MOTAG: Moving Target Defense Against Internet Denial of Service Attacks

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***Abstract*—Distributed Denial of Service (DDoS) attacks still pose a significant threat to critical infrastructure and Internet services alike. In this paper, we propose *MOTAG*, a moving target defense mechanism that secures service access for authenticated clients against flooding DDoS attacks. *MOTAG* employs a group of dynamic packet indirection proxies to relay data traffic between legitimate clients and the protected servers. Our design can effectively inhibit external attackers' attempts to directly bombard the network infrastructure. As a result, attackers will have to collude with malicious insiders in locating secret proxies and then initiating attacks. However, *MOTAG* can mitigate insider attacks and filter out innocent clients by continuously "moving" secret proxies to new network locations while shuffling client-to-proxy assignments. We develop a greedy shuffling algorithm to minimize the number of proxy re-allocations (shuffles) while maximizing attack isolation. Simulations are used to investigate *MOTAG*'s effectiveness versus proxy consumption on protecting services of different scales against intensified DDoS attacks.**

***Index Terms*—DDoS; Moving Target Defense; Secret Proxy; Insider; Shuffling**

I. Introduction

A report by Arbor Networks has indicated a significant increase in the prevalence of large-scale distributed denial-of-service (DDoS) attacks [1]. In 2010, the largest reported bandwidth achieved by a flood-based DDoS attack reached 100 Gbps. Meanwhile, the cost of performing a DDoS attack has turned out to be surprisingly low. A Trend Micro's white paper [2] about Russian underground market has revealed that the price for 1-week DDoS service could be as low as $150.

A number of mechanisms have been proposed in the past to prevent or mitigate DDoS attacks. For instance, filtering-based approaches [3], [4], [5] use ubiquitously deployed filters to block undesired traffic sent to the protected nodes. Capability-based defense mechanisms [6], [7], [8], [9] constrain the resource usage of the senders within the threshold permitted by the receivers. Secure overlay solutions [10], [11], [12], [13], [14], [15] interpose an overlay network to indirect packets between clients and the protected nodes, aiming to absorb and filter out attack traffic. However, these static defense systems either rely on global deployment of additional functionalities on Internet routers or require large, robust virtualized network to withstand the ever-exacerbating attacks. Besides, some of them are still vulnerable to sophisticated attacks, such as sweeping [11] and adaptive flooding attacks [12].

In this paper, we propose *MOTAG*, a dynamic DDoS defense mechanism that adopts moving target strategy to protect centralized online services. In particular, *MOTAG* offers DDoS resilience for authorized and authenticated clients of security sensitive services such as online banking and stock trade. *MOTAG* employs a layer of secret moving proxies to mediate all communications between clients and the protected application servers. The network-level filters surrounding the application servers only allow traffic from the working proxy nodes to reach the protected service.

Proxy nodes in *MOTAG* have two important characteristics. First, all proxy nodes are "secret" in that their IP addresses are concealed from the general public and are exclusively known by legitimate clients after successful authentication. Each legitimate client is provided with the IP address of one working proxy at any given time to avoid unnecessary information leakage. We apply existing proof-of-work (PoW) schemes [16], [17], [18], [19] to protect the client authentication channel. Second, proxy nodes are "moving". As soon as an active proxy node is attacked, it is replaced by another node at a different location, and the associated clients are migrated to alternative proxies. We show that these characteristics not only enable us to mitigate external DDoS attacks, but also empower us to discover and isolate malicious insiders that divulge the location of secret proxies to external attackers. We do so via shuffling (repositioning) clients' assignment to new proxy nodes when their original proxies are being attacked. We develop algorithms to accurately estimate the number of insiders and adjust client-to-proxy assignment accordingly to rescue most innocent clients after each shuffle.

Our solution does not rely on global adoption on Internet routers or collaboration across different ISPs to function. Neither do we depend on resource-abundant overlay network to out-muscle high bandwidth attacks and to provide fault tolerance. Instead, we take advantage of our proxies' secrecy and mobility properties to fend off powerful attackers. This entails lower deployment costs while offering substantial defensive agility, resulting as an effective DDoS protection.

II. Threat Model and Assumptions

Instead of targeting open and general-purpose web services, we focus our efforts on protecting security sensitive online services against *network flooding attacks*. The clients of the protected services are pre-authorized so that their identities can be authenticated before they are served. We assume a large pool of backup proxies that attackers are incapable of attacking altogether. However, only a small group of proxies are active at any time to avoid extensive operational costs. An ideal source for the proxy pool is one or several cloud environment where customers are charged only for running instances.

We assume powerful attackers with high aggregate bandwidth. They are capable of simultaneously overwhelming many standalone machines on the Internet. However, we do not assume attackers that can saturate well-provisioned Internet backbone links for ISPs, data centers, and cloud service providers. Attackers, in case of uncertainty, can first perform a reconnaissance attack, i.e. IP and port scanning, to pinpoint targets for the subsequent flooding attack.

Attackers can also target at flooding the authentication channel through which the legitimate clients can be authenticated. However, it is significantly harder for them to pass strong authentication by brute force and reach the proxies as legitimate clients. Some attackers may uncover certain secret proxies by compromising legitimate clients or eavesdropping on legitimate clients' network connections. We call those attackers "insiders" and assume that their number in a protected system is limited.

III. MOTAG Architecture

We depict the overall architecture of *MOTAG* in Figure 1. There are four inter-connected components: the authentication server, the proxies, the filter ring, and the application server. The application server provides the online service (e.g online banking, online stock exchange) that we want to protect and make accessible to authenticated clients. The proxy nodes are a group of dynamic and distributed machines that relay communications between clients and the application server. The filter ring, similar to what was described in [12], is comprised of a number of high speed routers placed around the application server, allowing inbound traffic only from valid proxy nodes. The authentication server is responsible for authenticating clients and linking legitimate ones with individual proxy nodes.

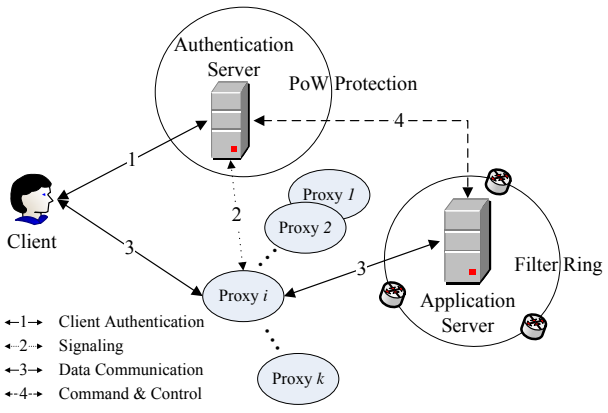


Fig. 1. Overview of the MOTAG Architecture.

Under *MOTAG*, all clients have to be authenticated before they are allowed to talk to the application server. A simple way to realize this is to associate the application domain name with the IP address of the authentication server during DNS registration. Each successfully authenticated client will be randomly assigned to one of the active proxy nodes whose identities are not publicly known. The authentication server will inform each client about the IP address of the designated proxy, and in the meantime, notify the proxy node about the forthcoming connection from the client. The authentication server, as well as each proxy node, maintains a dedicated interface for the purpose of signaling. Through this signaling channel, proxies report to the authentication server if they are attacked; the authentication server informs proxies about client assignment and coordinate their actions against DDoS attacks.

The authentication server also assigns a *capability token* for each client-to-proxy session. This token limits a client's throughput by specifying the number of packets (or, the number of bytes) allowed for the session in the next time window (t seconds). A proxy should receive identical copies of a capability token from two parties for every session, one from the authentication server to notify new client assignment and one from the client as a proof of identity. Every proxy node maintains a per-session counter and regulates traffic according to individual capability. Such capability-based policing is key for detecting external, brute-force flooding attacks in that it distinguishes authorized packets from illegal ones. Furthermore, it can detect and frustrate any internal attempt to abuse the assigned capability such as sharing capability with external attackers. For communications between proxy nodes and the application server, a lightweight authenticator (e.g. source address, destination #port) as described in Mayday [12] can be employed for proxy identity validation. The filter ring routers can perform fast lookups to verify such lightweight authenticators in proxy-to-application packets. These authenticators can be dynamically altered and active proxy nodes will receive timely updates via the signaling channel. To prevent the authentication server from being flooded by botnets, we employ proof-of-work (PoW) schemes [16], [17], [18], [19] to ensure its accessibility for legitimate clients.

A. Secret Moving Proxies

Since attackers only need to know the target's IP address to launch a flooding attack, one intuitive defense is to withhold such information from the attackers while keeping only legitimate clients informed. To achieve this goal, we have to distinguish legitimate clients from attackers. However, the distinction between the two may be blurred by IP spoofing, behavior mimicry, identity theft and malware infection. Moreover, a legitimate client may be compromised by attackers and become a malicious insider. Therefore, it is better to hide the application server from all clients while inserting a protection layer in the middle. In *MOTAG*, we build this intermediate layer with a pool of geographically distributed proxies to diffuse attackers' traffic and shield the application server behind. We do not activate all proxies at once. Instead, we only keep a small subset of proxies working at all times and dynamically substitute attacked ones at runtime, confusing attackers with "moving" proxies. The IP addresses of all proxies are also concealed from the general public. The mapping from clients to working proxies is many-to-one. Each proxy can accommodate many clients, while each client is only

appointed to (and knows the IP address of) a single proxy node.

If a proxy node is attacked, it will be shut down and a new proxy node at a different network location will be activated for replacement. All clients connecting to the attacked node will be re-assigned across the entire set of active proxies, according to the algorithm in Section IV-C. The new assignment can be pushed to the affected clients by the authentication server, or the clients can be re-authenticated for security assurance. We name the overall process of proxy replacement and client re-allocation as client-to-proxy shuffling. Shuffling is a coordinated operation in *MOTAG* that often involves multiple proxies and their associated clients. The details are to be discussed in Section IV. To preserve proxies' confidentiality and avoid introducing unnecessary communication jitters, no shuffling will be performed if there is no attack. A small, fixed set of proxy nodes with constant IP addresses are used to serve all legitimate clients under normal conditions. To prevent malicious proxy profiling by insiders, proxy assigned to each client will remain unchanged across different logins, if available. Moreover, to make physical proxy nodes more reusable over time, if the addresses of some secret proxies are disclosed during one instance of DDoS attack, they will be changed to a different, unknown set of addresses after the attack.

Secret moving proxies improve the agility and flexibility of defense against DDoS attacks. They support legitimate server access even during the course of an attack. *MOTAG* is different from existing overlay network solutions [10], [11], [12], [15]. Existing overlay solutions propose a fairly static network composition of overlay nodes that are known by all clients. A static and open overlay relies on its capacity and routing dynamics to tolerate and filter out the attack traffic. Building and maintaining such an overlay entails extensive and continuous investment to acquire more nodes and bandwidth. In addition, sweeping [11] and adaptive [12] flooding attacks may cause severe service disruptions. In contrast, *MOTAG* keeps its proxies confidential and mobile. Only authenticated clients are informed about their assigned proxies. This enhances defense agility against massive, sophisticated attacks while reducing its dependence on the volume of proxy resources.

B. Authentication with Proof-of-Work Protection

The authentication server with assured accessibility is essential to our moving target defense. It acts as the initial checkpoint where legitimate clients are separated from illegal ones. We use authentication as a mechanism to bind a client to a specific network flow. Every client has to pass authentication before assigned to a working proxy that eventually routes traffic to the application server. *MOTAG* is agnostic to the specific authentication mechanism employed. More than one physical authentication server can be used to increase system capacity and availability. The authentication server is also responsible for advertising the initial and subsequent client-to-proxy assignments during shuffling. To re-assign affected clients to non-attacked proxies without breaking the end-to-end connectivity, the authentication server will push new proxy assignment to each affected client. As an alternative, we could potentially re-authenticate clients upon re-appointment to ensure their liveness. The authentication server is the only part of the *MOTAG* architecture that can be publicly addressed. Therefore, it can be a new target of distributed flooding (i.e. Denial of Capability) attacks.

Instead of building new solutions to protect the authentication server, we take advantage of existing proof-of-work (PoW) schemes [16], [17], [18], [19], which force clients to solve certain cryptographic puzzles before allowing them to consume resources on the server side. In particular, they can realize per-computation fairness regarding bandwidth usage among all clients [19], prevent connection depletion attacks [18], and mitigate DDoS attacks on application-level authentication protocols [16], [17]. PoW approaches are suitable for protecting client authentication in that authentication packets are infrequently sent and are more delay-tolerant. However, they are improper for protecting application data communication because they incur heavy overhead.

IV. Client-to-Proxy Shuffling

Hiding proxies while enforcing client authentication can effectively prevent external attackers from reaching *MOTAG*'s packet delivery system. Moreover, by keeping proxies mobile and performing guided shuffling on client-to-proxy assignments, *MOTAG* can also mitigate insider attacks that aim to disclose the location of secret proxies.

Attackers can implant malicious insiders in the targeted system via social engineering, compromising legitimate clients, stealing clients' identities for authentication, and eavesdropping on clients' network connections. Once insiders uncover the IP addresses of some proxy nodes, they will notify external attackers who will carry out DDoS attacks against these exposed proxies. We address such attacks as insider-assisted DDoS attacks. The more insiders there are, the more secret proxies will be endangered, and consequently, the more innocent clients will be affected by the DDoS attack. Although such insider attacks cannot be fully prevented, we aim to minimize their impact on innocent clients.

When an insider-assisted attack hits one proxy, we cannot identify which affiliated clients are insiders by simply looking at the attack snapshot. Therefore, we cannot segregate the innocent clients from the insiders residing on the same proxy node, neither can we determine the number of insiders we are facing. To solve these problems, we design a client-to-proxy shuffling mechanism to quarantine insider-assisted DDoS attacks and ensure service accessibility for as many innocent clients as possible.

A. Shuffling Strategy

In *MOTAG*, a pool of proxy nodes are reserved and idled before DDoS attacks break out. As soon as an attack happens, a small number of proxy nodes in the pool are activated. The set of active proxy nodes can be logically classified into two groups, namely *serving proxies* and *shuffling proxies*. Serving

proxies provide more reliable connection services to the known innocent clients, while shuffling proxies are responsible for shuffling operations and only provide intermittent connections to suspicious clients. When attacked, shuffling proxies will be replaced and the associated clients are flushed and reassigned. For the ease of representation, we use the same logical identifier for a shuffling proxy and its replacement throughout our analysis. As a result, it appears that we re-use the same set of shuffling proxies over time. In fact, the attacked physical proxies are always replaced.

Here, shuffling refers to the action of changing the client-to-proxy assignment scheme in a semi-random fashion. For example, a client appointed to proxy node P may be appointed to proxy node Q after the next shuffle; a proxy node assigned with client set $\mathbf{X}$ can be assigned with client set $\mathbf{Y}$ later. The reason for the semi-randomness is that a greedy algorithm (discussed in Section IV-C) is used to dictate the number of clients attached to each shuffling proxy. At the beginning, all the active proxies are unmarked. All clients are randomly assigned to proxies. Each client will be assigned to only one proxy at a time. If some proxies are attacked after the initial assignment, they will be marked as shuffling proxies while others are considered serving proxies. By employing the greedy algorithm described in Section IV-C, we repeatedly shuffle the client-to-proxy assignment within the shuffling proxy group to distinguish insiders from innocent clients and segregate them.

As pointed out in the threat model, we assume attackers are aggressive and exhaustive to keep attacking all expose proxies. We also assume there are only a limited number of insiders. As a result, some shuffling proxies may be attacked after each shuffle and some will not. The intact shuffling proxies become serving proxies and the unaffected clients on them are saved and marked as trusted clients. Clients connected to the attacked proxies are also considered as attacked and untrusted, since we cannot tell who are actually the insiders within the whole population. To save the innocent but attacked ones, we will randomly re-distribute all the untrusted clients across the group of shuffling proxies. Given the specific number of suspicious clients and available proxy nodes, a few new proxies may be activated as shuffling proxies from the pool to help accelerate shuffling operations. Generally speaking, the more shuffling proxies are available, the faster insiders will be quarantined.

One round of client-to-proxy shuffling provides us some important information on quarantining suspicious clients. By repeating the client-to-proxy shuffling for multiple rounds and keeping record of the suspicious proxies/clients, we can narrow down the range of suspects and gradually identify most innocent clients. The insiders will eventually be quarantined and the attack damage will be minimized. To achieve this goal as quickly as possible, proxy consolidation can be performed to concentrate trusted clients onto less serving proxies, thereby sparing more proxy nodes for the shuffling purpose.

B. Shuffling Optimization

It is critical to design an optimal shuffling algorithm that can mitigate insider-assisted attacks with the fewest shuffles. To that end, we need to identify and separate as many innocent clients as possible after each round. First of all, we analytically evaluate the number of innocent clients to be saved under different client-to-proxy assignments. We provide a method to estimate the number of insiders in Section IV-D.

Specifically, among a total number of N clients to be shuffled, the number of insiders is N_i, and the number of innocent clients is N_c, so we have $N_i + N_c = N$. After one round of shuffling, N_{ca} innocent clients are still being attacked, and N_{cu} of them are not ($N_{ca} + N_{cu} = N_c$). Our goal is to mathematically compute the expected value of N_{cu} (denoted as $E(N_{cu})$) under different circumstances and find a way to maximize it, given a number of K available shuffling proxies. We use A_j to represent the number of clients appointed to proxy j.

Obviously, $E(N_{cu}) = \sum_{j=1}^{K} p_j A_j$, where p_j is the probability that proxy j is not being attacked. Considering an arbitrary proxy j, it is not being attacked only when none of the insiders are connecting to it. Hence, p_j is also the probability that all insiders are assigned to proxy nodes other than j. According to simple combinatorics, $p_j = \binom{N-A_j}{N_i} / \binom{N}{N_i}$, where $\binom{N}{N_i}$ is the total number of ways to distribute the N_i insiders within the population N, and $\binom{N-A_j}{N_i}$ is the number of combinations that all insiders are within the $N - A_j$ clients not connecting to proxy j. Therefore, the expected value of N_{cu} can be calculated by Equation IV.1.

$$E(N_{cu}) = \sum_{j=1}^{K} p_j A_j = \frac{\sum_{j=1}^{K} \binom{N-A_j}{N_i} A_j}{\binom{N}{N_i}} \tag{IV.1}$$

We also have $E(N_{ca}) = N_c - E(N_{cu})$.

Given the total number of clients N, the number of insiders N_i, the number of shuffling proxies K, and the client-to-proxy assignment vector $\mathbf{A}$, we want to maximize $E(N_{cu})$. Intuitively, the more shuffling proxies are used, the more innocent clients are expected to be saved via each shuffle. In the extreme case where $K \geq N$, each client can be allocated with an exclusive proxy node ($A_j = 1,\ \forall j \in (1,K)$). In this case, $E(N_{cu}) = N_c$, meaning no innocent client will be attacked. This is the ideal scenario where all insiders are quarantined their own proxy nodes within one round of shuffling. However, in practice, it is usually impossible to provide a dedicated proxy node for each client when clients are large in number. In most cases, the client population would outnumber the shuffling proxies by far ($K << N$). Consequently, the way of distributing clients across proxy nodes becomes utterly important.

Assuming we have a constant number of K shuffling proxies, we are facing an optimization/maximization problem with Equation IV.1 being the objective function. The variables are summarized into the vector $\mathbf{A}$ of natural numbers that defines the client-to-proxy assignment scheme, with the constraint being

$$\sum_{j=1}^{K} A_j = N, \ \ where \ \ \mathbf{A} \in \mathbb{N}^K \tag{IV.2}$$

For all cases that $N_i \geq 1$, the objective function is nonlinear. Since A_j has to be a non-negative integer for all $j \in (1,K)$, our optimization problem is in fact a nonlinear integer programming problem [20]. The general class of nonlinear integer programming problem is NP-hard [21]. For our special problem, we adopt a greedy approach that can produce a near optimal solution within polynomial time. Our simulations under various configurations show that the results produced by the greedy algorithm approach very closely to the theoretical upper bound of $E(N_{cu})$.

C. The Greedy Shuffling Algorithm

Algorithm 1 shows the greedy algorithm for computing the client-to-proxy assignment. The main function is called *GreedyAssign*. Since in Equation IV.1 $E(N_{cu})$ is the sum of pieces (i.e. $p_j A_j$) for all shuffling proxies computed in the same way, we firstly perform optimality analysis for an individual component. For an arbitrary proxy j, A_j can be any value within $[0, N-1]$. A_j cannot be N. Otherwise, everyone will be attacked if there is an insider onboard.

Since the value of N_i will affect the optimal choice of A_j, for a particular N_i, we enumerate all possible values of A_j and select the one (ω) that maximizes $p_j A_j$. This subroutine is described in procedure *MaxProxy* of Algorithm 1. Apparently, the computational complexity of *MaxProxy* for one proxy is $O(N * N_i)$. Under our greedy approach, we assign ω clients to as many proxies as possible.

Function *GreedyAssign* is called recursively to assign the remaining clients to the rest of the proxies. The computation will terminate under three conditions. First, when there are more proxy nodes left than clients, each client will be assigned to an exclusive proxy node. Second, when there is only one proxy left, all remaining clients will be appointed to it. Third, when the expected number of remaining insiders is rounded to 0, all remaining clients will be evenly distributed for load balancing. The overall computational complexity of the greedy algorithm is $O(N * K * N_i)$. Moreover, the client-to-proxy assignment vectors for different N, K, N_i configurations can be pre-computed and stored in the form of a lookup table, thereby avoiding extra computational overhead to our shuffling operations when attack happens.

We compare the results of the greedy algorithm with the theoretical upper bound of the global maximum of $E(N_{cu})$. Since Equation IV.1 is a summation of $p_j A_j$ for each individual shuffling proxy j, the max of IV.1 cannot be greater than the sum of the max of each $p_j A_j$ when relaxing Constraint IV.2, i.e. $Max(E(N_{cu})) \leq K * Max(p_j A_j)$. Here, $Max(p_j A_j)$ can be obtained by running subroutine *MaxProxy*$(N, 0, N-1, N_i)$. We implemented both *GreedyAssign* and *MaxProxy* on MATLAB. We then computed the results of our greedy algorithm as well as the theoretical upper bound of the global maximum under various configurations. The comparison is shown in Figure 2.

Algorithm 1 Greedy algorithm for computing client-to-proxy assignment.

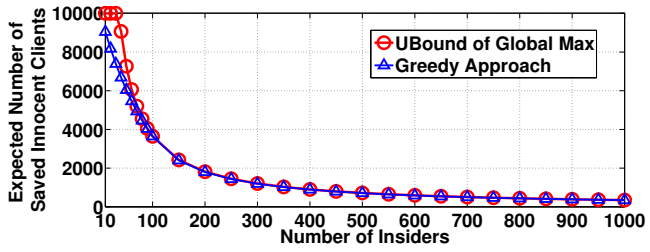
```
function GreedyAssign(Client, Insider, Prox)
    if Client ≤ Prox then
        Assign 1 exclusive proxy to each client
    else if Prox = 1 then
        Assign all clients to the proxy
    else if Insider = 0 then
        Evenly distribute Client over Prox
    else
        ω = MaxProxy(Client, 0, Client − 1, Insider)
        ProxToFill = floor(Client / ω)
        if ProxToFill ≥ Prox then
            ProxToFill = Prox − 1
        RemC = Client − ProxToFill * ω
        RemP = Prox − ProxToFill
        RemA = Round((Insider * RemC) / Client)
        Fill ProxToFill Proxies with ω clients each
        Fill the rest proxies according to
        GreedyAssign(RemC, RemA, RemP)

procedure MaxProxy(Client, Lbnd, Ubnd, Insider)
    Max=0, MaxAssign=0
    for i = Lbnd → Ubnd do
        Save = C(Client−i, Insider) * i / C(Client, Insider)
        if Save > Max then
            Max = Save, MaxAssign = i
    return MaxAssign
```

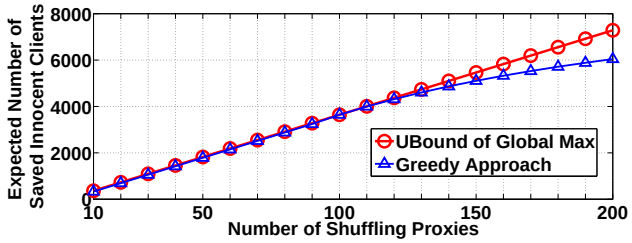
In our computation, three key parameters, namely the numbers of total clients (N), insiders (N_i), and employed shuffling proxies (K), collectively determine the final results. When we vary one parameter in each plot while keeping the other two constant, the expected number of saved clients by our greedy approach from one shuffle almost overlaps with the theoretical upper bound. This means that performance of the greedy algorithm performs is near optimal. The line denoting the greedy approach deviates slightly only when the number of insiders is well below the number of shuffling proxies. This is not a big problem because when the number of shuffling proxies becomes significantly higher, a majority of innocent clients can be isolated from an attack in just one shuffle, making it possible to save almost all innocent clients within very few rounds. It is also shown in Figure 2a that, when the number of insiders is low, we can easily minimize the impact of an insider-assisted attack. However, the result will quickly deteriorate as the number of insiders grows. When it becomes twice the number of shuffling proxies, more than 80% of the total clients will still be affected by the attack after one shuffle. In that case, more shuffles will be needed to protect a majority of innocent clients.

D. Estimating the Number of Insiders

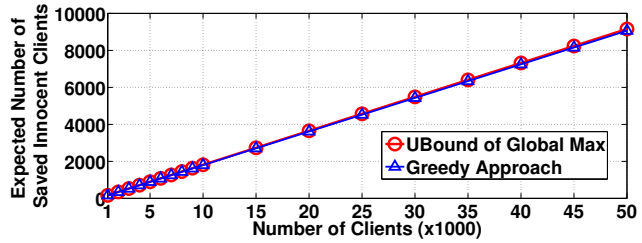
In our earlier discussion, we assume the number of insiders (N_i) is fixed and given; however, in practice, we have no such



(a) Changing the number of insiders under 10000 clients, 100 shuffling proxies



(b) Changing the number of proxy nodes under 10000 clients, 100 insiders



(c) Changing the number of clients under 200 insiders, 100 proxy nodes

Fig. 2. Compare the greedy approach with the theoretical upper bound of global maximum

prior knowledge. Since the value of N_i has direct influence on the client-to-proxy assignment, it is important to make accurate estimation. We solve this problem using maximum-likelihood estimation (MLE). We first establish a connection between the number of insiders N_i and the number of proxies that are not under attack (denoted as X). In a particular attack where $X = m$, we calculate the probabilities $Pr(X = m)$ with regard to different N_i values, and use the N_i value that maximizes the probability as the estimated number of insiders.

According to the inclusion-exclusion principle under balls-and-urns model [22], we can compose Equation IV.3 to calculate $Pr(X = m)$, where $Pr(X \geq M)$ stands for the probability that at least M $(M = m, m+1, \ldots, K)$ proxy nodes are not attacked, K is the total number of all shuffling proxies.

$$\begin{aligned} Pr(X = m) = Pr(X \geq m) - \binom{m+1}{m} Pr(X \geq (m+1)) \\ + \binom{m+2}{m} Pr(X \geq (m+2)) - \ldots \\ + (-1)^{K-m} \binom{K}{m} Pr(X \geq K) \end{aligned} \tag{IV.3}$$

In particular, these M not-under-attack proxies constitute the set $\mathbf{U} = \{u_1, u_2, \ldots, u_M\}$, where u_j is the real ID of the jth available proxy node. Set $\mathbf{U}$ can be any M sized subset of the K shuffling proxies.

The key idea to compute $Pr(X \geq M)$ is similar to how we derive Equation IV.1. If a particular set $\mathbf{U}$ of proxies are not attacked, the insiders must be among the clients assigned to the rest proxy nodes (the complement of $\mathbf{U}$). Thus, we have Equation IV.4, in which $\sum_{\mathbf{U}}^{(M)}$ denotes the summation over all possible combinations of $\mathbf{U}$ (all M sized subsets of the K shuffling proxies), and $N - \sum_{j=1}^{M} A_{u_j}$ gives the number of clients connecting to the proxies not in $\mathbf{U}$. u_j is an arbitrary proxy node in the set, and A_{u_j} denotes the number of clients assigned to that node.

$$Pr(X \geq M) = \frac{\sum_{\mathbf{U}}^{(M)} \binom{N - \sum_{j=1}^{M} A_{u_j}}{N_i}}{\binom{N}{N_i}} \tag{IV.4}$$

Under a certain client-to-proxy assignment scheme $\mathbf{A}$, we can now correlate $Pr(X = m)$ with N_i by combining Equation IV.3 and IV.4. Since the greedy algorithm recursively attempts to assign as many proxies as possible with the same client number that maximizes each individual component of the objective function, it usually produces groups of shuffling proxies with equal numbers of clients. Therefore, we can break down the overall estimation problem into each group and summarize the results from all groups at the end. It is worth noticing that since we do not have prior knowledge about the number of insiders, the entire client population is evenly distributed across all proxy nodes before the first shuffle. This allows *MOTAG* to quickly draw the first estimation as soon as an attack happens. Thus, we can simplify the calculation by transforming Equation IV.4 into Equation IV.5 for each proxy group. In Equation IV.5, $N_{\mathbf{G}}$, $N_{i_{\mathbf{G}}}$, $K_{\mathbf{G}}$, $A_{\mathbf{G}}$, and $M_{\mathbf{G}}$ represent the number clients, the number of insiders, the number of shuffling proxies, the number of clients assigned to each proxy node, and the number of proxy nodes not under attack within group $\mathbf{G}$, respectively.

$$Pr(X \geq M_{\mathbf{G}}) = \frac{\binom{K_{\mathbf{G}}}{M_{\mathbf{G}}} \binom{N_{\mathbf{G}} - M_{\mathbf{G}} A_{\mathbf{G}}}{N_{i_{\mathbf{G}}}}}{\binom{N_{\mathbf{G}}}{N_{i_{\mathbf{G}}}}} \tag{IV.5}$$

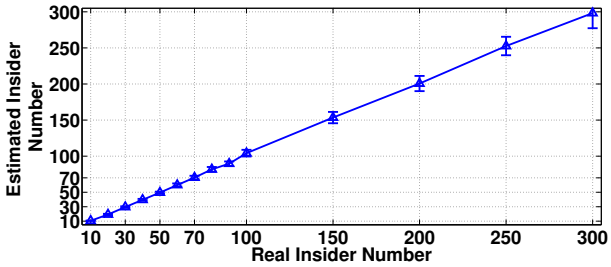


Fig. 3. Insider estimation under 10K clients, 100 shuffling proxies

To evaluate our insider estimation algorithm, we also implemented it on MATLAB and run simulations with different numbers of insiders. Based on the number of attacked proxies,

our algorithm makes educated guesses on the real insider numbers. The guess that maximizes the result of Equation IV.3 becomes the final estimation. These estimations, along with the actual insider numbers, are plotted in Figure 3. For each data point, we run the simulation 30 times to compute the mean and 99% confidence interval. According to the results in the figure, our algorithm gives very accurate estimations.

V. Security Analysis

MOTAG is a dynamic traffic indirection framework opened only to authenticated clients. It is designed to account for both brute force and sophisticated DDoS attacks against the protected application server and other potential targets.

a) **Resistance to external attacks:** In *MOTAG*, external attackers will not be able locate the secret proxies unless they are part of the system. Even if they are capable of attacking a large number of Internet nodes simultaneously, they will not be able to identify where to direct their attack. *MOTAG* is invulnerable to reconnaissance attacks. Our proxy nodes are widely distributed on the Internet, if external attackers do not have prior knowledge about the potential IP of a proxy, it would be impractical for them to locate the node by scanning the vast network. Even if they can manage to let their probing packets hit some proxies, the proxy nodes will not respond because no capability tokens are assigned for the attackers. As a result, *MOTAG* significantly raises the bar for brute force attackers. The mobility of proxy nodes adds another layer of protection against external attackers. In the case that attackers hit a secret proxy by chance, the attacked node will quickly "move away". Without the ability to trace the shifting proxies, external attackers will get lost in front of the moving targets.

b) **Resistance to insider-assisted attacks:** Insider-assisted attacks pose a more serious threat to the proxy-based defense because the addresses of secret moving proxies are only disclosed to authenticated clients. *MOTAG* is resilient to three types of malicious behavior initiated by insiders. *i) Capability sharing.* A capability token is bound to each client-to-proxy session for traffic policing. Even if an insider shares the assigned capability with external attackers, their aggregate throughput will still not be allowed to exceed the specified limit. *ii) Divulging secret proxies.* As discussed in Section IV, by dynamically "moving" proxy nodes and shuffling client-to-proxy designation, *MOTAG* can quarantine insiders that lead DDoS attacks by divulging secret proxies to external attackers. *iii) Silent proxy profiling.* As described in Section II, there might be inactive insiders that silently profile our proxy system throughout the entire shuffling process. However, since clients assigned to proxies that are not attacked will not be shuffled, it is highly likely that silent insiders will be staying with the same proxy all the time and unable to collect new proxy information.

c) **Resistance to compromised proxies:** With the help from malicious insiders, attackers may even compromise some proxy nodes. If successful, the application server and the authentication server will be directly exposed to attackers. However, the filter ring routers surrounding the application server will filter out any packets that fail to include a legal lightweight authenticator. Similar to what was used in [12], a lightweight authenticator can be proxy's unique IP address, or a carefully crafted destination IP address/port number assigned differently to each proxy node. Consequently, attack traffic has to use the credentials of the compromised proxies to get through, which can be readily identified and revoked. The signaling channels to the authentication server can be protected in the same manner.

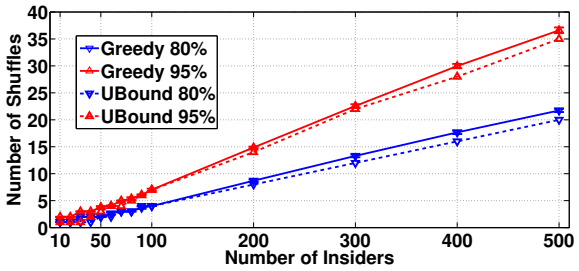
VI. MOTAG Evaluation

A. Insider Quarantine Capability

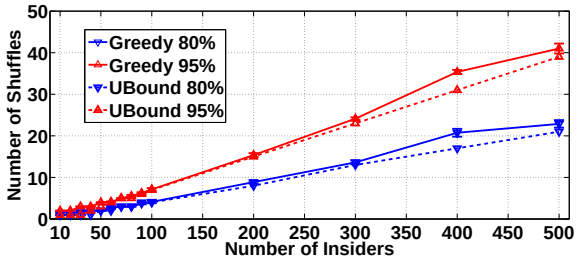
In this section, we experimentally evaluate *MOTAG*'s effectiveness on mitigating insider-assisted DDoS attacks. To that end, we implement all core algorithms of *MOTAG* in Matlab and run them with simulated clients and proxy nodes. We randomly select clients to be malicious insiders without informing *MOTAG*. *MOTAG* decides the number of clients assigned to each proxy node but each client is randomly appointed to a proxy with empty slots. In all simulations, we use Mersenne twister [23] as our random number generator. We assume attackers possess infinite bandwidth, so all proxies connected by the malicious insiders are considered as attacked. All clients on these attacked proxies are marked as suspicious. Then, *MOTAG* uses the method in Section IV-D to estimate the number of existing insiders and uses the algorithm in Section IV-C to determine the client-to-proxy assignment for the next shuffle. It usually takes more than one shuffle to save a majority of innocent clients when the number of insiders is large. Figure 4 quantitatively shows the number of shuffles needed to save 80% and 95% innocent clients by using our greedy algorithm (solid lines) and by applying the theoretical upper bound of Equation IV.1 (dotted lines) in each shuffle. Figure 4a and 4b vary the number of insiders while keeping the total number of clients and shuffling proxies constant. Figure 4c and 4d only change the number of shuffling proxies. $10,000$ clients are simulated in Figure 4a and 4c, while $100,000$ clients are simulated in Figure 4b and 4d. We run the same 30 times simulation for each data point and plot with 99% confidence interval.

We see that the performance of *MOTAG* is close to the theoretical optimum. In particular, Figure 4a and 4b show that the number of shuffles needed to save the same percentage of innocent clients grows almost linearly with the increase in the number of insiders. More shuffles indicate longer time to mitigate an attack, but it also means that attackers have to devote much more effort to recruit more insiders. Figure 4c and 4d reveal that the number of necessary shuffles increases as less proxy nodes are available. The lines climb slowly when the proxies outnumber the insiders and become significantly steeper otherwise. Moreover, the small confidence intervals of *MOTAG*'s data points indicate that the performance of our shuffling algorithm is reliable and predictable.

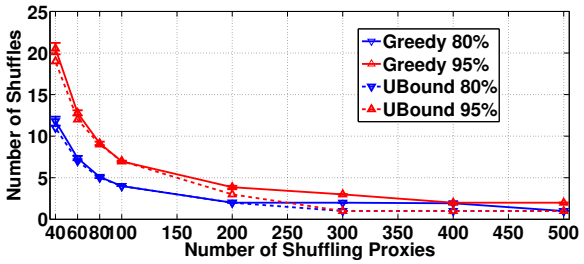
Notice that the change from $10,000$ to $100,000$ clients almost causes no difference in the simulation results. Instead, the ratio between the number of shuffling proxies and the



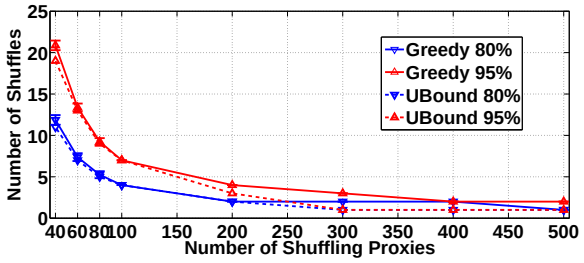
(a) Varying the number of insiders under 10K clients, 100 shuffling proxies



(b) Varying the number of insiders under 100K clients, 100 shuffling proxies



(c) Varying the number of shuffling proxies under 10K clients, 100 insiders



(d) Varying the number of shuffling proxies under 100K clients, 100 insiders

Fig. 4. The number of shuffles needed to save 80% and 95% of innocent clients

number of insiders is the decisive factor on protecting innocent clients. Figure 5 shows the minimum number of shuffling proxies required to save 95% of innocent clients within 5, 10, and 15 shuffles, respectively. The number of insiders ranges from 10 to 800. The solid lines represent a client population of 10 thousand and the dotted lines denote 100 thousand. We see a close to linear relationship between the number of required shuffling proxies and the number of insiders in achieving a constant security goal. These results can help system administrators decide how many proxy nodes they will need to achieve their security goals. Again, a 10 fold increase in the client population only has a minor impact on the results and the 99% confidence intervals are almost negligible.

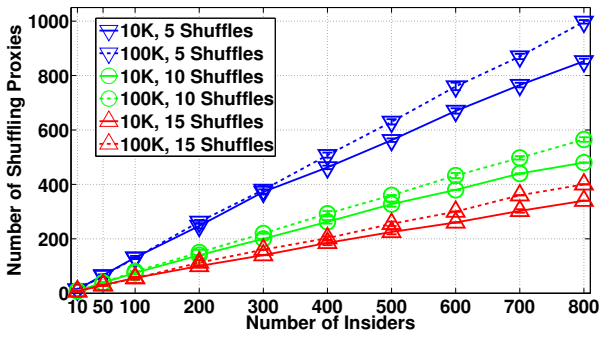


Fig. 5. Number of proxy nodes needed to save 95% of innocent clients within 5, 10, and 15 shuffles, with 10K and 100K clients and a increasing number of insiders

B. Overhead

MOTAG mainly introduces two aspects of overhead to communications between clients and the application server, namely proxy-based communication indirection, and client-to-proxy shuffling.

TABLE I
LATENCY OVERHEAD INTRODUCED BY PROXY INDIRECTION

	Direct	Indirect			
	RTT	Mean RTT	Overhead	Max RTT	Overhead
1	63ms	104ms	63.35%	143ms	125.41%
2	86ms	99ms	15.64%	128ms	49.45%
3	83ms	102ms	23.73%	133ms	60.47%
4	90ms	112ms	23.77%	131ms	45.18%
5	84ms	107ms	27.73%	120ms	42.48%

TABLE II
THROUGHPUT OVERHEAD INTRODUCED BY PROXY INDIRECTION (MB/S)

	1	2	3	4	5
Direct	90.66	83.46	86.24	123.30	121.20
Indirect	15.20	14.46	13.99	15.97	14.09

First, to assess the overhead introduced by proxy-based traffic indirection, we select 10 geographically distinct U.S. nodes from PlanetLab to form 5 end-to-end flows. We also randomly pick 24 other nodes that spread across the country to serve as proxies. We measure the latency and throughput for both direct and indirect communications of the 5 flows, and the results are shown in Table I and Table II, respectively. SSH tunneling through individual proxy node is employed to redirect traffic between end nodes. Round trip time (RTT) numbers are obtained by bouncing short TCP messages back and forth between the end nodes of each flow 100 times to get the mean. Throughput numbers are the average of 10 Iperf [24] sessions. Apparently, the impact of introducing proxies on latency (usually less than 30%) is much less significant than its influence on throughput. The drop on throughput is not only caused by traffic indirection by proxies, but is also a result of message encryption and decryption by SSH agents. In fact, different crypto strategies, including no encryption, can be

listed as options when implementing *MOTAG* based systems. Users can make informed decisions based on the nature of the protected application.

TABLE III
TIME TO SWITCH BETWEEN TWO PROXY NODES (SECONDS)

1	2	3	4	5
1.155	1.158	1.529	1.378	1.286

The time needed to shuffle clients among different proxy nodes determines the agility and usability of *MOTAG* against insider attacks. Quick shuffles will make it harder for attackers to "follow" and have insiders quarantined faster. At the same time, innocent but shuffled clients will suffer less severe service disruptions. Therefore, to quantify the impact of our system to the end users, we measure the time needed for a client to switch from one proxy node to another. Again, we choose 5 geographically dispersed nodes from PlanetLab to be the destination servers. We randomly pick another node to play the role of the authentication server. We time the entire process that our local client gets notified by the authentication server, then discards the current proxy and connects to the new proxy, until eventually reaches back to the destination server. During this process, the authentication server sends a session ticket to both the client and the new proxy node, the client will present this ticket to the proxy to get authenticated. Only after that, the new proxy node will start forwarding packets for the client. We use another 8 PlanetLab nodes as proxies and switch between them. The average switching time for each destination is listed in Table III. The numbers are fairly consistent. A proxy switching time slightly above 1 second should not cause significant service disruption for most non-realtime applications.

VII. RELATED WORK

A lot of research efforts have been devoted to defense against DDoS attacks over the past decade [25].

Filtering-based approaches [3], [4], [5] intend to use ubiquitously deployed filters to block unwanted traffic far away from the protected nodes. They assume that attack traffic can be differentiated from legitimate traffic. However, this is usually a difficult job because attackers can sneak through by IP spoofing and mimicking normal senders. Instead of trying to distinguish good clients from malicious ones at the beginning, *MOTAG* first does client authentication to filter out illegal clients. Only authenticated clients will be appointed to the secret moving Internet proxies that can directly talk to the protected application server.

Capability-based mechanisms adopt a different philosophy that gives the control over resource usage to the packet receiver [6], [7], [8], [9]. Senders have to obtain receivers' explicit permission before sending packets to them. Traffic from authorized or privileged senders with valid capability can be prioritized during an attack. Using capability is a more proactive way of defense. Nevertheless, such solutions also rely on a global adoption on the Internet routers to provide adequate protection, which is unlikely to happen given limited incentives. *MOTAG* uses capability token to identify and rate-limit authenticated clients. Rather than depending on high degree of deployment on the Internet routers, we employ a thin layer of secret moving proxies for traffic policing.

To eliminate the physical network constraints and administrative boundaries, secure overlay networks are proposed to be built on top of the Internet to provide flow authentication, filtering, indirection, as well as attack tracking and tolerance [10], [11], [12], [13], [14], [15]. The common goal is to hide the protected nodes behind the well-provisioned, distributed overlay network that absorbs DDoS traffic. TOR [26] is a well-known implementation of overlay network. By using an exposed, relatively static overlay network to withstand the ever-intensifying DDoS attacks inflicted by expanding botnets, the defenders will involve themselves in a never-ending armed race with the attackers. Even if a strong overlay network that can tolerate any DDoS attacks is in place, advanced attackers can start by attacking a small portion of the overlay nodes and sweep through the entire overlay step by step [11]. By doing so repeatedly, attackers are guaranteed to hit the critical nodes and cause major service disruptions (*Sweeping Attack*). Sophisticated attackers can even measure the impact of their attacks via recruited legitimate clients. They can use such feedback to spot and hence adapt their attack to focus on the pinch points [12] (*Adaptive Attack*). Moreover, the protected server can potentially be exposed via insider attacks [27].

Besides overlay network, there are other efforts that hide the paths to selected services behind intermediate protections [28], [29]. These solutions intend to employ a simpler, easier-to-deploy protection layer to filter out un-authorized traffic and are thus conceptually similar to *MOTAG*. Unfortunately, they fail to account for attacks in which authorized clients act as malicious insiders to compromise their interlayer protection. In this paper, we thoroughly analyzed insider threats and proposed a novel shuffling mechanism to quarantine insider-assisted attacks.

MOTAG endows mobility to its packet indirection proxies. This resembles the earlier network address randomization technique against hitlist worms [30] and the fast-flux scheme to sustain accessibility to illegal commercial websites [31]. To the best of our knowledge, we are the first in using such dynamic method on defense against DDoS attacks.

VIII. CONCLUSION

We present *MOTAG*, a framework that employs dynamic, hidden proxies as moving targets to mitigate network flooding DDoS attacks. To reach the protected service, authenticated clients are assigned to individual proxy nodes that perform packet forwarding and session policing. When a DDoS attack is mounted against *MOTAG* proxies, the authenticated clients connected to the attacked proxies are re-assigned to alternative proxies at realtime, enabling them to evade the ongoing attack and maintain access the protected service. With *MOTAG*, we can effectively hide the protected critical services from external attackers. Sophisticated attackers can only use insiders

to locate our proxy nodes and attack them. *MOTAG* employs a novel, efficient shuffling mechanism to quarantine insider-assisted attacks. Our simulations show that *MOTAG* can protect a majority of innocent clients from DDoS attacks assisted by hundreds of insiders within a small number of shuffles. In addition, our experimental methodology and the results can be used to guide the implementation and deployment of *MOTAG*-based DDoS defense systems.

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