CAIR: Using Formal Languages to Study Routing, Leaking, and Interception in BGP

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Abstract

The Internet routing protocol BGP expresses topological reachability and policy-based decisions simultaneously in path vectors. A complete view on the Internet backbone routing is given by the collection of all valid routes, which is infeasible to obtain due to information hiding of BGP, the lack of omnipresent collection points, and data complexity. Commonly, graph-based data models are used to represent the Internet topology from a given set of BGP routing tables but fall short of explaining policy contexts. As a consequence, routing anomalies such as route leaks and interception attacks cannot be explained with graphs.

In this paper, we use formal languages to represent the global routing system in a rigorous model. Our CAIR framework translates BGP announcements into a finite route language that allows for the incremental construction of minimal route automata. CAIR preserves route diversity, is highly efficient, and well-suited to monitor BGP path changes in real-time. We formally derive implementable search patterns for route leaks and interception attacks. In contrast to the state-of-the-art, we can detect these incidents. In practical experiments, we analyze public BGP data over the last seven years.

1. INTRODUCTION

Measuring, modeling, and analyzing the routing between Autonomous Systems (ASes) have gained increasing importance over the last decade [17, 44, 58], as the Internet infrastructure has become business critical and investigations of cyber security incidents intensified. Today the question of route integrity is prevalent in day-to-day operations and a clear understanding of how data should flow is urgently desired to quickly detect anomalies. However, modeling Internet routing is still a major challenge due to the complex decision making in the Internet backbone. This work contributes a rigorous approach to route modeling and analysis.

The Internet inter-domain routing system selects those paths from the topologically possible paths that are economically feasible and comply to individual policies. Path vectors in BGP represent the outcome of this hybrid decision process without revealing its underlying rules explicitly. As such, BGP effectively hides most of its operational semantics from observers and successfully withstands the quest for a simple explanatory model [50]. The collection of all locally valid paths is essentially what we can learn at any given observation point. These paths are represented by our Constructible Automata for Internet Routes (CAIR). CAIR offers two key advantages over existing solutions:

a) By preserving policy-related information in its routing model, CAIR can reliably detect interception attacks or route leaks as they violate policies.

b) CAIR is an efficient yet complete representation of the observable inter-domain routing, which opens up the field for new analyses—even in real-time.

Inter-provider connections are traditionally modeled as a graph [44]. BGP peerings that show up in AS paths are considered valid links between nodes (ASes). Network graphs adequately represent connectivity in terms of router links or AS peerings. For the analysis of policy-influenced routing, though, such graphs tend to oversimplify the real situation. Realistic routing paths are selected on a per-prefix basis and often influenced by local routing policies. In particular, network graphs falsely imply transitivity over individual links and thus introduce additional, potentially nonexistent (sub)paths. Therefore, graph models cannot diagnose policy violations such as route leaking or complex anomalies such as interception attacks.

In this paper, we solve the fundamental transitivity problem in graphs (§ 2) for Internet routes. We remain with the concept of (context-dependent) path vectors and introduce a finite route language (§ 3) to model BGP data. Starting from an alphabet of AS numbers and
prefixes, we formally construct a complete description of the observable routing system. With corresponding route automata (§ 4), we show how to put this concept into practical use. Using incrementally minimized finite-state automata (§ 6), we arrive at a most efficient representation of the path vector space, which outperforms network graphs. Route automata are policy-aware: They represent the full characteristics of the observable routing policies and, at the same time, reduce complexity to real-time compliant processing. With CAIR, we can further derive formal detection patterns for route anomalies and apply these to real BGP data.

In our analysis of real-world incidents (§ 5), we focus on two intricate anomalies. First, we search for interception attacks, in which an adversary falsely attracts traffic while maintaining a backhaul path to its victim to relay eavesdropped packets. Second, we study (ab)normal routing changes and gain insight into customer ASes that erroneously advertise transit in a so-called route leak. We validate our approach with well-known incidents and identify 22 so far unknown cases of interception.

2. BACKGROUND AND INTUITION

We approach CAIR by describing a gap we currently face in network modeling and analysis in connection with common graph models. We then illustrate with some background why a model based on formal languages and automata can actually close this gap. For detailed background on formal languages we refer to [31].

2.1 Motivating Example: Interception Attacks

Interception attacks are characterized by a subtle injection of illegitimate prefix routes to redirect traffic destined for a victim to the attacker. To search for such events we need patterns and data models. A crucial factor is to sustain global connectivity by relaying all communication back to the victim. Implementing such an attack in the Internet is feasible and has been demonstrated in practice [12, 30, 46]. A malicious AS needs to be connected to the Internet via at least two upstream ISPs. The first ISP is used to attract traffic by advertising the victim’s address space or a part thereof, also called a hijacking attack. The second ISP serves to preserve a stable backhaul path from the attacker to the victim. To implement the backhaul path, the attacker includes all ASes between himself and his victim in the malicious BGP announcement. As a consequence, all of these ASes discard the announcement due to loop prevention, and a stable link from the attacker to the victim’s AS remains intact. Figure 1 illustrates the corresponding change in traffic forwarding.

Our key observation to derive a search pattern for interception attacks is that an arbitrary ISP T normally redistributes all routes of a distant AS V along the same ways [2, 22] (Figure 1a). From a BGP policy point of view, however, the attack induces a specific policy for the redirected prefix. In our example, S forwards traffic to V via the malicious AS A only for the prefix under attack, but reaches all other prefixes of the victim directly via T (Figure 1b). It is worth mentioning that the attacker can easily hide his own identity by not adding his AS number to the AS_PATH attribute of forged BGP messages, as it is common practice with route servers [34], for instance.

To diagnose the difference, data models are needed to express route diversity. Unfortunately, common graph models lack this capability.

2.2 The Need for CAIR

Consider a routing table extract that includes routes to three IP prefixes $P_{1-3}$ originated by the same AS $AS_3$ as shown in Figure 2a. Obviously, a complete list of all paths preserves the observable routing properties but is inefficient to memorize and difficult to analyze. A common way to represent such network topologies reduces data to a graph $G = (N, L)$ that is a set of nodes $N$ and links $L$ describing connectivity between ASes. For the analysis of policy-based routing, though, such graphs tend to oversimplify real BGP operations. In our example, transit paths to $AS_3$ differ for individual prefixes. Such prefix-based policies [2] are not reflected in a graph model (compare to Figure 2b). Rather, the model implies transitivity, which presumes reachability that has not been observed. It is a modeling artifact.

Incorrect Transitivity Assumption in Graphs:

$$AS_1 \rightarrow AS_2, \ AS_2 \rightarrow AS_3 \Rightarrow AS_1 \rightarrow AS_3$$

Note that in our example, transitivity breaks for the prefix $P_3$, i.e. no route $AS_1 \rightarrow AS_2 \rightarrow AS_3 \rightarrow P_3$ has been observed. CAIR offers a natural solution to this problem. It allows for an accurate representation of observed routing paths and is a highly efficient approach at the same time.

2.3 Why Using Finite Automata

A finite language consists of characters and rules to construct words, which can be represented by a deterministic finite-state automaton (DFA). In this paper, we understand a given set of network paths as such a finite
language. AS paths towards prefixes represent words of this language. Our CAIR framework serves to construct and minimize corresponding automata providing the following unique features:

**Accuracy** All initially observed BGP paths are stored in an automaton without introducing further unobserved information. Consequently, CAIR accurately reflects the observable routing system.

**Expressiveness** The states of a minimal DFA represent equivalence classes such that two equivalent states exhibit the same (routing) behaviour. CAIR exploits this unique fact to reveal intrinsic routing properties, such as the importance of an AS or the location of a hidden attacker.

**Feasability** Well-understood algorithms exist to construct a DFA. Processing of paths equals traversing the automaton. As a consequence, CAIR supports random access of data. It can be deployed both in real-time to continuously monitor BGP as well as in retrospective on archived data sets.

**Efficiency** Any DFA can be minimized without sacrificing accuracy. The resulting minimal automaton is unique. This is a highly efficient way to represent a finite language in general [31], and consequently a set of network paths we model with CAIR.

Despite this powerful feature set, concepts of formal languages have not been applied, yet, in the context of Internet routes. It is worth mentioning that other, less popular data structures could correctly model network paths, e.g. tries [4]. We will see later, however, that CAIR naturally outperforms such data structures in terms of expressiveness and efficiency.

### 2.4 CAIR in a Nutshell

CAIR derives a finite route language and constructs a route automaton based on BGP data such that each transition (edge) is labeled with either an AS number or an IP prefix. CAIR thereby reduces the amount of states by on-the-fly minimization. Traversing edges until the final, accepting state of the automaton results into a complete AS path as included in the initial BGP data set. Having the automaton in place, we search for specific properties. Since a DFA exists for any finite language (and vice versa), route automata accurately model the underlying input data and can thus be used to precisely describe its intrinsic routing characteristics.

**Toy Model.** For our example in Figure 2a, corresponding DFA and minimal DFA (MDFA) are shown in Figure 2c and Figure 2d respectively. In our CAIR framework, we utilize the latter one for route analysis. An important aspect of minimization is that we can observe route diversity based on non-minimizable states. In the minimal automaton, we obtain a sequence of independent states \((q_1,q_2,q_3)\) and \((q_4,q_5,q_6)\) that represents the nonuniform redistribution of prefixes \(\{P_1,P_2\}\) and \(\{P_3\}\) (compare Figure 2c and Figure 2d).

It is worth noting that CAIR does not intend to improve on the incompleteness of measured BGP data. Instead, we present a novel data model with maximum expressiveness that allows for an accurate representation of observed routing paths.

### 3. **FINITE ROUTE LANGUAGES**

A formal language is a set of strings of symbols constrained by specific rules. The global Internet routing system can be represented as all active BGP routes, i.e. a set of AS paths from all vantage points towards all advertised IP prefixes. By adopting the immediate analogy, we define the Finite Route Language (FRL) as follows.

**Definition.** Let \(\Sigma_A\) be the set of all ASes, \(\Pi\) the set of all IP addresses, \(p \subset \Pi\) an IP prefix, and \(p' \subset p\) a more specific prefix of \(p\). Let further be \((w,p) \in \Sigma_A \times \Pi\) a route with an AS path \(w \in \Sigma_A\); i.e. an arbitrary concatenation of ASes, to a prefix \(p \in \Pi\), in the following denoted \(r = wp\). Then, we define \(L \subset \Sigma_A \times \Pi\) as the set of active routes to all advertised prefixes in the global routing system, i.e. the set of all observable routes. \(L(p) \subset L\) denotes the subset of routes to a given prefix \(p \subset \Pi\), such that

\[L(p) = \{wuo \in L \mid w \in \Sigma_A, u \in \Sigma_A, o \in \Sigma_A\}\]

with \(w\) being an AS subpath and \(u\) the upstream AS of the origin AS \(o\). For a given route \(r\) and a prefix \(p' \subset p\), we postulate \(r \in L(p) \Rightarrow r \in L(p')\) as a corollary, since routes to less specific prefixes also cover more specific prefixes. Note that the converse is false. Further, \(L_P \subset L\) denotes the set of all observable routes from a set of observation points \(P \subset \Sigma_A\). We reuse the unary operator \(|\cdot|\) to indicate the number of routes in...
a set \( \mathcal{O} \subseteq \mathcal{L} \), the length of a route \( r \in \mathcal{L} \) or a subpath \( w \in \Sigma_{\text{AS}}^* \), and the number of ASes in a set \( S \subseteq \Sigma_{\text{AS}} \).

### 3.1 Formalization of Routing Attacks

BGP-based routing attacks are caused by injecting illegitimate route updates that alter the global BGP routing table in order to modify traffic flows. Route injections are considered illegitimate, if they violate topological constraints or policies as derived from business relations.

**Attacker Model.** Our attacker is assumed capable of injecting arbitrary BGP messages into the global routing system, i.e., he operates a BGP router and maintains a BGP session to at least one upstream provider. The attacker is not hindered by local filters or other validation mechanisms of his upstream. Instead, the upstream AS indifferently redistributes all update messages to its peers, which thus may propagate throughout the Internet. An observation point shall be in place to monitor the propagation of BGP messages. It is worth mentioning that route updates with less attractive paths may not reach a particular observation point due to best path selection in BGP. Without loss of generality, an omnipresent observation point to observe the set of all active routes \( \mathcal{L} \) is assumed for the following definitions.

**Generic Routing Attacks.** We denote an attacker’s AS \( a \in \Sigma_{\text{AS}} \) and his victim’s AS \( v \in \Sigma_{\text{AS}} \). Further, a victim’s prefix is given by \( p_v \in \Pi \). Then, a generic routing attack is defined by an attacker extending the set of valid routes \( \mathcal{L} \) by injecting forged routes \( \mathcal{F}_a \) into the routing system, such that the altered set of globally active routes \( \hat{\mathcal{L}}(p'_v) \) is given by

\[
\hat{\mathcal{L}}(p'_v) = \mathcal{L}(p_v) \cup \mathcal{F}_a(p'_v) \text{ with } p'_v \subseteq p_v.
\]

In general terms, the attacker advertises reachability of a victim’s network—either entirely or in parts—and may thus attract a fraction of the victim’s inbound traffic.

**Requirements and Impact.** In BGP, the impact of a hijacking attack generally depends on a best path selection process. In particular, shorter AS paths are preferred over longer ones, although policy-induced exceptions on a case-by-case basis may exist. With respect to packet forwarding, routes to longer IP prefixes prevail. Assuming the ambition to forge globally accepted routes, an attacker thus succeeds if his routes towards a victim’s network are considered best by a vast majority of Internet participants. This implies that an attacker needs to ensure that his bogus routes \( \mathcal{F}_a(p'_v) \) are either

1) shortest from a global perspective, i.e. \( \forall r \in \mathcal{L}(p'_v), r_a \in \mathcal{F}_a(p'_v) : |r_a| < |r|, \) or

2) more specific than all others, i.e. \( \forall p''_v \subseteq p'_v \subset p_v : \mathcal{L}(p'_v) = \mathcal{L}(p'_v) = \mathcal{L}(p_v) \).

As a consequence, the prospects of identifying an attack naturally depend on the significance of changes in \( \hat{\mathcal{L}} \) and on the peculiarities of the forged routes.

### 3.2 Application to Interception Attacks

A BGP-based interception attack succeeds if data packets sent to a victim are re-routed via an attacker’s AS, who in turn needs to have a stable backhaul path to the victim to forward the eavesdropped packets. Such attacks are unfeasible to detect from a topological point of view since only new paths over already existing links emerge. In the following, we use our formalized route model to thoroughly study these subtle changes.

**Formal Model.** The attacker \( a \in \Sigma_{\text{AS}} \) chooses to advertise (a part of) the victim’s prefix \( p_v \in \Pi \), while including a backhaul path in his announcements. As a BGP speaker, the attacker can easily identify such a path to \( p_v \) in \( \mathcal{L}_a(p_v) \). The set of AS paths that represent a suitable backhaul link via an arbitrary upstream AS \( u \in \Sigma_{\text{AS}} \) thus reads

\[
W^a_v(u) = \{ w_v \in \Sigma_{\text{AS}}^* | uw_v p_v \in \mathcal{L}_a(p_v) \}.
\]

Note that in practice, exactly one such path \( w_v^a \) exists per upstream AS, since each AS redistributes its preferred routes only. For the attack to succeed, the attacker needs to employ at least two upstream providers. In the following, \( t \in \Sigma_{\text{AS}} \) serves to establish the backhaul link, while the remaining upstream providers \( S \subset \Sigma_{\text{AS}} \) are utilized to launch a particular (sub)prefix hijacking attack [51] against \( p'_v \subseteq p_v \) such that

\[
\hat{\mathcal{L}}(p'_v) = \{ w_v p_v | w \in \Sigma_{\text{AS}}^* \} \cup \text{legitimate}
\]

\[
\{ w s u v a p' v | w \in \Sigma_{\text{AS}}^* ; \text{forged} \}
\]

\[
s \in S ; w_v^a \in W^a_v(t) \}.
\]

Most notably, the attacker can hide his AS number (see Section 2.1) while still forwarding between the upstreams \( s \) and \( t \). In any case, the attack does not lead to suspicious topological changes. The observable sets of both origin and upstream ASes for \( v \) remain unchanged, while the forged route to \( p'_v \) generates the impression of originating from the victim’s AS \( v \) and propagating via his legitimate upstream providers (as well as theirs).

### 4. THE CAIR FRAMEWORK

After introducing the concept of **Constructible Automata for Internet Routes (CAIR)**, we formulate an implementable search pattern for interception attacks.

#### 4.1 Route Automata

We define a route automaton as a minimal deterministic finite-state automaton that accepts any given finite route language (see Section 3). In general terms, an automaton represents a state machine that accepts a formal language, i.e., processing one of its words ends in an accepting state. Let \( \mathcal{L} \subset \Sigma_{\text{AS}}^* \times \Pi \) be an FRL representing all routes in the global routing system. Then, we define a route automaton as the 5-tuple

\[
M = (Q, \Sigma_{\text{AS}} \cup \Pi, \delta, q_0, F)
\]
4.2 A Search Pattern for Interception Attacks

We present a methodology to search route automata for anomalies emerging from interception attacks. Before we explain the details, we briefly illustrate the intuition behind our approach (for background see Section 2.1).

4.2.1 Intuition behind the Detection Scheme

Figure 3 shows an interception attack on a (sub)prefix \( p_v \subseteq p_v \in \Pi \) of the victim \( v \in \Sigma_{AS} \), in which the attacker \( a \in \Sigma_{AS} \) fabricates an artificial path segment \( w^a_v = tvu \in \Sigma_{AS}^* \) over \( t, u \in \Sigma_{AS} \) as described in Section 3.2. Recall our assumption that a distant AS \( t \) that is not a direct upstream of \( v \) neutrally redistributes the routes of \( v \) (Section 2.1). Hence, the right language (Section 4.1) of the automaton state \( q_t \) should represent all transit routes over \( t \) (indicated by dashed lines in Figure 3). In an interception scenario, however, the attacker seemingly changes the routing policy of \( t \): It appears that \( t \) now forwards announcements of \( p_v \) and \( p_v' \), differently, i.e. selectively to \( a, d \in \Sigma_{AS} \). As a result of this diversity, our route automaton holds separate states \( \{q_a, q_d'\} \), \( \{q_u, q_u'\} \), and \( \{q_t, q_t'\} \).

In the remainder, we anticipate that the attacker hides his true identity by not adding his AS number \( a \) to the AS_PATH attribute of forged BGP messages (remove dotted elements in Figure 3). In this case, we rename \( q_a \) to \( q_{a_s} \) with \( s \in \Sigma_{AS} \) being the attacker’s second upstream provider. We further assume that the attacker seeks to globally attract traffic to \( v \) by means of a strict subprefix hijacking, i.e. \( p_v' \subset p_v \in \Pi \), \( p_v' \neq p_v \) holds.

4.2.2 Translation to Route Automata

In order to detect interception attacks, we need to search for a partial route that a) is used in a single routing context only (artificiality), b) is in contradiction to existing announcements (nonuniformity), and c) leads to a subprefix of the benign routes (interception alert). Within our route automata, these conditions can be easily expressed and implemented.

**Artificiality.** An artificial path segment \( w^a_v \in \Sigma_{AS}^* \) is given by a sequence of (at least) four states \( \delta^*(q_{a_s}, tw^a_v) = q_t' \) with a single outgoing transition each, i.e.

\[
\forall tw \in \Sigma_{AS}^* , w \neq w^a_v : \delta^*(q_a, tw) = \bot .
\]

**Nonuniformity.** We further search for a path segment \( w^d_v \) that is in contradiction with \( w^a_v \) such that

\[
\exists q_{d} \in Q : \delta^*(q_{d}, w^d_v) = q_v .
\]

**Interception alert.** We verify if the offending state \( q_t' \) represents a subprefix hijacking of \( q_v \), i.e. if the condition

\[
\exists p_v, p_v' \in \Pi, p_v' \subset p_v : \delta(q_v, p_v) = \delta(q_v', p_v') = q_f
\]

holds true. We then raise an interception alert and report \( p_v, p_v', \) and \( w^a_v \) for further investigation.

4.2.3 Discrimination of the Attacker

With our route automata, we are able to pinpoint the attacker’s location in the Internet topology. If the at-
tacker adds his AS number $a$ to the BGP updates, we can directly observe a transition labeled with $a$ that points to the offending state $q_a$. Under the assumption that the attacker is taking precautionary measures to hide his AS (refer to Section 2.1), the incoming and outgoing transitions of $q_a$ are labeled with $s$ and $t$ respectively. In this case, we can isolate the attacker to be a customer of both ISPs $s$ and $t$, which leaves us with a small number of possible ASs to be manually scrutinized.

5. INCIDENT DETECTION WITH CAIR

We now deploy CAIR in practice and analyze seven years of BGP data with respect to two applications of CAIR, the detection of interception in BGP and route leak analysis. First, we apply our detection scheme and reveal 22 critical interception incidents so far unknown with victims mostly belong to the R&D sector and to the medium-sized ISP business. We explain details along two case studies, including our ground truth DEFCON [46]. Second, we derive measures to study the importance of ASs with respect to global routing, and evaluate their characteristics over time. We compare our results to a medium-sized ISP business. We explain details along two case studies, including our ground truth DEFCON [46].

5.1 BGP Interception Incidents

We use CAIR to construct route automata based on BGP routing table entries from the RouteViews [43] Oregon2 collector, August, 2008 – November, 2015, analyzed in an interval of two weeks (i.e. 174 RIBs with a total of $\approx 2.4B$ entries).

5.1.1 Overview

In total, we identified 6,171 artificial path segments $w^v_a \in \Sigma_{AS}$ (see Section 3.2). For 527 of them, we found a corresponding segment $w^v_b \in \Sigma_{AS}$ that evidenced nonuniform redistribution of BGP updates (Section 2.1). Our detection scheme finally raised 41 alerts for (strict) subprefix hijacking attacks. Table 1 presents the results. Note that one of these events lasted for 8 weeks, i.e. accounts for four subsequent alerts. Additional five events were observed twice. This leaves us with a total number of 32 distinct cases.

Sanitizing: Exclude false positives. Our search pattern for interception is based on the observation that nonuniform redistribution of BGP announcements should only take place at a victim $v$ itself or at his direct upstream ISPs, i.e. we search for artificial path segments of length $|w^v_a| \geq 3$. This assumption breaks if the victim operates multiple ASes [7] that are consecutively visible in an AS path. We manually analyzed the 32 interception alerts carefully, and were able to identify 9 sibling cases, which we exclude from further investigation. The remaining 23 alerts are marked as suspicious (Table 2).

Substantial alerts. We summarize the 23 alerts in Table 2. Entries that are highlighted in grey represent the upstream AS $s \in \Sigma_{AS}$ that is used by an attacker to redistribute forged BGP updates. The corresponding AS neighbor $t \in \Sigma_{AS}$ represents the attacker’s second upstream, which is used to uphold the backhaul path. The underlined parts of the AS paths show the artificial segment $w^v_a$. In 13 cases, $w^v_a$ is of length 3 (plus the attacker’s two upstreams and possibly further intermediate ASes), while 6 cases exhibit a segment length of 4 AS hops. The 4 remaining incidents show longer segments. To better grasp the details of the incidents, we checked AS names in the WHOIS system. Note that some of these events date far back to the past. We consequently utilized archived WHOIS data for the respective dates.

5.1.2 Case Studies

Ground Truth: The DEFCON Attack (2008). The DEFCON attack [46] was a well-known experiment to demonstrate interception attacks in the Internet. All details on the attack are publicly available [11] and thus provide perfect ground truth for validating CAIR.

Figure 4 shows the resulting route automaton that corresponds to the alert raised by CAIR. The victim AS20195 (Sparkplug) initially advertises four distinct prefixes including 24.120.56.0/22. During the attack, two more specific prefixes (24.120.56.0/24 and 24.120.58.0/24) appear to originate from this AS. With our automaton, we can identify the highlighted artificial path segments. Note that none of the corresponding states shows any other outgoing transitions in contrast to the valid segment. We can locate the attacker at $q_a$: it is either AS26627, or a common customer of this AS and AS4436 (see Subsection 4.2.3). Our observations fully comply with the public, verified information about that DEFCON incident [11]. The attacker was located at AS4436.

The Tehran Incident (2013). Another interception alert of particular interest that was reported by CAIR affects AS25306 (INSTITUTE-ISIRAN Iran). We refer to this event as the Tehran Incident. Compared to the

| Artificial path segments $w^v_a$ | 6,171 | 100.0% |
|----------------------------------|-------|---------|
| Nonuniform redistribution $w^v_a \neq w^v_b$ | 527 | 8.54% |
| Interception alerts $|p^v_a| \subset |p^v_b|$ | 41 | 0.66% |
| Unique alerts (victims) | 32 | 0.52% |

| Manual inspection |
|--------------------|
| Sibling ASes (victim) | -7 | 0.11% |
| Sibling ASes (upstream) | -2 | 0.03% |

| Alerts after manual inspection | 23 | 0.37% |

Table 1: Interception alerts raised by CAIR.

1Concerning subprefix announcements only.
DEFCON attack, the analysis of this incident is more challenging for two reasons. First, this incident has not been discussed in the public so far. Second, the attack took place in 2013, which makes verification based on additional data sets difficult.

Figure 5 shows the corresponding details. On August 15, 2013, AS25306 advertised eight prefixes including 81.28.23.0/19. At the same time, we observe an artificial path $w^q_a \in \Sigma_A$ of length 5 to the subprefix 81.28.37.0/24. Within our route automaton we are able to localize the attacker at the state $q_a$. Our technique yields that he must be a common customer of both AS3549 (Level3) and AS3491 (Beyond the Network America (BTNA)).

To substantiate our observation, we searched operator mailing lists and online discussion platforms for further evidence. The incident itself was not reported. However, we may speculate about potential customers of the ISPs involved, who maybe benefit from an interception. Level 3 is a tier 1 ISP with a quite diverse set of customers. BTNA seems to have a particular reputation as a spammer-friendly service provider. Note that spam activities also misuse BGP [49] to prevent backtracking. Although interception itself has not been documented so far in the context of spamming, an operator of a spamming network could be interested to implement this attack: Any mitigation mechanism at the receiver side that requires the correct end point (e.g., callback verification) can be fooled using the backhaul path. Furthermore, we found an abuse report [28], where BTNA apparently served as upstream for a hijacking attack during another event.

To conclude, we do not have a proof that the Tehran Incident was indeed an interception attack. However, based on manual investigation we found strong evidence that the alarm triggered by CAIR was correct.

5.2 Analysis of Route Leaks

To further demonstrate the expressiveness of CAIR, we derive a simple yet effective metric to assess route leaks. In its most basic form, a route leak is given by the routing changes imposed by route leaks, we introduce a measure for routing dominance.

Table 2: Remaining interception alerts after manual inspection.

| Date       | Forged AS path / nonuniform route segment | Victim / country / company |
|------------|------------------------------------------|---------------------------|
| 2008/08/10 | AS26627 AS4346 AS22822 AS23005 AS20195 United States, Sparkplug Las Vegas |
| 2009/02/01 | AS3393 AS1299 AS701 AS3491 AS37004 AS30988 Nigeria, IS InternetSolutions |
| 2009/10/15 | AS3561 AS7016 AS4837 AS4808 AS1743 AS17964 China, Beijing Network Technologies |
| 2010/05/15 | AS2914 AS3549 AS3556 AS23148 AS20080 AS1916 Brasil, Rede Nacional de Ensino e Pesquisa |
| 2010/12/15 | AS3491 AS13201 AS3549 AS9121 AS27043 Turkey, Akbank |
| 2011/01/15 | AS9002 AS2130 AS3556 AS9121 AS4565 Turkey, Vital Teknoloji |
| 2011/03/01 | AS4134 AS0433 AS4643 AS9299 AS1823 India, India IP Information Systems |
| 2011/04/01 | AS1275 AS1298 AS3491 AS20485 AS3402 Jonsson, University of Sarajevo |
| 2011/04/01 | AS1275 AS1298 AS3491 AS20485 AS3402 South Korea, Gyoungdongong Cable TV |
| 2011/08/15 | AS6762 AS1133 AS12695 AS34123 AS28738 Russia, InterLAN Communications |
| 2011/12/15 | AS6762 AS1133 AS12695 AS34123 AS28738 Italy, Italy |
| 2012/09/15 | AS2828 AS1299 AS8490 AS58459 AS4613 Nepal, Mercantile Office Systems |
| 2012/09/15 | AS2828 AS1299 AS8490 AS58459 AS4613 Nepal, Mercantile Office Systems |
| 2012/12/15 | AS30496 AS1427 AS7843 AS6461 AS6481 AS40610 United States, Digital Passage |
| 2012/12/15 | AS30496 AS1427 AS7843 AS6461 AS6481 AS40610 United States, Digital Passage |
| 2013/02/15 | AS1289 AS2894 AS8928 AS5391 AS57888 Croatia, Telesat |
| 2013/06/01 | AS1299 AS6663 AS6939 AS197043 AS197890 Germany, Megaservers |
| 2013/07/15 | AS1299 AS6663 AS6939 AS197043 AS197890 Germany, Megaservers |
| 2013/08/15 | AS3549 AS3491 AS12880 AS43343 AS21343 AS25306 Iran, Institute IsIran |
| 2013/12/01 | AS1289 AS3491 AS12880 AS43343 AS21343 AS25306 Iran, Institute IsIran |
| 2015/02/15 | AS1299 AS2320 AS16735 AS28284 AS262353 Brasil, Marcelo Bonini |
| 2015/07/15 | AS3356 AS2009 AS721 AS27006 AS8747 United States, US Army ISC |
| 2015/08/15 | AS3356 AS2009 AS721 AS27006 AS8747 United States, US Army ISC |

$s$: ASN $t$: ASN $w^q_a$: ASN ... ASN

To conclude, we do not have a proof that the Tehran Incident was indeed an interception attack. However, based on manual investigation we found strong evidence that the alarm triggered by CAIR was correct.
state $q \in Q$ in our minimized automaton represents an equivalence class, i.e. a set of partial routes $L(q)$ accepted by $q$ (see Section 4). We extend this abstract concept to ASes $u \in \Sigma_{AS}$ such that $\tilde{Q}(u)$ yields the set of all states that are reachable via transitions labeled with $u$ as given by

$$\tilde{Q}(u) = \{q \in Q \mid \delta^*(\tilde{q}, uw) = q, \tilde{q} \in Q \setminus \{q_f\}, w \in \Sigma_{AS}^*\}.$$ 

The size of $|\tilde{Q}(u)|$ implicitly represents the number of (partial) routes over AS $u$. The larger this set is for a given AS, the more of its advertised routes are redistributed by its peers, i.e. the more it dominates routing in BGP. Contrary to intuition, this metric does not yield a particular high rank for the peers of our BGP collector. They exhibit an average rank of 3,808. The top-5 ASes ranked by $|\tilde{Q}|$ are AS2914 (NTT), AS3356 (Level3), AS3257 (Tinet), AS1299 (Telia), and AS174 (Cogent), which all are prominent tier-1 providers.

**Regular route updates and route leaks.** We evaluate regular changes in $|\tilde{Q}|$ for individual ASes over seven years based on our RouteViews data set and compare the results to a recent route leak caused by AS4788 (Telekom Malaysia) on June 12, 2015 between 08:00 and 10:00. On average, we observe 9,019 ASes that experience any change in $|\tilde{Q}|$ during the periods of two weeks. Note that the average number of ASes that newly appear in BGP—and thus regularly change $|\tilde{Q}|$ for their upstream ISPs—is 364, i.e. significantly lower. Taking into account this growth in BGP participants, we obtain a corresponding average of 19.61% of ASes with changes in $|\tilde{Q}|$. For the Malaysia route leak, we observed a change in routing dominance for 7,498 ASes (14.67%) in an interval of less than two hours.

We further observe an average of 76,785 states that are added to or removed from the set $\tilde{Q}(u)$ of any AS $u \in \Sigma_{AS}$. In contrast to that, the Malaysia route leak led to a total change in reachability of 248,760 states. Such a significant and abrupt re-routing is unprecedented during normal operations. The largest (regular) individual increase of 54,402 newly reachable states attributes to AS3257 (Tinet). For AS2914 (NTT), we find the largest decrease of 39,442 states. During the route leak, in contrast, we can observe that a single AS, namely AS577 (Bell Canada) loses reachability of 74,735 states (-98.57%) within the duration of the event. At the same time, the size of $|\tilde{Q}|$ for Telekom Malaysia increased by 32,621 entries (+2,239%). Such a sudden significant increase in global routing dominance is unlikely the result of a regular change in peering agreements.

**The Malaysia Route Leak (2015).** The incident started on June 12, 2015, at 08:40, and began to grad-
we are able to precisely identify the role of each party
Telekom Malaysia peers with the public route servers at
Table 3 shows further results.
We already observed a remarkably high shift in globally
dominating routes that lies well above the average
during normal operations. We see a vast increase in reachable states \(|\bar{Q}|\)—which notably correlates to inbound traffic—for the originator AS4788 and correspondingly for his upstream ISPs AS3549 (Level3) and AS6695 (DE-CIX). Note that the latter does not provide upstream connectivity under normal circumstances. Its high increase in dominant routes is rather an artifact: Telekom Malaysia peers with the public route servers at DE-CIX, which redistribute routes from 456 connected ASes to a total of 14,542 different ASes. Apparently, AS4788 leaked these routes such that the AS path of corresponding BGP updates comprised AS6695. This is surprising since route servers at DE-CIX Internet Exchange Point operate transparently and effectively hide their own AS (see Section 2.1).

The largest decrease in \(|\bar{Q}|\)—both in relative and absolute terms—attributes to AS577. A similar observation can be made for AS1267 (Wind Telecomunicazioni) and also to some extent for AS174 (Cogent). Since the originator’s routes are globally preferred during the incident, these ASes consequently lose a major part of their inbound traffic in exchange for an increase in outbound traffic towards AS4788. Note that only a smaller number of all ASes (14.67%) propagate routes towards AS4788; the greater part (85.33%) is affected outbound, i.e. only receives corresponding routes. Within two hours after the event, routing converged back to its original state (see right column in Table 3).

Towards a reliable detection scheme. With CAIR, we are able to precisely identify the role of each party involved in a route leak. We already showed that only a moderate number of ASes is directly affected by re-routing, which in turn can be classified into groups that either gain or lose in reachable states \(|\bar{Q}|\). The highest absolute increase in reachable states attributes to the originator of a leak, followed by his upstream ISPs. Hence, we are able to identify catalyst upstreams, which unwittingly propagate the leak. Note that the measure \(|\bar{Q}|\) directly correlates to the amount of traffic attracted by an AS. As a consequence, we can further assess the impact of a route leak on individual ISPs.

Based on these observations, we can easily derive a threshold to detect emerging route leaks. We will analyze more incidents in our future work.

6. PRACTICAL ASPECTS OF CAIR
For large volumes of input data such as a global set of routes in BGP, the construction of route automata is challenging. In the following, we describe our approach to minimization in CAIR in detail. and thoroughly quantify the performance of CAIR. We show that the required resources for the route automaton are competitive with graphs and can even decrease with more routes being added as an effect of minimization. We further study the correlation between automata size and Internet growth.

6.1 Implementation
The most basic algorithms to implement DFA minimization have a complexity of up to \(\mathcal{O}(|\Sigma| \cdot |\delta|)\) (for notations see Section 4). Although more efficient algorithms exist [57], the size of our intended input data greatly exceeds that of common use cases in language processing, both in terms of the number of words (i.e. observable routes) and the size of the alphabet (i.e. nodes in the network). For comparison, the English alphabet consists of 26 letters, whereas the technical size of a routing alphabet is \(|\Sigma| = 2^{32} + 2^{32}\) for the IPv4 address space of the Internet.

6.1.1 Minimization of Automata
To construct an M DFA efficiently, we adopt a special-purpose algorithm [15] that minimizes a DFA during construction without ever holding the full non-minimized automaton in memory. Its memory complexity is \(\mathcal{O}(|Q_m|)\), where \(|Q_m|\) is the number of states in the minimized automaton. The algorithm is capable to randomly add or remove routes, whereas common minimization algorithms need to re-minimize at each change of data.

Note that this particular approach expects an acyclic transition function \(\delta^*\) such that

\[
\forall r \in \mathcal{L}(M) : \exists q \in Q : \delta^*(q, r) = q
\]

Hence, corresponding automata do not support languages where symbols or substrings repeatedly occur within a given string. In the next section, we show that this is not a limitation in our context.

6.1.2 Incremental Construction Algorithm
The procedure to add a route to a given (possibly empty) route automaton is inspired by [15] and comprises three major steps. First, for each route the automaton is traversed along the longest common path segment, thereby ensuring that no invalid paths are introduced. Second, states that accept the remaining part of the route are newly created. The final step is to carry out an on-the-fly minimization while traversing the automaton in backward direction. In the following, we present an in-depth description of the individual steps. Note that during construction, we utilize a register of states \(Q_R\),
which is implemented as a hash table. Its keys represent unique right languages \(\hat{L}(q)\) for individual states \(q \in Q\). This provides an efficient way to search for equivalent states, i.e., for states with identical right languages.

**Step 1 Common Path Traversal.** To add a new route \(r \in \mathcal{L}\) to \(M\), we start at \(q_0\) and traverse the automaton along a (possibly empty) sequence of existing states for the longest common path segment \(w_{lp}\) in \(M\). For so-called confluence states that have more than one incoming transition, we need to create a new state with identical outgoing transitions and link it to the last state traversed. This cloning process prevents inadvertently adding false paths. Note that this is inherently the case with network graphs.

**Step 2 Remaining Route Insertion.** After finding a specific state \(q\) that represents the longest common path segment \(w_{lp}\), it is removed from the state register \(Q_{lp}\) since its right language is about to change. If the whole route is accepted in the first step, i.e., if \(|w_{lp}| = |r|\), it is already contained in the automaton. Otherwise, we add new states for the remaining part of the route and link them with corresponding transitions. The last created state is marked as an accepting state.

**Step 3 On-the-fly Minimization.** Finally, we traverse the automaton in backward direction along the sequence of states that represent the newly inserted route \(r\). For each state \(q\), we search our register \(Q_R\) for an equivalent state \(\hat{q}\) that already exists in \(M\). If found, we discard \(q\) and link its preceding state to \(\hat{q}\). Otherwise, \(q\) is unique across all states of \(M\) and needs to be added to the register \(Q_R\).

Note that by traversing the automaton backwards in step 3, the comparison of right languages to identify existing equivalent states is reduced to a comparison of transitions, since recursive application would only yield the results of already compared states. Hence, it is sufficient for keys in \(Q_R\) to represent the transitions of individual states instead of their full right language, which greatly reduces computational complexity.

Interestingly, by leaving out step 3, we obtain trie data structures (see Section 2.2). Beside redirection of transitions, this step only removes states from memory. As a consequence, route automata strictly outperform tries with respect to memory requirements and expressiveness due to the absence of redundancy.

To summarize, our construction algorithm allows to randomly add or remove routes while still ensuring minimality. CAIR is thus particularly well-suited for continuous monitoring of routing changes in BGP. We can also create and archive individual automata that represent the global routing system at specific points in time. We made use of this feature in our evaluation.

**Solving Loops.** Our finite route language, and thus CAIR, account for the construction of any set of network routes consisting of nodes and links [44] as long as the input is cycle-free. Even though most routing protocols such as BGP provide built-in support for loop prevention, loops may be included in routing data. Network operators, for example, may decide to influence route selection by adding their own AS number multiple times to the AS path (AS path prepending). Still, this is not a problem for our approach: A simple way to model subsequent occurrences of a particular AS \(o\) in \(M\) is to extend \(\Sigma_{AS}\) by multiple instances \(a_i \in \Sigma_{AS}\) with \(i \in \{1, 2, \ldots\}\).

## 6.2 Performance Properties of CAIR

To study the performance of CAIR in more detail, we construct a route automaton using the BGP routing table export from the RouteViews [43] collector Oregon2 on November 1, 2015.

**States and Transitions.** The RouteViews collector peers with 41 ASes that represent our set of observation points \(P_{ore} \subset \Sigma_{AS}\). These peers advertise 600,216 IP prefixes \(p \in \Pi\) via 2,875,026 distinct AS paths \(w \in \Sigma_{AS}\) that comprise 52,396 individual ASes \(o \in \Sigma_{AS}\). The full set of routes known to the collector is thus given by \(\mathcal{L}_{ore} = \{w \in \Sigma_{AS}; p \in \Pi\}\) and consists of \(22,303,775\) routes. The corresponding route automaton \(M_{ore}\) accepts the finite route language \(\mathcal{L}_{ore}\). It utilizes \(|\mathcal{L}_{ore}| = 302,598\) states and \(|\delta_{ore}| = 10,355,671\) transitions to hold the entire RIB export (Table 4). It is worth mentioning that CAIR clearly outperforms a trie [4] holding the same information, which would require 73.71 times as many nodes and 2.15 times the amount of transitions.

Our vanilla implementation in Python needs 18.4 minutes to parse the input data and 99.4 minutes to create the automaton; subsequent updates can be applied in real-time. An optimized C++ version for operational deployment is ongoing work.

**Comparison to network graphs.** We define a network graph \(\mathcal{G} = (N, L)\) as a set of nodes \(N = \Sigma_{AS} \cup \Pi\) and a set of links \(L \subset \Sigma_{AS} \times \Sigma_{AS} \cup \Pi\), which yields a total number of \(|N| = 652,612\) nodes and \(|L| = 725,425\) links for the collector studied above. In comparison, CAIR

| Table 4: Objects created after importing RIB data. |
|-----------------------------------------------|
| RIB entries | \(|\mathcal{L}_{ore}|\) |
|-------------|------------------|
| IP prefixes \(|\Pi|\) | 276,706 |
| AS numbers \(|\Sigma_{AS}|\) | 29,203 |
| Unique AS paths \(|\{w | w \in \mathcal{L}\}|\) | 1,421,062 |

| CAIR states | \(|Q_{ore}|\) |
|-------------|--------------|
| CAIR transitions | \(|\delta_{ore}|\) |
| Graph nodes | \(|N_{ore}|\) |
| Graph links | \(|L_{ore}|\) |

| Timepoints | Number of Routes | Number of States | Number of Links |
|------------|-----------------|-----------------|----------------|
| August 10, 2008 | 22,303,775 | 302,598 | 10,355,671 |
| November 1, 2015 | 302,598 | 10,355,671 | 725,425 |
requires only 46.37% of states but 14.28 times more transitions to represent the full routing table. Taking into account that CAIR also holds all observed routes on top of individual AS links as represented by the graph, its efficiency is remarkably competitive.

Figure 6a quantifies the evolvement of states and transitions in CAIR and the network graph while consecutively importing new routes. CAIR requires fewer states but needs more transitions to implement its expressiveness. The minimization approach in CAIR, however, introduces self-adaptive optimization. To clarify this, Figure 6b shows the number of states (transitions) relatively to their maximum number during construction. While the graph data structure created ≈90% of the required objects already after importing 10% of all routes in the input data set, CAIR grows slower. This nicely illustrates that the graph, in contrast to CAIR, does not learn additional information with additional routes observed. More importantly, the amounts of state decreases in CAIR significantly after adding 55% of the routes. This implies that adding further routes to the automaton can actually reduce its size, which is due to the minimization process getting more effective on larger volumes of input data. This finding is of particular interest with respect to possible applications of CAIR in real-time routing analysis.

**Resource requirements depending on Internet growth.** We now study retroactively the routing system at particular points in time. We use the RouteViews data as described above to construct different route automata in an interval of two weeks over the period of August, 2008 till November, 2015. Table 4 presents the absolute number of required resources. Figure 6c shows the relative evolution of the RIB information content compared to resource requirements in CAIR and the corresponding graph data structure. It is clearly visible that the graph depends mainly on the number of IP prefixes, whereas CAIR depends on the number of RIB entries as those provide additional routing insights.

**7. DISCUSSION**

**Is CAIR limited to subprefix hijacking, which could even be protected against by RPKI?** No. Even if an attacker intercepts an already announced prefix, CAIR would detect this incident. The interception leads to a different routing policy, i.e. the attacked prefix is announced differently compared to all other prefixes of the origin AS. Protection of the full AS path requires BGPsec, which will not be deployed in the near future [24], stressing the need for protective monitoring.

**Can CAIR detect incidents in which all prefixes of an origin AS are simultaneously intercepted?** Not now. The current search pattern is based on route diversity per AS. If all prefixes of an AS are comprehensively intercepted as announced by the victim, we would de facto observe a uniform redistribution. However, CAIR stores all routing paths and allows for easy integration of additional search patterns.

**Does CAIR depend on the selection of a specific set of observation points?** No. If an intercepted subprefix hijacking occurs, the update will be visible in the default-free zone, similar to the victim’s less specific prefixes. However, our chances to detect the hijacking of prefixes depend on the observation of competing routes. For this reason, we suggest to utilize a well-connected BGP collector such as the one we used in our evaluation.

**Does CAIR require training of the data set?** No. CAIR transforms routing data (either measured or artificially constructed) into a route automaton. Reasoning is defined by search patterns, which are based on common operational practice.

**Is the concept of FRLs self-contained?** Yes. The definition of finite route languages is consistent in itself and solely based on formal languages. We assume, though, that a partial algebra [40] defined over such an FRL could be embedded into Sobrinho’s routing algebra [53]. Given the existence of such a link, we would be able to approach the theory of policy-based routing [10] from an experimental point of view.
8. RELATED WORK

Graph-based models. Internet graphs oversimplify reality [8, 29, 32, 50, 58], in particular AS-level graphs as ASes are neither atomic [45] nor is there a clear notion of an edge between two AS nodes [58]. CAIR is in line with these observations as our framework does not consider an AS as a single node but in the context of its abutting paths. This provides the flexibility to model complex policy-based routing decisions. To improve modeling, sophisticated concepts, like multigraphs and hypergraphs [50], as well as annotated edges have been proposed. With finite route languages and corresponding route automata, CAIR provides a natural approach to formalize and evaluate the global routing system.

Routing Policies. The Gao Rexford model [21] is a good approximation for most AS relationships but does not hold in general [22]. Inter-AS routing is more complex [16], e.g. by partial transit [23], which directly affects routing export policies. Prefix diversity as implemented by origin ASes has been analyzed recently by Anwar et al. [2]. CAIR naturally reflects these prefix-specific policies. More importantly, such observations are consistent with our assumption that an origin AS may advertise its prefixes differently, and that an arbitrary AS will usually not distinguish between prefixes of the same origin AS. We addressed exceptions in Section 5.1. A theoretical approach for policy-based routing has been introduced with Sobrinho’s routing algebra [53]. Subsequent work focused mainly on abstract models of routing policies [54, 55] and their unification [10, 27].

Generic Hijacking Detection. A common way to detect and assess hijacking is based on the analysis of (i) control-plane information [6, 19, 20, 39, 41, 42, 59], (ii) data-plane measurements [13, 14, 36, 38, 48, 60], or (iii) the combination of both [5, 33, 35, 37, 52, 56]. CAIR belongs to the first class. We want to emphasize that CAIR is not solely a system for anomaly and hijacking detection, but a rigorous framework to model and assess various aspects of routing. Bogon route leaks have been studied in the past [18]. Hira et al. [30] argued that the China Telecom incident was most likely a route leak because of missing subprefix hijacking. We complement these findings with a study of the Telekom Malaysia incident.

Interception Attacks. The impact of interception attacks was studied in detail using a next-hop signature and simulations [3]. No decisive evidence for the discovered events could be found. In contrast to this, we verified CAIR using ground truth data, and confirmed new incidents using complementary data sources.

Current approaches [47] that use control-plane data to detect interdictions are challenged by the lack of a complete AS-level topology [9, 25]. Careful tuning of heuristic parameters is necessary to yield stable detection results. CAIR, instead, is well-suited to operate on incomplete data as it explores routing properties therein.

Real-time detection was analyzed by leveraging a light-weight, distributed active measurement scheme [61]. CAIR can be deployed for real-time analysis as well, but does not depend on active probing and thus is a non-invasive technique. A practical demonstration of the applicability of interception attacks was presented in [46]. Complementary results from an operational point of view are provided in [11]. We evaluate CAIR using this data in our ground truth case study.

9. CONCLUSION

In this paper, we introduce CAIR, a novel formalization of Internet routing to address a fundamental problem with network graphs. Our model is designed to preserve route diversity, where routes from $AS_1 \rightarrow AS_2$ and $AS_2 \rightarrow AS_3$ in general do not imply a route $AS_1 \rightarrow AS_3$. It is based on formal language theory. With so-called finite route languages, we provide a comprehensive formal framework in which routing aspects can be rigorously described. To put this theoretic concept into practical use, we propose CAIR as an implementable equivalent that is based on the construction of minimal deterministic automata. Corresponding route automata offer unique benefits in terms of efficiency and expressiveness. In particular, CAIR preserves route diversity and solves the transitivity problem of graphs. We will make our fully functional reference implementation available. CAIR can readily be used to study policy-based routing.

We applied our routing model to formalize a sophisticated man-in-the-middle attack in BGP, which can be translated into a practical search pattern that is implementable in our route automata. With an analysis of BGP routing tables of more than seven years, we demonstrated great potential in using CAIR for routing analysis. We gained insight into normal and abnormal routing changes, studied a known route leak incident in thorough detail, and identified 22 new cases of interception attacks. We showed that the applicability of CAIR reaches well beyond the detection of routing anomalies.

Future Work. We intend to advance our approach in several directions. The detection of interception attacks, and hijacking in general, can still be improved, and more incidents ought to be studied in detail. We further see a need to deploy CAIR on a continuous basis and to monitor the global routing table for route leaks and attacks in real-time. An optimized version of our implementation to handle live BGP streams is in development. We plan to investigate other research areas that utilize AS-level graphs and thus can naturally benefit from CAIR. In principle, our framework can be applied to any policy-based routing scenario. An evaluation of corresponding analysis techniques is part of our future work. We further intend to study the link between our formal model and algebraic approaches to routing analysis.
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