optimal paths. This is because oFIB delays convergence to enforce the loop-free order of routing updates.

5.2.6 Convergence Time

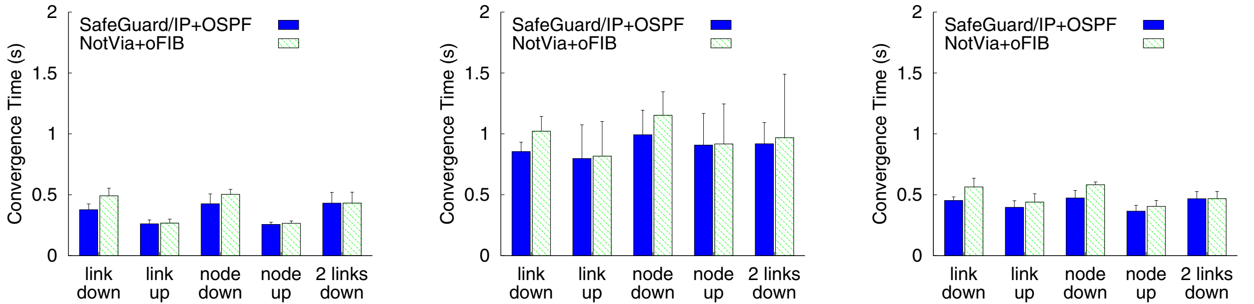
Finally, we measure the routing convergence time of each mechanism. Unlike oFIB and other existing work, a main design goal of SafeGuard is not to increase the complexity of routing convergence so that routers can independently update their routing tables without any state dependency or centralized coordination.

Figure 9 shows the convergence time of different mechanisms under the realistic OSPF settings for three topologies. Since SafeGuard does not change the convergence scheme, it converges as fast as OSPF. From the figure, one can see that even for the largest Sprint topology, the network can converge within one second, consistent with previous studies [8, 15]. This fast convergence property makes the network resilient and responsive to changes, and also reduces the time a packet follows a suboptimal path, *e.g.*, reaching a failure first before it is rerouted. NotVia with oFIB slightly increases the convergence time by up to 15%, consistent with previous studies [14]. The delay is caused by some routers waiting for



(a) Abilene (b) Sprint (c) Random

Figure 8: The average path stretch after a link failure. X-axis is the time-line. The failure happens at time 0, and is detected after 200-250ms. Y-axis is the path stretch for all probing packets that previously pass the failure.



(a) Abilene (b) Sprint (c) Random

Figure 9: The averaged convergence time after different network changes. The error bars show the standard deviations. SafeGuard achieves the same convergence time as OSPF because it does not modify convergence. NotVia+oFIB has slightly longer convergence time because routers must update their routing tables in a specific order rather than independently and in parallel.

others to complete updates before they can refresh their forwarding tables. Although NotVia with oFIB does not significantly increase the convergence time, it has altered the routing convergence process by introducing a reliable signaling protocol for routers to update routing tables in a specific order. This signaling protocol adds complexity to the convergence process, and could be error prone, *e.g.*, one slow or failed router may stall the entire routing convergence process.

6. RELATED WORK

In this section, we compare the SafeGuard design with related work. Table 6 summarizes the major differences between SafeGuard and some other solutions addressing the same problem. As we will show, SafeGuard is the only system that reduces periods of disruption to the failure detection time without changing the routing convergence process.

Researchers have proposed to redesign the routing convergence process to minimize periods of disruption [14, 17, 21, 25]. These schemes generally require routers to synchronize or to impose a strict order on their routing updates [14, 16, 17, 21]. Although they can effectively reduce disruption periods to the failure detection time as SafeGuard, these schemes introduce state dependency among routers, thereby increasing the complexity of the routing convergence process and slowing down routing convergence [12].

Convergence-free routing [25] eliminates routing convergence and uses a centralized coordinator to distribute static network maps to routers,similar to the Routing Control Platform (RCP) [11]. Packets carry a list of failed components they encountered as a router's static network map does not have failure information; packets must hit failures before they can be rerouted, and routers employ on-demand computation when they first learn of the failures to forward packets along a valid path. For non-concurrent failure or restoration events, SafeGuard and convergence-free routing are both able to reduce periods of forwarding disruption to the failure detection time. For concurrent events that happen within a routing convergence period, SafeGuard can still guarantee loop-free forwarding, but may suffer temporary packet loss until routing converges, while convergence-free routing does not. But we think the trade-off is favorable, because such concurrent events are rare, and SafeGuard has a fixed header overhead, does not require on-demand computation, and forwards packets along the shortest failure-free paths except during routing convergence periods.

Ordered FIB update (oFIB) [14] avoids micro-loops by enforcing a strict order of routing update among routers. The order can be computed based on the topology information. With oFIB, each router waits for its upstream routers to finish their updates before it can update its own, and later notifies its downstream routers after it finishes updating. In contrast, SafeGuard allows all routers to update independently, as it does not modify the convergence process.

Another loop-avoidance technique [16] performs multiple rounds of routing convergence with incremental link weight changes. In each round, independent router updates do not cause micro-loops, because the link cost changes are specifically calculated to prevent loops. This technique is suitable for planned failures because multiple convergence rounds must finish before a component can be removed. In contrast, SafeGuard can minimize forwarding disruptions for dynamic unplanned failures.

There is also much work in enabling routers to rapidly reroute packets using backup paths after failure detection, including NotVia

Mechanism	Fast Failure Recovery	Preventing Micro-loops	Does not Change Convergence	Does not Delay Convergence
Convergence-free Routing	√	√	×	×
Consensus Routing	×	√	×	×
Ordered FIB Update	×	√	×	×
Fast Rerouting (NotVia, FIR, MRC)	√	×	√	√
SafeGuard	√	√	√	√

Table 6: Summary of the major differences between SafeGuard and several existing mechanisms designed to reduce disruptions upon topology changes. Four critical aspects are listed, namely fast failure recovery (the ability to redirect traffic upon encountering a failure), preventing micro-loops, whether the convergence scheme is changed, and whether the convergence is delayed. SafeGuard is the only system that achieves both fast failure recovery and loop-free convergence without modifying or delaying convergence.

Addresses, Failure Insensitive Routing (FIR), Multiple Router Configurations (MRC), MPLS Fast Rerouting, and R-BGP [23, 24, 31, 32, 37]. These proposals provide fast failure recovery, but they do not prevent micro-loops during routing convergence. As a result, those mechanisms can only prevent packet losses when the failure is transient and the routing updates are suppressed throughout the entire failure duration.

NotVia Addresses [37] is an IETF proposal to fast reroute packets upon encountering a failure. It requires routers to be assigned with special protection addresses called the NotVia addresses. When a router detects its next hop is unreachable due to a failure, it will tunnel the packets to the NotVia address of its next hop or next next hop (if a node failure occurs). Similar to SafeGuard other routers pre-compute protection paths to a NotVia address by removing the link or node protected by the address. NotVia enables fast rerouting when packets encounter a failure, but it does not prevent micro-loops during convergence. Packets can still be trapped in a loop that is not adjacent to the failed component. In contrast, SafeGuard can eliminate any micro-loop regardless of its location.

Failure Insensitive Routing (FIR) [31] achieves fast rerouting by using interface-specific routing. An FIR-enabled router can distinguish a rerouted packet from a normal packet by observing its abnormal incoming interface, and forward the packet to a backup next hop instead of a normal one. Similar to NotVia Addresses, FIR has no mechanism to avoid micro-loops during convergence, and it is unknown how interface-specific routing would affect the forwarding during convergence.

Exact Hop Count [35] is a proposal to prevent micro-loops in bridge networks by strictly checking the hop count in each packet's header. Hop count can be used to detect path inconsistencies, but unlike path cost, the hop count difference between two paths does not tell which path is valid. This is because practical routing protocols such as OSPF and IS-IS use fine-grained cost metrics to compute paths: a forwarding path computed with a failed component may have either a higher or lower hop count than a working path. In contrast, such a path will always have a lower (or equal) cost than a working path. Furthermore, exact hop count forwarding is incompatible with equal cost multiple path forwarding, as equal cost paths may have different hop counts.

In [41] the authors propose to detect forwarding loops through interface-specific routing. Unlike SafeGuard, this mechanism does not guarantee the detection of forwarding loops in asymmetric networks or during concurrent topology change events. Anomaly-Cognizant Forwarding [13] is a recent proposal that aims to detect and repair forwarding anomalies caused by BGP routing convergence. An ACF packet carries the AS path it has visited. SafeGuard focuses on intra-domain routing, and uses the remaining path cost as a safeguard to detect path inconsistency. Carrying cost is more efficient than carrying path as it does not require a variable-length header, and is more effective than interface-specific routing as it can detect loops in any circumstance and help routers to select the valid alternative paths.

Multi-path routing is another approach to improve routing availability. Work in this area includes routing deflection [40], path splicing [30], and MIRO [39]. Routers or end systems can choose a different path if the default path does not work. SafeGuard aims to enable routers to rapidly detect forwarding anomalies and repair them during routing transitions. It works in both single- and multi-path routing systems.

7. CONCLUSION

An important networking task is to improve network availability to better support real-time and mission critical applications. In this paper, we present the design and evaluation of SafeGuard, an intra-domain routing system that can effectively reduce packet loss and forwarding loops during network changes without increasing the complexity of routing convergence. In the SafeGuard design, a packet carries the remaining path cost to its destination. Routers compare the packet cost with their locally computed costs to detect inconsistent paths and select a working one among pre-computed alternatives. Our NetFPGA implementation of SafeGuard shows that SafeGuard is suitable for high-speed hardware implementation and has low memory and computation overhead. Simulation results show that SafeGuard reduces periods of disruption to the failure detection time during anticipated network changes and greatly reduces packet loss even for non-anticipated changes.

Acknowledgements

This work was funded by NSF Awards CNS-0627166 and CNS-0925472. We thank Landon Cox, Srihari Nelakuditi, and the anonymous reviewers for their helpful feedback and suggestions.

References

[1] Abilene Observatory. `http://abilene.internet2.edu/observatory`.
[2] BRITE Topology Generator. `http://www.cs.bu.edu/brite`.
[3] OSPF Shortest Path First Throttling. `http://cisco.com/en/US/docs/ios/12_2s/feature/guide/fs_spftrl.html`.
[4] Quagga Routing Suite. `http://www.quagga.net`.
[5] Reducing Link Failure Detection Time with BFD. `http://www.networkworld.com/community/node/23380`.
[6] Scalable Simulation Framework. `http://www.ssfnet.org`.

[7] SPF Delay Timer. `http://www.juniper.net/techpubs/software/junos/junos74/swconfig74-routing/html/isis-summary53.html#1036104`.

[8] C. Alaettinoglu, V. Jacobson, and H. Yu. Towards Milli-Second IGP Convergence. Internet draft, draft-alaettinoglu-isis-convergence-00.txt, Nov 2000.

[9] C. Boutremans, G. Iannaccone, and C. Diot. Impact of link failures on VoIP performance. In *NOSSDAV*, 2002.

[10] S. Bryant, M. Shand, and S. Previdi. IP Fast Reroute Using Notvia Addresses. Internet draft, draft-ietf-rtgwg-ipfrr-notvia-addresses-00.txt, Dec 2006.

[11] M. Caesar, D. Caldwell, N. Feamster, J. Rexford, A. Shaikh, and J. Van der Merwe. Design and implementation of a routing control platform. In *NSDI'05: Proceedings of the 2nd conference on Symposium on Networked Systems Design & Implementation*, pages 15–28, Berkeley, CA, USA, 2005. USENIX Association.

[12] B.-G. Chun, S. Ratnasamy, and E. Kohler. Netcomplex: a complexity metric for networked system designs. In *NSDI'08: Proceedings of the 5th USENIX Symposium on Networked Systems Design and Implementation*, pages 393–406, Berkeley, CA, USA, 2008. USENIX Association.

[13] A. Ermolinskiy and S. Shenker. Reducing Transient Disconnectivity using Anomaly-Cognizant Forwarding. In *ACM SIGCOMM HotNets VII*, 2008.

[14] P. Francois and O. Bonaventure. Avoiding transient loops during the convergence of link-state routing protocols. *IEEE/ACM Transactions on Networking*, 15(6):1280–1932, Dec 2007.

[15] P. Francois, C. Filsfils, J. Evans, and O. Bonaventure. Achieving sub-second IGP convergence in large IP networks. *SIGCOMM Comput. Commun. Rev.*, 35(3):35–44, 2005.

[16] P. François, M. Shand, and O. Bonaventure. Disruption-free topology reconfiguration in OSPF Networks. In *IEEE INFOCOM*, Anchorage, USA, May 2007.

[17] J. J. Garcia-Luna-Aceves. Loop-free routing using diffusing computations. *IEEE/ACM Trans. Netw.*, 1(1):130–141, 1993.

[18] G. Gibb, J. Lockwood, J. Naous, P. Hartke, and N. McKeown. NetFPGA–An Open Platform for Teaching How to Build Gigabit-Rate Network Switches and Routers. *Education, IEEE Transactions on*, 51(3):364–369, Aug 2008.

[19] M. Goyal, G. Choudhury, A. Shaikh, K. Trivedi, and H. Hosseini. LSA correlation to schedule routing table calculations. Internet draft, draft-goyal-ospf-lsacorr-00.txt, Oct 2008.

[20] G. Iannaccone, C. nee Chuah, R. Mortier, S. Bhattacharyya, and C. Diot. Analysis of link failures in an IP backbone. In *IMW*, 2002.

[21] J. P. John, E. Katz-Bassett, A. Krishnamurthy, T. Anderson, and A. Venkataramani. Consensus routing: the internet as a distributed system. In *NSDI'08: Proceedings of the 5th USENIX Symposium on Networked Systems Design and Implementation*, pages 351–364, 2008.

[22] D. Katz and D. Ward. Bidirectional Forwarding Detection. Internet draft, draft-ietf-bfd-base-07.txt, Jan 2008.

[23] N. Kushman, S. Kandula, D. Katabi, and B. M. Maggs. R-BGP: Staying connected in a connected world. In *NSDI*, 2007.

[24] A. Kvalbein, A. F. Hansen, T. Cicic, S. Gjessing, and O. Lysne. Fast IP Network Recovery using Multiple Routing Configurations. In *INFOCOM*, pages 23–29, 2006.

[25] K. Lakshminarayanan, M. Caesar, M. Rangan, T. Anderson, S. Shenker, and I. Stoica. Achieving convergence-free routing using failure-carrying packets. In *SIGCOMM*, pages 241–252, 2007.

[26] A. Li, X. Yang, and D. Wetherall. SafeGuard: Responsive Routing with Consistent Forwarding. Technical Report DUKE-CS-TR-2008-04, Duke, 2008.

[27] R. Mahajan, N. T. Spring, D. Wetherall, and T. E. Anderson. Inferring link weights using end-to-end measurements. In *Internet Measurement Workshop*, pages 231–236, 2002.

[28] A. Markopoulou, G. Iannaccone, S. Bhattacharyya, C.-N. Chuah, and C. Diot. Characterization of Failures in an IP Backbone Network. In *INFOCOM*, 2004.

[29] A. P. Markopoulou, F. A. Tobagi, and M. J. Karam. Assessment of VoIP Quality over Internet Backbones. In *INFOCOM*, 2002.

[30] M. Motiwala, N. Feamster, and S. Vempala. Path Splicing: Reliable Connectivity with Rapid Recovery. In *ACM SIGCOMM HotNets VI*, 2007.

[31] S. Nelakuditi, S. Lee, Y. Yu, Z.-L. Zhang, and C.-N. Chuah. Fast local rerouting for handling transient link failures. *IEEE/ACM Trans. Netw.*, 15(2):359–372, 2007.

[32] P. Pan, G. Swallow, and A. Atlas. Fast Reroute Extensions to RSVP-TE for LSP Tunnels. RFC4090, May 2005.

[33] B. Rajagopalan, J. Luciani, and D. Awduche. IP over Optical Networks: A Framework. RFC3717, Mar 2004.

[34] E. Rosen, A. Viswanathan, and R. Callon. Multiprotocol label switching architecture. RFC3031, Jan 2001.

[35] M. Seaman. Exact hop count. 802.1aq draft, aq-seaman-exact-hop-count-1206-01.pdf, Dec. 2006.

[36] A. Shaikh and A. G. Greenberg. Experience in black-box ospf measurement. In *Internet Measurement Workshop*, pages 113–125, 2001.

[37] M. Shand and S. Bryant. IP Fast Reroute Framework. Internet draft, draft-ietf-rtgwg-ipfrr-framework-08.txt, Feb. 2008.

[38] N. T. Spring, R. Mahajan, D. Wetherall, and T. E. Anderson. Measuring ISP topologies with rocketfuel. *IEEE/ACM Trans. Netw.*, 12(1):2–16, 2004.

[39] W. Xu and J. Rexford. Miro: multi-path interdomain routing. In *SIGCOMM '06: Proceedings of the 2006 conference on Applications, technologies, architectures, and protocols for computer communications*, pages 171–182, New York, NY, USA, 2006. ACM.

[40] X. Yang and D. Wetherall. Source selectable path diversity via routing deflections. In *SIGCOMM*, pages 159–170, 2006.

[41] Z. Zhong, R. Keralapura, S. Nelakuditi, Y. Yu, J. Wang, C.-N. Chuah, and S. Lee. Avoiding transient loops through interface-specific forwarding. In *IWQoS*, pages 219–232, 2005.