How to Test DoS Defenses*

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Abstract

DoS defense evaluation methods influence how well test results predict performance in real deployment. This paper surveys existing approaches and criticizes their simplicity and the lack of realism. We summarize our work on improving DoS evaluation via development of standardized benchmarks and performance metrics. We end with guidelines on efficiently improving DoS evaluation, in the short and in the long term.

1. Introduction and Motivation

Denial of service has been a pressing Internet security problem for almost a decade. During that time, attacks have evolved from naive and limited to sophisticated and large-scale, and many defenses have been proposed. While much attention has been paid to design of effective solutions, little has been done to design sound, realistic tests to evaluate these solutions. The underlying reason is not the researchers' neglect, but inherent complexity of the denial-of-service phenomenon. Realistic, thorough evaluation requires an ordinary researcher to invest more time in test setup and design than in solution development, and the lack of sharing means that everyone must build tests from scratch. Consequently, many published papers contain naive evaluation scenarios that may generate misleading results about proposed solutions.

We illustrate this problem by surveying several selected recent papers, published in top venues: TVA [1], SOS [2], DefCOM [3], Speak-Up [4], PSP [5] and StopIt [6]. These papers likely contain more sophisticated evaluation approaches than other DoS publications, because they had to pass rigorous reviews. Thus, our survey pool illustrates the best evaluation practices in DoS research.

We use these selected papers to illustrate common pitfalls in DoS evaluation. Our goal is not to criticize — we ourselves have published extensively in the DoS area and our evaluation methods have been far from perfect. Two authors of this paper co-authored one of our surveyed papers — DefCOM [3]. Like others, it has evaluation missteps. Our goal is to draw on a rich experience we have built over the years in DoS solution evaluation, to discuss all possible testing approaches and to suggest how to improve the current situation.

Our recent work has focused on improving and standardizing DoS testing. In this paper, we summarize these efforts and their outcomes: a set of DoS defense benchmarks and a set of denial of service metrics. While our work on benchmarks and metrics has been extensively published [7–15], this paper focuses on specific applications of this work to improve the quality of DoS evaluation. Our solutions are not the final answers in the quest for more scientific DoS defense evaluation, but they are useful steps toward that goal.

2. Evaluation Goals

Network communication involves many devices and protocols, all of which must work correctly to deliver satisfactory service. Any device, protocol or end-service in this chain can be targeted to create denial-of-service. The attack can be performed by a single attacking machine — DoS —

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or by many machines — distributed DoS or DDoS. A *victim* is a set of hosts or networks whose service the attacker aims to deny. A successful attack prevents the victim from providing desired service quality to its legitimate clients. The most commonly researched type of service denial is a traffic flood intended to overwhelm a limited, critical resource at some point in the communication chain. Such a *flooding attack* usually requires use of DDoS to guarantee continued resource exhaustion at a well-provisioned target. The targeted resource could be CPU, memory (OS or application) or bandwidth. On the other hand, a *vulnerability attack* invokes an undesired behavior of some element in the communication chain, leading to less-than-acceptable service quality for victim's clients. Examples include a crash, infinite loop, increased delay in responding to service requests, random dropping of requests, incorrect firewall operation, providing false replies to service requests, etc. Vulnerability attacks usually consist of a few packets, which implies DoS rather than DDoS. Another popular DoS variant is the *reflector attack*, where the attacker floods a distributed service with seemingly legitimate service requests, spoofing the victim's IP address. Servers (reflectors) reply to the victim, and since the requests are crafted to elicit large replies, the reply flood causes denial of service. Reflector attacks usually require use of DDoS to achieve volume.

In this paper, we focus on high-level evaluation strategies that apply both to DoS and DDoS defenses, but will refer to these collectively as "DoS defenses", for short.

The main goal of DoS defense evaluation is to show that it is **effective**. Researchers must demonstrate that a given attack denies the service in absence of the defense, and that the service denial is significantly reduced or eliminated when the defense is present. Equally important is measuring **collateral damage** that the defense inflicts on the legitimate traffic, both in the presence and absence of attacks.

Most defenses take time to achieve their full effect, due to some delay in attack detection or identification of attack packets. Part of their evaluation is quantifying this **delay**.

All defenses have **memory and CPU costs** that must be quantified. Distributed defenses must also quantify their effectiveness and cost in **partial deployment**, in terms of the number of deployment points needed for a given effectiveness target.

Any defense must be evaluated for the **scalability** of its cost and effectiveness. A defense can also be the target of attacks or gaming attempts, and researchers must quantify its **resilience** to these. Ideally, a defense's failure should not make the service denial any worse than it was in a legacy network.

3. Overview of Surveyed Papers

Publication [1] proposes a DoS-limiting network architecture called TVA. Routers in TVA insert cryptographically secure capability information into requests flowing from the source to the destination. If the destination wants to communicate with the source, it returns the capability sequence, and the source inserts it into all its future packets. Routers prioritize capability-carrying traffic. To prevent the attack when a path to the victim is flooded by capability-carrying traffic to a colluding attacker in its vicinity, TVA shares the bandwidth fairly per destination. To prevent DoS via capability request floods, TVA limits the bandwidth allowed for total request traffic and shares this bandwidth fairly per path between a source and a TVA router.

Publication [2] proposes an overlay architecture called SOS. The overlay protects the location of the destination server via several layers of defense: secure access points (SOAPs) that verify a client's identity and "goodness," beacons that route traffic on the overlay to secret servlets, and a firewall that only lets traffic from secret servlets through. The overlay runs a routing protocol called Chord [16], which helps restore routing when nodes fail. SOS also handles SOAP, beacon and servlet failures through their detection and re-election of new nodes to take over these roles.

Publication [3] proposes a framework for DDoS defense cooperation called DefCOM. The framework enables source, core and destination defenses to securely communicate during attacks and plan a collaborative defense. Destination defenses detect attacks and raise alerts, while source defenses differentiate legitimate from suspicious traffic and tag legitimate packets for high-priority handling. Other packets are tagged as low-priority, and overly aggressive traffic is dropped. Core defenses rate-limit the traffic to the destination under attack, but prioritize traffic according to marks. They also re-tag traffic based on its rate and congestion responsiveness, which enables them to prioritize low-rate legitimate traffic from legacy networks and detect subtle attacks in some scenarios.

Publication [4] proposes the Speak-Up protocol where the destination under attack invites its clients to send "payment" traffic on a separate channel to a "thinner" in front of it. Payment traffic serves as bids in an auction for access to the destination. The underlying assumption, substantiated by some recent DDoS statistics, is that bots have lower available bandwidth than legitimate hosts, because they send aggressively.

Publication [5] proposes Proactive Surge Protection (PSP) to protect traffic on ISP links from collateral damage caused by high-volume DoS. It observes an ISP topology as a set of origin-destination (OD) pairs. Only pairs that carry no attack, but share the path with it — crossfire paths — are protected by PSP. It isolates OD pair traffic by tagging packets for each pair and fairly sharing the bandwidth between all pairs on a path, based on historic bandwidth demand of each.

Publication [6] compares the cost and effectiveness of filtering versus capability-based DoS defenses. It proposes a filtering defense called StopIt that a destination can use to invoke filtering of traffic from sources it considers as part of a DoS attack. StopIt deploys cryptographic identifiers to prevent spoofing at the inter-AS level. All sources tag their packets with these "Passports," and participating routers prioritize Passport-carrying traffic. Destinations invoke filtering requests first to a StopIt server within their AS. This server verifies that traffic from the source flows to this destination and then propagates the request hop-by-hop towards the source AS, which installs the filter.

4. Common Evaluation Approaches: Their Advantages and Pitfalls

We now survey common evaluation approaches, pointing out their advantages and pitfalls. No approach is inherently good or bad, and each can answer some set of research questions. Knowing the limitations and implicit assumptions of each approach can help researchers choose an appropriate testing tool for their hypothesis. Inappropriate tools lead to incorrect results.

An evaluation process consists of: (1) A testing approach, which can be a theoretical model, simulation, emulation or deployment in an operational network. (2) Test scenarios containing legitimate and attack traffic (and implicitly user and attacker behaviors) and topology. (3) A success metric, which should prove that a defense helps reduce or eliminate a DoS threat.

Figure 1 gives an overview of evaluation approaches in the surveyed papers, broken into categories.

4.1. Testing Approach

Theory is well-suited to answering questions about situations that can be accurately represented by existing models, such as M/M/1 queues, state diagrams, probabilistic models, hash tables, random selection from a set, etc. In the DoS context, theory may be useful to evaluate robustness of a given defense to cheating or a direct attack. Both require some guesswork on the attacker's part, whose success can be evaluated via theory. Theory may also be useful in answering specific questions about a defense's scalability, cost and delay, again depending on the defense's design, and if parts of it can be accurately represented by simple models. In general, theory is a poor choice for effectiveness evaluation. While it may be able to answer sub-questions related to effectiveness, we lack theoretical tools powerful enough to model the complexity of traffic mixes, their dynamics and their interaction with the underlying hardware and network protocols, especially in high-stress situations like DoS.

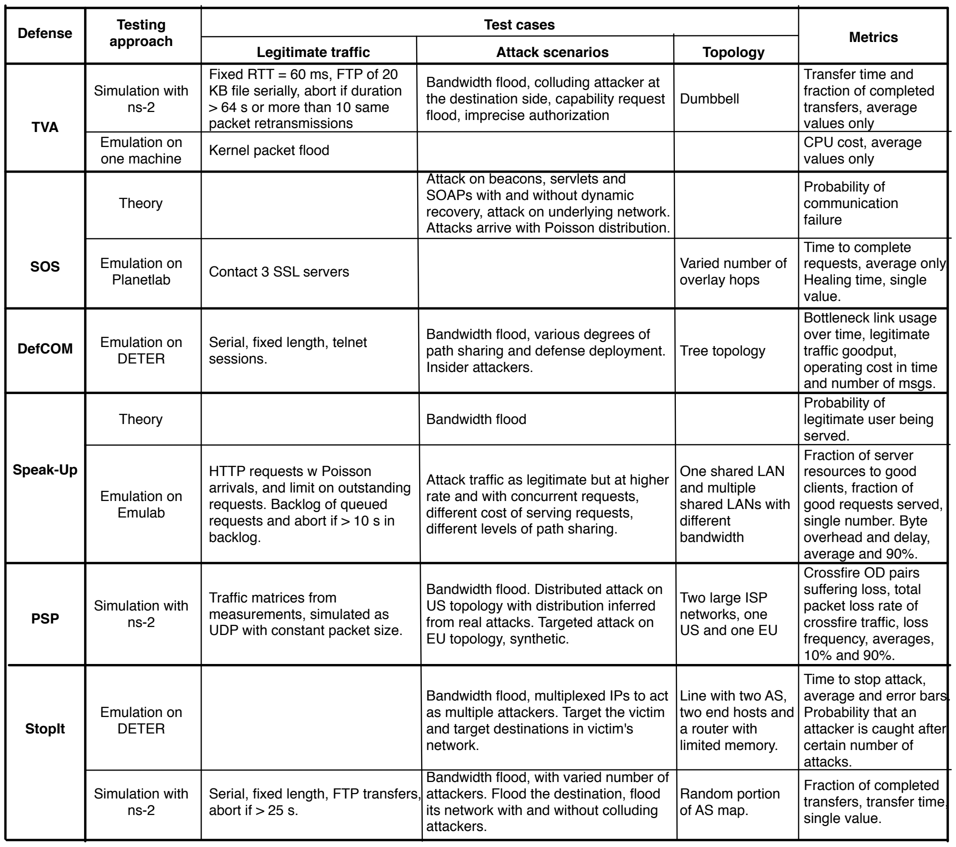
SOS [2] and Speak-Up [4] have effectively used theory to answer robustness questions. SOS used it to evaluate the overlay's resiliency to several types of direct attacks, while Speak-Up used it to evaluate the chances of a legitimate client getting service in the presence of cheating attackers.

Simulation is highly popular for addressing network performance questions. Network simulators must balance a tradeoff between fidelity and scalability [17, 18]. At one end of the spectrum, simulators can choose to sacrifice fidelity, especially at the lower layers of the protocol stack, for scalability. For example, Internet forwarding devices, such as switches and routers, are only modeled at a high-level in popular packet-level simulators such as ns-2 [19]. The ranges of intra-device latencies and maximum packet forwarding rates in commercial forwarding devices are not incorporated. Networking researchers further find it difficult to correctly set remaining router parameters, such as buffer size, in experiments with simulators. Hence, many research papers report results that are highly sensitive to the default forwarding model or the buffer size selected; these values may not be realistic [20].

Near the other end of the spectrum lie detailed but less scalable simulators such as OPNET [21] and OMNeT++ [22]. In OPNET, detailed models of routers, switches, servers, protocols, links, and mainframes, are based solely on vendor specifications [23]. Using complex models significantly increases computational cost, hindering scalability. Further, the model base needs to be constantly updated. Validation attempts reveal that even these detailed models are sensitive to parameters such as buffer sizes and forwarding rates that are hard to tune to mimic real router behavior [23].

Our comparisons between simulation and emulation results with software routers (PC and Click) and with commercial routers, all with seemingly identical configurations, revealed key differences. Such differences occur because simulators and emulated components abstract a number of system attributes, and make several assumptions about packet handling. For example, in PC routers on the Emulab [24] and DETER [25] testbeds, the CPUs, buses, devices, and device drivers may become bottlenecks that simulators do not model [26]. Results of DoS experiments are also highly sensitive to the particular software version [26]. For example, Linux TCP flows on the testbeds were less susceptible to DoS attacks than the SACK implementation on ns-2. Another key result is that DoS attacks are also effective on traffic in the reverse direction in the case of low-end Cisco routers and PC routers, but not in simulations or in emulations using Click [27].

Our experience with commercial Cisco routers has demonstrated that some, but not all, can be similar to software PC routers in performance. Therefore, simulation and emulation models have to account for variance in buffer-sizing strategies and backplane contention among routers. An important lesson from our experiments [26, 28] is the need to carefully configure parameters, and the importance



Defense	Testing approach	Test cases			Metrics
		Legitimate traffic	Attack scenarios	Topology	
TVA	Simulation with ns-2	Fixed RTT = 60 ms, FTP of 20 KB file serially, abort if duration > 64 s or more than 10 same packet retransmissions	Bandwidth flood, colluding attacker at the destination side, capability request flood, imprecise authorization	Dumbbell	Transfer time and fraction of completed transfers, average values only
	Emulation on one machine	Kernel packet flood			CPU cost, average values only
SOS	Theory		Attack on beacons, servlets and SOAPs with and without dynamic recovery, attack on underlying network. Attacks arrive with Poisson distribution.		Probability of communication failure
	Emulation on Planetlab	Contact 3 SSL servers		Varied number of overlay hops	Time to complete requests, average only. Healing time, single value.
DefCOM	Emulation on DETER	Serial, fixed length, telnet sessions.	Bandwidth flood, various degrees of path sharing and defense deployment. Insider attackers.	Tree topology	Bottleneck link usage over time, legitimate traffic goodput, operating cost in time and number of msgs.
Speak-Up	Theory		Bandwidth flood		Probability of legitimate user being served.
	Emulation on Emulab	HTTP requests w Poisson arrivals, and limit on outstanding requests. Backlog of queued requests and abort if > 10 s in backlog.	Attack traffic as legitimate but at higher rate and with concurrent requests, different cost of serving requests, different levels of path sharing.	One shared LAN and multiple shared LANs with different bandwidth	Fraction of server resources to good clients, fraction of good requests served, single number. Byte overhead and delay, average and 90%.
PSP	Simulation with ns-2	Traffic matrices from measurements, simulated as UDP with constant packet size.	Bandwidth flood. Distributed attack on US topology with distribution inferred from real attacks. Targeted attack on EU topology, synthetic.	Two large ISP networks, one US and one EU	Crossfire OD pairs suffering loss, total packet loss rate of crossfire traffic, loss frequency, averages, 10% and 90%.
StopIt	Emulation on DETER		Bandwidth flood, multiplexed IPs to act as multiple attackers. Target the victim and target destinations in victim's network.	Line with two AS, two end hosts and a router with limited memory.	Time to stop attack, average and error bars. Probability that an attacker is caught after certain number of attacks.
	Simulation with ns-2	Serial, fixed length, FTP transfers, abort if > 25 s.	Bandwidth flood, with varied number of attackers. Flood the destination, flood its network with and without colluding attackers.	Random portion of AS map.	Fraction of completed transfers, transfer time, single value.

Figure 1: Surveyed papers and their evaluation approach

of not generalizing results beyond the specific configurations used.

TVA [1], PSP [5] and StopIt [6] used ns-2 simulations for effectiveness evaluation. Our research on ns-2 fidelity suggests that these results may sometimes overestimate and sometimes underestimate the attack impact, and are not predictive of performance in real deployments.

Emulation involves testing in a mini-network, such as a lab or a shared testbed. Three testbeds have been popular for DoS defense testing: Emulab [24], DETER [25] and Planetlab [29]. Emulab and DETER allow users to gain exclusive access to a desired number of PCs, located at a central facility and isolated from the Internet. These can be loaded with a user-specified OS and applications, and users obtain root privileges. Planetlab is a distributed testbed where participating organizations contribute machines. Users gain shared access to those machines via virtual machine software that achieves user isolation. They can organize Planetlab nodes into overlays — traffic between nodes travels on the Internet and experiences realistic delays, drops and interaction with cross-traffic. Users can also install applications on Planetlab nodes, but their choice of OS and their privileges on nodes are much more limited than in Emulab or DETER.

Emulation offers a more realistic evaluation environment than theory and simulation, for several reasons: (1) a real OS and applications, and real hardware are used in testing, (2) live legitimate and DoS traffic can be generated and customized in various ways, (3) several router choices exist in testbeds, such as PC, Click, Cisco and Juniper routers, allowing realistic forwarding behavior. Emulation also means testing with a defense's prototype, instead of abstracting the defense and simulating it or developing its theoretical model. This produces higher-fidelity results.

Emulation, however, has its own particular set of challenges that may slow down and complicate testing. We list here several we encountered in our lengthy testing experience, but we anticipate that this is not an exhaustive list.

Realism, lengthy setup and reinventing the wheel — While a real OS, applications and devices provide some degree of realism for emulation-based testing, realistic scenarios still require recreation of realistic legitimate and attack traffic mixes, and the choice of a realistic topology. Often this requires a researcher to engage in a lengthy investigation looking for sources of traffic and topology data, and devising ways to "port" them onto the testbed. This is very challenging, first because sources are scarce and there is little agreement in the community which are good ones, and second because porting often means downscaling and learning about existing traffic generators or writing new ones. Downscaling a topology or traffic trace while keeping reasonable fidelity is an open research problem. Learning how to use existing traffic generators or writing new ones is time-consuming.

The necessity of identifying correct tools and data sources, and deploying them on the testbed means a lengthy setup for emulation tests. Data sources may be in the wrong format for a given tool, source files for the tool might not compile readily or the tool may not run as expected, which adds delay and draws the researcher further from her task of evaluating the defense. A related problem is lack of sharing of emulation tools and data sources in the DoS research community. This evaluation practice of each researcher "reinventing the wheel" (starting from scratch) is a major factor in poor emulation test design. Sharing of tools, data sources and testbed setup would lead to better testing approaches at a small individual time cost. We hope that this will be the future of DoS evaluation.

Small scale — Existing testbeds have a few hundred nodes, which seriously limits the scale of emulation tests, compared to simulation and theory approaches. Virtualization — multiplexing many virtual hosts on one physical host — can increase the scale and is sometimes a viable approach, but it adds another layer of artifice and thus reduces the realism of tests. These limitations should be fully understood by a researcher. If virtualization is not an option, the researcher must argue why and how her results on a small-scale topology can predict behavior on a larger topology. Sometimes this argument can be easily made if a defense's operation does not depend on topology or user/attacker diversity. Other times, though, an investigation of how the scale of topology or the user/attacker diversity influences a defense's performance is necessary.

Lack of diversity — Hardware in testbeds has a high degree of homogeneity, which is necessary to ease maintenance but makes testbeds different from real networks. While we cannot offer a ready solution to this problem, researchers should attempt two prudent approaches: (1) testing with the minimum-performance hardware that gives them satisfactory performance, and (2) arguing why hardware that would deploy the proposed defense in the real world will be more powerful (faster CPU, more memory, faster NIC, etc.) than testbed hardware.

Hardware intricacies — An important observation from our experiments on the Emulab [24] and DETER [25] testbeds is that although the hardware and software on both testbeds appear similar, the nodes on Emulab used in our experiments typically experienced a higher CPU load than the DETER nodes, for the same packet rate [26]. This means that the same experimental setup (configuration files, etc.) may produce widely different outcomes (in our experiments, a much more effective attack on Emulab than on DETER), as results are highly dependent on the details of underlying hardware and software, and their default settings. These different settings may not cause widely different outcomes in typical networking and operating systems experiments, but cause dramatic differences under DoS attacks that overload the system. Our results with Click routers have shown that we need a better understanding of intermediate queue sizes and device driver buffer sizes [26].

Complexity, fine-tuning and failures — One must carefully set up testbed experiments, as DoS attacks only succeed under certain conditions. For example, a SYN flood attack, which ties server's memory, will not work if the source addresses in SYN packets point to an existing host. This is because the host's OS will automatically send an RST packet when it receives a SYNACK for a non-existing connection. This packet will release allocated memory at the server, canceling the attack's effect. The attack will also not work if packets are sent to diverse destination ports — they must target the same port, the one that offers a legitimate TCP service. Further, it will not work if a SYN cookie [30] defense is on, which is the default setting on some operating systems. Researchers without network or system administration experience need to learn the nuances of each attack before setting it up in a testbed.

A related issue is the need to fine-tune test parameters to stay within resource limits while achieving a successful attack. For example, many testbeds use PC routers which have limited forwarding ability. Generating a high-rate attack may crash a router in the topology, while the goal was to crash a victim host. A low-rate attack will go through but be ineffective. Balancing this and many other parameters of a test setup requires experience and many iterations.

Finally, testbeds include real hardware and software, which may unexpectedly crash or misbehave. These failures may be provoked by an experiment or they may occur at random. Without careful supervision, the researcher may adopt results from an experiment with a failure as true ones. Detecting failures is challenging for several reasons. First, since the goal is to deny service, any failure on the path between the legitimate clients and the destination on the experimental topology may mimic this effect. Second, many researchers lack insight about testbed internals and possible failure sources, because such information is not publicized.

In our survey, TVA [1], SOS [2], DefCOM [3], Speak-Up [4] and StopIt [6] have used emulation. TVA and SOS used it for cost evaluation, in a limited setting — TVA on one machine and SOS on a limited-size overlay of Planetlab nodes. This is an appropriate use of emulation, because defense cost is often independent of traffic and topology settings, and emulator fidelity. DefCOM, Speak-Up and StopIt used emulation both for effectiveness and for cost evaluation. We will comment on the realism of their test settings in Section 4.2.

Deployment — Deployment of a defense in an operational network gives the most realistic test. The system sits in a real topology, handling real traffic and attacks. The main drawback of this approach is that it is not reproducible by others. Another drawback is that the researcher has no control over traffic the defense sees, which means that she has no way of knowing the ground truth, i.e., if a packet belongs to malicious or legitimate traffic. While this can be inferred to some extent, there is no way to quantify or guarantee accuracy of this inference. Yet another problem is that the network environment, legitimate traffic and attacks may differ widely among networks. While deployment in one network may yield good results, it is difficult to argue that another network would see a similar benefit. Researchers can strengthen their case by deploying the defense in a large, popular network. They can then argue that its traffic diversity, traffic volume and size are the same or higher than in most other networks, where similar or larger benefits should be expected. This leads us to the biggest problem with the deployment approach — many researchers lack access to a large, popular network and enough leverage to initiate deployment of research-grade defenses in it. None of our surveyed papers used deployment for evaluation.

4.2. Test Scenarios

In this section, we discuss choices of the legitimate traffic, attack scenarios and topology that are modeled/reproduced in theory, simulation and emulation. We repeat a lot of wisdom stated in [20] for Internet research: it is imperative that researchers design realistic tests, and that they understand how variations of their settings influence performance results. Failure to do so leads to test results that do not reflect reality, and may be misleading.

Legitimate Traffic — Because denial of service is a phenomenon experienced by the legitimate clients in presence of attack traffic, legitimate traffic settings will greatly influence the success of an attack, and by extension the success of any defense. The attack's and defense's interactions with legitimate traffic mostly result in continuous or sporadic packet drops and delays. Unfortunately, many DoS research papers use overly simplistic settings for the legitimate traffic. We list below the traffic parameters that affect sensitivity to service denial, and comment on how settings commonly seen in research papers may influence results.

Packet sizes — The most popular variant of DoS attacks — the bandwidth flood — overwhelms router queues. Depending on the queue implementation and attack packet size, small legitimate packets may have a better chance of winning queue space than larger ones. In reality, Internet traffic exhibits a variety of packet sizes, yet many DoS tests generate legitimate traffic with a single packet size, which may either over- or underestimate the defense's performance. PSP [5] used a uniform, large packet size, which may lead to an overestimate of an attack's impact, while other papers we surveyed let the packet size be determined by the higher-level application.

Transport protocol mix — According to many statistics of Internet traffic (e.g., [31]), a high percentage (80-95%) of it is TCP traffic. TCP differs significantly from other transport protocols because of its congestion response, and because delays, mapped into large round-trip times (RTT), slow down the data transfer. During sustained congestion, however small, TCP traffic will keep on reducing its sending rate, due to packet loss it experiences in each RTT. It is of paramount importance to capture this behavior, as well as TCP's data transfer slowdown in the presence of delays.

Some publications use UDP traffic as legitimate traffic, either in simulation or in emulation. Others may replay traffic from public traces in a non-congestion-responsive manner, e.g., by using `tcpreplay` [32]. Both approaches are clearly wrong because they do not capture the changing nature of TCP's bandwidth demand, nor do larger delays result in a data transfer slowdown. Results thus obtained will underestimate attack and collateral damage. Of our surveyed papers, PSP [5] used UDP as legitimate traffic in ns-2 simulations.

RTT values — TCP throughput is a function of a flow's RTT, which is defined by link delays in the topology. Flows with longer RTT values last longer, and suffer more during congestion and in the presence of drop-tail queues [33]. Many simulations and emulations use a single RTT value for all legitimate traffic, while in reality RTTs span a wide range of values [34]. This may either under- or overestimate the service denial and the collateral damage. TVA [1], DefCOM [3], Speak-Up [4], PSP [5] and StopIt [6] all use topologies with ad-hoc, single-value link delays that are either explicitly set up or chosen by default by the simulator or emulation platform. SOS [2] runs over a Planetlab overlay, thus exploiting the underlying, real link delays.

TCP connection dynamics and application mix — We use the term "connection dynamics" to denote how bursty a TCP connection is and how long it lasts. An application determines these dynamics to some extent, along with data volume to be exchanged and the underlying network properties. On one end, there are FTP-like connections on large-bandwidth links. These connections will stay in the slow-start stage unless there is loss, quickly sending all their data. Any packet loss may significantly prolong their duration. On the other end, there are long-lived, Telnet-like connections. They send traffic in small bursts, with potentially large pauses in between, and hence typically have small congestion windows.

Simulation and emulation tests in publications tend to use a single, simplistic parameter setting, such as consecutive FTP transfers of a single file, while Internet traffic exhibits a wide range of dynamics. This practice is likely to result in larger service denial and collateral damage than if a realistic connection mix were used. TVA [1], SOS [2], DefCOM [3], Speak-Up [4] and StopIt [6] all use a single application for legitimate traffic generation. TVA and StopIt use FTP transfers of a single file, thus fixing data volume and connection dynamics. DefCOM uses telnet sessions whose dynamics are selected from a narrow range of values. SOS uses SSL requests to three chosen Web servers, and Speak-Up uses same-file HTTP requests.

TCP connection arrivals — During packet loss periods, TCP connections that are just starting have no memory of previous loss and are thus more aggressive than existing connections. This implies that the connection arrival process should be accurately modeled during testing. TVA [1], SOS [2], DefCOM [3], and StopIt [6] all use serial connections that may time out after a while. Not only is this an unrealistic setting, it also significantly reduces connection density when an attack is present, introducing bias into percentage-based measures. Speak-Up [4] uses connections with Poisson arrivals and a backlog limit, but sets ad-hoc values for these parameters. This is unrealistic as shown by Surge [35], where requests observed in Web server logs arrive during a user's ON periods, separated by OFF periods following a Weibull distribution. Dynamics during ON periods depend on the number of embedded objects in the user-requested file. None of these parameters fits a Poisson distribution.

IP address diversity and turnover — While IP address diversity does not determine the degree of attack-induced damage, it may affect performance of defenses that try to achieve per-source, per-destination or per-path fairness. Similarly, many defenses protect those clients seen prior to the attack, but may have problems with legitimate clients that appear during attacks. It is thus important to simulate or emulate realistic IP address diversity and turnover. None of our surveyed defenses did so.

Attack Scenarios. To thoroughly evaluate a defense, one must stress-test it. Below, we list recommended test scenarios for some general defense categories that we identified in past and present DoS research literature. We make no claim that this list is exhaustive, but it should serve to illustrate our point about stress-testing. Further, some tests can be avoided if the researcher can reason about a defense's performance from its design.

- Defenses that deploy *path isolation* mark, sample or record packets to isolate traffic paths, for filtering or fair sharing of resources. Such defenses should be tested in situations with varying degrees of sharing between legitimate and attack traffic.

- Defenses with *resource accounting* share resources fairly per source or destination. They should be tested with highly distributed attacks (source fair-sharing) or with colluding attackers that share the resource with the attack's victim (destination fair-sharing).

- Defenses that deploy a *privileged customer* approach have legitimate users obtain "passes" that allow privileged access to the critical resource, in form of capabilities, authorization to enter a dedicated overlay, knowledge of the server's identity, good classification, etc. A defense prioritizes traffic with "passes." Tests should include three scenarios: (1) Attackers act as expected to receive a pass, then turn bad, (2) Attackers attempt to flood the system with pass requests, (3) Attackers attempt to bypass pass checking.

- Defenses with *behavior learning* observe either traffic or legitimate user's behavior to learn valid patterns. During attacks, some traffic parameters or user behavior will mismatch learned models, which can be used to devise fine-grained filters or to isolate attack packets. Such defenses should be tested with: (1) Attacks that mimic legitimate traffic features and slowly transition to malicious behavior to deny service. (2) Attacks that fit the model of legitimate behavior but still deny service (e.g., flash crowd attacks).

- Defenses with *resource multiplication* deploy distributed resources (statically or dynamically) to sustain large attacks. They should be tested with highly distributed, dynamic attacks.

- Defenses with *legitimate traffic inflation* multiply traffic amount to enhance chances to win the limited resource. They should be tested with highly distributed attacks, where each attacker sends at a low rate and inflates it as a legitimate client would.

In addition to the above, defenses that have collaborating elements or control messages should be stressed with message loss and collaborators that misbehave (insider attacks). Any defense should also be subjected to attacks on itself.

TVA [1] deploys both the privileged customer and path isolation approaches. Its tests included good-turn-bad clients, and pass request flooding. Attackers cannot bypass capability checking. TVA was not tested with a realistic or high degree of path sharing, as it should have been. In fact, the dumbbell topology in its tests had the lowest degree of sharing and thus likely generated better effectiveness results than a real deployment would. SOS [1] deploys the privileged customer approach, but it was not tested with good-turn-bad clients. SOS makes an argument that pass request flooding only has local effects but does not quantify this. Attackers cannot bypass the defense. DefCOM [3] deploys resource accounting per source path, path isolation and privileged customer approaches. It was tested with good-turn-bad clients. Attackers cannot flood the defense with pass requests because these are implicit in traffic; they also cannot bypass it. DefCOM was tested with distributed attacks to stress resource accounting, and with low and high degrees of path sharing. Speak-Up [4] deploys the resource inflation approach. While it was not tested with highly distributed attackers, an argument was made that such high numbers of attack machines are not common in today's Internet. PSP [5] deploys path isolation, resource accounting (per-path) and behavior modeling approaches. It was tested with low and high degrees of path sharing, and with focused and distributed attacks. It did not test or discuss the effect of increasing rate attacks on model accuracy. Low-rate attacks that fit the model would not be likely to create service denial on core networks, but this was not discussed either. StopIt [6] deploys privileged customer and resource accounting (per-destination) approaches. It handles good-turn-bad clients by design, and cannot be overwhelmed with pass requests or bypassed. It tested degrees of path sharing to stress its resource accounting. All defenses we surveyed properly discussed or tested attacks on themselves, but SOS [1] did not discuss insider attacks, while other collaborative defenses did.

Topologies — For defenses that operate on a traffic stream at a single deployment point, without consideration of traffic paths or distribution, the specific topology used in testing should not affect performance. We say this with a caveat that sufficient IP address and traffic diversity can be achieved independently of a topology, which is sometimes the case. Other defenses must be tested with realistic topologies, sampled from the Internet. We have seen two approaches to such testing: (1) An ISP topology, obtained from a private or public source, is used in full, (2) Reduction is performed on an ISP topology or AS map derived e.g., from Routeviews [36], for scalability, and a portion is used in tests. An ISP topology approach uses realistic data, which is a plus, but it is only justified if a defense is meant to be deployed at the ISP level. The reduction approach makes little sense unless the defense is meant to be deployed in a portion of an ISP's network. Otherwise, researchers should prove that those features that affect the defense's performance are same in the portion portion of an ISP topology and in the entire topology.

The performance of TVA [1], SOS [2], DefCOM [3], PSP [5] and StopIt [6] may depend on the underlying topology. Only PSP used a realistic ISP topology, and it is a single-ISP defense. TVA used a dumbbell topology, which favored the defense. SOS did not discuss the used topology. DefCOM used a tree topology, which may have been unfavorable for the defense and was certainly unrealistic. StopIt used a random portion of an AS map, which may have replicated realistic connectivity properties but not the path diversity. While this would not change StopIt's performance, it may have negatively affected the performance of other defenses compared with StopIt [6].

4.3. Metrics

Denial of service is a subjective phenomenon perceived by human users, which makes its precise measurement in tests challenging. We focus here on measurement of a defense's effectiveness, which requires accurate measurement of service denial with and without a defense. Other defense performance measures from Section 2 have straightforward and well-understood metrics.

Existing DoS research has focused on measuring denial of service through selected legitimate traffic parameters: (a) packet loss, (b) traffic throughput or goodput, (c) request/response delay, (d) transaction duration, and (e) allocation of resources. While these capture the impact of severe attacks, they often fail in specific scenarios that we will discuss below. Researchers have used both the simple metrics (single traffic parameter) and combinations of these to report the impact of an attack on the network.

Loss is defined as the number of packets or bytes lost due to the interaction of the legitimate traffic with the attack [37] or due to collateral damage from a defense's operation. The loss metric primarily measures the presence and extent of congestion in the network due to flooding attacks, but cannot be used for attacks that do not continually create congestion, or do not congest network resources at all, e.g., [38–40]. Further, the loss metric usually does not distinguish between the types of packets lost, whereas some packet losses have a more profound impact than others on service quality (for example, a lost SYN vs. data packet).

Throughput is defined as the number of bytes transferred per unit time from the source to the destination. **Goodput** is similar to throughput but it does not count retransmitted bytes [38,41]. Both throughput and goodput are meaningful for TCP-based traffic, which responds to congestion by lowering its sending rate, because they indirectly measure this effect. They cannot be applied to applications that are sensitive to jitter or to loss of specific (e.g., control) packets, because a high throughput level may still not satisfy the quality of service required by the user. Further, these metrics do not effectively capture DoS impact on traffic mixes consisting of short, low-volume connections that already have a low throughput.

Request/response delay is defined as the interval between the time when a request is issued and the time when a complete response is received from the destination [42]. It measures service denial of interactive applications (e.g., telnet) well, but fails to measure it for non-interactive applications (e.g., email), which have much larger thresholds for acceptable request/response delay. Further, it is completely inapplicable to one-way traffic (e.g., media traffic), which does not generate responses but is sensitive to one-way delay, loss and jitter.

Transaction duration is defined as the time needed for the exchange of a meaningful set of messages between a source and a destination [1,43,44]. This metric heavily depends on the volume of data being transferred, and whether the application is interactive and congestion-sensitive.

Allocation of resources is defined as the fraction of a critical resource (usually bandwidth) allocated to legitimate traffic vs. attack traffic [3,43]. This metric does not provide any insight into the user-perceived service quality. It assumes the service is denied due to lack of resources, which applies only to flooding attacks and cannot capture collateral damage of a given defense.

In summary, existing metrics suffer from two major drawbacks: (1) They measure a single traffic parameter assuming that its degradation always corresponds to service denial. This approach is flawed because traffic parameters that signal service denial are application-specific and because some attacks can deny service without affecting the monitored parameter. (2) They fail to scientifically define the parameter range that is needed for acceptable service quality, and that is application- and task-specific. Finally, the existing metrics predominantly capture service denial at the network layer, while attacks may target other layers.

TVA [1], SOS [2] and StopIt [6] use the fraction of completed requests as their main performance metric, assuming that outstanding requests are aborted after some ad-hoc interval. They also evaluate the transaction duration. Because a single application is used, and because the measured duration is not linked to human-expected values, these metrics simply show an improvement when a defense is present, but they do not accurately measure if the service denial has been reduced and by how much. DefCOM [3] and Speak-Up [4] measure the server resource allocation, and DefCOM also measures the legitimate traffic goodput. None of these are mapped into human-perceived service denial. PSP [5] measures packet loss of OD pairs, without quantifying how it affects human-perceived service denial.

Another frequent, yet incorrect, approach in DoS defense evaluation is to show measurements from a single test, or averages of a small number of tests. Because variability is possible in traffic and in network operations, multiple tests should be run for the same scenario, with the number of repetitions being driven by the resulting variance. Averages should be shown either with error bars, or with low and high percentile values, to properly communicate the variability in performance. TVA [1] and SOS [2] show averages only, while DefCOM [3] and Speak-Up [4] show single values. PSP [5] and StopIt [6] show a range of values; PSP with averages, 10-th and 90-th percentiles; and StopIt with averages and error bars.

5. DDoS Benchmark Overview

We now describe our efforts in developing benchmarks for DoS defense testing. While these are far from perfect, we believe they are a good first step towards improving DoS defense evaluation. Due to space constraints, we summarize our results here and refer readers to [7,8,10,12,15] for more details.

Our original idea for benchmark development was to sample legitimate and attack traffic and topologies from the Internet and port these into the DETER testbed. Towards this goal, we designed a collection of tools that harvest traffic and topology samples from the Internet. Our attack traffic sampler used a series of custom tests to detect attacks in public traces, and infer their type, rate, level of spoofing and duration. Our legitimate traffic sampler derived request arrivals, connection duration and dynamics from public traffic traces. Our topology sampler used a strategy similar to the Rocketfuel tool [45] to sample ISP topologies. We then developed traffic generators and topology translators to port these results onto the DETER testbed. These scenarios were just a start, because we needed to thoroughly explore the parameter space to comprehensively test a DoS defense. Our next goal was to understand which features of the attack, the legitimate traffic and the topology interact with each other and with the defense. Once isolated, these features were varied in the scenarios.

We first collected information about all the known DoS attacks and categorized them based on the mechanism they deploy to deny service. We focused on attacks where denial of service is a primary goal and not a secondary effect, i.e., attacks that target a specific resource or a service, as opposed to DoS created by worms or e-mail viruses. We arrived at the following attack categories: (1) packet floods, (2) invalid header values, (3) invalid application inputs, (4) invalid fragments, (5) large packets and (6) congestion control exploits (e.g., [38]). We then narrowed our focus to testing of DDoS defenses only, i.e., those that aim to handle distributed attacks. These attacks are packet floods and congestion control exploits. Table 1 lists all the attack types in the benchmark suite, and their denial-of-service mechanisms. Although there are a few attack categories, they can invoke a large variety of DoS conditions and challenge defenses, by varying attack features such as sending dynamics, spoofing and rates. All packet flood attacks can be converted into congestion control exploits by sending the flood in pulses.

Attack traffic generated by the listed attacks interacts with legitimate traffic by creating real or perceived contention at some critical resource. Table 2 lists attack features and their variations, for each attack type from Table 1. A single feature is varied during a test, while other features are kept at a specific default value. Table 3 lists scenario features that are varied to stress-test a given defense, and

Table 1: Attack types in the benchmark suite

Attack type	DoS mechanism
UDP/ICMP packet flood	Large packets consume bandwidth, while small packets consume CPU
TCP SYN flood	Consume end-host's connection table
TCP data packet flood	Consume bandwidth or CPU
HTTP flood	Consume Web server's CPU or bandwidth
DNS flood	Consume DNS server's CPU or bandwidth
Random fragment flood	Consume end-host's fragment table
TCP ECE flood	Invoke congestion control
ICMP source quench flood	Invoke congestion control

Table 2: Traffic feature variations that influence DoS impact

Feature	Variation
Rate	Low, moderate and severe.
Dynamics	Continuous rate vs. pulsing (vary on and off periods). Synchronous senders vs. interleaved senders
Legitimate traffic rate	Light, moderate and high traffic load on the bottleneck link
Critical resource	Covered by attack rate variations
Path sharing	Uniform vs. log-normal location of attack machines. Legitimate clients are distributed uniformly. Several topologies with various degrees of path sharing.
TCP traffic mix	80%/15%/5% mixes of traffic, choosing from: data transfers, Telnet-like communication and single-message request/reply exchanges.
Application mix	Create a mix of all supported applications and vary the contribution of each application to the mix.

their range of variation.

These benchmarks are now deployed on the DETER testbed [25] and integrated with the DETER experimentation environment called SEER [46], which offers a GUI for test control and a point-and-click interface to engage benchmarking. In the beginning, a user is offered a set of ISP topologies to choose from. The user can also input the script locations that deploy, start and stop her defense. The benchmarking module then automatically deploys traffic generators on the topology and runs tests, appropriately starting and stopping the defense during them. It then summarizes the results using our DoS metrics, which we describe in the next section.

Table 3: Test feature variations that interact with defense

Defense	Feature	Variation
Path isolation, resource multiplication and resource accounting	Path sharing	(1) Uniform vs. log-normal distributed attackers. (2) Pulsing, interleaved attacks
Privileged customer	Resource access pattern	Attacker mimics legitimate client behavior (1) prior to the attack or (2) throughout the experiment
Behavior learning	Legitimate vs. attack traffic parameters	(1) Randomized attack packets, (2) Attacker mimics legitimate client traffic, (3) Attack with slowly increasing rate
Traffic inflation	Legitimate user vs. attacker network resources	Vary attackers' locations
All	Attacker aggressiveness	Vary number of attack machines while keeping attack rate constant.
All	Attacker dynamics	Engage new attackers during the attack and retire old ones.
All	Legitimate client dynamics	Engage new legitimate clients during the attack and retire old ones.

6. DoS Metrics Overview

Our insight in developing DoS metrics was that DoS always causes degradation of service quality, and a metric that holistically captures a human user's QoS perception will be applicable to all test scenarios. Our goal in this research was to understand what traffic parameters influence human QoS perception and in which ranges. In this quest, we relied heavily on existing QoS research. We summarize our findings here. All metrics were thoroughly evaluated in [9].

A ***transaction*** represents a higher-level task whose completion is perceptible and meaningful to a user. A transaction usually involves a single request-reply exchange between a client and a server, or several such exchanges that occur close in time. A transaction is considered ***successful*** if it meets all the QoS requirements of its corresponding application. If at least one QoS requirement is not met, a transaction ***failed***. Transaction success/failure is at the core of our proposed metrics.

6.1. Application QoS Requirements

We first identified traffic measurements that are important for service quality for the popular applications today, mostly from [31, 47] statistics and 3GPP [48]. We then leveraged current research that attempts to link user QoS perception with traffic parameter levels for different applications [48–52].

Table 4 summarizes the application categories we propose, and their corresponding QoS requirements. For space reasons, we omit the rationale for these selections; details are in [9]. Should novel applications become popular in the future, the proposed application categories will need to be extended, but our DoS impact metrics will be immediately applicable to new applications. In the request/reply delay column, we differentiate between partial, full, echo delay and RTT values. Partial delay occurs between the time a request is sent to server, and when the first byte of a reply is received. It also refers to the delay between pieces of a reply being received. Whole delay occurs between sending of the request and when the full reply is received. Echo delay occurs in telnet applications from the time that characters are sent to the server, to when the client receives them echoed.

6.2. Measurement Approach

During simulation, collection of necessary traffic measurements usually implies slight modification of the simulator. Such collection is a challenge in testbed experimentation, and we explored two possible approaches: (i) Instrumented-clients: instrumenting each client application to compute required measurements, or (ii) Trace-based: using real, uninstrumented applications and traffic generators, identifying transactions in collected packet traces and computing traffic measurements. While the instrumented client approach has the advantage that it can precisely identify

Table 4: Application categories and QoS requirements.

Category	One-way delay	Req/rep delay	Loss	Duration	Jitter
email (srv/srv)		whole, RTT <4 h			
Usenet		whole, RTT <4 h			
chat, typing		RTT <4 s			
chat, typing	some data must be sent to server				
chat, audio	<150 ms	whole, RTT <4 s	$<3\%$		<50 ms
chat, video	<150 ms	whole, RTT <4 s	$<3\%$		
Web		part, RTT <4 s		<60 s	
Web	some data must be received from server				
FTP Data		part, RTT <10 s		$<300\%$	
FTP Control		part, RTT <4 s			
FTP	some data must be exchanged on data channel				
FPS games	<150 ms		$<3\%$		
RTS games	<500 ms				
telnet		part, RTT <250 ms			
telnet	some data must be received from server				
email (usr/srv)		part, RTT <4 s		$<300\%$	
DNS		whole <4 s			
ping		whole <4 s			
	media	control	media		media
audio, conv.	<150 ms	whole, RTT <4 s	$<3\%$		<50 ms
audio, messg.	<2 s	whole, RTT <4 s	$<3\%$		<50 ms
audio, stream	<10 s	whole, RTT <4 s	$<1\%$		<50 ms
videophone	<150 ms	whole, RTT <4 s	$<3\%$		
video, stream	<10 s	whole, RTT <4 s	$<1\%$		

transactions, it limits the usability of our metrics to open-source clients. We thus decided to utilize the trace-based approach, since it is easily applicable to most test scenarios and immediately usable by other researchers. In implementing trace-based QoS evaluation, we have encountered additional challenges with regard to transaction and request/response identification, which are discussed in detail in [9].

6.3. DoS Metrics

We aggregate the transaction success/failure measures into several intuitive composite metrics.

Percentage of failed transactions (pft) per application type. This metric directly measures the impact of a DoS attack on network services by quantifying the QoS experienced by end users. For each transaction *that overlaps with the attack*, we evaluate transaction success or failure. We then calculate the *pft* value as the difference between 1 (100%) and the ratio of the number of successful transactions divided by the number of all transactions *that would have been initiated by a given application during the same time if the attack were not present*. This approach is necessary to avoid biased results when legitimate traffic generators initiate transactions serially. In this case, timing of subsequent requests depends on the completion of previous requests, and transaction density changes during an attack.

The ***DoS-hist*** metric is the histogram of *pft* measures across applications.

The ***DoS-level*** metric is the weighted average of *pft* measures for all applications of interest: $\textit{DoS-level} = \sum_k \textit{pft}(k) \cdot w_k$, where k spans all application categories, and w_k is a weight associated with a category k. In some experiments, it may be useful to produce a single number that describes the DoS impact, but we caution that *DoS-level* is highly dependent on the chosen application weights and thus can be biased.

Let *QoS-ratio* be the ratio of the difference between a transaction's traffic measurement and its corresponding threshold, divided by this threshold. The ***QoS*** metric for each successful transaction measures the user-perceived service quality, in the range $(0, 1]$, where higher numbers indicate better quality. We compute this metric by averaging *QoS-ratios* for all traffic measurements of a given transaction that have defined thresholds.

For failed transactions, we compute the related ***QoS-degrade*** metric, to quantify severity of service denial. *QoS-degrade* is the absolute value of *QoS-ratio* of that transaction's measurement that exceeded its QoS threshold by the largest margin. This metric is in the range $[0, +\infty)$. Intuitively, a value N of *QoS-degrade* means that the service of failed transactions was N times worse than a user could tolerate.

The ***life diagram*** displays the birth and death of each transaction during the experiment with horizontal bars. The x-axis represents time and the bar position indicates a transaction's birth (start of the bar) and death (end of the bar). We display failed and successful transactions on separate diagrams. This metric can help researchers quickly evaluate which transactions failed and spot clusters that may point to a common cause.

The ***failure ratio*** measures the percentage of transactions that are alive in the current interval (we use 1-second intervals), but will fail in the future. The failure ratio is useful for evaluation of DoS defenses, to capture the timeliness of a defense's response, and for time-varying attacks [38]. Transactions that are born during the attack are considered live until they either complete successfully or fail. Transactions that are born before the attack are considered live after the attack starts. A transaction that fails contributes to the failed transaction count in all intervals where it was live.

We acknowledge that calculating our metrics is more complex than obtaining legacy ones. To ease this process, we have made the program used for DoS metrics calculation from network traces freely available at `http://www.isi.edu/~mirkovic/dosmetric`.

7. Steps Forward for DoS Researchers

We have just provided a lot of information about evaluation practices, and some suggestions we made are not so easy to follow in practice. Here, we summarize our guidelines for best practices in DoS defense testing, developed to strike a balance between test realism and the time investment required for test setup.

- **Use theory for certain research questions, but with realistic models.** As we discussed in Section 4.1, theory is a good tool for some evaluation questions. Care should be taken, however, to use it with appropriate models to arrive at useful results. For example, analysis of overlay resilience in SOS [2] assumes that attacks arrive with a Poisson distribution. While the authors had to adopt some model for attack arrivals, there is no proof that real attack arrivals indeed follow a Poisson distribution. The authors should have argued that either this distribution is the right choice, or that it is the worst case scenario for their defense.

- **Use emulation instead of simulation.** While network simulation is easier to set up and run than emulation, we believe its fidelity in DoS cases is severely limited. We suggest using emulation instead. Emulation has its own set of fidelity issues, especially when router models are concerned, but in general a testbed router model underperforms when compared with real routers. Thus, results obtained from emulation may overestimate attack and collateral damage, which means that realistic defense performance will be better. This seems to be a reasonable compromise.

- **Use realistic legitimate traffic features that matter.** Section 4.2 mentions many legitimate traffic features that should be faithfully replicated in tests. This is often difficult due to the lack of reliable data sources and appropriate traffic generators. Researchers should thus identify those features that interact with the defense and replicate them realistically. At the minimum, these are: TCP transport protocol, RTT value ranges, connection arrivals, lifetimes and dynamics. An acceptable practice is to replicate selected values from ranges (such as min, max and avg), or to replicate a worst case scenario for the defense. Another possibility is to replay public traffic traces in a congestion-responsive manner, e.g., by using the Swing tool [53].

- **Use realistic topologies when they matter.** If topological features, such as path diversity, client and attacker locations, influence a defense's performance, they should be replicated realistically. Unless a strong case for irrelevance is made, relevance should be assumed. While scaledown of large topologies (ISP or AS map) is an open research problem in the general case, researchers can devise appropriate scaledown techniques to preserve a specific feature that matters for their tests. Alternatively, they could use an existing scaledown approach (such as taking a random branch of a larger topology), evaluate the feature of interest there and explain how a defense's performance would change if that feature took more realistic values.

- **Test with all attacks of interest.** Attacks should be chosen to stress-test the defense (Section 4.2).

- **Use our DoS metrics.** Current DoS metrics are so ad-hoc that they prevent comparisons between defenses, or any prediction of human-perceived QoS in real defense deployment. We claim that our metrics are better and they are also easy to use since our publicly released code works on `tcpdump` files that can be easily collected in emulation.

- **Share tests publicly.** Greater sharing of emulation test setup and run scripts would promote better testing practices, as well as reproduction of others' work. Current testbeds lack mechanisms for such sharing — one cannot share experiments selectively but must share all of them. This should be easy to fix.

8. Conclusions and Future Work

The problem of effective evaluation of DoS attacks and defenses is inherently complex. Many evaluation approaches exist, such as theory, simulation, emulation and deployment. While each is beneficial to evaluate specific research questions, emulation approach seems best suited to evaluate a defense's effectiveness. To address the realism of emulation tests, we have worked to develop DDoS defense benchmarks. Ours is just a first step towards more systematic defense testing, where we hope the research community will head. Other future research directions we can highlight are: (1) the creation of better emulation testbeds and high-fidelity legitimate traffic mixes combined with the use of lossless scaledown models of realistic (and large) topologies, (2) development of repositories of realistic traffic and tools to mine relevant features from these and to reproduce such traffic in emulation.

With respect to measuring an attack's impact and thus a defense's effectiveness, most works have used low-level traffic metrics such as packet loss, throughput, end-to-end latency, etc. While these may capture the impact of an attack at the network layer, they do not capture user-perceived effects of it on application-level quality of service. To address this, we have proposed DoS metrics that measure attack's impact on user-perceptible quality of service. Our metrics are intuitive, easy to use and applicable to many DoS scenarios. In the future we plan to extend our set of application categories and refine our QoS criteria for each. We also hope our benchmarks and metrics will serve as motivation for DoS research community to focus on ways to improve science in DoS evaluation. One large step in this direction would be wide sharing of emulation scripts and scenarios for each published DoS paper, so that existing research can be replicated, improved and extended by others. Another important step is working toward a community consensus about components of realistic test scenarios such as legitimate traffic mixes, attack dynamics and topologies.

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