Detecting Malicious Packet Losses

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Abstract—In this paper, we consider the problem of detecting whether a compromised router is maliciously manipulating its stream of packets. In particular, we are concerned with a simple yet effective attack in which a router selectively drops packets destined for some victim. Unfortunately, it is quite challenging to attribute a missing packet to a malicious action because normal network congestion can produce the same effect. Modern networks routinely drop packets when the load temporarily exceeds their buffering capacities. Previous detection protocols have tried to address this problem with a user-defined threshold: too many dropped packets imply malicious intent. However, this heuristic is fundamentally unsound; setting this threshold is, at best, an art and will certainly create unnecessary false positives or mask highly focused attacks. We have designed, developed, and implemented a compromised router detection protocol that dynamically infers, based on measured traffic rates and buffer sizes, the number of congestive packet losses that will occur. Once the ambiguity from congestion is removed, subsequent packet losses can be attributed to malicious actions. We have tested our protocol in Emulab and have studied its effectiveness in differentiating attacks from legitimate network behavior.

Index Terms—Internet dependability, intrusion detection and tolerance, distributed systems, reliable networks, malicious routers.

1 Introduction

The Internet is not a safe place. Unsecured hosts can expect to be compromised within minutes of connecting to the Internet and even well-protected hosts may be crippled with denial-of-service (DoS) attacks. However, while such threats to host systems are widely understood, it is less well appreciated that the network infrastructure itself is subject to constant attack as well. Indeed, through combinations of social engineering and weak passwords, attackers have seized control over thousands of Internet routers [1], [2]. Even more troubling is Mike Lynn's controversial presentation at the 2005 Black Hat Briefings, which demonstrated how Cisco routers can be compromised via simple software vulnerabilities. Once a router has been compromised in such a fashion, an attacker may interpose on the traffic stream and manipulate it maliciously to attack others—selectively dropping, modifying, or rerouting packets.

Several researchers have developed distributed protocols to detect such traffic manipulations, typically by validating that traffic transmitted by one router is received unmodified by another [3], [4]. However, all of these schemes—including our own—struggle in interpreting the *absence* of traffic. While a packet that has been modified in transit represents clear evidence of tampering, a missing packet is inherently ambiguous: it may have been explicitly blocked by a compromised router or it may have been dropped benignly due to network congestion. In fact, modern routers routinely drop packets due to bursts in traffic that exceed their buffering capacities, and the widely used Transmission Control Protocol (TCP) is designed to *cause* such losses as part of its normal congestion control behavior. Thus, existing traffic validation systems must inevitably produce false positives for benign events and/or produce false negatives by failing to report real malicious packet dropping.

In this paper, we develop a compromised router detection protocol that dynamically infers the precise number of congestive packet losses that will occur. Once the congestion ambiguity is removed, subsequent packet losses can be safely attributed to malicious actions. We believe our protocol is the first to automatically predict congestion in a systematic manner and that it is necessary for making any such network fault detection practical.

In the remainder of this paper, we briefly survey the related background material, evaluate options for inferring congestion, and then present the assumptions, specification, and a formal description of a protocol that achieves these goals. We have evaluated our protocol in a small experimental network and demonstrate that it is capable of accurately resolving extremely small and fine-grained attacks.

2 Background

There are inherently two threats posed by a compromised router. The attacker may subvert the network control plane (e.g., by manipulating the routing protocol into false route updates) or may subvert the network data plane and forward individual packets incorrectly. The first set of attacks have seen the widest interest and the most activity—largely due to their catastrophic potential. By violating the routing protocol itself, an attacker may cause large portions of the network to become inoperable. Thus, there have been a variety of efforts to impart authenticity

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and consistency guarantees on route update messages with varying levels of cost and protection [5], [6], [7], [8], [9], [10]. We do not consider this class of attacks in this paper.

Instead, we have focused on the less well-appreciated threat of an attacker subverting the packet forwarding process on a compromised router. Such an attack presents a wide set of opportunities including DoS, surveillance, man-in-the-middle attacks, replay and insertion attacks, and so on. Moreover, most of these attacks can be trivially implemented via the existing command shell languages in commodity routers.

The earliest work on fault-tolerant forwarding is due to Perlman [11] who developed a robust routing system based on source routing, digitally signed *route-setup packets*, and reserved buffers. While groundbreaking, Perlman's work required significant commitments of router resources and high levels of network participation to detect anomalies. Since then, a variety of researchers have proposed lighter weight protocols for *actively probing* the network to test whether packets are forwarded in a manner consistent with the advertised global topology [5], [12], [13]. Conversely, the 1997 WATCHERS system detects disruptive routers passively via a distributed monitoring algorithm that detects deviations from a "conservation of flow" invariant [14], [3]. However, work on WATCHERS was abandoned, in part due to limitations in its distributed detection protocol, its overhead, and the problem of ambiguity stemming from congestion [15]. Finally, our own work broke the problem into three pieces: a traffic validation mechanism, a distributed detection protocol, and a rerouting countermeasure. In [16] and [4], we focused on the detection protocol, provided a formal framework for evaluating the accuracy and precision of any such protocol, and described several practical protocols that allow scalable implementations. However, we also assumed that the problem of congestion ambiguity could be solved, without providing a solution. This paper presents a protocol that removes this assumption.

3 Inferring Congestive Loss

In building a traffic validation protocol, it is necessary to explicitly resolve the ambiguity around packet losses. Should the absence of a given packet be seen as malicious or benign? In practice, there are three approaches for addressing this issue:

- *Static Threshold.* Low rates of packet loss are assumed to be congestive, while rates above some predefined threshold are deemed malicious.
- *Traffic modeling.* Packet loss rates are predicted as a function of traffic parameters and losses beyond the prediction are deemed malicious.
- *Traffic measurement.* Individual packet losses are predicted as a function of measured traffic load and router buffer capacity. Deviations from these predictions are deemed malicious.

Most traffic validation protocols, including `WATCHERS` [3], Secure Traceroute [12], and our own work described in [4], analyze aggregate traffic over some period of time in order to amortize monitoring overhead over many packets. For example, one validation protocol described in [4] maintains packet counters in each router to detect if traffic flow is not conserved from source to destination. When a packet arrives at router r and is forwarded to a destination that will traverse a path segment ending at router x, r increments an outbound counter associated with router x. Conversely, when a packet arrives at router r, via a path segment beginning with router x, it increments its inbound counter associated with router x. Periodically, router x sends a copy of its outbound counters to the associated routers for validation. Then, a given router r can compare the number of packets that x claims to have sent to r with the number of packets it counts as being received from x, and it can detect the number of packet losses.

Thus, over some time window, a router simply knows that out of m packets sent, n were successfully received. To address congestion ambiguity, all of these systems employ a predefined threshold: if more than this number is dropped in a time interval, then one assumes that some router is compromised. However, this heuristic is fundamentally flawed: how does one choose the threshold?

In order to avoid false positives, the threshold must be large enough to include the maximum number of possible congestive legitimate packet losses over a measurement interval. Thus, any compromised router can drop that many packets without being detected. Unfortunately, given the nature of the dominant TCP, even small numbers of losses can have significant impacts. Subtle attackers can selectively target the traffic flows of a single victim and within these flows only drop those packets that cause the most harm. For example, losing a TCP SYN packet used in connection establishment has a disproportionate impact on a host because the retransmission time-out must necessarily be very long (typically 3 seconds or more). Other seemingly minor attacks that cause TCP time-outs can have similar effects—a class of attacks well described in [17].

All things considered, it is clear that the static threshold mechanism is inadequate since it allows an attacker to mount vigorous attacks without being detected.

Instead of using a static threshold, if the probability of congestive losses can be modeled, then one could resolve ambiguities by comparing measured loss rates to the rates predicted by the model. One approach for doing this is to predict congestion analytically as a function of individual traffic flow parameters, since TCP explicitly responds to congestion. Indeed, the behavior of TCP has been excessively studied [18], [19], [20], [21], [22]. A simplified[1] stochastic model of TCP congestion control yields the following famous square root formula:

$$B = \frac{1}{RTT}\sqrt{\frac{3}{2bp}},$$

where B is the throughput of the connection, RTT is the average round trip time, b is the number of packets that are acknowledged by one ACK, and p is the probability that a TCP packet is lost. The steady-state throughput of

1. This formula omits many TCP dynamics such as time-outs, slow start, delayed acks, and so forth. More complex formulas taking these into account can be found in literature.

long-lived TCP flows can be described by this formula as a function of RTT and p.

This formula is based on a constant loss probability, which is the simplest model, but others have extended this work to encompass a variety of loss processes [22], [20], [23], [24]. None of these have been able to capture congestion behavior in all situations.

Another approach is to model congestion for the aggregate capacity of a link. In [25], Appenzeller et al. explore the question of "How much buffering do routers need?" A widely applied rule-of-thumb suggests that routers must be able to buffer a full delay bandwidth product. This controversial paper argues that due to congestion control effects, the rule-of-thumb is wrong, and the amount of required buffering is proportional to the square root of the total number of TCP flows. To achieve this, the authors produced an analytic model of buffer occupancy as a function of TCP behavior. We have evaluated their model thoroughly and have communicated with the authors, who agree that their model is only a rough approximation that ignores many details of TCP, including time-outs, residual synchronization, and many other effects. Thus, while the analysis is robust enough to model buffer size it is not precise enough to predict congestive loss accurately.

Hence, we have turned to measuring the interaction of traffic load and buffer occupancy explicitly. Given an output buffered *first-in first-out* (FIFO) router, congestion can be predicted precisely as a function of the inputs (the traffic rate delivered from all input ports destined to the target output port), the capacity of the output buffer, and the speed of the output link. A packet will be lost only if packet input rates from all sources exceed the output link speed for long enough. If such measurements are taken with high precision it should even be possible to predict individual packet losses. It is this approach that we consider further in the rest of this paper. We restrict our discussion to output buffered switches for simplicity although the same approach can be extended to input buffered switches or virtual output queues with additional adjustments (and overhead).

Because of some uncertainty in the system, we cannot predict exactly which individual packets will be dropped. So, our approach is still based on thresholds. Instead of being a threshold on rate, it is a threshold on a statistical measure: the amount of confidence that the drop was due to a malicious attack rather than from some normal router function. To make this distinction clearer, we refer to the statistical threshold as the *target significance level*.

4 System Model

Our work proceeds from an informed, yet abstracted, model of how the network is constructed, the capabilities of the attacker, and the complexities of the traffic validation problem. In this section, we briefly describe the assumptions underlying our model. We use the same system model as in our earlier work [4].

4.1 Network Model

We consider a network to consist of individual homogeneous routers interconnected via directional point-to-point links. This model is an intentional simplification of real networks (e.g., it does not include broadcast channels or independently failing network interfaces) but is sufficiently general to encompass such details if necessary. Unlike our earlier work, we assume that the bandwidth, the delay of each link, and the queue limit for each interface are all known publicly.

Within a network, we presume that packets are forwarded in a hop-by-hop fashion, based on a local forwarding table. These forwarding tables are updated via a distributed link-state routing protocol such as OSPF or IS-IS. This is critical, as we depend on the routing protocol to provide each node with a global view of the current network topology. Finally, we assume the administrative ability to assign and distribute cryptographic keys to sets of nearby routers. This overall model is consistent with the typical construction of large enterprise IP networks or the internal structure of single ISP backbone networks but is not well suited for networks that are composed of multiple administrative domains using BGP. At this level of abstraction, we can assume a synchronous network model.

We define a *path* to be a finite sequence $\langle r_1, r_2, \ldots r_n \rangle$ of adjacent routers. Operationally, a path defines a sequence of routers a packet can follow. We call the first router of the path the *source* and the last router its *sink*; together, these are called *terminal routers.* A path might consist of only one router, in which case the source and sink are the same. Terminal routers are leaf routers: they are never in the middle of any path.

An x-path segment is a consecutive sequence of x routers that is a subsequence of a path. A *path segment* is an x-path segment for some value of $x > 0$. For example, if a network consists of the single path $\langle a, b, c, d \rangle$, then $\langle c, d \rangle$ and $\langle b, c \rangle$ are both two-path segments, but $\langle a, c \rangle$ is not because a and c are not adjacent.

4.2 Threat Model

As explained in Section 1, this paper focuses solely on data plane attacks (control plane attacks can be addressed by other protocols with appropriate threat models such as [6], [7], [5], [8], [9], and [10]). Moreover, for simplicity, we examine only attacks that involve packet dropping. However, our approach is easily extended to address other attacks—such as packet modification or reordering—similar to our previous work. Finally, as in [4], the protocol we develop validates traffic whose source and sink routers are uncompromised.

A router can be *traffic faulty* by maliciously dropping packets and *protocol faulty* by not following the rules of the detection protocol. We say that a compromised router r is traffic faulty with respect to a path segment π during τ if π contains r and, during the period of time τ, r maliciously drops or misroutes packets that flow through π. A router can drop packets without being faulty, as long as the packets are dropped because the corresponding output interface is congested. A compromised router r can also behave in an arbitrarily malicious way in terms of executing

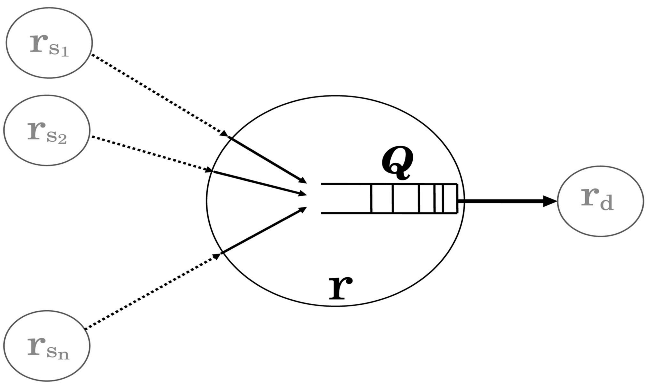


Fig. 1. Validating the queue of an output interface.

the protocol we present, in which case we indicate r as protocol faulty. A protocol faulty router can send control messages with arbitrarily faulty information, or it can simply not send some or all of them. A *faulty* router is one that is traffic faulty, protocol faulty, or both.

Attackers can compromise one or more routers in a network. However, for simplicity, we assume in this paper that adjacent routers cannot be *faulty*. Our work is easily extended to the case of k adjacent *faulty* routers.

5 PROTOCOL χ

Protocol χ detects *traffic faulty* routers by validating the queue of each output interface for each router. Given the buffer size and the rate at which traffic enters and exits a queue, the behavior of the queue is deterministic. If the actual behavior deviates from the predicted behavior, then a failure has occurred.

We present the failure detection protocol in terms of the solutions of the distinct subproblems: traffic validation, distributed detection, and response.

5.1 Traffic Validation

The first problem we address is *traffic validation*: what information is collected about traffic and how it is used to determine that a router has been compromised.

Consider the queue Q in a router r associated with the output interface of link $\langle r, r_d\rangle$ (see Fig. 1). The neighbor routers $r_{s_1}, r_{s_2}, \ldots, r_{s_n}$ feed data into Q.

We denote with $Tinfo(r, \mathbf{Q}_{dir}, \pi, \tau)$ the traffic information collected by router r that traversed path segment π over time interval τ. $\mathbf{Q}_{dir}$ is either Q_{in}, meaning traffic into Q, or Q_{out}, meaning traffic out of Q. At an abstract level, we represent traffic, a validation mechanism associated with Q, as a predicate $TV(Q, q_{pred}(t), S, D)$, where

- $q_{pred}(t)$ is the predicted state of Q at time t. $q_{pred}(t)$ is initialized to 0 when the link $\langle r, r_d\rangle$ is discovered and installed into the routing fabric. q_{pred} is updated as part of traffic validation.
- $S = \{\forall i \in \{1, 2, \ldots, n\} : Tinfo(r_{s_i}, Q_{in}, \langle r_{s_i}, r, r_d\rangle, \tau)\}$, is a set of information about traffic coming into Q as collected by neighbor routers.
- $D = Tinfo(r_d, Q_{out}, \langle r, r_d\rangle, \tau)$ is the traffic information about the outgoing traffic from Q collected at router r_d.

If routers $r_{s_1}, r_{s_2}, \ldots, r_{s_n}$ and r_d are not *protocol faulty*, then $TV(Q, q_{pred}(t), S, D)$ evaluates to *false* if and only if r was *traffic faulty* and dropped packets maliciously during τ.

$Tinfo(r, \mathbf{Q}_{dir}, \pi, \tau)$ can be represented in different ways. We use a set that contains, for each packet traversing Q, a three-tuple that includes: a fingerprint of the packet, the packet's size, and the time that the packet entered or exited Q (depending on whether $\mathbf{Q}_{dir}$ is Q_{in} or Q_{out}). For example, if at time t router r_s transmits a packet of size ps bytes with a fingerprint fp, and the packet is to traverse π, then r_s computes when the packet will enter Q based on the packet's transmission and propagation delay. Given a link delay d and link bandwidth bw associated with the link $\langle r_s, r\rangle$, the time stamp for the packet is $t + d + ps/bw$.

TV can be implemented by simulating the behavior of Q. Let P be a priority queue, sorted by increasing time stamp. All the traffic information S and D are inserted into P along with the identity of the set (S or D) from which the information came. Then, P is enumerated. For each packet in P with a fingerprint fp, size ps, and a time stamp ts, q_{pred} is updated as follows. Assume t is the time stamp of the packet evaluated prior to the current one:

- If fp came from D, then the packet is leaving $Q : q_{pred}(ts) := q_{pred}(t) - ps$.
- If fp came from S and $(fp \in D)$, then the packet fp is entering and will exit: $q_{pred}(ts) := q_{pred}(t) + ps$.
- If fp came from S and $(fp \notin D)$, then the packet fp is entering into Q and the packet fp will not be transmitted in the future: $q_{pred}(ts)$ is unchanged, and the packet is *dropped*.
  - If $q_{limit} < q_{pred}(t) + ps$, where q_{limit} is the buffer limit of Q, then the packet is dropped due to congestion.
  - Otherwise, the packet is dropped due to malicious attack. Detect failure.

In practice, the behavior of a queue cannot be predicted with complete accuracy. For example, the tuples in S and D may be collected over slightly different intervals, and so a packet may appear to be dropped when in fact it is not (this is discussed in Section 4.1). Additionally, a packet sent to a router may not enter the queue at the expected time because of short-term scheduling delays and internal processing delays.

Let $q_{act}(t)$ be the actual queue length at time t. Based on the central limit theorem[2] [26], our intuition tells us that the error, $q_{error} = q_{act} - q_{pred}$, can be approximated with a normal distribution. Indeed, this turns out to be the case as we show in Section 7. Hence, this suggests using a probabilistic approach.

We use two tests: one based on the loss of a single packet and one based on the loss of a set of packets.

2. The central limit theorem states the following. Consider a set of n samples drawn independently from any given distribution. As n increases, the average of the samples approaches a normal distribution as long as the sum of the samples has a finite variance.

$c_{single} = Prob(fp \text{ is maliciously dropped})$	
$= Prob(\text{there is enough space in the queue to buffer } fp)$	
$= Prob(q_{act}(ts) + ps \leq q_{limit})$	
$= Prob(X + q_{pred}(ts) + ps \leq q_{limit})$	Random variable $X = q_{act}(ts) - q_{pred}(ts)$ with mean μ and standard deviation σ
$= Prob(X \leq q_{limit} - q_{pred}(ts) - ps)$	
$= Prob(Y \leq \frac{q_{limit} - q_{pred}(ts) - ps - \mu}{\sigma})$	Random variable $Y = (X - \mu)/\sigma$
$= Prob(Y \leq y_1)$	$y_1 = \frac{q_{limit} - q_{pred}(ts) - ps - \mu}{\sigma}$
$= \frac{1 + erf(y_1/\sqrt{2})}{2}$	*erf* is the error function.

Fig. 2. Confidence value for single packet loss test for a packet with a fingerprint fp, size ps, and a time stamp ts.

5.1.1 Single Packet Loss Test

If a packet with fingerprint fp and size ps is dropped at time ts when the predicted queue length is $q_{pred}(ts)$, then we raise an alarm with a confidence value c_{single}, which is the probability of the packet being dropped maliciously. c_{single} is computed as in Fig. 2.

The mean μ and standard deviation σ of X can be determined by monitoring during a learning period. We do not expect μ and σ to change much over time, because they are in turn determined by values that themselves do not change much over time. Hence, the learning period need not be done very often.

A malicious router is detected if the confidence value c_{single} is at least as large as a target significance level s_{single}^{level}.[3]

5.1.2 Combined Packet Losses Test

The second test is useful when more than one packet is dropped during a round and the first test does not detect a malicious router. It is based on the well-known Z-test[4] [26]. Let L be the set of $n > 1$ packets dropped during the last time interval. For the packets in L, let $\overline{ps}$ be the mean of the packet sizes, $\overline{q_{pred}}$ be the mean of $q_{pred}(ts)$ (the predicted queue length), and $\overline{q_{act}}$ be the mean of $q_{act}(ts)$ (the actual queue length) over the times the packets were dropped.

We test the following hypothesis: "The packets are lost due to malicious attack": $\mu > q_{limit} - \overline{q_{pred}} - \overline{ps}$. The Z-test score is

$$z_1 = \frac{(q_{limit} - \overline{q_{pred}} - \overline{ps} - \mu)}{\sigma\sqrt{n}}.$$

For the standard normal distribution Z, the probability of $Prob(Z < z_1)$ gives the confidence value $c_{combined}$ for the hypothesis. A malicious router is detected if $c_{combined}$ is at least as large as a target significance level $s_{combined}^{level}$.

One can question using a Z-test in this way because the set of dropped packets are not a simple random sample. But, this test is used when there are packets being dropped and the first test determined that they were consistent with congestion loss. Hence, the router is under load during the short period the measurement was taken and most of the points, both for dropped packets and for nondropped packets, should have a nearly full Q. In Section 7, we show that the Z-test does in fact detect a router that is malicious in a calculated manner.

5.2 Distributed Detection

Since the behavior of the queue is deterministic, the traffic validation mechanisms detect *traffic faulty* routers whenever the actual behavior of the queue deviates from the predicted behavior. However, a faulty router can also be *protocol faulty*: it can behave arbitrarily with respect to the protocol, by dropping or altering the control messages of χ. We mask the effect of protocol faulty routers using distributed detection.

Given TV, we need to distribute the necessary traffic information among the routers and implement a distributed detection protocol. Every outbound interface queue Q in the network is monitored by the neighboring routers and validated by a router r_d such that Q is associated with the link $\langle r, r_d \rangle$.

With respect to a given Q, the routers involved in detection are (as shown in Fig. 1)

- r_{s_*}, which sends traffic into Q to be forwarded.
- r, which hosts Q.
- r_d, which is the router to which Q's outgoing traffic is forwarded.

Each involved router has a different role, as described below.

5.2.1 Traffic Information Collection

Each router collects the following traffic information during a time interval τ:

- r_{s_*}: Collect $Tinfo(r_{s_*}, Q_{in}, \langle r_{s_*}, r, r_d \rangle, \tau)$.
- r: Collect $Tinfo(r, Q_{in}, \langle r_{s_*}, r, r_d \rangle, \tau)$. This information is used to check the transit traffic information sent by the r_{s_*} routers.
- r_d: Collect $Tinfo(r_d, Q_{out}, \langle r, r_d \rangle, \tau)$.

5.2.2 Information Dissemination and Detection

- r_{s_*}: At the end of each time interval τ, router r_{s_*} sends $[Tinfo(r_{s_*}, Q_{in}, \langle r_{s_*}, r, r_d \rangle, \tau)]_{r_{s_*}}$ that it has collected. $[M]_x$ is a message M digitally signed by x. Digital

3. The significance level is the critical value used to decide to reject the null hypothesis in traditional statistical hypothesis testing. If it is rejected, then the outcome of the experiment is said to be statistically significant with that significance level.

4. The Z-test, which is a statistical test, is used to decide whether the difference between a sample mean and a given population mean is large enough to be statistically significant or not.

signatures are required for integrity and authenticity against message tampering.[5]

1. D-I. r: Let Δ be the upper bound on the time to forward traffic information.
    a. If r does not receive traffic information from r_{s_*} within Δ, then r detects $\langle r_{s_*}, r\rangle$.
    b. Upon receiving $[Tinfo(r_{s_*}, Q_{in}, \langle r_{s_*}, r, r_d\rangle, \tau)]r_{s_*}$, router r verifies the signature and checks to see if this information is equal to its own copy $Tinfo(r, Q_{in}, \langle r_{s_*}, r, r_d\rangle, \tau)$. If so, then r forwards it to r_d. If not, then r detects $\langle r_{s_*}, r\rangle$.

    At this point, if r has detected a failure $\langle r_{s_*}, r\rangle$, then it forwards its own copy of traffic information $Tinfo(r, Q_{in}, \langle r_{s_*}, r, r_d\rangle, \tau)$. This is required by r_d to simulate Q's behavior and keep the state q up to date.
2. D-II. r_d:
    a. If r_d does not receive traffic information $Tinfo(r_{s_*}, Q_{in}, \langle r_{s_*}, r, r_d\rangle, \tau)$ originated by r_{s_*} within 2Δ, then it expects r to have detected r_{s_*} as faulty and to announce this detection through the response mechanism. If r does not do this, then r_d detects $\langle r, r_d\rangle$.
    b. After receiving the traffic information forwarded from r, r_d checks the integrity and authenticity of the message. If the digital signature verification fails, then r_d detects $\langle r, r_d\rangle$.
    c. Collecting all traffic information, router r_d evaluates the TV predicate for queue Q. If TV evaluates to *false*, then r_d detects $\langle r, r_d\rangle$.

Fault detections D-Ia, D-Ib, D-IIa, and D-IIb are due to *protocol faulty* routers, and fault detection D-IIc is due to the traffic validation detecting *traffic faulty* routers.

Note that dropping traffic information packets due to congestion can lead to false positives. Thus, the routers send this data with high priority. Doing so may cause other data to be dropped instead as congestion. Traffic validation needs to take this into account. It is not hard, but it is somewhat detailed, to do so in simulating Q's behavior.

5.3 Response

Once a router r detects router r' as faulty, r announces the link $\langle r', r\rangle$ as being suspected. This suspicion is disseminated via the distributed link state flooding mechanism of the routing protocol. As a consequence, the suspected link is removed from the routing fabric.

Of course, a protocol faulty router r can announce a link $\langle r', r\rangle$ as being faulty, but it can do this for any routing protocol. And, in doing so, it only stops traffic from being routed through itself. Router r could even do this by simply crashing itself. To protect against such attack, the routing fabric needs to have sufficient path redundancy.

6 Analysis of Protocol χ

In this section, we consider the properties and overhead of protocol χ.

5. Digital signatures can be replaced with message authentication codes if the secret keys are distributed among the routers.

6.1 Accuracy and Completeness

In [4], we cast the problem of detecting compromised routers as a failure detector with *accuracy* and *completeness* properties. There are two steps in showing the accuracy and completeness of χ:

- Showing that TV is correct.
- Showing that χ is accurate and complete assuming that TV is correct.

Assuming that there exists no adjacent faulty routers, we show in Appendices B and C that if TV is correct, then χ is *2-accurate* and *2-complete*, where 2 indicates the length of detection: A link consisting of two routers is detected as a result. We discuss how to relax this assumption in Section 9.2.

We discuss traffic validation in Section 6.2.

6.2 Traffic Validation Correctness

Any failure of detecting malicious attack by TV results in a false negative, and any misdetection of legitimate behavior by TV results in a false positive.

Within the given system model of Section 4, the example TV predicate in Section 5.1 is correct. However, the system model is still simplistic. In a real router, packets may be legitimately dropped due to reasons other than congestion: for example, errors in hardware, software or memory, and transient link errors. Classifying these as arising from a router being compromised might be a problem, especially if they are infrequent enough that they would be best ignored rather than warranting repairs the router or link.

A larger concern is the simple way that a router is modeled in how it internally multiplexes packets. This model is used to compute time stamps. If the time stamps are incorrect, then TV could decide incorrectly. We hypothesize that a sufficiently accurate timing model of a router is attainable but have yet to show this to be the case.

A third concern is with clock synchronization. This version of TV requires that all the routers feeding a queue have synchronized clocks. This requirement is needed in order to ensure that the packets are interleaved correctly by the model of the router.

The synchronization requirement is not necessarily daunting; the tight synchronization is only required by routers adjacent to the same router. With low-level time stamping of packets and repeated exchanges of time [27], it should be straightforward to synchronize the clocks sufficiently tightly.

Other representations of collected traffic information and TV that we have considered have their own problems with false positives and false negatives. It is an open question as to the best way to represent TV. We suspect any representation will admit some false positives or false negatives.

6.3 Overhead

We examined the overhead of protocol χ in terms of computing fingerprints, computing TV, per-router state, control messages overhead, clock synchronization, and key distribution. We believe all are low enough to permit practical implementation and deployment in real networks.

6.3.1 Computing Fingerprints

The main overhead of protocol χ is in computing a fingerprint for each packet. This computation must be done at wire speed. Such a speed has been demonstrated to be attainable.

In our prototype, we implemented fingerprinting using UHASH [28]. Rogaway [29] demonstrated UHASH performance of more than 1 Gbps on a 700-MHz Pentium III processor when computing a 4-byte hash value. This performance could be increased further with hardware support.

Network processors are designed to perform highly parallel actions on data packets [30]. For example, Feghali et al. [31] presented an implementation of well-known private-key encryption algorithms on the Intel IXP28xx network processors to keep pace with a 10-Gbps forwarding rate. Furthermore, Sanchez et al. [32] demonstrated hardware support to compute fingerprints at wire speed of high speed routers (OC-48 and faster).

6.3.2 Computing TV

The time complexity of computing TV depends on the size of the traffic information collected and received from the neighbors that are within two hops, and so it depends on the topology and the traffic volume on the network. If traffic information stores the packet fingerprints in order of increasing time stamps, then a straightforward implementation of traffic validation exists.

In our prototype, which is not optimized, TV computation had an overhead of between 15 to 20 ms per validation round.

6.3.3 Per-Router State

Let N be the number of routers in the network, and R be the maximum number of links incident on a router. Protocol χ requires a router to monitor the path segments that are at most two hops away. By construction, this is $O(R^2)$. State is kept for each of these segments. The TV predicate in Section 5.1 requires that a time stamp and the packet size be kept for each packet that traversed the path segment. As a point of comparison, WATCHERS [3] requires $O(RN)$ state, where each individual router keeps seven counters for each of its neighbors for each destination.

6.3.4 Control Message Overhead

Protocol χ collects traffic information and exchanges this information periodically using the monitored network infrastructure. Suppose we compute a 4-byte fingerprint and keep packet size and time stamp in 2 bytes each. Then, message overhead is 8 bytes per packet. If we assume that the average packet size is 800 bytes, then the bandwidth overhead of protocol χ is 1 percent.

6.3.5 Clock Synchronization

Similar to all previous detection protocols, χ requires synchronization in order to agree on a time interval during which to collect traffic information. For a router r, all neighboring routers of r need to synchronize with each other to agree on when and for how long the next measurement interval τ will be.

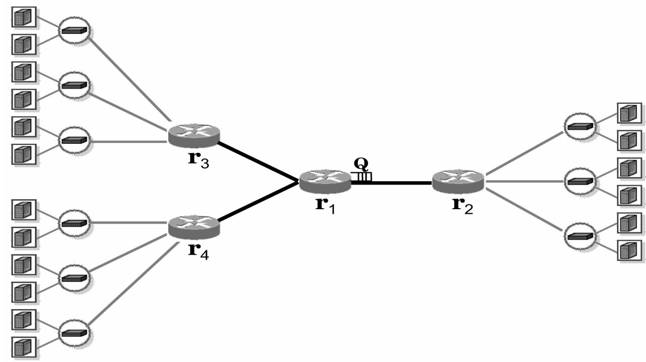


Fig. 3. Simple topology.

Clock synchronization overhead is fairly low. For example, external clock synchronization protocol NTP [33] can provide accuracy within 200 μs in local area networks (LANs). It requires two messages of size 90 bytes per transaction and the rate of transactions can be from once per minute to once per 17 minutes. Wedde et al. [34] presented an internal clock synchronization protocol (RTNP) that maintains an accuracy within 30 μs by updating the clocks once every second.

6.3.6 Key Distribution

To protect against *protocol faulty* routers tampering the messages containing traffic information, χ requires digital signatures or message authentication codes. Thus, there is an issue of *key distribution*, and the overhead for this depends on the cryptographic tools that are used.

7 EXPERIENCES

We have implemented and experimented with protocol χ in the Emulab [35], [36] testbed. In our experiments, we used the simple topology shown in Fig. 3. The routers were Dell PowerEdge 2850 PC nodes with a single 3.0-GHz 64-bit Xeon processor and 2 Gbytes of RAM, and they were running Redhat-Linux-9.0 OS software. Each router except for r_1 was connected to three LANs to which user machines were connected. The links between routers were configured with 3-Mbps bandwidth, 20-ms delay, and 75,000-byte capacity FIFO queue.

Each pair of routers shares secret keys; furthermore, integrity and authenticity against the message tampering is provided by message authentication codes.

The validation time interval τ was set to 1 second, and the upper bound on the time to forward traffic information Δ was set to 300 ms. At the end of each second, the routers exchanged traffic information corresponding to the last validation interval and evaluated the TV predicate after $2\Delta = 600$ ms. Each run in an experiment consisted of an execution of 80 seconds. During the first 30 seconds, we generated no traffic to allow the routing fabric to initialize. Then, we generated 45 seconds of traffic.

7.1 Experiment 1: Protocol χ with No Attack

We first investigated how accurately the protocol predicts the queue lengths of the monitored output interfaces. We considered the results for the output interface Q of r_1

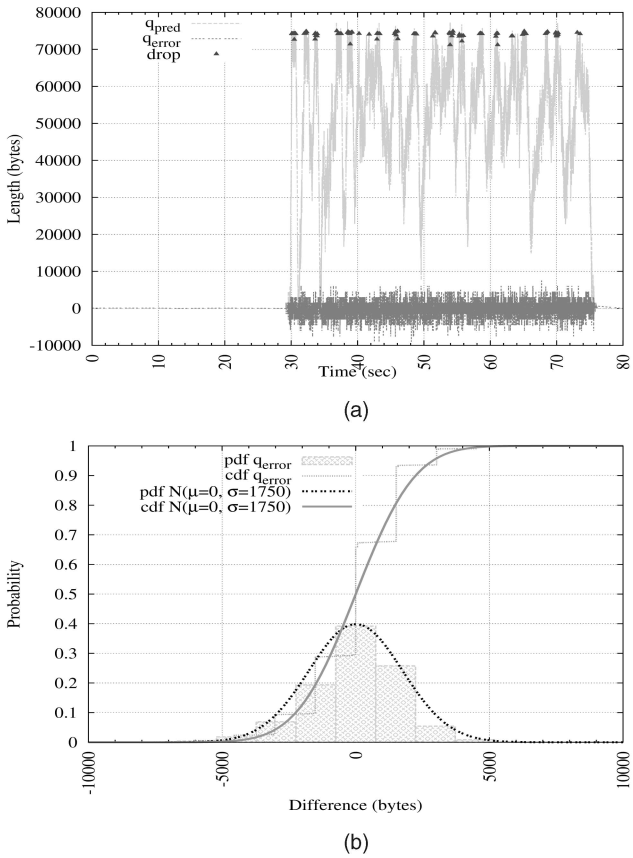


Fig. 4. (a) Queue length. (b) Distribution of q_{error}.

associated with the link $\langle r_1, r_2 \rangle$. Background traffic was created to make $\langle r_1, r_2 \rangle$ a bottleneck. Twenty percent of the bottleneck bandwidth was consumed by constant bit rate traffic, another 20 percent by short lived http traffic, and the rest by long lived ftp traffic.

The result of one run is shown in Fig. 4a. q_{pred} is the predicted queue length of Q computed by router r_2 executing the protocol χ. q_{act}, which is the actual queue length of Q recorded by router r_1, is not shown in the graph because it is so close to q_{pred}. Instead, the difference $q_{error} = q_{act} - q_{pred}$ is plotted; its value ranges approximately from $-7{,}500$ to 7,500 bytes. Packet drops—all due to congestion—are marked with triangles.

Next, we examine the distribution of q_{error}. In Fig. 4b, the probability distribution and cumulative distribution functions of q_{error} are plotted. It is clustered around the multiples of 1,500 bytes, since this is the maximum transmission unit and most frequent packet size of the traffic. Computing the mean, μ, and the standard deviation, σ, of this data, the corresponding normal distribution functions are also shown in the graph. It turns out that the distribution of q_{error} can be approximated by a normal distribution $N(\mu, \sigma)$.

We expected many different causes to contribute to q_{error}: inaccurate clock synchronization, scheduling delays, internal processing delays, and so on. It turns out that scheduling and clock synchronization inaccuracy are the dominant factors. In terms of scheduling, all routers are running Linux with a programmable interval timer of 1,024 Hz. This results in a scheduling quantum of roughly 1 ms. We verified the effect of the scheduling quantum by changing the frequency to 100 Hz, and we observed that the variance of the distribution of q_{error} changed accordingly. For clock synchronization, we used NTP [33] to synchronize the routers' clocks, but it takes a long time for the NTP daemon to synchronize the routers' clocks to within a few milliseconds. So, we used a different strategy: once every second, we reset each router's clock to the NTP server's clock. This resulted in the clocks being synchronized to within 0.5 ms. Finally, the processing delay of the packets within a router is typically less than 50 μs. So, it does not introduce significant uncertainty as compared to other factors.

7.2 Experiment 2: False Positives

In the second experiment, we first ran a training run to measure the mean and standard deviation of q_{error}. We found $\mu = 0$ and $\sigma = 1{,}750$. We then ran protocol χ under a high traffic load for more than 1 h, which generated more than half a million packets. Approximately 4,000 validation rounds occurred within this run, and approximately 16,000 packets were dropped due to congestion. Choosing significance levels $s_{single}^{level} = 0.999$ and $s_{combined}^{level} = 0.9$, there were eight false positives generated by the single packet drop test and two false positives generated by the combined packet drop test. Both results are lower than one would expect, given the number of samples. We suspect that the lower false positive rate for the single packet drop test is because the distribution of q_{error} is not truly a normal distribution, and the lower false positive rate for the combined packet drop test is because the test is not done on a simple random sample. We are investigating this further. In all of the subsequent experiments, we used the same mean, standard deviation, and two significance levels given here.

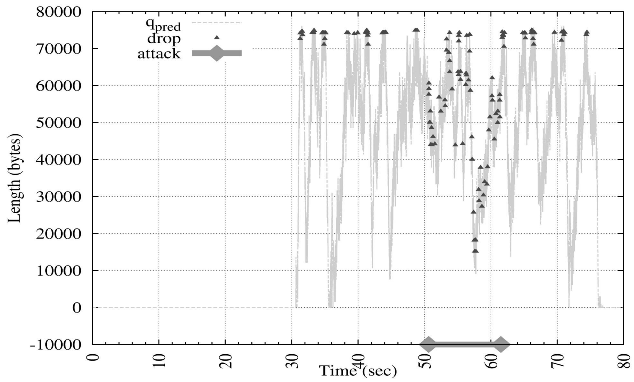
7.3 Experiment 3: Detecting Attacks

We then experimented with the ability of protocol χ to detect attacks. In these experiments, the router r_1 is compromised to attack the traffic selectively in various ways, targeting two chosen *ftp* flows. The duration of the attack is indicated with a line bounded by diamonds in the figures, and a detection is indicated by a filled circle.

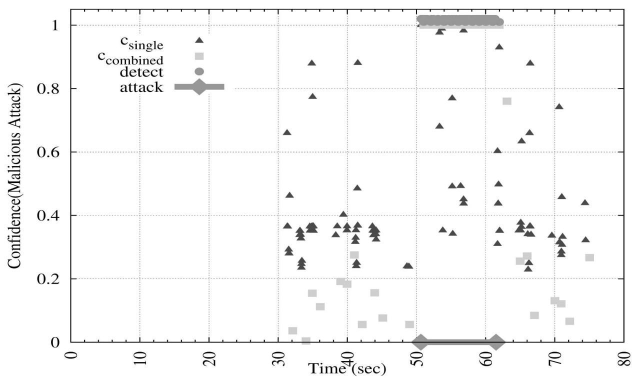
For the first attack, the router r_1 was instructed to drop 20 percent of the selected flows for 10 seconds. Predicted queue length and the confidence values for each packet drop can be seen in Figs. 5a and 5b. As shown in the graph, during the attack, protocol χ detected the failure successfully.

In the second attack, router r_1 was instructed to drop packets in the selected flows when the queue was at least 90 percent full. Protocol χ was able to detect the attack and raised alarms, as shown in Fig. 6.

Next, we increase the threshold for which r_1 attacks to 95 percent. No single drop test has enough confidence to raise an alarm because all of the drops are very close to the q_{limit}. However, χ raised alarms for the combined drops test. Even though few additional packets were dropped, the impact on the TCP flows of this attack was significant. Both attacked flows' bandwidth usage dropped more than 35 percent, and their share was used by the other flows (Fig. 7).

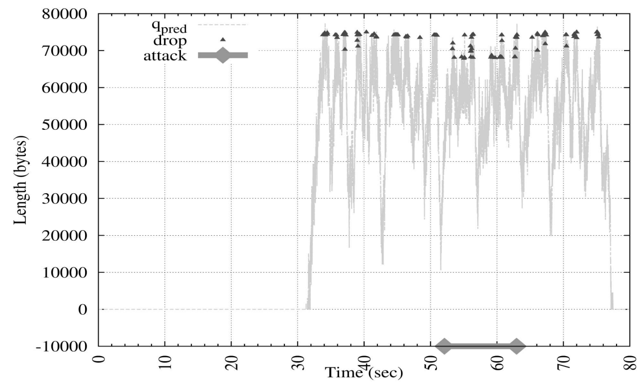


(a)

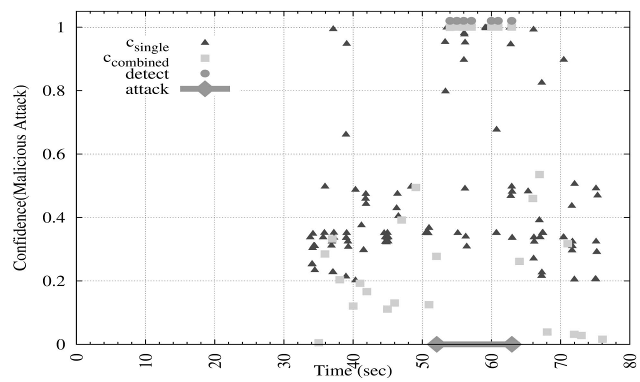


(b)

Fig. 5. Attack 1: *Drop 20 percent of the selected flows.* (a) Queue length. (b) Statistical test results.



(a)



(b)

Fig. 6. Attack 2: *Drop the selected flows when the queue is 90 percent full.* (a) Queue length. (b) Statistical test results.

Last, we looked in the SYN attack, which would prevent a selected host to establish a connection with any server: The router r_1 was instructed to drop all SYN packets from a targeted host, which tries to connect to an ftp server. In Fig. 8, five SYN packets, which are marked with circles, are maliciously dropped by r_1. Except for the second SYN packet drop, all malicious drops raised an alarm. The second SYN is dropped when the queue is almost full, and so the confidence value is not significant enough to differentiate it from the other packet drops due to congestion.

7.4 Protocol χ versus Static Threshold

We argued earlier the difficulties of using static thresholds of dropped packets for detecting malicious intent. We illustrate this difficulty with the run shown in Fig. 6. Recall that during this run, the router dropped packets only when the output queue was at least 90 percent full. Before time 52, the router behaved correctly, and 2.1 percent of the packets were dropped due to congestion. During the time period from 52 to 64, the router maliciously dropped packets, but only 1.7 percent of the packets were dropped (some due to congestion and some due to the attack). This may seem counterintuitive: fewer packets were dropped due to congestion during the period that the queues contained more packets. Such a nonintuitive behavior does not happen in every run, but the dynamics of the network transport protocol led to this behavior in the case of this run. So, for this run, there is no static threshold that can be used to detect the period during which the router was malicious. A similar situation occurs in the highly focused SNY attack of Fig. 8.

In contrast, protocol χ can detect such malicious behaviors because it measures the router's queues, which are determined by the dynamics of the network transport protocol. Protocol χ can report false positives and false negatives, but the probability of such detections can be controlled with a significance level for the statistical tests upon which χ is built. A static threshold cannot be used in the same way.

8 Nondeterministic Queuing

As described, our traffic validation technique assumes a deterministic queuing discipline on each router: FIFO with tail-drop. While this is a common model, in practice, real router implementations can be considerably more complex—involving switch arbitration, multiple layers of buffering, multicast scheduling, and so forth. Of these, the most significant for our purposes is the nondeterminism introduced by active queue management (AQM), such as *random early detection* (RED) [37], *proportional integrator* (PI) [38], and *random exponential marking* (REM) [39]. In this section, we describe how protocol χ can be extended to validate traffic in AQM environments. We focus particularly on RED, since this is the most widely known and widely used of such mechanisms.[6]

6. Although RED is universally *implemented* in modern routers, it is still unclear how widely it is actually used.

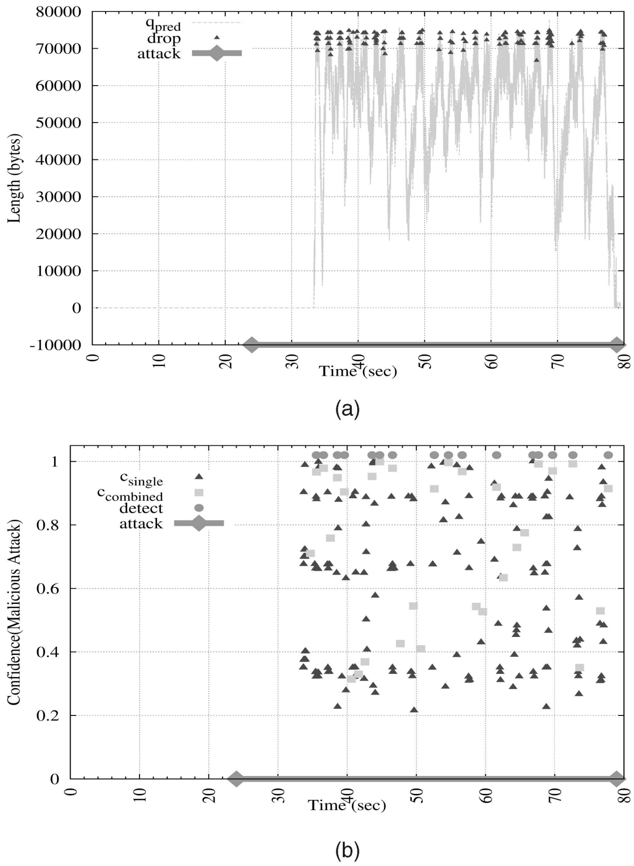


Fig. 7. Attack 3: *Drop the selected flows when the queue is 95 percent full.* (a) Queue length. (b) Statistical test results.

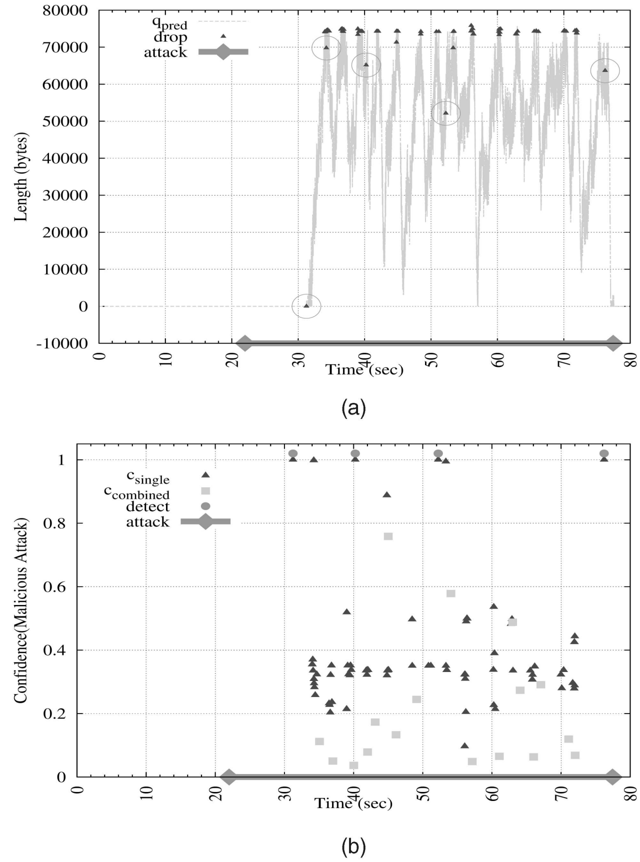


Fig. 8. Attack 4: *Target a host trying to open a connection by dropping SYN packets.* (a) Queue length. (b) Statistical test results.

RED was first proposed by Floyd and Jacobson in the early 1990s to provide better feedback for end-to-end congestion control mechanisms. Using RED, when a router's queue becomes full enough that congestion may be imminent, a packet is selected at random to signal this condition back to the sending host. This signal can take the form of a bit marked in the packet's header and then echoed back to the sender—*Explicit Congestion Notification* (ECN) [40], [41]—or can be indicated by dropping the packet.[7] If ECN is used to signal congestion, then protocol χ, as presented in Section 5, works perfectly. If not, then RED will introduce nondeterministic packet losses that may be misinterpreted as malicious activity.

In the remainder of this section, we explain how RED's packet selection algorithm works, how it may be accommodated into our traffic validation framework, and how well we can detect even small attacks in a RED environment.

8.1 Random Early Detection

RED monitors the average queue size, q_{avg}, based on an exponential weighted moving average:

$$q_{avg} := (1-w)q_{avg} + w \cdot q_{act} \tag{1}$$

7. ECN-based marking is well known to be a superior signaling mechanism [42], [43]. However, while ECN is supported by many routers (Cisco and Juniper) and end-systems (Windows Vista, Linux, Solaris, NetBSD, and so forth) it is generally not enabled by default, and thus, it is not widely deployed in today's Internet [44], [45].

where q_{act} is the actual queue size, and w is the weight for a low-pass filter.

RED uses three more parameters: q^{th}_{min}, minimum threshold; q^{th}_{max}, maximum threshold; and p_{max}, maximum probability. Using q_{avg}, RED dynamically computes a dropping probability in two steps for each packet it receives. First, it computes an interim probability, p_t:

$$p_t = \begin{cases} 0 & \text{if } q_{avg} < q^{th}_{min} \\ p_{max}\frac{q_{avg}-q^{th}_{min}}{q^{th}_{max}-q^{th}_{min}} & \text{if } q^{th}_{min} < q_{avg} < q^{th}_{max} \\ 1 & \text{if } q^{th}_{max} < q_{avg}. \end{cases}$$

Further, the RED algorithm tracks the number of packets, *cnt*, since the last dropped packet. The final dropping probability, p, is specified to increase slowly as cnt increases:

$$p = \frac{p_t}{1 - cnt \cdot p_t}. \tag{2}$$

Finally, instead of generating a new random number for every packet when $q^{th}_{min} < q_{avg} < q^{th}_{max}$, a suggested optimization is to only generate random numbers when a packet is dropped [37]. Thus, after each RED-induced packet drop, a new random sample, rn, is taken from a uniform random variable $R = Random[0,1]$. The first packet whose p value is larger than rn is then dropped, and a new random sample is taken.

Packet		fp_1	fp_2	fp_3	fp_4	fp_5	fp_6	fp_7	fp_8	fp_9	.	.	.	fp_n
Drop probability		p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	.	.	.	p_n
Outcome		*TX*	*TX*	*DR*	*TX*	*TX*	*TX*	*TX*	*DR*	*TX*	.	.	.	*TX*
Random number	rn_1			rn_2					rn_3					

Fig. 9. A set of n packets. Each packet fp_i is associated with a drop probability p_i, and the outcome is either transmitted (TX) or dropped (DR) based on the random number generated during the last packet drop.

8.2 Traffic Validation for RED

Much as in Section 5.1, our approach is to predict queue sizes based on summaries of their inputs from neighboring routers. Additionally, we track how the predicted queue size impacts the likelihood of a RED-induced drop and use this to drive two additional tests: one for the uniformity of the randomness in dropping packets and one for the distribution of packet drops among the flows.[8] In effect, the first test is an evaluation of whether the *distribution* of packet losses can be explained by RED and tail-drop congestion alone, while the second evaluates if the particular *pattern* of losses (their assignment to individual flows) is consistent with expectation for traffic load.

8.2.1 Testing the Uniformity Packet Drops

In Fig. 1, router r_d monitors the queue size of router r and detects whether each packet is dropped or transmitted. Given the RED algorithm and the parameters, r_d now can estimate q_{avg}, the average queue size in (1); *cnt*, the count since the last dropped packet; and finally p, the dropping probability in (2) for each packet as in Fig. 9. All of these computations are deterministic and based on observed inputs.

The router r drops a packet fp_i if its p_i value exceeds the random number rn_x that it generated at the most recent packet drop. So, r_d expects that rn_x is between p_{i-1} and p_i. For example in Fig. 9

- fp_3 is dropped: $p_2 < rn_1 < p_3$.
- fp_8 is dropped: $p_7 < rn_2 < p_8$.

Since each packet drop should be a sample of a uniform random distribution, we can detect deviations from this process via statistical hypothesis testing. In particular, we use the Chi-square test to evaluate the hypothesis that the observed packet losses are a good match for a uniform distribution [26]. Once the *Chi-square* value[9] is computed, then the corresponding critical value can be used as the confidence value $c_{randomness}$ to reject the hypothesis, which means the outcome is a result of nonuniform distribution and/or a detection of malicious activity. Thus, a malicious router is detected if the confidence value $c_{randomness}$ is at least a target significance level $s^{level}_{randomness}$.

8.2.2 Testing the Distribution of Packet Drops among Flows

One of the premises of RED [37] is that the probability of dropping a packet from a particular connection is proportional to that connection's bandwidth usage. We exploit this observation to evaluate whether the particular pattern of packet losses—even if not suspicious in their overall number—is anomalous with respect to per-flow traffic load.

This test requires per-flow state in order to count the number of received packets and dropped packets per flow during $q^{th}_{min} < q_{avg} < q^{th}_{max}$. Once again, we use the Chi-square test to evaluate the distribution of packet losses to flows.[10] Once the *Chi-square* value is computed, the corresponding critical value can be used as the confidence value $c_{drop/flow}$ to reject the hypothesis, which means that the distribution of packet drops among the flows is not as expected. A malicious router is detected if the confidence value $c_{drop/flow}$ is at least a target significance level $s^{level}_{drop/flow}$.

8.3 Experiences

We have experimented with protocol χ with this new traffic validation in a RED environment using the same setup as presented in Section 7. The capacity of the queue, q^{th}_{limit}, is 75,000 bytes. In addition, the RED parameters, as in Section 8.1, are configured as follows: the weight for the low-pass filter is $w = 0.5$, the minimum threshold is $q^{th}_{min} = 30{,}000$ bytes, the maximum threshold is $q^{th}_{max} = 60{,}000$ bytes, and the maximum probability is $p_{max} = 0.02$.[11]

For the *packet drop uniformity test*, a window of 30 packet drops is used. The *distribution of packet drops to flows test* examines a window of 15 seconds. Experimentally, we find that smaller windows lead to false positives, but larger windows do not improve the results notably. A more sophisticated version of our algorithm could adapt the window size in response to load in order to ensure a given level of confidence.

8.3.1 Experiment 1: False Positives

The result of one run is shown in Fig. 10a. q_{avg} is the predicted average queue length of Q computed by router r_2. Packet losses are also marked with triangles. The corresponding confidence values can be seen in Fig. 10b.

We executed protocol χ under high traffic load for more than half an hour. With significance levels aggressively chosen at $s^{level}_{randomness} = 0.999$ and $s^{level}_{drop/flow} = 0.999$, we did not observe any false positives.

8.3.2 Experiment 2: Detecting Attacks

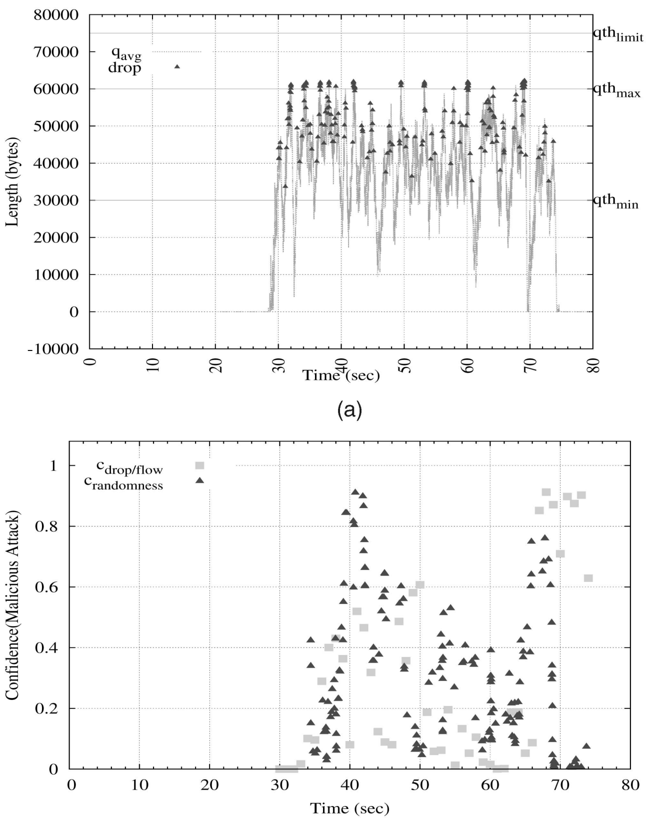
Next, we examined how effectively protocol χ detects various attacks. In these experiments, router r_1 is compromised to attack the traffic selectively in various ways, targeting *ftp* flows from a chosen subnet. The duration of

8. Consistent with our assumption that the network is under a single administrative domain (Section 4, we assume that all RED parameters are known).

9. $Chi\text{-}square = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$, where O_i is the observed frequency of bin i, E_i is the expected frequency of bin i, and k is the number of bins.

10. Short-lived flows with a few tens of packets are ignored unless the drop rate is 100 percent. Otherwise, a few packet drops from a short-lived flow lead to false detection.

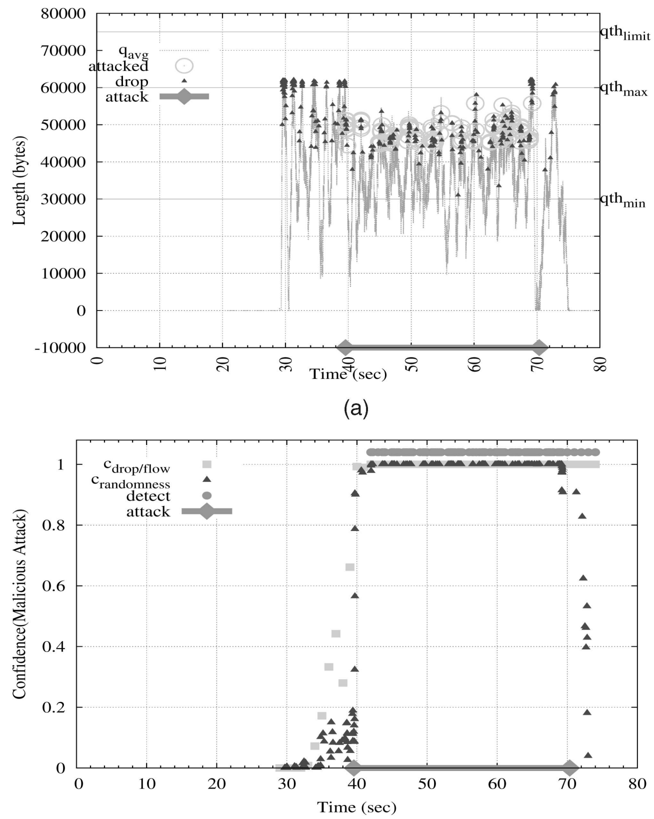
11. Setting the parameters is inexact engineering. We used the guidelines presented in [37] and/or our intuition in selecting these values.



(a)

(b)

Fig. 10. Without attack. (a) Average queue length. (b) Statistical test results.



(a)

(b)

Fig. 11. Attack 1: *Drop the selected flows when the average queue size is above 45,000 bytes.* (a) Average queue length. (b) Statistical test results.

the attack is indicated with a line bounded by diamonds in the figures, and a detection is indicated by a filled circle.

For the first attack, router r_1 drops the packets of the selected flows for 30 seconds when the average queue size computed by RED is above 45,000 bytes. The predicted average queue size and the confidence values can be seen in Fig. 11. As shown in the graph, during the attack, protocol χ detects the failure successfully.

As queue occupancy grows, the RED algorithm drops packets with higher probability and thus provides more "cover" for attackers to drop packets without being detected. We explore this property in the second attack, in which router r_1 was instructed to drop packets in the selected flows when the average queue was at least 54,000 bytes, which is very close to the maximum threshold, $q^{th}_{max} = 60{,}000$ bytes. As shown in Fig. 12, protocol χ was still able to detect the attack and raised alarms, except between 50 and 56 seconds. The reason is that between 44 and 50 seconds the compromised router did not drop any packets maliciously.

In the third and fourth attacks, we explore a scenario in which a router r_1 only drops a small percentage of the packets in the selected flows. For example, during the third attack 10 percent of packets are dropped (see Fig. 13) and 5 percent during the fourth attack (see Fig. 14). Even though relatively few packets are dropped, the impact on TCP performance is quite high, reducing bandwidth by between 30 percent and 40 percent. Since only a few packets are maliciously dropped, the *packet drop uniformity test* does not detect any anomaly. However, since these losses are focused on a small number of flows, they are quickly detected using the second test.

Finally, we explained a highly selective attack in which the router r_1 was instructed to only drop TCP SYN packets from a targeted host, which tries to connect to an ftp server. In Fig. 15, four SYN packets, which are marked with circles, are maliciously dropped by r_1. Since *all* the observed packets of the attacked flow are dropped, which is statistically unexpected given the RED algorithm, protocol χ still raises an alarm.

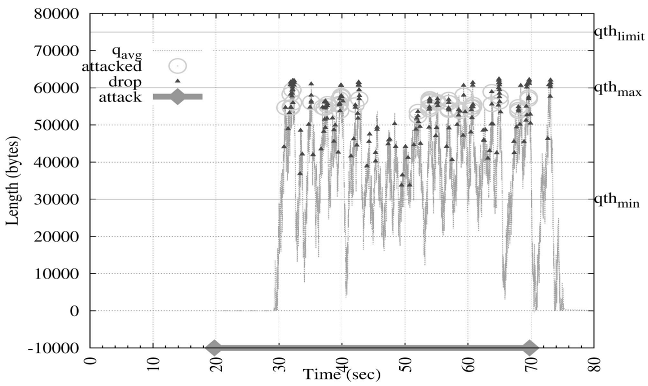
9 Issues

9.1 Quality of Service

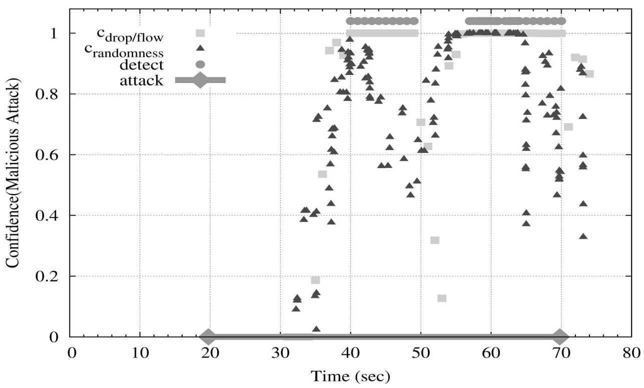
Real routers implement Quality of Service (QoS) providing preferential treatment to specified traffic via several different traffic-handling techniques, such as traffic shaping, traffic policing, packet filtering, and packet classification. Given the configuration files, our work can be extended to handle these fairly complex real-life functions, even those involving nondeterminism, if the expected behavior of the function can be modeled.

9.2 Adjacent Faulty Routers

We assume that there exists no adjacent faulty routers in our threat model for simplicity. This assumption eliminates consorting faulty routers that collude together to

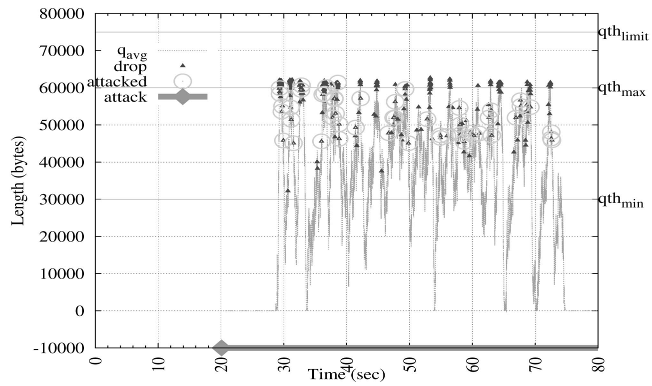


(a)

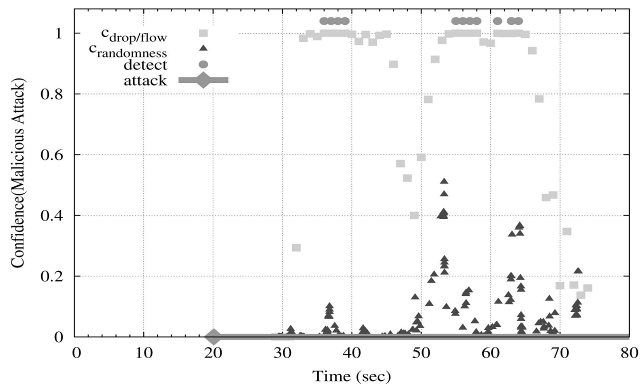


(b)

Fig. 12. Attack 2: *Drop the selected flows when the average queue size is above 54,000 bytes.* (a) Average queue length. (b) Statistical test results.



(a)



(b)

Fig. 13. Attack 3: *Drop 10 percent of the selected flows when the average queue size is above 45,000 bytes.* (a) Average queue length. (b) Statistical test results.

produce fraudulent traffic information in order to hide their faulty behavior. However, it can be relaxed to the case of $k > 1$ adjacent faulty routers by monitoring every output interface of the neighbors k hops away and disseminating the traffic information to all neighbors within a diameter of k hops. This is the same approach that we used in [4], and it increases the overhead of detection.

9.3 Good Terminal Routers

The path diversity within the network usually does not extend to individual hosts on LANs: single workstations rarely have multiple paths to their network infrastructure. In these situations, for fate-sharing reasons, there is little that can be done. If host's access router is compromised, then the host is partitioned and there is no routing remedy even if an anomaly is detected; the fate of individual hosts and their access routers are directly intertwined. Moreover, from the standpoint of the network, such traffic *originates* from a compromised router and therefore cannot demonstrate anomalous forwarding behavior.[12]

To summarize, these protocols are designed to detect anomalies between pairs of *correct* nodes, and thus for simplicity, it is assumed that a terminal router is not faulty with respect to traffic originating from or being consumed by that router. This assumption is well justified due to the fate-sharing argument and it is accepted by all of similar detection protocols.

This assumption is necessary, in order to protect against faulty terminal routers that drop packets they receive from an end host or packets they should deliver to an end host. However, it also excludes DoS attacks wherein a faulty router introduces bogus traffic claiming that the traffic originates from a legitimate end host. Yet, none of these protocols explicitly address this problem. Of course, standard rate-limit scheme can be applied against these kinds of DoS attacks.

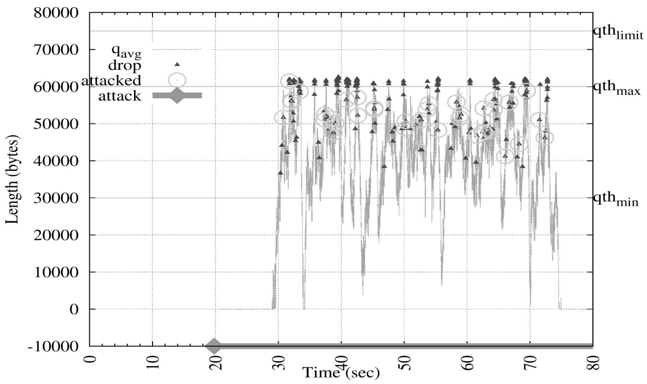
9.4 Others

Due to space limitation, in this paper, we do not discuss various issues, such as fragmentation, multicast, multiple paths with equal cost, and transient inconsistencies of link-state routing. We refer the reader to our earlier work [4] for details.

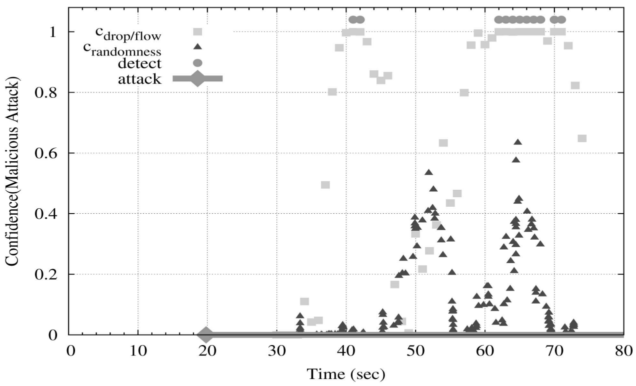
10 CONCLUSION

To the best of our knowledge, this paper is the first serious attempt to distinguish between a router dropping packets maliciously and a router dropping packets due to congestion. Previous work has approached this issue using a static user-defined threshold, which is fundamentally limiting. Using the same framework as our earlier work (which is based on a static user-defined threshold) [4], we developed

12. This issue can be partially mitigated by extending our protocol to include hosts as well as routers, but this simply pushes the problem to end hosts. Traffic originating from a compromised node can be modified before any correct node witnesses it.

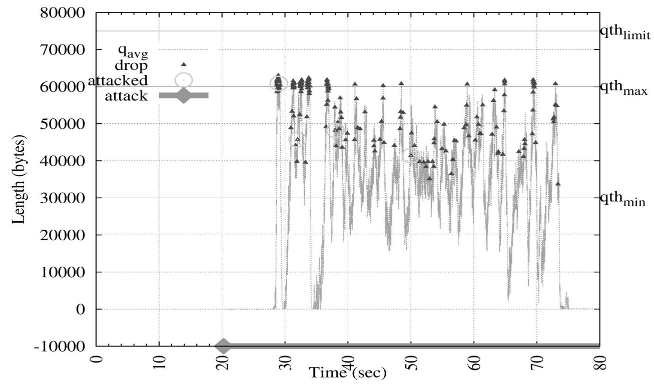


(a)

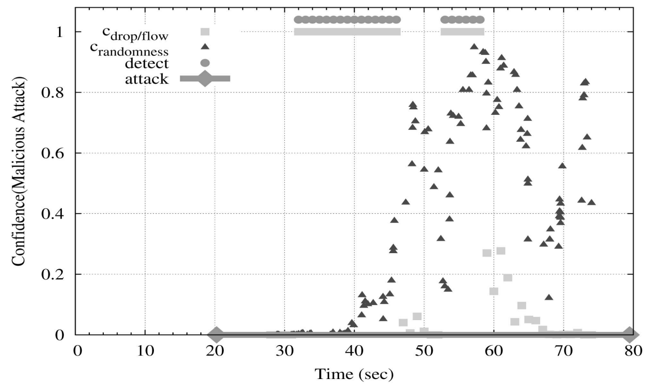


(b)

Fig. 14. Attack 4: *Drop five percent of the selected flows when the average queue size is above 45,000 bytes.* (a) Average queue length. (b) Statistical test results.



(a)



(b)

Fig. 15. Attack 5: *Target a host trying to open a connection by dropping SYN packets.* (a) Average queue length. (b) Statistical test results.

a compromised router detection protocol χ that dynamically infers, based on measured traffic rates and buffer sizes, the number of congestive packet losses that will occur. Subsequent packet losses can be attributed to malicious actions. Because of nondeterminism introduced by imperfectly synchronized clocks and scheduling delays, protocol χ uses user-defined significance levels, but these levels are independent of the properties of the traffic. Hence, protocol χ does not suffer from the limitations of static thresholds.

We evaluated the effectiveness of protocol χ through an implementation and deployment in a small network. We show that even fine-grained attacks, such as stopping a host from opening a connection by discarding the SYN packet, can be detected.

Appendix A

Specification

Similar to the specification that we have defined in [4], we cast the problem as a failure detector with *accuracy* and *completeness* properties.

- a-Accuracy: A failure detector is a-*Accurate* if whenever a correct router suspects (π, τ), then $|\pi| \leq a$ and some router $r \in \pi$ was faulty in π during τ.

We use the term *traffic faulty* to indicate a router that drop packets from transit traffic and the term *protocol faulty* to indicate a router that behaves arbitrarily with respect to the detection protocol. A *faulty* router is one that is traffic faulty, protocol faulty, or both. As before, we will add the phrase "in π" to indicate that the faulty behavior is with respect to traffic that transits the path π. The a-Accuracy requirement can result in a detection if a router is either protocol faulty or traffic faulty.

- a-Completeness: A failure detector is a-*Complete* if whenever a router r is traffic faulty at some time t, then all correct routers eventually suspect (π, τ) for some path segment $\pi : |\pi| \leq a$ such that r was traffic faulty in π at t, and for some interval τ containing t.

Distinguishing between protocol faulty and traffic faulty behavior is useful because, while it is important to detect routers that are traffic faulty, it is not as critical to detect routers that are only protocol faulty: routers that are only protocol faulty are not dropping packets maliciously.

Given an accurate and complete TV predicate, protocol χ is *2-accurate* and *2-complete*.

Appendix B

Accuracy

When a correct router e'' receives a suspicious link $\ell = \langle e, e' \rangle$ announcement originated by router e, e'' detects ℓ as faulty. Then, there must be at least one faulty router in ℓ:

- If e is *faulty* and it announces its link ℓ as faulty, indeed ℓ has a faulty router: $e \in \ell$. A *protocol faulty* router can always announce its link ℓ as faulty.

- If e is correct and suspects its neighbor e' announcing its link ℓ as faulty, then e' must be faulty. We show this by considering each detection in Section. 5.2.
  - D-Ia: Assume e' is correct, and it sends its traffic information $Tinfo(r', Q_{in}, \langle e', e, r_d \rangle, \tau)$ to router e at the end of validation time interval τ. The message must be delivered to e in Δ time, which is a contradiction of the fact that e is correct yet does not receive this message.
  - D-Ib: Assume e' is correct and sends digitally signed traffic information that is consistent and valid. Correct router e validates the signature and the consistency of the traffic information. This contradicts the fact that e suspects e'.
  - D-IIa: Assume e' is correct. Then, one of the following is true: 1) e' received traffic information from r_{s_*} in Δ time, verified it, and forwarded it to e in the next Δ time. This contradicts the fact that a correct router e did not receive the message. 2) e' did not verify traffic information from r_{s_*} or did not receive the message in Δ time. Then, it should have detected $\ell = \langle r_{s_*}, e' \rangle$ and announced the detection. This contradicts the fact that correct router e did not receive the detection announcement.
  - D-IIb: Assume e' is correct and forwards traffic information to e only if it validates the signature. Then, the correct router e validates the signature. This contradicts the failure of the digital signature verification.
  - D-IIc: Assume e' is correct and forwards traffic correctly. Since e' is correct, all traffic information of S, which e' sent to e, is verified by e'. With the input of S verified by correct router e' and the input of D collected by e, TV predicate evaluates to *true*. This contradicts the fact that TV evaluated to *false*.

All detections by protocol χ are 2-path segments. Hence, it is *2-accurate*.

Appendix C

Completeness

If a router e is traffic faulty[13] at some time t, then all correct routers eventually suspect $\langle \ell, \tau \rangle$ for some link ℓ such that $e \in \ell$ and e was traffic faulty at t, and for some interval τ containing t.

Let e have dropped packets maliciously from the traffic passing through itself toward e' during τ containing t. At the end of traffic validation round τ, e' will validate Q associated with ℓ.

As we assume that adjacent routers cannot be compromised in our threat model, all neighbors of e are correct and collect traffic information appropriately during τ. At the end of τ, they send this information to e to forward to e'.

Then, one of the following is true:

- D-IIc: e passes this information to e'. The complete TV evaluates to *false* with these correct inputs. So, e' detects $\ell = \langle e, e' \rangle$, where $e \in \ell$.
- D-IIb: e passes this information to e' after tampering with the content in order to hide the attack. e' fails to verify the signatures, so e' detects $\ell = \langle e, e' \rangle$, where $e \in \ell$.
- D-IIa: e passes its own copy of traffic information to e' to hide the attack. Then, e' expects e to detect r_{s_*} whose traffic information has not been forwarded to e'. 1) If e detects $\ell = \langle r_{s_*}, e \rangle$, then $e \in \ell$. 2) If e fails to detect $\ell = \langle r_{s_*}, e \rangle$, then e' detects $\ell = \langle e, e' \rangle$, where $e \in \ell$.
- D-IIa: e does not send any traffic information in S to e'. Due to the time-out mechanism, after 2Δ time, e' detects $\ell = \langle e, e' \rangle$, where $e \in \ell$.

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13. As in [4], the protocol we develop assumes that the terminal routers are correct. This assumption is common to all detection protocols. The argument is based on *fate sharing*. If a terminal router is compromised, then there is no way to determine what traffic was injected or delivered in the system. Thus, a compromised terminal router can always invisibly disrupt traffic sourced or sinked to its network. One could place terminal routers on each workstation, thus limiting the damage they can wreak to only a workstation.

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