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VeriTable: Fast equivalence verification of multiple large forwarding tables☆

Yaoqing Liu*, Garegin Grigoryan, Jun Li, Guchuan Sun, Tony Tauber

Computer Science Department, Fairleigh Dickinson University, 1000 River Road, Teaneck, NJ 07666 United States

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ABSTRACT

Due to network practices such as traffic engineering and multi-homing, the number of routes, also known as IP prefixes, in the global forwarding tables has been increasing significantly in the last decade and continues growing in a super linear trend. One of the most promising solutions is to use Forwarding Information Base (FIB) aggregation algorithms with incremental handling of BGP updates. FIB aggregation compresses the forwarding tables by reducing the number of prefixes in an FIB. Obviously, FIB aggregation should preserve the forwarding behavior of the data plane, i.e., packets must be forwarded in the same directions as if the original FIB is applied. Failures at the control plane or an incorrect algorithm may violate this rule. Thus we pose a research question, how can we efficiently verify that the original table achieves the same forwarding behavior for a router as the aggregated one? This paper proposes VeriTable, an algorithm that addresses the problem of verification of the equivalence of forwarding tables and the challenges caused by the Longest Prefix Matching (LPM) lookups. VeriTable employs a single tree traversal to quickly check if multiple forwarding tables are equivalent, as well as if they result in network "black-holes". VeriTable algorithm significantly outperforms the state-of-the-art work for both IPv4 and IPv6 tables in terms of the total running time, memory access times and memory consumption.

1. Introduction

While the amounts of the Internet traffic continues to increase, the Internet Service Providers' (ISP) task to provide fast, consistent and loop-free routing becomes more challenging. For example, the size of the global routing table, that is installed on backbone routers, exceeds 700,000 entries for IPv4 addresses [2] (see Fig. 1). The great amount of entries in the forwarding table leads to the problem known as the overflow of the Ternary Content Addressable Memory (TCAM). As TCAM is used for fast hardware-based selection of the Longest Prefix Match for each incoming packet, it has memory limitations, increased power consumption, and high operational costs [3–5]. To mitigate this problem, Forwarding Information Base (FIB) aggregation is considered as one of the most promising solutions [6]. The basic idea of FIB aggregation is that multiple prefix entries sharing a same next hop can be merged into a single entry. Unlike many other approaches, FIB aggregation requires neither architectural or hardware changes [7,8]. FIB aggregation is a software solution and can be applied locally on a single router. While FIB aggregation can compress forwarding tables by more than 50% [9], it is necessary to verify the correctness of such compression. More specifically, the forwarding behavior of a router should not change after the aggregated forwarding table replaces the original forwarding table. Moreover, the aggregation algorithm should correctly conduct incremental routing updates. Thus, the packet with any possible destination address will be forwarded or dropped regardless of what table was used, the original or the aggregated one.

This work is dedicated to the general problem of verifying the equivalence of forwarding tables, i.e. if a router's forwarding behavior is the same for each of the comparable tables. Besides a natural application as validating the correctness of FIB aggregation and the incremental updates, verifying the forwarding equivalence is necessary for testing a router's hardware and software. Due to distributed system design of a traditional router, it contains at least three copies of the same forwarding table. The first copy, called the master forwarding table, is located at the control plane of the router, which is responsible for collecting, selecting and distributing routes. The master forwarding table, in its turn, is derived from a Routing Information Base (RIB). The second copy is located in the forwarding engines of a router. Finally, the third copy is located in forwarding chips with TCAM memory. All the copies of

☆ This paper is an extension of our previous publication "VeriTable: Fast Equivalence Verification of Multiple Large Forwarding Tables" [1] that appeared in INFOCOM 2018.

* Corresponding author.
E-mail address: yliu@fdu.edu (Y. Liu).

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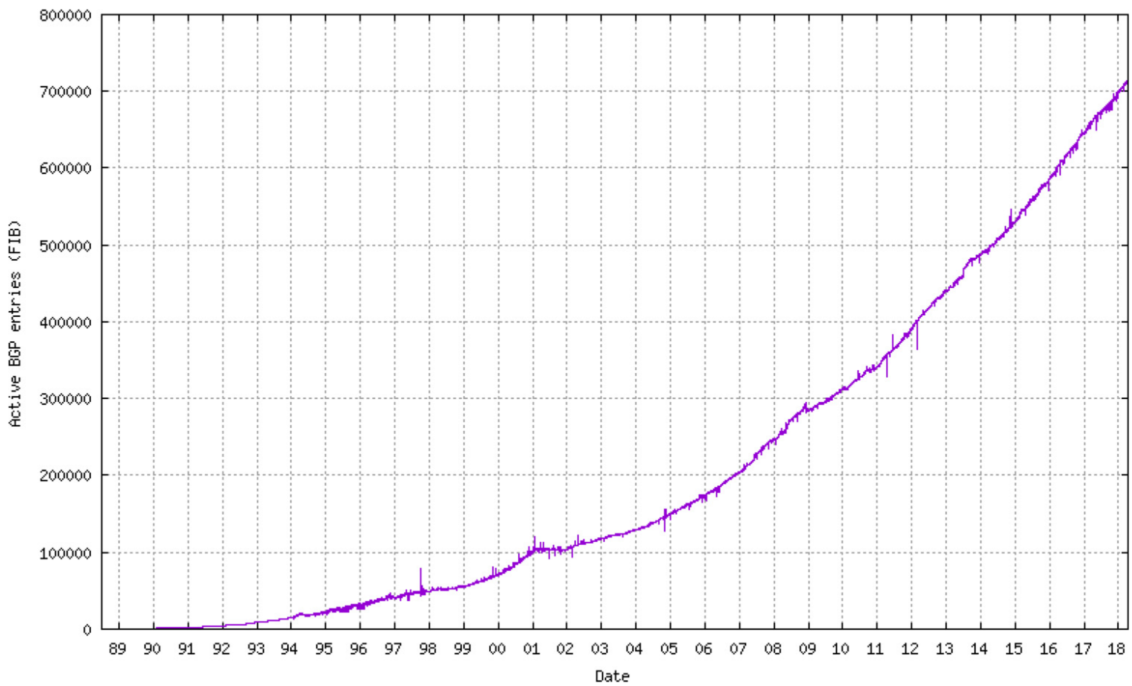


Fig. 1. Active BGP entries in AS65000 (FIB) [2].

the forwarding tables on a router must be equivalent, which may not be the case when a router is incorrectly configured or after link failures [10]. In addition, the routing updates accepted by a router shall simultaneously be reflected in all of its forwarding tables. Thus, verifying the equivalence of multiple forwarding tables is necessary for debugging and diagnosing misconfiguration. An example of such software is Cisco Express Forwarding (CEF) real-time consistency checkers, that discover prefix inconsistencies between the RIB and FIB ([11,12]). Such inconsistencies may happen due to the asynchronous nature of the distribution mechanism for both databases. They include missing prefix or different next hops on a line card and in the RIB.

A relaxed version of the forwarding equivalence verification, when an algorithm needs to verify if certain routes are missing in at least one of the comparable forwarding tables, but exist in other forwarding table(s), will help network operators to prevent so-called network "black-holes". The existence of "black-holes" may lead to a silent disappearance of the traffic destined for a certain scope of IP addresses. Such failures may occur due to several reasons, such as misconfiguration of an individual router and slow network convergence [13].

There are at least four challenges necessary to overcome for designing an efficient algorithm, that verifies the equivalence of forwarding tables:

(1) Verify forwarding equivalence over the entire IP address space, i.e. 2^{32} IP addresses for IPv4 and 2^{128} addresses for IPv6 protocol. More specifically, the equivalence condition is satisfied only if, for each IP address, the Longest Prefix Matching operation in FIB results in a same next hop.
(2) An efficient algorithm should be able to handle large forwarding tables for both IPv4 and IPv6 forwarding tables. It is estimated that millions of routing entries will be present in the global forwarding table in the next decade [14].
(3) The algorithm should be fast enough for processing incremental updates. Typically, the number of such updates is 100 per second on average, however, it can reach the frequency of several thousand updates per second during the spikes.
(4) In several cases, such as verification of a "black-hole-free" network or verifying the equivalence of all forwarding tables on the same device, the algorithm should be able to process multiple large forwarding tables simultaneously.

This work presents *VeriTable*, an algorithm that conquered all of the above-mentioned challenges and makes the following contributions:

(1) It presents the design and the implementation of an algorithm that verifies **multiple snapshots of arbitrary routing/forwarding tables** simultaneously through a single PATRICIA tree [15] traversal.
(2) For the first time, this work examines the forwarding equivalence over both real and large IPv4 and IPv6 forwarding tables; in addition, it for the first time demonstrates the results of aggregation of IPv6 forwarding tables.
(3) *VeriTable* significantly outperforms existing work *TaCo* and *Normalization*. This work both demonstrates and evaluates these two algorithms, using IPv4 and IPv6 forwarding tables. According to the evaluation results, *VeriTable* is **2 and 5.6 times** faster than *TaCo* in terms of verification time for IPv4 and IPv6, respectively, while it only uses **36.1% and 9.3% of total memory** consumed by *TaCo* in a two-table scenario. For *Normalization, VeriTable* is **1.6 and 4.5 times** faster in terms of the total running time for IPv4 and IPv6, respectively;
(4) In a relaxed version of *VeriTable*, it is able to quickly test if multiple forwarding tables cover the same routing space. We also extended the algorithm to quickly identify if there are loops and blackholes in a large network. The evaluation results are described in Section 4.

The rest of this paper is organized as follows. Section 2 presents the necessary background information on the Internet organization, a router's architecture, the Longest Prefix Match rule and the problem of verifying the equivalence of forwarding tables. In addition, it presents two state-of-the-art solutions: *TaCo* and *Normalization*. Section 3 describes the theorem and property used in *VeriTable* algorithm, the design of *VeriTable* algorithm, its data structures

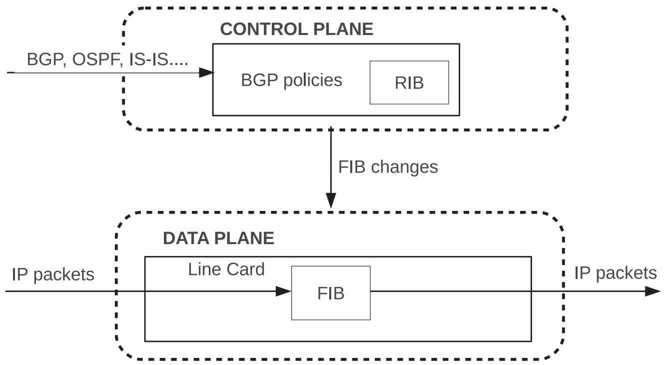


Fig. 2. The generic router architecture.

and the workflow. Section 4 shows the evaluation of *VeriTable* over *TaCo* and *Normalization*. Finally, Section 6 concludes this work.

2. Background

2.1. The generic router architecture

Routers play a vital role in computer networking. First, they calculate, select and distribute the paths towards different destinations in the global network. Second, they direct the network traffic along selected paths hop by hop. A typical network router consists of two main components (see Fig. 2):

(1) **Control plane.** Its duty is to run different routing protocols, such as the Border Gateway Protocol (BGP) [16], and to exchange routes towards other networks (i.e., their IP prefixes) with neighbor routers. In addition, for each destination prefix, the control plane runs BGP decision process, to pick the best routes among all collected. The destination IP prefixes and selected routes are stored in the Routing Information Base (RIB). Finally, each destination prefix and the next hop from the selected route is pushed in the data plane. The control plane usually runs on a cheap Dynamic Random Access Memory (DRAM).

(2) **Data plane.** Dedicated for packet forwarding. It maintains several copies of the Forwarding Information Base (FIB), the entries of which are derived from the routes, selected and pushed by the control plane. An FIB contains the IP prefixes of different length and the corresponding next hops, i.e., output ports. To guarantee fast next hop lookup for each incoming packet, FIB memory resides on highly expensive [3,17,18] line cards with Ternary Content-Addressable Memory (TCAM) chips. As the number of entries in the global FIB constantly grows, network operators try to compress the forwarding tables using different aggregation techniques, in order to prolong the lifetime of the legacy TCAM chips [6].

2.2. Longest prefix match rule

When a packet arrives at a router's data plane, its next hop is determined according to the Longest Prefix Match of packet's IP destination address in the FIB. An example of the Longest Prefix Match selection is shown in Table 1. The table represents a sample FIB for IPv4 addresses with 32-bit address space. Several cases may happen during the matching process:

(1) An IP destination address does not have a match in the FIB. In such case, the packet will be dropped by the router. For example, an IP destination address that does not start with the prefix 128.153.0.0/16, for example, 45.56.76.120, will be discarded.

(2) An IP destination address has a single match in the table. In such case, the packet will be simply forwarded to the corresponding next hop. An example of such an IP address is 128.153.0.11 with the match 128.153.0.0/16 and next hop *A*.

(3) An IP destination address has several matches in the table. In such case, a match with the longest prefix length will be selected. An example of such an IP address is 128.153.124.35, that matches prefixes 128.153.0.0/16, 128.153.64.0/18, 128.153.96.0/19. However, only the prefix 128.153.96.0/19 will be selected by the data plane engine, since it is the Longest Prefix Match. Thus, the packet will be forwarded to the next hop *E*.

Table 1
Forwarding Information Base (FIB).

Prefix	Next Hop
128.153.0.0/16	A
128.153.64.0/18	B
128.153.128.0/17	C
128.153.192.0/18	D
128.153.96.0/19	E

Table 2
Forwarding Equivalence of FIBs.

(a) FIB table 1		(b) FIB table 2	
Prefix	Next hop	Prefix	Next hop
–	A	–	B
000	B	001	A
01	B	1	A
11	A	100	A
1011	A		

2.3. The equivalence of forwarding tables

The forwarding tables are equivalent if and only if when applied to a router, a router's forwarding engine behaves similarly for a packet with any possible IP destination address (see Section 3.1 for a more formal definition).

In other words, a packet will be forwarded to the same next hop, regardless of what equivalent forwarding table was used for the FIB. We use Table 2 with the binary representation of prefixes as an example. In this example, the FIB tables 1 and 2 are equivalent, even though their default routes (with the prefix "_"[1]) are different. For example, a packet with destination IP address starting with 000 will be forwarded to the next hop *B* in both tables (LPM is "_" for the first table and 000 for the second table). On the contrary, if the FIB Table 1 changes its default next hop to *A*, the forwarding tables will be no longer equivalent. For example, an IP address starting with 011 will be forwarded to the next hop *A* by the first FIB (LPM: "_"), and to the next hop *B* by the second FIB (LPM: 01).

The naive way for verifying the forwarding equivalence of two or more forwarding tables is to match each possible IP address against those tables. However, such approach is not feasible, since the IP address space for IPv4 and IPv6 protocols contains 2^{32} and 2^{128} addresses, respectively. We present the current state-of-the-art approaches, *TaCo* and *Normalization* in the following section.

[1] Default route matches the IP addresses that don't have any match among other table entries. The default route can be used if only the table entries do not fully cover the IP address space.

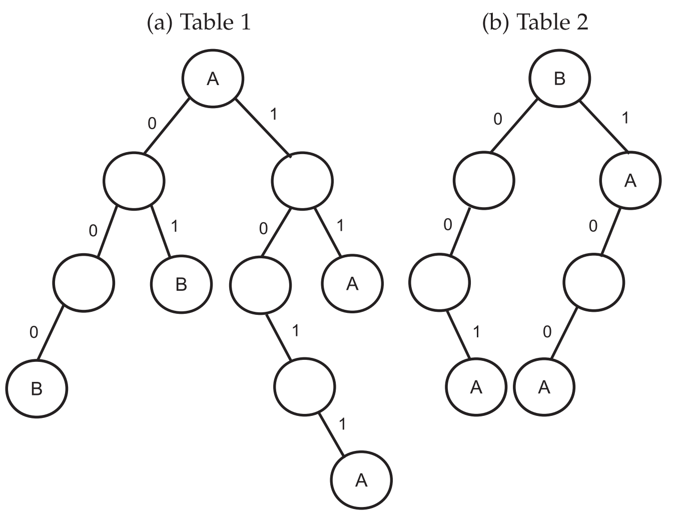


Fig. 3. Binary prefix trees.

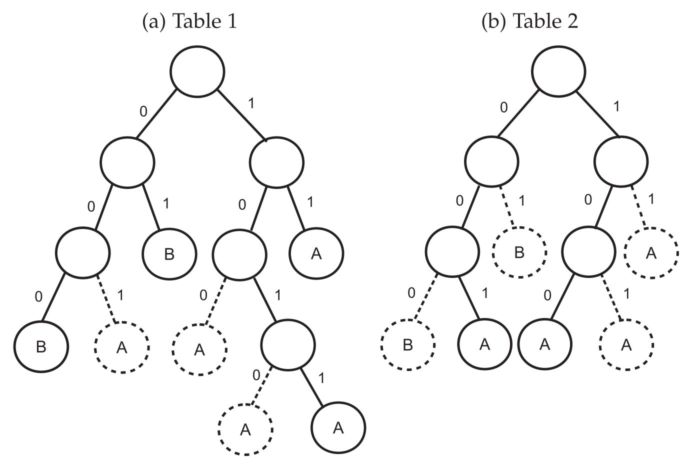


Fig. 4. Binary prefix trees after leaf pushing.

2.4. State of the art

2.4.1. Taco: Semantic equivalence of IP prefix tables

TaCo verification algorithm [19] bears the following features:

(1) TaCo is designed for comparing two tables simultaneously.
(2) It uses separate binary trees to store all entries for each forwarding/routing table.
(3) TaCo leverages leaf pushing to obtain non-overlapping prefixes in both trees.
(4) TaCo performs two types of comparisons: (a) direct comparisons of the next hops for prefixes, common between two tables, and (b) comparisons that involve LPM lookups of the IP addresses, extended from the remaining prefixes of each table.

More specifically, *TaCo* needs to use four steps to complete equivalence verification for the entire routing space. We illustrate each step using two FIBs, shown at Table 2a and b:

(1) Building a binary tree for each table, as shown in Fig. 3. The binary tree is built as a traditional prefix tree, where a left branch represents the bit 0 and the right branch represents the bit 1. The root node of such tree is a default node with the prefix length equal to zero. To add a prefix to the binary tree, a node should be generated according to the bits of the prefix, with the depth equal to the prefix length. Such node will contain the value of the next hop from the forwarding table. In the meantime, binary prefix tree requires generating auxiliary nodes at each level of the prefix tree.
(2) Perform leaf pushing for each binary tree. Leaf pushing operation requires each node with a single child on one branch to generate a second child on another branch. The next hops of the generated nodes should be inherited from their closest ancestor with the next hop value. Fig. 4 shows the resultant binary trees. Note, that after leaf pushing, TaCo's internal nodes do not need to carry next hop information, since all the possible Longest Prefix Matches are the leaf nodes.
(3) Finding common prefixes and their next hops, then making comparisons. In Fig. 4, those are the prefixes 000, 001, 01, 100, 11.
(4) Extending non-common prefixes, found in both binary trees, to IP addresses and making comparisons. Prefix extension is performed by adding enough zero bits at the end of a prefix, to obtain valid IP address (32-bit or 128-bit address for IPv4 and IPv6 protocols respectively). In the example, Table 1 needs to extend the prefix 1010 and 1011 to an IP address and perform an IP lookup traversal through the Table 2. At Table 2, the non-common prefix is 101. *TaCo* extends this prefix to an IP address and performs an IP lookup traversal through the Table 1. The IP lookups in the binary tree are performed in the following way: starting from the root node, the algorithm reads the IP address bit by bit. If 0 bit is encountered, the algorithm moves to the left branch; otherwise, it moves to the right branch. The IP lookup traversal ends at the leaf node and returns the next hop value of that node.

Finally, when all comparisons end up with the equivalence results, *TaCo* theoretically proves that two FIB tables have forwarding equivalence. To summarize, *TaCo* undergoes several inefficient operations:

(1) Leaf pushing for binary trees, a costly and slow operation.
(2) To find common prefixes for direct comparisons, *TaCo* must additionally perform tree traversals.
(3) IP address extension and mutual lookups for non-common prefixes are CPU-expensive.
(4) Finally, to compare n tables and find the entries that cause possible non-equivalence, it may require $(n-1) * n$ times of tree-to-tree comparisons. For example, for three tables *A, B, C* there are six comparisons: *A* vs *B, A* vs *C, B* vs *C, B* vs *A, C* vs *B, C* vs *A*. Thus, it may require 90 tree-to-tree combinations to compare 10 tables mutually. On the contrary, *VeriTable* eliminates all these expensive steps and accomplishes the verification over an entire IP routing space through a single traversal over the Patricia trie.

2.4.2. Normalization

Rétvári et al. in [20] show that a unique form of a binary tree for a forwarding table with the specific forwarding behavior can be obtained through *Normalization*, a procedure that eliminates brother leaf nodes with identical labels (e.g., next hop values) from a leaf-pushed binary tree. Indeed, if a recursive substitution is applied to the binary trees in Fig. 4, binary trees (a) and (b) will be identical (see Fig. 5). Authors in [20] prove that the set of tables with the same forwarding behaviors have identical normalized binary trees. More specifically, *Normalization* verification approach has three steps involved: (1) Leaf pushing; (2) tree compression and (3) side-by-side verification. Leaf pushing operation was described in details in Section 2.4.1. Tree compression involves compressing two brother leaf nodes with identical values, into their parent node. The parent node's next hop will be then equal to the

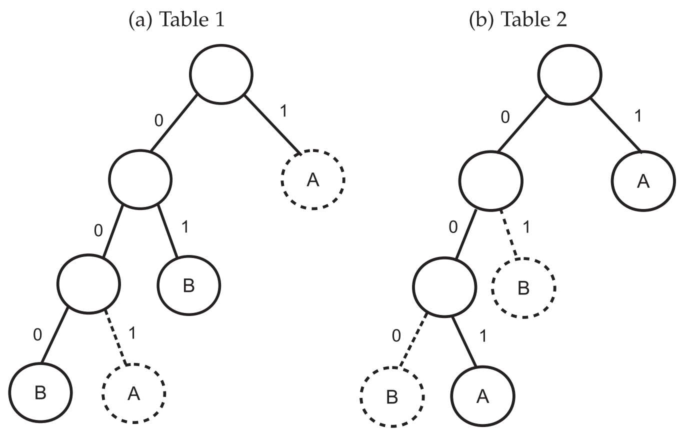


Fig. 5. Binary prefix trees after normalization.

next hop value of the compressed brother nodes. This is a recursive process until no brother leaf nodes have the same next hops. The final step for verification is to verify the sameness of the binary tree. For that goal, the algorithm needs to perform full simultaneous traversal over both trees.

Although *Normalization* needs to perform the expensive recursive leaf compression operation, it has several significant advantages over *TaCo*. First, unique binary trees contain fewer nodes, therefore the traversal over those trees is quicker. Second, verification of the identity of binary trees requires no IP address extensions and IP lookups (for satisfying the forwarding equivalence, each prefix in the first normalized tree must have a common prefix in the second normalized tree). In Section 4, we present the results of comparison between *VeriTable, TaCo* and *Normalization*.

The following section presents the design of *VeriTable* in details.

3. Design

In this section, first, we represent *VeriTable* theorem and the property derived from the theorem. Next, we introduce the data structures used in this work and the workflow of *VeriTable*. In addition, we used a smalll example to demonstrate each step of *VeriTable*.

3.1. Veritable theorem and property

First, we need to formalize the definition of the terms *Longest Prefix Match* and *Forwarding Equivalence*.

Definition 1 Longest Prefix Match**.** Suppose p is a prefix with length l_p in a forwarding table T. We denote p as $p_1 p_2 . p_{l_p}$, where $p = \{0,1\}^{l_p}$ (i.e., p_i is 0 or 1 for $i = 0, 1, 2, \ldots, l_p$). Also suppose there is a string $s = \{0,1\}^{l_s}$, where l_s is the length of s. Then, according to the Longest Prefix Matching rule, we define that p is the ***Longest Prefix Match***for s in T, namely, $p = LPM_s(T)$, if and only if

(1) $l_p \leq l_s$
(2) p is a prefix for s, i.e. $p_1 p_2 . p_{l_p} = s_1 s_2 . s_{l_p}$.
(3) $\nexists$ p' in T, where p' is a prefix of s and $l_{p'} > l_p$.

In the following proofs, we denote the value of the next hop for a prefix p in the table T as $N_T(p)$.

Definition 2 Forwarding Equivalence**.** The forwarding tables $T_1, T_2, \ldots, T_m$ are forwarding equivalent, if and only if, for every single IP address $\omega = \{0,1\}^n$, $N_{T_1}(LPM_\omega(T_1)) = N_{T_2}(LPM_\omega(T_2)) = \ldots = N_{T_m}(LPM_\omega(T_m))$, where n is the length of an IP address.

According to the definition above, verifying the equivalence of forwarding tables requires 2^{32} or 2^{128} IP addresses for IPv4 and IPv6, respectively. The goal of *VeriTable* is to reduce the number of comparisons by using prefixes, but still verify the entire routing space. To do that, we leverage a joint forwarding table, that is build by merging all comparable tables into a single table. The following theorem proves an important property of such a table; we design *VeriTable* based on that property.

Theorem 1. *Let T to be a joint forwarding table, built by merging individual forwarding tables $T_1, T_2, \ldots, T_m$. Assume that $p = LPM_\omega(T)$, then we can prove that $\forall \omega = \{0,1\}^n$, $LPM_\omega(T_i) = LPM_p(T_i)$, where n is the length of an IP address and $i = 1, 2, \ldots, m$.*

Proof. *Let a prefix p be $p_1 p_2 . p_l$ ($l \leq n$), and ω be $\omega_1 \omega_2 . \omega_n$. Suppose, $p = LPM_\omega(T)$, then $\omega = p_1 p_2 \ldots p_l \omega_{l+1} . \omega_n$. We prove the theorem using contradiction. Suppose, $LPM_\omega(T_i) \neq LPM_{p_1 p_2 . p_l}(T_i)$, namely, $LPM_{p_1 p_2 \ldots p_l \omega_l \omega_{l+1} . \omega_n}(T_i) \neq LPM_{p_1 p_2 . p_l}(T_i)$. Then, according to the Definition 2, there exists a different prefix p' in the forwarding table T_i, such as its length $l_{p'} > l_p$, and p' is a prefix for w. But then, p' exists in T. Thus, p can not be a Longest Prefix Match for ω in T (see Definition 2), which is contradictory to the initial assumption of this theorem, that $p = LPM_\omega(T)$.* □

Based on the Theorem 1, we derive *VeriTable* property: comparing next hops for each ω in $T_1, T_2, \ldots, T_m$ is equivalent to comparing next hops for each p in $T_1, T_2, \ldots, T_m$. More formally, we rephrase the definition of *Forwarding Equivalence*:

Definition 3. The forwarding tables $T_1, T_2, \ldots, T_m$ are *Forwarding Equivalent*, if and only if, $\forall \omega = \{0,1\}^n$, $\forall p = LPM_\omega(T)$, where T is the union of $T_1, T_2, \ldots, T_m$, $N_{T_1}(LPM_p(T_1)) = N_{T_2}(LPM_p(T_2)) = \ldots = N_{T_m}(LPM_p(T_m))$.

In other words, since all IP addresses ω are covered by all Longest Prefix Matches p in the joint forwarding table, *VeriTable* merely needs to go through all ps, match it against each comparable forwarding table and verify the equivalence of the next hops. The outcome of this property can be illustrated through an example with two forwarding tables with prefixes for 3-bit address space (see Table 3a and b). According to the original definition of *Forwarding Equivalence*, to verify it one needs to match any possible IP address against each of the tables (8 IP addresses in total). According to *VeriTable* property, it is necessary to do the following steps: (1) Join two tables into a single merged table; (2) Find all Longest Prefix Matches p in that table; (3) For each p, find next hops in each table. The resulting joint table is shown on Table 3c. Note, that since the address spaces 0 and 1 are fully covered in the join table T by other prefixes, the default prefix "_" is not a Longest Prefix Match (LPM) and is skipped during the verification process.

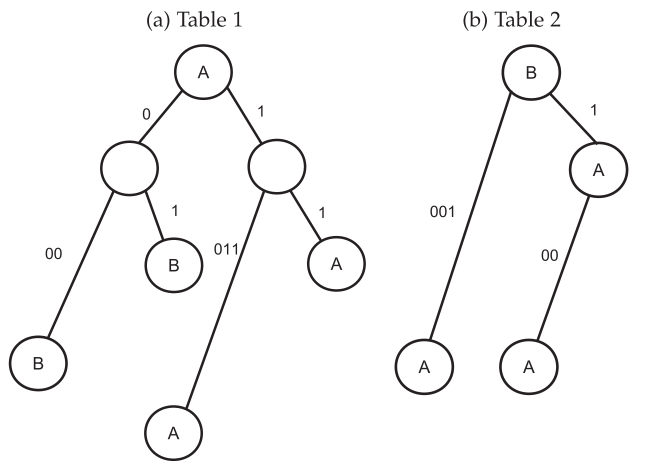
The following section shows the implementation and workflow of each of *VeriTable* steps in details.

Table 3
Forwarding tables for 3-bit address space.

(a) FIB table T_1		(b) FIB table T_2	
Prefix	Next hop	Prefix	Next hop
–	A	–	B
11	B	10	A
0	B		

(c) Joint FIB table T

Prefix	Next hop in Table 1	Next hop in Table 2
–	Not an LPM in T	
0	B	B
10	A	A
11	B	B



Hollow nodes denote *GLUE* nodes, that help to build the Patricia trie structure. Other non-hollow nodes are called *REAL* nodes, whose prefixes are derived from at least one of the forwarding tables.

Fig. 6. PATRICIA Trees (PTs) Hollow nodes denote *GLUE* nodes, that help to build the Patricia trie structure. Other non-hollow nodes are called *REAL* nodes, whose prefixes are derived from at least one of the forwarding tables..

3.2. VeriTable implementation and workflow

According to *VeriTable* property, the implementation of *VeriTable* should complete the following tasks: (1) Build a data structure of the joint forwarding table; (2) Identify all Longest Prefix Matches *p* of the joint table using that data structure; (3) For each *p*, find the values of next hops in the comparable tables. To satisfy the forwarding equivalence requirement, the next hop values from each table shall be equal.

3.2.1. Setup the joint patricia trie

Patricia Trie

Instead of using a binary tree to store the joint forwarding table, *VeriTable* uses the Joint Patricia trie data structure, derived from the PATRICIA (Practical Algorithm to Retrieve Information Coded in Alphanumeric) tree [15], a data structure based on a radix tree using a radix of two. PATRICIA Tree (PT) is a compressed binary tree and can be quickly built and perform fast IP address prefix matching. For instance, Fig. 6 demonstrates the corresponding PTs for FIB Table 2a and FIB Table 2b. The most distinguished part of a PT is that the length difference between a parent prefix and its child prefix can be equal to and greater than 1. This is different than a binary tree, where the length difference must be 1. As a result, as shown in the example, PTs only require 7 and 4 nodes, but BTs require 10 and 7 nodes for the two tables, respectively. While the differences for small tables are not significant, however, they are significant for large forwarding tables with hundreds of thousands of entries. An exemplary IPv4 forwarding table with 575,137 entries needs 1,620,965 nodes for a BT, but only needs 1,052,392 nodes for a PT. The detailed comparison in terms of running time, node accesses and memory consumption is presented in Section 4.

The above-mentioned features enable the PT to use less space and perform faster lookups. However, it results in more complicated operations in terms of node creations and deletions, e.g., what if a new node with prefix *100* needs to be added in Fig. 6a? In fact, PT has to use an additional glue node to accomplish this task.

Building the joint Patricia Trie The first step of *VeriTable* algorithm is to build the joint Patricia trie (PT), the main data structure used in this work. Rather than building multiple binary trees or PTs for each individual table and comparing them in a one-to-one peering manner, as *TaCo* and *Normalization* do, *VeriTable* builds an accumulated joint PT using all tables one upon another. In the beginning, *VeriTable* takes the first table as an input and initiates all necessary fields to construct a PT accordingly. Afterward, while reading other tables, the nodes with the same prefixes will be merged. In case of new prefixes, *VeriTable* will add corresponding nodes to the joint PT.

For the next hops, *VeriTable* uses an integer array, located at each node of the joint PT. The size of the array is the same as the number of tables for comparison. The array contains next hops from each individual forwarding table. More specifically, these next hops will be placed at the corresponding *n*th element in the array, starting from 0, where *n* is the index number of the input FIB table[2] For instance, the next hop *A* of prefix *001* in FIB Table 2 will be assigned as the second element in the *Next Hop Array* at the node with prefix *001*. If there is no next hop for a prefix in a particular table, the value in the array will be initialized as "_" by default, or called an *"empty"* next hop (in the implementation, *VeriTable* uses "-1"). The nodes derived from at least one of the forwarding tables are *REAL* and contain at least one non-empty next hop in the array. The rest of the nodes are called *GLUE* nodes. Algorithm 1 in Appendix A elaborates the detailed work-flow to build a joint PT for multiple tables. Table 4 describes a joint PT's node's attributes. Fig. 7a shows the resultant joint PT for FIB Table 2a and b.

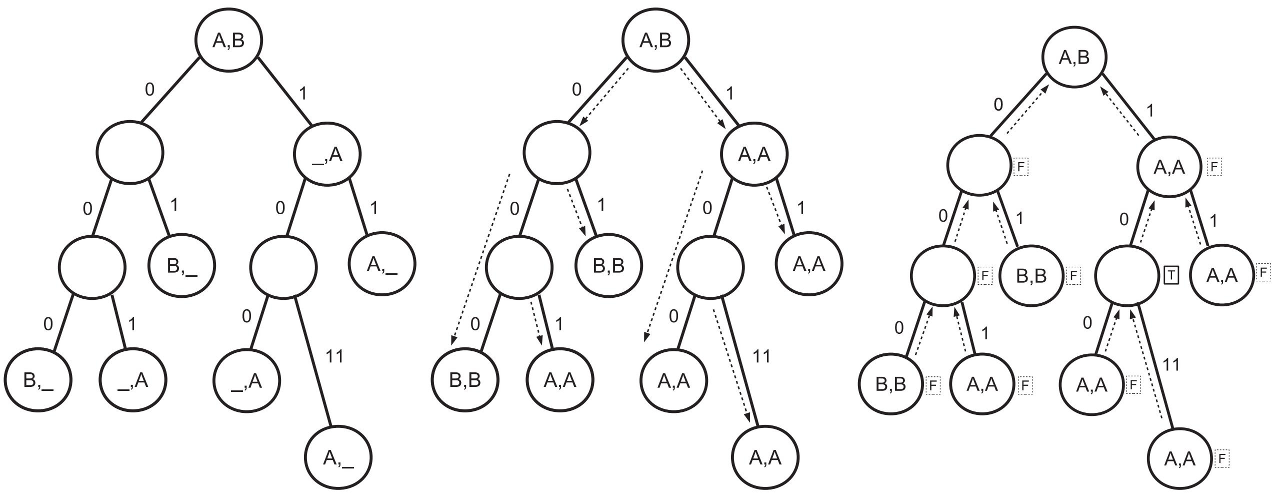
Algorithm 1 Building a Joint PT *T*.

```
procedure BuildJointPT(T_1, T_2, ..., T_n)
    Initialize a PT T with its head node
    Add prefix 0/0 on its head node.
    Set default next hop values in the Next Hops array.
    for each table T_i ∈ T_1, T_2, ..., T_n do
        for each entry e in T_i do
            Find a node n in T such as n.prefix is a longest match for e.prefix in T
            if n.prefix = e.prefix then
                n.nexthop_i ← e.nexthop
                n.type ← REAL
            else
                Generate new node n′
                n′.prefix ← e.prefix
                n′.nexthop_i ← e.nexthop
                n′.type ← REAL
                Assume n has a child n_c
                if the overlapping portion of n_c and n′ is longer than n.length but shorter than n′.length bits then
                    Generate a glue node g
                    n′.parent ← g
                    n_c.parent ← g
                    g.parent ← n
                    g.type ← GLUE
                    Set g as a child of n
                    Set n′ and n_c as children of g
                else
                    n′.parent ← n
                    n_c.parent ← n′
                    Set n_c as a child of n′
                    Set n′ as a child of n
                end if
            end if
        end for
    end for
end procedure
```

[2] In this work we assume only single next hop for each distinct prefix in an FIB table.

Table 4
Joint Patricia trie node's attributes.

Name	Data type	Description
parent	Node Pointer	Points to a node's parent node
l	Node Pointer	Points to a node's left child node if exists
r	Node Pointer	Points to a node's right child node if exists
prefix	String	Binary string
length	Integer	The length of the prefix, 0–32 for IPv4 or 0–128 for IPv6
nexthop	Integer Array	Next hops of this prefix in $T_1 \ldots T_n$, size n
type	Integer	Indicates if a node is a *GLUE* or *REAL*



(a) Initial Joint PT (b) Joint PT after the top-down process (c) Joint PT after bottom-up verification

In Figure a, for $REAL$ nodes, the nth element denotes the next hop value of the corresponding prefix from the nth forwarding table. "_" indicates that no such prefix and next hop exist in the forwarding table. In Figure b, after each top-down step, the fields with previous "_" value will be filled with new next hop values derived from the corresponding $Next\ Hop$ array elements of its nearest $REAL$ node. In Figure c, F denotes $False$ and T denotes $True$ for the $LEAK$ flag. $GLUE$ nodes will carry the $True$ flags over to its parent recursively until finding a $REAL$ node.

Fig. 7. VeriTable algorithm. In Figure *a*, for *REAL* nodes, the *n*th element denotes the next hop value of the corresponding prefix from the *n*th forwarding table. "_" indicates that no such prefix and next hop exist in the forwarding table. In Figure *b*, after each top-down step, the fields with previous "_" value will be filled with new next hop values derived from the corresponding *Next Hop* array elements of its nearest *REAL* node. In Figure *c*, *F* denotes *False* and *T* denotes *True* for the *LEAK* flag. *GLUE* nodes will carry the *True* flags over to its parent recursively until finding a *REAL* node.

There are a several advantages for the design of a joint PT:

(1) Mostly, common prefixes among comparable tables will share the same node and prefix, which can considerably reduce memory consumption and computational time for new node creations.
(2) Common prefixes and uncommon prefixes will be automatically gathered and identified in one single PT after the first step of building the joint PT.
(3) Such design will greatly speed up subsequent comparisons of next hops between multiple tables without traversing multiple individual trees.

In the rest of this section, we describe the second, verification step of *VeriTable*, during which (1) *VeriTable* identifies all longest prefix matches (LPMs) in the joint PT; (2) *VeriTable* finds next hops for each of those LPMs in the comparable tables; (3) Based on the comparison of those next hops, *VeriTable* either verifies the equivalence of the comparable forwarding tables or shows the discrepancies between those tables.

3.2.2. Verification steps

The verification step consists of a single post-order traversal over the joint PT. We divide this traversal into two phases: (1) Top-down phase, during which *VeriTable* inherits next hops from the *REAL* nodes towards the first *REAL* descendants; and (2) bottom-up phase, during which *VeriTable* verifies the equivalence of the next hops for each Longest Prefix Match (LPM) in the joint PT. Note, that both phases are rotating and replacing each other during the post-order traversal.

Top-down phase VeriTable follows the intuitive property of the LPM rule, according to which the real next hop value for a prefix that has an "empty" next hop on the joint PT should be inherited from its closest *REAL* ancestor, whose next hop exists and is "non-empty". For example, to search the LPM matching next hop for prefix *000* in the second table using Fig. 7a, the next hop value should return *B*, which was derived from the second next hop *B* of its nearest *REAL* ancestor – the root node. The top-down process will help each specific prefix on a *REAL* node in the joint PT to inherit the next hop from its closest *REAL* ancestor if the prefix contains an "empty" next hop. More specifically, when moving down, VeriTables is searching for "empty" next hops in the *Next Hop* array in each node. If "empty" next hops are found, *VeriTable* initializes them with the next hop of their closest *REAL* parent. In the meantime, "non-empty" next hops are always preserved in the *Next Hop* array. Note, that all *GLUE* nodes (hollow nodes in Fig. 7a) are skipped during this process because they are merely ancillary nodes helping to build up the tree structure and do not carry any next hop information.

After top-down phase, every *REAL* node will have a *Next Hop* array without any "empty" next hops. Fig. 7b shows the results of the top-down phase. If there is not a default route 0/0 in the original forwarding tables, for calculation convenience, *VeriTable* creates one, with the next hop value 0 and node type *REAL*.

*Bottom-up phase*As it was already mentioned above, this process is interwoven with the top-down phase in the recursive post-order verification step. While *VeriTable* moves downward, the top-down operations will be executed. While it moves upward, a series of operations will be conducted as follows. First of all, a leaf node may be encountered, where the *Next Hops* array will be checked linearly, i.e., element by element. If there are any discrepancies, then *VeriTable* can immediately conclude that the forwarding tables are non-equivalent. If all next hops share the same value, *VeriTable* moves upward to its directly connected parent node.

To identify the Longest Prefix Matches in the joint PT at the internal nodes, *VeriTable* needs to check the prefix length difference at each internal node. Two cases may occur: $d = 1$ and $d > 1$, where d denotes the length difference between the parent node and the child node.

The first case, i.e., $d = 1$ for all children nodes, implies that the parent node has no extra routing space to cover between itself and the children nodes. On the contrary, the second case $d > 1$ for at least one child node, indicates that the parent node covers more routing space than that of all its children nodes. If $d > 1$ happens at any time, *VeriTable* sets a *LEAK* flag variable at the parent node, to indicate that all of its children nodes are not able to cover the same routing space as the parent. In case if this parent is a *REAL* node, *VeriTable* identifies it as a Longest Prefix Match and verifies it, according to the *VeriTable* property, described in Section 3.1. If the parent with at least one *LEAK* flag is a *GLUE* node, the flag will be carried over up to the nearest *REAL* node, which can be an intermediate parent node of the *GLUE* node or a further ancestor. In this case, the verification of the "Next Hop" array will be executed at that *REAL* node, after which the flag will be cleared.

Intuitively, *VeriTable* checks the forwarding equivalence over the routing space covered by leaf nodes first, then over the remaining "leaking" routing space covered by internal *REAL* nodes. Fig. 7c demonstrates the bottom-up *LEAK* flag setting and carried-over process. For example, $d = 2$ between the parent *10* and its child *1011*, so the *LEAK* flag on node *10* will be set to *True* first. Since node *10* is a *GLUE* node, the *LEAK* flag will be carried over to its nearest *REAL* ancestor node *1* with the *Next Hops* array *(A,A)*, where the *leaking* routing space will be checked. Next, the *LEAK* flag will be cleared to *False* to avoid future duplicate checks of the same routing space.

In Algorithm 2 (see in Appendix A), we show the pseudocode of the verification step of *VeriTable*. Note, that *VeriTable* can exactly identify and print out the prefixes that cause non-equivalence of the comparable forwarding table by simply referring to the Longest Prefix Matches at the joint PT, on which the discrepancy was detected.

Algorithm 2 Forwarding Equivalence Verification.The initial value of *ancestor* is *NULL*, and the initial value of *node* is $T \rightarrow root$. For simplicity, we assume the root node is *REAL*.

```
procedure VeriTable(ancestor, node)
    if node.type = REAL then
        ancestor = node    ▷ The closest ancestor node for a REAL node is the node istelf
    end if
    l ← node.l
    r ← node.r
    if l ≠ NULL then
        if l.type = REAL then
            InheritNextHops(ancestor, l)    ▷ A REAL child node inherits next hops from the closest REAL ancestor to initialize "empty" next hops
        end if
        LeftFlag ← VeriTable(ancestor, l) ▷ LeftFlag and RightFlag signify the existing leaks at the branches
    end if
    if r ≠ NULL then
        if r.type = REAL then
            InheritNextHops(ancestor, r)
        end if
        RightFlag ← VeriTable(ancestor, r)
    end if
    if l = NULL ∧ r = NULL then
        CompareNextHops(node)    ▷ The leaf nodes' next hops are always compared; a verified node always returns the false LeakFlag.
        LeakFlag ← False
        return LeakFlag
    end if
    if l ≠ NULL ∧ l.length − node.length > 1 then
        LeakFlag ← True
    else if r ≠ NULL ∧ r.length − node.length > 1 then
        LeakFlag ← True
    else if l = NULL ∨ r = NULL then
        LeakFlag ← True
    else if LeftFlag = True ∨ RightFlag = True then
        LeakFlag ← True
    end if
    if LeakFlag = True ∧ node.type = REAL then
        CompareNextHops(node)
        LeakFlag ← False
    end ifreturn LeakFlag
end procedure
```

3.2.3. Complexity

As we show above in this work, at every stage of *VeriTable* algorithm we use the Patricia Tree data structure, which significantly reduces the number of memory accesses compared to the binary tree. In the worst case, when one of the comparable FIB tables consists of all possible IP addresses from the range (i.e., 2^{32} or 2^{128} prefixes for IPv4 and IPv6 respectively), the Patricia tree will be equivalent to the full binary tree. Thus, the running time of VeriTable is equal to $O(k^{*}m^{*}n)$, where:

- k is the maximum prefix length in the comparable FIBs;
- m is the number of those FIBs;
- n is the number of nodes in a joint table.[3]

In reality, prefixes in an FIB rarely exceed the length of 24 bits. As we show in Section 4, compared to TaCo, VeriTable reduces memory accesses by at least 35 times, consuming much smaller memory space.

3.3. Applications-network problem diagnosis

The *VeriTable* algorithm can be extended and applied to solve very serious network problems. One application is to detect network-wide loop issues mainly caused by incorrect network configuration. Another application is to discover if there are routing blackholes, which happen when there is not any matching route in the routing table and correspondingly the network traffic will be dropped. The cause of blackholes may be due to sudden link failures or misconfiguration. We designed two algorithms to detect loops and black holes in a realistic routing topology based on the *VeriTable* algorithm. We verified the results detailed in Section 4.

[3] $n = 2 * p - 1$ in the worst case, where p is the number of prefixes in a largest FIB.

Algorithm 3 Loop and Blackhole Detection in a Nexthop Array: DFS.

```
procedure Loop_and_blackhole(node n)
    a = n.nexthop array
    b = a new array with the same size as a
    Initialize b with status code "1"
    for each index i in a.size do
        if a_i = -1 then
            There is a blackhole at i
        end if
        while b_i = 1 do
            b_i = 0
            i = a_i
            if b_i = 0 then
                There is a loop at i
            else
                if b_i = -1 then
                    break
                end if
            end if
        end while
        Change all the visiting b_i values to -1
    end for
end procedure
```

3.3.1. Loop and blackhole detection with static FIBs

The first algorithm is shown in Algorithm 3. It uses Depth First Search (DFS) to trace every forward chain. A forward chain is to simulate the forwarding steps of a packet in a hop-by-hop manner. This algorithm allocates a temporary array *visit* for the current *nexthop* array. *visit* is used to record the visiting status, "-1" means already scanned, "0" means on the chain that is being scanned and "1" means not scanned. *visit* is initialized with all "1"s. The algorithm scans *nexthop* from left to right, checking $nexthop_i$ and $visit_i$: If $nexthop_i$ is equal to or bigger than the total FIB number, it means the package is forwarded outside the network and there is no loop or blackhole for this chain. If $nexthop_i$ is "-1" and it is not the starting point, it means there is a blackhole detected and the package forwarded to this position will be dropped. Otherwise, the $visit_i$ value is checked: If $visit_i$ is "-1", there is no need to check again. If $visit_i$ is "1", it is changed to "0". The iterator then moves to index $nexthop_i$, and repeats the previous check step. If $visit_i$ is 0, it means the position is in the current chain and visited again. In another word, this position is in a loop. If this is the case, the loop is reported and finally, all the $visit_i$ values are changed to "-1".

The second algorithm takes advantage of the property that every vertex in a single loop has the Indegree of 1. Blackhole detection is also included during the trace process. Detail is shown in Algorithm 4. This algorithm allocates a temporary array *indegree* for the curren *nexthop* array. *indegree* is used to count the in-degrees for every position. After all the elements in the array are initialized to 0, the algorithm scans *nexthop* from left to right: The count of the *indegree* value at $nexthop_i$ will be added by 1 unless $nexthop_i$ is "-1". After this step, the algorithm scans *indegree* and keeps looking for $indegree_i$ with "0" value, it changes $indegree_i$ to "-1", which means visited, and subtract 1 from it. The iterator continues to index $nexthop_i$, repeats the previous step and adds the blackhole check: if $nexthop_i$ is "-1", there is a blackhole at *i*. The iterator repeats the previous step as long as the $indegree_i$ is 0. Finally, the "1" values in *indegree* reveal the vertices into loops.

3.3.2. Loop and blackhole detection upon updates

The algorithm of the detections after adding an entry is shown in Algorithm 5. It has a precondition that there is no original record at that position. If the position *i* is valid, $nexthop_i$ is set to the given next hop. At the same time, $status_i$ is set to "1", which means there is an original record now. Then, the algorithm calls the detection function to check if there are new loops or blackholes formed. Afterwards, it keeps searching the left and right nodes of the current one, changes the $nexthop_i$ values, until a node with $status_i = 1$ is found.

The detection algorithm after modifying an entry is shown in Algorithm 6. It has a precondition that there was an original record at that position. If the position *i* is valid, $nexthop_i$ is changed to the given next hop. Then, the algorithm calls the detection function to check if there are new loops or blackholes formed. Afterwards, it keeps searching the left and right nodes of the current

Algorithm 4 Loop and Blackhole Detection in a Nexthop Array: Indegree.

```
procedure Loop_and_blackhole(node n)
    a = n.nexthop array
    b = a new array with the same size as a
    Initialize b with "0"s, which indicates the in-degree at that position
    for each index i in a.size do
        b_i ++
    end for
    for each index i in b.size do
        if b_i = 0 then
            i = a_i
            while i ≥ 0 do
                b_i --
                if b_i ≠ 0 then
                    break
                end if
            end while
            if i = -1 then
                There is a blackhole at position i
            end if
        end if
    end for
    for each index i in b do
        if b_i ≠ 0 then
            There's loop at position i
            Trace the loop from a_i and change b_{a_i} to 0
        end if
    end for
end procedure
```

Algorithm 5 Loop and Blackhole Detection after Adding an Entry.

```
procedure Add(ancestor, i, prefix, nxthop)
    target = search (ancestor, prefix)
    if target is NULL or GLUE then
        target = createREALnode(ancestor, prefix)
        inherit all the nexthops from target's nearest REAL ancestor except the one at index
    end if
    data = target.data
    data.status_i = 1
    data.nexthop_i = nxthop
    Detect Loops and Blackholes (target)
    Change target's left and right child nodes to data.nexthop_i = nxthop
    Detect Loops and Blackholes at the same time until a node with node.data.status_i = 1 is found
end procedure
```

Algorithm 6 Loop and Blackhole Detection after Modifying an Entry.

procedure $Mod(ancestor, i, prefix, nxthop)$
  $target$ = search ($ancestor$, $prefix$)
  $data$ = $target.data$
  $data.nexthop_i = nxthop$
  Detect Loops and Blackholes ($target$)
  Change $target$'s left and right child nodes to $data.nexthop_i = nxthop$
  Detect Loops and Blackholes at the same time until a $node$ with $node.data.status_i = 1$ is found
end procedure

one, changes the $nexthop_i$ values, until a node with $status_i = 1$ is found.

The algorithm of the detections after deleting an entry is shown in Algorithm 7. It has a precondition that there was an original

Algorithm 7 Loop and Blackhole Detection after Deleting an Entry.

procedure $Del(ancestor, i, prefix)$
  $target$ = search ($ancestor$, $prefix$)
  $data$ = $target.data$
  $data.status_i = 0$
  if All the $status$ in $target.data.status$ are 0 **then**
    if $target$ has two child nodes **then**
      change $target$ to GLUE node
    else
      $target = removenode(ancestor, target)$
    end if
    $nxthop = nexthop_i$ from $target$'s nearest REAL ancestor
  else
    Detect Loops and Blackholes ($target$)
    $nxthop = target.nexthop_i$
  end if
  Change $target$'s left and right child nodes to $data.nexthop_i = nxthop$
  Detect Loops and Blackholes at the same time until a $node$ with $node.data.status_i = 1$ is found
end procedure

record at that position. If the position i is valid, $nexthop_i$ is changed to "-1" and $status_i$ is changed to "0". Then the current $status$ array is checked. if all the values in the array are "0", the PT runs the *erase* operation and the nearest REAL ancestor node n is returned. Afterwards, the algorithm keeps searching the left and right nodes of the current one, changes the $nexthop_i$ values, until a node with $status_i = 1$ is found.

3.3.3. Complexity

As indicated by Algorithms 3 and 4, when we need to detect loops or blackholes, each of the algorithms needs to go through a top-down process from the joint Patricia trie root to the leaves one by one, and each internal node maintains an array with a constant number of next hops. If we use n to represent the number of the trie nodes and a to indicate the number of next hops in the array, then the complexity of the loop and blackhole detection is O(an), where a is a constant once the network topology is known. Therefore, the overall complexity is O(n).

4. Results

All experiments in this work were run on a machine with Intel Xeon Processor E5-2603 v3 1.60GHz and 64GB memory. This section presents three different sets of experiments: first, the comparison of *VeriTable* against *TaCo* and *Normalization* in a two-tables scenario. Next, it shows how scalable is VeriTable for the 10-tables scenario. Finally, it shows the performance of the "relaxed" version of *VeriTable* for "black-holes" detection in a network.

4.1. VeriTable vs TaCo vs Normalization

Datasets were provided by the RouteViews project of the University of Oregon (Eugene, Oregon USA) [21]. For the evaluation, 12 IPv4 Routing Information Bases (RIBs) and 12 IPv6 RIBs from the first day of each month in 2016 were collected. For the simulation purpose, AS numbers were used as next hops. By the end of 2016, there were about 633K IPv4 routes and 35K IPv6 routes in the global forwarding tables. To obtain different but equivalent forwarding tables, an optimal FIB aggregation algorithm[4] was applied to RIB tables. Fig. 8 shows the aggregation results for both IPv4 and IPv6 tables. IPv4 achieves a better compression ratio (about 25% of the original size) than IPv6 (about 60% percent of the original size) because IPv4 has the larger number of prefixes. The original and compressed tables were used to evaluate the performance of *VeriTable* vs the state-of-the-art *TaCo* and *Normalization* (see description of these two algorithms in Section 2.4) verification algorithms in a two-table scenario. The following metrics were used for the evaluations: data structure building time, verification time, the number of node accesses and memory consumption.

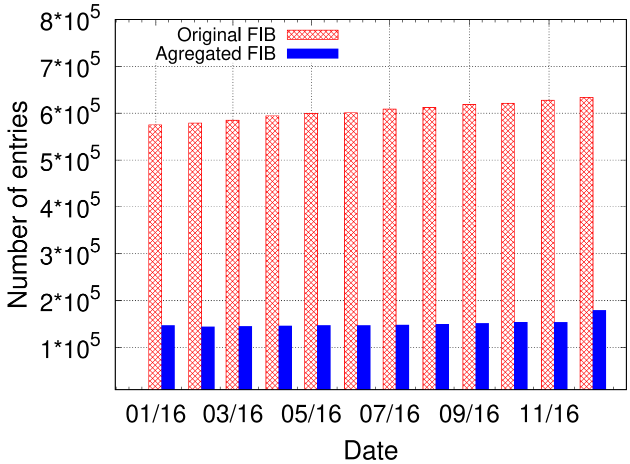
4.1.1. Data structure building time

TaCo and *Normalization* need to build two separate binary trees, while *VeriTable* only needs to build a single joint Patricia Trie (PT). Fig. 9 shows the building time for both IPv4 and IPv6. *VeriTable* outperforms *TaCo* and *Normalization* in both cases. In Fig. 9a for IPv4, *TaCo* uses minimum 939.38ms and maximum 1065.41ms with an average 986.27ms to build two BTs. For *Normalization*, it is 1063.42ms, 1194.95ms and 1113.96ms respectively. Our *VeriTable* uses minimum 608.44ms and maximum 685.02ms with an average 642.27ms to build a joint PT. *VeriTable* only uses 65.11% of the building time of *TaCo* and 57.65% of the building time of *Normalization* for IPv4 tables. In the scenario of IPv6 in Fig. 9b, *TaCo* uses minimum 137.94ms and maximum 186.73ms with an average 168.10ms to build two BTs; for *Normalization* these numbers are 162.40ms, 225.75ms and 197.25ms. *VeriTable* uses minimum 36.39ms and maximum 49.99ms with an average 45.06ms to build a joint PT. *VeriTable* only uses 26.78% and 22.84% of the building time of *TaCo* and *Normalization* respectively for IPv6 tables. Although IPv6 has much larger address space than IPv4, *VeriTable* achieves much less building time under IPv6 than that of IPv4, which is attributed to the small FIB size and the usage of a compact data structure – a joint PT. Note the slower *Normalization* building time due to the operation of tree compression performed by that algorithm.

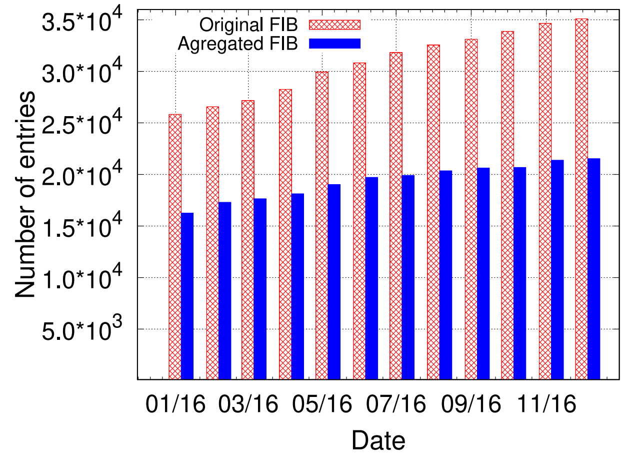
4.1.2. Verification time

A valid verification algorithm needs to cover the whole routing space (2^{32} IP addresses for IPv4 and 2^{128} IP addresses for IPv6) to check if two tables bear the same forwarding behaviors. The verification time to go through this process is one of the most important metrics that reflects whether the algorithm runs efficiently or not. Fig. 10 shows the running time of *TaCo, Normalization* and *VeriTable* for both IPv4 and IPv6, respectively. *VeriTable* significantly outperforms *TaCo* in both cases thanks to the *VeriTable* property, described in Section 3.1. *TaCo* takes minimum 355.06ms and maximum 390.60ms with an average 370.73ms to finish the

[4] We used FIFA-S algorithm, described in [9]

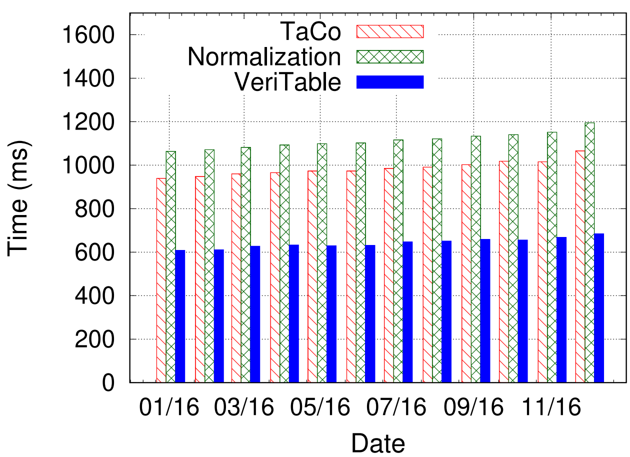


(a) IPv4 FIB size

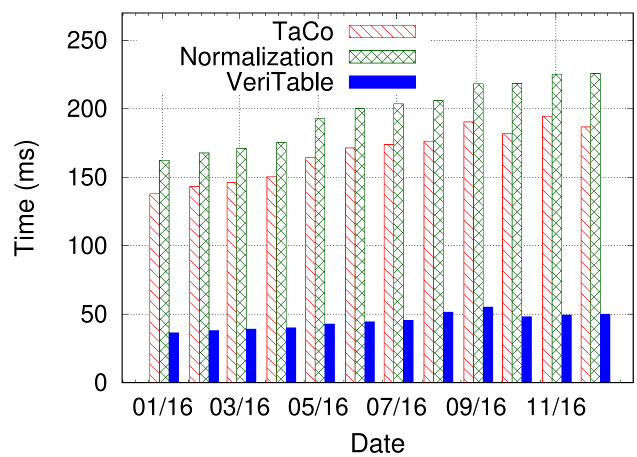


(b) IPv6 FIB size

Fig. 8. IPv4 and IPv6 FIB size before and after aggregation

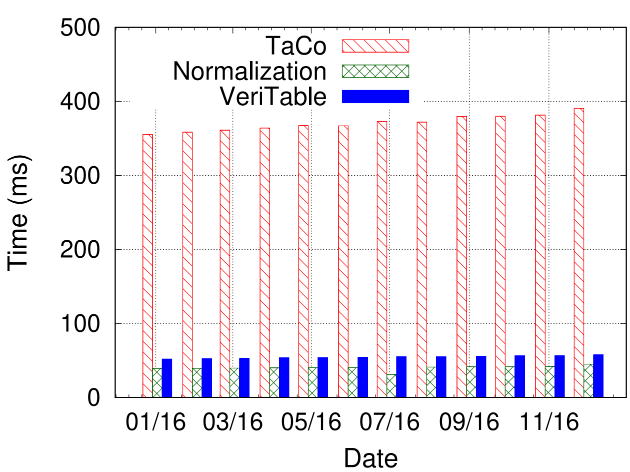


(a) IPv4 building time

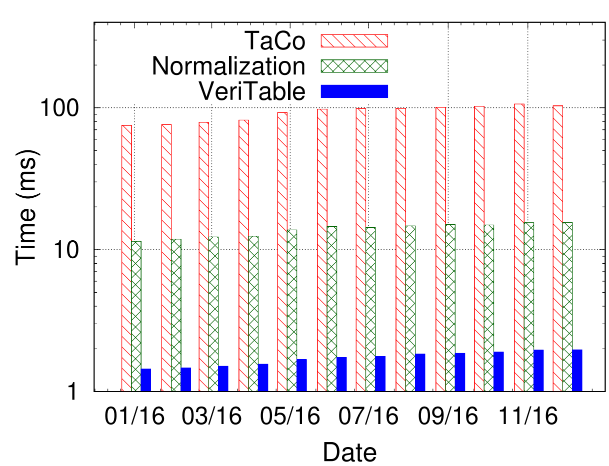


(b) IPv6 building time

Fig. 9. IPv4 and IPv6 data structure building time

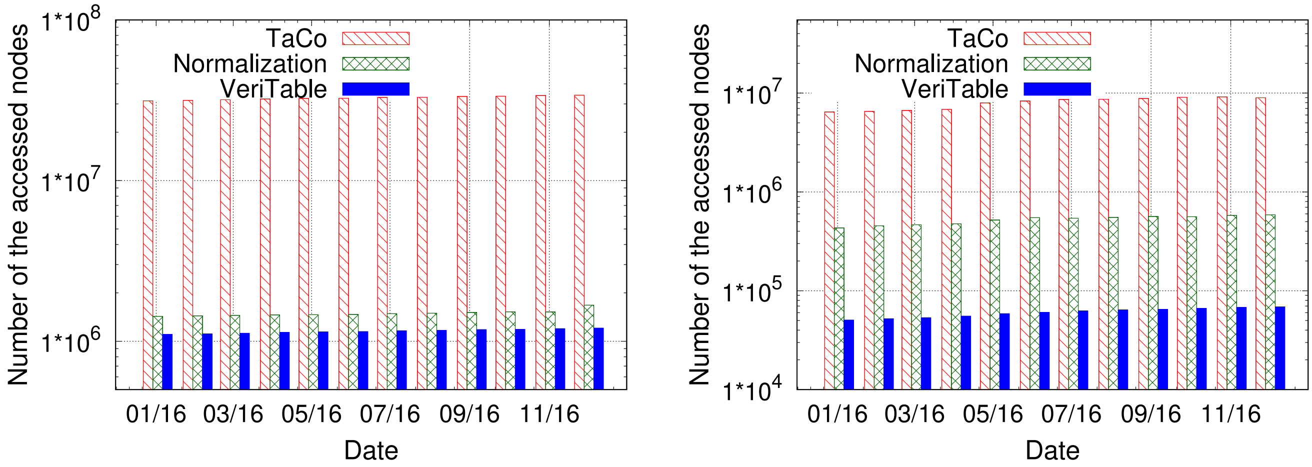


(a) IPv4 verification time



(b) IPv6 verification time

Fig. 10. IPv4 and IPv6 verification time



(a) IPv4 node accesses

(b) IPv6 node accesses

Fig. 11. IPv4 and IPv6 number of node accesses

whole verification process. *VeriTable* takes minimum 51.91*ms* and maximum 57.48*ms* with an average 54.63*ms* to verify the entire IPv4 routing space. *VeriTable* only takes 14.73% of the verification time of *TaCo* for verification over two IPv4 tables. **Taking building time into consideration, *VeriTable*is about 2 times faster than *TaCo*for IPv4 verification (1356*ms* VS 696*ms*).** *Normalization* verification time for IPv4 tables is slightly faster than that of *VeriTable* (which is not the case for IPv6 tables). This is achieved due to the compression that shrinks the size of the binary trees for verification process. However, *Normalization* has much longer building time than *VeriTable*. **Overall, considering both building and verification time, *VeriTable*is faster than *Normalization*by 40% (696.90*ms* VS 1154.08*ms*) for IPv4 verification**.

Fig. 10 b shows the IPv6 scenario (note the Y-axis is a log scale). *TaCo* takes minimum 75.17*ms* and maximum 103.18*ms* with an average 92.79*ms* to finish the whole verification process. For *Normalization* it is 11.47*ms*, 15.58*ms*, 13.87*ms* respectively. *VeriTable* takes minimum 1.44*ms* and maximum 1.97*ms* with an average 1.75*ms* to verify the entire IPv6 routing space. *VeriTable* only takes 1.8% and 12.6% of the verification time of *TaCo* and *Normalization* respectively for verification over two IPv6 tables. **Considering both building and verification time, *VeriTable*is 5.6 times faster than *TaCo*(261*ms* VS 47*ms*) and 4.5 times faster than *Normalization*(211*ms* VS 47*ms*) for IPv6 verification**. The fundamental cause for such a large performance gap is due to the single trie traversal used in *VeriTable* over a joint PT with selection of Longest Prefix Matches for comparisons, without tree normalization (see Section 3) for details). Note, that the leaf pushing operation over IPv6 forwarding table causes a significant inflation of the binary trees. That explains much slower speed of *TaCo* and *Normalization* verification for IPv6 tables than for IPv4 tables.

4.1.3. Number of node accesses

Node accesses, similarly to memory accesses, refer to how many nodes were visited during the verification process. The total number of node accesses is the primary factor to determine the verification time of an algorithm. Fig. 11 shows the number of total node accesses for both IPv4 and IPv6 scenarios. Due to the novel design of *VeriTable*, it is able to control the total number of node accesses to a significantly low level. For example, node accesses range from 1.1 to 1.2 million for 580K and 630K comparisons, which is **less than 2 node accesses** per comparison for IPv4. *VeriTable* achieves similar results for IPv6. On the contrary, *TaCo* and *Normalization* requires larger number of node accesses per comparison. For instance, *TaCo* bears **35 node accesses** per comparison, on average, for IPv4 and **47 node accesses** per comparison, on average, in IPv6. *Normalization* has **4 node accesses** per comparison in both cases. There are two main reasons for the gaps between *VeriTable, TaCo* and *Normalization*: (*a*) *VeriTable* uses a joint PT, but *TaCo* and *Normalization* uses separate binary trees; and (*b*) *VeriTable* conducts only single post-order PT traversal. *TaCo* conducts several repeated node accesses over a binary tree, including Longest Prefix Match lookups. Due to the unique form of a normalized binary tree, *Normalization* requires no mutual IP address lookups and thus conducts significantly fewer node accesses than *TaCo*.

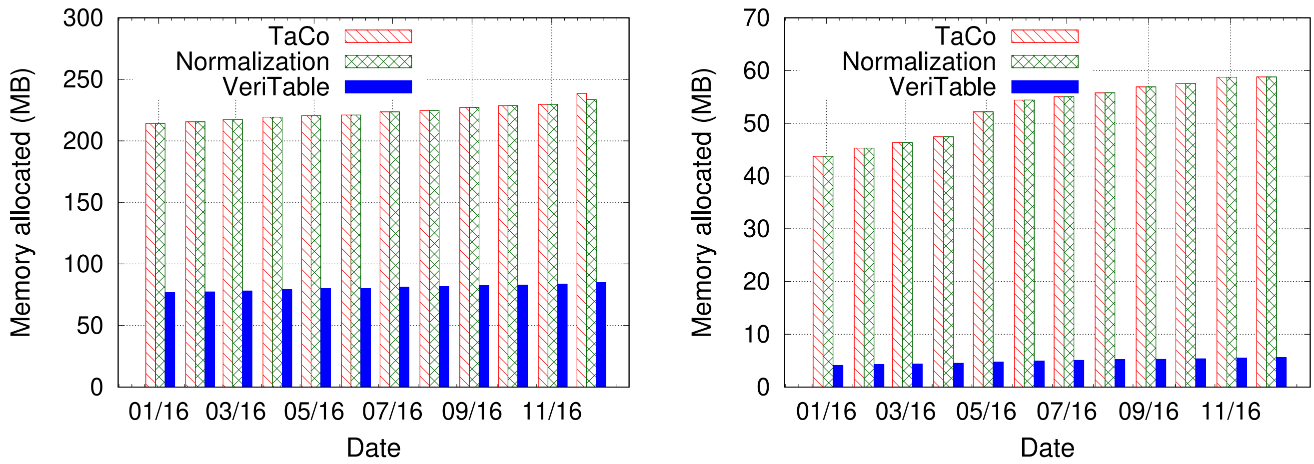
4.1.4. Memory consumptions

Memory consumption is another important metric to evaluate the performance of algorithms. Fig. 12 shows the comparisons between *TaCo, Normalization* and *VeriTable* for both IPv4 and IPv6 prefixes, in terms of their total memory consumptions. In both scenarios, *VeriTable* outperforms *TaCo* and *Normalization* significantly. ***VeriTable*only consumes around 38% (80.86*MB*)** of total memory space than that of *TaCo* and *Normalization* (223*MB*) on average for the same set of IPv4 forwarding tables. In the IPv6 case, *VeriTable* bears even more outstanding results, **consuming only 9.3% (4.9*MB*)** of total memory space than that of *TaCo* (53*MB*) and of *Normalization* on average. The differences in memory consumption by *VeriTable, Normalization* and *TaCo* are caused by the unique combined trie data structure used in *VeriTable*. A node in *Normalization* and *TaCo* holds a single next hop instead of an array of next hops, because *TaCo* and *Normalization* build separate BTs for each forwarding table. Moreover, those BTs inflate after leaf pushing.

Overall, thanks to the design of *VeriTable*, it outperforms *TaCo* and *Normalization* in all aspects, including total running time, number of node accesses and memory consumption.

4.1.5. Scalability of VeriTable

This experiment shows the performance of *VeriTable* when checking the forwarding equivalence and differences over multiple forwarding tables simultaneously. For the experimental purpose, 2000 distinct errors were intentionally added to each comparable forwarding table. It was verified that the same number of errors were detected by *VeriTable* algorithm. The evaluation results are showed in Table 5. There are two primary observations. First, *VeriTable* is able to check the whole address space quickly over 10 large forwarding tables (336.41*ms*) with relatively small memory consumptions (165*MB*). Second, the building time, verification time, node accesses, and memory consumptions grow significantly slower than the total number of forwarding entries. This indicates



(a) IPv4 memory consumption

(b) IPv6 memory consumption

Fig. 12. IPv4 and IPv6 memory consumption

Table 5
VeriTable's comparison of 10 IPv4 FIB tables simultaneously.

Number of tables	Total number of entries	Building time(*ms*)	Verification time (*ms*)	Number of comparisons	Node access times	Number of errors	*MB*
2	1230512	962	82	586942	1133115	4000	84
3	1845768	1326	108	1175884	1137115	6000	94
4	2461024	1684	135	1766826	1141115	8000	104
5	3076280	2060	172	2359768	1145115	10000	114
6	3691536	2471	194	2954710	1149115	12000	124
7	4306792	2869	213	3551652	1153115	14000	134
8	4922048	3248	224	4150594	1157115	16000	145
9	5537304	3630	322	4751536	1161115	18000	155
10	6152560	4007	337	5354478	1165115	20000	165

that *VeriTable* is scalable for equivalence checking of a large number of tables. On the contrary, *TaCo* and *Normalization* naturally were not designed to compare multiple forwarding tables. In theory, *TaCo* may need $n*(n-1)$ table-to-table comparisons to find the exact entries that cause differences, which is equal to 90 comparisons for this 10-table scenario. On the other hand, *Normalization* needs additional decompression steps to find such entries.

4.1.6. Routing space comparisons

A relaxed version with minor changes of *VeriTable* algorithm is able to quickly identify the routing space differences between multiple FIBs. More specifically, after building the joint PT for multiple FIBs, *VeriTable* goes through the same verification process recursively. When traversing each node, it checks if there is a case when the corresponding *Next Hop* array contains at least one default next hop (the next hop on default route 0/0) and at least one non-default next hop. If yes, it indicates that at least one FIB misses certain routing space while another FIB covers it, which may potentially lead to routing "black-holes". In our experiments, we used data from RouteViews [21] project, where 10 forwarding tables that contain the largest number of entries were collected and then merged into a super forwarding table with 691,998 entries. Subsequently, we compared the routing spaces of the 10 individual forwarding tables with the super forwarding table. The results of these comparisons (see Table 6 in detail) show that none of these 10 forwarding tables fully cover the routing space of the merged one. The leaking routes in Table 6 were calculated by the number of subtrees in the joint PT under which an individual forwarding table "leaks" certain routes, but the merged super forwarding table covers them. These facts imply that the potential routing "black-holes" may take place between routers in the same domain or between different domains. To this end, *VeriTable* verification algorithm can find out routing space differences quickly.

Table 6
Comparison of individual forwarding tables from RouteViews [21] with the merged super table.

Table size	Router IP	ASN	BGP peers	Leaking routes
673083	203.189.128.233	23673	204	489
667062	202.73.40.45	18106	1201	507
658390	103.247.3.45	58511	1599	566
657232	198.129.33.85	292	153	495
655528	64.71.137.241	6939	6241	667
655166	140.192.8.16	20130	2	879
646912	85.114.0.217	8492	1504	796
646892	195.208.112.161	3277	4	772
641724	202.232.0.3	2497	294	1061
641414	216.221.157.162	3257	316	1239

4.2. Network-wide loop and blackhole detection

In order to test the efficiency and scalability of the VeriTable's loop and blackhole detection algorithms. In the evaluation, we conducted 6 runs of the experiments. The number of the entries in each forwarding table in the network ranges from 100K, 200K, all the way to 600K. IP prefixes in each table are chosen from the routing tables on RouteViews [21] project. The network topology is shown in Fig. 13. We select the next hops for each prefix of each FIB in the following way: We can see from Fig. 13 that each node has some directly connected nodes, for example, the node numbered 8 is connected to nodes numbered 3, 5, 7 and 9. As a result, for each prefix entry in forwarding table of node 8, therefore, the next hops is randomly selected from values of {3,5,7,9}.

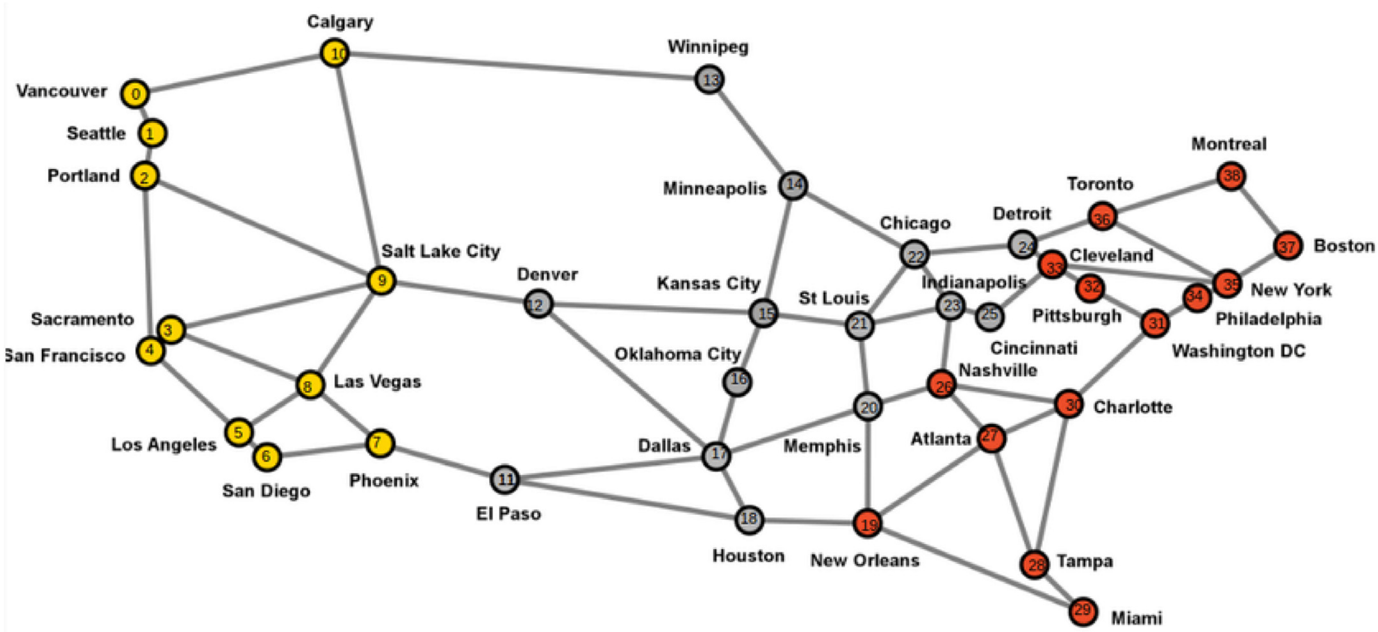


Fig. 13. Network topology used in loop and blackhole detection.

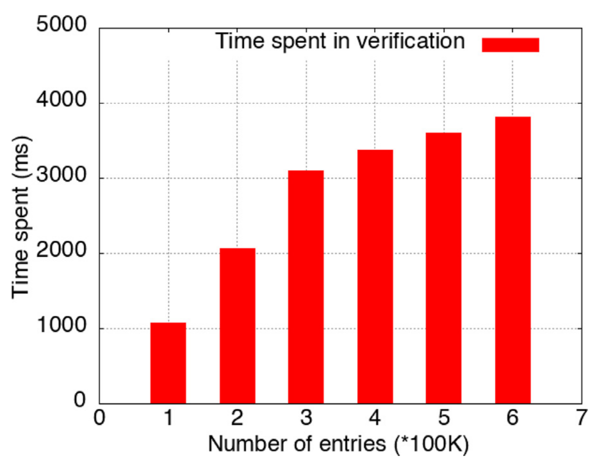


Fig. 14. Time consumption.

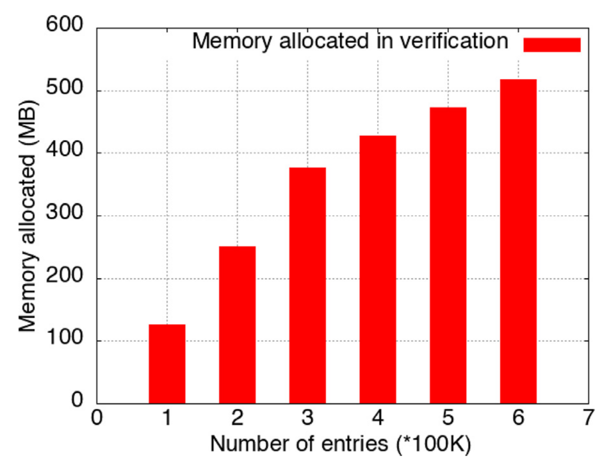


Fig. 15. Memory consumption.

4.2.1. Time and memory consumption

Fig. 14 shows the results of time used to detect loops and blackholes in the given topology versus the number of entries in each node. According to the figure, In general, the average time spent for loop and blackhole detection is 2838 ms for 350K entries, which is relatively small. It reveals the algorithm is very efficient as it has the time complexity better than linear. The advantage is outstanding especially when there is a huge amount of entries. The possible reason for this saving is, although the number of entries is increasing linearly, there might be more branch nodes hidden into the Patricia Trie and are fully covered by their child nodes. As a result, the number of nodes under detection does not increase that fast when compared with the situation with a small number of entries.

Fig. 15 shows the results of memory consumed to detect loops and blackholes. In general, the average memory spent for loop and blackhole detection is 362 MB for 350K entries, which is also relatively small. As a result, the algorithm used is very scalable, especially when there is a huge amount of entries. The possible reason for this saving is similar to that analyzed in the time consumption part: with the number of entries increases, the ratio of inner branch node increases. This results in a decrease of the ratio for the nodes that need to be checked.

4.2.2. Loop and blackhole size distribution

Fig. 16 shows the loop size distribution for the test results with 100K, 300K and 500K entries individually. It is concluded from the figure that, normally most of the loops have sizes no bigger than 10 and for a given size, the loop number increases with the entry number increases. the number of loops has a logarithmic decrease with the size increases. This reveals the detection algorithm works very well to detect a large scale of potential loops in a network.

Fig. 17 shows the blackhole size distribution for the test results with 100K, 300K and 500K entries individually. It is concluded from the figure that, normally most of the blackholes have sizes no bigger than 10. It is worth to note that, for a given blackhole size, the peak values of the blackhole numbers occur when there is a half number of prefixes chosen from the routing table. The possible reason for this result is, the chosen routing table has no blackhole when all the prefixes are chosen in the experiment. Before the routing space is half-filled, with the increase of the number of entries, there are more forwarding chains and the possibility for a forwarding chain to end up with a ”-1” increases. After half of the

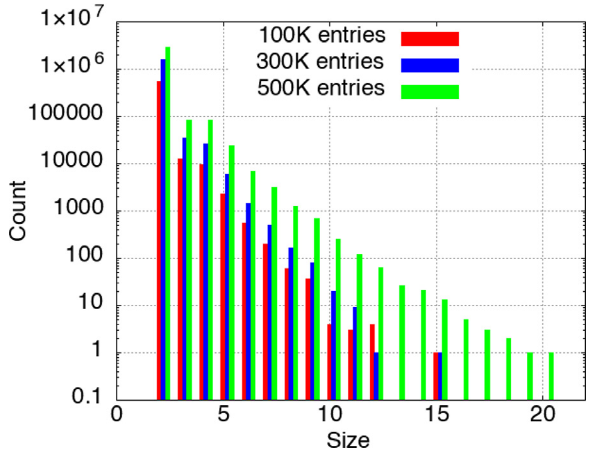


Fig. 16. Loop size distribution.

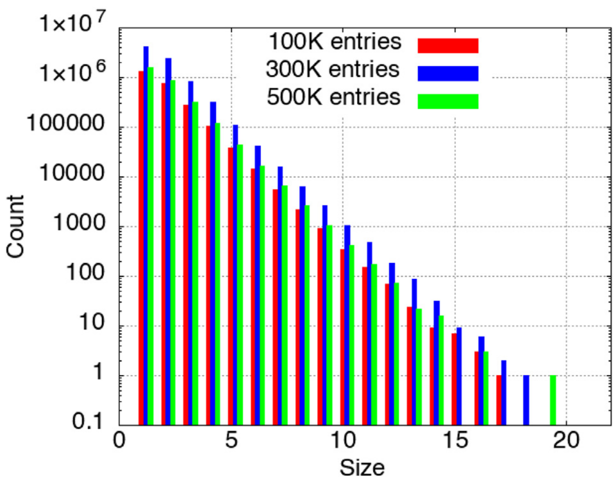


Fig. 17. Blackhole size distribution.

entries are filled into the FIB array, with the number of entries increasing, there are fewer new forward chains and more and more blackholes will get values instead of ending up with "-1". In addition, the number of blackholes has a logarithmic decrease with the size increases. This reveals the detection algorithm can scale very well to a large number of FIB entries and block holes.

5. Related work

The natural application for verifying the forwarding equivalence or routing tables is to verify the correctness of FIB aggregation of FIB caching algorithms. To this end, multiple solutions for compressing an FIB were proposed. FIB aggregation algorithm implementations [9,22–24] can incur misbehavior of the router after the entry merging process or when applying BGP updates to the compressed forwarding table. FIB caching approach implies storing the popular routes in a fast and expensive memory, while rest of the routes are stored on a slower memory [17,25–27]. Although such approach can be extremely efficient in compressing the routing table (2% of the cache can reach 99.5% cache hit ratio [28]), it poses a risk of a problem called "cache-hiding", when instead of a route with the longer prefix, which stays in the slower memory, the shorter prefix in the cache is selected for obtaining the next hop. Thus, "cache-hiding" may cause a forwarding behavior of a router different from its original forwarding behavior.

The above-mentioned risks of forwarding misconfiguration indicate the importance of developing efficient tools to verify the forwarding equivalence between original and compressed forwarding tables. *TaCo* algorithm, proposed by Tariq et al. [19], is designed to verify forwarding equivalence between two forwarding tables. *TaCo* builds two separate binary trees for two tables and performs tree normalization and leaf-pushing operations. Section 2.4 elaborates the algorithm in detail. *VeriTable* is different from *TaCo*, since it builds a single joint Patricia tree for multiple tables and leverages novel ways to avoid duplicate tree traversals and minimize node accesses. Thus, as shown in Section 4, *VeriTable* outperforms *TaCo* in all aspects.

Inconsistency of forwarding tables within one network may lead to different types of problems, such as "black-holes", looping of IP packets, packet losses and violations of forwarding policies. Network properties that must be preserved to avoid misconfiguration of a network can be defined as a set of invariants. In [29] authors present a patent for a system that validates the equivalence between an RIB and an FIB in a network. Mai et al. introduced *Anteater* in [30], that converts the current network state and the set of invariants into instances of boolean satisfiability problem (SAT) and resolves them using heuristics-based SAT-solvers. *Anteater* was evaluated with 178 FIBs with the mean size of 1627 entires. Zeng et al. introduced *Libra* in [31]. *Libra* used *MapReduce* [32] to analyze rules from forwarding tables on a network in parallel. Due to the distributed model of MapReduce, *Libra* analyzes the forwarding tables significantly faster than *Anteater*. *VeriFlow* [33], proposed by Khurshid et al., leverages software-defined networking to collect forwarding rules and then slice the network into *Equivalence classes* (*EC*s). Each *EC* consists of prefixes that exhibit the same forwarding behavior on the network. Upon routing update, *VeriFlow* finds all *EC*s affected by the update and generates a forwarding graph for each of them. Thus, *VeriFlow* confines the verification by the entries of affected *EC*s. Kazemian et al. introduced *NetPlumber* in [34], a real-time network analyzer based on *Header Space Analysis* protocol-agnostic framework, described in [35]. *NetPlumber* is compatible with both Software-Defined and conventional networks. It incrementally verifies the network configuration upon every policy change in a quick manner. However, *NetPlubmer* is not designed for networks with a high rate of routing updates (e.g. networks, operating in Default-Free Zone), because of high processing time for update verification. The problem of FIB equivalence in a programmable data plane is studied in [36]. Sanger et al. in [37] use a Multi-Terminal Binary Decision Diagram in order to verify consistency of the data plane in a Software-Defined Network.

Different from the network-wide verification methods above, *VeriTable* aims to investigate whether multiple static forwarding tables achieve the same forwarding behaviors, given an IP packet with an arbitrary IP destination address, or whether those tables cover the same routing space. *VeriTable* will is able to quickly identify if the forwarding tables return the same next hop after the Longest Prefix Matching lookups, and which prefixes result in discrepancy if the answer is no.

6. Conclusion

This paper presents the design and the implementation of *VeriTable*, which can quickly determine if multiple routing or forwarding tables achieve the same or different forwarding behaviors. The evaluation results of *VeriTable* show that *VeriTable* significantly outperforms its counterparts. The novel algorithm and compact data structures can offer the benefit not only in quick and efficient verification of the correctness of an FIB compression, but also in several other scenarios, when the Longest Prefix Matching rule is used for performing IP lookups. For example, *VeriTable* is able to check if routing updates in the control plane are consistent with the updates in the data plane. Moreover, the principles used in this work can be applied to network-wide abnormality diagnosis of network problems. To this end, we extended VeriTable to conduct a scalable and efficient forwarding loop detection and avoidance in the data plane of a network. The newly extended algorithms can handle incremental updates, applied to the forwarding tables in a network. Our evaluation results show that the designed algorithms are efficient enough to handle large scale of forwarding tables for identifying their loop and blackhole problems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Algorithms of VeriTable

Algorithm 1 shows the pseudo code of the first step of *VeriTable*, when the joint Patricia Tree is built. At this step, *VeriTable* reads the entries from each table, starting from the first table, and generates or updates the nodes corresponding to the prefixes from those tables. Note, that *GLUE* nodes need to be generated in case if two *REAL* nodes have the same parent and located at the same branch of that parent.

Algorithm 2 shows the pseudo code of the second step of VeriTable, when it performs single traversal over the joint Patricia tree, in order to:

(1) Initialize empty next hops at the nodes of the joint Patricia tree.
(2) Identify Longest Prefix Matches (LPM) in the joint Patricia tree.
(3) Compare the next hops in the *Next Hop* array at those LPM nodes, in order to verify, if they have the same value.

For the description of each node field in the algorithms see Table 4.

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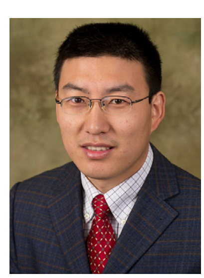
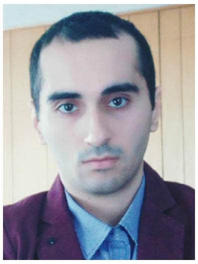


Dr. Yaoqing Liu received his Master's and PhD degrees from the University of Memphis in Computer Science. He is the program coordinator of M.S. in Cybersecurity and Information Assurance program (MSCSIA), and an Assistant Professor in Gildart Haase School of Computer Sciences & Engineering at Fairleigh Dickinson University (FDU). His research interests are networked systems (security, routing, algorithm and measurement), currently focusing on Named Data Networks (NDN) and Blockchain applications. His publications appear in highly reputed conference proceedings and journals, such as IEEE INFOCOM, ACM SIGCOMM CCR and ACM/IEEE ANCS. He has been a TPC member and technical paper reviewer for IEEE conferences, journal magazines and transactions. He is the inventor of four patents. His research work has been selected as one of the 2018 TechConnect Defense Innovation Awards recognizing the potential positive impact for the warfighter and national security.



Garegin Grigoryan was born in 1991 in Moscow, Russia. He received a Diploma degree in "Automated Data Processing and Management Systems" from the Department of Cybernetics of Moscow Engineering Physics Institute, in 2012. The same year, he joined Diasoft, a Moscow-based company that provides a wide range of financial software solutions. In 2016, he entered the graduate program of Clarkson University (Potsdam, NY, USA). After receiving his MS degree in Computer Science, he joined Rochester Institute of Technology as a Ph.D. candidate. His current research interests include routing scalability, aggregation and caching of forwarding tables, Software-Defined Networking, software switching, programmable data planes, Blockchain technology, and Information-centric networking.

Dr. Jun Li is a Professor in the Department of Computer and Information Science and founding director of the Center for Cyber Security and Privacy at the University of Oregon. He received his Ph.D. from UCLA in 2002 (with Outstanding Doctor of Philosophy honor), M.E. from Chinese Academy of Sciences in 1995 (with Presidential Scholarship), and B.S. from Peking University in 1992, all in computer science. His research is focused on networking, distributed systems, and network security, with about 90 peer-reviewed publications. He has served on US National Science Foundation research panels and more than 70 international technical program committees, including chairing six of them. He currently serves on the editorial board of IEEE Transactions on Dependable and Secure Computing and a few conference or workshop steering committees. He is a senior member of ACM and IEEE and an NSF CAREER awardee in 2007.

Guchuan Sun was born in the city of Zhenjiang, Jinagsu Province, China in 1988. He received a Master's degree in Computer science from Clarkson University in 2019, under the supervision of Dr. Yaoqing Liu. His major research interests include network optimization algorithms, network problem diagnosis and blockchain applications.

Tony Tauber is a distinguished engineer at Comcast since Jan 2014. His specialties include routing, instrumentation, measurement, scaling, and network planning to accommodate new services and achieve business objectives. He works on the design and engineering of Comcast's national backbone network including initial implementation and ongoing evolution. He served as the chair of NANOG from 2011 to 2016, and led the technical committee which solicit, review, and develop material for thrice-yearly conference on the state of the art in the Internet Service Provider and computer networking arena. He has been an active member of several standards groups.