Discriminating Defense Against DDoS Attacks
a Novel Approach

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Contents

1 Introduction  2
  1.0.1 On the Advantages and Drawbacks of Scrubbing Centers . . . . . . . 4

2 The Concept of an $\mathcal{L}$-Message  5

3 Scrubbing++: A Discriminating Scrubbing Mechanism  8
  3.0.1 Defending the CoS and the Registry Against DDoS Attacks . . . . . . 9

4 A Router-Based Discriminating Anti-DDoS (DAD) Defense Mechanism 12
  4.0.1 Incremental Recruitment of Routers . . . . . . . . . . . . . . . . . . . . 12
  4.0.2 The Requirements of DAD from the Routers that Support it: . . . . . . 13
  4.0.3 The Controller-Service (CoS), and its Defense . . . . . . . . . . . . . 14
  4.0.4 The DAD-Registry . . . . . . . . . . . . . . . . . . . . . . . . . . . . 14
  4.0.5 The Guard . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 14
  4.0.6 The Ingress of I-Packets and U-Packets of $\mathcal{L}$-Messages . . . . . 15
  4.0.7 The Ingress of Packets of Other Than $\mathcal{L}$-Messages . . . . . . 15
  4.0.8 The Flow of I-Packets and U-Packets Through the Routers . . . . . 16

5 Evaluation  17

6 Conclusion  18
Abstract

A recent paper (circa 2020) by Osterwile et al., entitled “21 Years of Distributed Denial of Service: A Call to Action”, states: “We are falling behind in the war against distributed denial-of-service attacks. Unless we act now, the future of the Internet could be at stake.”

And an earlier (circa 2007) paper by Peng et al. states: “a key challenge for the defense [against DDoS attacks] is how to discriminate legitimate requests for service from malicious access attempts.” This challenge has not been met yet, which is, arguably, a major reason for the dire situation described by Osterwile et al.—thirteen years later.

This paper attempts to meet an approximation to this challenge, by enabling a site to define the kind of messages that it consider important, and introducing an unambiguous criterion of discrimination between messages that a given site defined as important to it, and all other messages sent to it.

And this paper introduces two anti-DDoS mechanisms based on this criterion, which ensures the delivery to a given site of practically all the important messages sent to it, even when it is under attack. One of these mechanism relies on lightweight support by routers, and the other one does not.

1 Introduction

A circa 2007 paper [7] by Peng et al. states: “a key challenge for the defense [against DDoS attacks] is how to discriminate legitimate requests for service from malicious access attempts.” A similar view was expressed even earlier (circa 2002) by Ioannidis and Bellovin in their famous pushback paper [2], as follows: “If we could unequivocally detect packets belonging to an attack and drop just those, the problem would be solved.”

This challenge has not been met yet, which is, arguably, a major reason for the dire situation described by Osterwile et al. in their (circa 2020) paper [6], entitled “21 Years of Distributed Denial of Service: A Call to Action”. This paper states: “We are falling behind in the war against distributed denial-of-service attacks.” The seriousness of the situation is reflected by the large number of scholarly papers published on this topic recently. In particular, Google scholar reported on 2/21/21, that there were 4184 papers published during the past five years with the term “DDoS” or the phrase “Distributed Denial of Service” in their title.

The Goal of this Paper is Twofold: Our first goal is to meet an approximate version of the challenge posed by Peng et al. What we propose is that a site that wishes to defend itself against DDoS attacks—we refer to such a site as a defender, denoting it usually by D—will characterize explicitly the type of messages that it considers important; important enough for D to view itself as being well defended, if all the important messages sent to it during an attack would be delivered to it; and if most of the non-important messages are dropped, so that D can read the important messages, and reply to them. To ensure that such messages would be delivered to D under an attack, we need an unequivocal, and easily recognizable, criterion for discrimination between the messages that D defined as important, and all other messages sent to it. Such a criterion is introduced in the following section.
Our second goal is to use this criterion for constructing an effective defenses against DDoS attacks.

The Proposed Criterion of Discrimination To be effective for defending against DDoS attacks, we need a criterion of discrimination between the important message for a given defender, and all other messages sent to it. Such criterion needs to satisfy the following two requirements.

1. This criterion should be easily recognizable, at the source of messages and at their destination. (The importance of recognizing the criterion at the source of messages—which is usually hard to do—will be apparent in Section 4 where we introduce our second defense mechanism.)

2. Messages classified as important to \( D \) by this criterion should not be able to contribute meaningfully to a DDoS attack on it; or, they should be trusted by \( D \) not to do so.

The ability to construct such a criterion depends on the manner in which the set of important messages for a given defender are characterized.

Note that the characterization of important messages cannot be based on any predicate defined over their content, because attackers can learn about such a predicate, and then send messages characterized as important to a given defender. Moreover, the characterization of important messages cannot be based on the IP-address of the sender, because of the frequent use of IP-spoofing by attackers.

So, we propose that \( D \) would characterize the messages that are important to it not by the structure of the message itself, nor by the address of their sender, but by the behavior of their sender, before and during its process of sending messages to \( D \). This behavior is to be defined by \( D \) as a protocol of sending messages—which we call a law of \( D \), denoting it by \( L_D \).

More specifically, \( D \) would declare that messages sent to it, subject to the specified law \( L_D \) are important.

For example, such a law may impose a rate limiting discipline on the sender—say one message per 5 minute—which would prevent it to contribute meaningfully to an attack on \( D \). Another possibility is for a law to require that before starting to send messages to \( D \), the sender must authenticate itself in a specified manner. This would mean that a select group of senders, that \( D \) presumably trusts, would be able to communicate with \( D \) during an attack on it. And these two measures can be combined into a single law.

But such characterization of important messages may seem to be absurd—indeed, how can anybody tell what is the law that governs the process of sending message by a given sender, if any? Yet, this is actually possible. It can be done, in particular, by using a middleware called law-governed interaction (LGI) \[5, 3\]. Specifically, this middleware features the concept of an \( L \)-message, which is a message sent subject to a given law \( L \), and which can be verified cryptographycally as such. We will discuss such messages in Section 2.

Summary: The unequivocal criterion of discrimination we propose is whether a message sent to a given defender \( D \) has been sent as an \( L \)-message, subject to the law \( L_D \) defined by \( D \).
The manner in which such messages can be sent, and way they can be recognized as important messages with respect to a given defender, are discussed in Section 2.

Note that this criterion reverses the manner in which defense against DDoS attacks is currently carried out. Conventional defenses operate by trying to recognize attack-packets; and dropping them while letting all other packets to pass through. On the other hand, the defense based on our criterion of discrimination would recognize the messages and packets that the defender declared to be important to it; and letting them pass through, while dropping other messages and packets.

But although these are very different anti-DDoS approaches, they are complementary and can be combined, as we do in both of the defense mechanisms introduced in this paper.

State-of-the-Art of Defense Against DDoS Attacks Before introducing new anti-DDoS defense mechanisms, it is appropriate to review the state-of-the-art of such defense. Practically all current defense mechanisms are based on techniques of identifying attack-packets, in order to drop them before they arrive at the attacked defender. The identification of attack-packets is based on an analysis of many past DDoS attacks—using statistical techniques and machine learning—coming up with what is called a signature (or signatures) of attack-packets—defined, mostly over the content of packets.

This approach gave rise, recently, to defense by means of scrubbing centers [6], operating by commercial companies such as Akamai and Cloudflare. These centers operate, essentially, by intercepting the messages addressed to a given defender D—their client—carrying out deep packet inspection (DPI), of the packets addressed to the site they defend, in an attempt to identify and drop attack packets.

1.0.1 On the Advantages and Drawbacks of Scrubbing Centers

Scrubbing centers, or scrubbers for short, provide a decent, also flawed, defense against DDoS attacks. And perhaps their biggest advantage is that they can be deployed practically anywhere over the Internet, since they do not depend on any special support of routers. But scrubbers also have several substantial drawbacks, three of which are described below.

1. **Unequal arm race**: The ability of scrubbing to defend an attacked site is undermined when confronted with a new kind of attack—because scrubbing is based on the analysis of past attacks, assuming that the current attack resembles them, which it may not do completely. This creates an enduring “arm race” between the attackers and the defenders. And it is an unequal arm race, as it is far easier and cheaper to mount a new type of DDoS attack, than it is to incorporate the new attack into a new versions of the scrubber. Thus, to quote from [6], “we have been losing ground to our adversaries in the DDoS war, and we must take corrective action now”.

2. **Unreliability**: The underlying purpose of scrubbing is to enable a defender to receive “legitimate” messages and to respond to them. But the ability of scrubbers to satisfy this purpose is unreliable due to the lack of definition of which messages are legitimate with respect of a given defender, and because the process of scrubbing may drop many legitimate messages and packets.

3. **High Cost**: Scrubbing center are expensive to operate and thus expensive to be defended by. For example, according to information we recently obtained, Akamai
charges $1500 a month for the basic service, and a lot more for more advanced ones. CloudFlare provides free protection for very small sites, like personal websites, but the price goes up steeply for larger sites. And without an expensive long term subscription one is left basically defenseless. Although some scrubbing centers provide emergency on-boarding during an attack; such on-boarding takes time while the client remain defenseless, and may carry a hefty fee.

On the Use of our Discrimination Criterion for Defending Against DDoS Attacks

We offer two defense mechanisms, based on our discrimination criterion. The first mechanism is an upgrade of the conventional concept of scrubbing center, making it more reliable by delivering to a defender the messages it defined as important. We characterize this mechanism as a discriminating scrubbing mechanisms, calling it scrubbing++ (with apologies to, or honor of, Bjarne Stroustrup).

Our second mechanism is a brand new mechanism, which depend on a lightweight support by routers. It is called Discriminating Anti-DDoS, or DAD for short.

Although both of these mechanisms are based on our discrimination criterion, and thus share some of their aspects, they are very different and each of them has its pros and cons.

The rest of this paper is organized as follows: Section 2 introduces the concept of an \(\mathcal{L}\)-Message, on which our discrimination criterion depends; Section 3 introduces the \textit{scrubbing++ mechanism}; Section 4 introduces the DAD mechanism; Section 5 is an evaluation of these two defense mechanism; and Section 6 concludes this paper.

2 The Concept of an \(\mathcal{L}\)-Message

\textbf{Definition 1} An \(\mathcal{L}\)-message is a message sent subject to a law \(\mathcal{L}\) such that any receiver of this message can determine, with justified confidence, that it has been sent subject to this law.

As pointed out in Section 1, an \(\mathcal{L}\)-message, governed by law \(\mathcal{L}_D\) chosen by a defender \(D\), is what one should send to \(D\) to be considered important by it—particularly during an attack. Such messages addressed to \(D\) are denoted by \(\mathcal{L}_D\)-messages.

The concept of \(\mathcal{L}\)-message, as described here, is a very basic part of the middleware called \textit{Law-Governed Interaction} (LGI) [5]. Here we just explain how \(\mathcal{L}\)-messages are sent under LGI, and how they are identified as such.

\textbf{A note:} To use the concept of \(\mathcal{L}\)-message one does not need to be familiar with the entire LGI mechanism, but only to read the rest of this section.

\textbf{Sending \(\mathcal{L}\)-messages} In order to send \(\mathcal{L}\)-messages, a sender \(s\) must employ a software entity called the \textit{private controller} of \(s\), denoted by \(T_s^L\), to serve as its surrogate by mediating the interactions of sender \(s\) with others, subject to the given law \(\mathcal{L}\).

Such a private controller can be generated by \(s\) via the following two steps: First, acquiring the use of a \textit{generic controller} \(T\) from a trusted service, called a controller-server (CoS), that maintains a large number of \textit{generic controllers} (cf. Section 2). A generic controller is built to serve as a surrogate of any given message-sender or message-receiver, subject to any given LGI-laws—with no specific laws built into it.
The second step is to load a law $\mathcal{L}$ into this generic controller, thus forming its private controller $T_x^\mathcal{L}$. Once this is done, $s$ can start sending $\mathcal{L}$-messages via this controller.

Note, however, that a law $\mathcal{L}$ may refuse to serve the particular sender $s$—more about which, later.

The above two-steps are basically what a software process needs to do to send $\mathcal{L}$-messages. But tools can be build for making it easier for a human sender to send $\mathcal{L}$-messages. In particular, for senders operating via a smart phone an app can be developed to carry out this process. (We have done that with an experimental smartphone, as described in [1].)

And a browser-extension can be built to help sending $\mathcal{L}$-messages via a browser.

βAuthenticating an $\mathcal{L}$-Message: First note that every LGI-controller carries a certificate signed by the controller server (CoS) (acting as a CA), which, in effect, vouches for the controller’s authenticity. Now, the authentication is done by means of a TLS handshake between the controller and the receiver of this message. During this handshake the receiver of the message obtains the certificate from the controller, validates it to ensure that it’s signed by the CoS—of course, the validation of the certificate signed by the CoS requires the receiver to have the public key of the CoS. The receiver also gets the controller’s law hash. Moreover, the session’s symmetric encryption key is also established during the TLS handshake. The key exchange is based on Diffie-Hellman kex algorithm.

Note that the receiver gets the message itself only if the handshake succeeds.

βA Controller Service (CoS) To support a large number of senders of $\mathcal{L}$-messages, which may operate under a variety of laws, one needs to provide a large set of generic controllers that can be widely trusted to operate in compliance with any valid law loaded into them. As pointed out above, we call such a provider of controllers a controller service (CoS). Its function is to create, maintain, and certify a collection of controller. The certification is done by providing each controller with a certificate of its authenticity, signed by the CoS. And the CoS may be geographically distributed.

The current implementation of LGI includes an experimental version of a CoS. But the proposed defense against DDoS attacks would require a large scale CoS that needs to be managed by a reputable commercial company or governmental institution. This organization must be willing to vouch for the trustworthiness of its controllers, and to assume liability for their failures.

Finally, it should be pointed out that the controllers maintained by the CoS can be used by many other applications besides the defense against DDoS, such as making heterogeneous distributed systems dependable [4]; building decentralized social networks [8]; etc.

βOn the Roles of Laws in the Proposed Defenses Against DDoS Besides providing an unambiguous criterion for discrimination between $\mathcal{L}_D$-messages address to a defender $D$—the messages that $D$ declared as important for it—the law $\mathcal{L}_D$ can provide the following benefits:

• Limiting the ability of those that can send to $D$ important message to it, to contribute meaningfully to an attack on $D$.

• Ensuring that the senders that can send to $D$ messages that are important to it, belong to the type of senders that $D$ would want to communicate with, even under attack.

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1We assume here that the receiver does not operate via an LGI-controller, if it does then a different kind of handshake is used.
• Refusing to serve as a surrogate of some potential senders.

Here we will discuss, briefly, three types of measures that can be implemented, either separately or together, by a law $L_D$, for providing these benefits. (Two of them were mentioned, more briefly, in Section [I])

It is worth pointing out, before we start, that although some of these measures, like authentication of the sender, are computationally quite expensive, this computation is to be done by the controller and, perhaps, the sender, and not by the routers.

1: Rate Control: This is done by having a law $L_D$ impose an upper bound on the rate of messages that $L_D$-agents can send to $D$. This is a very simple measure, which can be implemented in several ways. And note that we cannot control the rate of messages sent by a sender to its controller. But the controller can limit the rate of messages sent to the defender $D$.

Another rate control method is the following: Initially, every sender $s$ operating under the given law $L_D$ is authorized to send just one message to $D$. But $D$ can enable $x$ to send more messages to it by sending an appropriate message to the controller of $x$, specifying the rate that it allows it to send messages.

2: Certification: A law may be written to require a sender that tries to adopt it to authenticate itself via one or several certificates. For example, one of these certificates may be provided by $D$ itself for its best customers. And supposing that $D$ is a military site, another certificate may authenticate the sender’s security classification level.

3: Refusing to Serve as a surrogate: A law that requires certification can be written to refuse to accept the sender $s$ as its client if it did not satisfy its certification requirements.

The law can also send a captcha puzzle to the sender, dropping this sender if it fails to solve it.

Comments About Usage: First, we expect that most users will send their $L$-messages to defenders via tools developed in browsers and smartphone, as described above.

Second, we expect the rate-control to be used most frequently in the $L_D$ of most defenders. On the other hand, certification is likely to be used in such laws only for employees of $D$, or for its key clients, and peers. And note that a single law can contain either of these options, or all of them.

Third, that a defender may define several laws for sending messages which it consider important, but for simplicity, we discuss just a single such law per defender.

Finally, a defender $D$ that have large numbers of clients and employees, would like to curtail the number of important messages that can sent to it. This can be done by having its law $L_D$ require certification via a certificate that $D$ will provide its most important clients, employees and peers. This besides imposing rate limits on all such senders.
3 Scrubbing++: A Discriminating Scrubbing Mechanism

One of the drawbacks of conventional scrubbing centers (or scrubber, for short) mentioned in Section 1 is their lack of reliability, in that they are likely to drop some of the legitimate packets—i.e., packets that the defender would like to get. (Conventional scrubbers cannot really address this issue, because they have no way of knowing which packets a given defender likes to get.)

But the reliability of conventional scrubbing centers can be enhanced by having such a center adopt our criterion of discrimination, and use it to form what we call scrubbing++ center, or scrubber++, for short.

The Rest of this Section is Organized as Follows: Section 3 describes the gist of this mechanism; Section 3 introduces the infrastructure of S; Section 3 discusses preparations of S for its role as a defender; Section 3 discusses the process of sending L-messages to P; Section 3 discusses the treatment of L-messages arriving at P; Section 3 discusses the defense of P from DDoS attacks; Finally, Section 3 is a summary of the defense provided by scrubbing++.

The Gist of the Scrubber++ Mechanism The purpose of this mechanism is to ensure that practically all L-D-messages sent to D, which are the types of messages that D declared as important to it, would be delivered to it.

For a given Scrubbing center to upgrade to a scrubber++, which we denote by S, it needs to add an application called appendix, denoted by P, which operates via its own port p and handles L-messages. Of course the L-messages addressed to the host scrubber (denoted by SC) should direct their messages to port p. Moreover, the scrubbing center SC on which S is based needs to avoid scrubbing messages addressed to P, in order to prevent packets sent to P from being dropped.

The main task of the appendix—relative to a given defender D under attack—is to verify that the L-messages addressed to D are important to it. Namely, that they are L-D-messages, were L-D is the law defined by D to characterize message important to it. And messages that are recognized by P as L-D-messages are sent by it to D, while the others messages addressed to D are dropped.

The Infrastructure of the Scrubbing++ Mechanism Besides a scrubbing center SC, on which the scrubbing++ mechanism S is squarely based, S requires the existence of three additional components: (1) the appendix, which was introduced briefly above; (2) a components called a registry, which serves as the administrative center for all the sites that are defended by a given S; and (3) the Controller Server (CoS), which was introduced in Section 2 but requires additional discussion in this context. In the following two paragraphs we introduce the registry, and discuss the CoS. The appendix is discussed later.

The Registry: The registry, is the administrative center of S. Its role is to register sites to be defended by S, and to supply the appendix with information about these sites. The functionality of the registry is discussed in detail later.

The registry may reside in the SC itself, or it may reside elsewhere, and it may serve several different scrubbing++ mechanisms. (But for simplicity, we mostly assume in this
paper that each registry administers only a single scrubbing++ mechanisms, i.e., a single $S$.

The Controller Server (CoS): The CoS was introduced in Section 2 as potentially serving many types of applications. But here we assume that it serves only the scrubbing++ mechanisms $S$. To play this role, the appendix $P$ would send the CoS its port number $p$. And the CoS should supply this port to every controller being acquired by an actor, to enable it to send $L$-messages to $P$.

3.0.1 Defending the CoS and the Registry Against DDoS Attacks

For the CoS to be used by the senders of $L$-messages to $P$ it needs to be defended against DDoS attacks. But this cannot be done by means of $S$. Because $S$ enables messages to get through only if they are $L$-messages, sent via a controller acquired from the CoS. But one needs to send a regular message to the CoS to acquire a controller. And if the CoS is defended by $S$, the packets of such a message may be dropped. Therefore, the CoS needs to be defended via one of the conventional scrubbing centers, such as $SC$ itself.

The registry, if it is not reside in our scrubber $SC$, would also need to be defended, and it can be defended by our $S$ or by $SC$. The appendix $P$ would also needs defense against DDoS, as discussed in Section 3.0.1.

Preparing for Defense For a website $D$ to be defended by the scrubbing++ Mechanism $S$, the following steps need to be carried out: (1) defining a defense law $L_D$; (2) registering $D$ as a defender; (3) providing information to the registry; and (4) providing information to the appendix.

1: Defining a Defense-Law $L_D$:  

1: Defining a Defense-Law: It should be pointed out that a single defender can specify several laws that define different types of message-sending behaviors that it consider important. But for the sake of simplicity, we will limit ourselves here to a single such law per defender.

We distinguish between two ways for defining laws. One way is for the defender to write its own law, or have somebody else write a law for it. The other way is to adopt a law that somebody else defined. The registry would have a list of laws that its clients—the registered defenders—use. It is worth pointing out that the law that a given defender $D$ is using as its $L_D$ need not be a secret, as the knowledge of it cannot really help in attacking $D$.

2: Registering $D$ as a defender: Only registered sites would be defended by the scrubber++. So registration constitute a permission to be defended. Such a permission, by the registry, is required for several reasons.

First, if anybody would be allowed to register, with any law, then would-be attackers can do so, using laws that enables them to attack, such as laws that do not require rate limitation. This may create a reverse attack on $S$. So, the registry should be selective about giving such a permission. It is also important for the registry to accept a given site $D$ as a defender, only if its, law $L_D$, can be shown to prevent actors operating under it to contribute meaningfully to an attack on $D$.
And second, registration would probably involve charging a fee for being a defender. But we do not address here the nature or the size of such a fee.

3: Providing Information to the Registry: A request by a site \( D \) to be registered as a defender should include the following two pieces of information: First, the pair \([D, H(\mathcal{L}_D)]\) where \( D \) is the IP-address of would-be a defender, and \( H(\mathcal{L}_D) \) is the one-way hash of its law \( \mathcal{L}_D \).

And second, \( D \) will submit to the registry the text of the law \( \mathcal{L}_D \). This can be useful for two reasons: (a) anybody who wants to send \( \mathcal{L}_D \)-messages to \( D \), can find in the registry the law \( \mathcal{L}_D \), which they need to load their controller with. And (b) a potential defender that does not know how to write LGI-laws can find a suitable law among those submitted to the registry.

4: Providing information to the appendix: For each registered defender \( D \), the registry would disseminate the pair \([D, H(L(D))]\) to the appendix.

It will also provide the appendix with the public key of the CoS, to be uses for decrypting the certificates signed by the CoS, and planted in all the controllers managed by it. We leave it unspecified how this information should be provided to the appendix.

βSending \( \mathcal{L}_D \)-Messages to a Defender \( D \) The act of sending an \( \mathcal{L} \)-message was described in Section 2, but the sending of such a message under the scrubbing++ mechanism differs as follows: Such a message should by addressed not to the scrubbing center \( SC \) that serves as the basis for a scrubbing++ mechanism, but to its appendix \( P \), which operates via its own port \( p \).

This change in the sending of \( \mathcal{L} \)-messages needs to be set up in the browser extension and in the sending app on the smart phone, respectively (cf. Section 2).

βThe Treatment of Messages Arriving at the Appendix First, recall that the messages that arrive at the appendix are not being scrubbed (cf. Section 3). Now, we distinguish between three types of messages that require different kind of treatment by \( P \). They are discussed below:

(1) Messages addressed to a site which is not a registered defender: Such messages would be forwarded to its destination without any verification of their nature. But they can also be dropped as they are likely to be attack messages.

(2) Messages addressed to a defender \( D \) which is not under attack: Such messages would be forwarded to \( D \), without any verification of their nature. Because, we assume that a defender not under attack is able to verify its own messages.

But if some packets are missing in a given message, \( P \) might wait, for a reasonable time, for the missing packets to be completed by the sender.

(3) Messages addressed a defender \( D \) under attack: In this case, the appendix \( P \) should verifying that \( m \) is important to \( D \). That is, \( P \) would verify that \( m \) was sent by a genuine LGI-controller operating subject to the law \( \mathcal{L}_D \). We denote such an \( \mathcal{L} \)-message by \( \mathcal{L}_D \)-message.
If this verification succeeds then \( m \) should be sent to \( D \)—perhaps after waiting for a reasonable time, for missing packets to be completed by the sender. But if the verification fails, \( m \) should be dropped.

The verification has two steps. First, as explained in Section 2, the controller that operates as the surrogate of the sender of the \( L \)-message conducts a TLS-handshake with the receiver of this message—\( P \) in this case. During this handshake, \( P \) validates the controller’s certificate to ensure it is signed by the CoS, and gets the controller’s hash \( h \) of the law, under which the controller operates.

Second, as explained in Section 3.0.1, the appendix \( P \) has in its possession the list of pairs \( [d,H(L_d)] \), one for every defender \( d \). Now, \( P \) would verify that there is a pair \( [D, h] \) in this list, which means that the controller in question operate subject to the law that \( D \) selected.

\( \beta \)Defending the Appendix from DDoS Attacks

Attackers are likely to discover the existence of the appendix and its role. And if port \( p \) is fixed for long enough time, attackers would eventually discover it, and may mount an attack on it. To prevent such an attack we will make \( p \) change dynamically, and in a manner that makes such changes hard to discover, or predict. The following is a strategy to do that.

Following starting port number \( p \) of \( P \), we let \( P \) change its port number regularly, but in randomized intervals, as follows: Consider a time \( t_1 \) when \( P \) started to operates under port \( p_1 \). We have \( P \) send to the CoS the following message at this time: \( (p_1,t_1+dt,p_2) \), which means, essentially, the following: \( \text{the current port number is } p_1, \text{it would change at time } t_1+dt \text{ to } p_2 \). In other words, both \( P \) and the CoS would change the port number to \( p_2 \) at time \( t_1+dt \).

The time period \( dt \) should satisfy two conditions: (a) it should be smaller, say half, of the estimated time that it takes for attackers to mount a new attack with a new port number; (b) \( dt \) should be randomized, for obvious reasons. This transformation of port numbers is to be repeated recursively.

A Complicating Factor: There is another issue to be considered: When the change from port number \( p_1 \) to \( p_2 \) is made, by both \( P \) and the CoS, there would likely be several controllers that still operate with the port number \( p_1 \). The problem is that the messages sent by these controller would not arrive at \( P \), which moved to a different gate, and would thus be lost.

This issue can be addressed by a pair of remedies. First, the CoS should update the gate numbers of the controllers still addressing port \( p_1 \), to \( p_2 \). But this would take some time, so we need to carry out the second remedy, described below.

When \( P \) changes its gate number to \( p_2 \), let it leave the previous gate \( p_1 \) to still function as \( P \). In other words, we have two instances of \( P \) operating at the same time. We call them \( P_{\text{previous}} \), that operates via gate \( p_1 \), and \( P_{\text{current}} \) that operates via gate \( p_2 \). So, the messages sent by controllers that still use gate \( p_1 \), would arrive at \( P_{\text{previous}} \). And this situation would be maintained invariant of the sequence of gate numbers selected by \( P \). Moreover, the scrubbing center \( SC \) on which \( S \) is based would avoid scrubbing messages addressed to both these versions of \( P \).

Note that although unlikely, the attackers may still manage to mount an attack, perhaps on \( P_{\text{previous}} \), which has longer life span than \( P_{\text{current}} \), but such an attack can last for only brief
amounts of time, due to the relentless changes of the port numbers under which $P$ operates.

The Defense: a Summary The scrubbing++ mechanisms provides two complementary defenses to registered defenders. One is the assurance to a defender $D$ that it will receive practically all the $L_D$-messages sent to it. The other defense carried out by underlying grabber $SC$ is the dropping of large number of attack-packets, which should enable $D$ to read the $L_D$-messages it gets, and to respond to them.

Notes that the scrubbing mechanism $SC$ is likely to drop a sufficient number of packets to enable $D$ to handle the messages that arrive at it. Some of these messages would be the important message sent to it by the appendix. But there may be other messages that may arrive at $D$, because the scrubber did not scrub them away, and which may interest $D$, although they do not belong to the set of important messages.

4 A Router-Based Discriminating Anti-DDoS (DAD) Defense Mechanism

The big difference between this mechanism and scrubbing++, is that DAD relies on the support of routers. Despite this fundamental difference between these two mechanisms there are considerable similarity between them due to the fact that both rely on the same criterion of discrimination between messages the defender declares as important to it and all other messages. When we get to such a similarity we will either refer here to the relevant part in Section 3 or we will repeat here verbatim a piece of text from Section 3.

The Rest of this Section is organized as follows: Section 4 described the role of routers in this defense, and describes the reasons for routers to agree to adopt this role: Section 4.0.2 presents the Gist of this mechanism; Section 4.0.2 describes the infrastructure of DAD; Section 4.0.3 describes the preparation for defense; Section 4.0.5 describes the treatment of $L$-messages; Section 4.0.5 describes the flow of a-packets and u-packets into and in routers; Finally, Section 4.0.8 describes the DAD’s defense.

The Routers We start with the recruitment of routers to support the operation of DAD, and we continue with the very lightweight requirements that DAD makes from the routers.

4.0.1 Incremental Recruitment of Routers

Our main goal is to be able to defend sites all over the 48 contiguous states of the US. This may follow the implementation of DAD in the rest of North America, in Hawaii, and perhaps in other places where one can trust the management of routers. But satisfying our main goal would require all the core routers in this vast region of the US to support DAD. This is very unlikely to happen in one fell swoop. What we need is to start incrementally, by having DAD operate in a smaller region.

A reasonable choice is the set of core router in one autonomous system (AS), managed by a given ISP—we will call such an autonomous system simply an ISP, which is a much better-known term than “AS.” And this paper is presented in terms of a single such ISP, assumed to satisfy the requirements of DAD. We often refer to this ISP as “our ISP,” or simply “ISP.”
Given such an ISP, DAD will be able to defend sites anywhere in its domain, while the senders of message to such sites can reside anywhere on the Internet.

Our plan for incremental recruitment is based on the following observation: If the DAD mechanisms will be proven effective in a single ISP, it would be likely to create pressure on other ISPs to provide the required support for DAD. Because the sites residing in the domains of other ISPs are likely to exert pressure on their ISPs, to support DAD. Moreover, these sites may offer a payment to their ISP to do that, thus creating a direct financial incentive for the ISP to support DAD. So, one can expect that the various ISPs in the 48 contiguous states of the US would incrementally support DAD’s requirements. And DAD would be able operate on any collection of ISPs which are pairwise contiguous with each other.

4.0.2 The Requirements of DAD from the Routers that Support it:

We distinguish here between structural and behavioral requirements that DAD makes from the routers of our ISP. The reasons for these particular requirements will become apparent in due course.

The main structural requirement is for the header of every packet to have one-bit field called the pass-field. And we say that the pass-field is on if its value is 1, and off when its value is 0. We will see below what does the pass-field signify. Alternatively, the pass-field may reside in the data-part of a packet, which should never be encrypted. This, alternative can be used if adding a field to the header of a packet would slow the router in a significant amount. We assume here the first option.

The main behavioral requirement from the routers of our ISP is not to accept a packet with the pass-field on, unless it is submitted to this router by its guard—more about which later. Also, if asked to do so, the routers will drop all the packets with their pass-field off addressed to a defender under attack.

There are a few additional lightweight requirements, which will be introduced in due course.

The Gist of DAD

The packets that flow in the routers of our ISP are classified into two disjoint categories: (a) the packets addressed to a defender $D$ that belong to messages that $D$ defines as important, which we denote by i-packets; and (b) all other packets, which we denote by u-packets.

Under DAD, i-packets are marked by having their pass field on (their values is 1); and u-packets are marked by having their pass-field off (their value is 0) (cf. Section 4.0.2). This makes it very easy and efficient to distinguish between these two types of packets, which gives rise to the main defense technique by DAD:

When a a defender $D$ is under attack, all u-packets addressed to it—most of which are likely to be attack packets—are dropped at their source. As we shall see, dropping such packet at their source has important consequences, one of which is the ability to discover the identity of the attackers that mastermind the DDoS attack in question.

The Infrastructure of DAD

Besides the routers in our ISP, (cf. Section 4.0.2) DAD requires the existence of three components: the controller service; the registry; and the guard. We elaborate on them, briefly, below.
4.0.3 The Controller-Service (CoS), and its Defense

The CoS, introduced in Section 2, needs to be resident within the domain of our ISP. And it needs to be defended against DDoS attacks. But due to consideration analogous to those in Section 3.0.1, it cannot be defended by DAD, which uses the CoS for its operation, so it must be defended either by a conventions scrubber, or by our scrubber++ mechanism.

4.0.4 The DAD-Registry

The DAD-registry, or simply registry, is the administrative center of DAD and it needs to reside within the domain of our ISP. The role of the registry in the DAD defense, and its functionality, are discussed in the following subsections.

Like the CoS, the registry needs to be protected against DDoS attacks. But unlike the CoS the registry can be defended via DAD. It can also be easily replicated—which will make it even more secure—because changes in the content of the registry are relatively rare.

4.0.5 The Guard

The guard is a device that handles $L$-messages. We use a Scrubbing++ center to serve as a guard—with one important modification to be described later.

We assume here that there is just one guard serving our ISP. But in a large ISP, or in a system of routers consisting of routers managed by several ISPs, we may have several guards.

The guard needs to be resident within the domain of our ISP, and it need to be trusted by its edge router. To gain such trust the router should authenticate the guard, probably via public key cryptography. We will not elaborate here on such the authentication itself, but we should address the following issue that it raises.

The authentication of a guard may be computationally expensive, perhaps too expensive for a router to perform. If this is the case the authentication can be done by autonomous component built into each router, which is running on its own processor and is not involved in routing. This components of a router, which we call its supplement, carries out the authentication of the guard, and is not involved in the routing itself.

βPreparation for Defense For a site $D$ to be defended by the DAD mechanism, the following steps need to be carried out:

1. $D$ should define its defense law, i.e., the LGI-law $L_D$ that would serve as basis for identifying the messages and packets that $D$ views as important.

2. $D$ should Register in the DAD-registry as a defender.

3. $D$ should provide certain information to the registry.

4. The registry should provide certain information to the guard.

The first three steps above, are identical to the three steps of preparation of the scrubbing++ mechanism (cf. Section 3.0.1), while the fourth step is new here. We will not repeat them here, but will spell out item number 4:
4: Providing Information to the Guard: For each registered defender $D$, the registry would disseminate the pair $[D, H(L(D))]$ to the guard. It will also provide the guard with the public key of the CoS.

βThe Treatment of $L$-messages $L$-messages are handled by a guard, implemented essentially as a scrubbing++ mechanism (cf. Section 3). So, $L$-messages are treated by the guard almost exactly as they are treated by the scrubbing++ mechanism, including the verification that a given $L$-message addressed to a defended $D$ under attack is the $L_D$-message; and the manner that the guard protect itself against DDoS attacks.

The only difference between the scrubbing++ and the guard, in their treatment of $L$-messages, is that while the former forwards $L$-messages to their destination without changing them, the latter would change the individual packets of a message, before delivering them to its edge-router. The way this is done is described below.

βThe flow of A-Packets and U-Packets Into Routers, and In Them

4.0.6 The Ingress of I-Packets and U-Packets of $L$-Messages

The guard carries out the three kind of treatments for three kinds of $L$-messages described in Section 3.0.1. But it handles the packets of these messages in the following manner:

(1) For a message $m$ addressed to a site which is not a registered defender, the guard will turn the pass-field of each packet of $m$ to be off (i.e., its value is set to 0), thus making it into a u-packet.

(2) For a message $m$ addressed to a defender $D$ that is not under attack, the guard will turn the pass-field of each packet of $m$ to be on (i.e., its value is set to 1), thus making it into an i-packet.

(3) For a message $m$ addressed to a defender $D$ under attack, there are two cases to consider. If the verification of this message as an $L_D$-message succeeds then the guard will turn each packet of $m$ to be an i-packet, as above. But if the verification fails, each packet of $m$ will turn to be a u-packet.

In all these cases the transformed message $m$ is then transferred to the edge-router of the guard, to be routed to their destination.

4.0.7 The Ingress of Packets of Other Than $L$-Messages

Packets that belong to anything but $L$-messages, are, by definition, u-packets. So, we need to make sure that such packets have their pass-field zero (i.e., off).

To Achieve this situation we make the following requirement from routers (this is one of the two main behavioral requirement from the Routers under DAD, see Section 4.0.2) every router in our ISP would set the pass-field to zero of every packet submitted to it either (a) directly from outside, excluding i-packets submitted to the router by its guard; or (b) or from a router that belongs to another ISP, which does not operate subject to DAD—this would require adding a new pass-field to each such packet.

An observation: Normally, a packet sent from a given router in a given ISP to its target in the same ISP ($D$ in our case) would be routed via routers in the same ISP. But this may not always be the case. So suppose that our packet was routed to an ISP that does not follow the above mentioned rules of our routers, would the pass-field of our packet retain its
value? We think that it will, with a high probability, because unless this router is rogue, which routers are generally not, there is no reason for it to change the pass field, so it is very likely to stay intact.

4.0.8 The Flow of I-Packets and U-Packets Through the Routers

Since DAD does not drop any packets—unless instructed to do so, as we shall see below—there will be an uninterrupted flow of i-packets and u-packets to the various defender.

The ease of discrimination between the two types of packets may be useful in two cases:

It is useful for defenders not under attack, as it makes it easy to recognize packets that belong to $L_D$-messages, which the defender may view as particularly important to focus on.

More importantly, it may also provide defenders under an attack a degree of resistance to it, by attempting to drop all u-packets, and retaining only the i-packets. But the attack maybe too strong for a defender to be able to handle the i-messages formed from the retained i-packets.

In this case, the attacked defender can invoke a stage of DAD, called DAD1, to protect it.

βThe Defense DAD has a normally dormant stage, called DAD1, that can be invoked to defend any given registered defender $D$ under attack. Once invoked, DAD1 would instruct all the routers of our ISP to start dropping all u-packets sent to $D$.

This dropping of u-packet would be done at the their very ingress to the router. Such dropping of u-packets at their source would have two important consequences. First, it would eliminate the clogging of routers with u-packets, which would otherwise be allowed to flow over the system of routers.

The second consequence of dropping u-packets at their source, may be even more important. It enable the identification of the members of the attacking botnet. And with careful analysis of the Internet traffic towards the members of the botnet in question, one should be able to identify the mastermind or masterminds of the botnet—the real attackers—and perhaps takes them down. This potential may prevent attacks on sites within our ISP altogether. Because would-be-attackers would be fearful of being discovered.

But this defense raises two issues: (1) who should invoke DAD1, and how; and (2) when should DAD1 be deactivated and by whom. We address these issues below.

Who Should Invoke DAD1, and How? The simple answer to this question is that the attacked defender $D$ itself would invoke DAD1 after noticing that it is under attack. It should be able to notice an attack, because the large increase of the number of u-packets it gets.

The invocation of DAD1 can be done as follows: $D$ will send an appropriate command to the guard, which would send that command to every router. And the router will start dropping u-packets at their ingress.

We note that $D$ should be able to send such a message to the guard, because its ability to recognize and drop the u-packed coming at it should enable it to send messages. But even if $D$ cannot do this electronically, it can advice the registry by phone about this attack, and the registry will send the right command to the guard.
When Should DAD1 be Deactivated, and How?

First note that deactivation of DAD1 needs to be done as soon as possible after the attack concludes, because $D$ would not want to lose the u-packets that may be of interest to it and that it can process when not under an attack.

But how can $D$ detect the conclusion of the attack on it? After all, it does not get any u-packets since DAD1 was invoked, and it will not see any, after the conclusion of the attack, until DAD1 is deactivated. Moreover, the router close to $D$ are in a similar bind, because they would experience much lower congestion once DAD1 started to drop packets addressed to $D$.

One solution to this problem is that $D$ would deactivate DAD1, as a test, say every hour. If it detects an attack it will invoke DAD1 again. And if there no attack, then deactivation is done.

Another potential solution is for all the routers to report periodically to the guard the number of packets addressed to $D$ they handled. The guard, in turn, would be able to conclude from these reports if the attack is over, and it can act appropriately.

The first solution above has the advantage of not making new requirements from the routers.

5 Evaluation

We have introduced two different defense mechanisms based on our criterion of discrimination between messages that a given defender defined as impotent to it, and all other message sent to it. One of thee mechanisms is scrubbing++, which is an upgrade of the conventional concept of scrubbing center; and the other is a brand new mechanism called DAD which relies on the support of routers, and which uses scrubbing++ as one of its tools. These mechanisms have their different pros and cons, but they have this in common:

Both ensure the delivery of practically all messages addressed to a defender $D$, which $D$ defined as important to it. Therefore, they both mitigate the unreliability drawback of the conventional scrubbing centers (cf. Section 1.0.1).

We will now spell out the very different pros and cons of each of these mechanisms.

The Pros and Cons of Scrubbing++:

Like the conventional scrubbing center, scrubbing++ can operate practically anywhere over the internet. This is a great advantage over DAD.

But, like the conventional scrubbing centers it suffers from an unequal arm race. And it is expensive to operate, and thus expensive for defenders to employ.

The Pros and Cons of DAD:

Unlike scrubbing++, DAD can operate only in a region where it gets the support of the routers. So it has a much narrower range of applicability than scrubbing++.

On the other hand, where it can be used it has the following advantages:

First, it may suffer only marginally from the unequal arm race with attackers, as this arm race can be felt only in the operation of the guard.
second, due to the dropping of u-packets, addressed to defenders under attack, at their source (cf. Section 4.0.8), DAD would eliminate the clogging of routers with u-packets, which would otherwise be allowed to flow in the system of routers.

Third, the consequence of dropping u-packets at their source, may be even more important. As it enable the identification of the members of the attacking botnet, which should help in identifying its masterminds. This capability may end up freeing the region defended by DAD from DDoS attacks.

And fourth, DAD provide a broad, relatively cheap, and enduring support for all registered sites resident in the domain of our ISP, and there can be many of them. (The types of sites that are eligible for this support depends on the judgment of the registry.)

**Recommendation:** The two defense mechanism introduced in this paper have distinct ranges of applicability. Scrubber++ can be deployed practically everywhere over the Internet. And it is preferable over the conventional scrubbing center of which it is a simple extension.

DAD can be used only in a region where it can get the support of routers. And it is preferable over scrubbing++ in such a region, due to its quite unique advantages. However, as we have seen, scrubber++ has a role to play along with DAD, as it serves as one of its components.

## 6 Conclusion

This paper introduces an unequivocal criterion of discrimination between two kind of messages and packets; those that are defined as *important* by a given defender, and those that are not. This criterion gave rise to two novel, and very different defense mechanisms.

One of them, called *scrubber++*, which is a simple upgrade of the conventional scrubbing centers, and eliminates some of its drawbacks. This mechanism can be deployed practically everywhere over the Internet.

The other mechanism, called DAD, requires lightweight support by router. It has, thus, a limited applicability. But when DAD gets the support of the routers in a given region, it provides powerful capabilities. One of them is that it enables the identification of the attackers.

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