Contra: A Programmable System for Performance-aware Routing

In this paper, we describe Contra, a general and programmable system for performance-aware routing. Network operators configure Contra by describing the network topology as well as a high-level policy that defines routing constraints and performance objectives. Contra then generates P4 programs for switches in the network, which execute in a fully distributed fashion. Collectively, they implement a specialized version of a distance-vector protocol that forwards traffic based on routing constraints and optimizes for the user-defined performance objectives. This protocol operates by generating periodic probes that traverse policy-compliant paths and collect user-defined performance metrics. Switches analyze the incoming probes and rank paths in real time, storing the current best next hop to reach any given destination. Since the programs run in the data plane, switches can react to performance changes quickly. Overall, Contra is designed to achieve the following objectives:

- General – operates over a wide range of policies
- Reusable – works correctly for any topology
- Distributed – does not require central coordination
- Responsive – adapts to changing metrics quickly
- Implementable – on today’s programmable data planes
- Policy-compliant – packets only use allowed paths
- Loop-free – mitigates persistent/transient loops
- Optimal – converges to best paths under stable metrics
- Stable – mitigates oscillation under changing metrics
- Efficient – avoids undue traffic and switch overhead
- Ordered – limits out-of-order packet delivery

To achieve all of these objectives, we need to address several challenges. First, to operate over arbitrary topologies, Contra requires new techniques to search the set of possible paths for optimal routes. State-of-the-art solutions, such as Conga [10] and Hula [26], assume a tree-based data center topology, which makes exploring possible paths, avoiding forwarding loops, and finding optimal routes straightforward. Second, link and path metrics can change constantly, leading to additional challenges for distance-vector protocols. In such situations, switches may have unsynchronized views of the network in transient states, and they may make forwarding decisions based on these inconsistent views, which can result in forwarding loops and/or forwarding paths that violate the routing policy. Third, a naïve solution that constantly changes routes can cause transient or even persistent chaos. We draw inspirations from wireless network routing [5][2][34] and design mechanisms that
leverage programmable data planes to address this. Finally, to mitigate out-of-order packet delivery, we develop policy-aware flowlet switching [38] to forward flowlets while ensuring policy compliance.

Summary. We make several contributions in the design of Contra, and Figure 1 summarizes the key ideas.

- We define a new programming abstraction that views policies as path-ranking functions, and generalizes existing languages by allowing operators to specify path constraints and dynamic metrics simultaneously.
- We design a new configurable, performance-aware, distance-vector routing protocol.
- We develop compilation algorithms that generate per-device P4 programs that implement a particular configuration of the protocol based on user policy.
- We have built a system prototype, and conducted thorough experiments to demonstrate that Contra is competitive with state-of-the-art systems that are customized for a specific topology and routing policy.

Non-goals. There has been abundant recent research on efficient load-balancing strategies, especially in data centers. The goal of this work is not to outperform such strategies in the contexts for which they have been manually optimized. Rather, our goal is to facilitate the deployment of such techniques on a much broader set of networks and with a broader collection of optimization criteria, and to do so without asking network operators to take the time, or acquire the expertise necessary, to write “assembly-level” P4 programs.

2 Policy language

Contra has a high-level language that can express a wide range of sophisticated policies, which are functions that rank network paths. The goal of the Contra compiler is to ensure that switches always use the best policy-compliant paths. The language has two main components: a) matching on paths using regular expressions, and b) computing path metrics. As a concrete example, consider the following policy:

\[
\text{minimize}( \text{if } A \cdot * \text{ then path.util } \text{ else path.lat })
\]

Figure 1: Key ideas in Contra.

It first classifies paths using a regular expression \((A \cdot *)\), and then based on the classification, it defines the rank to be either path utilization or latency. Each node will separately choose its best paths according to this function. So node A will always choose the least utilized path, while all other nodes will select the path with the lowest latency.

The Contra language can also capture static policies in existing systems that are not related to performance. For instance, FatTire [35] uses regular expressions to classify legal and illegal paths (though it says nothing about the performance of such paths). To route packets through a waypoint \(W\), a FatTire policy would be \((.* W .*)\), which allows any path through \(W\) but no other paths. Contra can represent this by mapping all legal paths to 0 and illegal paths to \(\infty\):

\[
\text{minimize}( \text{if }.* W .* \text{ then } 0 \text{ else } \infty )
\]

This policy will ensure that every node always selects a path through \(W\) if one exists in the network, and drops traffic otherwise; no path is preferred to a path with rank \(\infty\).

As another example, Propane [13] allows users to write policies about failover preferences. A Propane policy \((A \ B \ D) \Rightarrow (A \ C \ D)\) indicates a preference for sending traffic through path \(A \ B \ D\) and only using \(A \ C \ D\) if the first path is not available (e.g., a link has failed). In Contra, we can achieve the same effect by ranking paths statically as below:

\[
\text{minimize}( \text{if } A \ B \ D \text{ then } 0 \text{ else if } A \ C \ D \text{ then } 1 \text{ else } \infty )
\]

In Contra, it is also possible to rank paths based on multiple metrics. For example, suppose we prefer that \(A\) reaches \(D\) via \(B\) instead of via \(C\), and we also prefer shorter, less utilized paths. This can be achieved by lexicographically ranking paths, e.g., prefer paths through \(B\) first, then shortest paths, and finally, least utilized paths.

\[
\text{minimize}( \text{if } A \cdot B \cdot D \text{ then } (0, \text{path.len}, \text{path.util})
\text{ else if } A \cdot C \cdot D \text{ then } (1, \text{path.len}, \text{path.util})
\text{ else } \infty )
\]
The key novelty of the language is that it can capture many of Propane’s preferences based on current network conditions. Advanced policy analysis. Contra requires policies to be isotonic (switches have consistent preferences) and monotonic (metrics do not improve for longer paths), so that switches can converge to best paths. If a policy is non-isotonic (e.g., P9 in Figure 3), then the Contra compiler will decompose it into multiple isotonic subpolicies that can be processed separately. Due to space limitation, we refer interested readers to the appendix (A) for more detail.

Limitations. Currently, Contra does not support traffic classification, but extending the language with header predicates as in prior work [17][12] should not present any significant intellectual challenge. A more notable limitation involves policies that prioritize one traffic class over another. For instance, B4 [22] prioritizes small, latency-sensitive user requests over large, latency-insensitive bulk transfers. Currently, Contra ranks paths and selects the best path for each flowlet, but does not compare different types of traffic in order to prefer one over the other. We leave integration of such policies into our framework to future work.

3 Selected Challenges

The design of Contra needs to address three key challenges. To illustrate these challenges, we first describe a strawman solution that only works on a specific topology (data center networks) and policy (use least utilized paths).

A simple policy on a simple topology. Consider the simple leaf-spine topology shown in Figure 4(a), where switch S wants to send traffic to switch D using the least-utilized path:

\[
\text{minimize} \left( \begin{array}{l}
\text{if } S \rightarrow D \text{ then } \text{path.util} \\
\text{else } \infty
\end{array} \right)
\]

One strawman solution is to use a distance-vector protocol, where each switch propagates link metrics (i.e., utilization) to its neighbors via periodic probes, and builds up a local forwarding table of “next hops” to reach other switches.

More concretely, at time 1, D sends two probes to A and B carrying utilizations \(u(A-D)=0.1\) and \(u(B-D)=0.2\), respectively. Upon receiving a probe, a spine switch updates its metric, and then disseminates the probe to its downstream neighbors. The updated probe metric is the maximum of a) the original probe metric, and b) the utilization of the in-bound link from the switch’s neighbor, so the probe always carries the utilization of the bottleneck link on its traversed path. For instance, when B receives the probe from D, it updates the utilization to 0.3, which is the maximum of a) the original probe metric, \(u(B-D)=0.2\), and b) the utilization of the in-bound link, \(u(B-S)=0.3\); when A receives the probe from D, it updates the utilization in the probe to be 0.4, which is the maximum of \(u(A-D)=0.1\) and \(u(S-A)=0.4\). At time 2, both A and B then disseminate the updated probes to S. Now, S has received probes on both paths S-A-D (\(u=0.4\)) and S-B-D (\(u=0.3\)), and it chooses B as the best next hop to reach D due to its lower utilization. Changes in link metrics are then captured and propagated by the next round of probes.

In fact, this solution describes Hula [26], a state-of-the-art solution for utilization-aware routing in data centers.

Challenge #1: Arbitrary topologies. On a tree topology, simple mechanisms (e.g., defining a set of “downstream” and “upstream” neighbors for each switch) suffice to explore paths and prevent forwarding loops [26], but on a non-hierarchical topology, it is insufficient.

Consider the sequence of events in Figures 4(b)-(e), where S prefers the least-utilized path to D. Suppose that at time 1, D sends out probes to A and S, and A propagates D’s probe to B and S, with the utilizations shown in Figure 4(b); now, both B and S prefer to reach D via A. At time 2, S propagates A’s probe to B about S-A-D (\(u=0.1\)), so B changes its preference to go through S; B then propagates S’s probe to A (\(u=0.2\)), but it gets delivered only at time 4. At time 3, u(A-
D) increases to 0.5, which is discovered by a new periodic probe from D to A and S. From A’s perspective, the best path to reach D is still A-D, except that now the utilization is 0.5 instead. At time 4, when B’s (old) probe to A arrives with \( u=0.2 \), A mistakenly thinks that it should instead reach D via B, not knowing that A is itself on B’s best path to reach D. As a result, a forwarding loop S-A-B-S would form, and it will persist as long as the link utilizations remain stable.

In fact, it is well-known that distance-vector protocols can result in forwarding loops on an arbitrary topology. One might consider using a path-vector protocol instead, where probes record the paths they have traversed, so that switches never use paths with loops. However, since probes will be sent out frequently, carrying path information would result in much higher traffic overhead, especially in large networks.

**Solution.** Our solution is inspired by DSDV [4] and a more recent proposal Babel [5], which were originally developed for wireless mesh networks. At a high level, switches assign version numbers to probes, so that they can identify and avoid using outdated probes. However, even with version numbers, non-monotonic policies can still create loops within a given probe period. So the Contra compiler additionally performs monotonicity checks on user policies. Finally, when Contra is integrated with flowlet switching, which pins traffic to particular paths to avoid out-of-order packet delivery, loops might still form when flowlet entries expire at different times. To address this, Contra lazily detects and breaks loops by flushing flowlet switching entries.

**Challenge #2: Constrained routing.** Supporting rich routing policies that admit way-pointing, service-chaining, or other path constraints complicates the protocol implementation dramatically. Consider the scenario in Figure 4(f), where the policy is not only to prefer least-utilized paths, but also that traffic should never first go through B and then A due to security concerns:

\[
\text{minimize}(if \rightarrow BA \ast \text{then } \infty \text{ else path.util})
\]

Under this policy, S can only send traffic to D via a) S-D, b) S-A-D, or c) S-B-D; initially, S prefers c) \( (u=0.1) \). Now consider the sequence of events shown in Figures 4(f)-(h). Suppose that at time 1, the traffic from S arrives at B. At time 2, the \( u(B-D) \) increases to 0.7, and \( u(S-D) \) decreases to 0.1, so B updates its best next hop (to reach D) to be S, preferring the path B-S-D. At time 3, B sends the traffic back to S, which already forms a loop. But things can get even worse: at time 3, \( u(S-D) \) increases to 0.3, so S changes its preference to be S-A-D \( (u=0.2) \). So the traffic has been forwarded along a path S-B-S-A-D, which not only contains a loop but also violates the intended policy.

**Solution.** To address this problem, Contra tags both probes and packets with policy states, which track the paths being traversed and whether these paths have satisfied the intended policy. When a switch processes a packet, it relies on the embedded tag to determine a local forwarding action that is compliant with the global, network-wide policy. When a switch changes its path preference locally, it applies a new tag on packets so that downstream switches know about the change and process the packets based on the latest preference—somewhat akin to a distributed version of consistent updates [36]. By tagging packets at the source, different switches can then freely make independent forwarding decisions that optimize for the policy.

**Challenge #3: Custom performance metrics.** Sophisticated policies may also require a more advanced probe propagation mechanism. In the mechanism we have discussed so far, a switch only propagates the probe with the best metric to its neighbors; this is due to an implicit assumption that probes arriving at a switch with worse metrics can be safely discarded, because the metrics will only degrade or remain the same as probes are propagated further along a path. However, it is only safe to discard probes when a user’s policy is isotonic [20], meaning that downstream nodes respect the preference of the upstream node. Unfortunately, some useful policies are not isotonic [23].

**Solution.** To address this problem, Contra first performs a static program analysis to check if a policy is isotonic. If not, it attempts to decompose a non-isotonic policy into multiple
isotonic subpolicies. These different isotonic subpolicies can then be propagated separately in different probes and only recombined and evaluated later at the switch to make the final forwarding decision. To avoid sending a large number of probes, Contra uses a data structure called a product graph to minimize the number of probes while ensuring correctness.

4 Compilation: Stable metrics

The goal of the compiler is to generate a particular configuration of the Contra protocol that efficiently implements the desired policy in the data plane. We describe compilation in two phases. First, in this section, we describe an algorithm that operates as if link metrics do not change, so probes only need to be propagated once. The next section explains how this algorithm is extended to handle changing metrics.

Challenge. One key challenge during compilation involves policies with conditional regular expression matches, such as (if \( r \) then \( m_1 \) else \( m_2 \)), because nodes may rank paths differently based on the branch of the conditional they use. In fact, regular expressions are one source of non-isotonicity: if every node selects the best next hop according to its own preferences alone, other nodes might wind up with suboptimal routes. For example, consider the following policy when applied to the topology in Figure 5:

\[
\text{minimize( if (A B D) then 0 else path.util)}
\]

In this example, A prefers path ABD over anything else, but B prefers the least utilized path, which is currently BCD. The correct behavior in this scenario would be for B to carry A's traffic along path ABD while simultaneously sending its own traffic along path BCD.

However, a naïve (and erroneous) implementation may disseminate probes along the paths DB and DBC[1] and ask B to decide which path is best. In this case, B would use the probe from DCB and discard the one from DB. However, if the latter probe is discarded, A will not receive information about its preferred route! To avoid this, another naïve solution would be to propagate probes along all possible paths in the network to avoid missing good paths. For instance, B might send every probe it receives to A. However, this would lead to far too many probes, as the number of paths in a graph may be exponential in the number of nodes.

1Recall that probes travel in the opposite direction to actual traffic.

Solution. Instead, for a conditional (if \( r \) then \( m_1 \) else \( m_2 \)), if one could determine the path with minimal metric \( m_1 \) that matches \( r \) using one probe, and separately determine the path with minimal metric \( m_2 \) that does not match \( r \) using another probe, then nodes could delay choosing their best path until both probes have been received and only then combine the information to make a decision. This is one concrete instance where Contra needs to decompose the non-isotonic policy (due to regular expressions) into multiple isotonic subpolicies. Contra achieves this by creating a compact data structure that combines all regular expressions appearing in a policy with the network topology, and by sending separate probes for different regular expression matches.

4.1 Finding policy-compliant paths

Inspired by Merlin [39] and Propane [13], Contra constructs a data structure called a product graph (PG), which compactly represents all paths allowed by the policy.

Policy automata. A policy’s regular expressions define the different ways the shape of a path can affect its ranking. To process a policy, we first convert all such regular expressions into finite automata. Because probes disseminate information starting from the destination, but policies describe the direction of traffic that flows in the opposite direction, we actually construct an automaton for the reverse of each regular expression. Each automaton is a tuple (\( \Sigma, Q_i, F_i, q_0, \sigma_i \)). \( \Sigma \) is the alphabet, where each character represents a switch ID in the network. \( Q_i \) is the set of states in automaton \( i \). The initial state is \( q_0 \). \( F_i \) is the set of accepting / final states. \( \sigma_i : Q_i \times \Sigma \rightarrow Q_i \) is the transition function.

Consider the example policy shown in Figure 6(b), which a) allows A to send traffic to D via the path A-B-D, b) allows B to send traffic to D via any path with the least utilization, and c) disallows all other paths. The Contra compiler would generate the automata shown in Figure 6(c).

Network topology. The construction of the automata has not considered the actual network topology, so not all automaton transitions are legitimate. For instance, although the automaton for D, A-B could in principle accept a sequence of transitions D-A-B, this sequence would never happen in the network shown in Figure 6(a), simply because D is not directly connected to A. Therefore, our compiler merges the topology with the automata and prunes invalid transitions.

Product graph (PG). If there are \( k \) automata (one for each regular expression used in the policy), then each state in the PG would have \( k + 1 \) fields, \((X, s_1, \ldots, s_k)\), where the first field \( X \) is a topology location, and \( s_i \) is a state in the \( i \)-th automaton; there is a directed edge from \((X, s_1, \ldots, s_k)\) to \((X', s'_1, \ldots, s'_k)\), if a) \( X - X' \) is a valid link on the topology, and b) for each automaton \( i \), we have \( \sigma_i(s_i, X') = s'_i \).

Concretely, in the PG in Figure 6(d), every edge represents both valid transitions on the two policy automata and a valid forwarding action on the topology. Notice, for in-
stance, no edges exist from any \((D, *, *)\) state to \((A, *, *)\) state, because such edges have been eliminated due to topology constraints. As an example, there is a transition between node \(D0\) and \(B0\) in the PG because a) the topology connects \(D\) and \(B\), and b) applying \(B\) to each automaton from state 1 leads to state 2. Note that we use the symbol ‘−’ to denote the special “garbage” state—the state from which there is no valid transition in an automaton.

**Virtual nodes.** To distinguish PG nodes from the topology locations, we call the former ‘virtual nodes’ and the latter “physical nodes”. A physical node \(X\) may have multiple virtual nodes, because probes could arrive at \(X\) via different paths, and reach different automaton states as a result. For instance, the physical node \(B\) has two virtual nodes \((B0, -, 2)\) and \((B1, 2, 2)\): we have labeled their location fields as \(B0\), \(B1\) to capture this, and we call them *tags*. At a high level, having multiple virtual nodes in the PG means that probes must be duplicated in order to find the best path for each path constraint. In the example, node \(B\) will receive two probes: one for \(B0\) representing a path on the way to matching regex \(ABD\), and one for \(B1\) representing a path on the way to matching regex \(B \cdot D\).

**Probe sending states.** If a physical node \(X\) is a valid destination allowed by the policy (i.e., not always ∞), then exactly one of its virtual nodes is a *probe sending* state. This state has the form \((X0, σ0(q00, X), \ldots, σ_k(q0k, X))\); all probes that originate from \(X\) initially carry this state. This is because, when probes start at the originating node, they can be considered to have already traversed the first hop “\(X\)” from the initial automata states \(q0\).

**Policy-compliance.** Any path through the PG from any state to a probe sending state is a valid, policy-compliant path that is allowed by the policy. In addition, all policy-compliant physical paths also exist in the PG.

### 4.2 Packet forwarding

Before diving into the operation of the protocol itself, we first describe the structure of the forwarding (FwdT) tables on each switch. The compiler does not generate the actual forwarding entries for the tables—these are populated at runtime by the protocol logic based on the link metrics, which is described in the following subsection.

An entry in the forwarding table has several fields, in the form of \([\text{dst}^+, \text{tag}^+, \text{pid}^+, \text{mv}, \text{ntag}, \text{nhop}]\), where the fields with stars are used as keys for table lookups. Each row of the table indicates where the given switch will send packets destined for router \(\text{dst}\) when those packets are tagged by PG node tag \(\text{tag}\) and probe number \(\text{pid}\). The sender of packets will set the initial tag and the probe number associated with the best path it has found. At each intermediate hop, when a packet with a given \(\text{dst}\), \(\text{tag}\), and \(\text{pid}\) matches an entry in FwdT, the switch will look up the next tag (ntag) to write into the packet to replace the current tag, and it will look up the next hop (nhop) to forward the packet to. The metrics vector (mv) is not used during packet forwarding, but is used when table entries are populated (following subsection). A property of the forwarding table is that any tag-ntag pair found in a row of a table should correspond to an edge in the product graph, and when a particular ntag is written into a packet it is then forwarded out the nhop port that leads to a topology node corresponding to that ntag. This process implies that forwarding will always follow edges in the product graph—in other words, forwarding is guaranteed to be policy compliant so long as ntag and nhop are written consistently.

As an example, consider the FwdT table for switch B: the policy allows B to reach D either through a) \(B-D\), satisfying (part of) the regular expression \(ABD\), or through b) the best of \(B-D, B-C-D,\) and \(B-A-C-D\), satisfying the regular expression \(B \cdot D\). The former corresponds to the virtual node \(B0\) in the PG, and the latter is implemented by a combination of both \(B0\) and \(B1\). Hence, the reader may observe that it is
possible for nodes of the product graph to contribute to the implementation of more than one regular expression in the policy—this sharing improves algorithm performance as a single probe can contribute to uncovering information useful in more than one place in the policy.

Ignoring for now how the forwarding entries were populated, consider the first entry in B’s table in Figure 6(e). The entry is generated from the virtual node B0; if a packet is at B with \( \text{tag}=B0 \) and a destination D, then either that packet was sent from A, and traveled to B or it was sent directly from B. In either case, the current best path is through the next hop \( \text{nhop}=D \) and it has a metric \( m_v=0.3 \). Moreover, before B sends the packet to D, it should update the tag to the new virtual node’s tag, which is B0. The second entry in B’s table is generated from B1. When packets are tagged with B1, there are two paths they could take to D: B-C-D and B-A-C-D. Currently, the least utilized path is B-C-D, so \( \text{nhop}=C \) and \( m_v=0.2 \). The updated tag in this case will be C0. For this policy, a static analysis has determined that only one probe is needed (carrying utilization), so there is only a single probe id (p$id$) of 0. The asterisk next to the entry for B1 indicates that B prefers B-C-D over B-D, which is determined after evaluating the policy on both paths (it is easy to evaluate a regular expression match given the PG tag since we know which regexes are accepted in each PG state). Hence, traffic sourced from B will choose to use the BCD path. Note that each source can determine its own preference: although B prefers C as the next hop, A will still be able to use A-B=D since A’s traffic will be forwarded using the B0 entry.

Function \texttt{SwiForwardPktx} in Figure 7 summarizes the packet forwarding logic. When a packet first arrives at the switch from a host, it is treated differently. In this case, this first switch must determine the preferred path for the packet (with each path having a representative destination, PG start node and probe id), which is stored in the BestT table.

4.3 Sending probes

While the forwarding tables compactly encode how devices should forward traffic in a policy-compliant way, we have yet to describe how these tables are populated. To this end, the Contra compiler generates protocol logic for propagating probes from probe sending states in order to populate the tables with the best paths to each destination.

At a high level, each node in the PG propagates probes to its neighbors. For instance, a probe starts at D0 (D with tag 0) and is sent to B0 and C0. C0 updates the utilization to be 0.1 and adds this entry to its forwarding table before sending a new probe to A0 and B1. Similarly, B0 adds an entry for the probe it received from D0 with utilization now 0.3 before sending a new probe to A1. A1 receives a probe from B0 and adds an entry with utilization 0.5, etc. A0 receives a probe from C0 with metric now 0.4 and adds this entry to its table before sending the probe to C0 and B1. Probes will continue to propagate through the PG so long as they decrease the best available metric for that probe type and PG node. Since a static analysis ensures that policy metrics are monotonically increasing, probes will not be propagated endlessly in loops.

To determine which entry to use for forwarding local traffic, switches compute the best path by keeping a pointer to their overall best entry (the asterisks in Figure 6(e)). For example, A must decide whether to use the entry for A0 or A1. Evaluating the policy on A0 results in \( \infty \) because A0 is not an accepting state for regex ABD or B.*D. On the other hand, evaluating the policy in A1 results in 0 (the best rank) because A1 is an accepting state for regex ABD. Hence, the asterisk appears by A1.

**Probe generation.** Probes are generated from initial PG states (e.g., \((D0,1,1)\) in our example). These sending states use the procedure in \texttt{InitProbe} to initiate probes, and use \texttt{MulticastProbe} to multicast the probes along the outgoing PG edges to all downstream neighbors. Each probe carries four fields: (1) \textit{origin} denotes the topology location of the sending switch (i.e., D for the state \((D0,1,1)\)); (2) \textit{p$id$} is the probe id, as obtained from the policy decomposition; (3) \textit{m$v$} denotes the metrics vector used in the policy (i.e., utilization in the example, which is initialized to a default value 0); and (4) \textit{tag} denotes the id of the PG node the probe is at.

**Probe dissemination.** The \texttt{ProcessProbe} algorithm describes how a switch processes a probe from its neighbor. This algorithm first obtains the product graph node for the
neighbor \(n\). Next, it updates the metrics in the probe based on the port at which the probe arrived. For instance, it computes and stores the maximum of the probe’s current utilization and the local port’s utilization. If this probe \(p\) (with id \(i\) and tag \(t\)) contains a better metric according to \(f\) than what is currently associated with \(i\) and \(t\) in the table then it updates its forwarding table \(FwT\) with the new next hop, next tag, and metrics vector corresponding to this probe. If an update occurs, then we also need to check if this affects the overall best choice for the switch \((i.e., \text{where the asterisk points to})\). The \(BestT\) table records the current best key for that choice. We look up the existing value and compare it to the current probe using the function \(s\) that checks the overall value of the probe \((\text{not just per tag / probe id})\). Finally, the probe tag is updated to the correct value for \(n\), and the probe is multicast to all PG neighbors.

5 Compilation: Unstable metrics

Consider using the same solution as described in Section 4 but instead of sending just one probe, sending many probes periodically, one per time interval. This introduces new complications due to the lack of synchronization; certain parts of the network may be working with outdated information. In fact, the example sequence from Section 4 Figure 4(b)-(f) demonstrates exactly how a problem can arise—the example culminates with the forwarding loop \(S-A-B-S\). Notice also that this problem can be addressed by ensuring (with high probability) that old probes are fully propagated throughout the network before new probes are sent out. In the above scenario, if we set the probe period to be 0.2 ms or larger, then \(S\) would instead pick \(p_2\) to be the better path after both probes have been received.

5.2 Probe frequency

Versioning the probes, however, leads to an additional complexity: a node may not always be able to pick the best path. Consider a case where \(D\) sends probes to \(S\) every 0.2 ms along two available paths: a) \(p_1\) with utilization of 0.4 and a latency of 0.1 ms, and b) \(p_2\) with utilization of 0.1 but a latency of 0.2 ms. Due to the higher latency of \(p_2\), whenever \(S\) receives a probe from this path, it would find the probe to be outdated, since newer probes had arrived from \(p_1\). As a result, \(S\) ends up always using \(p_1\), which has a higher utilization, even if the policy prefers the least-utilized path \(p_2\).

We observe that this problem can be addressed by ensuring (with high probability) that old probes are fully propagated throughout the network before new probes are sent out. In the above scenario, if we set the probe period to be 0.2 ms or larger, then \(S\) would instead pick \(p_2\) to be the better path after both probes have been received.

5.3 Policy-aware flowlet switching

Since Contra can spread traffic in the same flow across multiple paths, it is important to mitigate the potential out-of-order packet delivery at the receiver side. One classic approach is \textit{flowlet switching} [38], where packets in the same flow are grouped in bursts/flowlets and the same forwarding decision is applied to the entire flowlet. By doing so, the first packet in the flowlet is always forwarded to the best path, and subsequent packets in the same flowlet would inherit this (slightly outdated) forwarding decision. In addition to ensuring in-order delivery, this approach has the additional benefit of increasing network stability. Although each switch’s best path is constantly fluctuating, at any given point, much of the current network traffic will already be pinned to a particular path to avoid out-of-order delivery. Only new flowlets will make use of the current path information.

A first attempt to implement policy-aware flowlet switching in Contra would be to have each switch maintains a table of the form \([\text{fid}^*, \text{nhop}, \tau]\), where \(\text{fid}\) is the flowlet ID (from hashing a packet’s five tuple), \(\text{nhop}\) is the temporarily
“pinned” next hop, and $t$ is the timestamp of the last packet in $f_{id}$. When the next packet in $f_{id}$ arrives, the switch computes the gap between its timestamp and $t$: if the gap is small, this packet will use the current nhop; otherwise, the switch expires this entry and starts a new flowlet.

Perhaps surprisingly, deploying such a flowlet switching implementation with Contra may result in policy violations. Consider the example in Figure 8(a), where the policy prefers the least utilized of the upper or lower paths, but avoids the “zigzag” path.

```
if SCEFD + SAEBD then path.util else \infty
```

Suppose that at $t=1$, $S$ sends traffic to $D$ via the lower path due to its lower utilization; using flowlet switching, all switches temporarily pin this flowlet to their respective next hops along the path when they receive the first packet in the flowlet (e.g., A pins to E at $t=1.1$, which expires at $t=2.1$; E pins to B at $t=1.2$, which expires at $t=2.2$; and so forth). At $t=2$, $S$ discovers that the utilization of the upper path has improved, and changes its preference to D instead. However, if the packets from $S$ arrive at E before $t=2.2$, which is its flowlet switching expiration time, E will continue to forward these packets to the lower path, causing a policy violation.

The fundamental reason for this is that flowlet switching is oblivious to any network-wide routing policy. Our solution works by making it policy-aware. The idea is, again, that packets can carry tags that represent policy constraints, and in order to ensure policy-compliance, switches need to make forwarding decisions based on the tags. Therefore, policy-aware flowlet switching extends the table format to be $[\text{tag}^*, \text{pid}^*, f_{id}^*, \text{nhop}, t]$, where tag and pid are obtained from the probe that created the forwarding entry, and tag, pid, and $f_{id}$ are match keys. This enables flowlet switching within each policy constraint and probe type. Now, when $E$ processes the packet at $t=2.2$, it would see that the packet was constrained to travel the upper path, and would use a separate flowlet switching table entry for the upper path to forward it.

**Refinement (Policy-aware flowlet switching).** As before, except that switches perform policy-aware flowlet switching by maintaining multiple entries for the same flowlet, each for a different path constraint/tag and probe type.

### 5.4 Handling failures

Switches also need to discover new best paths when links or switches fail. Suppose that the best path for $S$ to reach $D$ is $S$-$A$-$D$, but the link $A$-$D$ goes down at some point. We need to ensure that $S$ will learn about the failure and change to another available path if one exists. Our solution is to first detect failed links, and then to expire flowlet entries when their next hop is along a link that is believed to be failed.

**Refinement (Expiration).** As before, except that, and a flowlet entry is expired when a packet arrives at a switch and is going to be forwarded by the flowlet entry, and the next hop is along a failed link.

This approach ensures that the switch will have to route around the failure in the future. Note that as long as there is a sound way to detect failed links, this scheme will work. In our implementation of Contra, we have a switch mark a link as failed when there have been no probes along the link for $k$ probe periods, where $k$ is a parameter that determines how fast (in terms of RTTs) failures should be discovered. However, other methods are possible as well, for example if the hardware could locally detect the failure of a link.

### 5.5 Breaking transient loops

As discussed in Section 5.1, even with versioned probes, transient loops may still occur when probes are in propagation. Figure 8(b) is a concrete example. At $t=1$, the best path for $S$ to reach $D$ is $S$-$B$-$A$-$D$. Then, at $t=2$, $A$ receives a probe from $D$ carrying a worse metric, therefore it propagates the probe to $S$ and $B$. Before this probe arrives at $S$ and $B$, $A$ learns of the better path through $S$, and traffic that is already in flight will be forwarded along a transient loop $S$-$B$-$A$-$S$; this loop will be broken once $S$ and $B$ receive the new probe because it has a higher version number.

Interestingly, flowlet switching may lengthen the duration of transient loops because flowlet switching decisions may expire at different times across hops. Suppose that $A$'s timer expires at $t=3$, and it starts using the new best next hop $S$ to reach $D$; however, the timers at $S$ and $B$ do not expire until $t=4$. Then the traffic would continue to be forwarded in the loop $S$-$B$-$A$-$S$ regardless of the newer probe, until $S$ and $B$ have updated their flowlet switching decisions.

We address this by detecting loops lazily and flushing the offending flowlet switching entries upon detection. Concretely, each switch maintains a loop detection table $\{\text{pkt.hash}, \max_{\text{max}, \text{min}}\}$, which maps a packet’s CRC hash to the maximum and minimum TTL values seen at this switch. $\delta=max_{\text{max}, \text{min}}$ should be stable in the absence of loops: it is the difference between the longest and the shortest paths packets could have traversed to reach the current switch. However, when there is a loop, $\delta$ would continue to grow. Therefore, switch detects a potential loop (with false positives) when its $\delta$ exceeds a threshold. When this happens, the switch expires its flowlet switching deci-
sion, and starts a new flowlet using the latest metric in the FwdT table. Hence, we arrive at our final solution below.

**Final solution.** As before, except that switches use loop detection tables to detect and break loops by refreshing their flowlet switching decisions using the latest metrics.

### 6 Evaluation

We aim to answer three main questions in our evaluation: a) How well does Contra scale to large networks? b) How competitive is Contra compared to hand-crafted systems? and c) How well does Contra work on general topologies?

#### 6.1 Prototype implementation and setup

Our Contra prototype consists of 7485 lines of code in F# [6]. It processes policy and topology descriptions, and then generates device-local P4 programs. In addition to implementing the algorithms described in this paper, it also performs a variety of optimizations, such as minimizing the number of tags, minimizing the forwarding table sizes, and reducing the number of bits to represent the tags.

**Experimental setup.** Our experiments were performed on a Dell OptiPlex 7060 computer, with an Intel i7-8700 CPU with 6 cores and 12 hyperthreads at 3.2 GHz, 16 GB of RAM, and a 64-bit Ubuntu 16.04 OS. We have validated our prototype both in Mininet [30] and on ns-3, but our main results were obtained from ns-3 since Mininet does not support large topologies as efficiently. We have used a custom tool that can compile P4 programs to run on ns-3.

We have used three types of network topologies: a) data center topologies, b) random graph topologies, and c) real-world topologies (e.g., the Abilene network [1] and those from Topology Zoo [2]). Our baseline systems for data center networks are ECMP and Hula [26], both of which are specifically designed for a Fattree topology. ECMP balances traffic randomly without considering network load, and Hula always chooses the least-utilized path among all shortest paths. Our baseline system for arbitrary graphs is SPAIN [31], which statically (i.e., independently of network load) selects multiple paths along which to route flows. We used two workloads obtained from production networks for our evaluation: a web search workload [11], and a cache workload [37]. Due to space constraints, we have included a subset of the results as appendix (B-E).

#### 6.2 Compiler scalability

To test the scalability of our compiler, we used topologies of varying sizes from 20 to 500 nodes. For each topology, we evaluated three different policies: a) minimum utilization (MU: no regular expressions, single performance metric), b) waypointing (WP: three regular expressions, single performance metric), and c) congestion-aware routing (CA: no regular expression, non-isotonic policy with two performance metrics). Figure 9 presents the results. The compiler scales roughly linearly with topology size, and completes in seconds on topologies with hundreds of nodes. Use of regular expressions increases product graph size and hence compilation time. In addition, non-isotonic policies add some small amount of overhead due to the additional policy analysis.

Figure 10 further plots the switch state used by the generated P4 programs. As expected, WP and CA require more state than MU: WP’s regular policy requires tag processing to track automaton states, and CA’s non-isotonic policy requires a separate table for each metric in the decomposed policy (i.e., separate entries for different πd values). However, no more than 70 kB of switch state was necessary in any experiment—a tiny fraction of the available space on modern switch hardware (tens of megabytes) [3].

#### 6.3 Performance: Data center topology

Our performance evaluation starts with the simplest case: a data center network topology. We compare Contra with ECMP and Hula in terms of their flow completion time (FCT), and note that the latter two mechanisms are designed specifically for a Fattree topology, whereas Contra can work over any topology.

In our topology, we used 32 hosts with 10 Gbps links, a bi-section bandwidth of 40 Gbps, and an oversubscription ratio of 4:1. Half of these hosts were configured as senders, and the other half receivers. We set the probe period to 256\(\mu\)s for both Contra and Hula, and the flowlet timeout to be 200\(\mu\)s for all systems. All links have a buffer size of 1000 MSS.
The cache workload

<table>
<thead>
<tr>
<th>Throughput (Gbps)</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>0.0</td>
</tr>
<tr>
<td>49</td>
<td>0.2</td>
</tr>
<tr>
<td>50</td>
<td>0.4</td>
</tr>
<tr>
<td>51</td>
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<td>0.8</td>
</tr>
<tr>
<td>53</td>
<td>1.0</td>
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</table>

<table>
<thead>
<tr>
<th>Network load (%)</th>
<th>Average FCT (ms)</th>
<th>Average FCT (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
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<td>3</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 11: Contra achieves a similar FCT as Hula, outperforming ECMP considerably.

Figure 12: Contra achieves a significantly shorter FCT on an asymmetric topology with a failed link.

Figure 13: Contra has shorter queues than ECMP.

Figure 14: Contra recovers from the link failure within 1 ms.

default. Moreover, we tuned the desired network load from 10% to 90% by adjusting the flow arrival times, and obtained the FCT for each setting.

**Symmetric Fattrees.** Figure 11 shows our results for the datacenter setting. As we can see, both Contra and Hula outperform ECMP considerably because they balance traffic based on network load. At 90% load, they reduce the average FCT by 30% for web search dataset and by 47% for cache dataset. Hula outperforms Contra slightly, by 0.33% on average across different datasets and network loads. This is because Hula knows statically what paths are shortest paths (and hence what ports to send probes from), whereas Contra has to discover this information dynamically (i.e., by carrying the path length as well as the utilization, and also by sending probes both “up” and “down” at each level in the datacenter)—hence Contra sends more probes than Hula in order to achieve generality over different topologies and policies. Further compiler optimizations could likely reduce this gap further (e.g., by identifying shortest paths statically).

**Asymmetric Fattrees.** Next, we ran the same experiment after injecting a failure on a link between an aggregation switch and a core switch, so that the topology became asymmetric. Figure 12 shows the FCT for this setting. In this case, we found that ECMP incurred heavy traffic loss beyond 50% network load, even though 75% of all capacity remains after the link failure. The average FCT was inflated by $3.18 \times$ for web search dataset and $1.67 \times$ for cache dataset, relative to the FCTs on the symmetric topology.

We further measured the queue sizes under ECMP and Contra with 60% workload on the web search dataset. Figure 13 shows the results. We found that Contra’s queue lengths never exceeded 1000 MSS, whereas ECMP had lengths larger than this value more than 97% of the time, which caused heavy traffic loss when the queues are full.

We also tested the time for Contra to respond to link failures. Figure 14 shows the aggregate throughput before and after a link failure, using UDP workloads at a stable rate of 4.25 Gbps. We brought down an aggregate-core link at $t = 50$ ms. Contra successfully detected this failure 800 µs afterwards, which is close to the failure detection threshold (3×RTT=768µs) that we used for this experiment. Upon detection, Contra routed around the failure and was able to recover the throughput within 1 ms. We have found Hula to perform similarly to Contra, as shown in the same figure.

### 6.4 Performance: Arbitrary topologies

We now turn to evaluate the performance of Contra on general topologies. We modeled our network after the Abilene [1] topology, configured all links to be 40 Gbps, and randomly chose four pairs of senders/receivers. Since Hula is specialized to a Fattree topology and will not work outside of this context, and since ECMP will not load balance when there is only a single shortest path, we have used two other baselines: a) shortest path routing (SP), which simply sends traffic to the shortest paths, and b) SPAIN [31], which precomputes all paths using (static) heuristics that avoid overlap, and then load balances between these paths.
The cache workload

Figure 15: Contra outperforms SPAIN in FCT.

Figure 16: The traffic overhead of Contra is low.

Figure 15 shows the FCT for these different systems. A naïve strategy that simply chooses shortest paths performs the worst. Since SPAIN can utilize multipath routing, it outperforms SP by 32.5% on average for the web search workload and 26.9% on for the cache workload. Contra achieves the best performance among the three: it evenly distributes traffic based on path utilization, and reduces FCT relative to SPAIN by 31.3% on average for the web search workload and 13.8% for the cache workload.

6.5 Protocol overhead

To evaluate the traffic overhead incurred by Contra due to packet tags and probes, we measured the amount of traffic sent over the network by Contra, Hula, and ECMP at 10% and 60% network load. Figure 16 shows the traffic overhead as normalized by ECMP as the baseline. Across workloads, Contra incurred 0.79% more traffic than ECMP, and 0.44% more than Hula, which seems to be reasonable. We have similar observations for Contra on the Abilene network, as well as for the WP policy, and we have included these results in the appendix (D+E).

Another type of overhead comes from transient loops, which may arise as performance metrics change and nodes are temporarily out of sync. To quantify this, we measured the amount of traffic that has experienced transient loops using the MU policy on a Fattree and on Abilene with 60% workload. We found that 0.026% and 0.007% of the traffic traveled in a loop, respectively, and that our loop detection mechanism successfully broke such loops upon detection.

7 Related Work


Data-plane load balancing. Recent work on data-plane load-balancing mechanisms, such as Hula [26], Conga [10], and DRILL [19] perform load balancing at a finer granularity and achieve a faster response to changes in network load. They are also utilization-aware—an improvement over simpler mechanisms such as ECMP, which splits traffic randomly regardless of network conditions. However, these are mostly point solutions that are specialized for a particular topology with a hard-coded policy. Contra supports a wide range of policies, and works over arbitrary topologies.

Routing protocols and route updates. There is a long line of work on distance-vector routing protocols with a variety of loop prevention techniques [18, 62, 9, 34, 5, 2] with different tradeoffs between overhead, convergence time, (in)stability, etc. Contra is most related to DSDV [14], AODV [2], and Babel [5], which use sequence numbers on route updates to achieve timely convergence. Compared to existing work, the novelty of Contra lies in its use of programmable data planes to implement a wide array of distance-vector protocols in the presence of unstable metrics, and its design of policy-aware flowlet switching mechanisms.

Regular languages for networking. NetKAT [12], Merlin [39], FatTire [35], path queries [33], and Propane [13] all use regular expressions, like Contra, to specifying path constraints. A key difference is that Contra supports specification and implementation of route preferences based on dynamic network conditions.

8 Conclusion

We have presented Contra, a system for specifying and enforcing performance-aware routing policies. Policies in Contra are written in a declarative language, and compiled to switch programs that run on the data plane to implement a variant of distance-vector protocols. These programs generate probes to collect path metrics, and dynamically choose the best paths along which to forward traffic. Our evaluation shows that the compiler scales well to large topologies, and that the synthesized switch programs can achieve performance competitive with hand-crafted solutions that are specialized to particular topologies and hard-coded policies. However, it is also substantially more general, allowing network operators to specify a wide range of policies and to apply these policies to networks with arbitrary topologies.
References


A Policy analysis and decomposition

At a high level, the Contra compiler implements the policies in a distance-vector protocol, where switches propagate periodic probes and compute a best next hop for each destination using the path metrics. To avoid flooding the network with probes, a switch will only disseminate the best probe in a batch and discard the rest. Moreover, if a policy uses multiple metrics, each probe will carry all metrics to further reduce traffic. However, these techniques are not always safe—the policy needs to be isotonic, because otherwise downstream switches can wind up with suboptimal paths. The policy also needs to be monotonic, because otherwise loops may form.

Monotonicity. A policy \( f \) is monotonic iff. extending a path \( p \) by an additional link \( l \) does not result in a better ranked path, i.e., \( f(p) \leq f(p \cdot l) \); \( f \) is strictly monotonic if \( f(p) < f(p \cdot l) \). Strict monotonicity ensures that loops will not form in distance-vector protocols (assuming static metrics that do not change), because a path’s rank only degrades as it gets longer \([20]\). In principle, one could write a policy that is not monotonic, such as \text{minimize} (\text{- path.util})\), but in practice, we are not aware of such policies actually in use. On the other hand, there are practical policies such as \text{minimize} (\text{path.util})\) that are not strictly monotonic. To ensure safety, the Contra compiler implements a conservative monotonicity analysis and alerts a programmer of a potential error if the policy is non-monotonic. But our compiler accepts non-strict monotonic programs: our probe propagation mechanism associates an “age” with each probe stored in a switch, and break ties by rejecting more recent probes if they have the same value as the currently used metric, because they may have traversed zero-weight cycles.

![Figure 17: Contra requires (sub)policies to be isotonic.](image)

Isotonicity. A policy \( f \) is isotonic iff. for any paths \( p_1, p_2 \), and any link \( l \), extending both paths by \( l \) preserves the original relative ranking, i.e., \( f(p_1) \leq f(p_2) \iff f(p_1 \cdot l) \leq f(p_2 \cdot l) \). Isotonicity guarantees convergence to the best paths \([20]\) even if a switch discards suboptimal probes. Figure 17 demonstrates the idea: if \( C \) prefers the probe from path \( p_1 \) over that from \( p_2 \) and discards the latter, then its downstream neighbor \( D \) must have the same preference, or else it would miss a path with a better metric. However, there are some useful policies that are non-isotonic, such as the following congestion-aware routing policy \([23]\) that switches between metrics depending on the network condition:

\[
\text{if path.util } < 0.8 \ : \text{ then } 1, \text{path.util} \ :\text{ else } 2, \text{ path.len}^2
\]

To see why the policy is non-isotonic, consider the switch \( C \) in Figure 17 that receives two probes with metrics \( \{u=0.5, l=5\} \) and \( \{u=0.6, l=4\} \). \( C \) prefers the first probe because \( \text{path.util} < 0.8 \) evaluates to true for both probes and the two probes will be ranked based on utilization. However, \( C \) cannot simply discard the second probe, because all paths to its downstream neighbor \( D \) may be highly congested (e.g., \( u(D-S)=0.9 \)). In this case, \( \text{path.util} < 0.8 \) evaluates to false at \( D \) for both probes, causing \( D \)'s preference to be inverted.

Policy decomposition. The Contra compiler tries to decompose non-isotonic policies into multiple isotonic (and monotonic) subpolicies, and generates different types of probes to propagate each subpolicy. If such a decomposition is impossible, then it rejects the policy. For instance, the compiler decomposes the previous policy as follows:

\[
\text{if path.util}^0 < 0.8 \ : \text{ then } 1, \text{ path.util}^0 \ : \text{ else } 2, \text{ path.len}^1
\]

where type-0 probes carry \text{path.util}, and type-1 probes carry \text{path.len}. Switches can discard suboptimal probes within each type, but must propagate both types of probes. The complete policy is only evaluated at source nodes.

More generally, our compiler performs an analysis to try to decompose \( f \) to a collection of subpolicies \( s(f_1, \ldots, f_n) \), where each \( f_i \) is monotonic and isotonic, and \( s \) combines the subpolicies such that \( f(p) = s(f_1(p), \ldots, f_n(p)) \). For this decomposition to be correct, \( s \) needs to be strictly increasing in each of its arguments, i.e., for any \( x_i \leq x_i' \), we need to have \( s(x_1, \ldots, x_{i-1}, x_i, x_{i+1}, x_n) \leq s(x_1, \ldots, x_{i-1}, x_i', x_{i+1}, x_n) \). Intuitively, this condition allows a switch to safely discard any non-minimum \( x_i \) values of each probe type.

B Key topologies for experimental evaluation

Most of our experiments have been conducted over two topologies—Fattree networks and the Abilene network topology, as shown in Figure 18. We have also used topologies in the Topology Zoo \([7]\). By default, we have set the link latency to be 10\( \mu \)s for all links, and the buffer capacity to be 1000 MSS.

![Figure 18: The topologies we have used in the evaluation.](image)
C  Comparison with the FMCF solution

Although the experiments on flow completion times already demonstrate that Contra can boost application performance, we would like to further investigate how Contra performs when compared to an idealized solution for which we can derive an optimal bound. To this end, we use a Fractional Multi-Commodity Flow problem (FMCF) [25] to model this scenario, and note that similar formulations have been used in other projects [27, 42]. An MCF problem takes as input the (fixed) demand for sender/receiver pairs and the network topology, and computes the optimal traffic splitting across paths in order to minimize the utilization of the most congested link. The fractional version of MCF simply means that a flow can be split across different paths as well. This formulation makes several simplifying assumptions, which require minor modifications to the tested systems. Nevertheless, we believe that the results we obtain are still illustrative, as these assumptions make it possible to derive an optimal solution to compare against.

C.1  The FMCF formulation

We have used the same formulation as the Linear Programming Formulation (LPF) in [40]. This formulation models the physical network as \( G(V, E) \), where \( V \) denotes the set of switches and \( E \) the set of links. For each link \((i, j)\), \( c_{ij} \) represents its link capacity. \( X_{ij}^k \in [0, 1] \) is the percentage of traffic a solution sends to link \((i, j)\) for a given commodity flow from the source \( s_k \) to the destination \( t_k \), where \( k \in K \) represents a commodity flow chosen from the set \( K \) of flows to be sent. The total demand for a flow \( k \) is \( d_k \). Our goal is to minimize the maximum link utilization \( \alpha \in [0, 1] \) across the network.

The problem can then be formulated as follows:

\[
\begin{align*}
\text{min} \ & \alpha \\
\text{s.t.} \ & \sum_{j: (i,j) \in E} X_{ij}^k - \sum_{j: (j,i) \in E} X_{ji}^k = 0, \quad k \in K, \ i \neq s_k, t_k \\
& \sum_{j: (i,j) \in E} X_{ij}^k - \sum_{j: (j,i) \in E} X_{ji}^k = 1, \quad k \in K, \ i = s_k \\
& \sum_{k \in K} d_k X_{ij}^k \leq c_{ij} \alpha, \quad (i, j) \in E \\
& 0 \leq X_{ij}^k \leq 1, \alpha \geq 0.
\end{align*}
\]

Equations 1 and 4 define \( \alpha \) as the maximum link utilization and set the objective function to minimize this. Equation 2 encodes the flow conservation principle, which specifies that all nodes should have the same amount of incoming and outgoing traffic, except for the sources and destinations. Equation 3 specifies the source switch of each flow.

Simplifying assumptions: We note that this formulation makes several simplifying assumptions when testing the systems. In order to ensure that the created demands are static, we used UDP instead of TCP to avoid its flow control algorithm, and we artificially made the buffers deep enough to avoid packet loss. Given that the FMCF formulation does not have the notion of flowlets (which requires reasoning with timing behaviors), we have configured ECMP, SPAIN, and Contra to perform per-packet load balancing to emulate the problem that FMCF models. This configuration significantly disadvantages Contra, because unlike ECMP, SPAIN, which are inherently multipath, Contra is designed to spread traffic per-flowlet over time, and it only changes paths based on periodic probes. Since this feature is disabled, we instead measured the utilization of all systems at a coarser timescale over multiple RTTs, so that Contra is given an opportunity to balance the load. Despite the above simplifications, we believe that the results we obtain are still illustrative, as these assumptions make it possible to derive an optimal solution that we can compare the actual systems against.

C.2  Experimental results for FMCF

Figures 29 and 31 show three setups where the optimal solutions returned by our solver are 20%, 40%, and 60%, respectively. For each setup, we have tested the systems on a Fatree topology and on Abilene. On a Fatree, both ECMP and Contra are very close to the optimum: they are 0.049% and 0.16% higher than optimum on average. Since ECMP splits traffic on a per-packet basis, it is expected to achieve almost perfect load balancing; Contra underperforms slightly since it only changes forwarding decisions based on periodic probes, but it performs close to ECMP and the optimum.

On a general topology, the performance of SPAIN is highly dependent on the locations of senders and receivers, as its load balancing mechanism precomputes non-
overlapping paths when possible. We found that, when alternative paths in SPAIN do not overlap, it performs very close to optimum (worse only by 2.53%), but when paths overlap, SPAIN could underperform by as much as 6.55%. Contra, on the other hand, has consistent performance, and achieves similar performance with the same scenarios used to evaluate SPAIN. Compared to the optimum, the results for Contra are 2.41% and 2.36% higher, respectively. Figure 19 shows the two setups we have used for the experiments with SPAIN.

D Evaluation: Waypoint policy

The performance evaluation in our main paper has focused on policies that do not involve regular expressions, because regular expressions constrain paths rather than optimize for performance. Nevertheless, we have conducted a set of experiments on such policies, and report the key findings in this section. We have used the waypoint policy (WP) with one regular expression, and measured the performance and protocol overhead in different workloads.

Flow completion time. Figures 22 and 23 show the FCT achieved by the WP policy on a symmetric data center topology, and on an asymmetric data center topology with a failed link, respectively. As we can see, on the symmetric topology, WP performs similarly to MU and Hula on both workloads. When the topology is asymmetric, WP performs worse than ECMP, as it imposes additional path constraints. Figures 24 and 25 show the FCT results for the asymmetric topology.

Protocol overhead. Figure 26 shows the traffic overhead of the WP policy. As we can see, WP sends more traffic than MU because it tags packets with policy states and creates separate probes for different regular expression matches.

E Evaluation: Traffic overhead on Abilene

We also evaluated the traffic overhead of SPAIN and Contra on the Abilene network, at 10% and 60% network load. Fig-
Figure 26: The tags in the waypoint (WP) policy introduce more traffic overhead.

Figure 27: The traffic overhead of Contra and SPAIN on the Abilene network.

Figure 27 shows the results. We found that only 0.54% of traffic is due to the extra probes in Contra. Interestingly, although SPAIN did not use any extra probes, the amount of traffic SPAIN sent across the network is higher than that of Contra, and even higher than the total traffic of Contra. This is because SPAIN’s paths are on average longer than those used in Contra. As a result, Contra requires 6.65% less network bandwidth than SPAIN.