

# LADS: Large-scale Automated DDoS detection System

Vyas Sekar  
Carnegie Mellon University

Nick Duffield  
AT&T Labs-Research

Oliver Spatscheck  
AT&T Labs-Research

Jacobus van der Merwe  
AT&T Labs-Research

Hui Zhang  
Carnegie Mellon University

## Abstract

Many Denial of Service attacks use brute-force bandwidth flooding of intended victims. Such volume-based attacks aggregate at a target's access router, suggesting that (i) detection and mitigation are best done by providers in their networks; and (ii) attacks are most readily detectable at access routers, where their impact is strongest. In-network detection presents a tension between scalability and accuracy. Specifically, accuracy of detection dictates fine grained traffic monitoring, but performing such monitoring for the tens or hundreds of thousands of access interfaces in a large provider network presents serious scalability issues. We investigate the design space for in-network DDoS detection and propose a triggered, multi-stage approach that addresses both scalability and accuracy. Our contribution is the design and implementation of LADS (Large-scale Automated DDoS detection System). The attractiveness of this system lies in the fact that it makes use of data that is readily available to an ISP, namely, SNMP and Netflow feeds from routers, without dependence on proprietary hardware solutions. We report our experiences using LADS to detect DDoS attacks in a tier-1 ISP.

## 1 Introduction

The last few years have seen a steady rise in the occurrence and sophistication of distributed denial of service (DDoS) attacks. Armies of botnets comprised of compromised hosts can be utilized to launch attacks against specific Internet users such as enterprises, campuses, web servers, and homes. In this paper, we focus on an important class of DDoS attacks, namely, brute force flooding attacks. We observe that access links are typically the bottlenecks for most Internet users, and that attackers can easily send sufficient traffic to exhaust an user's access link capacity or overload the packet handling capacity of routers on either end of the link [9].

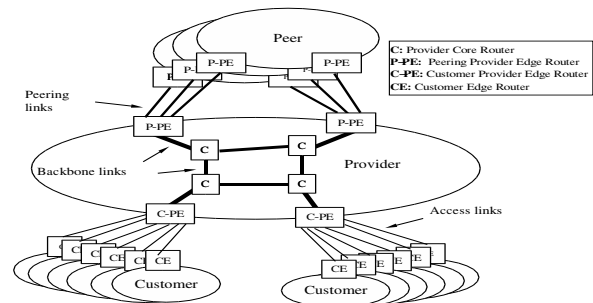


Figure 1: Components of a Provider Network

Brute force flooding attacks are easy for attackers to launch but are difficult for targeted users to defend, and therefore represent a threat to Internet users and services. Given the limited capacity of most access links on the Internet, a successful DDoS attack needs to involve a relatively small number of attack sources. In addition, the size of some reported botnets [27] suggests that a determined attacker might be capable of overloading even the largest access links. From a user's perspective, a bandwidth attack means its in-bound capacity is exhausted by incoming attack traffic. Given that a user often controls only one end of the access link, for example via a Customer Equipment or CE router (see Figure 1), while its ISP controls the other end (referred to as C-PE, or Customer-Provider Edge router), once an access link is overloaded there is precious little that the target of the attack can do without the assistance of its ISP. In fact, automated DDoS detection and mitigation mechanisms originating from the customer side of an access link become useless once the access link itself is overloaded.

For such brute-force bandwidth attacks, we reason that a very promising architecture is one that performs *in-network detection and mitigation*. While it is possible for individual customer networks to deploy detection mechanisms themselves, several practical constraints arise. Small to medium-sized enterprise customers typically possess neither the infrastructure nor the operational ex-

pertise to detect attacks, as it is not cost-effective for them to deploy and manage dedicated monitoring capabilities. Also, the customers' limited resources (human and network) are already substantially overwhelmed during DDoS attacks. Further, detecting attacks at the edge will have little or no effect unless the upstream provider takes appropriate actions for attack mitigation. Network providers on the other hand already possess the monitoring infrastructure to observe and detect attacks as they unfold. Also, since it is upstream of users' access links, an ISP can help customers defend against bandwidth attacks by deploying appropriate filtering rules at routers, or alternatively using routing mechanisms to filter packets through scrubbers [8] to drop malicious packets. In this paper, we focus on in-network detection of DDoS attacks. The challenge is to come up with a solution that satisfies multiple competing goals of scalability, accuracy, and cost-effectiveness.

We propose a triggered, multi-stage infrastructure for detection and diagnosis of large-scale network attacks. Conceptually, the initial stages consist of low cost anomaly detection mechanisms that provide information to traffic collectors and analyzers to reduce the search space for further traffic analysis. Successive stages of the triggered framework, invoked on-demand and therefore much less frequently, then operate on data streams of progressively increasing granularity (e.g., flow or packet header traces), and perform analysis of increasing computational cost and complexity. This architecture fits well with the hierarchical and distributed nature of the network. The early stages require processing capabilities simple enough to be implemented in a distributed fashion for all customer-facing interfaces. The later, more sophisticated, processing capabilities can be more centralized and can thus be shared by many edge routers.

We have designed and implemented an operational DDoS detection system called LADS, based on this triggered multi-stage architecture, within a tier-1 ISP. Our system makes use of two sources of data: SNMP and Netflow, both of which are readily available in commercial routers today. We adopt a two-stage approach in LADS. In the first stage, we detect volume anomalies using low-cost SNMP data feeds (e.g., packets per second counters). These anomalies are then used to trigger flow-collectors that obtain Netflow records for the appropriate routers, interfaces, and time periods. We then perform automated analysis of the flow records, using uni-dimensional aggregation and clustering techniques, to generate alarm reports for network operators.

There are several natural advantages to our approach, in terms of deployment cost, detection coverage, and manageability. Providers incur little or no additional deployment and management costs, because we use data sources that are readily available, and the infrastructure

to instrument and manage the data feeds is typically already in place. Our system provides a low-cost solution for ubiquitous deployment across thousands of customer interfaces, as it does not rely on proprietary hardware solutions. In order to minimize the number of hardware monitoring devices, and hence cost, providers deploy commercial monitoring solutions at selective locations in the network (for example, in the core and at peering edges). Such an infrastructure is likely to miss smaller attacks which, while large relative to the targeted interface, are small amongst aggregate traffic volumes in the core. In contrast, our system has ubiquitous monitoring but no additional cost, and can perform anomaly detection considering both traffic volume and link speed for all customer-facing interfaces.

## 2 Related Work

The spectrum of anomaly detection techniques ranges from time-series forecasting (e.g., [5, 26]) and signal processing (e.g., [4]), to network-wide approaches for detecting and diagnosing network anomalies (e.g., [19, 34]). These approaches are intended for detecting coarse-grained anomalies, which are suitable for use as initial stages in a triggered approach for scalable DDoS detection.

Also related to our multi-stage approach are techniques for fine grained traffic analysis. These include techniques for performing detailed multi-dimensional clustering [11, 32] and solutions for online detection of heavy-hitters and attacks using counting algorithms and data structures [12, 17, 35].

Moore et al. [24] observed that many types of attacks generate backscatter traffic unintentionally. Network telescopes and honeypots [30] have also been used to track botnet and scan activity. Some early DoS attacks used source address spoofing to hide the sources of the attacks, and this motivated work on IP traceback (e.g., [6, 28, 29]).

There are several commercial DDoS detection systems (e.g., [2, 22]) available today. Since these rely on proprietary hardware and algorithms, we cannot evaluate the differences between the algorithms used in LADS and these commercial systems. There are, however, two qualitative architectural advantages of LADS over these systems. The first issue is one of deployment cost. To provide diagnostic capabilities and detection coverage across all customer interfaces, similar to LADS, providers would have to deploy proprietary hardware devices covering every customer-facing interface and thus incur very high deployment costs. In contrast, LADS uses existing measurement feeds, providing a significant reduction in deployment and management cost for providers. The second issue is one of scale – dealing

with large-scale data feeds from thousands of network monitors. We use a triggered approach to scale down the collection and computation requirements of large-scale attack investigation. We are not aware of any existing work or commercial product which addresses problems at this scale.

Solutions for mitigating DDoS attacks often rely on infrastructure support for either upstream filtering (e.g., [21]), or use network overlays (e.g., [16]). Capabilities-based approaches (e.g., [33]) focus on re-designing network elements to prevent flooding attacks. End-system solutions for handling attacks combine Turing tests and admission control mechanisms (e.g., [15, 25]) to deal with DDoS attacks. Reval [31] helps network operators to evaluate the impact of DDoS attacks and identify feasible mitigation strategies in real-time. Mirkovic and Reiher [23] provide an excellent taxonomy of DDoS attacks and defenses.

The use of triggers for scalable distributed traffic measurement and monitoring has been suggested in AT-MEN [18] and by Jain et al. [13]. While scalability using triggered monitoring is a common theme, our contribution is the use of triggered framework for DDoS detection using heterogeneous data sources.

### 3 Scalable In-Network DDoS Detection

Having argued for the necessity of in-network DDoS detection (and mitigation), we now consider the implications of this approach for building a detection system in a large provider network. Like any anomaly detection system the main requirement is accuracy, i.e., having a low false alarm and miss rate. The second requirement is timeliness: to be of practical value a detection system should provide near real time detection of attacks to allow mitigation mechanisms to be applied. Third, the system should cover all (or most) customers of a provider. The number of customers could range from a few hundred for small providers to hundreds of thousands for very large providers.

These requirements have significant system scalability implications: (i) Is it feasible to collect information that is detailed enough to allow attack detection on a per-customer basis? (ii) Is it feasible to perform in timely fashion the processing involved with the detection on a per-customer basis?

#### 3.1 Triggered Multistage DDoS Detection

There are two sources of complexity for large-scale attack detection and diagnosis: *Collection* and *Computation*. The collection complexity arises from the fact that data streams have to be selected from monitoring points

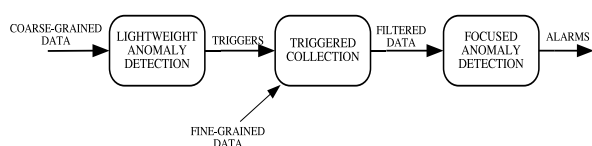


Figure 2: Triggered Multistage DDoS Detection

(links/routers), and either transported to an analysis engine (possibly centralized) or provided as input to local detection modules. The computation complexity arises from the algorithms for analyzing the collected data, and the sheer size of the datasets. We observe that not all detection algorithms have the same complexity: the differences arise both from the type of data streams they operate on and the type of analysis they perform.

Consider two types of data streams that are available from most router implementations: simple traffic volume statistics that are typically transported using SNMP [7], and Netflow-like [3] flow records. Enabling the collection of these two measurements on routers incurs significantly different costs. There are three main cost factors: (i) memory/buffer requirements on routers, (ii) increase in router load due to the monitoring modules, and (iii) bandwidth consumption in transporting data-feeds. SNMP data has coarse granularity, and the typical analysis methods that operate on these are lightweight time-series analysis methods [4, 5, 26]. Flow-level data contains very fine grained information, and as a result is a much larger dataset (in absolute data volume). It is easy to see that the flow data does permit the same kind of volume based analysis that can be done with the SNMP data. However, the flow data is amenable to more powerful and fine-grained traffic analysis [11, 32] which can provide greater diagnostic information.

The presence of heterogeneous data sources which offer varying degrees of diagnostic abilities at different computation and collection costs raises interesting design questions. At one extreme we could envision running sophisticated anomaly detection algorithms on the fine granularity data (i.e., Netflow) on a continuous basis. The other extreme in the design space would be an entirely light-weight mechanism that operates only on the coarse-granularity data. Both these extremes have shortcomings. The light-weight mechanism incurs very little computational cost, but lacks the desired investigative capabilities that more fine-grained analysis can provide. The heavy-weight mechanism, on the other hand, incurs a much higher collection and computation cost. Further, the heavy-weight mechanism may be operating in an *unfocused* manner, i.e., without knowledge about the seriousness of the incidents that actually need operators' attention. Operating in such a setting is detrimental to not only the scalability (due to high collection and computation complexity), but also the accuracy (the false alarm rate may be high).

Our work attempts to find an operationally convenient space between these extremes. The key idea in our approach is to use *possible* anomalous events detected in coarse grained data *close* to the attack target, to *focus* the search for anomalies in more detailed data. A simple but powerful observation, is that close to the attack target, e.g., at the customer access link, detecting flooding attacks using coarse-grained data becomes reasonably easy. Even though such coarse-grained indicators might generate false alarms and lack the ability to generate useful attack reports, they can be used to guide further, more fine-grained, analysis. Based on this insight, we propose a triggered multistage detection approach (Figure 2) in which the successive stages can have access to and operate on data streams of increasing granularity. A triggered approach helps focus collection and computation resources intelligently – performing inexpensive operations early on, but allowing sophisticated, data and compute intensive tasks in later stages.

## 3.2 Design Alternatives

While our approach generalizes to any number of detection stages, the system described in this paper is limited to two stages. We briefly describe our methods as well as other potential alternatives for each stage.

### 3.2.1 Lightweight Anomaly Detection

As the name suggests the key constraint here is that the method not require significant processing so that it can be applied to a large number of interfaces. Since the output of this stage triggers more detailed analysis in the second stage, false positives are less of a concern than false negatives. A false positive from the first stage will only cause more unnecessary work to be done in the second stage, and hence not necessarily much of a concern for the operator who only sees the final alarms after the second stage. However, a false negative is a more serious concern as the attack might be missed altogether.

**Volume anomaly detection:** Traffic anomalies on volume and link utilization data available from egress interfaces are often good indicators of flooding attacks. Traffic metrics that are available from most current router implementations include the traffic volume (either in bytes per second or packets per second), router CPU utilization, and packet drop counts. Our approach (described in Section 4.1) involves the use of traffic time-series modeling to predict the expected future load on each customer-facing interface. These prediction models are then used to detect significant deviations to identify future volume anomalies.

**Using traffic distribution anomalies:** Lakhina et al. [20] discuss the use of distributions (using entropy)

for diagnosing anomalies in networks. The key insight behind their work is that many attacks can be identified by substantial changes in traffic distributions, specifically the distribution across source and destination addresses and ports. While the use of distribution information in [20] was suggested as a means for augmenting volume-based anomaly detection, we can use distribution anomalies as triggers for further analysis. The use of such metrics in a triggered approach may not necessarily reduce the collection cost, since measuring these metrics may need access to very fine-grained traffic information.

### 3.2.2 Focused Anomaly Detection

Even though our triggered approach will reduce the search space for the second stage significantly, the scale of the problem is such that the computational overhead remains a concern. The other key requirements are accuracy, and the ability to generate useful incident reports for network operators.

**Rule-based detection:** Some DDoS attacks have distinct characteristics that can be easily captured with a small set of detection rules. For example, a large number of single-packet flows (e.g., ICMP-ECHO or TCP-SYN) sent to a single destination IP address is often indicative of a DDoS attack. Another option is to use *botnet blacklists* to check if the set of source addresses that occur frequently in the traffic belong to known compromised machines (commonly referred to as zombies) used for launching attacks. Rule-based approaches have near-term appeal since they typically have low false-positive rates, even though their detection capabilities are limited to the set of attacks spanned by the rule-sets.

**Uni-dimensional aggregation:** Our specific implementation for the second stage involves the use of uni-dimensional hierarchical aggregation algorithms. Conceptually, uni-dimensional clustering attempts to discover heavy-hitters along source/destination prefixes, using a thresholding scheme to compress reports along the prefix hierarchy. Since the computational overhead with performing uni-dimensional aggregation is low, and the functionality provided is sufficient for investigating most known types of DDoS attacks we choose this approach. Our implementation, which is a combination of uni-dimensional clustering and rule-based approaches, is described in Section 4.2.

**Multi-dimensional clustering:** Multi-dimensional clustering provides another alternative for fine-grained analysis [11, 32]. The basic theme of these approaches is to abstract the standard IP 5-tuple (srcaddr, dstaddr, protocol, srcport, dstport) within multi-dimensional clustering techniques to report traffic patterns of interest. Typically, the complexity of the algorithm can be reduced by tuning the technique to report only interesting clusters, those

that either have a high volume or those that have a significant deviation from an expected norm.<sup>1</sup>

### 3.3 Benefits and Pitfalls

The benefits of our triggered approach are as follows:

**Detecting high-impact attacks:** Since our triggers are generated close to the customer egresses, we are more likely to detect attacks that actually impact the end-user. Note that this is in contrast to more centralized approaches, even those that work on more fine-grained data feeds.<sup>2</sup> For example, by monitoring SNMP byte counts on a T1 access link it is straightforward to determine when the link is being overloaded. Looking for the same information from a different vantage point, e.g., at a set of major peering links is a much more challenging task. Not only could the traffic flowing towards the T1 interface be spread across many such peering interfaces, but the traffic will be hidden inside an overwhelming amount of background traffic on the peering links.

**Efficient data collection:** SNMP data is lightweight enough that it can be collected on the access routers without imposing significant load. Netflow data, on the other hand, can be more efficiently collected at more powerful and better-provisioned core routers so that access routers are not burdened with this more expensive process.

**Reduced computation cost:** We use high cost operations and expensive algorithms in a focused manner, and also significantly reduce the data volumes that the expensive operations need to handle.

**Low operational complexity:** The different stages are simple and easy to understand, and vendor-independent, and managing the operation should be relatively simple. More importantly, our implementation works with data streams that are already available to most provider networks. Deploying LADS does not incur any overhead in terms of instrumenting new monitoring capabilities or deploying special hardware for data collection and analysis.

**Near real-time incident reports:** Since the computational complexity is significantly reduced, we can operate the system in near real-time, without relying on specialized hardware or data structure support.

**Flexibility:** Our approach is flexible in two aspects. First we can easily accommodate other data streams as and when they are available. Second, within each stage the performance and algorithms can be optimized to reach desired levels. For example, our first stage trigger currently uses simple time-series volume anomaly detection. It is fairly easy to augment this step with other data streams and traffic metrics, or alternatively use other anomaly detection methods for the same dataset.

In our approach, there are four potential pitfalls. The first pitfall is one relating to possible undesirable interac-

tions between the trigger stage and the detailed analysis stage. While our approach allows for each component to be optimized in isolation, optimizing the overall system performance would require a detailed understanding of the interfaces and interactions between different components. Managing and optimizing such multi-component systems is inherently complicated – we believe our specific implementation is based on a clean set of interfaces between components which are sufficiently decoupled, and hence has very few, if any, undesirable interactions.

The second, more serious problem, is one of misses due to the triggered approach. While the low-level triggers reduce the collection and computation complexity, they may be doing so by compromising the sensitivity of the system, i.e., by increasing the false negative rate. Attacks which can cause the greatest disruption in terms of traffic engineering, routing etc., are flooding attacks, and these will invariably show up as volume anomalies on the egress interfaces closest to the customers. Since our primary focus is on such flooding attacks, there is almost no impact on the false negative rate. The benefits we gain in terms of operational simplicity and reduced false alarm rate greatly outweigh the negligible decrease in the detection sensitivity toward low-impact attacks.

The third pitfall is related to the ability of the monitoring infrastructure to sustain data collection during attacks. While collecting low-volume SNMP feeds is not a serious overhead, collecting flow records at the customer egresses and transporting them back to a centralized processing engine is clearly infeasible during volume floods. The access link is already overloaded, and reporting large volumes of flow records can only worsen the congestion. Large providers typically deploy flow collectors at core network elements, which are usually well-provisioned, and they can subsequently map the flow records to the appropriate egresses using routing and address space information. Thus, there will be no perceivable reduction in the data collection capabilities during attacks.

Finally, there is a concern regarding the resolution limits of in-network DDoS detection – whether such an approach can detect anomalies on all possible scales of network prefixes. Our system deals primarily with flooding attacks that impact immediate customers directly connected to the provider network. Our experiences with both the SNMP and the flow analysis indicates that at this granularity, LADS is effective at identifying anomalies and providing sufficient information for operators to respond to the alarms.

## 4 Implementation

Our implementation of LADS, currently works as an offline DDoS detection system within a tier-1 ISP. The described implementation works on real traffic feeds of the

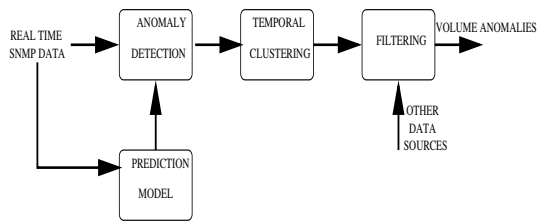


Figure 3: Overview of SNMP Anomaly Detection

tier-1 ISP and is only classified as off-line in that the data currently provided to the system might be substantially delayed. We are actively working on deploying the system in an on-line environment in which real-time data feeds are available. Our performance evaluation (Section 6.1) indicates that our design and implementation will be adept to the task of on-line monitoring.

#### 4.1 Lightweight Anomaly Detection

The first stage of the detection system uses SNMP link utilization data to report volume anomalies. Figure 3 provides a conceptual overview of the SNMP anomaly detection module. Specifically, we are interested in flow anomalies on customer-facing interfaces, since volume based DDoS attacks will be most visible at the egress links of the customers under attack. SNMP data is collected on an on-going basis at most providers, and typically contains CPU and link loads (in terms of octet and packet) counts. Since most DDoS attacks use small packets we use the egress packet counts (i.e., with reference to Figure 1, the C-PE interface towards the customer) to detect volume anomalies.

To keep the operational, storage, and computation resources low, we devised a simple trigger algorithm with good performance. Conceptually, the algorithm builds a prediction model which indicates the expected mean and expected variance for the traffic time series. Using this model it assigns a deviation score to current observations, in terms of the number of standard deviations away from the mean that each observation is found to be. Borrowing some formal notation [26] one can think of the traffic time series, denoted by  $T(t)$  as being composed of three components,  $T(t) = P(t) + V(t) + A(t)$ , where  $P(t)$  represents the predicted mean traffic rate,  $V(t)$  represents the stochastic noise that one expects for the traffic, and  $A(t)$  is the anomaly component. Our goal is to obtain models for  $P$  (the periodic component) and  $V$  (the stochastic component), so that we can identify the anomaly component  $A$  in future traffic measurements.

Our algorithm, depicted in Figure 4, works as follows. For each customer interface, we take the last  $k$  weeks of data (this historical time-series data is referred to as  $TS$ ). We build an empirical mean-variance model by simple point-wise averaging, assuming a basic period-

---

```

    TIMEDOMAINMODELING( $TS, W, N$ )
    //  $TS$  is the training set
    //  $W$  is the number of weeks
    //  $N$  is the number of data points per week
  
```

```

  1 for  $i \leftarrow 1$  To  $N$  do
    //  $P$  is the periodic mean
  2    $P(i) \leftarrow \text{MEAN}(TS(1 : W, i))$ 
    // Fourier denoising
  3    $P' \leftarrow \text{DENOISE}(P)$ 
    //  $V$  is the variance
  4    $V(i) \leftarrow \text{VARIANCEMODEL}(TS, P', W, N)$ 
  5 return  $P', V$ 
  
```

---

Figure 4: Procedure for timeseries modeling

---

```

    ANOMALYDETECTION( $T, TS, W, N$ )
    //  $T$  is the new time series
    //  $TS$  is the historical time series
    //  $W$  is the number of weeks for building model
    //  $N$  is the number of data points per week
  1 ( $P, V$ )  $\leftarrow$  TIMEDOMAINMODELING( $TS, W, N$ )
  2 for  $i \leftarrow 1$  To  $N$  do
  3    $D(i) \leftarrow (T(i) - P(i))/V(i)$ 
  4 TEMPORALCLUSTER( $D, \alpha_{trigger}, \alpha_{add}, \text{keepalive}$ )
  5 Use filtering rules on clustered alarms
  
```

---

Figure 5: Outline of SNMP anomaly detection

icity of one week. For example, for estimating the expected traffic for the 5 minute interval *Fri 9:00-9:05 am*, we take the average of the observations over the past  $k$  Fridays, for the same 5 minute timeslot. As the training data might itself contain anomalies we perform a denoising step using a Fourier transform from which we pick the top 50 energy coefficients.<sup>3</sup> In the final step, for each point per week (e.g., *Fri 9:00-9:05, Mon 21:00-21:05*), the algorithm determines the variance over the last  $k$  observed data points with respect to the de-noised historical mean. The implicit assumptions in the method are that the basic periodicity of the traffic data is one week and that traffic patterns are relatively stable week to week, which has been suggested in other traffic analysis on similar datasets [1, 26].

Figure 5 outlines the four main stages in the anomaly detection process. We first obtain the historical prediction model, to get the deviation scores. Then, we use the estimated model to obtain deviation scores for current SNMP data to obtain volume anomalies. We use a natural definition of the deviation,  $D(t) = (T(t) - P(t))/V(t)$ , which represents the number of standard deviations away from the prediction that the observed data point is. Once the deviation scores have been computed, we perform a temporal clustering procedure (Figure 6) to report anomalous incidents to the flow collector and analyzer. Temporal clustering can reduce the load

```

TEMPORALCLUSTER( $D, \alpha_{trigger}, \alpha_{add}, keepalive$ )
// D is the deviation score time series
//  $\alpha_{trigger}$  is trigger deviation score threshold
//  $\alpha_{add}$  is the event extension threshold
//  $keepalive$  is the time for which an event is active
1 if there is a current active event E
  then
2   if  $D(currenttime) \geq \alpha_{add}$ 
    then
3     Extend the current event E
4     if  $((Starttime(E) - currenttime) > keepalive)$ 
      then
5       Expire the current event E
  else
    // Check if new event has occurred
6     if  $D(currenttime) \geq \alpha_{trigger}$ 
      then
7       Create a new anomaly event
8     Return anomaly events, with start and stop times

```

Figure 6: Temporal clustering to reduce query load

on the collection mechanism by reducing the number of queries that we issue to the collector. Such a load reduction is indeed significant, as many attacks do last quite long. The clustering method operates based on two pre-defined deviation score thresholds, the event trigger threshold ( $\alpha_{trigger}$ ) and the event extension threshold ( $\alpha_{add}$ ), as well as a keep alive time ( $keepalive$ ). The clustering process tries to extend the current active event, if the new observation has a deviation score that exceeds the event extension threshold  $\alpha_{add}$ , within a time duration of  $keepalive$ , since the start of the event. If there is no active ongoing event, it creates a new event if the observed deviation score is higher than the event trigger threshold ( $\alpha_{trigger}$ ).

After detecting the SNMP anomalies, we perform additional filtering steps to allow the operators to remove known or uninteresting anomalies. We use an absolute volume threshold to remove all SNMP alarms which have an average bandwidth less than a pre-defined threshold. This allows the operator to specify a minimum attack rate of interest, to reduce the overall workload for the flow collectors. Second, we remove anomalies in the SNMP data caused by router resets and SNMP implementation bugs. In particular we remove the first SNMP counters after a reset (e.g., we saw in a few cases, immediately after a reset, a SNMP counter corresponding to -1), as well as measurements which indicate a bandwidth utilization greater than the physical bandwidth. Even though such events are extremely rare, they do occur daily on a large network, and we remove such measurement anomalies.

At the end of the SNMP anomaly stage, we receive a set of volume anomalies, each anomaly being specified

by the egress interface, and the start and end time. This information is then used to trigger Netflow collection for detailed investigation.

## 4.2 Focused Anomaly Detection

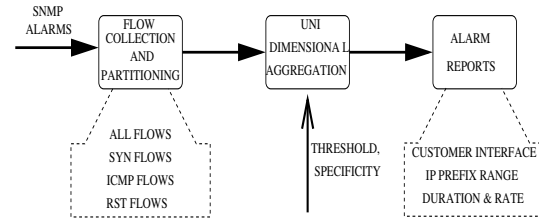


Figure 7: Incident diagnosis using flow data

The second stage of our DDoS detection system performs detailed analysis on Netflow data as shown in Figure 7. We first collect all Netflow records for the egress interface indicated by the first stage trigger. Section 5.1 describes the collection infrastructure in greater detail. Then for each SNMP-alarm we build the following Netflow datasets containing,

- Records with the TCP SYN flag set (*SYN* set)
- Records with the TCP RST flag set (*RST* set)
- Records for ICMP flows (*ICMP* set)
- All flow records (*All* set)

Finally, for each of the Netflow datasets, we report the traffic volumes for all destination prefixes with a prefix length larger than a /28, using the uni-dimensional clustering algorithm described in Figure 8. The algorithm generates a bandwidth attack alarm if the *All* set contains a prefix smaller than /28 which carries more traffic than the configurable *Bandwidth Attack Threshold*. It will also generate a SYN/ICMP/RST alarm if the corresponding SYN/ICMP/RST sets observe an IP prefix range which carries more traffic than the configurable SYN/ICMP/RST Threshold. Instead of using a fixed rate threshold, we use a duration-adaptive rate threshold mechanism, which takes into account the duration of the SNMP volume anomaly. This will balance the sensitivity between high-rate low duration attacks, and relatively lower-rate but longer duration attacks. This can be achieved by using a simple rate-depreciation approach, so that the rate threshold is a monotonically decreasing function of the alarm duration. Our current implementation uses a geometrically decreasing depreciation, where the average rate for longer duration events will be generated according to the following formula  $Rate(Duration) = Rate(BaseDuration) * DecreaseFactor^{\frac{Duration}{BaseDuration}}$ , where the *BaseDuration* is 300 seconds, and the *DecreaseFactor* is set to 0.95.

There are two steps of the uni-dimensional clustering (Figure 8): Aggregation and Reporting. The aggregation

step simply counts the total traffic volume received by each distinct destination prefix, larger than a minimum prefix-range size, denoted by *MinPrefix*. Since we are interested in DDoS attacks on customer egress links, we can afford to perform the traffic aggregation on smaller prefix ranges, than would be the case for more general purpose traffic analysis applications [11, 32, 35]. Thus the computational and memory overhead during the aggregation phase is upper-bounded by the prefix range we are interested in. For example, we are only interested in the traffic intended for prefixes smaller than a /28, which can be potential attack targets. The next step is the *Reporting* stage, which uses the aggregated counters to decide whether to report each particular prefix range as a potential attack target. The reporting step is conceptually similar to the work of Estan et al. [11] and Singh et al. [35], to generate traffic summaries indicating heavy-hitters. Intuitively, we generate reports on larger prefixes, if they carry substantially more traffic than a previously reported smaller prefix range, and if they are above the absolute volume threshold. We scale the absolute volume threshold according to the size of the prefix range by a multiplicative *Specificity* parameter that determines the scaling factor. We chose this approach due to its simplicity and we observe that the diagnostic capability provided by our approach is sufficient for detecting DDoS attacks, and generating alarm reports comparable to commercial DDoS solutions (Section 6.4). We found in our experiments that this approach is computationally efficient, in terms of memory and processing time, which makes it a viable alternative for real-time analysis.

## 5 Experimental Setup

To evaluate our LADS implementation we collected SNMP and Netflow data for a subset of the access interfaces of a tier-1 ISP ranging from T1 to OC-48 speeds. We describe this data collection next followed by a description of the LADS parameter settings we used.

### 5.1 Data Description

For our LADS evaluation we collected SNMP and Netflow data for over 22000 interfaces within a large tier-1 ISP. To allow our evaluation to be repeatable during development we archived all relevant data for an eleven day period in August 2005 with the exception of the SNMP data used which was archived for a period in excess of 12 months. We also collected alarms from the commercial DDoS detection system for this period.

**SNMP Feeds** The SNMP reports are generated from each egress router within the tier-1 ISP and reported periodically for each 5 minute interval. For each interface,

the SNMP reports contain the total traffic volume per interface (both packet and byte counts), and router utilization information for the recent 5 minute interval. The reporting interval can be configured in most router implementations. Within the ISP, this value is set to 5 minutes – small enough to initiate real-time response, but large enough to keep the router overhead low. The total collection overhead for SNMP data over the entire provider's network is around 200 MB of compressed (ASCII) data per day, which represents a small bandwidth overhead compared to large volumes (of the order of few petabytes per day) of traffic that a tier-1 ISP carries. In LADS, we only use the egress packet counts, i.e., the packets from the ISP toward the customer, to generate triggers.

**Netflow Feeds** The Netflow collection infrastructure collects sampled flow records covering the entire backbone network (more than 500 routers within the ISP). The records are based on 1:500 packet sampled data. The sampling is performed on the router and the records are subsequently smart sampled [10] to reduce the volume. In smart sampling, flow records representing a total volume greater than a threshold of 20 MB are always sampled, while smaller records are sampled with a probability proportional to their size. Appropriate renormalization of the reported volume (in bytes) yields unbiased estimates of the traffic volume prior to sampling [10]. In the resulting data set each record represents, on average, at least 20 MB of data. After collecting the records we annotate each record with its customer egress interface (if it was not collected on the egress router) using route simulation and tag records which could have been observed twice within the collection infrastructure to avoid double counting of flow records. We emulate a triggered flow retrieval system on the entire set of smart sampled flow records. i.e., we query the flow data available from all collectors to obtain the flow records relevant to each SNMP anomaly. Since our current implementation runs in off-line emulation mode, the benefits of a triggered collection approach are not realized.

**Alarms from commercial system** The ISP has a commercial DDoS detection system deployed at key locations within its network. We collected the high priority DDoS alarms from this commercial DDoS detection system. The alarms were combined into attack records if we found multiple alarms for the same target with an idle time of less than 15 minutes in between alarms. Even though we are not aware of the detailed algorithms used within this product, operational experience indicates that the system detects most large DDoS attacks while generating a manageable number of high priority alarms. The system is deployed in a substantial fraction of the core of the ISP at high speed interfaces and, therefore, only analyzes aggregate customer traffic. We use the commercial detection system as a basis for comparison with our im-



---

```

UNIDIMENSIONALCLUSTERING(MinPrefix, Threshold, Specificity)
  // MinPrefix is the minimum prefix length – Set to 28, MaxPrefix is the maximum IP prefix length (32 for IPv4)
  // Threshold is given in terms of an attack rate, Specificity is used for compressing the report – Set to 1.5
1  Aggregation: Read flow records and update traffic counts for prefixes between MinPrefix and MaxPrefix
2  Reporting: for  $i \leftarrow \text{MaxPrefix}$  DownTo MinPrefix do
3    for each prefix  $P$  of prefix-length  $i$  do
      // We use the IP/prefix notation,  $P/\{i\}$  refers to prefix  $P$  with a prefix-mask of length  $i$ 
4       $AbsoluteThreshold \leftarrow Specificity^{(MaxPrefix-i)} \times Threshold$ 
5      if  $i \neq MaxPrefix$ 
6        then
7           $CompressThreshold \leftarrow Specificity \times PredictedVol(P/\{i\})$ 
8          else
9             $CompressThreshold \leftarrow 0$ 
10            $ReportThreshold \leftarrow \text{MAX}(AbsoluteThreshold, CompressThreshold)$ 
11          if  $Volume(P) > ReportThreshold$ 
12            then
13              Report alarm on prefix  $P/\{i\}$  with rate  $Volume(P)$ 
14               $PredictedVol(P/\{i-1\}) \leftarrow \text{MAX}(PredictedVol(P/\{i-1\}), Volume(P))$ 

```

---

Figure 8: Procedure for uni-dimensional prefix aggregation and generating compressed reports

plementation even though we are aware that due to its deployment locations and configuration (we only collect high priority alarms) the commercial system might not detect some of the DDoS attacks which are detectable with our system. In an ideal scenario, we would like to evaluate the false positive and false negative rates of our system against some *absolute ground truth*. We are not aware of any system which can generate such ground truth at the scale that we are interested in, and this commercial system is our closest available approximation despite its inherent limitations.

## 5.2 System Configuration

In terms of the specifics of our implementation, our approach requires a number of configurable parameters which we set to the following values:

**SNMP training period** The training period for model building for SNMP anomaly detection is  $k = 5$  weeks.

**Absolute Volume Threshold** The absolute volume threshold provides a lower bound on DDoS attacks we detect in the SNMP data. We set this value to 250 Kbps which considering that the smallest link size in the Tier-1 ISP's network is a T1 (1.5 Mbps) allows us to detect any sizable attack on any interface under consideration.

**Event Score Threshold** ( $\alpha_{trigger}$ ) The threshold on the deviation score which triggers an SNMP-based alarm. We evaluate the sensitivity and overhead for different threshold values in Section 6.2.2. For our evaluation we use  $\alpha_{trigger} = 5$ .

**Temporal Clustering Parameters** The temporal clustering procedure uses an event extension threshold ( $\alpha_{add}$ ) and a *keepalive* duration value, for deciding on

combining SNMP anomalies. We set  $\alpha_{add} = 2.5$ , and the *keepalive* duration to be 15 minutes.

**Bandwidth Attack Threshold** This threshold is applied to determine if a particular incident should be reported as a potential DDoS attack, if none of the other DDoS related signatures (e.g., high volumes of SYN, ICMP, or RST packets) are present. We set this threshold to a high-intensity threshold of 26 Mbps,<sup>4</sup> targeted at a single /32 behind a customer interface. The rate for alarms of longer duration will be lower due to the rate depreciation described in Section 4.2. The thresholds for larger prefixes (upto /28) are scaled according to the algorithm described in Figure 8.

**SYN/ICMP/RST Threshold** This threshold is applied to determine within the flow data if a particular incident could be considered a SYN, ICMP or RST attack. Currently we set this rate to a high intensity rate of 2.6 Mbps,<sup>5</sup> averaged over a 300 second interval. Again, we use a similar rate depreciation function for longer duration alarms.

## 6 Experimental Results

We first study our system performance in Section 6.1, followed by an evaluation of the SNMP based trigger phase in Section 6.2, before analyzing the incidents generated by our system in Section 6.3 and Section 6.4.

### 6.1 Performance

The data was collected using an existing SNMP and Net-flow data collection infrastructure. The SNMP data is being collected by a commercial off the shelf SNMP

collection tool which seems to scale easily to large networks. The Netflow collection system on the other hand was specifically build for this large ISP and is described in more detail in [10]. Currently this infrastructure monitors in excess of one petabyte of traffic each day.

Using these existing data sources we implemented our data extraction using a combination of flat files and an in-house database system. The data-extraction and analysis modules were implemented in Perl. The model-building phase uses additional MATLAB scripts for performing the de-noising operation.

The model-building phase uses 5 weeks of data per interface to get a mean-variance model for the anomaly detection. It took roughly 26 hours to perform the data extraction, de-noising, and model extraction for all the 22000 interfaces. This is not a concern since this part of the analysis can be performed offline, as it is not on the critical path for real-time attack detection.

We ran LADS in off-line emulation mode for our entire 11 day period on a heavily shared multi-processor 900MHz SUN Ultra. The anomaly detection stage was parallelized using 6 processes, and it took 11.2 seconds to report volume anomalies (i.e., finding deviation scores, doing the clustering, and filtering out measurement errors), for each 5 minute interval across the 22000 interfaces. The biggest bottleneck for our performance is the extraction of flow records for each reported SNMP volume anomaly (even after the reduction due to the triggers). The main reasons being (a) all flow data is compressed to meet storage constraints, and (b) the flow data is collected and indexed on a per-collector basis and not indexed based on the egress interface. Even with these performance inhibitors, it takes around 212.5 seconds to extract the flow data that needs to be analyzed. We note that this time can be reduced significantly by indexing the data appropriately.

The last stage of our analysis performs uni-dimensional aggregation on the collected flow data, taking approximately 40 seconds for each 5 minute interval. Thus, for each 5 minute interval of data arriving at the processing engine, the total time that is needed to report alarms, is the sum of the time taken to generate SNMP anomalies, the time taken to extract flow data for the triggered data, and the time taken to process the flow data, which is equal to  $11.2+212.5+40 = 263.7$  seconds. The resulting maximum latency with which we will report an alarm is, therefore, at most 263.7 seconds, implying that even with our current implementation (with very few performance optimizations) we can perform near real-time attack detection. On a more state of the art platform (900MHz UltraSparcs are quite dated!), with additional implementation optimizations and better data indexing we can achieve substantially better performance.

## 6.2 SNMP-based Trigger Evaluation

We evaluate our SNMP based trigger implementation in three stages. First, we discuss the choice of our trigger algorithm, then we compare our trigger events against the commercial-alarms and finally we highlight the savings our triggered approach provides.

### 6.2.1 Choice of Algorithm

In the context of our system we are looking for a model which is efficient, uses only historically available data and detects anomalies early. Those requirements are motivated by the fact that we have to perform this analysis in real time on tens of thousand of times series to provide DDoS alarms within a reasonable timeframe. Our mean-variance based model provides these features.

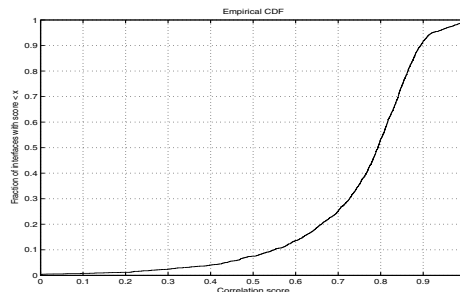


Figure 9: Correlation with the anomaly detection procedure proposed by Roughan et al. [26]

As a preliminary verification of the correctness of our anomaly detection system, Figure 9 depicts the correlation of our trigger algorithm with the one proposed by Roughan et al. [26]. The basic difference between these approaches lies in the assumption about the variance of the time-series. We use an empirical data-driven approach while Roughan et al. [26] assume that the stochastic component is of the form  $\sqrt{a} \times P_t$ , where  $a$  is a peakedness factor, and  $P_t$  is the periodic component of the time-series model (obtained using moving averages). Figure 9 shows a correlation score of greater than 0.7 between these two methods for more than 75% of all the 22000 interfaces selected for detection.

We find that in our problem domain, the simple trigger model has similar properties to more complex models and is adequate to perform the trigger function. One direction for future work is to compare our lightweight detection mechanism with other algorithms for time-series anomaly detection [34].

### 6.2.2 Accuracy

The objective of the trigger phase of our system is to reduce the flow data collected and analyzed to a manageable amount, and not to diagnose attacks directly. Therefore, an interesting question is the sensitivity of the trig-

gers with respect to known actual attacks – how often and by what magnitude do the known flooding attacks show up as volume anomalies.

To evaluate the sensitivity of the trigger, we use synthetically introduced volume anomalies of varying magnitude, and tested the detection false negative rate as a function of the detection threshold. For each of the 22000 interfaces under analysis, we introduce 20 randomly located anomalies for a chosen magnitude. Figure 10 shows the false negative rate for different thresholds ( $\alpha_{trigger}$ ). We notice that the false negative rates are indeed low, and that with anomalies of increased magnitude the false negative rates drop off quite significantly. Also, we notice that for larger anomalies, the false negative rate is expectedly less sensitive to the choice of the anomaly detection threshold.

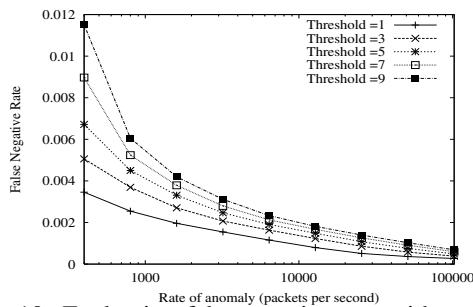


Figure 10: Evaluating false negative rate with synthetic volume anomalies

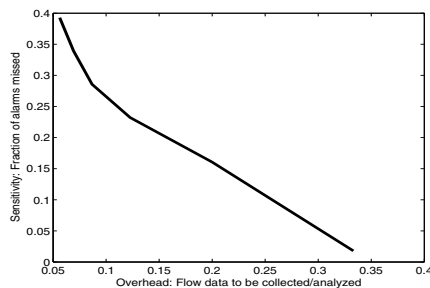


Figure 11: Tradeoff between sensitivity and scalability

A related question is how frequently the SNMP based triggers miss an attack in the commercial-alarm set. Figure 11 depicts the tradeoff between the sensitivity of the triggers and the overall data complexity reduction the trigger can achieve. The sensitivity of the anomaly detection module, for a particular deviation score threshold, is the percentage of commercial-alarms which match a SNMP anomaly for the threshold. The data complexity reduction achieved by the trigger can be calculated in terms of the flow data that will be collected after the trigger step and which needs to be further analyzed. Ideally, we would like to have a trigger that has perfect sensitivity (i.e., zero false negative rate), that can provide very low collection overhead for later stages.

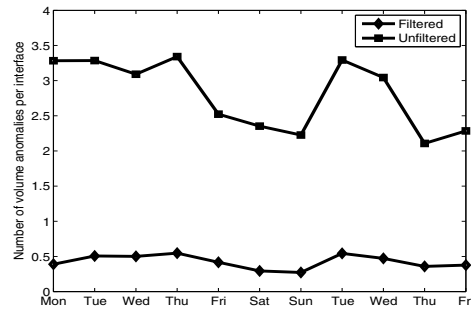


Figure 12: Number of SNMP events per interface per day

As a tradeoff between sensitivity and data reduction we chose an anomaly detection threshold of 5. This results in an 85% overlap with the commercial-alarms, and corresponds to an 80% data reduction (i.e., only 20% of the original flow data needs to be collected and analyzed in the second stage of our system). The reduction in collection overhead is significant considering that the total bandwidth overhead for collecting (1 in 500 sampled) flow records is around 2-3 TB per day, for a tier-1 ISP. With an 80% reduction rate, the total bandwidth overhead for collecting flow records would be roughly 40 Mbps over the entire network which is quite manageable. From a provider’s perspective, the alarms that are of paramount importance are those that affect the customers the most, and typically these are attacks which overload the egress link. If the misses occur on well-provisioned interfaces, the loss in sensitivity is not a serious concern. We will further discuss the alarms that do not appear as volume anomalies in Section 6.4.

Figure 12 shows the number of SNMP anomaly events per customer interface per day over the evaluation period before and after applying the filters. The filtering reduces the number of SNMP anomaly events on average by a factor of 6 (the predominant contribution being one from the absolute volume threshold). Considering the fact that these events will be automatically processed by the second phase of LADS, the number of SNMP anomalies is quite manageably low.

### 6.3 Incident Analysis

Next we characterize the alarms generated by LADS after performing the Netflow analysis described in Section 4.2. Each alarm specifies a duration and a customer-facing interface. It also contains a set of destination IP-prefixes which are receiving high incoming traffic volumes (and hence potential DDoS targets), the bandwidth of the suspected DDoS event, along with the alarm-type (BW, SYN, RST, ICMP).

Figure 13 shows the number of alarms during our 11-day evaluation period.<sup>6</sup> Here we consider incidents at the

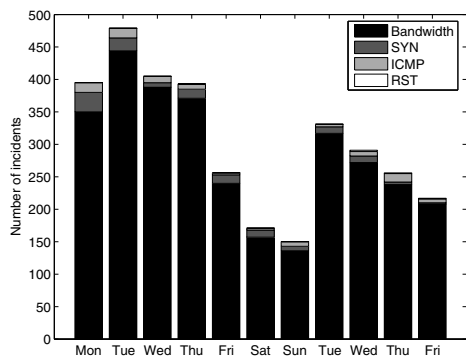


Figure 13: Number of reported incidents (at egress interface granularity) in 11 day period in Aug 2005

granularity of egress interfaces, i.e., concurrent floods against multiple IP addresses on the same egress interface will be considered a single incident. We generate approximately 15 incidents per hour which seems reasonable considering that we monitor 22000 customer interfaces and that this number of incidents could easily be handled by the security staff of a large network provider. We observe that a large fraction of the incidents are reported as potential bandwidth attacks.

The number of distinct IP addresses involved in an attack might be a better indicator of the workload for operators to investigate these alarms. If we split all alarms which target multiple IP addresses at a single egress interface into multiple alarms, we only see a slightly higher alarm rate (around 17 per hour). That is not surprising considering that most (76%) of the incidents involve only one IP address. We also find that in around 19% of the cases we get repeated alarms for the same IP address within the same day. These alarms would most likely only require one investigation by the network operator. Therefore, we believe that the above alarm rates are actually an upper bound of the number of trouble tickets network operators need to process.

Some of these alarms may indeed be benign bandwidth floods or flash crowds. Nevertheless, they are a cause of concern and we believe there is value in bringing these incidents to the attention of network operators. First, in the absence of ground truth regarding these incidents, such incidents should be brought to the notice of network operators. Second, since there was a large volume anomaly on the interface, with one or more destination IPs receiving a high data rate during this time, such reports may benefit other aspects of network operations such as traffic engineering and route management. We are investigating other techniques to independently characterize these alarms (e.g., [14]).

## 6.4 Comparison with Commercial DDoS Detection System

In this section we compare LADS alarms against the commercial-alarms. Since the commercial DDoS detection system only covers key locations and we only receive high level alarms from this system we would expect that our alarm set contains substantially more attacks than the commercial-alarms. The objective of LADS is not necessarily to provide better detection than the commercial system on the links covered by the commercial system. Rather the goal is to provide detection functionality comparable to deploying the commercial system on all the interfaces of the ISP, but to do so at a fraction of the cost that would be incurred in having to deploy the commercial system on every interface. Hence, we use this data set primarily to evaluate the false negative rate of LADS on the links covered by the commercial system.

Figure 14 presents a breakdown of the comparison of LADS alarms versus the commercial-alarms. The breakdown uses the following categories to classify the 86 alarms obtained from the commercial system.

**Successes** Between the LADS alarms and the commercial-alarms the interface matches, the IP prefix alarmed matches, and the durations of the reported alarms overlap.

**Found early incidents** Between the LADS alarms and the commercial-alarms the interface matches, the IP address alarmed matches, but we find the alarm slightly earlier than what is reported.

**Found late incidents** Between the LADS alarms and the commercial-alarms the interface matches, the IP address alarmed matches, but we find the alarm slightly later than what is reported by the commercial system.

**Anomaly detection misses** There is no SNMP event on the interface corresponding to a commercial-system alarm, i.e., the deviation score for the corresponding time is less than the threshold ( $\alpha_{trigger} = 5$ ).

**Potential commercial-alarm false positive** The interface information and the anomaly match between our SNMP alarm and the commercial-alarm. However, we find little or no flow data for the corresponding attack target reported by the alarms.

**Threshold misses** We have an SNMP volume anomaly, and we have flow data for the commercial-system alarm. We find quite a large number of flows to the IP, but LADS did not raise an alarm for the IP address.

The false negative rate of our system compared to the commercial DDoS detection system is essentially the sum of the anomaly misses, and threshold misses. Manual analysis of the anomaly detection misses indicates that all 7 SNMP anomaly misses are caused by relatively small attacks on OC-48 interfaces (2.48 Gbps). They did not saturate the customer interface and therefore are not

in the category of DDoS attacks of immediate concern. The number of threshold misses on our system is low - just one out of 86 incidents are missed due to the threshold settings. We conclude that the overall false negative rate of our system, compared to a commercial DDoS detection system, is 1 out of 80, or 1.25%.

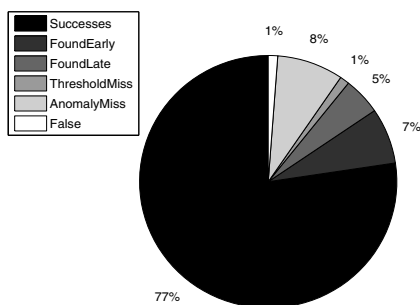


Figure 14: Comparison with the proprietary system

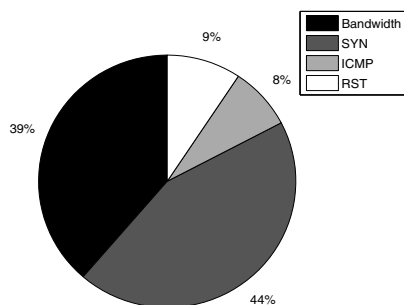


Figure 15: Breakdown of overlapping incidents

Next we proceed to analyze the incidents that are common to both LADS alarms and the commercial-system alarms. We give a breakdown of the 4 types of incidents *Bandwidth*, *SYN*, *ICMP*, *RST* in Figure 15. Interestingly, the largest portion of the reported incidents which overlap are SYN floods. Figure 16 shows the average bitrate (calculated from the flow records) of the DDoS alarms generated by our system and the commercial DDoS detection system. The overlapping incidents appear to have a minimum rate of 10 Mbps, which is most likely due to the fact that we only had access to the high priority alarms of the commercial DDoS detection system. Interestingly, this makes the high level alerts of this system unsuitable for detecting DDoS attacks against small customer links. Since, it is primarily deployed in the core the system ranks attacks as high level alerts not by customer impact but by the overall attack size. This is of course less desirable, if the goal is to protect customers with diversity in subscription line rates. For 40% of the LADS alarms we find a reported bandwidth which is smaller than 10Mbps.<sup>7</sup> Further investigation reveals that more than 70% of these low volume alarms are in fact caused by volume floods against low speed links.

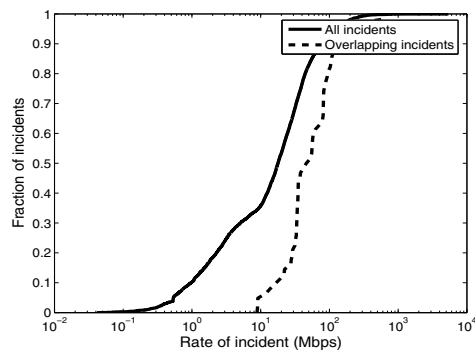


Figure 16: Rates of potential attack incidents

## 7 Conclusions

We presented the design of a triggered framework for scalable threat analysis, and a specific implementation based on SNMP and Netflow feeds derived from a tier-1 ISP. Our evaluations and experience with large networking datasets demonstrate the need for such an approach. LADS, our large-scale automated DDoS detection system, can provide detection and diagnostic capabilities across all customer interfaces of a large tier-1 ISP, without relying on the deployment of additional hardware monitoring devices. Of particular practical significance is the fact that our system uses data feeds that are readily available to most providers. We are investigating other ways in which we can confirm the validity of the alarms generated by our system (for example, using customer incident reports and other historical traffic profiles). Finally, we are currently pursuing the implementation of real time data feeds to our system to allow us to use it as an online attack detection mechanism.

## Acknowledgments

We wish to thank Jennifer Yates and Zihui Ge for helping us with collecting the SNMP data. We acknowledge the valuable feedback provided by Albert Greenberg. We thank Vidhyashankar Venkataraman and the anonymous reviewers for their comments on the paper, and thank Geoff Voelker for shepherding our paper.

## References

- [1] AIELLO, W., GILBERT, A., REXROAD, B., AND SEKAR, V. Sparse Approximations for High-Fidelity Compression of Network Traffic Data. In *Proceedings of ACM/USENIX Internet Measurement Conference (IMC)* (2005).
- [2] Arbor Networks. <http://www.arbor.com>.
- [3] B. CLAISE, E. Cisco Systems NetFlow Services Export Version 9. RFC 3954, 1990.
- [4] BARFORD, P., KLINE, J., PLONKA, D., AND RON, A. A Signal Analysis of Network Traffic Anomalies. In *Proceedings of ACM SIGCOMM Internet Measurement Workshop (IMW)* (2002).

- [5] BRUTLAG, J. D. Aberrant Behavior Detection in Time Series for Network Monitoring. In *Proceedings of USENIX Large Installation Systems Administration Conference (LISA)* (2000).
- [6] BURCH, H., AND CHESWICK, B. Tracing Anonymous Packets to Their Approximate Source. In *Proceedings of USENIX Large Installation Systems Administration Conference (LISA)* (2000).
- [7] CASE, J., FEDOR, M., SCHOFFSTALL, M., AND DAVIN, J. A Simple Network Management Protocol (SNMP). RFC 1157, 1990.
- [8] Cisco Guard. <http://www.cisco.com/en/US/products/ps5888/>.
- [9] COOKE, E., JAHANIAN, F., AND MCPHERSON, D. The Zombie Roundup: Understanding, Detecting, and Disrupting Botnets. In *Proceedings of USENIX Workshop on Steps to Reducing Unwanted Traffic on the Internet (SRUTI)* (2005).
- [10] DUFFIELD, N., LUND, C., AND THORUP, M. Learn more, sample less: Control of volume and variance in network measurement. *IEEE Transactions in Information Theory* 51, 5 (2005), 1756–1775.
- [11] ESTAN, C., SAVAGE, S., AND VARGHESE, G. Automatically Inferring Patterns of Resource Consumption in Network Traffic. In *Proceedings of ACM SIGCOMM* (2003).
- [12] GIL, T., AND POLETTI, M. MULTOPS: A Data-structure for Bandwidth Attack Detection. In *Proceedings of USENIX Security Symposium* (2001).
- [13] JAIN, A., HELLERSTEIN, J. M., RATNASAMY, S., AND WETHERALL, D. A Wakeup Call for Internet Monitoring Systems: The Case for Distributed Triggers. In *Proceedings of ACM SIGCOMM Workshop on Hot Topics in Networks (HotNets)* (2004).
- [14] JUNG, J., KRISHNAMURTHY, B., AND RABINOVICH, M. Flash crowds and denial of service attacks: Characterization and implications for CDNs and web sites. In *Proceedings of the International World Wide Web Conference (WWW)* (2002).
- [15] KANDULA, S., KATABI, D., JACOB, M., AND BERGER, A. Botz-4-sale: Surviving organized ddos attacks that mimic flash crowds. In *Proceedings of USENIX/ACM Symposium on Networked Systems Design and Implementation (NSDI)* (2005).
- [16] KEROMYTIS, A., MISRA, V., AND RUBENSTEIN, D. SOS: Secure Overlay Services. In *Proceedings of ACM SIGCOMM* (2002).
- [17] KOMPPELLA, R. R., SINGH, S., AND VARGHESE, G. On Scalable Attack Detection in the Network. In *Proceedings of ACM/USENIX Internet Measurement Conference (IMC)* (2004).
- [18] KRISHNAMURTHY, B., MADHYASTHA, H. V., AND SPATSCHKE, O. ATMEN: a triggered network measurement infrastructure. In *Proceedings of International World Wide Web Conference (WWW)* (2005).
- [19] LAKHINA, A., CROVELLA, M., AND DIOT, C. Diagnosing network-wide traffic anomalies. In *Proceedings of ACM SIGCOMM* (2004).
- [20] LAKHINA, A., CROVELLA, M., AND DIOT, C. Mining anomalies using traffic feature distributions. In *Proceedings of ACM SIGCOMM* (2005).
- [21] MAHAJAN, R., BELLOVIN, S., FLOYD, S., IOANNIDIS, J., PAXSON, V., AND SCOTT, P. Controlling high bandwidth aggregates in the network. *ACM SIGCOMM CCR* 32 (2002).
- [22] Mazu Networks. <http://www.mazu.com>.
- [23] MIRKOVIC, J., AND REIHER, P. A Taxonomy of DDoS Attacks and DDoS Defense Mechanisms. *ACM SIGCOMM CCR* 34 (2004).
- [24] MOORE, D., VOELKER, G. M., AND SAVAGE, S. Inferring Internet Denial-of-Service activity. In *Proceedings of USENIX Security Symposium* (2001).
- [25] MOREIN, W. G., STAVROU, A., COOK, D. L., KEROMYTIS, A., MISRA, V., AND RUBENSTEIN, D. Using Graphic Turing Tests to Counter Automated DDoS Attacks Against Web Servers. In *Proceedings of Networking and Distributed Systems Security Symposium (NDSS)* (2005).
- [26] ROUGHAN, M., GREENBERG, A., KALMANEK, C., RUMSEWICZ, M., YATES, J., AND ZHANG, Y. Experience in Measuring Internet Backbone Traffic Variability: Models, Metrics, Measurements and Meaning. In *Proceedings of International Teletraffic Congress (ITC)* (2003).
- [27] SANDERS, T. Cops smash 100,000 node botnet. <http://www.vnunet.com/2143475>, Oct 2005.
- [28] SAVAGE, S., WETHERALL, D., KARLIN, A., AND ANDERSON, T. Practical Network Support for IP Traceback. In *Proceedings of ACM SIGCOMM* (2000).
- [29] SNOEREN, A. C., PARTRIDGE, C., SANCHEZ, L. A., JONES, C. E., TCHAKOUNTIO, F., KENT, S. T., AND STRAYER, W. T. Hash-Based IP Traceback. In *Proceedings of ACM SIGCOMM* (2001).
- [30] THE HONEYNET PROJECT. Know your enemy: Tracking botnets. <http://www.honeynet.org/papers/bots>.
- [31] VASUDEVAN, R., MAO, Z. M., SPATSCHKE, O., AND VAN DER MERWE, J. Reval: A Tool for Real-time Evaluation of DDoS Mitigation Strategies. In *Proceedings of USENIX Annual Technical Conference* (2006).
- [32] XU, K., ZHANG, Z.-L., AND BHATTACHARYA, S. Profiling internet backbone traffic: Behavior models and applications. In *Proceedings of ACM SIGCOMM* (2005).
- [33] YANG, X., WETHERALL, D., AND ANDERSON, T. A DoS-limiting Network Architecture. In *Proceedings of ACM SIGCOMM* (2005).
- [34] ZHANG, Y., GE, Z., GREENBERG, A., AND ROUGHAN, M. Network anomography. In *Proceedings of ACM/USENIX Internet Measurement Conference (IMC)* (2005).
- [35] ZHANG, Y., SINGH, S., SEN, S., DUFFIELD, N., AND LUND, C. Online detection of hierarchical heavy hitters: algorithms, evaluation, and applications. In *Proceedings of ACM/USENIX Internet Measurement Conference (IMC)* (2004).

## Notes

<sup>1</sup>Despite this tunability, our experiments with a publicly available multi-dimensional analysis tool [11], suggest that this approach is too compute intensive to scale to the data volumes to be analyzed.

<sup>2</sup>Due to cost and operational constraints commercial vendor detection systems are typically constrained to operate in such a centralized model using feeds near the core of the network.

<sup>3</sup>Prior work [1] indicates that using 40-50 frequency coefficients can obtain a good predictive model for weekly traffic volume counts.

<sup>4</sup>Our implementation sets a threshold of  $2 \times 10^6$  bytes every 300 seconds on smart-sampled flow data, which roughly translates into a raw data rate of  $\frac{2 \times 10^6 * 500 * 8}{300} \approx 26$  Mbps.

<sup>5</sup>Our implementation counts the number of distinct flows and sets a threshold of 5 flows every 300 seconds, which translates into an absolute data rate of  $\frac{5 * 20MB * 8}{300} \approx 2.6$  Mbps.

<sup>6</sup>Due to collection issues we missed data for the second Monday.

<sup>7</sup>The rates for alarms of duration longer than 300 seconds will be lower than the high intensity thresholds of 26 Mbps for the bandwidth attacks, and 2.6 Mbps for SYN/RST/ICMP attacks, due to the rate depreciation we discussed earlier.