Switch as a Verifier: Toward Scalable Data Plane Checking via Distributed, On-Device Verification

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ABSTRACT

Data plane verification (DPV) is important for finding network errors. Current DPV tools employ a centralized architecture, where a server collects the data planes of all devices and verifies them. Despite substantial efforts on accelerating DPV, this centralized architecture is inherently unscalable. In this paper, to tackle the scalability challenge of DPV, we circumvent the scalability bottleneck of centralized design and design Coral, a distributed, on-device DPV framework. The key insight of Coral is that DPV can be transformed into a counting problem on a directed acyclic graph, which can be naturally decomposed into lightweight tasks executed at network devices, enabling scalability. Coral consists of (1) a declarative requirement specification language, (2) a planner that employs a novel data structure DVNet to systematically decompose global verification into on-device counting tasks, and (3) a distributed verification (DV) protocol that specifies how on-device verifiers communicate task results efficiently to collaboratively verify the requirements.

We implement a prototype of Coral. Extensive experiments with real-world datasets (WAN/LAN/DC) show that Coral consistently achieves scalable DPV under various networks and DPV scenarios, i.e., up to 1250× speed up in the scenario of burst update, and up to 202× speed up on 80% quantile of incremental verification, than state-of-the-art DPV tools, with little overhead on commodity network devices.

1 INTRODUCTION

Network errors such as forwarding loops, undesired black-holes and waypoint violations are the outcome of various issues (e.g., software bugs, faulty hardware, protocol misconfigurations, and oversight negligence). They can happen in all types of networks (e.g., enterprise networks, wide area networks and data center networks), and have both disastrous financial and social consequences [1–5]. How to detect and prevent such errors efficiently is a fundamental challenge for the network community. A major advance for this problem has been network verification, which analyzes the control plane [6, 11, 13–15, 26–28, 30–32, 40, 59, 64, 68, 71, 78, 84] and data plane [8, 9, 35, 39, 42, 43, 51, 58, 69, 70, 73, 74, 76, 77, 81, 83] of network devices to identify errors.

There has been a long line of research on data plane verification (DPV), because this approach can detect a wider range of network errors by checking the actual data plane at the network devices (e.g., switch OS bugs). More specifically, earlier tools analyzed a snapshot of the complete data plane of the network [8, 9, 42, 49, 51, 58, 69, 70, 73, 74, 76, 77, 81]; and more recent solutions focus on incremental verification (i.e., verifying forwarding rule updates) [35, 39, 41, 43, 83]. State-of-the-art DPV tools (e.g., [83]) can achieve incremental verification times of tens of microseconds per rule update.

Despite the substantial progress in accelerating DPV, existing tools employ a centralized architecture, which lacks the scalability needed for deployment in large networks. Specifically, they use a centralized server to collect the data plane from each network device and verify the requirement. Such a design requires a management network to provide reliable connections between the server and network devices, which is hard to build itself. Moreover, the server becomes the performance bottleneck and the single point of failure of DPV tools. To scale up DPV, Libra [81] partitions the data plane into disjoint packet spaces and uses MapReduce to achieve parallel verification in a cluster; Azure RCDC [39] partitions the data plane by device to verify the availability of all shortest paths with a higher level of parallelization in a cluster. However, both are still centralized designs with the limitations above, and RCDC can only verify that particular requirement.

In this paper, we systematically tackle the important problem of how to scale the data plane verification to be applicable in real, large networks. Not only can a scalable DPV tool quickly find network errors in large networks, it can also support novel services such as fast rollback and switching among multiple data planes [21, 45, 67], and data plane verification across administrative domains [22, 75].

To this end, instead of continuing to squeeze incremental performance improvements out of centralized DPV, we embrace a distributed design to circumvent the inherent scalability bottleneck of centralized design. Azure [39] takes a first step along this direction by partitioning verification
into local contracts of devices. It gives an interesting analogy between such local contracts and program verification using annotation with inductive loop invariants, but stops at designing communication-free local contracts for the particular all-shortest-path availability requirement and validating them in parallel on a centralized cluster. In contrast, we go beyond this point and show that for a wide range of requirements (e.g., reachability, waypoint, multicast and anycast), with lightweight tasks running on commodity network devices and limited communication among them, we can verify these requirements in a compositional way, achieving scalable data plane checkups in generic settings.

To be concrete, we design Coral, a generic, distributed, on-device DPV framework with a key insight: the problem of DPV can be transformed into a counting problem in a directed acyclic graph (DAG) representing all valid paths in the network; the latter can then be decomposed into small tasks at nodes on the DAG, which can be distributively executed at corresponding network devices, enabling scalability. Figure 1 gives the architecture and basic workflow of Coral, which consists of three novel components:

A declarative requirement specification language (§3). This language abstracts a requirement as a tuple of packet space, ingress devices and behavior, where a behavior is a predicate on whether the paths of packets match a pattern specified in a regular expression. This design allows operators to flexibly specify common requirements studied by existing DPV tools (e.g., reachability, blackhole free, waypoint and isolation), and more advanced, yet understudied requirements (e.g., multicast, anycast, no-redundant-delivery and all-shortest-path availability).

A verification planner (§4). Given a requirement, the planner decides the tasks to be executed on devices to verify it. The core challenge is how to make these tasks lightweight, because commodity network devices have little computation power to spare. To this end, the planner first uses the requirement and the network topology to compute a novel data structure called DVNet, a DAG compactly representing all paths in the network that satisfies the path patterns in the requirement. It then transforms the DPV problem into a counting problem on DVNet. The latter can be solved by a reverse topological traversal along DVNet. In its turn, each node in DVNet takes as input the data plane of its corresponding device and the counting results of its downstream nodes to compute for different packets, how many copies of them can be delivered to the intended destinations along downstream paths in DVNet. This traversal can be naturally decomposed to on-device counting tasks, one for each node in DVNet, and distributed to the corresponding network devices by the planner. We also design optimizations to compute the minimal counting information of each node in DVNet to send to its upstream neighbors, and prove that for requirements such as all-shortest-path availability, their minimal counting information is an empty set, making the local contracts in RCDC [39] a special case of Coral.

On-device verifiers equipped with a DV protocol (§5). On-device verifiers execute the on-device counting tasks specified by the planner, and share their results with neighboring devices to collaboratively verify the requirements. In particular, we are inspired by vector-based routing protocols [53, 61] to design a DV protocol that specifies how neighboring on-device verifiers communicate counting results in an efficient, correct way.

Experiment results (§7). We implement a prototype of Coral and will open-source it upon the publication of this paper. We evaluate it extensively using real-world datasets, in both testbed and simulations. Coral consistently outperforms state-of-the-art DPV tools under various networks (WAN/LAN/DC) and DPV scenarios, i.e., up to 1250× speed up in the scenario of burst update, and up to 202× speed up on 80% quantile of incremental verification, with little overhead on commodity network devices. Coral achieves scalable DPV for two reasons. First, by decomposing verification into lightweight tasks executed on devices, the performance of Coral achieves a scalability approximately linear to the network diameter. Second, when a data plane update happens, only devices whose counting results may change need to incrementally update their results, and send them to needed neighbors incrementally. As such, its verification time can be substantially shortened in large networks.

Updates from v2. Compared with the previous version, we have redone the incremental update experiment on the datacenter topologies of the two data plane verification tools, APKeep and AP, and updated the experimental results here. The reasons are as follows. For APKeep, in our previous incremental update experiment on datacenter topologies, we mistakenly used only 1000 rule updates, but 10000 for other tools. We correct this mistake to make the results fair and consistent, by using 10,000 rule updates in the experiments of APKeep. For the same experiments on the datacenter topologies of AP, we accidently misconfigured the rules in one switch, making the datasets inconsistent with other tools.
2 OVERVIEW
This section introduces some key concepts in Coral, and illustrates its basic workflow using an example.

2.1 Basic Concepts
Data plane model. For ease of exposition, given a network device, we model its data plane as a match-action table. Entries in the table are ordered in descending priority. Each entry has a match field to match packets on packet headers (e.g., TCP/IP 5-tuple) and an action field to process packets. Possible actions include modifying the headers of the packet and forwarding the packet to a group of next-hops [29, 39]. An empty group means the action is to drop the packet. If an action forwards the packet to all next-hops in a non-empty group, we call it an ALL-type action. If it forwards the packet to one of the next-hops in a non-empty group, we call it an ANY-type action. Given an ANY-type action, we do not assume any knowledge on how the device selects one next-hop from the group. This is because this selection algorithm is vendor-specific, and sometimes a blackbox [29].

Packet traces and universes. Inspired by NetKAT [9], we introduce the concept of packet trace to record the state of a packet as it travels from device to device, and use it to define the network behavior of forwarding packets. When a packet enters a network from an ingress device \( S \), a packet trace of \( p \) is defined as a non-empty sequence of devices visited by \( p \) until it is delivered to the destination device or dropped.

However, due to ALL-type actions, a packet may not be limited to one packet trace each time it enters a network. For example, in Figure 2, Case 1, the network forwards \( p \) along a set of two traces \( \{(S, A, B, D), (S, A, C)\} \) because \( A \) forwards \( p \) to both \( B \) and \( C \). We denote this set to be a universe of packet \( p \) from ingress \( S \). In addition, with the existence of ANY-type actions, a packet may traverse one of a number of different sets of packet traces (universes) each time it enters a network. For example, in Figure 2, if the action of \( B \) is changed to \( \text{fwd}(\text{ANY}, \{C, D\}) \), when \( p \) enters the network in different instances, the network may forward \( p \) according to the universe \( \{(S, A, B, C), (S, A, C)\} \) or the universe \( \{(S, A, B, D), (S, A, C)\} \), because \( B \) forwards \( p \) to either \( C \) or \( D \). These universes (each being a set of traces) can be thought of as a “multiverse” - should the packet enter the network multiple times, it may experience different fates each time.

The notion of universes is a foundation of Coral. We are inspired by multipath consistency [28], a property where a packet is either accepted on all paths or dropped on all paths, but go beyond. In particular, for each requirement, we verify whether it is satisfied across all universes.

2.2 Workflow
We demonstrate the basic workflow of Coral using an example in Figure 3. We consider the network in Figure 3a and the following requirement: for all packets destined to 10.0.0.0/23, when they enter the network from \( S \), they must be able to reach \( D \), the device with an external port reachable to 10.0.0.0/23, via a simple path passing \( W \). Coral verifies this requirement in three phases.

2.2.1 Requirement Specification. In Coral, operators specify verification requirements using a declarative language. A requirement is specified as a (packet_space, ingress_set, behavior) tuple. The semantic means: for each packet \( p \) in packet_space entering the network from any device in ingress_set, the traces of \( p \) in all its universes must satisfy the constraint specified in behavior, which is specified as a tuple of a regular expression of valid paths path_exp and a match operator. Figure 3a gives the program of the example requirement, where loop_free is a shortcut in the language for a regular expression that accepts no path with a loop. It specifies that when any \( p \) destined to 10.0.0.0/23 enters from \( S \), at least 1 copy of it will be delivered to \( D \) along a simple path waypointing \( W \).

2.2.2 Verification Decomposition and Distribution. Given a requirement, Coral uses a planner to decide the tasks to be executed distributively on devices to verify it. The core challenge is how to make these on-device tasks lightweight, because a network device typically runs multiple protocols (e.g., SNMP, OSPF and BGP) on a low-end CPU, with little computation power to spare. To this end, the Coral planner employs a data structure called DVNet to decompose the DPV problem into small on-device verification tasks, and distribute them to on-device verifiers for distributed execution.

From requirement and topology to DVNet. The planner first leverages the automata theory [46] to take the product of the regular expression path_exp in the requirement and the topology, and get a DAG called DVNet. Similar to the logical topology in Merlin [62] and the product graph in Propane [16] and Contra [37], a DVNet compactly represents all paths in the topology that match the pattern path_exp. It is decided only by path_exp and the topology, and is independent of the actual data plane of the network.

Figure 3c gives the computed DVNet in our example. Note the devices in the network and the nodes in DVNet have a 1-to-many mapping. For each node \( u \) in DVNet, we assign a
unique identifier, which is a concatenation of $u.dev$ and an integer. For example, device $C$ in the network is mapped to two nodes $C1$ and $C2$ in DVNet, because the regular expression allows packets to reach $D$ via $[C, W, D]$ or $[W, C, D]$.

Backward counting along DVNet. With DVNet, a DPV problem is transformed into a counting problem on DVNet: \textit{given a packet $p$, can the network deliver a satisfactory number of copies of $p$ to the destination node along paths in the DVNet in each universe?} In our example, the problem of verifying whether the data plane of the network (Figure 3b) satisfies the requirement is transformed to the problem of counting whether at least 1 copy of each $p$ destined to 10.0.0.0/23 is delivered to $D$ in Figure 3c in all of $p$’s universes.

This counting problem can be solved by a centralized algorithm that traverses the nodes in DVNet in reverse topological order. At its turn, each node $u$ takes as input (1) the data plane of $u.dev$ and (2) for different $p$ in packet space, the number of copies that can be delivered from each of $u$’s downstream neighbors to the destination, along DVNet, by the network data plane, to compute the number of copies that can be delivered from $u$ to the destination along DVNet by the network data plane. In the end, the source node of DVNet computes the final result of the counting problem.

Figure 3c illustrates this algorithm. For simplicity, we use $P_1, P_2, P_3$ to represent the packet spaces with destination IP prefixes of 10.0.0.0/23, 10.0.0.0/24, and 10.0.1.0/24, respectively. Note that $P_2 \cap P_3 = \emptyset$ and $P_1 = P_2 \cup P_3$. Each $u$ in DVNet initializes a packet space $\mapsto$ count mapping, $(P_1, 0)$, except for $D1$ that initializes the mapping as $(P_1, 1)$ (i.e., one copy of any packet in $P_1$ will be sent to the correct external ports). Afterwards, we traverse all the nodes in DVNet in reverse topological order to update their mappings. Each node $u$ checks the data plane of $u.dev$ to find the set of next-hop devices $u.dev$ will forward $P_1$ to. If the action of forwarding to this next-hop set is of ALL-type, the mapping at $u$ can be updated by adding up the count of all downstream neighbors of $u$ whose corresponding device belongs to the set of next-hops of $u.dev$ for forwarding $P_1$. For example, node $C1$ updates its mapping to $(P_1, 1)$ because device $C$ forwards to $D$, but node $W2$’s mapping is still $(P_1, 0)$ because $W$ does not forward $P_1$ to $D$. Similarly, although $W1$ has two downstream neighbors $C1$ an $D1$, each with an updated mapping $(P_1, 1)$. At its turn, we update its mapping to $(P_1, 1)$ instead of $(P_1, 2)$, because device $W$ only forwards $P_1$ to $C$, not $D$.

Given a node $u$ in DVNet, if the action of forwarding is of ANY-type, the count may vary at different universes. As such, we update the mapping at $u$ to record distinct counts at different universes. Consider the mapping update at $A1$. $A$ would forward $P_2$ to either $B$ or $W$. As such, in one universe where $A$ forwards $P_2$ to $B$, the mapping at $A1$ is $(P_2, 0)$, because $B1$’s updated mapping is $(P_1, 0)$ and $P_2 \subset P_1$. In the other universe where $A$ forwards $P_2$ to $W$, the mapping at $A1$ is $(P_2, 1)$ because $W3$’s updated mapping is $(P_1, 1)$. Therefore, the updated mapping for $P_2$ at $A1$ is $(P_2, [0, 1])$, indicating the different counts at different universes. In the end, the updated mapping of $S1 ([P_2, [0, 1]), (P_3, 1])$ reflects the final counting results, indicating that the data plane in Figure 3b does not satisfy the requirements in Figure 3b in all universes. In other words, the network data plane is erroneous.

Counting decomposition and distribution. The centralized counting algorithm in DVNet allows a natural decomposition into on-device counting tasks to be executed distributively on network devices. Specifically, for each node $u$ in DVNet, an on-device counting task: (1) takes as input the data plane of $u.dev$ and the results of on-device counting tasks of all downstream neighbors of $u$ whose corresponding devices belong to the set of next-hop devices $u.dev$ forwards packets to; (2) computes the number of copies that can be delivered from $u$ to the destination along DVNet, by the network data plane in each universe; and (3) sends the computed result to devices where its upstream neighbors in DVNet reside in. After the decomposition, the planner sends the on-device counting task of each $u$, as well as the lists of $u$’s downstream and upstream neighbors, to device $u.dev$.

2.2.3 Distributed, Event-Driven Verification using DV Protocol. After receiving the tasks from the planner, on-device verifiers execute them in a distributed, event-driven way. When events (e.g., rule update, link down and the arrival of
updated results from neighbor devices) happen, on-device verifiers update the results of their tasks, and send them to neighbors if needed. We design a DV protocol that specifies how on-device verifiers incrementally update their on-device tasks, as well as how they communicate task results, efficiently and correctly.

Consider a scenario in Figure 3, where $B$ updates its data plane to forward $P_1$ to $W$, instead of to $C$. The changed mappings of different nodes are circled with boxes in Figure 3c. In this case, device $B$ locally updates the task results of $B1$ and $B2$ to $[(P_1, 1)]$ and $[(P_1, 0)]$, respectively, and sends corresponding updates to the devices of their upstream neighbors, i.e., $[(P_1, 1)]$ sent to $A$ following the opposite of $(A1, B1)$ and $[(P_1, 0)]$ sent to $W$ following the opposite of $(W3, B2)$.

Upon receiving the update, $W$ does not need to update its mapping for node $W3$, because $W$ does not forward any packet to $B$. As such, $W$ does not need to send any update to $A$ along the opposite of $(A1, W3)$. In contrast, $A$ needs to update its task result for node $A1$ to $[(P_1, 1)]$ because (1) no matter whether $A$ forwards packets in $P_3$ to $B$ or $W$, 1 copy of each packet will be sent to $D$, and (2) $P_2 \cup P_3 = P_1$. After updating its local result, $A$ sends the update to $S$ along the opposite of $(S1, A1)$. Finally, $S$ updates its local result for $S1$ to $[(P_1, 1)]$, i.e., the requirement is satisfied after the update.

### 3 SPECIFICATION LANGUAGE

Coral provides a declarative language for operators to specify verification requirements based on the concepts of traces and universes. Figure 4 gives its simplified grammar.

**Language overview.** On a high level, a requirement is specified by a $(\text{packet\_space}, \text{ingress\_set}, \text{behavior})$ tuple, with the semantic explained in §2.2.1. To specify behaviors, we use the building block of $(\text{match\_op}, \text{path\_exp})$ entries. The basic syntax provides two $\text{match\_op}$ operators. One is $\text{exist count\_exp}$, which requires that in each universe, the number of traces matching $\text{path\_exp}$ (a regular expression over the set of devices) satisfies $\text{count\_exp}$. For example, $\text{exist} >= 1$ specifies at least one trace should match $\text{path\_exp}$ in each universe, and can be used to express reachability requirements. The other operator is $\text{equal}$, which specifies an equivalence behavior: the union of universes for each $p$ in $\text{pkt\_space}$ from each ingress in $\text{ingress\_set}$ must be equal to the set of all possible paths that match $\text{path\_exp}$ [39]. Finally, behaviors can also be specified as conjunctions, disjunctions, and negations of these $(\text{match\_op}, \text{path\_exp})$ pairs.

Two of these operators can be used to form a wide range of requirements in data plane verification. Table 1 provides examples of requirements that can be specified and verified in Coral, and the corresponding specifications in the Coral language. For example, using $\text{exist count\_exp}$, operators can express simpler requirements such as reachability, waypoint reachability, and loop-freeness, which are well studied by existing DPV tools [41–43, 74, 83], as well as more advanced requirements, such as multicast, anycast and no-redundant-delivery routing. Another example is a requirement given in Azure RCDC [39], which requires that all pairs of ToR devices should reach each other along a shortest path, and all ToR-to-ToR shortest paths should be available in the data plane. This can be formulated as an $\text{equal}$ behavior on all shortest paths across all universes (row 9 in Table 1).

Note that once a requirement is specified, Coral checks whether it is consistently satisfied across all universes. As such, the multipath consistency [28, 49] is expressed separately as reachability and isolation requirements.

**Convenience features.** Coral builds and provides operators with a $(\text{device}, \text{IP\_prefix})$ mapping for network devices with external ports (e.g., a ToR switch or a border router), where each tuple indicates that $\text{IP\_prefix}$ can be reached via an external port of $\text{device}$. If a requirement is submitted with inconsistencies between the destination IP's in $\text{packet\_space}$ and the end (destination) devices in its corresponding $\text{path\_exp}$, Coral will raise an error for operators to update this requirement.

The language provides syntax sugar to simplify the expression of requirements. For example, it allows users to specify a device set and provides device iterators. It provides shortcuts of behaviors, e.g., $\text{loop\_free}$ for the loop-free requirement. It also provides a third $\text{match\_op}$ called $\text{subset}$, which requires for packet $p$ entering the network from ingress $S$, the set of traces of $p$ in each universe is a non-empty subset of $\text{path\_exp}$. A behavior $\text{subset} \text{path\_exp}$ is a shortcut of $(\text{match} >= 1 \text{path\_exp})$ and $(\text{match} == 0 \text{\_\_} \text{and} \text{not} \text{path\_exp})$. We omit their details for the sake of simplicity.

**Expressiveness and limitation.** Our language is expressive in that it can specify all verification requirements studied in DPV literature, except for middlebox traversal symmetry [49] (i.e., $S$-$D$ and $D$-$S$ must pass the same middlebox). In addition, although not studied in DPV literature, path node/ link-disjointness cannot be expressed using our language, either. To be precise, our language can express all "single-path" requirements that compare the packet traces of one packet space with a regular-expression $\text{path\_exp}$, but cannot specify "multi-path" requirements that compare the packet
Requirements | Coral specifications
--- | ---
Reachability [28, 49, 52] | \((P, [S.\text{exist} \geq 1, S'.D])\)
Isolation [28, 49, 52] | \((P, [S.\text{exist} = 0, S'.D])\)
Loop-freeness [52] | \((P, [S.\text{exist} = 0, S'.D])\) or \((\text{not}(X'X(\text{not} Y'))\) and \((\text{not} Y')\) or \((\text{not} Y')\) for \(X'\) and \(Y'\) \(\in \Sigma\ mass\).
Black hole freeness [52] | \((P, [S.\text{exist} = 0, S'.D])\)
Waypoint reachability [41] | \((P, [S.\text{exist} = 1, S'.W'.D])\)
Reachability with limited path length [41] | \((P, [S.\text{exist} = 1, SD(S.D)]\)
Different-ingress same-paths reachability [43, 52] | \((P, [X,Y.\text{exist} = 1, X'.D'(Y'.D)])\)
In-/Cross-pod all-shortest-path reachability [39] | \((P, [S.\text{equal} S.D]) = (P, [S.\text{equal} S.D])\)
Non-redundant reachability [Coral] | \((P, [S.\text{exist} = 1, S'.D])\)
Mulicast [Coral] | \((P, [S.\text{exist} = 1, S'.D])\) and \((\text{exist} \geq 1, S'.E)\)
Anycast [Coral] | \((P, [S.\text{exist} = 1, S'.D])\) and \(\text{exist} \geq 1, S'.E)\)

Table 1: Selected requirements and their Coral specifications.

Figure 5: The finite automata of \(S.\text{W'.D with an alphabet } \Sigma = \{S, W, A, B, C, D\}\). Traces of two packet spaces. We discuss how to extend Coral to specify and verify such requirements in §6.

4 Verification Planner

We now present the design details of the planner. For ease of presentation, we first introduce DVNet and how to use it for verification decomposition assuming a requirement has only one regular expression. We then describe how to handle requirements with more than one regular expressions.

4.1 DVNet

Given a regular expression \(\text{path}_\text{exp}\) and a network, DVNet is a DAG compactly representing all paths in the network that matches \(\text{path}_\text{exp}\). There are different ways to construct a DVNet (e.g., graph dual variables). In Coral, we are inspired by network synthesis [16, 37, 62], and leverage the automata theory [46] for DVNet construction.

Specifically, given a \(\text{path}_\text{exp}\), we first convert it into a finite automata \((\Sigma, Q, F, q_0, \delta)\). \(\Sigma\) is the alphabet whose symbols are network device identifiers. \(Q\) is the set of states. \(q_0\) is the initial state. \(F\) is the set of accepting states. \(\delta: Q \times \Sigma \to Q\) is the state transition function. For example, for regular expression \(S'.W'.D\) with a network of devices \(S, W, A, B, C, D\), its corresponding finite automata is in Figure 5.

After converting \(\text{path}_\text{exp}\) to a finite automata, the planner multiplies it with the topology. The multiplication yields a product graph \(G' = (V', E')\). Each node \(u \in V'\) has an attribute \(\text{dev}\) representing the identifier of a device in the network and attribute \(\text{state}\) representing its state in the finite automata of \(\text{path}_\text{exp}\). Given two nodes \(u, v \in V'\), there exists a directed link \((u, v) \in E'\) if (1) \((u.\text{dev}, v.\text{dev})\) is a link in the network, and (2) \(\delta(u.\text{state}, v.\text{dev}) = u.\text{state}\).

Finally, the planner performs state minimization on \(G'\) to remove redundant nodes, and assigns each remaining node \(u\) a unique identifier (a concatenation of \(u.\text{dev}\) and an integer), to get the DVNet. An example of DVNet was given in Figure 3.

4.2 Verification Decomposition

The core insight of Coral is that we can transform DPV into a counting problem on DVNet, which can be naturally decomposed to small on-device counting tasks running distributively. To be concrete, first consider a requirement on a packet \(p\) in the form of \((\text{exist } \text{count}_\text{exp}, \text{path}_\text{exp})\). We can verify it by counting whether the network can deliver a satisfactory number of copies of \(p\) to the destination along paths in the DVNet in each universe. Such a problem can be solved by a traversal of nodes in DVNet in reverse topological order (Algorithm 1), during which each node \(u\) counts the number of copies of \(p\) in all allowable universes that can reach the destination nodes of DVNet from \(u\).

**Algorithm 1: Count(DVNet, \(p\)).**

1. Sort nodes in DVNet in reverse topological order: \(u_1, \ldots, u_n\).
2. foreach \(u_i, i = 1, \ldots, n\) do
   3. if \(u_i\) is a destination then
      4. \(c_i → 1\)
   5. else
      6. foreach \(v_j \in N_d(u_i)\) do
         7. if \(v_j.\text{dev} = u_i.\text{dev}, f.\text{wd}(p)\) then
            8. \(b_{ij} → 1;\)
      9. if \(u_i.\text{dev}, f.\text{wd}(p).\text{type} = \text{ALL}\) then
         10. Update \(c_u\) with Equation (1);
      11. else
         12. Update \(c_u\) with Equation (2);
   13. return \(c_u\);

For example, in Figure 3c, for packets in \(P_1\), the count at \(W'1\) is \(1\), the result of \(C1\), because \(W'\) only forwards \(P_1\) to \(C,\) not other devices.
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Next, define $\oplus$ as the union operator for sets. Let $\delta = 1$ if $u_i.deo$ forwards $p$ to at least one device that does not have a corresponding node in $N_D(u_i)$ in DVNet, and 0 otherwise. If $u_i$'s forwarding action for $p$ is of type ANY, i.e., $p$ will be forwarded to one of the next-hops in the rule, the count of $p$ at $u_i$ is,

$$c_{u_i} = \begin{cases} \bigoplus_j h_j = 1(c_{v_j}), & \text{if } \delta = 0, \\ \bigoplus_j h_j = 1(c_{v_j}) \oplus 0, & \text{if } \delta = 1. \end{cases} \quad (2)$$

Still in Figure 3c, for packets in $P_2$, the count at $A1$ is $[0, 1]$, the union of $[0]$ from $B1$ and $[1]$ from $W3$ because $A1$'s device $A$ forwards packets in $P_2$ to either $B$ or $W$. We give a proof sketch of Algorithm 1's correctness in Appendix A.1.

**Distributed counting.** Algorithm 1 can be naturally decomposed to small counting tasks, one for each node $u$ in DVNet, to enable distributed counting. The planner sends the task of $u$ to $u.deo$, with the lists of downstream and upstream neighbors of $u$. $u.deo$ receives the counts from $v_j.deo$, where $v_j \in N_D(u)$, computes $c_u$ using Equations (1)(2), and sends $c_u$ to the corresponding devices of all $u$'s upstream neighbors in DVNet. In the end, the counts at source node of DVNet (e.g., $c_{S1}$ at $S1$ in Figure 3c) is the numbers of copies of $p$ delivered to the destination of $DVNet$ in all $p$'s universes. The device of the source node can then easily verify the requirement.

**Optimizing counting result propagation.** When there are a huge number of paths in DVNet, the counting result set $c_u$ can be large due to ANY-type actions at devices (e.g., a chained diamond topology). Letting $u.deo$ send the complete $c_u$ to the devices of $u$'s upstream neighbors may result in large communication and computation overhead at devices. Given a requirement, we define the minimal counting information of each node $u$ as the minimal set of elements in $c_u$ that needs sending to its upstream nodes so that the source node in $DVNet$ can correctly verify the requirement, assuming arbitrary data planes at devices. We design optimizations to find such minimal counting information for requirements with exist count_exp and equal operations, respectively.

For exist count_exp operation, our optimization is based on the monotonicity of $\oplus$. Suppose two sets $c_1$, $c_2$ whose elements are all non-negative. For any $x \in c_1$ and $y \in c_2$, $a = x + y \in c_1 \oplus c_2$ satisfies $a \geq x$ and $a \geq y$. We then have:

**Proposition 1.** Given a requirement with exist count_exp operation, the minimal counting information of node $u$ is $\min(c_u)$, $\max(c_u)$ if count_exp is $\geq N$ or $> N$ ($\leq N$ or $< N$), and the first $\min(|c_u|, 2)$ smallest elements in $c_u$ if count_exp is $== N$. The proof is in Appendix A.2.

For a requirement with an equal operator, we prove that the minimal counting information of any $u$ is $\emptyset$, making distributed verification become local verification. Specifically, no node $u$ even needs to compute $c_u$. Instead, it only needs to check if $u.deo$ forwards any packet specified in the requirement to all the devices corresponding to the downstream neighbors of $u$ in DVNet. If not, a network error is identified, and $u.deo$ can immediately report it to the operators. This optimization achieves local verification on generic equivalence requirements, making the local contracts on all-shortest-path availability in Azure RCDC [39] a special case.

**Computing consistent counting results.** Counting tasks are event-driven. Given a task for $u$, when an event (e.g., a rule update or a physical port down at $u.deo$, or a count update received from the device of a downstream neighbor of $u$), $u.deo$ updates the counting result for $u$, and sends it to the devices of $u$'s upstream neighbors if the result changes. As such, assuming the network becomes stable at some point, the device of source node of DVNet will eventually update its count result to be consistent with the network data plane.

**Updating tasks.** The process of the planner decomposing requirement to count tasks and sending to devices is similar to configuring routing protocols. After the planner sends the tasks to devices, the on-device verifiers run independently without the need of the planner. Only when the planner receives a new requirement, or the topology is changed by administrator (e.g., adding a link), the planner will update the tasks by regenerating DVNet, and send them to the devices.

### 4.3 Compound requirements
We now describe how the planner decides the on-device counting tasks for a requirement with multiple path_exp. We focus on requirements with a logic combination of multiple (exist count_exp, path_exp) pairs, because equal operator can be verified locally. In particular, the case where a compound requirement with path_exp with different sources can be handled by adding a virtual source device connecting to all the sources. As such, we divide compound requirements based on the destinations of regular expressions.

**Regular expressions with different destinations.** One may think a natural solution is to build a DVNet for each path_exp, let devices count along all DVNets, and cross-produce the results at the source. However, this is incorrect. Consider an anycast requirement for $S$ to reach $D$ or $E$, but not both (Figure 6a). This requirement is satisfied in the network. However, if we build two DVNets, one for each destination, we get two chains $S1 \rightarrow D1$, and $S2 \rightarrow E1$. After

Figure 6: Verifying an anycast, a requirement with multiple path_exp with different destinations.
counting on both DVNets, S1 gets a set [0, 1] for reaching D1, and S2 gets [0, 1] for reaching E1. The cross-product computed by device S would be [(0, 0), (0, 1), (0, 1), (1, 1)], raising a false positive of network error.

To address this issue, for a requirement with multiple \( (\text{exist } \text{count}_\text{exp}, \text{path}_\text{exp}) \) pairs where \( \text{path}_\text{exp} \)s have different destinations, we let the planner construct a single DVNet representing all paths in the network that match at least one \( \text{path}_\text{exp} \), by multiplying the union of all regular expressions with the topology, and specify one counting task for one regular expression, at all nodes in DVNet, including all destination nodes. Consider the same anycast example. The planner computes one DVNet in Figure 6b. Each node counts the number of packets reaching both D and E. The count of D1 is \( (S^*D, 1), (S^*E, 0) \) and E1 is \( (S^*D, 0), (S^*E, 1) \). Such results are sent to S1. After S1 processes it using Equation (2), it determines that in each universe, a packet is sent to D or E, but not both, i.e., the requirement is satisfied.

**Regular expressions with the same destination.** Following the design for the case of different destinations, one may be tempted to handle this case by also constructing a single DVNet for the union of such \( \text{path}_\text{exp} \)s. However, because these \( \text{path}_\text{exp} \)s have the same destination, the counting along DVNet cannot differentiate the counts for different \( \text{path}_\text{set} \)s, unless the information of paths are collected and sent along with the counting results. This would lead to large communication and computation overhead across devices.

Another strawman is to construct one DVNet for one regular expression, count separately and aggregate the result at the source via cross-producing. However, false positives again can arise. Consider Figure 7a and the requirement

\[
(P, [S], (\text{exist } \geq 2, (S^*D \text{ and loop_free}) \text{ or } (\text{exist } \geq 1, S^*W^*D \text{ and loop_free}))), \tag{3}
\]

which specifies at least two copies of each packet in P should be sent to D along a loop-free path, or at least one copy should be sent to D along a loop-free path passing W. We observe that the data plane satisfies this requirement. However, suppose we construct a DVNet for each \( \text{path}_\text{exp} \), and perform counting separately. S will receive a counting result [1, 2] for reaching D with a simple path, and a counting result [0, 1] for reaching D with a simple path passing W. The cross-product results \( [(1, 0), (1, 1), (2, 0), (2, 1)] \) indicate that a phantom violation is found.

To address issue, we handle this requirement by adding virtual destination devices. Suppose a requirement has \( m \) \( (\text{exist } \text{count}_\text{exp}_i, \text{path}_\text{exp}_i) \) pairs with \( \text{path}_\text{exp}_i \)s have the same destination D. The planner changes D to \( D^i \) and adds \( m - 1 \) virtual devices \( D^i \) \( (i = 2, \ldots, m) \). Each \( D^i \) has the same set of neighbors as D does, in the network topology. It then rewrites the destination of \( \text{path}_\text{exp}_i \) to \( D^i \) \( (i = 1, \ldots, m) \).
destination node in DVNet. Specifically, for each X.node, X stores three distinct types of CIB:

- **CIBIn(v)** for each of X.node’s downstream neighbors v: it stores the latest, unprocessed counting results received from v in a (predicate, count) mapping;
- **LocCIB(X.node)**: it stores for different predicates, the latest number of packet copies that can reach from X.node to the destination node in (predicate, count, action, causality) tuples, where the causality field records the input to get the count field (i.e., the right hand side of Equations (1)(2));
- **CIInOut(X.node)**: it stores the counting results to be sent to the upstream nodes of X.node in (predicate, count) tuples.

Figure 8a gives an example DVNet. with the counts of node u, v, z, the LEC table of u.dev, and CIBIn(u), CIBIn(z) and LocCIB(u) at node u. Specifically, the causality field is ([v, P1, 1], [z, P1, 1]) because the count 2 of predicate P1 is computed via the results of both v and z (i.e., 2 = 1 + 1).

5.2 Message Format and Handling

Messages in the DV protocol are sent over TCP connections. The protocol defines control messages (e.g., OPEN and KEEPALIVE) to manage the connections between devices. We focus on the UPDATE message, which is used to transfer counting results from the device of a node to the devices of its upstream neighbors in DVNet.

**UPDATE message format.** An UPDATE message includes three fields: (1) intended link: a tuple indicating along which link in DVNet the counting result is propagated oppositely; (2) withdrawn predicates: a list of predicates whose counting results are obsolete; and (3) incoming counting results: a list of predicates with their latest counts. The intended link is to differentiate links in DVNet with the same pair of devices (e.g., (W1, C1) and (W3, C1) in Figure 3c).

**UPDATE message invariant.** For the withdrawn predicates and incoming counting results, the DV protocol maintains an important invariant: for each UPDATE message, the union of the withdrawn predicates equals the union of the predicates in the incoming counting results. This ensures that a node always receives the latest, complete counting results from its downstream neighbors, guaranteeing the eventual consistency between the verification result at the device of source node of DVNet and a stable data plane.

**UPDATE message handling.** Consider link (u, v) in DVNet. Suppose u.dev receives from v.dev an UPDATE message whose intended link is (u, w). u.dev handles it in three steps. **Step 1: updating CIBIn(v).** u.dev updates CIBIn(v) by removing entries whose predicates belong to withdrawn predicates and inserting all entries in incoming counting results. **Step 2: updating LocCIB(u).** To update LocCIB(u), u.dev first finds all affected entries, i.e., the ones that need to be updated. To be concrete, an entry in LocCIB(u) needs to be updated if its causality field has one predicate from v and belongs to the withdrawn predicates of this message. It then updates the counting results of all affected entries one by one. Specifically, for each pair of an affected entry r and an entry r’ from the incoming counting results, u.dev computes the intersection of their predicates. If the intersection is not empty, a new entry r.new is created in LocCIB(u) for predicate r.pred ∩ r’.pred. The count of r.new is computed in two steps: (1) perform an inverse operation of ⊕ or ⊗ between r.count and v’s previous counting result in v.causality, to remove the impact of the latter; and (2) perform ⊕ or ⊗ between the result from the last step and r’.count to get the latest counting result. The action field is the same as r. The causality of this entry inherits from that of r, with tuple (v, r’) replacing v’s previous record. After computing and inserting all new entries, all affected entries are removed from LocCIB(u).

Figure 8b shows how u in Figure 8a processes an UPDATE message from v.dev to update its CIBIn(v) and LocCIB(u).

**Step 3: updating CIInOut(u).** u.dev puts the predicates of all entries removed from LocCIB(u) in the withdrawn predicates. For all inserted entries of LocCIB(u), it strips the action and causality fields, merges entries with the same count value, and puts the results in the incoming counting results.

After processing the UPDATE message, for each upstream neighbor w of u, u.dev sends an UPDATE messaging consisting of an intended link (w, u) and CIInOut(u).
Internal event handling. If u.dev has an internal event (e.g., rule update or link down), we handle it similar to handling an UPDATE message. For example, if a link is down, we consider predicates forwarded to that link update their counts to 0. Specifically, the predicates whose forwarding actions are changed by the event are considered as withdrawn predicates and the predicates in incoming count results of an UPDATE message. Different from handling regular UPDATE messages, no CIBIn(𝑢) needs updating. The counts of newly inserted entries in LocCIB(𝑢) are computed by inverting ⊕/⊖ and reading related entries in different CIBIn(𝑢)s. Only predicates with new counts are included as withdrawn predicates and incoming counting results in CIBOut(𝑢).

Outbound UPDATE message suppression. Multiple rule updates may occur in a short time during a network event (e.g., a configuration update). Verifying the transient DP may not be necessary, and waste computation and communication resources. As such, the DV protocol provides an optional dampening mechanism: after u.dev finishes processing an UPDATE message, before sending any UPDATE messages, it first checks if it still has unprocessed UPDATE messages with an intended link from u or internal events. If so, it continues processing them until no one is left unprocessed, and sends the latest CIBOut(𝑢) in one UPDATE message.

6 EXTENSIONS
Packet transformations. For data planes with packet transformations, Coral uses BDD to encode such actions [77], and extends the CIB and the DV UPDATE message to record and share the count results of packet transformation actions.

Large networks with a huge number of valid paths. One concern is that DVNet may be too large to generate in large networks with a huge number of valid paths. First, our survey and private conversations with operators suggest that they usually want the network to use paths with limited hops, if not the shortest one. The number of such paths is small even in large networks. Second, if a network wants to verify requirements with a huge number of valid paths, Coral is inspired by BGP to verify them via divide-and-conquer: divide the network into partitions abstracted as one-big-switches, construct DVNet on this abstract network, and perform intra-/inter-partition distributed verifications.

Incremental deployment. Coral can be deployed incrementally in two ways. The first is to assign an off-device instance (e.g., VM) for each device without an on-device verifier, who plays as a verifier to collect the data plane from the device and exchange messages with other verifiers based on DVNet. This is a generalization of the deployment of RCDC, whose local verifiers are deployed in off-device instances. The second is the divide-and-conquer approach above. We deploy one verifier on one server for each partition. The verifier collects the data planes of devices in its partition to perform intra-partition verification, and exchanges the results with verifiers of other partitions for inter-partition verification. The two approaches are not exclusive.

Multi-path comparison. The Coral specification language (§3) currently does not support specifying “multi-path” requirements that compare the packet traces of two packet spaces (e.g., route symmetry and node-disjointness). To address this issue, one may extend the syntax with an id keyword to refer to different packet spaces, and allow users to define trace comparison operators using predicate logic. To verify them, one may construct the reachability DVNet for each packet space, let on-device verifiers collect the actual downstream paths and send them to their upstream neighbors, and eventually perform the user-defined comparison operation with the complete paths of the two packet spaces as input. We leave its full investigation as future work.

7 PERFORMANCE EVALUATION
We implement a prototype of Coral in Java with ~8K LoC (Appendix B) and conduct extensive evaluations. We focus on answering the following questions: (1) What is the capability of Coral in verifying a wide range of requirements? (§7.1) (2) What is the performance of Coral in a testbed environment with different types of network devices, mimicking a real-world wide area network (WAN)? (§7.2) (3) What is the performance of Coral in various real-world, large-scale networks (WAN/LAN/DC) under various DPV scenarios? (§7.3) (4) What is the overhead of running Coral on commodity network devices? (§7.4)

7.1 Functionality Demonstrations
To demonstrate the capability of Coral in verifying a wide range of DPV requirements, we assemble a network of six switches: 4 Mellanox SN2700 switches, 1 Edgecore whitebox switch and 1 Barefoot Tofino switch (Table 2). The first two models are installed SONiC [55], and the third is installed ONL [60]. The topology is the same as in Figure 3a. For each device, we deploy a Coral on-device verifier.

We run experiments to verify (1) loop-free, waypoint reachability from 𝑆 to 𝐷 in Figure 3a, (2) loop-free, multicast from 𝑆 to 𝐶 and 𝐷, (3) loop-free, anycast from 𝑆 to 𝐵 and 𝐷, (4) different-ingress consistent loop-free reachability from 𝑆 and 𝐵 to 𝐷, and (5) all-shortest-path availability from 𝑆 to 𝐶. After the planner sends the on-device tasks to switches, we disconnect it from the switches. We then configure devices with a correct data plane satisfying these requirements and run the experiment. As expected, no data plane error is reported by on-device verifiers. Next, we iteratively reconfigure devices with an erroneous data plane that violates one

| Models               | CPU                     | Cores |
|----------------------|-------------------------|-------|
| Mellanox SN2700 [54] | Intel(R) Celeron(R) CPU D4317E @ 1.60GHz | 2     |
| Edgecore Wedge32-100X [24] | Intel(R) Pentium(R) CPU D3157 @ 1.60GHz | 4     |
| Barefoot s9180-32X [12] | Intel(R) Xeon(R) CPU D-1527 @ 2.08GHz | 8     |

Table 2: Devices in the testbed.
of the requirements above, and rerun the experiments. Each time, the on-device verifier at S successfully reports the error, except for the final experiment, where we configure device B with an incorrect data plane to violate the all-shortest-path reachability from S to C. This time, the verifier on B locally detects and reports this error without propagating any message to neighbors. This shows that Coral can verify the all-shortest-path availability locally as RCDC does, making it a special case of Coral. Details of these demos can be found at [10].

7.2 Testbed Experiments
We extend our testbed with 3 Barefoot switches, to mimic the 9-device Internet2 WAN [56]. We install the forwarding rules of different devices to corresponding switches in the testbed, and inject latencies between switches, based on the propagation latencies between the locations of Internet2 devices [72]. We verify the conjunction of loop-freeness, blackhole-freeness and all-pair reachability between switches along paths with (≤x+2) hops, where x is the smallest-hop-count for each pair of switches.

Experiment 1: burst update. We first evaluate Coral in the scenario of burst update, i.e., all forwarding rules are installed to corresponding switches all at once. Coral finishes the verification in 0.99 seconds, outperforming the best centralized DPV in comparison by 2.09× (Figure 9a).

Experiment 2: incremental update. We start from the snapshot after the burst update, randomly generate 10K rule updates distributed evenly across devices and apply them one by one. After each update, we incrementally verify the network. For 80% of the updates, Coral finishes the incremental verification ≤ 5.42ms, outperforming the best centralized DPV in comparison by 4.90×. This is because in Coral, when a rule update happens, only devices whose on-device task results are affected need to incrementally update their results, and only these changed results are sent to neighbors incrementally. For most rule updates, the number of these affected devices is small (shown in Appendix D).

For both experiments, we also measure the overhead of running Coral on-device verifiers on switches. We present the results in a more comprehensive way in §7.4.

7.3 Large-Scale Simulations
We implement an event-driven simulator to evaluate Coral in various real-world networks, on a server with 2 Intel Xeon Silver 4210R CPUs and 128 GB memory.

7.3.1 Simulation Setup. We first introduce the settings. Datasets. We use 13 datasets in Table 3. The first four are public datasets and the others are synthesized with public topologies [34, 38, 44, 63]. Fattree is a 48-ary fattree [7]. NG-Clos is a real, large, Clos-based DC. For WAN, we assign link latencies based on the device locations in the datasets [72]. For LAN and DC, we assign 10µs latency for each link.

Table 3: Datasets statistics.

| Network          | #Devices | #Links | #Rules | Type  |
|------------------|----------|--------|--------|-------|
| Internet2 [56]   | 9        | 28     | 3.84×10^2| WAN   |
| Stanford [42]    | 16       | 74     | 3.84×10^2| LAN   |
| Airtel1-1 [35]   | 16       | 26     | 2.83×10^2| WAN   |
| Airtel2-1 [35]   | 35       | 135    | 3.81×10^2| WAN   |
| Airtel1-2        | 16       | 26     | 9.60×10^2| WAN   |
| Airtel2-2        | 35       | 135    | 4.56×10^2| WAN   |
| NTT              | 11       | 43     | 7.92×10^2| WAN   |
| BT North America | 96       | 76     | 2.52×10^2| WAN   |
| OTEGlobe         | 93       | 103    | 7.22×10^4| WAN   |
| Fatree (E = 85)  | 2.850    | 9.285 | 3.13×10^4| LAN   |
| NG-Clos          | 6.016    | 6.008 | 3.13×10^4| DC    |

Comparison methods. We compare Coral with four state-of-the-art centralized DPV tools: AP [74], APKeep [83], Delta-net [35] and Veriflow [43]. We reproduce APKeep and Delta-net, and use the open-sourced version of AP and Veriflow.

Requirements. We verify the all-pair loop-free, blackhole-free, (≤x+2)-hop reachability in §7.2 for WAN/LAN and the all-ToR-pair shortest path reachability for DC. We also use Coral to verify the local contracts of all-shortest-path availability of DC, as RCDC does, in Appendix F.

Metric. We study the verification time. It is computed as the period from the arrival of data plane updates at devices to the time when all requirements are verified, including the propagation delays. For centralized DPV, we randomly assign a device as the location of the server, and let all devices send data planes to the server along lowest-latency paths. We also measure Coral’s message overhead in Appendix D.

7.3.2 Results: Burst Update. Figure 9a gives the results. For WAN/LAN, Coral completes the verification in ≤ 1.60s and achieves an up to 6.35× speedup than the fastest centralized DPV. For DC, this speedup is up to 1250.28×. This is because Coral decomposes verification into lightweight on-device tasks, which have a dependency chain roughly linear to the network diameter. A DC has a small diameter (e.g., 4 hops). As such, on-device verifiers achieve a very high level of parallelization, enabling high scalability of Coral.

We note that Coral is slower than AP in Airtel1-1 and Airtel1-2, but faster in Airtel2-1 and Airtel2-2 whose topologies are the same pairwise. This is because the latter two have a much higher number of rules (3.39× and 11.97×). The bottleneck of AP is to transform rules to equivalence classes (ECs), whose time increases linearly with the number of rules, leading to a linear increase of total time. In contrast, Coral only computes LEC on devices in parallel, and is not a bottleneck (Appendix C). As such, with more rules, Coral becomes faster than AP.

7.3.3 Results: Incremental Update. We evaluate Coral for incremental verification using the same methodology as in §7.2. Figure 9b gives the results. The 80% quantile verification time of Coral is up to 202.58× faster than the fastest centralized DPV. Among all datasets, Coral finishes verifying at least 72.72% rule updates in less than 10ms, while this lower
bound of other tools is less than 1%. This is for the same reason as in experiments (§7.2) and shown in Appendix D, and demonstrates that Coral consistently enables scalable data plane checkups under various networks and DPV scenarios.

7.4 On-Device Microbenchmarks

We run extensive microbenchmarks to measure the overhead of Coral on-device verifiers. We also measure the latency of computing DVNet and on-device tasks in Appendix G.

**Initialization overhead.** For each of 414 devices from WAN/LAN and 6 devices from NGClos/Fattree (one edge, aggregation and core switch, respectively), we measure the overhead of its initialization phase in burst update (i.e., computing the initial LEC and CIB), in terms of total time, maximal memory and CPU load, on the three switch models in our testbed. The CPU load is computed as CPU time / (total time × number of cores). Figure 10 plots their CDFs. On all three switches, all devices in the datasets complete initialization in ≤ 1.5s, with a CPU load ≤ 0.48, and a maximal memory ≤ 19.6MB.

**DV UPDATE message processing overhead.** For each of the same set of devices in the datasets, we collect the trace of their received DV UPDATE messages during burst update and incremental update experiments, replay the traces consecutively on each of the three switches, and measure the message processing overhead in terms of total time, maximal memory, CPU load and per message processing time. Figure 11 shows their CDFs. For 90% of devices, all three switches process all UPDATE messages in ≤ 2.29s, with a maximal memory ≤ 32.08MB, and a CPU load ≤ 0.20. And for 90% of all 835.2k UPDATE messages, the switches can process it in ≤ 4ms.

To summarize, the initialization and messaging processing overhead microbenchmarks show that Coral on-device verifiers can be deployed on commodity network devices with little overhead.

**8 RELATED WORK**

Network verification includes control plane verification (CPV) that finds errors in configurations [6, 11, 13–15, 26–28, 30–32, 40, 59, 64, 68, 71, 78, 84]; and DPV that checks the correctness of the data plane. Coral is a DPV tool, and can help simulation-based CPV [28, 47, 50] verify the simulated DP.

**Centralized DPV.** Existing DPV tools [8, 35, 39, 41–43, 49, 51, 58, 69, 70, 73, 74, 76, 77, 81, 83] use a centralized server to collect and analyze the data planes of devices. Despite substantial efforts on performance optimization, the centralized design makes them unscaleable in nature due to the need for reliable server–network connections and the server being a bottleneck and single PoF. To scale up DPV, Plotkin et al. [58] exploit the symmetry and surgery in topology to aggregate the network to a smaller one. Libra [81] parallelizes DPV by partitioning the data plane into subnets. RCDC [39] parallelizes verifying all-shortest-path availability by partitioning the data plane by device. However, they are still centralized designs with the limitations above. In contrast, Coral adopts a distributed design, to systematically decompose DPV into
We design Coral, a distributed DPV framework to achieve scalable data plane checkups on a wide range of requirements.

**Verification of stateful/programmable DP.** Some studies investigate the verification of stateful DP (e.g., middleboxes) [20, 57, 79, 80, 82] and programmable DP (e.g., P4 [18]) [23, 48]. Studying how to extend Coral to verify stateful and programmable DP would be an interesting future work.

**Network synthesis.** Synthesis [16, 25, 37, 62, 65] is complementary to verification. Coral is inspired by some of them [16, 37, 62] to use automata theory to generate DVNet.

**Predicate representation.** Coral chooses BDD [19] to represent packets for its efficiency. Recent data structures (e.g., ddNF [17] and #PEC [36]) may have better performance and benefit Coral. We leave this as future work.

## 9 CONCLUSION

We design Coral, a distributed DPV framework to achieve scalable DPV by decomposing verification to lightweight on-device counting tasks. Extensive experiments demonstrate the benefits of Coral to achieve scalable DPV. This work does not raise any ethical issues.

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A PROOFS OF DVNET BACKWARD COUNTING

A.1 Proof Sketch of the Correctness of Algorithm 1

Given a packet $p$ and a DVNet, the goal of Algorithm 1 is to compute the number of copies of $p$ that can be delivered by the network to the destination of DVNet along paths in the DVNet in each universe. Suppose Algorithm 1 is incorrect. There could be three cases: (1) there exists a path in DVNet that is provided by the network data plane, but is not counted by Algorithm 1; (2) There exists a path in DVNet that is not provided by the network data plane, but is counted by Algorithm 1; (3) Algorithm 1 counts a path out of DVNet.

None of these cases could happen because at each node $u$, Equations (1) (2) only counts $c_v$ of $v$ with $b_{ij} = 1$, i.e., the downstream neighbors of $u$ whose devices are in the next-hops of $u.dev$ forwarding $p$ to. As such, Algorithm 1 is correct.

A.2 Proof of Proposition 1

Consider $c_u$ of packet $p$ at $u$, and an upstream neighbor of $u$, denoted as $w$. Suppose $u.dev$ is in the group of next-hops where $w.dev$ forwards $p$. Because of the monotonicity of $\otimes$, in each universe that $w.dev$ forwards $p$ to $u.dev$, the number of copies of $p$ that can be sent from $w$ to the destination in DVNet is greater than or equal to the number of copies of $p$ that can be sent from $u$ to the destination in DVNet. As such,

- When $\text{count}_{\text{exp}} \geq N$ or $> N$, each $u$ only sends $\min(c_u)$ to its upstream neighbors. With such information, in the end, the source node of DVNet can compute the lower bound of the number of copies of $p$ delivered in all universes. If this lower bound satisfies $\text{count}_{\text{exp}}$, then all universes satisfy it. If this lower bound does not satisfy $\text{count}_{\text{exp}}$, a network error is found.
- When $\text{count}_{\text{exp}} \leq N$ or $< N$, each $u$ only sends $\max(c_u)$ to its upstream neighbors. The analysis is similar, with the source node computing the upper bound.
- When $\text{count}_{\text{exp}} = = N$, if $c_u$ has more than 1 count, it means any action to forward $p$ to $u$ would mean a network error. In this case, $u$ only needs to send its upstream neighbors any 2 counts in $c_u$ to let them know that. If $c_u$ has only 1 count, $u$ sends it to $u$’s upstream neighbors for further counting. Summarizing these two sub-cases, $u$ only needs to send the first $\min(|c_u|, 2)$ smallest elements in $c_u$ to its upstream neighbors.

With this analysis, we complete the proof of Proposition 1.

B IMPLEMENTATION

Our Coral prototype has ~8K lines of Java code, including a verification planner and on-device verifiers. Figure 12 shows the implementation structure. The planner computes the
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C Local Equivalence Class (LEC) Table

Figure 12: The implementation of Coral.

DVNet based on the requirement and the topology, and decides the counting task of on-device verifiers.

An on-device verifier has (1) an LEC builder that reads the data plane of the device to maintain an LEC table of a minimal number of LECs, and (2) a verification agent that maintains TCP connections with the verifiers of neighbor devices, takes in the LEC table and the DV protocol UPDATE messages from neighbor devices to update the on-devices CIBs, and sends out UPDATE messages with latest counting results to neighbor devices, based on counting tasks. For the verification agent, we use a thread pool implementation, where a thread is assigned for a node in a DVNet. To avoid creating too many threads and hurting the system performance, we design an opportunistic algorithm to merge threads with similar responsibilities (e.g., requirements with different source IP prefixes but same destination IP prefixes) into a single thread. A dispatcher thread receives events (e.g., an LEC table update or a DV protocol UPDATE message), and dispatches events to the corresponding thread. An LEC table update is sent to all threads whose requirements overlap with the update, and an UPDATE message is dispatched based on the intended link field of the UPDATE message. For predicate operation and transmission, we adapt and modify the JDD [66] library to support the serialization and deserialization between BDD and the Protobuf data encoding [33], so that BDDs can be efficiently transmitted between devices in UPDATE messages.

C VERIFICATION TIME BREAKDOWN OF BURST UPDATE

This section studies why Coral is slower than AP in burst update verification for Airtel1-1 and Airtel2-1, but faster for Airtel1-2 and Airtel2-2. Figure 13 provides a verification time breakdown of burst update of different DVP tools for these four datasets. Airtel1-1 and Airtel2-1 have the same topology but different numbers of rules. So are Airtel2-1 and Airtel2-2. In particular, centralized DVP tools work in three phases: (1) FIB collection that collects data planes of all devices to the server, (2) model computation that takes as input the data planes of all devices and computes the equivalence classes, and (3) verification computation that takes as input the computed ECs to verify requirements. We observe that model computation is the bottleneck of all four centralized DVP tools (except for VeriFlow, whose bottleneck is both model computation and verification computation). The model computation time is proportional to the total number of rules in the data plane. As such, with the number of rules increasing from Airtel1-1/Airtel2-1 to Airtel1-2/Airtel2-2 (3.39× and 11.97×), the performance of centralized DVP tools degrades approximately with the same ratio.

In contrast, to verify burst update, Coral operates in two phases: (1) LEC initialization at devices and (2) counting and propagation among devices. Because LEC initialization is performed by each device in parallel, its time is only proportional to the number of rules at each device. As such, it is not the performance bottleneck of Coral, and has only a small impact on the total verification time of Coral when the total number of rules increases (e.g., from Airtel1-1/Airtel2-1 to Airtel1-2/Airtel2-2). As such, with more rules, Coral becomes faster than AP. As a result, we conclude that Coral achieves better scalability than centralized DVP tools such as AP when the total number of rules increases.

D MESSAGING OVERHEAD OF CORAL IN INCREMENTAL VERIFICATION

For all datasets in our experiments and simulations, we first plot CDFs of the number of DV UPDATE messages sent in the network per rule update (Figure 14a) and the number of devices whose counting results change per rule update (Figure 14b).

Figure 14a shows that for each dataset, at least 70% of rule updates do not incur any DV UPDATE message in Coral. Figure 14b further shows that for at least 75% of rule updates, the number of devices whose counting results change is no more than two. This shows that by decomposing verification to on-device counting tasks, a large portion of incremental verifications become local verification on a single network device, or only require sharing counting results among a small number of network devices. As such, the Coral achieves substantial scaling up on incremental verification.

We next plot the size of DV UPDATE message incurred across 10,000 rule updates (Figure 14c). We observe that all UPDATE messages are smaller than 150KB, in particular, for NGClos and Fatree, their UPDATE messages are all smaller than 396 bytes. This indicates that the bandwidth overhead of Coral is very low.

In the end, we plot the number of CIB entries of each device after 10,000 rule updates (Figure 14d), in supplementary to the maximal memory microbenchmark results in Figure 11, which shows that the Coral on-device verifiers only consume a small amount of memory on commodity network switches.
Figure 13: Verification time breakdown of different tools in burst update.

Figure 14: The messaging overhead of Coral in incremental verification.

E CDF OF INCREMENTAL UPDATE VERIFICATION TIME
As a supplementary to the statistics in Figure 9b, Figure 15 and Figure 16 plot the CDF of the incremental verification...
time of Coral and centralized DPV tools in comparison for each dataset, to show that Coral consistently outperforms state-of-the-art centralized DPV tools for incremental update verification in all datasets.

F VERIFYING RCDC LOCAL CONTRACTS USING CORAL

In §4.2, we have proved that the local contracts to verify all-shortest-path availability requirement in Azure RCDC [39] is a special case of the counting tasks in Coral. One distinction, however, is that RCDC verifies those local contracts in centralized computation instances. In this experiment, we study the feasibility of letting Coral on-device planners verify these local contracts on commodity network devices. Specifically, we pick three devices (one edge, one aggregation and one core) in the 48-ary Fattree and the NGClos datasets, respectively, and verify their local contracts on three commodity switches. We plot the results in Figure 17. Results show that all local contracts are verified on commodity switches in less than 320ms, with a CPU load ≤ 0.47 and a maximal memory ≤ 15.2MB. The latency is consistent with the result of RCDC running in off-device computation instances (e.g., $O(100) ms$ in Section 2.6.1 of RCDC [39]).

We further go beyond verifying these local contracts from a green start to verifying them incrementally. To this end, for each DC network, we randomly generate 1,000 rule updates across the three devices, and evaluate how fast the Coral on-device verifiers on commodity network devices can incrementally verify their counting tasks. Results in Figure 18 show that the 90% quantile of incremental verification time on each switch model is 0.08ms in 48-ary Fattree, and 0.15ms in NGClos.

From these results, we demonstrate that Coral can efficiently verify the local contracts of RCDC on commodity network switches, with low overhead.

G OVERHEAD OF CORAL PLANNER

Figure 19 shows the overhead of Coral planner, in terms of the total time to compute DVNet and on-device tasks for each dataset in our testbed experiments and simulations. Note that for the pair of datasets Airtel1-1 and Airtel1-2, and the pair of Airtel2-1 and Airtel2-2, we only generate DVNet and on-device tasks once for each pair, because they each have the same requirement and the topology. It shows that for 9 out of 11 datasets in the evaluation, the planner finishes computing DVNet and deciding on-device tasks in less than 50s, and that the longest time is 338.10s. We note that for Fattree and NGClos, the overhead of the planner (49.40s and 37.93s) is even lower than some WAN networks. This is because our implementation leverages the high symmetry of Clos-based topology to avoid redundant computation, resulting in low overhead. Because the Coral planner is only needed to configure on-device verifiers before they run, we conclude that its overhead is reasonably low and acceptable for scalable data plane checking in various networks.
Figure 16: The CDF of incremental verification time of all datasets - part 2.

(a) BT North America. (b) NTT. (c) OTEGlobe. (d) Fattree ($k = 48$). (e) NGClos.

Figure 17: Time and overhead of verifying all-shortest-path availability in DC networks from green start on commodity network devices.

(a) Total time. (b) Maximal memory. (c) CPU load.

Figure 18: Time of verifying all-shortest-path availability in DC networks incrementally on commodity network devices.

(a) 48-ary Fattree. (b) NGClos.
Figure 19: Total time of Coral planner in computing $DVNet$ and on-device tasks (seconds).