Active Switching: Packet-Steering Flow Annotations

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Abstract

Our previous experience building systems for middlebox chain composition and scaling in software-defined networks has revealed that existing mechanisms of flow annotation commonly do not survive middlebox-traversals, or suffer from extreme identifier domain limitations resulting in excessive flow table size. In this paper, we analyze the structural artifacts resulting in these challenges, and offer a framework for describing the behavior of middleboxes based on actions taken on traversing packets. We then present a novel mechanism for flow annotation that features an identifier domain significantly larger than existing techniques, that is transparent to hosts traversed, and that conserves flow-table resources by requiring only a small number of match rules and actions in most switches. We evaluate said technique, showing that it requires less per-switch state than conventional techniques. We then describe extensions allowing implementation of this architecture within a broader class of systems. Finally, we close with architectural suggestions for enabling straightforward integration of middleboxes within software-defined networks.

1 Introduction

As the enabling technology of many recent networking innovations, SDN has been widely described and viewed as a "swiss-army knife" capable of solving all manner of challenges within the networking domain. While this reputation is primarily well-deserved, less discussed are the problem spaces in which SDN is counterproductive or of non-obvious utility.

In previous work, we explored the challenges and opportunities of SDN as an infrastructure for the implementation of complex traffic intermediation and modification functionality utilizing middleboxes [7]. Our experience of constructing said controller lead us to identify a seemingly-significant, yet little-discussed, impediment to the use of SDN for this use case as well as for broader scenarios involving middlebox chaining [9] and/or network functions virtualization [5].

Consider an administrative policy requiring all traffic to be shunted through a middlebox prior to its arrival at the destination host, and suppose there are multiple identical instances of that middlebox the controller might choose from. In order to effect a unique per-flow path to ensure effective load balancing, the controller must install rules in the switches adjacent to the middleboxes and endpoints that uniquely identify each possible traversing flow, leading to a state-size requirement in each switch that is proportional to the number of concurrent flows in the network. This problem is usually described as state-space explosion, and it presents a significant limitation to the scalability of SDN architectures.

However, consider the possibility that the middleboxes interposed on traffic not only inspect, but also mangle (modify) said traffic. Such a middlebox could, conceivably, alter the traffic such that, on egress, it no longer appears to belong to the same flow to which it belonged on ingress (for example, by modifying header addressing fields.) When the behavior of the middlebox is known and deterministic, this challenge can be overcome by informing the controller of the modifications the middlebox will make to traffic; however, this requires middleboxes and controllers to share state, and duplicate some work. In the case of a middlebox that might arbitrarily and unpredictably alter traffic, though, the controller cannot craft a match-rule that will reliably identify the...
flow post middlebox-traversal. We call this problem the post-traversal flow reassociation problem, and, in general, we call the challenges involved in the implementation of such a system the traffic-steering problem.

In [7], we partially obviated these problems by accepting certain design and functional limitations to the behavior the controller might effect, and by placing certain restrictions on the behavior of middleboxes that can be utilized within the system. While functional, the mechanisms we employed suffer from significant limitations in scalability (e.g., imposing a fairly small limit on the number of potential next hops in a chain) and functionality (e.g., re-purposing DSCP bits in the IP header precludes certain forms of QoS). Similar limitations can also be found in other approaches to this challenge (e.g., [6]).

This paper seeks an architecturally clean, yet immediately deployable approach to this problem of growing importance. We present a solution that we believe to be more flexible and more efficient than comparable systems previously described in literature. In brief, we utilize fields within each packet that have been rendered useless by SDN to cache the result of the first flow-table lookup for a packet. Put differently, we annotate each packet at the ingress point to the network with the controller’s routing decisions, thereby eliminating the need for each packet to be matched against a flow-unique rule at each switch in the network. We dub this technique active switching.

During design and implementation of our prototype active switching controller (SOFT), we came to believe that this solution has broader utility beyond the challenges involved in middlebox chain-composition and traffic steering. While the primary focus of this paper is that set of problems, later sections describe how active switching may be useful in different scenarios, such as the construction of network fabrics, and routing within non-acyclic topologies.

We begin this paper by discussing the architectural artifacts that inform the implementation and behavior of commonly available middleboxes, and offer a taxonomy for describing and classifying them by their operation as it is visible to the network. We then discuss previously identified solutions to the traffic-steering problem, and their limitations. We proceed to describe the architecture of a novel potential solution to this problem, and evaluate a proof-of-concept implementation. Finally, we close with a general sketch of extensions to this technique allowing it to address a broader class of problems to which this technique may be applicable, and take-away implications for various members of the networking community.

2 Motivation

Previous work (e.g. [6], [7]) have discussed the general set of problems related to traffic steering in detail. As such, we do not attempt to fully describe that problem space herein, and refer the interested reader to related works for an in-depth treatment. Herein, we describe the challenges only to the degree sufficient to motivate the remainder of this paper.

2.1 Definition

For the purposes of this system, we define a middlebox as a network device that interposes on network traffic prior to its receipt by the intended destination. This definition is somewhat surprising in its generality, in that switches and routers can be validly and reasonably considered to be middleboxes under it. However, we’ve found that more-limited definitions of middlebox are insufficient to describe the full spectrum of extant devices that are traditionally considered to be one. For example, in terms of network-visible behavior, a simple switch and a transparent intrusion detection system operate identically, as both receive traffic and re-emit it without modification. Similarly, a traditional IP router and a MAC-layer network address translation device both emit traffic received with modifications to the network addressing header fields. As such, we believe that any reasonable definition of middlebox that encompasses devices such as IDSs and MAC NAT must also encompass devices such as traditional switches and routers.

2.2 Taxonomy

For reasons historical, there are two predominant architectural foundations upon which the higher-level functionality of middleboxes is implemented. In general, the distinction between these types of middleboxes can be distinguished by the type of traffic the middlebox is able to "see":

- A bridging middlebox receives all packets available on the medium.
- A routing middlebox only receives packets that are constructed so as to appear that the middlebox is a valid "next-hop" on a route from the source address to the destination address, given the middlebox’s IP configuration.

While this distinction implies the potential side-effects of a given middlebox, it’s important to note that it does not meaningfully describe or constrain the behavior a given middlebox may exhibit with respect to traffic "seen". For the purpose of discussing the behavior and higher-level functionality implemented by a middlebox,
this distinction is not useful, as these types of middlebox are roughly equipotent.

To the end of describing the behavior of middleboxes from the perspective of the network itself, we can also classify middleboxes based on their possible behavior upon those packets received:

- A **transparent middlebox** emits all packets received from upstream without alteration in the downstream direction.
- A **translucent middlebox** need not emit all packets, but all packets that are emitted in the downstream direction are identical to some packet received from upstream.
- A **mangling middlebox** may emit packets downstream that are not identical to some packet received from upstream; however, each packet emitted downstream "corresponds" to some packet received from upstream.
- A **connection-originating middlebox** may act as an originator of new flows.
- A **connection-terminating middlebox** may terminate flows received.

We will be using this latter terminology to describe middleboxes through which traffic might be steered throughout the rest of the paper.

We employ a convenient abstraction in this work, that all middleboxes have exactly three interfaces:

- An **ingress interface**, upon which traffic is only received.
- A **egress interface**, upon which traffic is only transmitted.
- A **control interface**, responsible for management traffic.

We do not believe that this abstraction in any way lessens the generality of the discussion to follow. Consider another occasionally-useful abstraction of interfaces, which we employ in later sections:

- An **upstream interface**, upon which traffic originating from the external network is received, and through which traffic originating from endpoint hosts within the network is transmitted.
- A **downstream interface**, which functions as the inverse of the upstream interface.
- A **control interface**, as in the previous abstraction.

These abstractions are equivalent, as the following construction demonstrates: on a middlebox featuring physical upstream/downstream interfaces, the abstract ingress interface traffic can be identified as that which is received by either physical interface. Conversely, the abstract egress interface traffic is necessarily all traffic transmitted by either physical interface. The control interface behaves identically under either abstraction.

### 2.3 Topology

We assume the existence of a network fabric as described by M. Casado, *et al.* in [1], with OpenFlow-enabled edge switches. Positioned about the fabric is a collection of servers, middleboxes, and gateway switches connecting to an external network. This abstract topology is illustrated by Figure 1, where the numerals situated about the fabric identify the egress port from the network for traffic bound for a particular device. The figure omits, and we do not define identifiers for, the fabric’s ingress ports.

Multiple tenants may co-exist within this network; as such, the various endpoints may not share a common owner, and their connectivity may be logically isolated from that of other tenants within the same network by means of a network virtualization facility such as 802.1q [2], STT [3], VXLAN [10] or NVGRE [13].

### 2.4 Policy

We further assume a policy language for describing rules interposing chains of middleboxes between the ingress switch and destination for traffic matching given patterns, and an OpenFlow controller, connected to the fabric’s edge switches.

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5This relationship is left vague somewhat intentionally, as a middlebox which appears to originate and terminate flows when considered as a black-box may, in fact, be recognizable as a mangling middlebox given a sufficiently nuanced understanding of its behavior.

6This could also be viewed as an extreme case of middlebox translucency.

4Only a subset of this taxonomy is employed in the remainder, as only that subset is relevant to the design of active switching. We believe though that this taxonomy, as a whole, could have broader utility for related middlebox research, and offer it to that end.
We will consider, as an example, a policy that specifies traffic destined for host $H$ must first traverse one of two redundancy eliminators $RE1$ or $RE2$, followed by a single intrusion prevention device $IPS$. This policy is illustrated in Figure 2.

We further specify two general requirements on the behavior of the system:

- A flow initially submitted to one of multiple potential equivalent middleboxes must maintain **affinity** with that instance over the life of the flow.
- A flow that passes through a given sequence of middleboxes on the downstream path to the destination must maintain **symmetricality** on the return path, meaning that the very same middleboxes must be traversed in reverse order.

We now consider the question of how such a controller might program the edge switches of the fabric to effect this policy.

### 3 Steering

Previous work (e.g. [6], [7]) have discussed the general set of problems related to traffic steering in detail. As such, we do not attempt to fully describe that problem space herein, and refer the interested reader to related works for an in-depth treatment. Herein, we describe the challenges only to the degree sufficient to motivate the remainder of this paper.

In order for a controller to implement the desired functionality as described in the previous section, it must be able to select, on a per-flow basis, a sequence of intermediary devices through which traffic is shunted prior to arrival at its destination. It must also be able to induce behavior satisfying its policy decisions from each device along that sequence (i.e. each network device must be able to identify the correct output port for each flow.) Under constructions where flows are identified by a distinct per-switch match-rule, this rapidly leads to state-space explosion within the network, as the number of match rules required in aggregate is proportional to the product of the number of concurrent flows, and the number of switches traversed by those flows.

Additionally, a controller implementing that desired functionality must also be able to support middleboxes within the network that arbitrarily modify traffic, without relying on an understanding of the behavior of that middlebox. However, as such a middlebox might alter the fields of the packet upon which match-rules rely, it does not appear that a match-rule per-switch per-flow construction could possibly satisfy this requirement.

A number of techniques have been proposed to effect the goal of flexible traffic steering through an SDN that do not suffer from the above-described challenges, which we refer to generally as the traffic steering problem. Some of these techniques, while superficially plausible, are insufficient for the obviation of, or subtly still-impeded by, the traffic steering problem. Others impose severe limitations that constrain the utility of the approach.

We consider these techniques and discuss their shortcomings herein.

#### 3.1 Policy Matching in Edge Switches

An initially appealing, yet naive approach is to install flow rules steering matched traffic in each edge switch of the fabric. While this technique is easy to implement, and requires only those primitives commonly available within software-defined networks (e.g. those defined by the OpenFlow 1.0 standard), it presents a number of serious problems that effectively preclude its utilization in all but the most trivial of scenarios.

One such issue with this approach restricts the variety of middlebox employed within the network, or requires undue state-sharing between all middleboxes and the controller. We refer to this issue as the post-traversal flow re-association problem: during the traversal of certain types of middlebox (specifically those that mangle L2 and/or L3 headers), it is possible for the packet to be modified such that it no longer maintains the expected values upon which match rules were constructed. For
example, a L4-NAT middlebox might conceivably alter all header fields upon which a traditional OpenFlow 10-tuple might match.

Supposing that the post-traversal flow annotation re-association problem were sufficiently addressed in a given context so as to not represent a severe limitation, another issue exists that would restrict the scalability of this system. In general, re-associating packets with their correct annotation at every edge switch requires each switch to maintain at least as many flow-table entries as there are flows that might traverse the switch at any given time. While there are specific situations where a sufficiently informed controller could craft flow-table entries that correctly match on more than one flow, such a technique is not generally applicable, and still suffers from the same flaw: the amount of state in each switch remains proportional to the number of flows that might be expected to traverse it, and, therefore, the number of flows supported across any given switch along the edge of the fabric is limited by the size of the flow table of that switch.

3.2 Packet Tagging in Ingress Switches

We now consider the viability of techniques that require state proportional to the number of current flows at ingress switches only.

Tunneling

"Tunneling" protocols such as VXLAN [2], STT [3], or NVGRE [13] are often proposed (in a hand-wavey fashion) as potential tools to steer traffic among middleboxes. Upon more serious consideration, however, a number of flaws to these approaches become apparent.

When considering the case of a tenant with a single, "linear" policy chain, these technologies may appear to offer a plausible solution to the traffic steering issue. However, when considering the case of a policy-chain with multiple potential next-hops at any point along the path, it is obvious that this approach suffers from the same post-traversal flow annotation re-association problem discussed previously.

This could be obviated by informing the controller of the behavior of the middlebox in some cases, but we reject this as a suitable general proposal for two reasons: it requires re-implementing substantial middlebox functionality in the controller, and it doesn’t work when the behavior of a middlebox is non-deterministic, anyway.

In fact, the most straightforward implementation requires even more state than that: each switch would need an ingress rule and an egress rule for traffic entering and departing the middlebox, respectively.

We believe this to be a more tractable scalability limitation, as multiple ingress switches could be employed simultaneously in parallel, or switches with larger flow tables could be used, without requiring such capability at every edge-switch in the network.

Consider also the case of a tenant with multiple linear policy chains that share a subset of middleboxes, or that describe policy requiring traversal in a different order.

Fundamentally, these techniques operate by assigning a unique identifier to each tunnel or virtualized network existing upon the underlying network, that is carried by all packets belonging to these tunnels. As the identifiers serve to allow the underlying network to differentiate between individual links or tenants, it does not seem plausible that the very same identifier could also be reasonably extended to differentiate between paths within the overlay.

We believe that tunneling protocols are not appropriate tools to this end, as their utilization for this purpose conflates the goals of tenant isolation and traffic steering. Their design was motivated by the need to provide the appearance of an isolated broadcast domain to tenants. Given that the challenges around traffic-steering are not at all mitigated by the existence of an isolated broadcast domain, it does not seem plausible that tools designed to effect an isolated broadcast domain would be sufficient to meet this need.

DiffServ Code Point Repurposing

Prior work (e.g. [6], [7]) has proposed repurposing the DSCP bits in the IP header to the end of annotating packets for correct steering. While this approach can work in practice, it, too, suffers from many of the limitations previously described: for example, the number of flows such a technique is capable of supporting concurrently is constrained by the number of annotations that might be encoded with the 6 DSCP bits ($2^6 = 64$).

More significantly, the correctness of this approach is predicated on a pair of brittle and potentially unsafe assumptions: that the DSCP bits are otherwise unused within the network, and that middleboxes emit them unmolested. The former assumption precludes the use of QoS within the network, and the latter may simply not be true.

3.3 Other techniques

Related work has suggested the use of shims between the L2 and L3 header, or requiring modifications to middleboxes that are to be employed within the SDN. We reject the former approach for suffering from the same limitations as tunneling-based solutions, and the latter for not being generally applicable.

The elimination of middleboxes entirely has also been suggested, by, e.g., [4]. To an extent, we agree that this is a valid approach in some cases: software-defined networking has made available, within the network, sufficient functionality to effect many network-layer tasks traditionally performed by middleboxes (e.g., NAT).
We believe that the responsibility for such functionality should be devolved to the network itself where possible, and that such devolution is entirely appropriate. However, there exist many tasks for which middleboxes are commonly used that do not lend themselves to being integrated into the network proper, as they require actions to be taken based on an understanding of upper-layer protocols. It does not seem plausible to assume that all middlebox functionality possible could ever be devolved to the network entirely, and, as such, we dismiss this approach as fantasy.\footnote{We have, however, limited the types of middleboxes under consideration in this paper to those which cannot be adequately handled by the network itself, as a result of this argument.}

### 3.4 Active Switching

The remainder of this paper discusses an approach to traffic steering that we believe to be novel as a whole, although inspired by various aspects of the techniques previously discussed. We call this method active switching, as it requires that edge switches to act on packets in ways other than just forwarding based on match-rule logic. We believe that it substantially mitigates the flaws of the previously discussed possibilities.

### 4 Construction

Active switching’s design is inspired by the following observations:

- OpenFlow-enabled switches need not be compliant with IEEE 802.1d, and, by default, are not. In other words, “this ain’t DIX Ethernet.”
- As OpenFlow-enabled switches are able to forward traffic based on L3 header match, L2 addressing need not uniquely identify a network host.
- In fact, L2 addressing conveys no additional information to the network that could not be gleaned by examining L3 headers and network topology.

Given those observations, we have chosen to re-purpose the source and destination MAC address fields in the Ethernet frame header to encode the policy-defined hop-by-hop path a packet should follow between the ingress gateway and the destination endpoint host.

#### 4.1 Required flow-rule actions

We require three register extensions to the OpenFlow 1.0 standard:

- bit-oriented partial load from field offset to register
- bit-oriented partial save to field offset from register
- output to port given in register

Given that fabric-edge switches in cloud architectures tend to be implemented in software, and as these actions are already supported by Open vSwitch\footnote{There may also be designs employing features of the OpenFlow 1.3 standard that can achieve reasonable facsimiles of this functionality, possibly at the cost of increased flow-table size.}, we do not believe that these requirements impose a significant limitation to this approach.

### 4.2 Baseline Functionality

We initially consider only the composition of middleboxes that do not mangle L2 traffic headers, and that do not originate connections. We additionally restrict the port identifiers of the fabric to 8 bits, and exclude paths with a hop-count greater than 5 from consideration.

In section 5, we will loosen these restrictions in order to better support a greater variety of middleboxes under less-abstract network topologies.

#### 4.2.1 Ingress Switch Behavior

The default action for packets received by an ingress switch that fail to match any current flow rules is to forward the packet to the controller.

Upon receipt of a packet from an ingress switch, the controller considers its configuration, policy, and knowledge of the network topology to construct a port-by-port path through the network. It then writes a flow-rule into the ingress switch that matches the flow under consideration and causes the destination MAC address to be rewritten. We encode the hop-by-hop path through the network as follows:

\[
\text{dst} \leftarrow 00:00:00:00:FF \\
\text{for } h \in \text{reverse}(P): \\
\text{dst} \leftarrow (\text{octet left shift} (\text{dst} \& h))
\]

Figure 3: Destination MAC address construction

Subsequent to destination MAC address re-writing, the packet is handled as though it were received by an edge switch.

#### 4.2.2 Edge Switch Behavior

Given the register extensions previously discussed, the operation of edge-switches is quite simple: upon receipt of a packet, the switch rewrites the destination MAC address by shifting it one octet right. The packet is then output through the port identified by the byte that was shifted off the destination MAC address.
octet_rshift_field(Field F)  
1  let R := allocate_and_zero_register()  
2  R ← load_field(F, 8, len(F) − 8)  
3  F ← R

handle_packet(Packet P)  
4  let F := P.dst_mac  
5  let R := allocate_and_zero_register()  
6  R ← load_field(F, 0, 8)  
7  octet_rshift_field(F)  
8  output_to_port(P, R)

Figure 4: Basic edge-switch logic

4.2.3 Upstream path

While constructing the downstream path through the network, the controller can also construct a reverse path from the endpoint back to the ingress switch by simply reversing the hop order and pushing a flow-rule into the switch adjacent to the endpoint. Alternatively, the controller could become involved in processing the first packet of a flow in either direction, in which case similar logic would be employed, with the conceptual ingress-point for the unidirectional flow being the switch adjacent to the end host.

In either case, the only additional logic required is a rule at the gateway to the external network rewriting all destination MAC addresses to that of the upstream external router.

4.2.4 Example

Consider the topology and policy described in section 2.

Upon receipt of the first packet of a new flow from the external network that is addressed for receipt by host H, the ingress switch discovers that the packet received fails to match any existing flow-rules, and therefore sends it to the controller. Using its knowledge of the network’s topology and the policy configuration, the controller selects a redundancy eliminator for handling the flow. Suppose it selected RE1.

The controller will then construct the destination MAC address 00:00:FF:04:05:02, and program the ingress switch to rewrite packets for this flow accordingly. From this point forward, the packet is processed by edge switch logic only.

The initial traversal of the fabric results in the destination MAC address being re-written to 00:00:00:FF:04:05, and that altered packet to be output from port 2 (to which RE1 is connected.) As the middlebox does not mangle L2 headers, that address will remain intact when the packet is re-received by the fabric. It will then be output from port 5, to the IPS, and, finally, from port 4, the endpoint for which the packet was originally destined.

Subsequent packets of the flow received at the ingress switch will be annotated and steered identically, without controller involvement.

5 Supporting arbitrary middleboxes

In previous sections, we limited those middleboxes supported within an active switching architecture to only those that do not modify the network address fields of traversing packets, and maintain a one-to-one correspondence between packets received and packets emitted. Those limitations, while helpful in describing the design of this system, dramatically restrict the variety of middleboxes that can be supported.

Herein we present extensions to the logic described by previous sections that can be employed to the end of supporting arbitrary middleboxes, including those that manipulate MAC addresses and originate flows.

5.1 Flow-originating middleboxes

Middleboxes that originate new flows can be trivially supported within this architecture via logic similar to that employed for reverse-path construction. Conceptually, each edge-switch adjacent to a middlebox from whence a flow might originate is treated as an ingress switch: the controller produces a path annotation for the initial packet of the flow, and subsequent packets are annotated directly in the edge switch. Each edge switch so used must then maintain state of size $O(n)$, where $n$ is again the number of flows originating at the device adjacent to the switch.

12Assuming, of course, that the link between the gateway and the upstream router is, in fact, traditional Ethernet.

13In order for H to receive this packet, the destination MAC address on the packet must be identical to the hardware address of H’s receiving interface. This is trivial, as modern interfaces near-universally support administrator-configured Ethernet addresses. We assume herein that all interfaces connected to an actively switched network will be configured with the Ethernet address "00:00:00:00:00:FF", and all ARP queries will receive a response indicating that address.

14One alternative we have explored is to have the controller respond to ARP requests directly with a path-encoded MAC address, rather than rewriting flows in the edge-switch. This mechanism can be useful, in that it reduces controller overhead substantially. It comes, however, at the cost of flexibility: individual flows cannot be independently steered; all traffic between two endpoints must follow the same path, as ARP requests are only issued on a per-host basis. What’s more, the controller may not be able to invalidate a network participant’s cached ARP-table entry: although it seems reasonable that an unsolicited ARP reply should suffice, we’ve observed that default security policy on many devices cause such packets to be ignored.

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5.2 L2-mangling middleboxes

In order to support middleboxes that are not L2-transparent, it's useful to take a step back and consider the purpose of L2-header mangling. There are two cases to consider:

5.2.1 Middleboxes providing network-layer service

By "network-layer service," we are referring to functionality that acts on packets' layer 2 headers exclusively. This would be applications such as ARP-spoofing detection, or ether-NAT.

Active switching cannot support integration of such middleboxes within the architecture. In many cases, the functionality provided by such middleboxes is not applicable to networks other than traditional Ethernet. As software-defined networking provides requisite primitives to effect the functionality of the remainder directly within the network, we do not believe that the lack of support for this class of middlebox represents a significant limitation of the architecture.

5.2.2 Middleboxes providing application-layer service

We describe a middlebox that coerces L2-transparency from middleboxes implemented as routers. This middlebox has four logical interfaces:
- upstream outer
- upstream inner
- downstream outer
- downstream inner

The outer interfaces connect to the edge of the switching fabric in the directions indicated. The inner interfaces connect to the encapsulated middlebox’s interfaces in the directions indicated. These connections are illustrated in Figure 5.

There are several plausible mechanisms by which this encapsulation layer can address the post-traversal flow re-annotation challenge resulting from the encapsulated middlebox’s L2-header mangling. We present two alternatives: the first requires some amount of semantic understanding of the behavior of the middlebox; the second does not, but constrains the number of possible path continuations of flows traversing the middlebox.

**Associative array.** Upon receipt of a packet on the upstream outer interface, the encapsulating middlebox extracts sufficient information from the packet to identify it when emitted from the encapsulated middlebox in the downstream direction, and uses that information as a key into an associative array storing the packet’s L2 addressing. The encapsulating middlebox then mangles the L2 headers as/if required by the middlebox encapsulating, and emits that packet on the upstream inner interface.

Upon receipt of a packet on the downstream inner interface, the middlebox extracts from the packet the information required to dereference the associative array, and rewrites the packet with the L2 headers thereby produced before emitting it on the downstream outer interface.

**Local DSCP tagging.** This mechanism operates similarly to the previous, with one major exception: rather than extracting information from the packet to key the array, we instead assign an identifying tag to each path continuation observed on packets prior to traversing the interior middlebox, and tag the packet with said identifier using the DSCP bits.

Using the DSCP bits in this fashion substantially mitigates the drawbacks described in section 3.2, as tags need not be globally unique, nor have consistent meaning at different points in the network. In fact, this technique can be employed even when the network as a whole utilizes the DSCP bits for QoS, although it further constrains the number of possible path continuations beyond the encapsulation layer.

6 Extensions

We present a number of example extensions to the active switching architecture that might be employed to support its use in service of policies requiring longer path-lengths, and upon network topologies other than an abstract fabric.

6.1 Path length

There are a number of mechanisms that can be employed to effect traffic steering over paths longer than five hops.
6.1.1 Address swapping

In order to support paths of up to 10 hops, simple changes are required to the algorithms presented in sections 4.2.1 and 4.2.2.

In order to encode hops six through ten, we can also utilize the source address field in the Ethernet header. We omit a detailed description of the construction algorithm, as it is obvious.

We present the modified edge-switch behavior in figure 6.

```plaintext
handle_packet(Packet P)
1  let F := P.dst_mac
2  let R := allocat_and_zero_register()
3  R ← load_field(F, 0, 8)
4  if R == 0xFE:
5    let S := P.src_mac
6  R ← load_field(S, 0, 48)
7  F ← R
8  S ← 0
9  handle_packet(P)
10  else:
11    octet_shift_field(F)
12    output_to_port(P, R)
```

Figure 6: Edge-switch logic supporting 10-hop paths

6.1.2 Flow re-annotation

To handle circumstances where even a 10 hop path is insufficient to effect steering policy, a number of techniques may be employed to re-annotate flows within the network. Three options are presented herein; the first fails to meet the goal of supporting arbitrarily long paths, while the latter two represent the extrema of a spectrum of possibilities trading switch state and performance.

**Alternative storage.** Conceivably, a number of other writable header fields within the packet could be appropriated to encode path extensions. This method would require a deeper understanding of the behavior of the middleboxes along the path, however, and would still impose a constant upper-bound on the length of a path that a packet might be steered through; we thus reject it as an insufficient solution.

**Table lookup.** When the number of possible path continuations from an edge switch is small, the final octet of a MAC address can be used as an index into a lookup-table of possibilities. This requires that the controller’s behavior upon receipt of a packet be modified such that, if a packet will require in-network re-annotation, an identifier $i$ is allocated; and a flow rule installed at the switch adjacent to the 10th hop re-annotating packets matching 00:00:00:00:00:i.

When the number of path continuations is large, match rules against L3 headers may be employed to re-annotate packets.

**Controller involved.** Trivially, every edge switch could submit all packets with empty source and destination addresses to the controller for reconsideration. This might be necessary if, for example, the path continuation of a flow beyond a certain point cannot be ascertained by the controller prior to the packet’s processing by some prior middlebox.

6.2 Larger Fabrics

The only challenge with supporting fabrics exposing more than 255 ports is that we cannot conveniently encode port identifiers in a single octet. It is, however, straightforward to modify the techniques described previously to consider, e.g., pairs of bytes to identify a port, at the cost of path-length, when the number of ports on the fabric is known or bounded. The details are omitted for brevity.

6.3 Alternate topologies

The abstraction of a network fabric is convenient for these purposes, because it allows us to cleanly differentiate between inter-hop and intra-hop routing. However, active switching can be used to effect intra-hop traffic-steering as well.

We assume a network topology consisting of an ingress switch, and no more than fifteen interior 32-port switches, connected so as to form a maximally-interconnected graph. To each interior switch are connected no more than fifteen middlebox or endpoint devices. The ingress switch connects to an external network, as before. An example of such a topology is shown in figure 7. On each switch, only the port with

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17These examples are not suggestions; they are provided only to illustrate the potential of active switching. The author respectfully submits that traffic steering over paths longer than 10 hops is a solution in search of a problem.

18Conceivably, an encoding could be developed that did not assume fixed-width port identifiers as well, although the edge-switch logic to support such a scheme appears daunting.

19It’s interesting to note that a fully-connected mesh of switches where there is only one middlebox or endpoint device connected to each interior switch is indistinguishable from a fabric for the purposes of this construction.
identifier 1 is shown; the identifiers of subsequent ports are sequential, moving in the clockwise direction.

We present two techniques for traffic steering through such a topology.

6.3.1 Hop-by-hop

Under the given topology, all traffic at any point in the network is no more than two switch traversals away from its next hop. What’s more, all traffic received by any switch from an endpoint device or middlebox must traverse at most one switch, at which point one of the attached devices must be the next hop. We can exploit these known constraints to encode a five-hop path into a MAC address by using nibbles to identify the egress port from whence a packet should be transmitted. As there are no more than sixteen possible next-hop switches, and each switch connects to no more than 15 endpoint devices, this representation is non-ambiguous.

Example. Suppose policy specified that traffic received at the ingress switch and addressed for receipt by host 8 should be first steered through host 1. The first packet of such a flow would be sent to the controller, which would determine that the sequence of ports through which the flow should be emitted are as follows: from switch A’s port 2, then from switch B’s port 1 (at which point the flow will traverse host 1), then from switch B’s port 5, and finally from switch E’s port 2 (to host 8). The controller, using this information, constructs the flow annotation “00:00:00:FF:25:12”, and installs a flow-rule tagging this flow with that destination address.

At each switch in the network, the least significant nibble is shifted off the address, and the packet is emitted out the port so identified.

6.3.2 Destination encoding

When dealing with fabrics, we claimed to be encoding port identifiers into the MAC address of packets. In order to extend that port-by-port traffic steering concept to non-fabric topologies, in the previous section we encoded the egress port from each switch into the MAC address.

However, implicit in the fabric abstraction was a one-to-one correspondence between port identifiers and the devices situated adjacent to those ports. It is as reasonable to claim that the fabric techniques encoded not port identifiers, but device identifiers, into the packet itself. We can extend this concept to non-fabric networks when the set of endpoint devices and middleboxes in the network is fixed, and the topology is known. The trade-off is that this requires maintaining $O(n)$-size state in each switch, where $n$ is the number of devices in the network.

We begin by assigning a unique identifier to the ingress switch, and to each middlebox and endpoint device. As in section 4 the controller will construct MAC addresses encoding the identifiers of each middlebox through which traffic will be steered prior to arrival at the flow endpoint.

In order to preserve identifiers over, potentially, multiple inter-switch links, the flow-table actions must be altered. In figure 8 we present an algorithm for the controller to program the switches in the network, assuming the existence of functionality to interrogate the network topology, and global arrays of network device identifiers and switches.

The function "install_rewrite_rule" installs a flow-table rule that operates as described in section 4.2.2. The function "install_forward_rule" installs a rule matching the final octet of the destination MAC address against the given identifier, and forwards the packet out the given port unmodified.

Effectively, we build a forwarding table for all identifiers in the network, for each switch in the network.

Example. Suppose the policy described in the example from section 6.3.1. Suppose further that the next-hop tables shown in table 6.3.2 have been already installed by the controller in each switch, such that destination MAC address is only shifted when a switch outputs a packet from ports 1 or 2.

The controller simply constructs the MAC address 00:00:00:FF:08:01. Switch A outputs the packet unmodified on port 2, leading to switch B, which shifts the MAC address right by an octet, and outputs the packet on port
program\_switch(Switch S)
1 for id ∈ ALL\_IDS:
2 if is\_adjacent(S, id):
3 install\_rewrite\_rule(S, id, get\_port\_for\_id(S, id))
4 else:
5 install\_forward\_rule(S, id, get\_next\_hop(S, id))

program\_network()
6 for s ∈ ALL\_SWITCHES:
7 program\_switch(s)

Figure 8: Controller algorithm for mesh-topology programming

| Source Switch | Destination ID |
|---------------|----------------|
| A | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| B | 6 | 1 | 2 | 3 | 4 | 5 | 5 | 5 |
| C | 5 | 6 | 6 | 1 | 2 | 3 | 3 | 4 |
| D | 4 | 5 | 5 | 6 | 6 | 1 | 2 | 3 |
| E | 3 | 4 | 4 | 5 | 5 | 6 | 6 | 1 |

Table 1: Next hop table showing per-switch egress port for each destination ID.

1. Upon re-receipt by switch B, it is emitted on port 5 towards switch E, unaltered. Switch E shifts the MAC address right by an octet, and emits the packet on port 2.

7 Implementation

We have implemented the functionality described in section 6.3.1 as a proof-of-concept, subject to the alteration described in footnote 14. The implementation is written in Python, and contains approximately 500 lines of code. It is constructed as a module for the POX [11] controller, and has been successfully deployed on a Mininet [8] testbed utilizing Open vSwitch.

We have additionally implemented the encapsulation layer described in section 5.2.2 so as to support middleboxes that act as routers.

8 Analysis

We consider an abstract network fabric and network controller to demonstrate the state-space advantage resulting from active switching compared to traditional match-and-forward logic. To the network fabric are attached six servers and an external connection. Of those six servers, two are connection-terminating endpoints (e.g. web servers), and the remaining four consist of two pairs of equivalent middleboxes. The controller’s configured policy is such that each new flow received from the external connection is randomly assigned to one of each type of middlebox, and one endpoint server.

Under the traditional paradigm, each new flow would result in a number of new rules being installed in all switches along the flow’s path: a match rule forwarding ingress traffic to the correct first middlebox’s edge switch, no less than four rules in each middlebox-attached edge switch (received from upstream, middlebox-bound; received from middlebox, downstream-bound; etc), and two rules in the endpoint device-attached switch. As each rule would need to uniquely identify a flow, multiple flows cannot be handled by the same rule; every new flow results in at least eleven new flow-rules being installed in the network, and control messages being sent to at least four switches.

Using active switching, we can support an arbitrary number of up to 5-hop paths through a fabric with up to 254 ports. Each edge switch adjacent to an endpoint, and the ingress switch, must maintain state of size $O(n)$, where $n$ is the number of flows that originate from the adjacent device. All other edge-switches, such as those adjacent to middleboxes, need only maintain constant-size ($O(1)$) state.

To the best of our knowledge, no existing techniques can make such claims.

9 Implications

We arrived at a number of unexpected implications relevant to various subsets of the networking community in the course of this research. We offer them herein.

For middlebox designers. Perhaps the most frustrating aspect of this work has been attempting to integrate L2-mangling middleboxes (or, as we have come to describe them informally, ”routers-with-side-effect”) into
this architecture, and we still are not entirely satisfied
with the resolution presented in section 5.2.1. Our frus-
tration is exacerbated by the fact that this L2-mangling
does not meaningfully contribute to the overall function-
ality implemented within a middlebox, but is simply an
artifact of legacy network construction and operation.
We urge middlebox designers to design middleboxes as
bridges, not routers.

For SDN architects and switch designers. We believe
that the degree to which the OpenFlow specification in-
corporates semantic understanding of upper-layer proto-
cols (such as IP and TCP) is excessive, and results in di-
minished flexibility and increased maintenance cost. Al-
though we utilize the MAC address header fields, the use
to which we put them is decidedly not for storing ad-
dresses; the semantic meaning attached to those fields
by OpenFlow is effectively a legacy meaning rendered
obsolete by SDN. However, the restrictions of active
switching (i.e. path length, port identifier size) are all
direct result of that legacy meaning— specifically, that
the addresses used in the 802.1d MAC are six bytes in
length. We suggest that primitives matching and acting
on bit-strings at given offsets into the packet would result
in a more flexible protocol, and that ease-of-use concerns
could be mitigated by incorporating the upper-layer pro-
tocol semantic awareness into a controller or switch pro-
gramming library.

We also note that register and rewrite actions vastly
increase the flexibility of software-defined networking,
and, thus, the availability and feasibility of solutions to
challenges within the networking space. We encourage
their broader availability.

For developers of SDN applications. We note that
there is a striking similarity between the logic commonly
programmed into SDN switches, and the behavior of legacy
("flood-and-learn") switches. In many applica-
tions that we have observed, it appears that the primary
contribution of SDN is to eliminate the need to flood and
to allow forwarding decisions to be made on upper-layer
headers. However, as the specificity of match rules in-
creases, a greater number of such rules are required to
describe policy for the same volume of traffic, and the
size of said match rules are significantly larger than those
of the rules learned by legacy switches.

As a result, we believe that this common approach to
the construction of software-defined networks does not
result in the promised efficiency gains of SDN, and may, in
fact, be less efficient than legacy networking. We
encourage the developers of SDN applications to explore
techniques that do not result in flow-table explosion on
the order of the number of flows.

10 Conclusion

This paper presents "active switching", a novel technique
for the construction of software-defined networks. Ac-
tive switching is a general descriptor for any technique
where flow-state is embedded into traffic, rather than
maintained in flow-table entries; and where switches' flow-
tables act as transition functions modifying flow state.
We have described the use of active switching to solve a number of issues, broadly characterized as
"traffic-steering," across a variety of network topologies;
although we suspect that the technique has far broader
applications that are left for future work. We have shown
that this technique can effect behavior from a software-
deefined network that would be challenging or impossi-
ble to implement based solely on "match-and-forward"
logic, and that this technique can result in a dramatic ef-
ficiency gains.

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