

DDoS Attack and Defense: Review of Some Traditional and Current Techniques

Muhammad Aamir and Mustafa Ali Zaidi
SZABIST, Karachi, Pakistan

Abstract—Distributed Denial of Service (DDoS) attacks exhaust victim’s bandwidth or services. Traditional architecture of Internet is vulnerable to DDoS attacks and an ongoing cycle of attack & defense is observed. In this paper, different types and techniques of DDoS attacks and their countermeasures are reviewed. The significance of this paper is the coverage of many aspects of countering DDoS attacks including new research on the topic. We survey different papers describing methods of defense against DDoS attacks based on entropy variations, traffic anomaly parameters, neural networks, device level defense, botnet flux identifications and application layer DDoS defense. We also discuss some traditional methods of defense such as traceback and packet filtering techniques so that readers can identify major differences between traditional and current techniques of defense against DDoS attacks. Before the discussion on countermeasures, we mention different attack types under DDoS with traditional and advanced schemes while some information on DDoS trends in the year 2012 Quarter-1 is also provided. We identify that application layer DDoS attacks possess the ability to produce greater impact on the victim as they are driven by legitimate-like traffic making it quite difficult to identify and distinguish from legitimate requests. The need of improved defense against such attacks is therefore more demanding in research. The study conducted in this paper can be helpful for readers and researchers to recognize better techniques of defense in current times against DDoS attacks and contribute with more research on the topic in the light of future challenges identified in this paper.

Index Terms—DDoS, Defense, Network, Performance, Security

I. INTRODUCTION

DENIAL OF SERVICE (DoS) attacks [1] are very common in the world of internet today. Increasing pace of such attacks has made servers and network devices on the internet at greater risk than ever before. Due to the same reason, organizations and people carrying large servers and data on the internet are now making greater plans and investments to be secure and defend themselves against a number of cyber attacks including Denial of Service.

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The traditional architecture of World Wide Web is vulnerable to serious kinds of threats including DoS attacks. The attackers are now quicker in launching such attacks because they have sophisticated and automated DoS attack tools available which require minimal human effort. The attack aims to deny or degrade normal services for legitimate users by sending huge traffic to the victim (machines or networks) to exhaust services, connection capacity or the bandwidth. In a broader classification, types of DoS attacks can be mentioned as in figure 1.

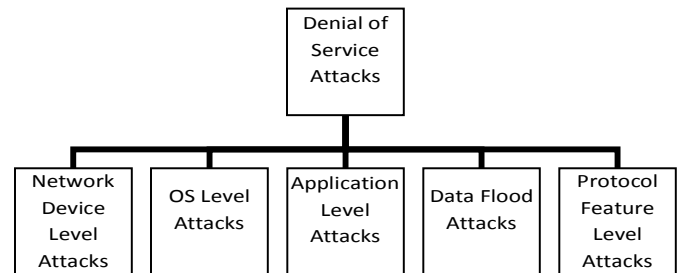


Fig. 1. DoS attack types in a broader classification.

In figure 1, five types of DoS attacks are mentioned. In network device level attacks, the target is some hardware device on the network such as a router. The attack is launched by exploiting some software bug or hardware resource vulnerability. In Operating System (OS) level attacks, vulnerabilities of operating system in the victim machine are used to launch DoS attack. In application level attacks, bugs or vulnerabilities in the application are identified to exploit them for DoS attack. Port scanning for identifying open ports of a remote application is very common in this perspective. Such attacks are now getting more popular as they present the traffic to a network and its devices similar to the legitimate traffic. Therefore, in a scenario where most of other attacks are now identifiable, application level attacks offer more success rate to attackers. In data flood attacks, targets are the connection capacity of a remote host or the bandwidth of a network. Heavy traffic is generated by the attacker towards the victim to exhaust connectivity or bandwidth resources so that normal services are denied or degraded for requests of legitimate users. In protocol feature attacks, the weaknesses of some protocol features are used to exploit them for launching a DoS attack. For example, the source IP address of a data packet

(which relates to Internet Protocol and is a part of TCP/IP stack) can be spoofed by an attacker to launch a DoS attack which can be harder to trace due to a fake address [1].

II. DISTRIBUTED DENIAL OF SERVICE ATTACKS

In a Distributed Denial of Service (DDoS) attack, the attacker makes a huge impact on the victim by having multiplied power of attack derived by a large number of computer agents. It is made possible by the attacker through making a large number of computer machines under his control over the internet before applying an attack. In fact, these computers are vulnerable in the public network and the attacker exploits their weaknesses by inserting malicious code or some other hacking technique so that they become under the control of the attacker. These compromised machines can be hundreds or thousands in numbers. They behave as agents of the attacker and are commonly termed as ‘zombies’. The entire group of zombies is usually named as a ‘botnet’. The size of the botnet decides the magnitude of attack. For larger botnet (increased number of zombies in a botnet), attack is more severe and disastrous.

Within a botnet, the attacker chooses ‘handlers’ which perform command and control functions and pass the instructions of the attacker to the zombies. The zombies directly attack on the victim. There is a group of zombies or agents under each handler. These handlers also pass the information received from zombies about the victim to the attacker [2]. Therefore, handlers are the machines which directly communicate with the attacker and zombies. As the handlers and zombies are also compromised machines in the public network under the control of an attacker, the users of such machines are usually unaware of the fact that there machines are being used as a part of some botnet. A typical architecture of DDoS attack is mentioned in figure 2.

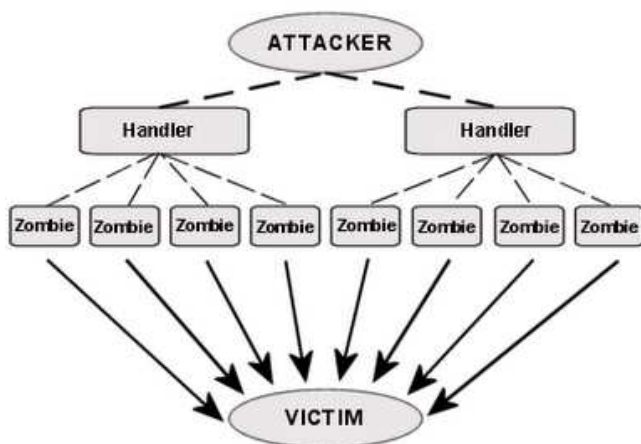


Fig. 2. Architecture of DDoS attack.

The attack employs client server technology and a stream of data packets is sent to the victim for exhausting its services, connections, bandwidth etc. The *data flood attack* type of DoS is mostly used in DDoS attacks.

A. Classification of DDoS Attacks

With the evolution of internet, cyber attacks have also increased manifold. Earlier DDoS attacks were manual where attacker had to perform many steps before the launch of final attack, such as port scanning, identifying available machines in the public network to create botnet, inserting malware etc. With the passage of time, sophisticated attack tools have been developed to assist attackers in performing all or some steps automatically to reduce human effort. The attackers can just configure desired attack parameters and the rest is done by the automated tools. Some common automated attack tools available are *Trinoo*, *TFN* (Tribe Flood Network), *TFN2K*, *Stacheldraht*, *Shafit*, *Knight* and *Trinity*. Some of them work on IRC (Internet Relay Chat) where handlers and zombies do not know identities of each other and the communication among them is done indirectly. The others are agent based in which communication is direct and handlers and zombies know each other’s identity [3]. Therefore, when DDoS attacks are classified by the degree of automation, they are mentioned as *Manual*, *Semi-automatic* and *Automatic* attacks.

DDoS attacks are further classified by attack rate dynamics i.e. the way how rate of attack varies with respect to the passage of time. The classes are *Continuous Rate* and *Variable Rate* attacks. In continuous rate, the attack has constant flow after it is executed. On the other hand, variable rate attack changes its impact and flow with time, making it more difficult to detect and respond. Within variable rate, the attack rate dynamics can further be implemented as *Fluctuating* or *Increasing*. Moreover, based on the data rate of attack traffic in a given network, the attacks are also categorized as *high rate* and *low rate* DDoS attacks [4].

DDoS attacks are also classified in the literature as ‘by impact’ i.e. it can be *Disruptive* in which the normal service is completely unavailable to users, or it can be *Degrading* in which the service is not completely unavailable but experiences considerable decrease in the productivity.

The major classification of DDoS attacks is ‘by exploited vulnerability’ through which the attacker launches an attack on the victim. The classification is given in figure 3. In the said classification, *flood attack* is used to bring down the victim’s machine or network’s bandwidth. It has a few major sub-classes like *UDP flood*, *ICMP flood* and *TCP flood*. In fact, all flooding attacks generated through DDoS can be of two types; *direct attacks* and *reflector attacks* [5]. In direct attacks, zombie machines directly attack the victim as shown in the attack architecture in figure 2. On the other hand, in reflector attacks, zombies send request packets with spoofed IP (IP of the victim) in source address to a number of other compromised machines (PCs, routers etc.) and the reply generated from such machines is targeted towards the victim for the impact desired by the attacker. In such a way, reflection of the traffic is observed in these kinds of attacks. A classic example is sending ‘ping’ requests with spoofed source IP and the ‘ping’ replies are targeted towards the victim. The goal of attacker launching such attacks is to saturate the bandwidth of

the victim with huge amount of traffic. The architecture of reflector attack is shown in figure 4.

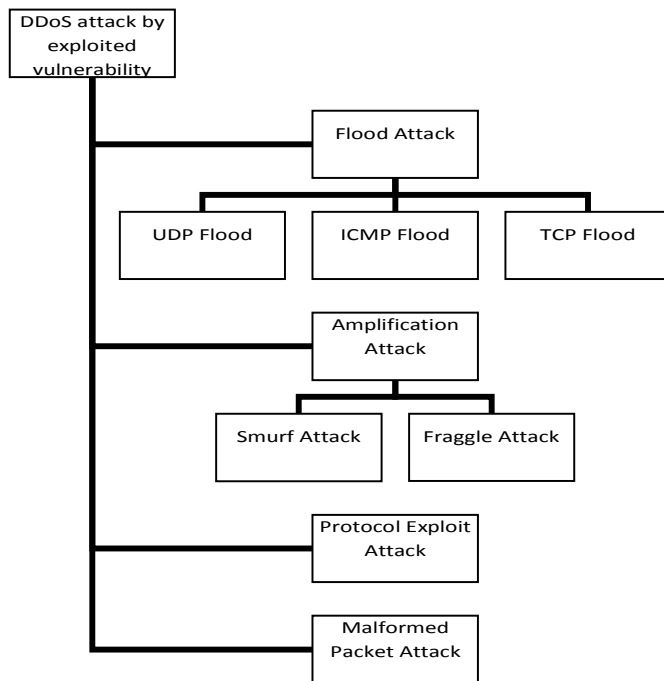


Fig. 3. DDoS attack by exploited vulnerability – Classification.

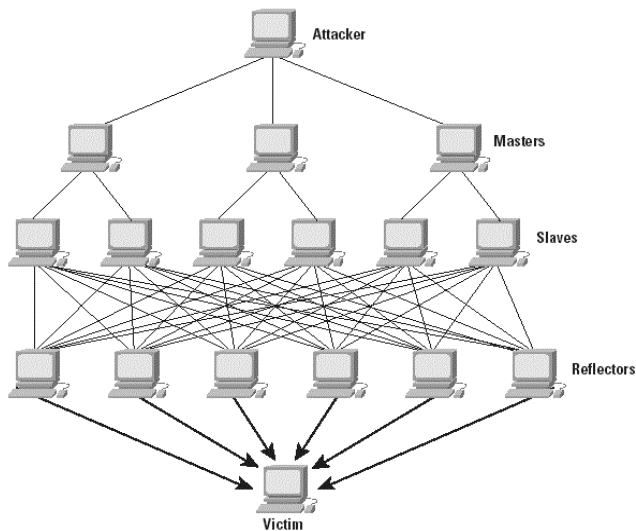


Fig. 4. Architecture of DDoS reflector attack ('Masters' represent Handlers and 'Slaves' represent Zombies).

In UDP (User Datagram Protocol) flood attack, the target is usually the victim's machine. The agents of botnet send huge amount of UDP packets to the victim with randomly selected destination port. The machine identifies that there is no application running on the specific port and replies with ICMP (Internet Control Message Protocol) packet(s) of 'Destination host unreachable' [1]. The source IP is spoofed by the attacker to prevent its own machine(s) from any return effect or trace back, therefore the reply is not reached to actual traffic

generated sources. When the victim's machine is continuously made busy to identify ports and send reply messages at a very fast rate i.e. beyond its processing speed and capacity, it crashes or is brought down. Moreover, the huge amount of UDP packets sent by the attack sources can also lead congestion in victim's bandwidth and degrade services for other legitimate requests that may be sent to other machines on the same network.

In ICMP flood attack, the target is bandwidth saturation. In this attack, huge amount of echo packets i.e. 'ping' requests are sent by the attack sources to remote host(s). The source IP is spoofed and contains victim's address on targeted network. As a result, massive traffic is generated in the network which ultimately leads to the bandwidth saturation. The 'ping' requests can be sent directly or through agents to multiply the effect.

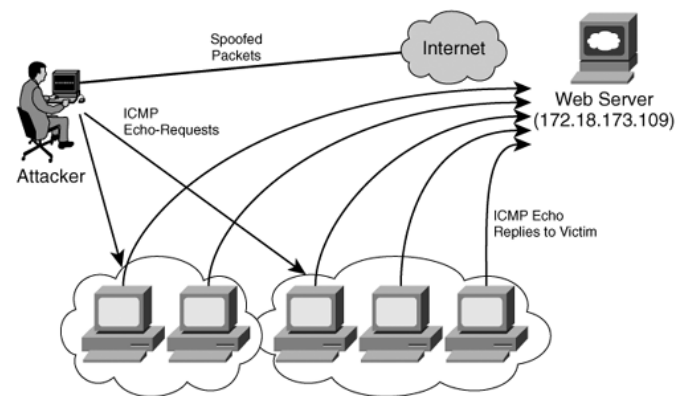


Fig. 5. ICMP flood attack.

In figure 5, it is shown that an attacker spoofs IP packets before sending ICMP-ECHO-REQUEST or 'ping' packets to remote hosts. The hosts then generate ICMP-ECHO-REPLY packets to respond to the spoofed source on targeted network resulting in the bandwidth saturation.

In TCP flood attack, sophisticated attackers generate TCP traffic with legitimate-like packet headers so that traffic is not easily detectable as an attack. The payload is formed with random values and huge amount of such traffic is sent towards the victim targeting the bandwidth saturation and CPU consumption of the server for degrading services to legitimate clients [5].

In amplification attacks, the broadcast feature of IP addresses is exploited on network routers. The attack is generated with spoofed source IP addresses so that routers broadcast the same within their broadcast domains to update routing tables. In this way, amplification and reflection of IP traffic are observed as all routers broadcast spoofed IP addresses to all addresses in their broadcast domain. As a result, massive traffic is generated in the network reducing the bandwidth for legitimate requests. Two major classes of amplification attacks are *smurf attack* and *fraggle attack*. They are effectively the same as ICMP flood attack and UDP flood attack respectively and work through sending ICMP echo and

UDP echo packets to bring down a victim or saturate bandwidth with the help of spoofed source IP addresses.

The protocol exploit attacks make use of some weakness of a protocol. A common example is TCP SYN attacks which exploit three-way handshake feature of Transmission Control Protocol. In this client / server model, the client first initiates communication by sending a SYN signal to the server and requesting to establish a connection. The server responds with ACK signal which is an acknowledgement that the server is ready to establish the requested connection. Finally, the server waits for ACK signal from the client and when it receives the same, connection is successfully established.

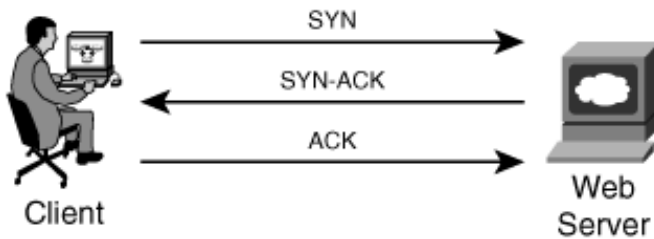


Fig. 6. Three-way handshake in TCP.

The SYN ACK attack or *SYN flood attack* is generated by sending a large number of spoofed SYN signals to the victim and never acknowledging the same for which the server waits after sending ACK signal to the client. The server has to wait for a certain period of time before it releases the connection for any new request (normally it is between 45 to 360 seconds) [4]. The buffer capacity is limited for connections and if large number of such attack based SYN messages is sent through multiple agents to occupy the space in buffer, it results in a full queue buffer which makes the server unable to process new legitimate requests. Moreover, if the server is to maintain full queue buffer all the time and high quantity of resources is consumed in the process, it may give a rise to TCP / IP stack overflow leading the server to crash [6]. It is also considered under the category of flood attacks.

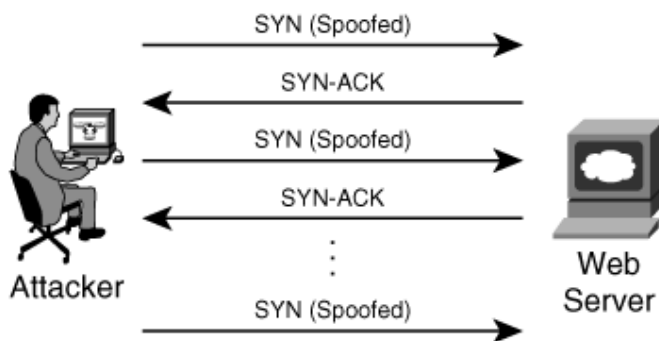


Fig. 7. SYN ACK attack in TCP.

In malformed packet attacks, the attacker relies on malicious data within IP packets that are sent by agents to the victim.

These attacks can completely crash the victim machine. Two subcategories of such attacks are *IP address attack* and *IP packet options attack*. In IP address attack, the packets are formed with same source and destination address. As a result, the victim machine is unable to process such packets and tricked in a way that it can finally crash. On the other hand, in IP packet options attack, the optional fields in IP packets are randomized by the attacker to trick the processing of victim machine. For example, all quality of service bits are made '1' for which the victim is unable to extract the information from packets and the system speed is greatly reduced. When this attack is applied with different combinations through multiple agents, it may also lead a victim machine to crash.

B. Application Layer DDoS Attacks

In the network layer or infrastructure layer (Layer 3) attacks, the malicious part resides in packet header or payload to compromise victim's CPU cycles, processing, bandwidth etc. However, with the introduction of sophisticated DDoS detection & mitigation tools, attackers have also started changing their strategies to avoid detection and mitigation by increasing their focus towards *application layer (Layer 7) attacks*. These attacks mimic the legitimate clients to disturb or destroy the victim's resources. Therefore, traditional DDoS detection techniques are unable to identify such attacks. In these attacks, complete communication with the victim is established just like legitimate users. However, numerous connections are generated aiming to deny or degrade the service or bandwidth for legitimate clients.

Application layer attacks are subject to the establishment of complete TCP connections with the victim. Therefore, the attacker has to disclose real IPs of zombie machines to the victim. Otherwise, it is not possible to make such connections. However, due to large number of zombies, the attacker does not worry about this attack limitation [5]. If such machines are identified and filtered at some stage, the attacker uses other group or pool of zombies to process the continuity of the attack. After establishing TCP connections with the victim in a large number, the attacker starts communication through sending requests for relatively large processing such as downloading heavy image files or making database queries. In this way, resources are reserved against such attack traffic to deny or degrade the services for legitimate users. Effectively, application layer attacks are also flooding attacks and categorized as *HTTP flood*, *HTTPS flood*, *FTP flood* etc. Sometimes, they are collectively mentioned as *GET floods*.

C. Motivation behind DDoS Attacks

People behind DDoS attacks may be motivated by personal, social or financial benefits. Attackers may do so due to personal revenge, getting publicity or some political motivation. However, most DDoS attacks are launched by organized criminal groups targeting financial websites such as banks or stock exchanges. They also focus on targeting other

finance related businesses such as e-commerce and gambling sites.

The financial impact of DDoS attacks on victims can be disastrous. In recent past, criminal groups have launched a number of attacks on stock exchange websites throughout the world. A few DDoS attacks reported in years 2011 and 2012 were on NASDAQ & BATS stock exchanges along with Chicago Board Options Exchange (CBOE), New York stock exchange and Hong Kong stock exchange [7], [8], [9]. As a consequence, incidents have been observed as disruption of business activities of some major trading companies for some duration of time resulting in financial losses.

D. DDoS Attacks on Networks in 2012 – Quarter-1

Here we include some information on DDoS attack statistics obtained in the first quarter of 2012 on networks of various sectors in the world including *financial sector networks*. The source of data is ‘Prolexic Attack Report Q1 2012’ [10] provided by *Prolexic Technologies*, the world’s largest and most trusted DDoS attack mitigation provider. Ten of the world’s largest banks and the leading e-commerce companies get services of Prolexic to protect themselves from DDoS attacks. The range of data is based on all DDoS attacks dealt by Prolexic in different regions of the world. Some key information extracted from the report regarding comparison of first quarter of 2012 with the last quarter of 2011 is:

- 1) Total number of DDoS attacks was increased by 25%.
- 2) Layer 7 (application layer) attacks were increased by 25%.
- 3) Attack duration became shorter i.e. 28.5 hours vs. 65 hours.
- 4) A decline was observed in UDP flood attacks.

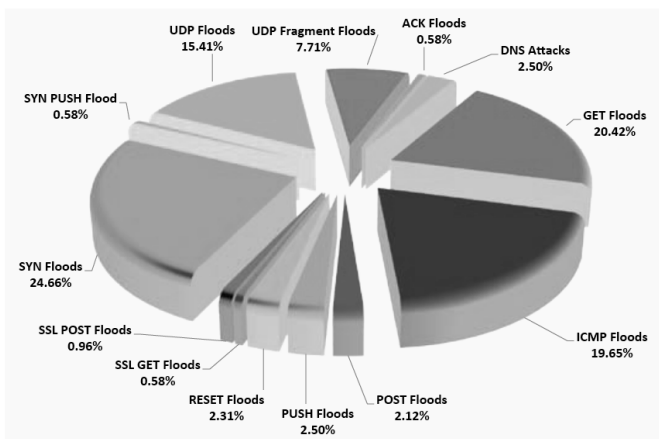


Fig. 8. Total DDoS attack types (2012 Q1).

In figure 8, total DDoS attack types observed in first quarter of 2012 are presented. It is shown that attackers preferred infrastructure layer (Layer 3) attacks than application layer (Layer 7) attacks. Major attacks were SYN flood attacks,

ICMP flood attacks, UDP flood attacks and GET flood attacks. SYN floods, ICMP floods and UDP floods are the part of infrastructure layer attacks whereas GET floods belong to application layer attacks.

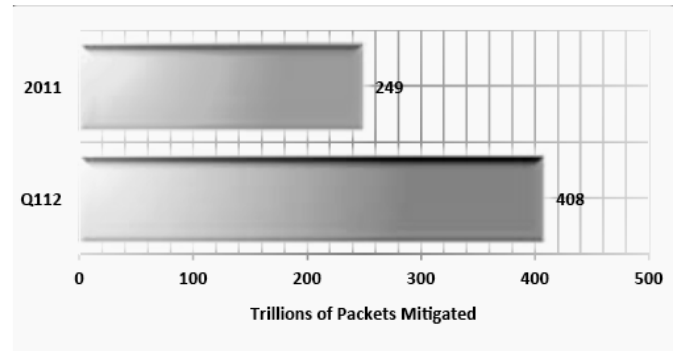


Fig. 9. Total DDoS traffic mitigated by Prolexic.

In figure 9, numbers of packets related to DDoS attacks mitigated by Prolexic are mentioned. It is observed that packets mitigated only during the first quarter of 2012 are more than total traffic mitigated in year 2011. In quarter 1 of 2012, 408 trillion packets of DDoS attacks were mitigated. It clearly indicates about increasing pace of DDoS attacks on the internet and related networks of current time.

III. DDoS DETECTION AND MITIGATION

Distributed Denial of Service is a huge threat to the Internet today [11]. Attackers are now quicker to launch DDoS attacks with sophisticated attack tools, aiming to get financial benefits and other advantages by denying or degrading victim’s resources for legitimate users. Numerous research papers have been presented to review DDoS attacks and propose their detection & mitigation techniques [1], [2], [3], [4], [5], [6], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [85]. However, it is a fact that accurate detection and mitigation of DDoS attacks is still a difficult task as the traffic is so aggregated at network hops that it is not easy to identify attack packets within a mix of normal and attack traffic. In this section, we review some detection and mitigation mechanisms against DDoS attacks which are more promising in recent times such as statistical analysis of network traffic to estimate attack strength in real time, role of neural networks in real time attack analysis and research attempts to mitigate application layer DDoS attacks which are drawing more attention of attackers today. In addition to this, traditional methods of traceback such as packet marking, packet logging and pushback etc. are also discussed ahead.

The ability of a DDoS detection and mitigation technique lies on its accuracy and reliability so that false positives and false negatives in a system can effectively be reduced i.e. it should not allow the packets to pass through the mitigation mechanism that belong to the attack traffic (false negatives) and reach the victim, and it should also not drop the packets

that belong to the legitimate traffic (false positives). As far as the countermeasures against DDoS are considered, they are usually categorized as three types of techniques mentioned below:

- Survival techniques
- Proactive techniques
- Reactive techniques

In survival techniques, the devices and systems which may be a victim of some DDoS attack are equipped with sufficient resources so that services may still be available for legitimate users in case of occurrence of a DDoS attack. The resources such as CPU power, bandwidth, memory etc. are made sufficient and redundancy of resources is also maintained wherever applicable.

In proactive techniques, the aim is to detect an attack earlier than it can reach the victim. After detection, a mitigation procedure can be called immediately to filter or rate-limit the attack traffic.

In reactive techniques, the victim actually encounters a DDoS attack on its services and then a detection & mitigation procedure is called to trace the attack origin and filter the traffic coming from identified sources.

The above mentioned defense mechanisms can be applied by the control centers that may be located at different points such as:

- Source-end
- Core-end
- Victim-end
- Distributed ends

At source-end defense point, the source devices identify malicious packets in outgoing traffic and filter or rate-limit the traffic. It is the best point of defense as minimum damage is done on the legitimate traffic. Moreover, another advantage is the minimum amount of traffic at this point for which fewer resources are required by the detection & mitigation mechanism.

In core-end defense, any core router in the network can independently attempt to identify the malicious traffic and filter or rate-limit the same. However, at this point of defense, the traffic is aggregated i.e. both attack and legitimate packets arrive at the router. In case of a filtering technique, it is a possibility that legitimate packets would also be dropped. On the other hand, it is a better place to rate-limit all the traffic.

In the victim-end defense technique, the victim detects malicious incoming traffic and filter or rate-limit the same. It is a place where a legitimate and attack traffic can clearly be distinguished. However, attack traffic reaching the victim may have severe effects such as denied or degraded services and bandwidth saturation.

Attack detection and mitigation at distributed ends can be the most promising strategy against DDoS attacks [24]. As discussed before, source-end is a better place for both filtering and rate-limiting the attacks. The core-end is good to rate-limit all kinds of traffic whereas the victim-end can clearly identify

the attack traffic in a mix of legitimate and attack packets. Therefore, distribution of the methods of detection and mitigation at different ends can be more advantageous. For example, an attack can be identified at the victim-end for which an attack signature can be generated. Based on this signature, the victim can send requests to upstream routers to rate-limit such attack traffic. There are various intrusion detection systems available to detect attacks and prevent systems at device or network level such as Host-based Intrusion Detection System (HIDS), Network-based Intrusion Detection System (NIDS), Host-based Intrusion Prevention System (HIPS), Network-based Intrusion Prevention System (NIPS), and Wireless Intrusion Prevention System (WIPS) etc.

A. Statistical Analysis of Network Traffic

Researchers have so far made good contributions to make use of statistical features of network traffic for detection of DDoS attacks. They are also used for traceback schemes i.e. identifying the attack source and applying mitigation techniques such as filtering or rate-limiting [5], [24]. The use of *Regression Analysis* has been proposed in [26] and [27] where strength of DDoS attack was estimated and compared with actual strength. The comparison results were promising, indicating that the method is applicable for DDoS strength evaluation in router or a separate unit communicating with the router. Two forms i.e. multiple and polynomial regressions have been discussed. The multiple regression method is described as:

$$Y_i = \hat{Y}_i + \epsilon_i \quad (1)$$

$$\hat{Y}_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_p X_{pi} \quad (2)$$

Here, Y is the dependent variable. X_1, X_2 upto X_p are p independent variables and β_0 is the intercept. β_1, β_2 upto β_p are coefficients of p independent variables and ϵ is the regression residual. i represents a particular flow count for which Y is determined.

Using the above description and applying it on the network traffic monitored at a router, the strength of DDoS attack can be estimated. A flow-volume based approach is applied in the process to construct the traffic profile under normal traffic scenario. When total traffic arriving at a router in a designed time window ' Δt ' is deviated from the constructed profile based on flow-volume relationship, attack is detected and its strength is calculated that can be used to estimate the risk and level of compromise against the attack. The multiple regression is applied when more than one independent variables are studied to be linked with one dependent variable or the output. In this case, independent deviations in flow and volume (inputs) of the traffic are studied in specific time intervals and the strength of DDoS attack (output) is calculated. Several more statistical parameters contribute towards changing the traffic flow and volume, hence the overall aggregation in the network. Such parameters are also considered and carefully calibrated to make an effective detection and strength estimation of DDoS attacks.

In polynomial regression, relationship between one independent variable and one dependent variable is expressed as an i_{th} order polynomial. Eq. (1) is the same whereas \hat{Y}_i is described as:

$$\hat{Y}_i = \beta_0 + \beta_1 X + \beta_2 X^2 + \dots + \beta_n X^n \quad (3)$$

Again, Y is the dependent variable as expressed in Eq. (1). X is the independent variable appearing upto n_{th} order of the polynomial and β_0 is the intercept on XY -plane. β_1, β_2 upto β_n are coefficients of X in the n_{th} order.

In this DDoS attack estimation technique; a relationship is established between the deviation in sample entropy (input) of the traffic in specific time interval and the strength of DDoS attack (output). The scheme is based on the assumption that the attack traffic is seen different in the network from the normal traffic. The deviation in entropy i.e. X is represented here as:

$$X = H_c - H_n \quad (4)$$

Here, H_c is the calculated entropy in a time interval ' Δt ' and H_n is normal entropy i.e. the entropy value under normal traffic scenario. When deviation is observed in the value of entropy in a specific time interval, it is detected that DDoS attack has occurred and the strength of DDoS attack is thus calculated by applying the polynomial regression model [27].

Sample entropy H [27], [28] is defined as the degree of concentration of a distribution. It is given as:

$$H = -\sum_{i=1}^N p_i \log_2 p_i \quad (5)$$

In Eq. (5), p_i is equal to n_i/S where n_i represents number of bytes arriving in i_{th} flow of traffic in a specified time interval and S is the summation of total number of bytes in N flows. It is represented as:

$$S = \sum_{i=1}^N n_i \quad (6)$$

Here in Eq. (6), $i = 1, 2, \dots, N$. In order to detect the attack and estimate the attack strength, the sample entropy is calculated in time intervals ' Δt ' continuously. When the calculated entropy is different from the normal entropy H_n , the attack is detected and the difference between entropy values i.e. X is used to estimate the attack strength through polynomial regression. The value of sample entropy indicated in Eq. (5) lies between the range of 0 to $\log_2 N$.

B. Traceback Schemes

The traceback in DDoS defense refers to identify the attack source through some mechanism so that the attack may be blocked or mitigated at the origin. However, effectively implementing the traceback to identify DDoS source is difficult due to some well known reasons such as easy

spoofing of source IP addresses by the attacker, the stateless nature of IP routing where complete path is not known i.e. only next hop is usually inserted and updated in router's routing table, link layer spoofing i.e. MAC address spoofing and intelligent attack techniques provided by the modern attack tools [29].

In a research attempt found in [30], the authors used entropy variations of the network traffic to implement a traceback scheme. The difference in entropy values between normal traffic and the traffic under DDoS attack was used to detect the attack. Once it is detected, the traceback is initiated through a pushback tracing procedure. The proposed scheme has an advantage over traditional packet marking schemes in terms of scalability and storage requirements in victim or intermediate routers. The method stores only short-term information of traffic entropy in order to detect the DDoS attack. The authors also presented experimental analysis to claim that the method is able to implement accurate traceback in a large-scale DDoS attack scenario (attack with thousands of zombies) within a few seconds.

In [31], the authors focused on detection and traceback of low-rate DDoS attacks as they are very much like normal traffic and have more ability to conceal their attack related identities in the aggregate traffic. Two new information metrics were proposed (generalized entropy metric and information distance metric) to detect the low-rate DDoS attacks. In said approach, they measured difference between the legitimate and attack traffic through their newly proposed information metrics and were able to detect the attack a number of hops earlier than the counts mentioned in previously proposed schemes. Their information metrics can increase the detection sensitivity of the system and thus the scheme is capable of identifying low-rate DDoS attacks reducing the false positive rate effectively. Moreover, the traceback mechanism can efficiently trace all attacks generated at the attacker's own LAN i.e. zombies.

In addition to entropy variation scheme, a few other traditional methods also exist to traceback DDoS sources [29]. They are the schemes of reactive nature. The classification is given in figure 10.

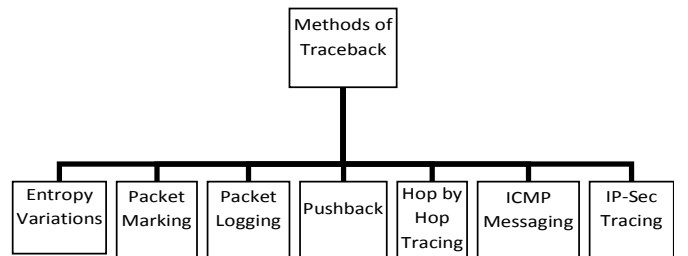


Fig. 10. Traceback Schemes – Classification.

In packet marking schemes, the idea is to trace the path through upstream routers upto the attack sources i.e. zombies. It is a common method employed in traceback implementations but contains some inherent drawbacks. There are two types of packet marking i.e. *probabilistic* and

deterministic packet marking. In probabilistic packet marking (PPM), each router embeds its IP address probabilistically into the packets travelling from the source to destination. The method is based on the assumption that attack packets are much more frequent than legitimate packets. Once the attack is identified, the victim needs sufficient number of packets to reconstruct the path up to the source through the embedded information inside the packets. There is no specific field in an IP packet for such markings. Therefore, it utilizes rarely used 16-bit fragment ID in IP packets for the markings [14]. However, this technique has some major drawbacks with it. For example, it is valid only for direct attacks. It cannot detect the true location of the attack source in case of reflector attacks as the traced location will be of reflector machines and not of zombies. Moreover, in a well distributed attack with a fairly large number of zombies, the chance of wrong construction of the path increases. It is also a known fact that today, due to large number of zombies, the attackers disclose real IPs of zombie machines (as in application layer attacks) and hence the sources are already revealed. In such cases, packet marking schemes as well as other traceback methods are useless. The packet marking scheme also places significant computational overhead on the intermediate routers when traceback is initiated. It also assumes that victim remains available during the process of traceback (which requires some minutes) as the victim has to send control messages to the upstream routers. However, in real scenarios, the bandwidth is saturated due to attack impacts and therefore the control messages are dropped, resulting in wrong construction or misconstruction of the attack path. In addition to these drawbacks, the packet marking scheme can also be easily paralyzed. That is, if the attacker sends packets with larger than MTU (Maximum Transmission Unit) size of packets, the packet marking is not possible as fragment ID field is used in such cases for packet identification. The routers do not mark packets and according to [32], routers will then be sending the marking information through ICMP packets which is even more complicated and contains some additional drawbacks. For example, due to bandwidth saturation after DDoS attack, several such ICMP packets may be dropped in the network path and the victim would not be able to construct the path. Moreover, some networks do not allow passing ICMP packets through their border routers; therefore the attack tree would not be accurately constructed [24].

In deterministic packet marking (DPM), the router embeds its IP address deterministically into the IP packets. The scheme was introduced to overcome some drawbacks of probabilistic packet marking as it has simple implementation and requires less computational overhead on intermediate routers. However, it has its own limitations. In this scheme, the packets are marked with the information of only the first ingress edge router i.e. the complete path is not stored as in PPM. Therefore, it requires even more packets to reconstruct the attack path. Moreover, it also has some inherent shortcomings just like PPM scheme as discussed above [14].

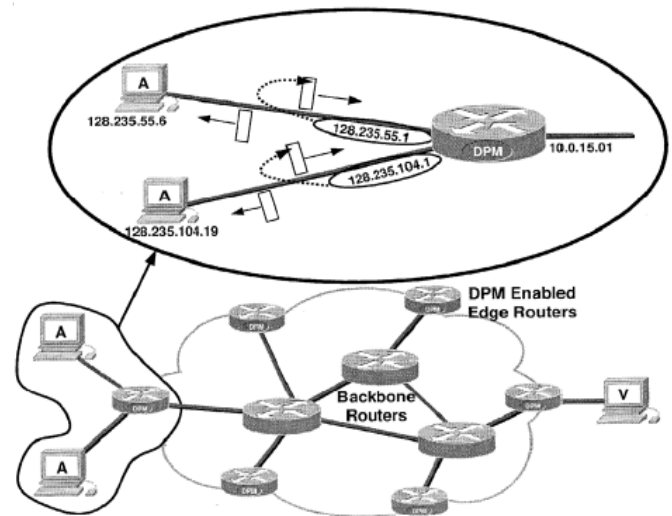


Fig. 11. Deterministic Packet Marking (DPM).

In figure 11, it is shown that under DPM scheme, packets are marked at the first ingress edge router closest to the source. This marking remains unchanged as long as the packet traverses the network. If the victim is also a part of the internet under single administration (as shown), the same first mark will be available for the victim to traceback the source. The scheme is also more efficient due to deterministic marking of packets as an attempt by the attacker to spoof the mark is overwritten with the correct mark by the first router through which the packet traverses [29].

In the packet logging scheme [29], which is also referred as Source Path Isolation Engine (SPIE), the information of each packet is stored or logged at routers through which the packet is passed. The routers under this scheme are termed as Data Generation Agents (DGAs). The stored information of the packet contains constant header fields and first 8 bytes of the payload which are hashed through many hash functions to produce *digests*. These digests are stored by DGAs using *bloom filter*, a space-efficient data structure. This structure is capable of reducing storage requirements by large magnitude. When about 70% of a bloom filter is filled, it is archived for later information processing and the new bloom filter is used. The duration of using a single bloom filter is called *time period*. Hash functions are changed during different time periods and the data necessary to reconstruct the attack path is stored in a table called Transform Lookup Table (TLT).

When an attack is detected under packet logging scheme, the central management unit called SPIE Traceback Manager (STM) sends requests to the units allocated for region wise management of DGAs known as SPIE Collection and Reduction Agent (SCARs). Each SCAR obtains copies of digests and TLTs from DGAs of its own region for the appropriate time period. It can identify which packets were forwarded by which router and reconstruct the path based on the obtained information. All SCARs report the calculated information to the STM. The STM is finally able to

reconstruct the attack path through the whole network based on the information provided by SCARs. The main drawback of this scheme has been identified as the requirements of enormous computational power and storage capacity due to hash processing and bloom filter usage.

In the pushback scheme [33], the router under congestion sends the rate-limit request to upstream routers. In fact, it determines from which routes the stream of packets is arrived and devises an attack signature for such traffic. The signature belongs to the aggregate traffic having some common property such as the same destination address [24]. A local mechanism called Aggregate Congestion Control (ACC) is responsible to determine the congestion on the router and create the attack signature. Based on this signature, the router sends requests to adjacent neighbors (upstream routers) to rate-limit such aggregate traffic. The neighbors then recursively send requests (propagate pushback) to further upstream routers. However, congested router sends rate-limit requests only to those upstream routers from which it receives a significant fraction of the aggregate traffic. It also determines the rate-limit amount for each of its upstream routers according to the *max-min fairness* algorithm. Under this algorithm, a bandwidth share is allocated in such a way that the minimum data rate which a flow can achieve is brought to the maximum first. Then, the second lowest data rate which a flow can achieve is brought to the maximum etc. In this way, the same share of bandwidth is allocated to all.

In hop by hop tracing scheme, the debugging idea is used where the source of attack traffic is identified on the router closed to the victim considering the incoming aggregate traffic flow by the adjacent routers. The process is repeated iteratively to the upstream routers until the attack source is revealed [29]. In ICMP messaging scheme [34], routers are programmed to send ICMP messages along with the network traffic. Such ICMP packets contain some path information in them such as source address, destination address and authentication parameters etc. A typical router programmed under such scheme normally sends one ICMP messaging packet for every 20,000 packets passing through it i.e. a traceback message is sent with the proportion of 0.005 percent of the network traffic [29]. It does not affect the flow of other network traffic and victim can still possibly traceback the source after an attack is detected. Like PPM, the method assumes that attack packets are much more frequent than legitimate packets. However, the saturation in bandwidth and other attack impacts may lead the ICMP messaging to drop in its path. In such a condition, the victim may not be able to identify the attack source in the absence of ICMP messaging packets.

The IP-Sec [35] refers to per packet authentication in IP networks through shared secret keys. It is based on the belief that per packet authentication provides more secure communication of IP terminals through the network. It is also assumed that per packet authentication is enough to prevent DDoS attacks as bogus packets are identified during the

authentication process and accordingly discarded [36]. However, a major shortcoming of IP-Sec is the requirement of high computational power during the process of authentication. In such cases, a large volume of incoming packet streams may shift the DDoS impact from the victim server to the authentication module. Before authentication, the IP-Sec mechanism checks Security Parameter Index (SPI) value which resides in the packet header in addition to the authentication information. The SPI value is unique for each flow and only those packets are forwarded to authentication phase which have a valid SPI whereas packets with invalid SPI are discarded. In real cases, attackers are able to discover a session's SPI through intercepting the messages in traffic flow pertaining to that particular session on internet, or by observing the impacts as a result of their own actions such as hit & try methods. The successful discovery of SPI leads to the success in denial of service attack [13].

In IP-Sec based traceback scheme, the idea is to examine the bond or linkage between the devices exercising IP-Sec mechanism. It further assumes that the traceback system knows the complete network topology. The principle is: If IP-Sec is exercised between a router 'A' and the victim 'V' and if an attack is detected, it is to be checked where the attack packets have been authenticated. If 'A' has authenticated such packets, it means that the attack is originated at a place beyond 'A'. On the other hand, if 'A' has not authenticated the attack packets, they are generated at some place between 'A' and 'V'. By examining this linkage of IP-Sec devices and establishing the security associations, the route of the origination of attack can be constructed and the device or group of devices can be located where the attack is generated [29].

C. Application of Neural Networks in DDoS Detection

Artificial Neural Networks (ANNs) are famous learning models for their ability to cope with the demands of a changing environment [37]. They are self-learning and self-organizing models which make them a suitable choice for processes requiring advantages like robustness, fault tolerance and parallelism. Moreover, due to self-learning characteristic, they are good enough to identify and resist unknown disturbances in a system. This property of neural networks has been utilized in DDoS attack detections in some research attempts, as they are capable of identifying the unknown attack patterns that may occur in DDoS attacks.

In [38], the authors have used Linear Vector Quantization (LVQ) model of ANN. In this model, the input layers accept the input vectors called neurons with specified weights which are adjustable according to ANN's self-learning mechanism. The middle layers process the information and pass it on to output layers. In fact, the input and middle layers exhibit the same kind of functionality in all ANN models. However, the transfer function used for information processing at middle layers is unique for each kind of neural network and the appropriate result is consequently forwarded to the output layers. In the case of LVQ model, the information in middle

layers is processed in such a way that the winner neuron takes all of the output share and accordingly passed on to the output layers. It is similar to self-organizing maps and applied in techniques of pattern recognition, multi-layer classification and data compression. Under supervised learning, it knows the target output against different forms of various input patterns [38], [39].

The authors in [38] have simulated the dataset pertaining to a typical DDoS attack flow in five steps which are given in figure 12.

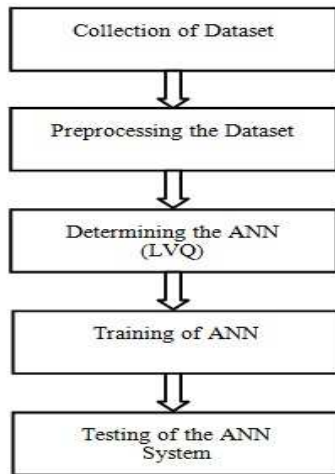


Fig. 12. Implementation Phase – Analyzing DDoS with LVQ.

After testing the system with LVQ as shown above, the authors used the same dataset with Backpropagation (BP) model of ANN (to be discussed ahead) for comparative study. On the basis of their comparison results, they claim that LVQ is more accurate in determining DDoS attacks than BP. They have shown that LVQ was 99.723% accurate on average against their tested dataset whereas the average accuracy of BP was 89.9259% for the same dataset. The accuracies were computed on the basis of percentages of obtained false positives and false negatives against each sample of testing data. There were 10 samples used to test the systems for each of the LVQ and BP models.

In other research attempts found in [40] and [41], the authors have used the Backpropagation (BP) model of neural networks to estimate the strength of DDoS in real time and predict the number of zombies respectively. Backpropagation neural network is a multilayer feed forward network with backpropagation (feedback) of an error function [42]. A simple feed forward neural network has only three layers i.e. input, output and middle layers as shown in figure 13. It is mentioned in the said figure that the input layer has ‘m’ neurons, middle layer has ‘n’ neurons and output layer contains ‘k’ neurons. X_m is the magnitude of input fed to m_{th} input layer’s neuron having weight of W_m and Y_k is the output provided by k_{th} neuron of the output layer. Input layer passes on W_{mn} weights to middle layer which processes them and

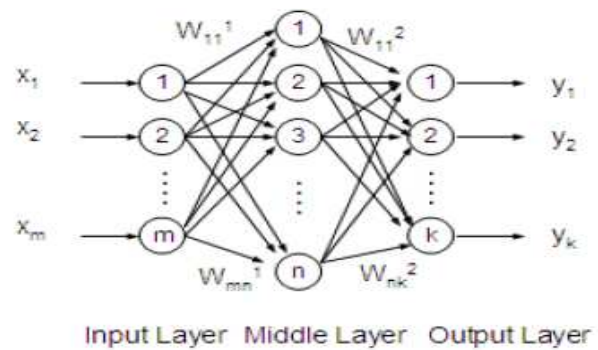


Fig. 13. A simple feed forward neural network.

sends W_{nk} weights to the output. Each weight is revised according to gradient descent of the error through output layer, backpropagated to hidden layer and then to the input layer. Again the information is fed forward and error is fed backward. In this way, weights are adjusted to reduce the error and execute learning and training of the neural network. This process is continued until network’s output error is brought down to an acceptable level or the preset time of learning is achieved [43].

In [40], the authors have trained the BP neural network with a dataset of variations in traffic entropy as inputs and the corresponding actual DDoS strengths as outputs. 20 different samples in the dataset were used for training with 10 Mbps attack strength as the lowest and 100 Mbps being the highest in the dataset. The entropy variations were calculated as discussed before. Therefore, the scheme is based on the assumption that the attack traffic is seen different in the network from the normal traffic. The model was tested with four random inputs of entropy variations for which the calculated attack strengths were 20, 50, 70 and 95 Mbps. The BP neural network’s output was seen promising with little errors. The false positives and false negatives were also very less. Moreover, they also tested the system with variations in network size i.e. number of neurons in the processing layer. They used two layer feed forward network with BP algorithm and found that with the increase in network size, errors are further reduced and more accuracy is achieved. However, in real cases, increasing the network size also increases both training time and the implementation cost.

In [41], the authors have trained the BP neural network to predict the number of zombies behind a DDoS attack. They trained the system with a dataset of variations in traffic entropy as inputs and the corresponding actual number of zombies behind DDoS attack as outputs. The dataset was used for training from 10 to 100 zombies with an increment of 5. The attack strength was a constant rate of 25 Mbps. Effectively, it changed the attack rate per zombie in each data sample ranging from 0.25 Mbps to 2.5 Mbps. The model was tested with different random inputs of entropy variations and the BP neural network’s output was seen promising with little errors. Moreover, they also tested the system with variations in

network size and found that with the increase in network size, errors are further reduced and more accuracy is achieved.

D. Some Common Countermeasures Against DDoS Today

In this part, we study some well known countermeasures against DDoS attacks. They are quite common today in various DDoS defense implementations. Two proactive and two reactive techniques are discussed:

- Ingress / Egress Filtering
- D-WARD
- Hop Count Filtering (HCF)
- SYN Cookies

In the ingress / egress filtering [44], the edge routers are programmed by network administrators to filter the packets coming inside the network (ingress filtering) and going outside (egress filtering). The packet filtering is commonly based on the source IP addresses beyond the allocated address space to a network from which the packet is received at router's interface. The source address beyond the allocated space is deemed to be spoofed and hence the packet is discarded. However, the filtering can also be based on some other criteria such as port number, protocol type etc. This method is a source-end, proactive technique capable of protecting against both direct and reflector types of DDoS attacks [24].

The ingress / egress filtering is easy to deploy as ISPs and network administrators have the knowledge of assigned IP address spaces allocated to different customer networks. Therefore, IP spoofing can be prevented. However, it has some limitations such as:

- 1) The sophisticated attackers can spoof IP addresses from the subnet range. For such an attack, the ingress or egress filtering cannot detect the IP address spoofing.
- 2) The attackers are now more focused towards application layer attacks in which the spoofing is not used and actual addresses of zombies are revealed such as HTTP flood attacks to download images from a website. The ingress / egress filtering cannot identify such attacks.
- 3) The implementation of filtering policies and rules increases the administrative overhead.

D-WARD [45] refers to a firewall installed at source-end networks. It detects DDoS attacks originated from such networks by collecting traffic statistics of outgoing packets from the border routers and comparing them with the given models of network traffic based on transport and application protocol specifications. In this way, it can differentiate the legitimate, suspicious and attack traffic. It further rate-limits all traffic for a destination identified to be under attack and prefers the legitimate traffic to pass for other destinations and connections. This method is also a source-end, proactive technique capable of protecting against both direct and reflector DDoS attacks [24].

The D-WARD defense technique is capable of quickly detecting the attacks based on traffic anomalies with reference to given protocol specifications. It can identify heavy floods and accordingly rate-limit the traffic to prevent the victim from severe damage. It is a source-end defense; therefore impact of DDoS attack on a victim is limited. However, it still has a few major limitations such as:

- 1) The network performance is highly degraded due to the computation of traffic anomalies at the edge router.
- 2) Sufficiently large overhead is imposed on the router for which the router requires high processing power.
- 3) Since the accuracy of discriminating attack traffic from legitimate traffic at source-end may not be very high, there is a chance of high false positives and false negatives in this technique.

Hop Count Filtering (HCF) [46] is a packet filtering technique at victim-end which observes the TTL (Time-To-Live) values of incoming packets. The TTL value of a packet is observed and a guess is made about the same which should be inserted in the packet at sender. The difference between the initial and observed values provides the hop count. In fact, the victim-end server maintains a table of frequently communicating legitimate clients with their source IP addresses and corresponding hop counts. In a DDoS attack scenario, packets with spoofed source addresses are dropped having no entry in the table or their source addresses do not match with relevant hop counts. For such requests, the victim does not offer its resources such as TCP buffer etc. This method is a victim-end, reactive technique capable of protecting against direct DDoS attacks [24]. However, the technique has also some major shortcomings such as:

- 1) The technique is valid only for static IP addresses. Legitimate traffic of clients working under a Dynamic Host Configuration Protocol (DHCP) pool suffers from the denial of service.
- 2) The technique does not explain the availability of services to legitimate users behind Network Address Translation (NAT) since all users behind a NAT usually communicate over the internet with same public IP address. Such legitimate clients also suffer from the denial of service problems.
- 3) Users with legitimate requests having their IP addresses not in the table at the victim-end also suffer from the rejection of requests.

The SYN cookies technique [47] is considered to be the most promising defense against SYN flood attacks. In this method, instead of storing the Initial Sequence Number (ISN) of SYN packets, the server stores the authentication information of SYN/ACK packets. This authentication code is also a sequence number (authentication cookie) generated and stored by the server upon replying with a SYN/ACK packet to the requesting party. In order to calculate this sequence code

(the cookie value), the server uses hash function (MD5 is normally used) on some packet parameters i.e. source address, source port, destination address, destination port, and the Maximum Segment Size (MSS) value. In addition, a counter is used which is a different value approximately after every minute. Further, a secret value is also used which is changed at every boot of the server. The server, upon receiving a packet with ACK flag set i.e. the last signal of TCP three-way handshake, verifies the cookie. If the value is found correct, it establishes the connection. This method is a victim-end, reactive technique (filtering method) capable of protecting against SYN flood attacks [24]. However, the method has a few major shortcomings such as:

- 1) The server exercising SYN cookies method does not offer robustness against the SYN flood attacks overwhelming the bandwidth.
- 2) The server is unable to resend any lost SYN/ACK packet since the relevant information is not available any more.
- 3) The computational power and resources of the server may exhaust against large SYN flood attacks due to the need of calculating cookie values through hash function against each SYN packet.

E. Botnet Fluxing and Defense

In recent times, DDoS attackers use sophisticated attack tools to hide necessary traffic information for successful attacks and prevention from any traceback. Many schemes have been deployed to detect botnets behind a DDoS attack based on the attack signature. However, new attack techniques employing botnets (handlers & zombies) are clever enough not to be detected by such schemes as they have unknown signatures or are polymorphic (in many forms) in existence [48]. Two advanced botnet mechanisms surveyed in [2] are:

- Fast Flux (FF)
- Domain Flux (DF)

These two mechanisms behind botnets may not necessarily be used for DDoS. They can also be employed by attackers for other kinds of attacks such as cross-site scripting and e-mail spamming etc. However, as they can be the sources behind DDoS attacks as well, we discuss these techniques and the possible defense against them in this section.

In FF [49], frequent change in a set of IP addresses occurs that belong to a particular domain name. In DF [50], frequent change in a set of domain names occurs that belong to a particular IP address. Behind the fast flux technique, the idea is to compromise a Domain Name Service (DNS) with spoofed IP addresses of short TTLs and from a large IP pool against a single domain name. DNS query is sent to the compromised server by the victim to access the domain name. Due to short TTLs of IP addresses, the victim has to resend the query to DNS server when an assigned IP is expired. In the response of each query, DNS gives a different IP (spoofed address) to the

victim which connects it to a fluxing agent (botnet agent). In this way, different agents connect to the victim at different times. Each time, the agent redirects the request to actual server and the response is relayed back to the victim. The DNS server in this technique is a compromised machine but not a fluxing agent. The botnet agents are controlled by a Command and Control (C&C) server. The C&C (under the attacker's instructions) is responsible to manage the IP pool and the corresponding domain. The process makes the detection of botnet and identification of attack source quite complicated and difficult which is beyond the reach of traditional traceback schemes. However, it has a single point of failure due to one domain name i.e. once the fluxing behind a domain name is identified and it is taken down, the botnet is lost from the attacker's point of view [2].

In DF, the Domain Name Service is also a part of fluxing where malicious botnet agents (acting as DNS servers) generate domain names through a Domain Generation Algorithm. The domain names are obtained by the agents from the C&C server and other servers under the control of a botnet master [2], [51]. The domain names are dynamically generated through the domain generation algorithm and remain consistent at a point of time. The C&C server and the agents are seeded with same values to make sure the consistency of domain names. For this purpose, C&C server and the agents follow the same algorithm. The agents try to obtain the domain name from a maintained domain list by communicating with the C&C server and other servers. The names are obtained repeatedly until a DNS query is fulfilled. In the cases where a current domain name is not accessible or blocked by the concerned authorities, the botnet agents try to calculate the other one through the algorithm [2]. It has been identified in [52] that the algorithm in Torpig (a DF based botnet) uses current week and current year values to calculate the Top Level Domain (TLD). In case of failure in resolving a domain name, it uses other information (such as current day value) or some hard-coded information from a configuration file.

Some FF and DF detection methods are mentioned in [53], [54] and [55]. In [53], the authors developed an empirical metric to detect the fast fluxing in networks commonly known as Fast-Flux Service Networks (FFSN). Their metric is based on three possible parameters which can be used to identify the difference between normal traffic and FFSN behavior. The parameters are:

- Number of IP domain mappings in all DNS lookups.
- Number of name server records in a single domain lookup.
- Number of autonomous systems in all IP domain pairs.

They developed a metric called flux-score based on above mentioned parameters and used a linear decision function to identify the existence of an FFSN. The results of their two-month long experimental observations showed that their metric could differentiate the normal traffic and the FFSN behavior with very low false positives.

In [54], the authors developed a real time FFSN prediction model to analyze a website's DNS with a distributed

architecture through a mix of active and passive methods. The model is based on three major components mentioned below:

- Sensors
- Fast Flux Monitor Database
- Fast Flux Monitor

The sensors were further categorized into active and passive sensors. They were used to monitor different IP traffic parameters such as TTL, IP address validity, activity and footprint index etc. The FF monitor database was used to record the parameters obtained by sensors. The analysis of this stored data is a source to establish some analytical knowledge about different parameters of FFSN such as footprints, IP sharing statistics, country of origin and the Internet Service Provider (ISP) etc. The third component was used to classify the FFSN through a Bayesian network and calculate a prediction confidence with the help of parameters obtained through sensors. They showed that the report generated by the model can assist security analysts in analyzing a website's security with fair accuracies.

In [55], the authors used a supervised machine learning method to prevent users from accessing malicious websites. They classified automated URLs based on statistical analysis. The model was designed to make use of lexical features as well as host based properties of malicious domain names. The training of the model was achieved through three classification techniques mentioned below:

- Naive Bayes
- Support Vector Machine (SVM)
- Logistic Regression

With the help of these techniques, four different data sets were presented to the model (two malicious and two benign). The analyzed lexical features are entire URL length and dots & words in a domain name etc. The selected host-based features include registrar properties (WHOIS analysis) and properties of domain name such as geographical properties (physical location) etc. The results of the analysis proved to be fair enough to distinguish malicious domains and benign ones with a modest rate of false positives. They found that lexical features along with WHOIS analysis provide rich information whereas the overall analysis is used to extract the full classification for accurate detection. They further improved their model in [56] where the same set of lexical and host-based features was used but additionally the model was given a live feed of labeled domain names over the time to make it capable of identifying the suspicious URLs with enhanced accuracy.

F. Device Level Defense Features in Switches and Routers

In addition to covering the various DDoS detection and mitigation techniques focusing on traffic parameters and anomalies, there exist some authentication based security schemes at device level such as routers and switches to prevent networks and devices from a wide range of attacks. They also

provide an effective first line of defense against DDoS attacks. Therefore, we provide a discussion on some of them in this section.

In [6], some schemes have been studied that belong to new device level capabilities of routers and switches against various attacks including DDoS. The schemes are:

- 1) Defense against DDoS using a Router's packet forwarding mechanism in a more effective way.
- 2) Defense against SYN flooding attacks using *TCP blocking* in CISCO Routers.
- 3) Employing Trusted Platform Module (TPM) hardware incorporated Switches.

The defense against DoS or DDoS using a Cisco router can be accomplished by setting effective packet forwarding mechanism through Unicast RPF (Unicast Reverse Path Forwarding) function which checks the CEF (Cisco Express Forwarding) table after receiving a packet. If the route is defined in the table for particular IP scheme of which the packet is received, it forwards the packet. If the route is not in the table, it discards the same.

Defense against SYN flooding attacks using *TCP blocking* in CISCO Routers can be accomplished by working in an Internetwork Operating System (IOS) environment for which Cisco has introduced the feature after version 11.3. In this feature, the router can be programmed for any of the two available modes i.e. intercept mode and monitoring mode. In intercept mode, the router makes TCP connections with clients on behalf of the server. It sends the acknowledgement to client (second signal of three-way handshake) and waits for final acknowledgement from the client. When the acknowledgement is received, it shifts the connection transparently to the server. In case the final acknowledgement is not received, the connection is closed without transferring the impact to the server. The time-out limits are very strict to prevent connections from illegitimate users and save the router's own resources. In the monitoring mode, the router just observes the connection establishment phase between the client and the server. If the final acknowledgement is not received within a preset time limit, the connection is closed by the router. The TCP intercept feature in Cisco routers is enabled after creating an extended access list to define the source and destination IP addresses used for the intercept to prevent the internal host or the network [6]. It has been analyzed in [57] that the Access List (ACL) rules can be defined in routers to prevent networks from potential intrusions. These rules are normally based on the alerts generated by some Intrusion Detection System (IDS) such as Snort (an open source IDS) [58].

Trusted Platform Module (TPM) [59] is the name of a published specification and its implementation to ensure the information security in a given system. It is given by the Trusted Computing Group (TCG), an industrial organization developing standards for TPM [60]. It is implemented through the *TPM chip* or *TPM security device*. The idea behind the implementation is to provide a security mechanism to a given system by establishing a chain of trust from the root to the entire system through an authentication process. The

authentication is based on cryptographic keys stored inside the hardware of TPM chip, capable of providing a range of passwords through different security algorithms such as random number generator, RSA algorithm and SHA-1 algorithm etc. All the cryptographic functions are executed inside the TPM chip. A network switch incorporated with a TPM chip can trigger a TPM authentication process upon detecting a DDoS attack through a detection mechanism. The flow of executions in such a case will be as follows:

1) Function of Network Switch

- Detect DDoS through a detection mechanism.
- Open TPM authentication process.

2) Function of TPM Chip

- Send request to obtain Public Key of Server (PKS) and Client Certification Authentication Table (CCAT) through the switch to the server.
- Receive client's request to access the server through the switch.
- Generate a random number 'Ri' and send it to the client.
- Get the 'Ri' signed by the authentication server and send it to the switch.
- Get the Public Key of Client (PKC) from CCAT, decrypt it (say 'Rc') and match with 'Ri'.
- In case $R_c = R_i$, mark that the client as authenticated and ask the switch whether the client is sending legitimate traffic or the same is a DDoS source according to the detection mechanism. (The switch verifies the same by further communication with the server. The switch and server maintain a Client Permission Table in dynamic mode for the purpose).

A virtual connection is first established between the server and the client under monitoring mode. After specific time with positive client response, the connection is made direct. The Client Permission Table (CPT) is signed by the server. When a client is identified as a malicious user, the CPT is updated and the access is denied. The reason of generating a random number is to generate a different challenge for each client or multiple connection attempts of the same client so that an effective measure can be applied against replay attacks. When the detection mechanism identifies that the attack has been stopped, it notifies the switch to stop the authentication and validation process through TPM chip [6].

G. Defenses Against Application Layer DDoS Attacks

Application layer DDoS attacks are now very popular in the networking world. They establish complete TCP connections with the victim and then start flooding with several *GET* requests to bring down the victim or saturate the bandwidth through outbound traffic such as downloading heavy images from a website. In this way, they conceal their identity in a more sophisticated way to trick the detection schemes. In fact,

most of the detection and mitigation mechanisms can identify network layer attacks through packet inspection techniques. Therefore, application layer attacks are more successful tools for attackers to harm the victim in current times.

Researchers have made some good contributions towards identifying DDoS attacks through the inspection of traffic anomalies that arise due to attack based traffic flow and connection attempts. The most important challenge in this perspective is to differentiate between an attack and a flash crowd. The flash crowd refers to a sudden increase in legitimate connections on a server or website occurring at the same time or within a short period [61]. Some attempts to examine traffic anomalies to detect DDoS attacks can identify both network layer and application layer attacks, whereas some are focused towards shielding against application layer DDoS attacks only. In this section, we review both types of proposed schemes to provide a better insight of defense against application layer DDoS.

In [62], the authors proposed an early discovery of DDoS flooding attacks through the network-wide monitoring effects. They found that such macroscopic effects reveal a shift in the spatial-temporal patterns of the network traffic when a DDoS attack strikes. They tested the effects with different modes of attack such as pulsing attack, increasing rate attack and constant rate attack etc. The simulation results showed that the shift in spatial-temporal patterns can be captured effectively with a few observation points. Moreover, the time and location of an attack can also be revealed without observing the changes at victim side.

In [63], the authors devised a mechanism of parametric methods to detect anomalies in network traffic using aggregate traffic properties without any need of flow separation. The mechanism developed is called bivariate Parametric Detection Mechanism (bPDM). It uses the packet size and traffic rate statistics to make a probability ratio test and is able to highly reduce the false positive rate. The metric used to detect the network traffic anomalies through their mechanism was bit-rate Signal to Noise Ratio (SNR). They claimed that it is an effective metric to detect anomalies and validated the claim by evaluating bPDM with bit-rate SNR in three different scenarios, including a real-time DoS attack. They found that the method was able to detect different attacks in a few seconds. It is also mentioned that bit-rate SNR is more effective to detect network traffic anomalies as compared to earlier proposed packet SNR [64]. They evaluated both metrics through bPDM and concluded that bit-rate SNR is better in terms of detection time. They also evaluated when bit-rate SNR is used as detection metric, the detection time decreases with increase in bit-rate SNR value. Moreover, the detection time also decreases with increase in the attack rate.

In a recent research attempt in [65], the authors addressed the issue of group synchronization required by a server while maintaining multiple clients through port-hopping mechanism [66]. In the cases where clock-rate drifts are present among different communicating parties, there are chances that control signals might be lost, keeping the server port open for long time and thus becoming vulnerable to application layer DDoS

attacks. They proposed an algorithm called BIGWHEEL that offers port-hopping mechanism for servers in multiparty communications without any need of group synchronization. Moreover, an adaptive algorithm called HOPERAA was proposed to execute the port-hopping in presence of clock-rate drifts. In fact, the need of group synchronization raises scalability issues in port-hopping; whereas the work in [65] mentions that the port-hopping can be achieved in a scalable way (through the proposed algorithm, without the need of group synchronization). The proposed algorithm, offered to a server, employs a simple interface with each client. The protocol's port-hopping period is fixed; therefore it creates minimal chances for an adversary to launch application attack at the server's port after eavesdropping [67]. However, the work is tested for fixed clock drifts and hopping frequencies. Further investigations are required for the same parameters in variable mode.

In [68], an attempt has been made to distinguish DDoS attacks from flash crowds through hybrid probability metric. Application layer DDoS attacks are similar to flash crowds; however, they still have some differences like traffic rate, access dynamics and source distributions of IP addresses. Using such differences, the authors devised an algorithm to distinguish DDoS traffic from flash crowds and tested the same in simulation as well as on a small experimental test-bed. In their algorithm, they basically worked on traffic flows and tested the anomalies by setting two grouping thresholds for variation and similarity index. Based on the calculated variations of any two distributions and comparing them with given threshold values, they were able to distinguish DDoS attacks from flash crowds within a normal network flow with reduced false positives and false negatives. Hence the algorithm also increased the system's sensitivity. A simple flow of their work is given in figure 14. The decision device stops the DDoS flow and allows legitimate flow to pass.

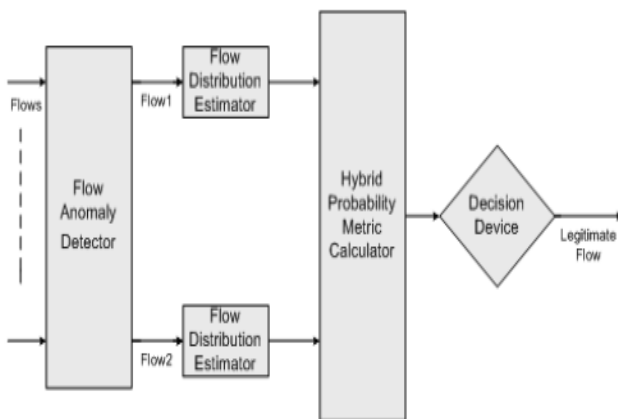


Fig. 14. DDoS detection through hybrid probability metric to differentiate between DDoS attacks and flash crowds.

In [69], the authors have made an attempt to detect application layer DDoS attacks in real Web traffic under the event of flash crowd. They introduced a scheme based on document popularity [70] and devised a multidimensional

Access Matrix to obtain the spatial-temporal patterns of a flash crowd in normal flow. The matrix is abstracted by component analysis of the flow [71] and document popularity of a certain website is obtained from the server log. The anomaly in network traffic is then detected through a detector based on hidden semi-Markov model, proposed in their previous work [72]. This detector is used to explain the dynamics of the matrix and detect DDoS attacks. The authors experimented different types of application layer DDoS attacks (constant rate attack, pulsing attack etc.) during a real-time flash crowd event and fitted the obtained data in their proposed detector. The results showed that the model could detect potential application layer DDoS attacks using entropy of the document popularity.

In [73], the authors proposed a mechanism to counter application layer DDoS attacks called *DDoS Shield*. It has two components, one is suspicion assignment mechanism and the other, which they proposed earlier as a foundation of their work [74], is called *DDoS Resilient Scheduler*. They chose some specific properties of attack based sessions such as asymmetric workload and request flooding to identify application layer attacks. Based on these properties, the suspicion assignment mechanism issues a continuous value (not a binary value) to a session according to its variation from the reference behavior (legitimate behavior) and employs the DDoS resilient scheduler to determine whether and when a session is to be processed. They used an experimental test-bed with a hosted web application to determine the efficiency of their proposed mechanism. The results described that the DDoS Shield significantly improves victim's performance when an attack is applied with asymmetric workload with an aim to overwhelm server's resources.

Another well known defense against application layer DDoS attacks is CAPTCHA (Completely Automated Public Turing test to tell Computers and Humans Apart) puzzle [75], considered to be the most promising technique against application layer DDoS in current times [24]. In this scheme, a challenge-response test is presented to a prospective client requesting to establish a connection with a server. The purpose is to make sure that the response is generated by a human and not an automated machine targeting the server against some kind of an attack. It is a good defense against e-mail spam and automated posting to forums and blogs etc. Today, many websites use CAPTCHA at initial login and registration phases to protect servers against application layer DDoS attacks such as HTTP flood etc. In figure 15, an example of CAPTCHA test is shown.

The CAPTCHA test is an effective technique against HTTP flood and SYN flood attacks. It is a victim-end, filtering technique with threshold-based mechanism [24]. However, it has some limitations as mentioned below:

- 1) The technique is not effective against bandwidth flooding attacks such as TCP flood and UDP flood. Moreover, it does not counter reflector attacks.
- 2) This technique prevents any legitimate automated client (if non-human users are required in the system) to establish a connection with the server.

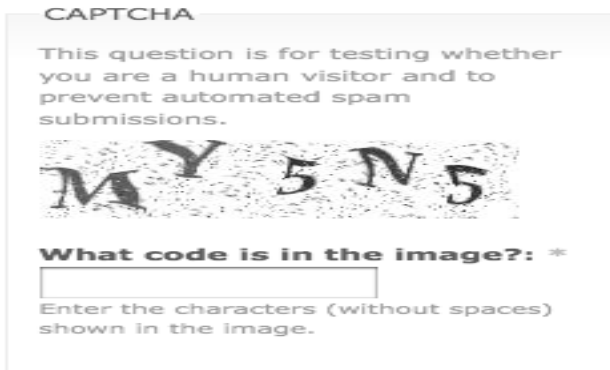


Fig. 15. An example of CAPTCHA test.

- 3) The codes are predictable when small pools of fixed images are used.
- 4) CAPTCHA is annoying for users as they have to solve the test and wait for the response before accessing the server. It is not a user-friendly technique and thus legitimate user count may be dropped for a given server, especially when images are not clear [76].
- 5) CAPTCHA codes are broken by attackers using image recognition techniques [77]. In such schemes, background noise is removed from CAPTCHA image and then it is segmented to pass through the recognition algorithms. In order to improve the defense against such schemes, modern CAPTCHA images include background noise and animations [78] which make an image harder to be recognized by machine based recognition. However, inclusion of such contents often makes images very difficult to be easily read by a human. As a result, legitimate human users become very annoying and the use of connected services are found limited.

H. Future Research and Challenges

While surveying DDoS attack and defense techniques, we analyze that a repetitive cycle of attack and defense goes on with the inclusion of more automated, enhanced and sophisticated tools. Moreover, the research brains also make interesting and practical contributions to improve the performance level of such tools. In this paper, our aim has been to review both traditional and current types of schemes in DDoS attack and defense portfolios. We can draw some observations in our study regarding future research and challenges in DDoS defense as mentioned below:

- 1) Application layer attacks are now getting more popular in attackers due to their unique properties of legitimate-like behavior. It is a fact that network layer attacks which contain packet manipulations are now relatively easier to detect with modern detection and mitigation tools. However, application layer DDoS defense needs more research for effective defense tools. Although some papers have been presented on the topic which we reviewed [68], [69], [72], [73], but their practical implementation has not

been checked at a widespread level. As mentioned in our previous discussion, CAPTCHA is considered to be the most promising technique against application layer DDoS attacks but it has some major shortcomings which we pointed out. Therefore, application layer DDoS detection and mitigation would require more research with the challenge of distinguishing attack events from flash crowds.

- 2) Even at the level of network layer attacks, some enriched schemes have been developed by attackers such as reflector attacks. The detection of such attacks needs huge security investment as well as overhead on intermediate routers and devices. The reduction of such investment cost and overhead is still a major challenge for the future research.
- 3) There is a need of strong research cooperation among various ISPs to share protocols and records for an effective defense against DDoS attacks. The source of attack is located through upstream routers which may belong to other ISPs. Therefore, more collaborative efforts would be required to design criteria of blocking traffic for servers belonging to other ISPs.
- 4) In addition to the World Wide Web, DDoS attacks are also common in specific protocols, services and infrastructures such as SIP (Session Initiation Protocol) flood attacks in VoIP (Voice over IP) [79], [80]; WLAN (Wireless Local Area Network) [81] and MANETs (Mobile Ad-hoc NETWORKS) [82]. Therefore, mitigating DDoS against these specific services and networks also needs significant research and implementation attempts.
- 5) DDoS is now considered to be a scalability problem in networks [83]. The current architecture of World Wide Web is not fundamentally scalable, thus susceptible to DDoS attacks. A network which is fundamentally and dynamically scalable in all aspects may not have DDoS problems associated with it. Normally, the communications with world are made through networks built upon the fundamental internet architecture which is vulnerable to DDoS attacks. Therefore, such networks are also the part of ongoing offense and defense of the DDoS [84]. On the other hand, networks created upon a separate, clean infrastructure are immune to DDoS. However, such networks are not found in existence due to the need of heavy investments and resources behind them. The creation of such networks and increasing the scalability of underlying internet architecture to improve defense against DDoS is a huge challenge for the future research.

IV. CONCLUSION

In this paper, we presented a review on Distributed Denial of Service attack and defense techniques with an emphasis on current DDoS defense schemes based on entropy variations and other traffic anomalies, neural networks and application layer DDoS defense. Some traditional techniques such as traceback and packet filtering have also been covered in the discussions. We found that new attack techniques have been

introduced with sophisticated DDoS attack tools such as botnet fluxing, GET floods and reflector attacks. With such enriched attacks, the defense is even more challenging especially in the case of application layer DDoS attacks where the attack packets are a form of legitimate-like traffic mimicking in the events of flash crowds. The major challenge in the research has been identified to distinguish application layer DDoS attacks from the flash crowds with an acceptable rate of false positives and false negatives. Although some good research attempts have been presented in the defense against application layer DDoS attacks, their practical implementation across a wide range of networks has not been verified i.e. only test-bed cases are evaluated and discussed. The defense techniques mentioned in this paper have been reviewed critically identifying their inherent shortcomings. Even the most promising technique against application layer DDoS attacks in current times i.e. CAPTCHA has also some major drawbacks. Therefore, the future research in this domain is even more challenging. DDoS is now considered to be a scalability problem for networks built upon the current internet architecture and it may not be a problem of the same magnitude for fully scalable networks designed upon separate and clean infrastructure.

REFERENCES

- [1] A. Mitrokotsa, and C. Douligeris, "Denial-of-Service Attacks," *Network Security: Current Status and Future Directions (Chapter 8)*, Wiley Online Library, pp. 117-134, June 2006.
- [2] L. Zhang, S. Yu, D. Wu, and P. Watters, "A Survey on Latest Botnet Attack and Defense," *Proc. of 10th Intl' Conference On Trust, Security and Privacy in Computing and Communications (TrustCom)*, IEEE, pp. 53-60, November 2011.
- [3] A. Mishra, B.B. Gupta, and R.C. Joshi, "A Comparative Study of Distributed Denial of Service Attacks, Intrusion Tolerance and Mitigation Techniques," *Proc. of European Intelligence and Security Informatics Conference (EISIC)*, IEEE, pp. 286-289, September 2011.
- [4] K. W. M. Ghazali, and R. Hassan, "Flooding Distributed Denial of Service Attacks-A Review," *Journal of Computer Science 7 (8)*, Science Publications, 2011, pp. 1218-1223.
- [5] H. Beitollahi, and G. Deconinck, "Denial of Service Attacks: A Tutorial," *Electrical Engineering Department (ESAT), University of Leuven*, Technical Report: 08-2011-0115, August 2011.
- [6] Z. Chao-yang, "DoS Attack Analysis and Study of New Measures to Prevent," *Proc. of Intl' Conference On Intelligence Science and Information Engineering (ISIE)*, IEEE, pp. 426-429, August 2011.
- [7] Information WeekSecurity: <<http://www.informationweek.com>>, February 2012.
- [8] Business Insider: <<http://articles.businessinsider.com>>, October 2011.
- [9] SecureList: <<http://www.securelist.com>>, February 2012.
- [10] Prolexic Technologies: "Prolexic Attack Report Q1 2012", <<http://www.prolexic.com>>, April 2012.
- [11] M. Conti, S. Chong, S. Fdida, W. Jia, H. Karl, Y. D. Lin, P. Mahonen, M. Maier, R. Molva, S. Uhlig, and M. Zukerman, "Research challenges towards the Future Internet," *Computer Communications*, Elsevier, vol. 34, issue 18, pp. 2115-2134, December 2011.
- [12] N. Ahlawat, and C. Sharma, "Classification and Prevention of Distributed Denial of Service Attacks," *International Journal of Advanced Engineering Sciences and Technologies*, vol. 3, issue 1, 2011, pp. 52-60.
- [13] G. Badishi, A. Herzberg, I. Keidar, O. Romanov, and A. Yachin, "An Empirical Study of Denial of Service Mitigation Techniques," *IEEE Symposium On Reliable Distributed Systems (SRDS '08)*, IEEE, pp. 115-124, October 2008.
- [14] K. Subhashini, and G. Subbalakshmi, "Tracing Sources of DDoS Attacks in IP Networks Using Machine Learning Automatic Defence System," *International Journal of Electronics Communication and Computer Engineering*, vol. 3, issue 1, pp. 164-169, January 2012.
- [15] S. C. Lin, and S. S. Tseng, "Constructing detection knowledge for DDoS intrusion tolerance," *Expert Systems with Applications*, Elsevier, 2004, pp. 379-390.
- [16] Y. Wang, C. Lin, Q. L. Li, and Y. Fang, "A queuing analysis for the denial of service (DoS) attacks in computer networks," *Computer Networks*, Elsevier, 2007, pp. 3564-3573.
- [17] V. Priyadarshini, and K. Kuppusamy, "Prevention of DDOS Attacks using New Cracking Algorithm," *International Journal of Engineering Research and Applications*, vol. 2, issue 3, pp. 2263-2267, May 2012.
- [18] A. Aissani, and M. Y. Achour, "Evaluation of the Severity of DoS Attacks on Computer Networks," *Proc. of 2nd Intl' Conference On Performance, Safety and Robustness in Complex Systems and Applications (PESARO)*, IARIA, 2012, pp. 8-13.
- [19] A. Bhang, A. Syad, S. S. Thakur, "DDoS Attacks Impact on Network Traffic and its Detection Approach," *International Journal of Computer Applications*, vol 40, no. 11, pp. 36-40, February 2012.
- [20] M. Abliz, and T. Znati, "New Approach to Mitigating Distributed Service Flooding Attacks," *Proc. of 7th Intl' Conference On Systems (ICONS)*, IARIA, 2012, pp. 13-19.
- [21] J. Sen, P. R. Chowdhury, and I. Sengupta, "A Mechanism for Detection and Prevention of Distributed Denial of Service Attacks," *Distributed Computing and Networking*, Lecture Notes in Computer Science (LNCS), Springer-Verlag, 2006, vol. 4308, pp. 139-144.
- [22] S. H. Kang, K. Y. Park, S. G. Yoo, and J. Kim, "DDoS avoidance strategy for service availability," *Cluster Computing*, Online First, Springer, DOI: 10.1007/s10586-011-0185-4, October 2011.
- [23] Y. Lee, and Y. Lee, "Detecting DDoS Attacks with Hadoop," *ACM CoNEXT Student Workshop*, December 2011.
- [24] H. Beitollahi, and G. Deconinck, "Analyzing well-known countermeasures against distributed denial of service attacks," *Computer Communications*, Elsevier, vol. 35, issue 11, pp. 1312-1332, June 2012.
- [25] U. Tariq, M. Hong, and K. Lhee, "A Comprehensive Categorization of DDoS Attack and DDoS Defense Techniques," *Advanced Data Mining and Applications*, Lecture Notes in Computer Science (LNCS), Springer-Verlag, 2006, vol. 4093, pp. 1025-1036.
- [26] B. B. Gupta, P. K. Agrawal, R. C. Joshi, and M. Misra, "Estimating Strength of a DDoS Attack Using Multiple Regression Analysis," *Communications in Computer and Information Science*, Springer, 2011, vol. 133, part 3, pp. 280-289.
- [27] B. B. Gupta, P. K. Agrawal, A. Mishra, and M. K. Pattanshetti, "On Estimating Strength of a DDoS Attack Using Polynomial Regression Model," *Communications in Computer and Information Science*, Springer, 2011, vol. 193, part 2, pp. 244-249.
- [28] C. E. Shannon, "A mathematical theory of communication," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 5, issue 1, pp. 3-55, January 2001.
- [29] K. Kumar, A. L. Sangal, and A. Bhandari, "Traceback Techniques Against DDoS Attacks: A Comprehensive Review," *Proc. of 2nd Intl' Conference On Computer and Communication Technology (ICCCT)*, IEEE, pp. 491-498, September 2011.
- [30] S. Yu, W. Zhou, R. Doss, and W. Jia, "Traceback of DDoS Attacks Using Entropy Variations," *IEEE Transactions On Parallel and Distributed Systems*, vol. 22, no. 3, pp. 412-425, March 2011.
- [31] Y. Xiang, K. Li, and W. Zhou, "Low-Rate DDoS Attacks Detection and Traceback by Using New Information Metrics," *IEEE Transactions On Information Forensics and Security*, vol. 6, no. 2, pp. 426-437, June 2011.
- [32] S. Savage, D. Wetherall, A. Karlin, and T. Anderson, "Network Support for IP Traceback," *IEEE/ACM Transactions On Networking*, vol. 9, no. 3, pp. 226-237, June 2001.
- [33] R. Mahajan, S. M. Bellovin, S. Floyd, J. Ioannidis, V. Paxson, and S. Shenker, "Controlling high bandwidth aggregates in the network," *ACM SIGCOMM Computer Communication Review*, vol. 32, issue 3, pp. 62-73, July 2002.

- [34] H. F. Lipson, "Tracking and Tracing Cyber-Attacks: Technical Challenges and Global Policy Issues," *CERT Coordination Center*, Special Report: CMU/SEI-2002-SR-009, November 2002.
- [35] S. Kent, and R. Atkinson, "Security Architecture for the Internet Protocol," RFC 2401, November 1998.
- [36] L. Garber, "Denial-of-Service Attacks Rip the Internet," *IEEE Computer*, vol. 33, issue 4, pp. 12-17, April 2000.
- [37] Y. Liu, B. Cukic, and S. Gururajan, "Validating neural network-based online adaptive systems: a case study," *Software Quality Journal*, Springer, vol. 15, no. 3, pp. 309-326, May 2007.
- [38] J. Li, Y. Liu, and L. Gu, "DDoS Attack Detection Based On Neural Network," *Proc. of 2nd Intl' Symposium On Aware Computing (ISAC)*, IEEE, pp. 196-199, November 2010.
- [39] M. Biehl, A. Ghosh, and B. Hammer, "Dynamics and Generalization Ability of LVQ Algorithms," *The Journal of Machine Learning Research*, MIT Press, vol. 8, pp. 323-360, May 2007.
- [40] P. K. Agarwal, B. B. Gupta, S. Jain, and M. K. Pattanshetti, "Estimating Strength of a DDoS Attack in Real Time Using ANN Based Scheme," *Communications in Computer and Information Science*, Springer, 2011, vol. 157, part 6, pp. 301-310.
- [41] B. B. Gupta, R. C. Joshi, M. Misra, A. Jain, S. Juyal, R. Prabhakar, and A. K. Singh, "Predicting Number of Zombies in a DDoS Attack Using ANN Based Scheme," *Communications in Computer and Information Science*, Springer, 2011, vol. 147, part 1, pp. 117-122.
- [42] Z. H. Xu, W. B. Chen, W. F. Yang, and F. Liu, "Fast Algorithm of Evolutional Learning Neural Network," *Proc. of Int'l Conf. On Intelligent Systems Design and Engineering Application (ISDEA)*, IEEE, pp. 262-265, January 2012.
- [43] Z. Zhao, H. Xin, Y. Ren, and X. Guo, "Application and Comparison of BP Neural Network Algorithm in MATLAB," *Proc. of Int'l Conf. On Measuring Technology and Mechatronics Automation (ICMTMA)*, IEEE, pp. 590-593, March 2010.
- [44] P. Ferguson, and D. Senie, "Network Ingress Filtering: Defeating Denial of Service Attacks which employ IP Source Address Spoofing," RFC 2827, May 2000.
- [45] J. Mirkovic, and P. Reiher, "D-WARD: a source-end defense against flooding denial-of-service attacks," *IEEE Transactions On Dependable and Secure Computing*, vol. 2, no. 3, pp. 216-232, July 2005.
- [46] H. Wang, C. Jin, and K. G. Shin, "Defense Against Spoofed IP Traffic Using Hop-Count Filtering," *IEEE/ACM Transactions On Networking*, vol. 15, no. 1, pp. 40-53, February 2007.
- [47] W. Eddy, "TCP SYN Flooding Attacks and Common Mitigations," RFC 4987, August 2007.
- [48] C. Li, W. Jiang, and X. Zou, "Botnet: Survey and Case Study," *Proc. of 4th Intl' Conference On Innovative Computing, Information and Control (ICICIC)*, IEEE, pp. 1184-1187, December 2009.
- [49] X. Hu, M. Knysz, and K. G. Shin, "Measurement and analysis of global IP-usage patterns of fast-flux botnets," *Proc. of IEEE INFOCOM*, pp. 2633-2641, April 2011.
- [50] L. Bilge, E. Kirda, C. Kruegel, and M. Balduzzi, "EXPOSURE: Finding Malicious Domains Using Passive DNS Analysis," *Proc. of 18th Annual Network & Distributed System Security Symposium*, Internet Society, February 2011.
- [51] J. Lee, J. Kwon, H. Shin, and H. Lee, "Tracking Multiple C&C Botnets by Analyzing DNS Traffic," *Proc. of 6th IEEE Workshop On Secure Network Protocols (NPsec)*, IEEE, pp. 67-72, October 2010.
- [52] B. Stone-Gross, M. Cova, L. Cavallaro, B. Gilbert, M. Szydowski, R. Kemmerer, C. Kruegel, and G. Vigna, "Your botnet is my botnet: analysis of a botnet takeover," *Proc. of 16th ACM Conference On Computer and Communications Security (CCS '09)*, ACM, pp. 635-647, November 2009.
- [53] T. Holz, C. Gorecki, K. Rieck, and F. C. Freiling, "Measuring and Detecting Fast-Flux Service Networks," *Proc. of 16th Annual Network & Distributed System Security Symposium*, Internet Society, February 2008.
- [54] A. Caglayan, M. Tothaker, D. Drapeau, D. Burke, and G. Eaton, "Real-Time Detection of Fast Flux Service Networks," *Proc. of Cybersecurity Applications & Technology Conference for Homeland Security (CATCH '09)*, IEEE, pp. 285-292, March 2009.
- [55] J. Ma, L. K. Saul, S. Savage, and G. M. Voelker, "Beyond blacklists: learning to detect malicious web sites from suspicious URLs," *Proc. of 15th ACM SIGKDD Intl' Conference On Knowledge Discovery and Data Mining (KDD '09)*, ACM, pp. 1245-1254, June 2009.
- [56] J. Ma, L. K. Saul, S. Savage, and G. M. Voelker, "Identifying suspicious URLs: an application of large-scale online learning," *Proc. of 26th Annual Intl' Conference On Machine Learning (ICML '09)*, ACM, pp. 681-688, June 2009.
- [57] M. Naveed, S. Un Nihar, and M. Inayatullah Babar, "Network Intrusion Prevention by Configuring ACLs on the Routers, based on Snort IDS Alerts," *Proc. of 6th Intl' Conference On Emerging Technologies (ICET)*, IEEE, pp. 234-239, October 2010.
- [58] SNORT: Open Source Network Intrusion, Prevention and Detection System (IDS/IPS), <<http://www.snort.org>>.
- [59] M. Sidheeq, A. Dehghantanha, and G. Kananparan, "Utilizing Trusted Platform Module to Mitigate Botnet Attacks," *Proc. of Intl' Conference On Computer Applications and Industrial Electronics (ICCAIE)*, IEEE, pp. 245-249, December 2010.
- [60] Trusted Computing Group (TCG), <<http://www.trustedcomputinggroup.org>>.
- [61] I. Ari, B. Hong, E. L. Miller, S. A. Brandt, and D. D. E. Long, "Managing flash crowds on the Internet," *Proc. of 11th IEEE/ACM Intl' Symposium On Modeling, Analysis and Simulation of Computer Telecommunications Systems (MASCOTS)*, IEEE/ACM, pp. 246-249, October 2003.
- [62] J. Yuan, and K. Mills, "Monitoring the Macroscopic Effect of DDoS Flooding Attacks," *IEEE Transactions On Dependable and Secure Computing*, vol. 2, no. 4, pp. 324-335, October 2005.
- [63] G. Thatte, U. Mitra, and J. Heidemann, "Parametric Methods for Anomaly Detection in Aggregate Traffic," *IEEE/ACM Transactions On Networking*, vol. 19, no. 2, pp. 512-525, April 2011.
- [64] X. He, C. Papadopoulos, J. Heidemann, U. Mitra, and U. Riaz, "Remote detection of bottleneck links using spectral and statistical methods," *Computer Networks*, Elsevier, vol. 53, issue 3, pp. 279-298, February 2009.
- [65] Z. Fu, M. Papatriantafilou, and P. Tsigas, "Mitigating Distributed Denial of Service Attacks in Multiparty Applications in the Presence of Clock Drifts," *IEEE Transactions On Dependable and Secure Computing*, vol. 9, no. 3, pp. 401-413, May 2012.
- [66] K. Hari, and T. Dohi, "Sensitivity Analysis of Random Port Hopping," *Proc. of 7th Intl' Conference On Ubiquitous Intelligence & Computing and 7th Intl' Conference On Autonomic & Trusted Computing (UIC/ATC)*, IEEE, pp. 316-321, October 2010.
- [67] G. Badishi, A. Herzberg, and I. Keidar, "Keeping Denial-of-Service Attackers in the Dark," *IEEE Transactions On Dependable and Secure Computing*, vol. 4, no. 3, pp. 191-204, July 2007.
- [68] K. Li, W. Zhou, P. Li, J. Hai, and J. Liu, "Distinguishing DDoS Attacks from Flash Crowds Using Probability Metrics," *Proc. of 3rd Intl' Conference On Network and System Security (NSS '09)*, IEEE, pp. 9-17, October 2009.
- [69] Y. Xie, and S. Z. Yu, "Monitoring the Application-Layer DDoS Attacks for Popular Websites," *IEEE/ACM Transactions On Networking*, vol. 17, no. 1, pp. 15-25, February 2009.
- [70] S. A. Krashakov, A. B. Teslyuk, and L. N. Shchur, "On the universality of rank distributions of website popularity," *Computer Networks*, Elsevier, vol. 50, issue 11, pp. 1769-1780, August 2006.
- [71] J. Shlens, "A Tutorial on Principal Component Analysis," ver. 3.01, <<http://sloan-swartz.salk.edu/~shlens/pca.pdf>>, April 2009.
- [72] Y. Xie, and S. Z. Yu, "A Novel Model for Detecting Application Layer DDoS Attacks," *Proc. of 1st Intl' Multi-Symposiums On Computer and Computational Sciences (IMSCCS '06)*, IEEE, pp. 56-63, June 2006.
- [73] S. Ranjan, R. Swaminathan, M. Uysal, A. Nucci, and E. Knightly, "DDoS-Shield: DDoS-Resilient Scheduling to Counter Application Layer Attacks," *IEEE/ACM Transactions On Networking*, vol. 17, no. 1, pp. 26-39, February 2009.
- [74] S. Ranjan, R. Swaminathan, M. Uysal, and E. Knightly, "DDoS-Resilient Scheduling to Counter Application Layer Attacks Under Imperfect Detection," *Proc. of 25th Intl' Conference On Computer Communications (INFOCOM)*, IEEE, pp. 1-13, April 2006.

- [75] L. V. Ahn, M. Blum, and J. Langford, "Telling humans and computers apart automatically," *Communications of the ACM*, vol. 47, issue 2, pp. 56-60, February 2004.
- [76] L. O. Caum, "Why is CAPTCHA so annoying?," 2011, <<http://lorenzocaum.com/blog/why-is-captcha-so-fing-annoying/>>.
- [77] G. Mori, and J. Malik, "Recognizing Objects in Adversarial Clutter: Breaking a Visual CAPTCHA," *Proc. of IEEE Computer Society Conference On Computer Vision and Pattern Recognition*, IEEE, vol. 1, pp. I-134 – I-141, June 2003.
- [78] E. Athanasopoulos, and S. Antonatos, "Enhanced CAPTCHAs: Using Animation to Tell Humans and Computers Apart," *Communications and Multimedia Security*, Springer, 2006, vol. 4237/2006, pp. 97-108.
- [79] T. Peng, C. Leckie, and K. Ramamohanarao, "Survey of Network-Based Defense Mechanisms Countering the DoS and DDoS Problems," *ACM Computing Surveys (CSUR)*, vol. 39, issue 1, article number 3, April 2007.
- [80] A. D. Keromytis, "Voice-over-IP Security: Research and Practice," *IEEE Security and Privacy*, vol. 8, issue 2, pp. 76-78, March 2010.
- [81] U. Tupakula, V. Varadharajan, and S. K. Vuppala, "Countering DDoS Attacks in WLAN," *Proc. of 4th Intl' Conference On Security of Information and Networks (SIN '11)*, ACM, pp. 119-126, November 2011.
- [82] G. Kaur, Y. Chaba, and V. K. Jain, "Distributed Denial of Service Attacks in Mobile Adhoc Networks," *World Academy of Science, Engineering and Technology*, vol. 73, pp. 725-727, 2011, <<http://www.waset.ac.nz/journals/waset/v73/v73-128.pdf>>.
- [83] Y. Chung, "Distributed Denial of Service is a Scalability Problem," *ACM SIGCOMM Computer Communication Review*, vol. 42, issue 1, pp. 69-71, January 2012.
- [84] M. Walfish, M. Vutukuru, H. Balakrishnan, D. Karger, and S. Shenker, "DDoS Defense by Offense," *ACM Transactions On Computer Systems*, vol. 28, issue 1, article no. 3, March 2010.
- [85] M. Aamir and M. Arif, "Study and Performance Evaluation on Recent DDoS Trends of Attack & Defense," *International Journal of Information Technology and Computer Science*, MECS Publisher, vol. 5, no. 8, pp. 54-65, July 2013.
- [86] M. Aamir and M. A. Zaidi, "A Survey on DDoS Attack and Defense Strategies: From Traditional Schemes to Current Techniques," *Interdisciplinary Information Sciences*, vol. 19, no. 2, pp. 173-200, November 2013.