Elmo: Source-Routed Multicast for Cloud Services

Muhammad Shahbaz*, Lalith Suresh†, Jen Rexford*, Nick Feamster*, Ori Rottenstreich‡, and Mukesh Hira‡
*Princeton University †VMware ‡Technion

Abstract

We present Elmo, a system that addresses the multicast scalability problem in multi-tenant data centers. Modern cloud applications frequently exhibit one-to-many communication patterns and, at the same time, require sub-millisecond latencies and high throughput. IP multicast can achieve these requirements but has control- and data-plane scalability limitations that make it challenging to offer it as a service for hundreds of thousands of tenants, typical of cloud environments. Tenants, therefore, must rely on unicast-based approaches (e.g., application-layer or overlay-based) to support multicast in their applications, imposing overhead on throughput and end host CPU utilization, with higher and unpredictable latencies.

Elmo scales network multicast by taking advantage of emerging programmable switches and the unique characteristics of data-center networks; specifically, the symmetric topology and short paths in a data center. Elmo encodes multicast group information inside packets themselves, reducing the need to store the same information in network switches. In a three-tier data-center topology with 27K hosts, Elmo supports a million multicast groups using a 325-byte packet header, requiring as few as 1.1K multicast group-table entries on average in leaf switches, with a traffic overhead as low as 5% over ideal multicast.

1 Introduction

Cloud applications are commonly driven by systems that deliver large amounts of data to groups of endpoints in a multi-tenant data center. Common workloads include streaming telemetry workloads [83,85,89,91], where hosts continuously send telemetry data in incremental updates to a set of collectors; replication for databases [5] and state-machines [75,76,93]; distributed messaging [1,7], file-sharing [3], and machine learning [82] frameworks; as well as schedulers and load balancers that require a steady stream of telemetry information about the load on servers to make effective server selection decisions [45,101]. Publish-subscribe systems are also common building blocks for large-scale systems today [51,55,63,103]. These systems create a large number of publish-subscribe topics per tenant [57]. Infrastructure applications [106] running on top of a provider’s network, likewise, need to replicate broadcast, unknown unicast, and multicast traffic for its tenants [41].

These types of workloads naturally suggest the use of multicast, yet today’s multi-tenant data centers typically do not deploy IP multicast [14,58,86]. In practice, IP multicast is not effective, since data-center tenants introduce churn in the multicast state (e.g., due to virtual machine allocation [17,60] and migration [35,40]). IGMP [29] and PIM [47,64,100] trigger many control messages during churn, querying the entire PIM broadcast domain periodically; and are not robust to network failures [44,72,80,108]. While SDN-based solutions (like OpenFlow [84]) alleviate the control plane shortcomings of IGMP and PIM, they still do not scale to support a large number of groups in a multi-tenant data center. In particular, switching hardware supports a limited number of group-table entries only, typically thousands to a few tens of thousands [43,77,80,87].

Cloud providers, however, host hundreds of thousands of tenants [4], each of which may run tens to hundreds of applications that might benefit from network multicast. If cloud providers want to offer network multicast as a service to tenants, we believe they need to scale up to millions of multicast groups in a single data center.

In the absence of IP multicast, cloud providers and tenants typically implement multicast using a unicast overlay [13,21,30,42,68,104,109], which imposes load on the end host CPU and, therefore, cannot match network line rates. Due to such scaling limitations, certain classes of workloads (e.g., many workloads introduced by financial applications [16]) and approaches to scaling existing workloads (like Coded MapReduce [79]) cannot benefit from today’s cloud-based infrastructure at all.

In this work, we present Elmo, a system for network multicast that scales to support millions of groups in a multi-tenant data center. Our approach to scaling multicast groups is to encode the forwarding policy (i.e., multicast tree) in the packet header, as opposed to maintaining group-table entries inside network switches. Such a solution is more flexible and dynamic: the group membership is encoded in the packet itself and groups can be reconfigured by merely changing the information in the header of each packet. The challenge in doing so involves finding the right balance between how much of the forwarding information to place in the packet header (inflating both the packet size and the complexity of parsing the packet header at each switch) and how much state to put in each switch (increasing memory requirements at the switch and limiting the rates at which multicast group memberships change). As long as group sizes remain small enough to encode the entire multicast tree in the packet, there is practically no limit on the number of groups Elmo can support. To enable our scheme, we introduce a hardware primitive that is inexpensive to implement in today’s programmable switching ASICs.

Previous network multicast designs explored the tradeoff...
between packet header size and switch memory in the context of arbitrarily flexible switch architectures [69][94][111].

This paper, on the other hand, studies this tradeoff in the context of multi-tenant data centers, where we can exploit the characteristics of data-center topologies to design a more efficient packet-header encoding that can be implemented and deployed on programmable switches today. This new context allows us to take advantage of the unique characteristics of data-center topologies. First, data-center topologies tend to be symmetric (i.e., having core, spine, and leaf tiers). Second, they have a limited number of switches on any individual path. The main result of this work is a system, Elmo, to encode multicast forwarding policies in packets which takes advantage of these unique characteristics of data-center topologies and to create an encoding for multicast groups that is compact enough to fit in a header that can be parsed by programmable switches that are being deployed in today’s data centers [22][27][31].

This paper makes the following contributions. First, we develop a technique for compactly encoding multicast groups that are subtrees of multi-rooted Clos topologies (§3.2), the prevailing topology for today’s data centers [15][59][88]. These topologies create an opportunity to design a multicast group encoding that is compact enough for today’s programmable switches to process. Second, we optimize the encoding so that it can be efficiently implemented in both hardware and software targets (§3.1); our hardware primitive requires only 0.0515% in additional area cost on a modern programmable switching ASIC. Our evaluation shows that our encoding facilitates a feasible implementation in today’s multi-tenant data centers (§5). In a data center with 27K hosts, Elmo scales to millions of multicast groups with minimal group-table entries and control-plane update overhead on switches. Lastly, Elmo supports applications that use multicast without modification; we demonstrate two such applications.

2 Elmo Architecture

In Elmo, a logically-centralized controller manages multicast groups for tenants by installing flow rules in hypervisor switches (to encapsulate packets with a compact encoding of the forwarding policy) and the network switches (to handle forwarding decisions for groups too large to encode entirely in the packet header). Performing control-plane operations at the controller and having the hypervisor switches place forwarding rules in packet headers, significantly reduces the burden on network switches for handling a large number of multicast groups. Figure 1 summarizes our architecture.

**Logically-centralized controller.** The logically-centralized controller receives join and leave requests for multicast groups via an application programming interface (API). Cloud providers already expose such APIs [55] for tenants to request VMs, load balancers, firewalls, and other services. Each multicast group consists of a set of tenant VMs. The controller knows the physical location of each tenant VM, as well as the current network topology—including the capabilities and capacities of the switches, along with unique identifiers for addressing these switches. Today’s data centers already maintain such soft state about network configuration at the controller [88] (using distributed directory systems [59]). The controller relies on a high-level language (like P4 [26][28]) to configure the programmable switches at boot time so that the switches can parse and process Elmo’s multicast packets. The controller computes the multicast trees for each group and uses a control interface (like P4Runtime [112]) to install match-action rules in the switches at run time. When notified of events (e.g., network failures, and group membership changes), the controller computes new rules and updates only the affected switches (data-center controllers are capable of executing these steps in sub-second timescales [88].) The controller uses a clustering algorithm for computing compact encodings of the multicast forwarding policies in packet headers (§3.2).

**Hypervisor switch.** A software switch [49][92][96], running inside the hypervisor, intercepts multicast data packets originating from VMs. The hypervisor switch matches the destination IP address of a multicast packet in the flow table to determine what actions to perform on the packet. The actions determine: (i) where to forward the packet and (ii) what header to push on the packet. The header consists of a list of rules (packet rules, or p-rules for short)—each containing a set of output ports along with zero or more switch identifiers—that intermediate network switches use to forward the packet. These p-rules encode the multicast tree of a given group inside the packet, obviating the need for network switches to store a large number of multicast forwarding rules or update these rules when the tree changes. Hypervisor switches run as software at the edge of the network, they do not have the hard constraints on flow-table sizes and rule
update frequency that network switches have \cite{32, 49, 62, 92}. Each hypervisor switch only maintains flow rules for multicast groups that have member VMs running on the same host, discarding packets belonging to other groups.

**Network switch.** Upon receiving a multicast data packet, a physical switch (or network switch) running inside the network simply parses the header to look for a matching p-rule \textit{i.e.}, a p-rule containing the switch’s own identifier \textit{and} forwards the packet to the associated output ports, as well as popping p-rules when they are no longer needed to save bandwidth. When a multicast tree is too large to encode entirely in the packet header, a network switch may have its own group-table rule (called a switch rule, or s-rule for short). As such, if a packet header contains no matching p-rule, the network switch checks for an s-rule matching the destination IP address (multicast group) and forwards the packet accordingly. If no matching s-rule exists, the network switch forwards the packet based on a default p-rule—the last p-rule in the packet header. Elmo installs only a small number of s-rules on network switches, consistent with the small group tables available in high-speed hardware switches \cite{33, 71, 87}. The network switches in data centers form a layered topology \textit{e.g.}, Clos with leaf and spine switches grouped into pods, and core switches. Together they enable Elmo to encode multicast trees efficiently.

## 3 Encoding Multicast Trees

Upon receiving a multicast data packet, a switch must identify what set of output ports (if any) to forward the packet while ensuring it is sent on every output port in the tree and as few extra ports as possible. In this section, we first describe how to represent multicast trees efficiently, by capitalizing on the structure of data centers (topology and short paths) and capabilities of programmable switches (flexible parsing and forwarding).

### 3.1 Packet Header Design

Elmo encodes a packet forwarding policy efficiently in a packet header as a list of p-rules (Figure 2a). We introduce five key design decisions \textbf{(D1-5)} that make our p-rule encoding both \textit{compact} and \textit{simple} for switches to process.

Throughout this section, we use a three-tier multi-rooted Clos topology (Figure 3) with a multicast group stretching across three pods (marked in orange) as a running example. The topology consists of four core switches and pods, and two spine and leaf switches per pod. Each leaf switch further connects to eight hosts.

**D1: Encoding switch output ports in a bitmap.** Each p-rule uses a simple bitmap to represent the set of switch output ports (typically, 48 ports) that should forward the packet (Figure 2b). Using a bitmap is desirable because it is the internal data structure that network switches use to direct a packet to multiple output ports \cite{27}. Alternative encoding strategies use destination group members, encoded as bit strings \cite{111}; bloom filters, representing link memberships \cite{69, 94}; or simply a list of IP addresses \cite{25} to identify the set of output ports. However, these representations cannot be efficiently processed by network switches without violating line-rate guarantees (discussed in detail in \cite{3}).

Having a separate p-rule—with a bitmap and an identifier for each switch—for the multicast group in our example three-tier Clos topology (Figure 3) needs a header size of 161 bits. For identifiers, we use two bits to identify the four core switches and three bits for spine and leaf switches, each.

With bitmap encoding, the p-rule for switch $L_0$ (in Figure 3) may look like 00010111-00000000:00000000. Each bit corresponds to an output port on the given switch, indicating the downstream and upstream ports participating in the multicast tree.

**D2: Encoding on the logical topology.** Instead of having separate p-rules for each switch in the multicast tree, Elmo exploits the tiered architecture and short path lengths\footnote{\textit{e.g.}, a maximum of five hops in the Facebook Fabric topology \cite{15}} in today’s data-center topologies to reduce the number of required p-rules. In multi-rooted Clos topologies, such as our example topology (Figure 3), leaf-to-spine and spine-to-core links use multipathing. All spine switches in the same pod behave as one giant logical switch (forwarding packets to the same destination leaf switches), and all core switches together behave as one logical core switch (forwarding packets...
We order $p$-rules inside a packet by layers according to the following topological ordering: upstream leaf, upstream spine, core, downstream spine, and downstream leaf (Figure 2a). Doing so also accounts for varying switch port densities per layer. Organizing $p$-rules by layers together with the other characteristics of the logical topology allow us to further reduce header size and traffic overhead of a multicast group in four key ways:

- **a)** We only require one $p$-rule per logical switch, with all switches belonging to the same logical group using not only the same bitmap to send packets to output ports, but also requiring only one logical switch identifier in the $p$-rule.

- **b)** A multicast packet visits a layer only once, both in its upstream and downstream path. Grouping $p$-rules by layer, therefore, allows switches to pop all headers of that layer when forwarding a packet from one layer to another. This is because $p$-rules from any given layer are irrelevant to subsequent layers in the path. This also exploits the capability of programmable switches to decapsulate headers at line rate, discussed in §3. Doing so further reduces traffic overhead.

- **c)** For switches in the upstream path, $p$-rules contain only the bitmap—including the downstream and upstream ports, and a flag bit (Figure 2b: Type = 0)—without a switch identifier list. These switches simply read the first upstream $p$-rule in the packet header (Figure 2b), popping it before forwarding to the next switch in the upstream path. The flag bit indicates whether a switch should use the configured underlying multipath scheme (e.g., ECMP, CONGA, or HULA) or not. Otherwise, the upstream ports are used for forwarding packets upward to multiple switches in cases where no single spine or core has connectivity to all members of a multicast group (e.g., due to network failures, §3.3).

- **d)** Again, because a multicast packet visits a layer only once, the only switches that require upstream ports represented in their bitmaps are the leaf and spine switches in the upstream path (Figure 2c). The bitmaps of all other switches only require their downstream ports represented using bitmaps (Figure 2c: Type = 1). The shorter bitmaps for these switches, therefore, reduce space usage even further. Note, upstream ports differ based on the source, whereas, downstream ports remain identical within the same multicast group.

In our example (Figure 3), encoding on the logical topology drops the header size to 83 bits (a reduction of 48.44% from D1).

**D3: Sharing a bitmap across switches.** Even with a logical topology, having a separate $p$-rule for each switch in the downstream path could lead to very large packet headers, imposing bandwidth overhead on the network. In addition, network switches have restrictions on the packet header sizes they can parse (e.g., 512 bytes [27]), limiting the number of $p$-rules we can encode in each packet. To further reduce header sizes, Elmo assigns multiple switches within each layer (enabled by D2) to the same $p$-rule, if the switches have the same—or similar—bitmaps. Mapping multiple switches to a single bitmap, as a bitwise OR of their individual bitmap, reduces header sizes because the output bitmap of a rule requires more bits to represent than switch identifiers; for example, a datacenter with 27K hosts has approximately 1000 switches (needing 10 bits to represent switch identifiers), whereas switch port densities range from 48 to 576 (requiring that many bits) [12]. The algorithm to identify sets of switches with similar bitmaps is described in §3.2.

We encode the set of switches as a simple list of switch identifiers, as shown in Figure 2b. Alternate encodings, such as bloom filters [24], are more complicated to implement—requiring a switch to account for false positives, where mul-

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**Figure 3:** An example multicast tree on a three-tier multi-rooted Clos topology with upstream and downstream $p$- and $s$-rules assignment for a group. A packet originating from the sender is forwarded up to the logical core using the upstream $p$-rules, and down to the receivers using the downstream $p$-rules (and $s$-rules). For example, when $R = 0$ and $#s$-rules = 1, a packet arriving at $P_2$ ($S_4$ or $S_5$) from the core is forwarded using the $p$-rule 01, whereas at $P_3$, it is forwarded using the $s$-rule 11.
Multiple p-rules are a “match.” To keep false-positive rates manageable, these approaches lead to large filters [80], which is less efficient than having a list, as the number of switches with similar bitmaps is relatively small compared to the total number of switches in the data-center network.

With p-rule sharing, such that the bitmaps of assigned switches differ by at most two bits (i.e., \( R = 2 \)), logical switches \( P_2 \) and \( P_3 \) (in Figure 3) share a downstream p-rule at the spine layer. At the leaf layer, \( L_0 \) shares a downstream p-rule with \( L_6 \) and \( L_5 \) with \( L_7 \). This further brings down the header size to 62 bits (a decrease of 25.30% from D2).

**D4: Limiting header size using default p-rules.** A default p-rule accommodates all switches that do not share a p-rule with other switches (D3). Default p-rules act as a mechanism to limit the total number of p-rules in the header. For example, in Figure 3 with \( R = 0 \) and no s-rules, leaf switches \( L_6 \) and \( L_7 \) both get assigned to a default p-rule. The default p-rules are analogous to the lowest priority rule in the context of a flow table. They are appended after all the other p-rules of a downstream layer in the header (Figure 2).

The output bitmap for a default p-rule is computed as the bitwise OR of port memberships of all switches being mapped to the default rule. In the limiting case, the default p-rule causes a packet to be forwarded out of all output ports connected to the next layer at a switch (packets only make progress to the destination hosts); thereby, increasing traffic overhead because of the extra transmissions.

**D5: Reducing traffic overhead using s-rules.** Combining all the techniques discussed so far allows Elmo to represent any multicast tree without using any state in the network switches. This is made possible because of the default p-rules, which accommodate any switches not captured by other p-rules. However, the use of the default p-rule (and bitmap sharing across switches) results in extra packet transmissions that increase traffic overhead.

To reduce the traffic overhead without increasing header size, we exploit the fact that switches already support multicast group tables. Each entry, an s-rule, in the group table matches a multicast group identifier and sends a packet out on multiple ports. Before assigning a switch to a default p-rule for a multicast group, we first check if the switch has space for an s-rule. If so, we install an s-rule in that switch, and assign only those switches to the default p-rule that have no spare s-rule capacity. For example, in Figure 3 with s-rule capacity of one entry per switch (and \( R = 0 \)), both leaf switches \( L_6 \) and \( L_7 \) now have an s-rule entry instead of the default p-rule, as in the previous case (D4).

### 3.2 Algorithm for Generating p- and s-Rules

Having discussed the mechanisms of our design, we now explain how Elmo expresses a group’s multicast tree as a combination of p- and s-rules. The algorithm is executed once per downstream layer for each group. The input to the algorithm is a set of switch identifiers and their output ports for a multicast tree (input bitmaps).

**Constraints.** Every layer needs its own p-rules. Within each layer, we ensure that no more than \( H_{max} \) p-rules are used. We budget a separate \( H_{max} \) per layer such that the total number of p-rules is within a header size limit. This is straightforward to compute because (i) we bound the number of switches per p-rule to \( K_{max} \)—restricting arbitrary number of switches from sharing a p-rule and inflating the header size—so the maximum size of each p-rule is known a priori, and (ii) the number of p-rules required in the upstream direction is known, leaving only the downstream spine and leaf switches. Of these, downstream leaf switches use most of the header capacity (5).

A network switch has space for at most \( F_{max} \) s-rules, a shared resource across all multicast groups. For p-rule sharing, we identify groups of switches to share an output bitmap where the bitmap is the bitwise OR of all the input bitmaps. To reduce traffic overhead, we bound the total number of spurious transmissions resulting from a shared p-rule to \( R \), where \( R \) is computed as the sum of Hamming Distances of each input bitmap to the output bitmap.

**Clustering algorithm.** The problem of determining which switches share a p-rule maps to a well-known MIN-K-UNION problem, which is NP-hard but has approximate variants available [105]. Given the set of bitmaps \( B = \{b_1, b_2, \ldots, b_n\} \), the goal is to find \( K \) sets such that the cardinality of their union is minimized. In our case, a set is a bitmap—indicating the presence or absence of a switch port in a multicast tree—and the goal is to find \( K \) such bitmaps whose bitwise OR yields the minimum number of set bits.

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Algorithm 1 Clustering algorithm for each layer of a group

Constants: \( R, H_{max}, K_{max}, F_{max} \)

Inputs: Set of all switches \( S \), Bitmaps \( B = b_i \forall i \in S \)

Outputs: p-rules, s-rules and default-p-rule

1. p-rules ← ∅, s-rules ← ∅, default-p-rule ← ∅
2. unassigned ← B, K ← K_{max}
3. while unassigned ≠ ∅ and |p-rules| < H_{max} do
   4. bitmaps ← approx-min-k-union(K, unassigned)
   5. output-bm ← Bitwise OR of all \( b_i \) in bitmaps
   6. if dist(b_i, output-bm) ≤ R ∀ b_i ∈ bitmaps then
      7. p-rules ← p-rules ∪ bitmaps
      8. unassigned ← unassigned \ bitmaps
   9. else
      10. K ← K − 1
      11. for all \( b_i \) in unassigned do
         12. if switch \( i \) has |s-rules| < F_{max} then
            13. s-rules ← s-rules \ {b_i}
         14. else
            15. default-p-rule ← default-p-rule \ {b_i}
      return p-rules, s-rules, default-p-rule
```
Algorithm 1 shows our solution. For each group, we assign p-rules until \( H_{\text{max}} \) p-rules are assigned or all switches have been assigned p-rules (Line 3). For p-rule sharing, we apply an approximate MIN-K-UNION algorithm to find a group of \( K \) input bitmaps (Line 4) [105]. We then compute the bitwise OR of these \( K \) bitmaps to compute the resulting output bitmap (Line 5). If the output bitmap satisfies the traffic overhead constraint (Line 6), we assign the \( K \) switches to a p-rule (Line 7) and remove them from the set of unassigned switches (Line 8), and continue at Line 5. Otherwise, we decrement \( K \) and try to find smaller groups (Line 10). When \( K = 1 \), any unassigned switches receive a p-rule each. At any point if we encounter the \( H_{\text{max}} \) constraint, we fallback to computing s-rules for any remaining switches (Line 13). If the switches do not have any s-rule capacity left, they are mapped to the default p-rule (Line 15).

### 3.3 Ensuring Reachability via Upstream Ports under Network Failures

Network failures (due to faulty switches or links) require recomputing upstream p-rules for any affected groups. These rules are specific to each source and, therefore, can either be computed by the controller or, locally, at the hypervisor switches—which can scale and adapt more quickly to failures using host-based techniques like Clove [73].

When a failure happens, a packet may not reach some members of a group via any spine or core network switches using the underlying multipath scheme. In this scenario, the controller deactivates multipathing using a flag bit (D2) and does not require updating the network switches. The controller disables the flag bit in the bitmap of the upstream p-rules of the affected groups, and forwards packets using the upstream ports. Furthermore, to identify the set of possible paths that cover all members of a group, we reuse the same greedy set-cover technique as used by Portland [88] and therefore do not expand on it in this paper; for a multicast group \( G \), upstream ports in the bitmap are set to forward packets to one or more spines (and cores) such that the union of reachable hosts from the spine (and core) network switches covers all the recipients of \( G \). We evaluate how Elmo performs under failures in §5.2.3.

### 4 Elmo on Programmable Switches

In this section, we describe how we implement Elmo to run at line rate on both network and hypervisor switches. Our implementation assumes that the data center is running programmable switches like PISCES [96] and Barefoot Tofino [22] Having so entails multiple challenges for programmable switches to efficiently parse, match, and act on p-rules.

#### 4.1 Implementing on Network Switches

In network switches, typically, a parser first extracts packet headers and then forwards them to the match-action pipeline for processing. This model works well for network protocols (like MAC learning and IP routing) that use a header field to lookup match-action rules in large flow tables. In Elmo, on the other hand, we find a matching p-rule from within the packet header itself. Using match-action tables to perform this matching is prohibitively expensive (Appendix A). Instead, we present an efficient implementation by exploiting the match-and-set capabilities of parsers in modern programmable data planes.

**Matching p-rules using parsers.** Instead of using a match-action table to lookup p-rules, the switch can scan the packet as it arrives at the parser. The parser linearly traverses the packet header and stores the bits in a header vector based on the configured parse graph. Parsers in programmable switches provide support for setting metadata at each stage of the parse graph [26,27,90]. Hence, enabling basic match-and-set lookups inside the parsers.

Elmo exploits this property, augmenting the parser to check at each stage—when parsing p-rules—to see if the identifier of the given p-rule matches that of the switch. The parser parses the list of p-rules until it reaches a rule with “next p-rule” flag set to 0 (Figure 2b), or the default p-rule. If a matching p-rule is found, the parser stores the p-rule’s bitmap in a metadata field and skips parsing remaining p-rules, jumping directly to the next header (if any).

By matching p-rules inside the parser, we no longer require a match-action stage to search p-rules at each switch, thus, making switch’s memory resources available for other use, including s-rules. However, the size of a header vector (i.e., the maximum header size a parser can parse) in programmable switch chips is also fixed. For RMT [27] the size is 512 bytes. We show in §5.2 how Elmo’s encoding scheme easily fits enough p-rules within 325 bytes while supporting millions of groups. The effective traffic overhead of 325 bytes is low (§5.2.2), as these p-rules get popped with every hop.

**Forwarding based on p- and s-rules.** After parsing the packet, the parser forwards metadata to the ingress pipeline, which includes a bitmap, a matched flag (indicating the presence of a valid bitmap), and a default bitmap. The ingress pipeline implements the control flow to check for the following cases: If the matched flag is set, write the bitmap metadata to the queue manager [27], using a bitmap_port_select primitive (§5.1.2). Else, lookup the group table using the destination IP address for an s-rule. If there is a match, write the s-rule’s group identifier to the queue manager, which then converts it to a bitmap. Otherwise, use the bitmap from the default p-rule.

The queue manager generates the desired copies of the packet and forwards them to the egress pipeline [27].
the egress pipeline, we execute the following post-processing checks. For leaf switches, if a packet is going out towards the host, the egress pipeline invalidates all p-rules indicating the de-parser to remove these rules from the packet before forwarding it to the hosts. This offloads the burden at the receiving hypervisor switches, saving unnecessary CPU cycles spent to decapsulate p-rules. Otherwise, the egress pipeline invalidates all p-rules up to the p-rules(s) of the next-hop switch before forwarding the packet.

4.2 Implementing on Hypervisor Switches

In hardware switches, representing each p-rule as a separate header is required to match p-rules in the parsing stage. However, using the same approach for the hypervisor switch (like PISCES [96]) reduces throughput because each header copy triggers a separate DMA write call. Instead, to operate at line rate, we treat all p-rules as one header and encode it using a single write call (§5.4). Not doing so, decreases throughput linearly with increasing number of p-rules to pack.

5 Evaluation

In this section, we evaluate the resource and scalability requirements of Elmo. Table 1 summarizes our results.

5.1 Hardware Resource Requirements

We study the hardware resource requirements of programmable switching ASICs to process p-rules. We found Elmo inexpensive to implement in such ASICs.

5.1.1 Header usage with varying number of p-rules

Figure 4 shows percentage header usage—for a chip that can parse a 512-byte packet header e.g., RMT [27]—as we increase the number of p-rules. Each p-rule consists of four bytes for switch identifiers and a 48-bit bitmap. With 30 p-rules, we are still well within the range, consuming only 63.5% of header space for p-rules with 190 bytes available for other protocols, which in enterprises [53] and data centers [52] consume about 90 bytes [54]. We evaluated these results using the open-source compiler for P4’s behavioral model (i.e., bmv1 [23]).

5.1.2 Enabling bitmap-based output port selection

Data-plane languages (like P4 [26]) do not yet expose the output-port bit vector, network switches use for replicating packets [27], as a metadata field that a parser can set. We add support for specifying this bit vector using a new primitive action in P4. We call this new primitive bitmap_port_select. It takes a bitmap of size $N$ as input and sets the output-port bit vector field that a queue manager then uses to generate copies of a packet, routed to each egress port. The function is executed by a match-action stage in the ingress pipeline before forwarding the packet to the queue manager. We evaluate the primitive using Synopsys 28/32 nm standard cell technology [102], synthesized with a 1 GHz clock. All configurations meet the timing requirements at 1 GHz.

A typical ASIC implements multicast using a group table that maps a group identifier to a bit vector [48, 66, 97]. We implement a multiplexer block representing the hardware requirements to pass this bit vector directly to the queue manager, and a shift register showing the hardware required to pass the bit vector from the parser, through all stages of the ingress pipeline, and up to the queue manager in an RMT-style switching ASIC [22, 27]. We compute the resource requirements for four switch-port counts: 32, 64, 128, 256.

We quantify the area cost and power requirements of adding the multiplexer and shift register blocks. We evaluate the area cost against a 200 mm$^2$ baseline switching chip (as-
Hardware resource requirements: Elmo is inexpensive to implement in programmable switching ASICs ([5.1]). For a 256-port, 200 $mm^2$ baseline switching ASIC that can parse a 512-byte packet header ([54]), Elmo consumes only 63.5% of header space, at the first-hop leaf switch, even with 30 $p$-rules (Figure 4), and its primitives add only 0.0515% in area and 176 mW in power costs (Figures 5 and 6).

Scalability: Elmo scales to millions of multicast groups with minimal group-table usage and control-plane update overhead on network switches ([5.3]). In a multi-rooted Clos topology having 27K hosts and 1M multicast groups, with group sizes based on a production trace:

(i) 95-99% of groups can be encoded using a 325-byte $p$-rule header (Figure 7 and 8, left).
(ii) Spine and leaf switches use only a mean (max) of 3.8K (11K) and 1.1K (2.9K) $s$-rules (Figure 7 and 8, center).
(iii) Traffic overhead is kept within 34% and 5% of the ideal for 64-byte and 1,500-byte packets, respectively (Figure 7 and 8, right).
(iv) On average, a membership change triggers an update to 50% of hypervisor switches in a group, less than 0.006% of leaf and 0.002% of spine switches relevant to that group’s multicast tree (Table 2). With 1,000 changes per second, the average update load on hypervisor, leaf, and spine switches is 21, 5, and 4 updates per second, respectively.

Applications run unmodified, and benefit from reduced CPU and bandwidth utilization for multicast workloads ([5.3]). We run ZeroMQ (a publish-subscribe system) and sFlow (a monitoring application) on top of Elmo. Elmo enables these systems to scale to hundreds of receivers while maintaining constant CPU and bandwidth overhead at the transmitting VM (Figure 9).

End-host resource requirements: Elmo adds negligible overheads to hypervisor switches ([5.4]). A PISCES-based hypervisor switch encapsulates $p$-rules and forwards packets at line rate on a 20 Gbps link (Figure 10).

Table 1: Summary of results.

| Resource Requirement | Description |
|----------------------|-------------|
| Hardware resource    | Elmo is inexpensive to implement in programmable switching ASICs ([5.1]). For a 256-port, 200 $mm^2$ baseline switching ASIC that can parse a 512-byte packet header ([54]), Elmo consumes only 63.5% of header space, at the first-hop leaf switch, even with 30 $p$-rules (Figure 4), and its primitives add only 0.0515% in area and 176 mW in power costs (Figures 5 and 6). |
| Scalability           | Elmo scales to millions of multicast groups with minimal group-table usage and control-plane update overhead on network switches ([5.3]). In a multi-rooted Clos topology having 27K hosts and 1M multicast groups, with group sizes based on a production trace:
  (i) 95-99% of groups can be encoded using a 325-byte $p$-rule header (Figure 7 and 8, left).
  (ii) Spine and leaf switches use only a mean (max) of 3.8K (11K) and 1.1K (2.9K) $s$-rules (Figure 7 and 8, center).
  (iii) Traffic overhead is kept within 34% and 5% of the ideal for 64-byte and 1,500-byte packets, respectively (Figure 7 and 8, right).
  (iv) On average, a membership change triggers an update to 50% of hypervisor switches in a group, less than 0.006% of leaf and 0.002% of spine switches relevant to that group’s multicast tree (Table 2). With 1,000 changes per second, the average update load on hypervisor, leaf, and spine switches is 21, 5, and 4 updates per second, respectively. |
| Applications run      | Applications run unmodified, and benefit from reduced CPU and bandwidth utilization for multicast workloads ([5.3]). We run ZeroMQ (a publish-subscribe system) and sFlow (a monitoring application) on top of Elmo. Elmo enables these systems to scale to hundreds of receivers while maintaining constant CPU and bandwidth overhead at the transmitting VM (Figure 9). |
| End-host resource     | A PISCES-based hypervisor switch encapsulates $p$-rules and forwards packets at line rate on a 20 Gbps link (Figure 10). |

5.2 Scalability

5.2.1 Experiment setup

We now describe the setup we use to test the scale of the number of multicast groups Elmo can support and the associated traffic and control-plane update overhead on switches.

Topology. The scalability evaluation relies on a simulation over a large data-center topology; the simulation places VMs belonging to different tenants on end hosts within the data center and assigns multicast groups of varying sizes to each tenant. We simulate using a Facebook Fabric topology—a three-tier topology—with 12 pods ([15]). A pod contains 48 leaf switches each having 48 ports. Thus, the topology with 12 pods supports 27,648 hosts, in total. (We saw qualitatively similar results while running experiments for a two-tier leaf-spine topology like that used in CONGA ([12]).)

Tenant VMs and placement. Mimicking the experiment setup from Multicast DCN ([80]): the simulated data center has 3,000 tenants; the number of VMs per tenant follows an exponential distribution, with min=10, median=97, mean=178.77, and max=5,000; and each host accommodates at most 20 VMs. A tenant’s VMs do not share the same physical host. Elmo is sensitive to the placement of VMs in the data center; which is typically managed by a placement controller, running alongside the network controller ([10],[11]).

We, therefore, perform a sensitivity analysis using a placement strategy where we first select a pod uniformly at random, then pick a random leaf within that pod and pack up $P$ VMs of that tenant under that leaf. $P$ regulates the degree of co-location in the placement. We evaluate for $P = 1$ and $P = 12$ to simulate both dispersed and clustered placement strategies. If the chosen leaf (or pod) does not have any spare capacity to pack additional VMs, the algorithm selects another leaf (or pod) until all VMs of a tenant are placed.

Multicast groups. We assign multicast groups to each tenant such that there are a total of one million groups in the data center. The number of groups assigned to each tenant is proportional to the size of the tenant (i.e., number of VMs in that group). We use two different distributions for groups’ sizes, scaled by the tenant’s size. Each group’s member (i.e., a VM) is randomly selected from the VMs of the tenant. The minimum group size is five. We use the group-size distributions described in the Multicast DCN paper ([80]). We model the first distribution by analyzing the multicast patterns of an IBM WebSphere Virtual Enterprise (WVE) deployment,
with 127 nodes and 1,364 groups. The average group size is 60, and nearly 80% of the groups have fewer than 61 members, and about 0.6% have more than 700 members. The second distribution generates tenant’s groups’ sizes that are uniformly distributed between the minimum group size and entire tenant size (Uniform).

5.2.2 Elmo scales to millions of multicast groups with minimal flow-table usage

We first describe results for the various placement strategies under the IBM’s WVE group size distribution. We cap the p-rule header size at 325 bytes per packet, which allows up to 30 p-rules for the downstream leaf layer and two for the spine layer. We vary the number of redundant transmissions (R) permitted due to p-rule sharing. We evaluate (i) the number of groups covered using only the non-default p-rules, (ii) the number of s-rules installed, and (iii) the total traffic overhead incurred by introducing redundancy via p-rule sharing and default p-rules.

Figure 7 shows groups covered with non-default p-rules, s-rules installed per switch, and traffic overhead for a placement strategy that packs up to 12 VMs of a tenant per rack (P = 12). p-rules suffice to cover a high fraction of groups; 89% of groups are covered even when using R = 0, and 99.78% with R = 12. With VMs packed closer together, the allocated p-rule header sizes suffice to encode most multicast trees in the system. Figure 7 (left) also shows how increasing the permitted number of extra transmissions with p-rule sharing allows more groups to be represented using only p-rules.

Figure 7 (center) shows the trade-off between p-rule and s-rule usage. With R = 0, p-rule sharing tolerates no redundant traffic. In this case, p-rules comprise only of switches having exactly same bitmaps; as a result, the controller must allocate more s-rules, with 95% of leaf switches having fewer than 4,059 rules (mean 1,059). Increasing R to 6 and 12 drastically decreases s-rule usage as more groups are handled using only p-rules. With R = 12, switches have on average 2.74 rules, with a maximum of 107.

Figure 8 (right) shows the resulting traffic overhead assuming 1,500-byte packets. With R = 0 and sufficient s-rule capacity, the resulting traffic overhead is identical to ideal multicast. Increasing R increases the overall traffic overhead to 5% of the ideal. Overhead is modest because even though a data packet may have as much as 325 bytes of p-rules at the source, p-rules are removed from the header with every hop (37), reducing the total traffic overhead. For 64-byte packets, the traffic overhead for WVE increases only to 29% and 34% of the ideal when R = 0 and R = 12, still significantly improving over overlay multicast (92%) and unicast (406%).

p-rule sharing is effective even when groups are dispersed across leaves. Thus far, we discussed results for when up to 12 VMs of the same tenant were placed in the same rack. To understand how our results vary for different VM placement strategies, we explore an extreme case where the placement strategy spreads VMs across leaves, placing no more than a single VM of a tenant per rack. Figure 8 (left) shows this effect. Dispersing groups across leaves requires larger headers to encode the whole multicast tree using only p-rules. Even in this case, p-rules with R = 0 can handle as many as 750K groups, since 77.8% of groups have less than 36 switches, and there are 30 p-rules for the leaf layer—just enough header capacity to be covered only with p-rules. Increasing R to 12 ensures that 95.9% of groups are covered using p-rules. We see the expected drop in s-rule usage as well, in Figure 8 (center), with 95% of switches having fewer than 2,435 s-rules. The traffic overhead increases to within 25% of the ideal when R = 12, in Figure 8 (right), but still improving significantly over overlay multicast (92%) and unicast (406%).

p-rule sharing is robust to different group size distributions. We also study how the results are affected by different distrib-

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3In overlay multicast, the source host’s hypervisor switch replicates packets to one host under each participating leaf switch, which then replicates packets to other hosts under that leaf switch.
distributions of group sizes, larger than the Uniform group size distribution. We expect that larger group sizes will be more difficult to encode using only p-rules. We found that with the P = 12 placement strategy, the total number of groups covered using only p-rules drops to 814K at R = 0 and to 922K at R = 12. When spreading VMs across racks with P = 1, only 250K groups are covered by p-rules using R = 0, and 750K when R = 12. The total traffic overhead for 1,500-byte packets in that scenario increases to 11%.

Reducing s-rule capacity increases default p-rule usage if p-rule sizes are insufficient. Limiting the s-rule capacity of switches allows us to study the effects of limited switch memory on the efficiency of the encoding scheme. Doing so increases the number of switches that are mapped to the default p-rule. When limiting the s-rules per switch to 10K rules, and using the extreme P = 1 placement strategy, the uniform group size distribution experiences higher traffic overheads, approaching that of overlay multicast at R = 0 (87% vs 92%), but still being only 40% over ideal multicast at R = 12. Using the WVE distribution, however, brings down traffic overhead to 19% and 25% for R = 6 and R = 12, respectively. With the tighter placement of P = 12, however, we found the traffic overhead to consistently stay under 5% regardless of the group-size distribution.

Reduced p-rule header sizes and s-rule capacities inflate traffic overheads. Finally, to study the effects of the size of the p-rule header, we reduced the size so that the header could support at most 10 p-rules for the leaf layer (i.e., 125 bytes per header). In conjunction, we also reduced the s-rule capacity of each switch to 10K and used the P = 1 placement strategy to test a scenario with maximum dispersement of VMs. This challenging scenario even brought the traffic overhead to exceed that of overlay multicast at R = 12 (123%). However, in contrast to overlay multicast, Elmo still forwards packets at line rate without any overhead on the end host CPU utilization.

5.2.3 Elmo is robust to membership churn and network failures

We use the same Facebook Fabric setup to evaluate the effects of group membership churn and network failures on the control-plane update overhead on switches.

Group membership dynamics. In Elmo, we distinguish between three types of members: senders, receivers, or both. For this evaluation, we randomly assign one of these three types to each member. All VMs of a tenant who are not a member of a group have equal probability to join; similarly, all existing members of the group have an equal probability of leaving. Join and leave events are generated randomly, and the number of events per group is proportional to the group size.

| switch          | event  | # Switches updated per event |
|-----------------|--------|------------------------------|
| hypervisor      | join   | 0.3351                       |
| leaf            | join   | 0.0042                       |
| spine           | join   | 0.0015                       |
| hypervisor      | leave  | 0.4999                       |
| leaf            | leave  | 0.0061                       |
| spine           | leave  | 0.0023                       |

Table 2: The average number of hypervisor, leaf, and spine switches updated during an event in a multicast tree of a group (normalized by group sizes). Results are shown for WVE distribution.

If a member is a sender, the controller only updates the source hypervisor switch. By design, Elmo only uses s-rules if the p-rule header capacity is insufficient to encode the entire multicast tree of a group. Membership changes trigger updates to sender and receiver hypervisor switches of the group depending on whether upstream or downstream p-rules need to be updated. When a change affects s-rules, it triggers updates to the leaf and spine switches.

Reduced p-rule sizes and s-rule capacities inflate traffic overheads. Finally, to study the effects of the size of the p-rule header, we reduced the size so that the header could support at most 10 p-rules for the leaf layer (i.e., 125 bytes per header). In conjunction, we also reduced the s-rule capacity of each switch to 10K and used the P = 1 placement strategy to test a scenario with maximum dispersement of VMs. This challenging scenario even brought the traffic overhead to exceed that of overlay multicast at R = 12 (123%). However, in contrast to overlay multicast, Elmo still forwards packets at line rate without any overhead on the end host CPU utilization.

Network failures. Elmo gracefully handles spine and core switch failures[4] forwarding multicast packets via alternate paths using upstream ports represented in the groups’ p-rule bitmap ([3, 4]). During this period, some groups might experience transient loss while the network is reconfiguring [83]. In our simulations, up to 12.25% of groups are impacted when a single spine switch fails and up to 25.81% when a core switch fails. Hypervisor switches incur average (max) updates of 176.86 (1712) and 674.89 (1852), respectively. We measure that today’s hypervisor switches are capable of

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[4] When a leaf switch fails, all hosts connected to it lose connectivity to the network, and must wait for the switch to get back online.
handling batched updates of 80K requests per second (on a modest server) and, hence, can reconfigure within 25 ms of these failures.

5.2.4 Elmo’s controller computes p- and s-rules for a group within a millisecond

Our controller consistently executes Algorithm 1 for computing p- and s-rules in less than a millisecond. Across our simulations, our Python implementation computes the required rules for each group in 0.20 ms ± 0.45 ms (SD), on average, for all group sizes with a header size limit of 325 bytes. Existing studies report that it takes up to 100 ms for a controller to learn an event, issue updates to the network, and for the network state to converge [88]. Elmo’s control logic, therefore, contributes little to the overall convergence time for updates and is fast enough to support the needs of large data centers today, even before extensive optimization.

5.3 Evaluating End-to-end Applications

We ran two popular data-center applications on top of Elmo: ZeroMQ [63] and sFlow [91]. We found that these applications ran unmodified on top of Elmo and benefited from reduced CPU and bandwidth utilization for multicast workloads.

Testbed setup. The topology for this experiment comprises nine PowerEdge R620 servers having two eight cores Intel(R) Xeon(R) CPUs running at 2.00 GHz and with 32 GB of memory, and three dual-port Intel 82599ES 10 Gigabit Ethernet NICs. Three of these machines emulate a spine and two leaf switches; these machines run an extended version of the PISCES [96] switch with support for the bitmap_port_select primitive for routing traffic between interfaces. The remaining machines act as hosts, with three hosts per leaf switch.

5.3.1 Publish-subscribe using ZeroMQ

We implement a publish-subscribe (pub-sub) system using ZeroMQ (over UDP). ZeroMQ enables tenants to build pub-sub systems on top of a cloud environment (like AWS [2], GCP [6], or Azure [8]), by establishing unicast connections between publishers and subscribers.

Throughput (rps). Figure 9 (left) shows the throughput comparison in requests per second. With unicast, the throughput at subscribers decreases with an increasing number of subscribers because the publisher becomes the bottleneck; the publisher services a single subscriber at 185K rps on average and drops to about 0.25K rps for 256 subscribers. With Elmo, the throughput remains the same regardless of the number of subscribers and averages 185K rps throughout.

CPU utilization. The CPU usage of the publisher VM (and the underlying host) also increases with increasing number of subscribers, Figure 9 (right). The publisher VM consumes 32% of the VM’s CPU with 64 subscribers and saturates the CPU with 256 subscribers onwards. With Elmo, the CPU usage remains constant regardless of the number of subscribers (i.e., 4.97%).

5.3.2 Host telemetry using sFlow

As our second application, we compare the performance of host telemetry using sFlow with both unicast and Elmo. sFlow exports physical and virtual server performance metrics from sFlow agents to collector nodes (e.g., CPU, memory, and network stats for docker, KVMs, and hosts) set up by different tenants (and teams) to collect metrics for their needs. We compare the egress bandwidth utilization at the host of the sFlow agent with increasing number of collectors, using both unicast and Elmo. The bandwidth utilization increases linearly with unicast, with the addition of each new collector. With 64 collectors, the egress bandwidth utilization at the agent’s host is 370.35 Kbps. With Elmo, the utilization remains constant at about 5.8 Kbps (equal to the bandwidth requirements for a single collector).

5.4 End-host Microbenchmarks

We conduct microbenchmarks to measure the incurred overheads on the hypervisor switches when encapsulating p-rule headers onto packets (decapsulation at every layer is performed by network switches). We found Elmo imposes negligible overheads at hypervisor switches.

Setup. Our testbed has a host H1 directly connected to two hosts H2 and H3. H1 has 20 Gbps connectivity with both H2 and H3, via two 10 Gbps interfaces per host. H2 is a traffic source and H3 is a traffic sink; H1 is running PISCES with the extensions for Elmo to perform necessary forwarding.

A drawback of native multicast is that we cannot use TCP. However, protocols (like PGM [99] and SRM [50]) can support applications that require reliable delivery using native multicast.

Figure 9: Requests-per-second and CPU utilization comparison of a pub-sub application using ZeroMQ (over UDP) for both unicast and Elmo with a message size of 100 bytes.
Throughput (Mpps)

Throughput (Gbps)

Figure 10: PISCES throughput in millions of packets per second (left) and Gbps (right) when adding different number of p-rules, expressed as a single P4 header.

$H_2$ and $H_3$ use MoonGen [46] for generating and receiving traffic, respectively.

**Results.** Figure 10 shows throughput at a hypervisor switch when encapsulating different number of p-rule headers, in both packets per second (pps) and Gigabits per second (Gbps). Increasing the number of p-rules reduces the pps rate, as the packet size increases, while the throughput in bps remains unchanged. The throughput matches the capacity of the links at 20 Gbps, demonstrating that Elmo imposes negligible overhead on hypervisor switches.

6 Related Work

**Wide-area multicast.** Multicast has been studied in detail in the context of wide-area networks [20, 37, 38, 43, 95], where the lack of applications and architectural complexities led to limited adoption [44]. Furthermore, the decentralized protocols such as IGMP and PIM faced several control-plane challenges with regards to stability in the face of membership churn [44]. Over the years, much work has gone into IP multicast to address issues related to scalability [34, 69], reliability [18, 19, 50, 77], security [70], and congestion control [61, 110]. Elmo, however, is designed for data centers which differ in significant ways from the wide-area context.

**Data-center multicast.** With SDN-based data centers, a single administrative domain has control over the entire topology and is no longer required to run the decentralized protocols like IGMP and PIM. However, SDN-based multicast is still bottlenecked by limited switch group-table capacities [33, 71, 87]. Approaches to scaling multicast groups in this context have tried using rule aggregation to share multicast entries in switches with multiple groups [39, 67, 80, 81]. Yet, these solutions do not operate well in cloud environments because (1) a change in one group can cascade to other groups, (2) they do not provide address-space isolation between tenants, and (3) they cannot utilize the full bisection bandwidth of the network [80, 88]. Elmo, on the other hand, operates on a group-by-group basis, maintains address-space isolation, and makes full use of the entire bisection bandwidth.

**Application/overlay multicast.** The lack of IP multicast support, including among the major cloud providers [14, 58, 86], requires tenants to use inefficient software-based multicast solutions such as overlay multicast or application-layer mechanisms [21, 36, 42, 63, 103]. These mechanisms are built on top of unicast, which as we demonstrated in [5], incurs a significant reduction in application throughput and inflates CPU utilization. SmartNICs (like Netronome’s Agilio [9]) can help offload packet-replication burden from end hosts’ CPUs. However, these NICs are limited in their capabilities (such as flow-table sizes and the number of packets they can clone). The replicated packets contend for the same egress port; further restricting these NICs from sustaining line rate and predictable latencies. With native multicast, as in Elmo, end hosts send a single copy of the packet to the network and use intermediate switches to replicate and forward copies to multiple destinations at line rate.

**Source-routed multicast.** Elmo is not the first system to encode forwarding state inside packets. Previous work [69, 78, 94] have tried to encode link identifiers inside packets using bloom filters. BIER [111] encodes group members as bit strings, whereas SGM [25] encodes them as a list of IP addresses. Switches then look up these encodings to identify output ports. However, all these approaches require unorthodox processing at switches (e.g., loops, multiple lookups on a single table, and more) and are infeasible to implement and process multicast traffic at line rate. BIER, for example, requires flow tables to return all entries (wildcard matching the bit strings—a prohibitively expensive data structure compared to traditional match-action tables in emerging programmable data planes. SGM, on the other hand, looks up all the IP addresses in the routing table to find their respective next hops, requiring an arbitrary number of routing table lookups, thus, breaking the line-rate invariant. Contrary to these approaches, Elmo is designed to operate at line rate using modern programmable data planes (like Barefoot Tofino [22] and Cavium XPliant [31]).

7 Conclusion

In this paper, we presented Elmo, a solution to scale multicast to millions of groups per data center. Elmo encodes multicast forwarding rules inside packets themselves, reducing the need to install corresponding group-table entries in network switches. Elmo takes advantage of emerging programmable switches and unique characteristics of data-center topologies to identify compact encodings of multicast forwarding rules inside packets. Our simulations show that a 325-byte header sufficed to support a million multicast groups in a three-tier data center with 27K hosts, while using minimal group-table entries in network switches. Furthermore, Elmo is inexpensive to implement in programmable switches today and supports applications that use multicast without modification.
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A Strawman: p-rule lookups using match-action stages is expensive

Lookups in network switches are typically done using match-action tables, after the parser. We could do the same for p-rules, but using match-action tables to look up p-rules would result in inefficient use of switch resources. Unlike s-rules, p-rules are headers. Hence, to match on p-rules, we need a table that matches on all p-rule headers. In each flow rule, we only match the switch identifier with one p-rule, while wildcarding the rest. This is a constraint of match-action tables in switches that we cannot avoid. To match N p-rules, we need some number of flow-table entries.

The fundamental problem here is that instead of increasing the depth, p-rules increase the width of a table. Modern programmable switches can store millions of flow-table entries (depth). However, they are severely limited by the number of headers they can match on in a stage (width). For example, in case of RMT [27], a match-action stage consists of 106...
1K x 112b SRAM blocks and 16 2K x 40b TCAM blocks. These blocks can combine together to build wider or deeper SRAMs and TCAMs to make larger tables. For example, to implement a table that matches on ten $p$-rules, each 11-bit wide, we need three TCAM blocks (as we need wildcards) to cover 110b for the match. This results in a table of 2K entries x 120b wide. And out of these 2K entries, we only use ten entries to match the respective $p$-rules. Thus, we end up using three TCAMs for ten $p$-rules while consuming only 0.5% of entries in the table, wasting 99.5% of the entries (which cannot be used by any other stage).

An alternative to using TCAMs for $p$-rule lookups is to eschew wildcard lookups and use SRAM blocks. In this case, a switch needs $N$ stages to lookup $N$ $p$-rules in a packet, where each stage only has a single rule. This too is prohibitively expensive. First, the number of stages in a switch is limited (RMT has 16 stages for the ingress pipeline). Second, as with TCAMs, 99.9% of the SRAM entries go to waste, as each SRAM block is now used only for a single $p$-rule each (out of 1K available entries per block).