# On the Effectiveness of Secure Overlay Forwarding Systems under Intelligent Distributed DoS Attacks

Xun Wang, Sriram Chellappan, Phillip Boyer and Dong Xuan

**Abstract**

In the framework of a set of clients communicating with a critical server over the Internet, a recent approach to protect communication from Distributed Denial of Service (DDoS) attacks involves the usage of overlay systems. SOS, MAYDAY and I3 are such systems. The overlay system serves as an intermediate forwarding system between the clients and the server, where the systems typically have fixed architectures that employ a set of overlay nodes controlling access to the server. Although such systems perform well under random DDoS attacks, it is questionable whether they are resilient to intelligent DDoS attacks which aim to infer architectures of the systems to launch more efficient attacks. In this paper, we define several intelligent DDoS attack models and develop analytical/simulation approaches to study the impacts of architectural design features on the system performance in terms of path availability between clients and the server. Our data clearly demonstrate that the system performance is indeed sensitive to the architectural features and the different features interact with each other to impact overall system performance under intelligent DDoS attacks. Our observations provide important guidelines in the design of such secure overlay forwarding systems.

**Index Terms**

Secure Overlay Forwarding System, DDoS attacks

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# I. INTRODUCTION

Distributed Denial of Service (DDoS) attacks are currently major threats to communications in the Internet [1]. Current level of sophistication in system resilience to DDoS attacks is far from definite. Tremendous amount of research is being done in order to improve the system security under DDoS attacks [2], [3], [4], [5], [6], [7], [8]. For many applications, reliability of communication over the Internet is not only important but mandatory. Typical examples of such applications are emergency, medical, and other related services. The system needs to be resilient to attacks from malicious users within and outside of the system that aim to disrupt communications.

A recent body of work in the realm of protecting communications between a set of clients and a server against DDoS attacks employs proactive defense mechanisms using overlay-based architectures [6], [7], [8]. Typically, in such overlay-based architectures, a set of system deployed nodes on the Internet form a communication bridge between clients and a critical server. The deployed nodes are intermediate forwarders of communication from clients to the server. These nodes are arranged into overlay-based architectures (or structures) that provide attack-resistant features to the overall communication. For example, the architecture in the SOS system [6] is a set of overlay nodes arranged in $three$ layers between clients and the server through which traffic is authenticated and then routed. These layers are SOAP (Secure Overlay Access Point), Beacons and Secret Servlets. A client that wishes to communicate with a server first contacts a node in the SOAP layer. The node in the SOAP layer forwards the message to a node in the beacon layer, which then forwards the message to a node in the secret servlet layer, which routes the message to the server. In the Mayday system [7], the authors extend work on SOS [6] by primarily releasing the restrictions on the number of layers (unlike in SOS, where it is fixed at *three*). In the Internet Indirection Infrastructure (I3) [8], one or more Indirection points are introduced as intermediaries for communication between senders and receivers.

The design rationale in all these systems is to ensure, using proactive architectures, (i) that the server and intermediate communication mechanisms are hidden from outsiders, (ii) the presence of multiple/alternate

paths to improve reliability and (iii) access control to prevent illegitimate users from being serviced, and dropping attack traffic far away from the server. The final objective though is to ensure that there are high degrees of *path availabilities* from clients to the server even when attackers try to compromise communication using random *congestion-based* DDoS attacks, by bombarding randomly chosen nodes in the system with huge amounts of traffic.

While the above systems provide high degrees of path availabilities under random congestion-based DDoS attacks, such systems can be targeted by *intelligent* attackers that can break-into the system structure apart from congesting nodes. By *break-in* attacks, we mean attacks that can break-into a node and disclose its neighbors in the communication chain. By combining break-in attacks with congestion attacks, attackers can significantly worsen damages, as opposed to pure random congestion. In fact attackers can employ results of break-in attacks (disclosed nodes) to guide subsequent congestion attacks on the disclosed nodes. Under intense break-in attacks, the attacker can traverse the communication chain between the forwarder nodes, and can even disclose the server to eventually congest it and completely annul services.

We believe that such intelligent DDoS attacks that can combine break-in attacks with congestion attacks are *representative* and *potent* threats to overlay-based systems, such as [6], [7], [8] that protect communications between clients and the servers. However, existing work does not study system performance under these intelligent attacks. In this paper, we extensively study performance of such overlay-based systems when targeted by intelligent DDoS attacks that combine break-in and congestion attacks. We also subsequently study how design features of such systems impact performance under intelligent attacks. As a first step, we generalize such systems as Secure Overlay Forwarding Systems (SOFS). There are certain standard architectural features of such systems [1]. These are; layering (the number of layers between the client and server), mapping degree (number of next layer neighbors a node can communicate with), node distribution (number of nodes per layer).

Our objective is to study the impacts of the design features of SOFS system on its performance under intelligent DDoS attacks, and to provide guidelines to design SOFS systems highly resilient to intelligent

[1]We use the terms *architectural features* and *design features* interchangeably in this paper.

DDoS attacks. Towards this extent, we develop formal mathematical models of intelligent attacks, and use analytical approaches and simulations to study the system performance and sensitivity of design features on performance under our attack models. Our performance metric is the probability that a client can find a path to communicate with the server under on-going attacks. Our analysis results clearly demonstrate that (i) The SOFS system performance is sensitive to intelligent DDoS attacks. The performance degrades significantly as the attack intensity increases. (ii) The design features of SOFS systems (layering, mapping degree and node distributions) have critical impacts on system performance under intelligent DDoS attacks. In fact they interact among each other to impact system performance, further highlighting the sensitivity of system performance to them. (iii) We find that the above trends hold even when the system is equipped with recovery mechanisms, although attack impacts are reduced with recovery. Under extremely intensive attacks, with system recovery, the system can always maintain a certain level of system performance especially with large mapping degrees. Our final contribution is presenting important and general design guidelines for building resilient overlay architecture that can sustain performance even when intelligent DDoS attacks are intense.

The rest of the paper is organized as follows. In Section II, we discuss the SOFS architecture and intelligent DDoS attacks. In Sections III and IV, we analyze the resilience of SOFS architecture to discrete round based and continuous attacks respectively. Section V discusses related work, and Section VI concludes our paper by giving out a set of SOFS design guidelines and our future work.

## II. The SOFS Architecture and Intelligent DDoS Attacks

### A. The SOFS Architecture

In its most basic version, the SOFS architecture consists of a set of overlay nodes arranged in layers of a hierarchy as shown in Fig. 1. The nodes in these layers serve as intermediaries between the clients and the critical target [2]. Such a system has three distinguishable design features. They are Layering, Mapping (Connectivity) Degree and Node Distribution across layers. A clearer description is given below.

[2]We use the terms *target* and *server* interchangeably in this paper.

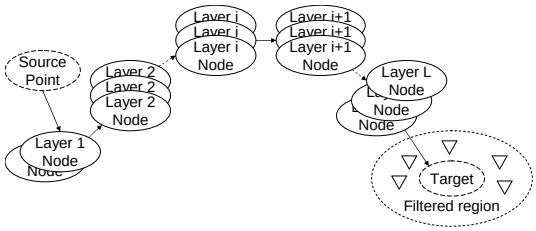



Fig. 1. The generalized SOFS architecture.

- Number of Layers (Layering): The number of layers in the architecture is an estimate of the depth of control during access to the target. If the number of layers is $L$, then clients must pass through these $L$ layers before communicating with the target. The importance of layering is that if the number of layers is larger, implicitly it means that the target is better hidden against external clients.
- Mapping (Connectivity) Degree: Each node in Layer $i$ routes to node(s) in Layer $i+1$ towards the target to complete the communication chain. The mapping degree in the SOFS architecture is a measure of the number of neighbors a node in Layer $i$ has in Layer $i+1$. Typically, the larger the mapping degree is, the more reliable is the communication due to the availability of more paths. The largest is actually $1$ *to all*, where each node in Layer $i$ has all nodes in Layer $i+1$ as its neighbors.
- Node Distribution: Node distribution is a measure of the number of nodes in each layer. Intuitively it may seem that the uniform node distribution across layers is preferred to ensure a degree of load balancing in the system. However, for a fixed amount of nodes to be distributed across a fixed number of layers, it may be advisable to deploy more nodes at layers closer to the target to increase defenses in *sensitive* layers nearer the target.

A client that wishes to communicate with the target first contacts node(s) in the first layer which contact node(s) in the second layer and so on till the traffic reaches the target. In this architecture each node is only aware of neighbors in its neighboring layer. A set of filters acts as a firewall surrounding the target through which only legitimate traffic is allowed.

### *B. Intelligent DDoS Attack Models*

The attacker in our model is intelligent. It has the ability to break-into nodes to disclose the victims' next-layer neighbors. The attacker also has the ability to congest nodes to prevent them from servicing

legitimate clients. We formally define these two attacks below.

- Break-in Attacks: The attacker has the ability to attempt to break-into nodes in the SOFS system. A successful break-in results in dysfunction of the victim node and disclosure of the neighbors of the victim node.
- Congestion Attacks: The attacker has the ability to congest nodes in the SOFS system. By *congest*, *congestion-based* DDoS attacks or simply *congestion attacks*, we mean any of the distributed attack methods that prevent a victim machine from providing services.

Our work focuses on the theoretical analysis of the impacts of intelligent DDoS attacks on SOFS system, rather than the actual attack methods. However, we believe that both the break-in attacks and congestion attacks models we present are practical. The execution of break-in attacks can be through some intrusion attacks, or through malicious code hidden in the message sent by malicious clients as those in Trojan horse or active worm attacks [1]. When received by the victim node, the malicious code can execute on the victim node to make it un-functional, and retrieve the victim node's neighbor list. The malicious code can even then self propagate to the disclosed neighbors. The execution of congestion attacks on a victim machine will result in, the victim being prevented from servicing requests or, disconnecting the victim from the system. This can be due to exhausting its key resource, overloading the machine to disable communication, crashing its service, blocking its network link. Typical examples are TCP SYN attack, TCP and UDP flood attack, ICMP echo attack and Smurf attack [1]. The above two attacks can be conducted in several possible ways. However, keeping in mind the above attack types, and with the intention of maximizing attack impacts, the attacker will usually first conduct break-in attacks to disclose the identities of many nodes. Congestion attacks on the disclosed nodes then follow after the break-in attacks. In this realm, we define two attack models below.

- A discrete round based attack model: In our attack models, the attacker can launch break-in attacks on limited number of nodes. In round based attack model, it launches the break-in attacks in a round by round fashion, with part of attempts made in each round. The rationale is that, by successively

breaking-into nodes and locating their neighbors, the attacker can disclose more nodes. We call this model as *discrete* because, here the attacker starts a fresh round only after the results of all attempted break-ins in the current round are available to it. Congestion attacks follow next, and are conducted in one round.

- A continuous attack model: In this model, the attacker attempts to disclose some nodes first, using part of its break-in attack resources. However in this model, the attacker continuously keeps breaking-into disclosed nodes as and when they are identified. Congestion attacks follow next in a similar fashion.

The attack models are described in more details in Sections III and IV. We wish to emphasize here that the SOFS system also has the recovery ability to defend against attacks. However any meaningful execution of the recovery mechanism is contingent on the attacks. In some cases, the system may not be able to conduct any effective recovery if the attacker can speedily conduct its attack, disrupting system performance for some short duration of time. However, if the attack is slow enough, the system can attempt to take effective recovery action to restore performance. More details on system recovery are given in Section IV.

In this paper, we study the SOFS system performance under discrete round based attacks and continues attacks. We demonstrate that system performance is sensitive to design features and attacks, and the architecture needs to be flexible in order to achieve better performance under different attacks.

## III. Analysis of the SOFS Architecture under Round based Attacks

In this section we conduct an extensive mathematical analysis on the SOFS architecture under the discrete round based intelligent DDoS attack model with no system recovery. In our analysis, the system we study consists of a total of $N$ overlay nodes that can be *active* or *dormant*. By *active*, we mean that the nodes are currently in the SOFS architecture and ready to serve legitimate requests [3]. A *dormant* overlay node is one that is a part of the system but currently is not in the SOFS architecture and is not serving requests. In this paper, when we use the term *overlay node*, it could mean either an active or

[3]In the remaining of the paper, if the context is clear, we will just use *node* or *SOFS node* to represent an active node.

TABLE I

THE MAIN NOTATIONS USED IN THE PAPER

| Notation | Definition | Notation | Definition |
|---|---|---|---|
| $N$ | Number of overlay nodes | $n$ | Number of SOFS nodes |
| $L$ | Number of layers except filter layer | $P_S$ | Probability that a client can find a path to the server |
| $n_i$ | Number of SOFS nodes on Layer $i$ | $m_i$ | Number of $i^{th}$ Layer neighbors of a node on Layer $i-1$ |
| $P_B$ | Probability that the attacker can break-into a node | $P_E$ | Probability a first layer node's identity is pre-known |
| $N_C$ | Number of overlay nodes the attacker can congest | $N_T$ | Number of overlay nodes the attacker can break-in attack |
| $P_i$ | Probability that a message can be forwarded from Layer $i-1$ to Layer $i$ | $N_D$ | Average total number of SOFS nodes that are disclosed but not broken-in successfully |
| $s_i$ | Number of compromised SOFS nodes on Layer $i$ | $N_B$ | Average number of broken-in overlay nodes |
| $c_i$ | Number of congested SOFS nodes on Layer $i$ | $b_i$ | Number of broken-in SOFS nodes on Layer $i$ |
| $R$ | Number of break-in attack rounds in successive round based attack | $X_j$ | Number of SOFS nodes whose identities are known by the attacker at the start of round $j$ |
| $h_i$ | Number of SOFS nodes on which break-in attempts have been made on Layer $i$ | $m$ | Value of mapping degree in the case the mapping degrees are equal across layers |
| $\alpha$ | Minimal number of break-in attack in each round | $\beta$ | Available break-in attack capacity |

a dormant node. We denote the number of *active* nodes in the SOFS architecture (also called as SOFS nodes) by $n$ ($n \leq N$) which are distributed across $L$ layers. Layer $i$ has $n_i$ nodes and $\sum_{i=1}^{L} n_i = n$. Each node in Layer $i$ has one or more neighbors in its next higher layer to complete the communication chain. We define the number of next layer (Layer $i$) neighbors that a Layer $i-1$ node has as $m_i$.

In this paper, we assume that the *attack resources* are limited. By *attack resources*, we mean the attack capacity, which depends on the amount of attack facilities. For instance, this can be the number of slave machines recruited by the attacker to launch DDoS attacks [1]. We denote that the break-in attack and congestion attack resource as $N_T$ and $N_C$ respectively. Thus $N_T$ and $N_C$ are the maximum number of nodes the attacker can launch break-in and congestion attacks on. Here $N_T + N_C \leq N$. With a probability $P_B$, the attacker can successfully break-into a node and disclose its neighbors in a break-in attempt.

In the SOFS system we study in this section, the system does not do any recovery to counter attacks. The significance of our analysis and the results therein we observe here is in obtaining a fundamental understanding of attack impacts to the system (and its features). Nevertheless, our analysis here is still practical as in some cases, the speed of attacks may be quite high, preventing the system from performing recoveries. In such cases, our analysis here provides insights into damages that are caused under such rapid/burst attacks. With the SOFS system and attack specifics in place, we now formally define our *performance metric*, $P_S$, as the probability that a client can find a path to communicate with the target under on-going attacks. Some important notations used in the paper are given in Table I.

### A. Under a One-burst Round Based Attack Model

*1) Attack Model:* The model we define here is an instance of the discrete round based attack model where the number of rounds is 1. The attacker will spend all the break-in attack resources randomly and instantly in one round and then launch the congestion attack. Even though this model may appear simple, in reality such a type of attack is possible when say, the system is in a high state of alert anticipating imminent attacks, which the attacker is aware of and still wishes to proceed with the attack. Here we assume the attacker has no prior knowledge about the identities of the SOFS nodes, i.e., which overlay nodes are current SOFS nodes.

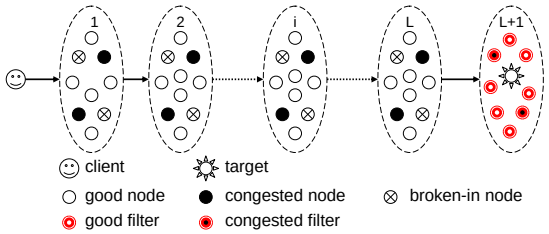



Fig. 2. A Snapshot of the generalized SOFS architecture under the intelligent DDoS attacks.

*2) Analysis:* Our goal is to determine $P_S$, the probability that a client can find a path to communicate with the target under attacks. This is directly related to the number of nodes compromised due to attacks (both break-in and congestion attacks). Thus, the key defining feature of our analysis is in determining the set [4] of attacked SOFS nodes in each layer. An intuitive way to analyze the system is to list all possible combinations of attacked nodes in each layer. Then calculate and summarize $P_S$ over all combinations. It is easy to see that there could be many such possible combinations. For a system with $L$ layers and $n$ nodes evenly distributed, such combinations will be in $\theta(\frac{n}{L})^{2L}$. For a system with 3 layers and 100 SOFS nodes evenly distributed, we have about $1.0 * 10^{10}$ combinations. This is a very large number, it is not practical to analyze the system in this fashion. To circumvent the salability problem, we take an alternate approach. Based on the weak law of large numbers we use average case analysis. We calculate the average number of attacked SOFS nodes in each layer to obtain $P_S$. In the following, we first derive $P_S$, which depends on the SOFS architecture and number of attacked SOFS nodes in each layer. We will then discuss how to calculate the number of attacked SOFS nodes in each layer (including nodes

[4]We use the terms *set* and *number of nodes in a set* interchangeably.

broken-into and congested).

*a) Derivation of $P_S$:* Recall that $P_S$ is the probability that a client can successfully communicate with the target under attacks, which depends on the SOFS architecture and number of attacked SOFS nodes. In the SOFS architecture, a SOFS node maintains a neighbor/routing table that consists of a number of (decided by the mapping degree) SOFS nodes in its next higher layer that it can communicate with. Upon receiving a message, a node in Layer $i$ will contact a node in Layer $i+1$ from its neighbor table and forward the received message to that node. This process repeats till the target is reached via the nodes in successive higher layers. The routing thus takes place through active SOFS nodes in a distributed fashion. We call a *bad* or *compromised* node as one that has either been broken-into or is congested and thus cannot route a message. The other overlay nodes are *good* nodes. The neighbor table will contain entries pointing to *bad* neighbors during break-in or congestion attacks that can cause failure of a message being delivered. A snapshot of the system under an on-going attack is shown in Fig. 2.

To compute $P_S$, we should first know the probability $P_i$ that a message can be successfully forwarded from Layer $i-1$ to Layer $i$ ($1 \leq i \leq L+1$). Here Layer $L+1$ refers to the set of filters that surround the target, which are also intermediate forwarders. In our analysis, we consider this layer also because it is possible that filter identities can be disclosed during a successful break-in at Layer $L$. With the property of distributed routing algorithm, we can obtain $P_S$ by direct product of all $P_i$'s, i.e., $P_S = \Pi_{i=1}^{L+1} P_i$. Obviously, $P_i$ depends on the availability of good nodes in Layer $i$ that are in the routing table of nodes in Layer $i-1$. Towards this extent, we define $P(x, y, z)$ as the probability that a set of $y$ nodes selected at random from $x > y$ nodes contains a specific subset of $z$ nodes. Then $P(x, y, z) = \binom{y}{z} / \binom{x}{z}$ if $y \geq z$, and $0$ otherwise. We denote $s_i$ as the number of bad SOFS nodes in Layer $i$. Recall that each SOFS node in Layer $i-1$ has $m_i$ neighbors in Layer $i$. Then, on average $P(n_i, s_i, m_i)$ is the probability that all next-hop neighbors in Layer $i$ of a node in Layer $i-1$ are bad nodes. Hence $P_i = 1 - P(n_i, s_i, m_i)$. Thus, the probability $P_S$ that a message will be successfully received by the target can be expressed as

$$P_S = \Pi_{i=1}^{L+1} P_i = \Pi_{i=1}^{L+1} (1 - P(n_i, s_i, m_i)). \quad (1)$$

In (1), only $s_i$ (number of bad nodes) is undetermined. If we define $b_i$ and $c_i$ as the number of nodes that

have been broken-into and the number of congested nodes respectively in Layer $i$, we have $s_i = b_i + c_i$. In the following we will derive $b_i$ and $c_i$.

*b) Derivation of $b_i$:* In the one-burst round based attack model, $b_i$ depends on break-in resource $N_T$, and the probability of break-in $P_B$. Since the attacker launches its break-in attacks randomly, the $N_T$ break-in attempts are uniformly distributed on the overlay nodes in the SOFS system. Thus the average number of broken-in SOFS nodes, $N_B = P_B \frac{n}{N} N_T$, and hence,

$$b_i = P_B(\frac{n_i}{N})(N_T),\ i = 1, \ldots, L. \quad (2)$$

We assume here that the filters are well-protected and cannot be broken-into. Filters are special and they are not among the $N$ overlay nodes thus not the targets of random attacks. Hence $b_{L+1} = 0$.

*c) Derivation of $c_i$:* We now discuss the derivation of $c_i$ (number of congested nodes in Layer $i$). Unlike $b_i$, $c_i$ depends on the result of break-in attacks and congestion capacity $N_C$. Thus, we first need to know the set of SOFS nodes which are disclosed in the break-in attack phase on Layer $i$. We divide the disclosed nodes on Layer $i$ into three sets; (i) set of nodes on which break-in attempts have not been made (denoted as $d_i^N$), (ii) set of nodes that have been unsuccessfully broken-into (denoted as $d_i^A$) and (iii) set of nodes that were successfully broken-into (which we do not need to consider here). The nodes in sets $d_i^N$ and $d_i^A$ will be targeted now by congestion attacks. We calculate $d_i^N$ and $d_i^A$ as follows. Let $Y_{i,j}$ be a random variable whose value is 1 when the $j^{th}$ node in Layer $i$ is either a disclosed node or one on which a break-in attempt has been made. Let $z_i$ denote the average number of nodes that have been disclosed or have been tried to be broken-into. Thus,

$$z_i = E(\textstyle\sum_{j=1}^{n_i} Y_{i,j}) = \sum_{j=1}^{n_i} E(Y_{i,j}) = \sum_{j=1}^{n_i} \Pr\{Y_{i,j} = 1\}, \quad i = 1, \ldots, L+1. \quad (3)$$

Denoting $h_i$ as the number of nodes on which break-in attempts have been made in Layer $i$, we have $h_i = N_T(\frac{n_i}{N})$ for $i = 1, .., L$, and $h_{L+1} = 0$ because filters are not targets of break-in attacks as discussed above. Thus, the probability that the $j^{th}$ node in Layer $i$ is neither a disclosed node nor one on which a break-in attempt has been made, is given by $(1 - \frac{m_i}{n_i})^{b_{i-1}}(1 - \frac{h_i}{n_i})$. The same node can be disclosed by more than one node in the previous layer. The part $(1 - \frac{m_i}{n_i})^{b_{i-1}}$ excludes such overlaps. We now have,

$$\Pr\{Y_{i,j} = 1\} = 1 - (1 - \frac{m_i}{n_i})^{b_{i-1}}(1 - \frac{h_i}{n_i}), \quad i = 1, \ldots, L+1,\ j = 1, \ldots, n_i. \quad (4)$$

$$z_i = \textstyle\sum_{j=1}^{n_i}(1 - (1 - \frac{m_i}{n_i})^{b_{i-1}}(1 - \frac{h_i}{n_i})) = n_i(1 - (1 - \frac{m_i}{n_i})^{b_{i-1}}(1 - \frac{h_i}{n_i})), \quad i = 1, \ldots, L+1. \quad (5)$$

We hence have,

$$d_i^N = z_i - h_i = n_i(1 - (1 - \frac{m_i}{n_i})^{b_{i-1}}(1 - \frac{h_i}{n_i})) - h_i, \quad i = 2, \ldots, L+1. \tag{6}$$

$$d_i^A = \sum_{j=1}^{h_i - b_i}(1 - (1 - \frac{m_i}{n_i})^{b_{i-1}}) = (h_i - b_i)(1 - (1 - \frac{m_i}{n_i})^{b_{i-1}}), \quad i = 2, \ldots, L+1. \tag{7}$$

Note that nodes in the first layer cannot be disclosed due to a break-in attack and so $d_1^N = d_1^A = 0$.

The attacker will now congest the SOFS nodes in the set $d_i^N$ and $d_i^A$ as their identities have been disclosed and they have not been successfully broken-into. We denote $N_D$ to be the average number of SOFS nodes that are disclosed but not broken-into successfully. It is given by, $N_D = \sum_{i=1}^{L+1}(d_i^N + d_i^A)$. Now, we proceed to derive $c_i$, the number of congested nodes in Layer $i$. Recall that $N_C$ is the overall number of overlay nodes that the adversary can congest, and the congestion attacks follow after break-in attacks. There are two cases here;

- $N_C \geq N_D$: In this case, all $N_D$ disclosed SOFS nodes will be congested. Since the attacker still has capacity to congest $N_C - N_D$ overlay nodes, it will expend its spare resources randomly. The extra congested nodes will be uniformly randomly chosen from the remaining $N - N_B - (N_D - d_{L+1}^N - d_{L+1}^A)$ good overlay nodes, among which only a part are SOFS nodes. Here $d_{L+1}^N$ and $d_{L+1}^A$ are parts of the filers and hence are excluded from $N_D$ to determine the remaining overlay nodes that are targets for random congestion attacks [5]. Therefore,

$$c_i = \begin{cases} d_i^N + d_i^A + (N_C - N_D) * \frac{n_i - b_i^A - d_i^N - d_i^A}{N - N_B - (N_D - d_{L+1}^N - d_{L+1}^A)}, & i = 1, \ldots, L, \\ d_i^N, & i = L+1. \end{cases} \tag{8}$$

- $N_C < N_D$: The attacker randomly congests $N_C$ nodes among $N_D$ disclosed nodes. In this case,

$$c_i = \frac{N_C}{N_D}(d_i^N + d_i^A), \ i = 1, 2, \ldots, L+1. \tag{9}$$

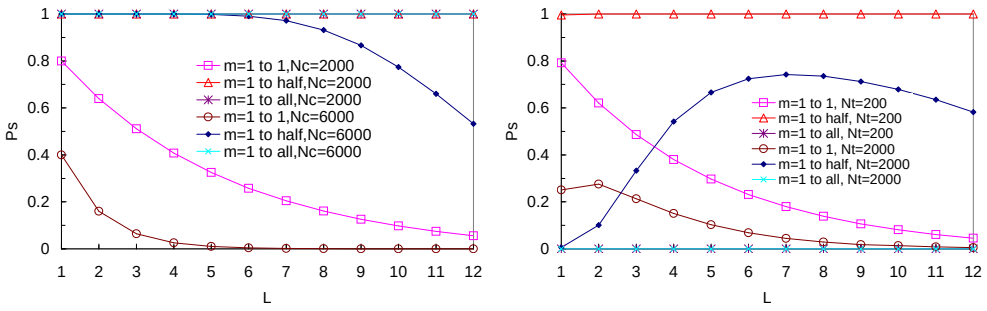
Recall that $s_i = b_i + c_i$ is the set of bad nodes in Layer $i$. Having thus computed $b_i$ and $c_i$, we obtain $P_S$ from (1).

*3) Numerical Results and Discussion:* We now present here numerical results based on our analysis above. We specifically highlight the overall sensitivity of system performance to attacks and the impacts of specific SOFS design features (layering and mapping degree) on performance under attacks. Impacts

[5]In our model, the filters' identities are hidden from attackers and they can be congested only upon disclosure by break-in attacks.

of node distribution per layer are discussed in the successive round based attack model in Section III-B.

Fig. 3 shows the relationship between $P_S$ and the layering and mapping degree under different attack intensities. The mapping degrees (referred as $m$ in the figures) used here are; $1\ to\ 1$ mapping which means each SOFS node has only one neighbor in the next layer; $1\ to\ half$ mapping which means each node has half of all the nodes in the next layer as its neighbors; and $1\ to\ all$ mapping which means each node has all the nodes in next layer as its neighbors. Other system and attack configuration parameters are; $N = 10000$, $n = 100$, $P_B = 0.5$, SOFS nodes evenly distributed among the layers, and number of filters is 10. In Fig. 3 (a), $N_T$ is set as 0 and we evaluate performance under two congestion intensities; $N_C = 2000$ and $N_C = 6000$ representing moderate and heavy congestion attacks. In Fig. 3 (b), we fix $N_C = 2000$ and analyze two intensities of break-in; $N_T = 200$ and $N_T = 2000$. We make the following observations.




(a) (b)

Fig. 3. Sensitivity of $P_S$ to $L$ and $m_i$ under different attack intensities.

Fig. 3 (a) shows that under the same attack intensities, different layer numbers result in different $P_S$. When $N_T = 0$ (pure random congestion attack), as $L$ increases, $P_S$ goes down. This is because, there are less nodes per layer, which means under random congestion, few nodes per layer are left uncompromised. This behavior is more pronounced when the mapping degree is small. We wish to remind the reader about the SOS architecture [6], where for defending against random congestion-based DDoS attacks (same attack model as in this instance), the number of layers is fixed as 3 and the mapping degree is $1\ to\ all$. From Fig. 3 (a), we can see that fixing the number of layers as 3 is not always the best solution to defend against such attacks. Instead, 1 layer is the best configuration to defend against pure congestion-based attacks.

For any $L$, a larger mapping degree (more neighbors for each node) means more paths from nodes in one layer to nodes in the next layer, thus increasing $P_S$ as seen in Fig. 3 (a) under the absence of break-in attacks. Under break-in attacks, a high mapping degree is not always good as more nodes are disclosed due to break-ins. For instance when the mapping is $1\ to\ all$, $P_S = 0$ in Fig. 3 (b). Thus the effect of mapping typically depends on the attack intensities in the break-in and congestion phase. Finally, we see that an increase in $N_C$ and $N_T$ (attack intensities) leads to a decrease in $P_S$ as more nodes could be congested or broken-into, leading to a reduction in path availabilities.

### *B. Under a Successive Round Based Attack*

*1) Attack Model:* In the following, we extend our one-burst attack model significantly in order to study performance under a highly sophisticated attack model called successive round based attack model (successive attack in short). The successive attack model is representative of sophisticated attacks targeting the SOFS system and extends from the one-burst attack model in two ways: (i) the attacker exploits prior knowledge about the first layer SOFS nodes. Let $P_E$ represent the percentage of nodes in the first layer known to the attacker prior to attack (typically, these are first layer nodes advertized to clients), (ii) the break-in attack phase is conducted in $R$ rounds ($R > 1$), i.e., the attacker will launch its break-in attacks successively rather than in one burst. In this attack model, more SOFS nodes are disclosed in a round by round fashion thus accentuating the effect of break-in attacks.

The strategy of the successive attack is shown in Procedure 1. We denote $\beta$ to be the available break-in attack resources at the start of each round, and $\beta = N_T$ at the start of round 1. For each round, the attacker will try to break-into a minimum of $\alpha$ nodes and is fixed as $\frac{N_T}{R}$. If the number of disclosed nodes is more than $\alpha$, the attacker *borrows* resources from $\beta$ to attack all disclosed nodes. Otherwise it attacks the nodes disclosed and some other randomly chosen nodes to expend $\alpha$ resources for that round. The break-in attack capacity available ($\beta$) keeps decreasing till the attacker has exhausted all of its $N_T$ resources. At any round, if the attacker has discovered more nodes than its available capacity($\beta$), it tries to break-into a subset ($\beta$) of the disclosed nodes then starts the congestion phase. The attacker will congest

**Procedure 1** Pseudocode of the successive attack strategy

System parameters: $N$, $n$, $L$, $P_B$; Attack parameters: $N_T$, $N_C$, $R$, $X_1$, $\beta$, $\alpha$

Phase 1 Break-in attack:

$\beta = N_T$, $\alpha = \frac{N_T}{R}$;
**for** $j = 1$ to $R$ **do**
  **if** $X_j < \alpha < \beta$ **then**
    launch break-in attack on all $X_j$ nodes and randomly launch break-in attack on $\alpha - X_j$ nodes and calculate the set $X_{j+1}$ disclosed nodes; update $\beta = \beta - \alpha$;
  **end if**
  **if** $X_j < \beta \leq \alpha$ **then**
    launch break-in attack on all $X_j$ nodes and randomly launch break-in attack on $\beta - X_j$ nodes and calculate the set $X_{j+1}$ disclosed nodes; break;
  **end if**
  **if** $\alpha \leq X_j < \beta$ **then**
    launch break-in attack on all $X_j$ nodes and calculate the set $X_{j+1}$ disclosed nodes; update $\beta = \beta - X_j$;
  **end if**
  **if** $X_j \geq \beta$ **then**
    launch break-in attack on $\beta$ nodes among $X_j$ nodes and calculate the set $X_{j+1}$ disclosed nodes; break;
  **end if**
**end for**
calculate $N_D$;

Phase 2 Congestion attack:

**if** $N_C > N_D$ **then**
  congest the $N_D$ nodes and randomly congest $(N_C - N_D)$ nodes;
**else**
  congestion $N_C$ nodes among $N_D$ nodes randomly;
**end if**

all disclosed nodes and more, or only a subset of the disclosed nodes depending on its congestion capacity $N_C$. Here we assume the attacker will not attempt to break-into a node twice and a node broken-into will not be targeted by congestion attack. Although there can be other variations of such successive attacks, We believe that ours is a representative enough model of sophisticated attacks.

*2) Analysis:* We again use average case analysis approach and use a similar method to derive $P_S$ as in (1). In calculating $b_i$ and $c_i$ in the one-burst attack model we analyzed before, we had to take care of two possible overlap scenarios (i) a disclosed node could have been already broken-into, (ii) the same node being disclosed by multiple lower layer nodes. The complexity in overlap is accentuated here due to the nature of successive attacks. This is because there are multiple rounds of break-in attacks before congestion. We thus have to consider the above overlaps in the case of multiple rounds as well. In the following, we will first introduce a concept of SOFS node demarcation in order to deal with above overlaps, and follow that with deriving $b_i$ and $c_i$ in each round.

*a) Node demarcation:* In order to preserve the information about a node per round and across layers, we introduce subscript $j$ for round information, and subscript $i$ for layer information. We define $X_j$ as the number of nodes whose identities are known to the attacker at the start of round $j$. In order to deal with overlaps within and between rounds, we need to separate the SOFS nodes into multiple sets as follows. At the beginning of each round $j$, the attacker will base its break-in attack on the set of nodes disclosed at the completion of round $j-1$. We denote the set of nodes which are disclosed at round $j-1$ and on which break-in attempts are made in round $j$, as $h^D_{i,j}$. Depending on its spare capacity for that round, the attacker can also select more nodes to randomly break-into. We denote this set as $h^A_{i,j}$. We define $h_{i,j} = h^D_{i,j} + h^A_{i,j}$, which is the number of nodes on which break-in attempts (successfully/unsuccessfully) have been made at Layer $i$ in round $j$. Once the attacker has launched its break-in attacks on these $h_{i,j}$ nodes, it will successfully break-into a set of nodes. We denote $b^D_{i,j}$ and $b^A_{i,j}$ as the set of nodes successfully broken-into, and denote $u^D_{i,j}$ and $u^A_{i,j}$ as the set of nodes unsuccessfully broken-into, after the attacker launches its break-in attacks on the $h^D_{i,j}$ and $h^A_{i,j}$ set of nodes respectively. We have,

$$b^D_{i,j} = P_B * h^D_{i,j},\ and\ b^A_{i,j} = P_B * h^A_{i,j}, \quad i = 1, \ldots, L, \tag{10}$$

$$u^D_{i,j} = (1 - P_B) * h^D_{i,j},\ and\ u^A_{i,j} = (1 - P_B) * h^A_{i,j}, \quad i = 1, \ldots, L. \tag{11}$$

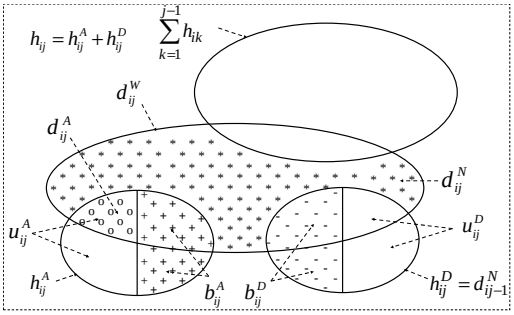



Fig. 4. Node demarcation in our successive attack at the end of Round $j$.

Breaking-into nodes in sets $b^D_{i,j}$ and $b^A_{i,j}$ will disclose a set of nodes denoted by $d^W_{i,j}$. This set, $d^W_{i,j}$ will overlap with (i) the nodes attacked in all previous rounds given by $\sum_{k=1}^{j-1} h_{i,k}$, (ii) the nodes in set $b^A_{i,j}$, (iii) the nodes in set $b^D_{i,j}$ and $u^D_{i,j}$ and (iv) the nodes in set $u^A_{i,j}$, where we denote the set of nodes in $d^W_{i,j}$ overlapping with $u^A_{i,j}$ as $d^A_{i,j}$. Fig. 4 shows such overlaps at the end of round $j$. After discounting all the

above overlaps from $d_{i,j}^W$, we can get the set of disclosed nodes which have not been attacked till the end of round $j$ denoted as $d_{i,j}^N$. Based on the definitions for $h_{i,j}^D$ and $d_{i,j}^N$, and that the filters are not targets of break-in attacks, we have

$$h_{i,j}^D = d_{i,j-1}^N, \quad i = 1, \ldots, L. \tag{12}$$

Note that $d_{i,j-1}^N$ and $d_{i,j-1}^A$ are 0 for $i = 1$. This is because the nodes at the first layer cannot be disclosed by means of a break-in attack in any round $j$. Recall that $X_j$ is the set of disclosed nodes whose identities are known to the attacker before round $j$ and on which break-in attacks will be made at round $j$. Thus it can be calculated as $X_j = \sum_i^L d_{i,j-1}^N$. In the following, we proceed to derive the number of broken-in nodes ($b_i$) and then compute the number of congested nodes ($c_i$) for each round.

*b) Derivation of $b_i$:* To derive $b_i$, we need to first calculate the sets defined above. For ease of elucidation, we take a representative case $X_j < \alpha < \beta$ in Procedure 1 as an example to explain our analysis. Recall that $\beta$ is the amount of available break-in attack resource at current round. This is the most representative case among the ones possible. We also discuss other possible cases briefly after analyzing this case. In this case, the attacker at the beginning of round $j$ of its break-in attack phase has resources to break-into more nodes than those disclosed already prior to that round ($d_{i,j-1}^N$), and has attack resources left ($\alpha - X_j$) to randomly conduct break-in on other overlay nodes. Now there are $N - X_j - \sum_{q=1}^L \sum_{k=1}^{j-1} h_{q,k}$ unattacked overlay nodes and among them $n_i - d_{i,j-1}^N - \sum_{k=1}^{j-1} h_{i,k}$ are at Layer $i$. Thus, we can get the number of nodes ($h_{i,j}^A$) on which random break-in attempts have been made on Layer $i$ in round $j$ as

$$h_{i,j}^A = \frac{n_i - d_{i,j-1}^N - \sum_{k=1}^{j-1} h_{i,k}}{N - X_j - \sum_{q=1}^L \sum_{k=1}^{j-1} h_{q,k}} (\alpha - X_j), \quad i = 1, 2, \ldots, L. \tag{13}$$

We define $b_{i,j}$ as the number of nodes broken-into on Layer $i$ in round $j$, which is the summation of $b_{i,j}^A$ and $b_{i,j}^D$. Based on (10), (12) and (13), we have, [6]

$$b_{i,j} = P_B * \frac{n_i - d_{i,j-1}^N - \sum_{k=1}^{j-1} h_{i,k}}{N - X_j - \sum_{q=1}^L \sum_{k=1}^{j-1} h_{q,k}} * (\alpha - X_j) + P_B * d_{i,j-1}^N, \quad i = 1, 2, \ldots, L. \tag{14}$$

We can now obtain $b_i$ as,

$$b_i = \sum_{k=1}^{J} b_{i,k}, \quad i = 1, 2, \ldots, L. \tag{15}$$

where $J$ is the number of rounds attacker takes to exhaust all break-in resources ($N_T$). Note that $J \leq R$.

To obtain $b_i$, we need to compute the set of nodes $d_{i,j}^N$, which is used in (14). As discussed above, we

[6]Recall that $h_{L+1,j}^D$, $h_{L+1,j}^A$ and $b_{L+1,j}$ are all 0 because filters are not targets of break-in attacks.

have to extract the set $d_{i,j}^N$ from $d_{i,j}^W$. Similar to the discussion in the one-burst attack model, we can derive $d_{i,j}^N$ and $d_{i,j}^A$ as follows. We first calculate the set of nodes that have been either disclosed or attacked. This is given by,

$$z_{i,j} = n_i(1 - (1 - \frac{m_i}{n_i})^{b_{i-1,j}}(1 - \frac{\sum_{k=1}^{j} h_{i,k}}{n_i})), \quad for\ b_{i-1,j} > 0\ and\ i = 2, \ldots, L+1. \tag{16}$$

Note that in our attack model, the attacker will not try to break-into a node twice. Hence, to calculate $d_{i,j}^N$, from $z_{i,j}$, we subtract the nodes on which break-in attempts have been made ($\sum_{k=1}^{j} h_{i,k}$). Thus, we have,

$$d_{i,j}^N = z_{i,j} - \sum_{k=1}^{j} h_{i,k}, \quad for\ b_{i-1,j} > 0\ and\ i = 2, \ldots, L+1. \tag{17}$$

Having computed $d_{i,j}^N$, we can use (14) and (15) to obtain $b_i$. Now, $d_{i,j}^A$ (which will be used to compute $c_i$) is given by,

$$d_{i,j}^A = (h_{i,j}^A - b_{i,j}^A)(1-(1-\frac{m_i}{n_i})^{b_{i-1,j}}), \quad for\ b_{i-1,j} > 0\ and\ i = 2, \ldots, L+1. \tag{18}$$

Having discussed the necessary derivations for the representative case above in detail, we now clarify the readers about the situations involving particular cases for the successive attack. Apart from the representative case we have just discussed, there are three other cases: (i) $X_j < \beta \leq \alpha$, (ii) $\alpha \leq X_j < \beta$, and (iii) $\beta \leq X_j$. For case (i), all the formulas we derived for the above case can be directly applied, except that $\alpha$ has to be replaced by $\beta$. For case (ii), all the formulas in the above case can be applied except that $h_{i,j}^A = 0$. For case (iii), we have $h_{i,j}^A$ = 0, and the formulas derived in the representative case have to be suitably modified. In this case, there are some disclosed nodes that the attacker does not try to break-into due to consumption of all break-in resources. Such nodes will be attacked during the congestion phase. We denote this set of nodes in Layer $i$ after round $j$ as $f_{i,j}$. We wish to state here that $f_{i,j}$ has relevance ($f_{i,j} > 0$) only when the attacker completes its break-in attack phase at round $j$. Thus in this case, there is no left resource for random break-in attacks. Only $\beta$ disclosed nodes will be attempted to be broken-into on all the layers and they are uniformly randomly distributed on each layer. Then we have,

$$f_{i,j} = d_{i,j-1}^N - d_{i,j-1}^N * (\frac{\beta}{X_j}), \quad h_{i,j}^A = 0, \quad h_{i,j}^D = d_{i,j-1}^N - f_{i,j}, \ for\ i = 1, 2, \ldots, L, \quad and \tag{19}$$

$$d_{i,j}^N = n_i(1 - (1 - \frac{m_i}{n_i})^{b_{i-1,j}}(1 - \frac{\sum_{k=1}^{j} h_{i,k} + \sum_{k=1}^{j} f_{i,k}}{n_i})) - \sum_{k=1}^{j} h_{i,k} - \sum_{k=1}^{j} f_{i,k}, \quad i = 2, \ldots, L+1, \tag{20}$$

where $b_{i-1,j} > 0$. Here, $d_{i,j}^A$ is the same as (18) and $f_{L+1,j} = 0$ because filters are not targets of break-in attacks. With the above derivations in this case, we can now use (14) and (15) to calculate $b_i$.

*c) Derivation of $c_i$:* Recall that in the congestion attack phase, the attacker will first congest the disclosed SOFS nodes disclosed in break-in attack phase. Let the final round of the break-in attack be $J(J \leq R)$. Denoting $N_D$ as the number of disclosed nodes but not broken-into, based on the definitions of $u_{i,j}^D$, $d_{i,j}^N$, $d_{i,j}^A$ and $f_{i,j}$, we have,

$$N_D = \sum_{i=1}^{L}\sum_{k=1}^{J} u_{i,k}^D + \sum_{k=1}^{J} d_{L+1,k}^N + \sum_{i=2}^{L} d_{i,J}^N + \sum_{i=1}^{L} f_{i,J} + \sum_{i=1}^{L}\sum_{k=1}^{J} d_{i,k}^A. \tag{21}$$

We have the total number of broken-in nodes, $N_B = \sum_{i=1}^{L}\sum_{k=1}^{J} b_{i,k}$. If $N_C \geq N_D$, similar as (8) we have the number of congested nodes per layer, $c_i$ as

$$c_i = \begin{cases} \sum_{k=1}^{J} u_{i,k}^D + d_{i,J}^N + \sum_{k=1}^{J} d_{i,k}^A + f_{i,J} + (N_C - N_D)(n_i - \sum_{k=1}^{J} b_{i,k} - \sum_{k=1}^{J} u_{i,k}^D \\ \quad - d_{i,J}^N - \sum_{k=1}^{J} d_{i,k}^A - f_{i,J})/(N - N_B - (N_D - \sum_{k=1}^{j} d_{L+1,k}^N)), & i = 1, \ldots, L, \\ \sum_{k=1}^{j} d_{L+1,k}^N, & i = L+1. \end{cases} \tag{22}$$

If $N_C < N_D$, similar as (9) we have

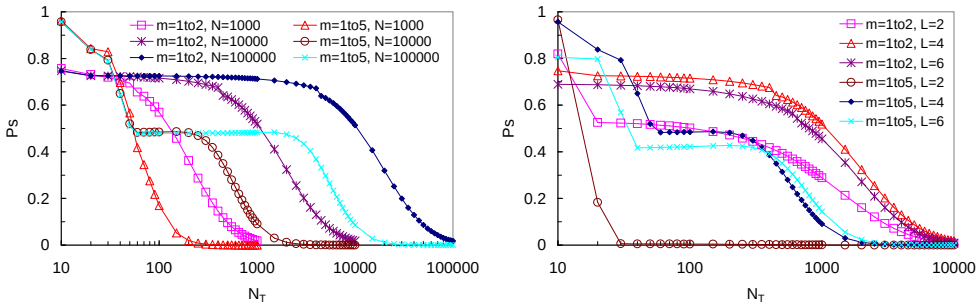
$$c_i = \begin{cases} \frac{N_C}{N_D} * (\sum_{k=1}^{J} u_{i,k}^D + d_{i,J}^N + f_{i,J} + \sum_{k=1}^{J} d_{i,k}^A), & i = 1, \ldots, L, \\ \frac{N_C}{N_D}(\sum_{k=1}^{J} d_{L+1,k}^N), & i = L+1. \end{cases} \tag{23}$$

Recall that $s_i = b_i + c_i$ is the set of bad nodes in Layer $i$. We can now obtain $P_S$ from (1).

Note that prior knowledge about identities of the first layer SOFS nodes ($P_E$) determines $X_1$, i.e., $X_1 = n_1 * P_E$. In fact, we can consider this information as that obtained from a break-in attack at *Round 0*. The number of nodes "disclosed" at *Round 0* is thus $n_1 * P_E$, all of which are distributed at the first layer. At round 1, the attacker will launch its break-in attack based on this information. Thus $b_{i,j}, d_{i,j}^N, c_i$ etc., can be calculated by application of Formulas (10) to (23). We wish to point out that if we set $P_E = 0$ and $R = 1$, the successive attack model degenerates into the one-burst attack model. Thus the formulas to compute $b_{i,j}, d_{i,j}^N, c_i$ etc., will be simplified to the corresponding ones derived in the previous sub-section.

*3) Numerical Results:* In the following, we discuss the system performance ($P_S$) under successive attacks. Unless otherwise specified, the default system and attack parameters are $N = 10000$, $n = 100$, $L = 4$, $N_C = 2000$, $N_T = 200$, $R = 3$, $P_B = 0.5$, $P_E = 0.2$ and the SOFS nodes are evenly distributed among the layers. We introduce two new mapping degrees here, namely $1\ to\ 2$ mapping, meaning each SOFS node has 2 neighbors in the next layer; and $1\ to\ 5$ mapping, meaning each node has 5 neighbors

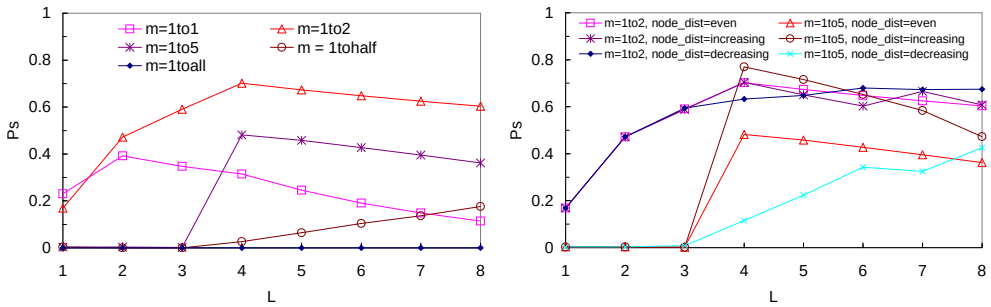
in the next layer.




(a) (b)

Fig. 5. Sensitivity of $P_S$ to $N_T$ under different $L$, $m_i$ and $N$.

In Fig. 5 we show how system performance, $P_S$, changes with $N_T$ as the other SOFS system parameters change. Fig. 5 (a) shows how the mapping degree and total number of overlay nodes influence the relation between $N_T$ and $P_S$. In this configuration, we set $N_C = 2000$ and even SOFS node distribution. Fig. 5 (b) shows the sensitivity of $P_S$ to $N_T$ under different number of layers, $L$, and different mapping degree. We make the following observations. First, $P_S$ is sensitive to $N_T$. A larger $N_T$ results in a smaller $P_S$. For higher mapping degrees, $P_S$ is more sensitive to changing $N_T$. The reason follows from previous discussions that a higher mapping degree discloses more nodes under break-in attacks. Second, in Fig. 5, there is portion of the curve, where $P_S$ almost remains unchanged for increasing $N_T$. This stable part is due to advantages offered by means of the layering in SOFS architecture against break-in attacks guided by prior disclosure of SOFS nodes. The fall in $P_S$ beyond this stable part is due to the effect of random break-in attacks apart from break-in attacks guided by prior disclosure of SOFS nodes.




(a) (b)

Fig. 6. Sensitivity of $P_S$ to $L$, $m_i$ and node distribution.

Fig. 6 (a) shows the impact of layer number, $L$, on system performance, $P_S$, under different mapping degrees. Similar to Fig. 3 (a) (b), $P_S$ is sensitive to $L$ and the mapping degree, even under multiple rounds

of break-in attacks, i.e., when $N_T > 0$ and $R > 1$. An increase in the number of layers can always slow down penetration of the break-in attacks towards the target. However, if the system deploys too many layers, it decreases the number of nodes on each layer and the number of paths between layers decreases correspondingly, which will cause a decrease in $P_S$ (Recall that in our evaluation, the total number of SOFS nodes is fixed). Among the configurations we tested, the one with $L = 4$ and mapping degree $1\ to\ 2$ provides better overall performance than others.

Fig. 6 (b) shows the impact of node distribution on $P_S$ when $L$ and the mapping degree change. Other parameters remaining unchanged, here we show the sensitivity of performance to three different node distributions per layer. The first is even node distribution wherein the nodes in each layer are the same (given by $\frac{n}{L}$). The second is increasing node distribution, wherein the number of nodes in the first layer is fixed ($\frac{n}{L}$). This is to maintain a degree of load balancing with the clients. The other layers have nodes in an increasing distribution of $1 : 2 : \ldots : L - 1$. The third is decreasing node distribution where the number of nodes in the first layer is fixed ($\frac{n}{L}$) and those in the other layers are in decreasing order of $L - 1 : L - 2 : \ldots : 1$. However, there can be other node distributions. We believe the above ones are representative to study the impact of node distributions.

We make the following observations. The node distribution does impact system performance. The sensitivity of $P_S$ to the node distribution seems more pronounced for higher mapping degrees (more neighbors per node). A very interesting observation we make is that increasing node distributions performs best among the tested node distributions. This is because when the mapping degree is larger than $1\ to\ 1$, breaking-into one node will lead to multiple nodes being disclosed at the next layer, hence the layers closer to the target will have more nodes disclosed and are more vulnerable. More nodes at these layers can compensate the damage of disclosure. Also, we observe that as the number of layers increases, the sensitivity to node distribution gradually reduces. This is because as $L$ increases, the difference in the number of nodes per layer turns to be less for the different node distributions.

Fig. 7 (a) shows the impact of $R$ (the number of rounds) on $P_S$ under different $L$ with mapping degree

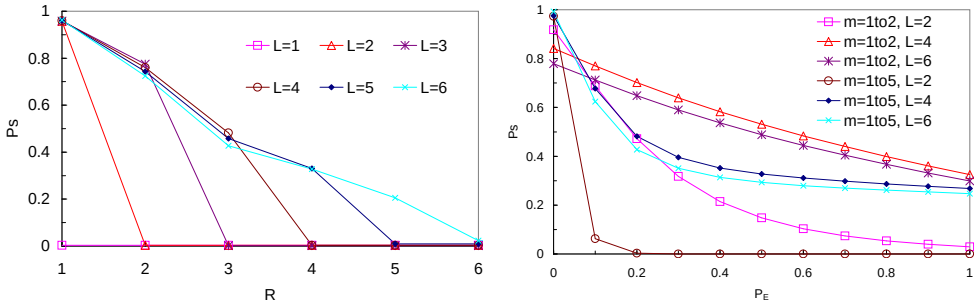



Fig. 7. Sensitivity of $P_S$ to $R$ (a) and $P_E$ (b).

$1\ to\ 5$. The nodes are evenly distributed among the layers in this case. Overall, $P_S$ is sensitive and decreases when $R$ increases. For larger values of $L$, $P_S$ is less sensitive to $R$ because more layers can provide more protection from break-in attacks even for large round numbers. We also observe that $P_S$ is sensitive to $P_E$ in Fig. 7 (b). For higher mapping degrees, $P_S$ is more sensitive to changing $P_E$. The reason follows from previous discussions that a higher mapping degree discloses more nodes. For smaller $L$, $P_S$ is more sensitive to changing $P_E$ because a smaller $L$ increases the attacker's chance to penetrate the system, layer by layer.

*4) Discussions:* In the above, we have made important observations on system performance, and the impacts of the design features on system performance under intelligent DDoS attacks, using extensive analytical derivations. A natural question here is the following; Using our analytical results, can we obtain optimal configurations for the design features to optimize system performance? In the following, we address this issue. Due to space restrictions, we answer the above question by explaining how to obtain optimal mapping degree and node distribution as examples. Optimal configurations for other design features can be obtained similarly.

The performance of the SOFS system, i.e., $P_S$, is a function of system design features and attack parameters, as seen in (24) below, where $m[\ ]$ and $n[\ ]$ are the mapping degree and the number of nodes on each layer. Function $F$ contains all parameters that are used to calculate $P_S$ and summarizes the above formulas to calculate $P_S$.

$$P_S = F(N, n, N_C, N_T, L, m[\ ], n[\ ], P_B, P_E, R) \tag{24}$$

If all other system and attack parameters are fixed and we keep $m[\ ]$ as variables, then we can use existing mathematic tools such as MATLAB to get the optimal mapping degree under the system and

TABLE II

OPTIMAL MAPPING DEGREE WITH DIFFERENT $N_T$

| $N_T$ | $N_T = 0$ | $N_T = 20$ | $N_T = 200$ | $N_T = 2000$ |
|---|---|---|---|---|
| *Optimal mapping degree* | $1\ to\ all$ | $1\ to\ 4$ | $1\ to\ 3$ | $1\ to\ 2$ |

TABLE III

OPTIMAL NODE DISTRIBUTION UNDER 1 TO 2 MAPPING WITH DIFFERENT $N_T$

| $N_T$ | $n_1$ | $n_2$ | $n_3$ | $n_4$ | $N_T$ | $n(1)$ | $n(2)$ | $n(3)$ | $n(4)$ |
|---|---|---|---|---|---|---|---|---|---|
| 200 | 25 | 20 | 21 | 34 | 600 | 25 | 22 | 22 | 31 |

attack parameter configuration. Table II shows optimal mapping degrees under default system and attack parameters that were used in Section III-B.3. We can see that the optimal mapping degree changes from $1\ to\ all$ to $1\ to\ 2$ [7], when $N_T$ changes from 0 to 2000. This matches our previous observation that smaller mapping degrees improve the resilience of the system to break-in attacks. In Table III, we get the optimal node distributions under two different $N_T$ values when $L = 4$, $n_1$ is fixed as $\frac{n}{L}$, i.e., 25, mapping degree is $1\ to\ 2$, and all other parameters are set as the default configuration values. The results match our previous observation that increasing node distribution performs better than other node distributions.

While the above approach is useful in some cases, the real problem is how to optimize multiple structure parameters simultaneously to achieve optimum performance. To complicate this further, some of the parameters especially attack related (such as $N_C, N_T$) may be unknown to the system designer at design time. In some cases some parameters can be estimated to be within ranges. Also, the system may have other constraints like latency, workload per node etc., that impact choices in number of layers, mapping degree etc. The optimization of design features needs to take these issues into consideration too. It can be easily seen that solving the overall optimization problem is thus not easy. Nevertheless, we do provide some discussions on how to obtain optimal configurations under reasonable assumptions on system and attack generalities.

Consider an instance, where intensities can be predicted within some interval. i.e., we know the ranges and the distributions of $N_C$ and $N_T$ values. Then, a reasonable approach to address this problem is to obtain configurations to optimize the expected value of the path availabilities denoted as $E(P_S)$. It is

[7]While obtaining optimal mapping degrees we constrain the mapping degrees to be equal across layers for consistency in workload across nodes in the system. However this constraint can be relaxed if need be.

formally defined in (25), where $Pr(N'_C, N'_T)$ is the probability that the $N_C$ and $N_T$ have values of $N'_C$ and $N'_T$ respectively.

$$E(P_S) = \sum_{N'_C, N'_T} Pr(N'_C, N'_T) \times F(N, n, N'_C, N'_T, L, m[\ ], n[\ ], P_B, P_E, R). \quad (25)$$

Based on (25), we can use optimization tools such as those in MATLAB to get the optimal mapping degree ($m[\ ]$) and node distribution ($n[\ ]$) to achieve overall optimal performance under certain ranges of $N_C$ and $N_T$. In reality, the range and distribution of $N_C$ and $N_T$, and even other attack parameters can be obtained from historical experience and run-time measurement. Other attack parameters that can be estimated within ranges can be handled in the same way we deal with $N_C$ and $N_T$.

To summarize here, the attack strategies, intensities, prior knowledge about the system significantly impact system performance. However, the impacts are deeply influenced by the system design features. Larger values of $L$ and smaller mapping degrees improve system resilience to break-in attacks, while the reverse is true for congestion-based attacks. Increasing node distribution performs better than other node distributions. These design features interact among each other to impact system performance under intelligent DDoS attacks.

## IV. Analysis of the SOFS System under Continuous Attacks

In this section, we study the performance of the SOFS system in the presence of another type of intelligent DDoS attacks called continuous attacks. We also study the impacts of recovery mechanisms the SOFS can incorporate in this section. The performance metric here is still $P_S$.

### *A. Attack Model and System Recovery*

The continuous attack model is different from the discrete round based attack model proposed above in the sense that the attacker continuously breaks into SOFS nodes as and when their identities are revealed to the attacker (and not in rounds). We define $N_T$ and $N_C$ to be the maximum number of overlay nodes that can be simultaneously under break-in or congestion attacks. Furthermore, here the attacker reuses its resources ($N_T$ and $N_C$) in a more sophisticated way as follows. During system recovery (discussed

next), the attacker will know that a compromised node is recovered (it is replaced with a *good* node). If the attacker attacks a non-SOFS node [8], it will also know that it is a non-SOFS node. In either case, the attacker will redirect the attack to a new node in time $T_{red}$, which is referred as *attack redirection delay*.

Under on-going congestion attack, the attacker will keep attacking a victim node as long as it is an SOFS node. During break-in attacks, once a break-in attempt is completed on a node (irrespective of the result), the attacker will redirect the break-in attack to another node also in time $T_{red}$. When the attacker redirects the attack, it will use the disclosed node list if there is any node in that list, otherwise it will randomly pick a node from all the overlay nodes except ones currently under attack. Obviously, the disclosed nodes are all SOFS nodes, so they will be targeted first by break-in attacks if there are enough resources. Otherwise, the nodes are attacked by congestion attacks.

In our analysis here, the SOFS system employs recovery to defend against attacks. While there can be many potential recovery mechanisms, the one we employ is *proactive recovery*, where a proactive reset mechanism periodically resets every SOFS node. When a proactive reset event happens on a SOFS node, the SOFS system immediately replaces that node with a new SOFS node chosen from the set of non-SOFS nodes. We denote the interval between two successive proactive resets on a SOFS node as $T_p$, which is called *system recovery delay*. In this study, we mainly focus our discussion on *proactive recovery*. Interested readers can refer to [9] for our discussion and analysis on other recovery mechanisms.

### *B. Analysis*

The goal of our analysis here is to study the impacts of system design features on system performance under continous attacks with system recovery. An analytical approach for this case, similar to the one conducted under discrete round based attacks, is too complicated. We use simulations here to study system performance under continuous attacks in the presence of system recovery.

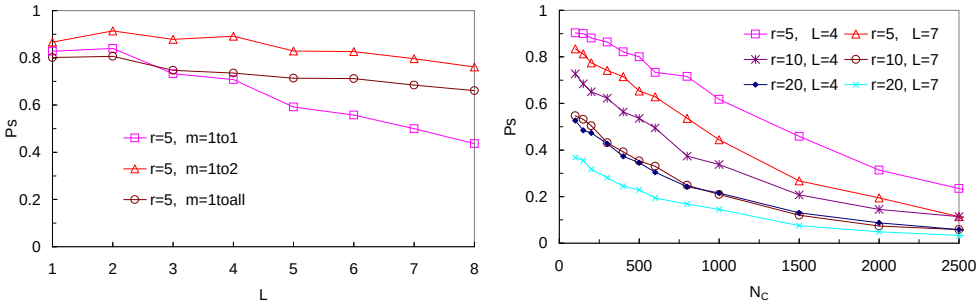
In order to analyze the system, we implement a discrete event driven simulation tool to simulate the attack model and system recovery. The simulated system consists of $5000$ overlay nodes among which

[8]Recall that a SOFS node is one that currently is active in the SOFS structure, while a non-SOFS node is one that is a part of the overlay system, but is not a part of the SOFS structure currently.

there are 40 SOFS nodes, and 10 filters. Each client is connected to 5 first layer SOFS nodes. In our simulations below, the attack redirection delay ($T_{red}$) and the system recovery delay ($T_p$) follow exponential distributions. The system recovery is sensitive to $\frac{mean\ value\ of\ T_p}{mean\ value\ of\ T_{red}}$, denoted as $r$, instead of the individual value $T_{red}$ or $T_p$. Thus $r$ measures the competition between attacks and system recovery in terms of speed. A smaller value of $r$, implies faster recovery, which is beneficial for the system. In the simulations below we only use $r$ to discuss the impacts of continous attacks and system recovery.

### C. Numerical Results and Discussions

In following simulations, the default system and attack parameters are $L = 4$, $P_B = 0.5$, $P_E = 0.2$, $N_T = 200$ and $N_C = 200$. Fig. 8 (a) shows the impact of layer number, $L$, on $P_S$ under different mapping

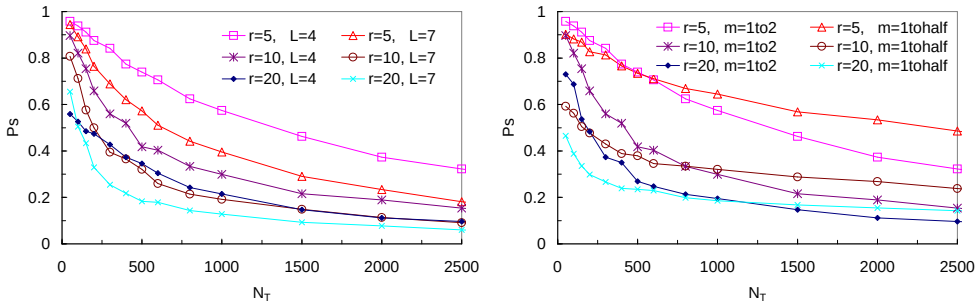



(a) (b)

Fig. 8. Sensitivity of $P_S$ to $L$ under different $m$ (a), and to $N_C$ under different $L$ and $r$ (b).

degrees when both $N_T$ and $N_C$ are fixed as 200, and $r = 5$. Similar to Fig. 6 (a), $P_S$ is sensitive to $L$ and the mapping degree. The sensitivity of $P_S$ to $L$ and mapping degree is less than that in the discrete round based attack model. The reason is due to the presence of system recovery, where the system replaces the compromised and disclosed SOFS nodes, attack impacts are reduced. Fig. 8 (b) shows how $L$ and $r$ influence $P_S$ when $N_T = 200$, mapping degree is $1\ to\ 2$, and $N_C$ changes. Here $L = 4$ is always better than $L = 7$. This is because, when $N_T$ is fixed and $N_C$ increases, random congestion attacks dominate, and hence less layers will improve performance as discussed in the round based attack model.

Fig. 9 (a) shows how $P_S$ changes with $N_T$ under different $L$ and $r$. The mapping degree is fixed as $1\ to\ 2$. In most of the cases, $L = 4$ performs better than $L = 7$. This is because, in our simulations the total number of SOFS nodes is fixed. Under this situation, deploying more layers decreases the number of nodes on each layer, and so decreases the number of paths from clients to the target. However, there is one




(a) (b)

Fig. 9. Sensitivity of $P_S$ to $N_T$ under different $r$ and $L$ (a), and different $r$ and $m$ (b).

exception to this claim. When $r = 20$ and $N_T = 50$, $L = 7$ performs better than $L = 4$, which shows that more layers can be beneficial. The reason is, when $N_T$ is very small, there are few nodes disclosed and compromised at each layer. In this situation, decrease in $P_S$ is mainly due to disclosure and compromise of filters which are at the last layer. Here, slow recovery (large $r$) cannot recover the compromised filters effectively. In this case, more layers can slow down the penetration of break-in attacks towards the filters and helps achieve better performance. The data also demonstrate that faster system recovery (smaller $r$) improves system performance more effectively.

Fig. 9 (b) shows how $P_S$ changes with $N_T$ under different mapping degrees and $r$, when $L = 4$. When $N_T$ is small, smaller mapping is better, especially when $r$ is large. But when $N_T$ is large, larger mapping performs better. This is because, when $N_T$ is not large and mapping degree is small, fewer nodes are disclosed. Hence fewer nodes are attacked, resulting in high $P_S$. However, when $N_T$ is very large, many SOFS nodes are disclosed and compromised and it is the system recovery that maintains a certain (possibly small) number of nodes alive, which guarantees $P_S > 0$. The number of alive nodes here is mainly determined by $r$, which is not related to mapping degree. But mapping degree decides the number of available paths. Given a number of alive nodes, a larger mapping degree means more paths. Hence, $P_S$ increases with larger mapping degree, especially when $r$ is small (fast system recovery).

From the above,we see that attack intensities and system design features have significant impacts on system performance under continuous attacks with system recovery. We also find that recovery plays a significant role in reducing impacts caused by even intense attacks, by still sustaining a certain level of

system performance. Large mapping degrees help achieve better system performance in this circumstance.

## V. Related Work

The main scope of this work is in the realm of overlay systems (organized into definite structures) for defending against Distributed DoS attacks. The surveys in [1], [2], [3] on DDoS attacks and defense are exhaustive, and interested readers can refer to those papers. We have also provided some background related to this in Section I in this paper. In the following, we focus on work using overlay systems in general to defend against DDoS attacks.

Recently, several works have proposed solutions based on overlay networks to enhance security of communication systems like [6], [7], [8], [10], [11], [12], [13], [14]. An overlay solution to track DDoS floods has been proposed in [10]. [11] proposes a overlay routing infrastructure to enhance the resilience of the Internet. Chen and Chow designed a random Peer-to-Peer network that connects the registered client networks with the registered servers to defend against DDoS attacks in [12]. Badishi et. al present a systematic study of the vulnerabilities of gossip-based multicast protocols to DoS attacks and propose a simple gossip-based multicast protocol that eliminates such vulnerabilities in [13]. The effectiveness of location-hiding of proxy-network based overlays is discussed in [14].

Anonymity systems share some features with our SOFS system. Anonymity systems usually use intermediate forwarding to achieve anonymity. However, there are some significant differences between SOFS and anonymity systems. The goal of SOFS is to ensure paths from clients to the server by putting multiple connections between nodes in successive layers. Many anonymity systems depend on one or more third party nodes to generate an anonymous path [15], [16], which is not good for SOFS. SOFS cannot rely on a centralized node to achieve receiver anonymity, since the centralized node can itself be the target of a DDoS attack.

## VI. Final Remarks

In this paper, we have studied the impacts of architectural design features on SOFS, a generalized overlay intermediate forwarding system under intelligent DDoS attacks. We analyzed our SOFS system

under discrete round based attacks using a general analytical approach, and analyzed the system under continuous attacks using simulations. We observed that the system design features, attack strategies, intensities, prior knowledge about the system, system recovery significantly impacts system performance. Even under sophisticated attack strategies and intensities, we show that with smart designing of system features and recoveries, attack impacts can be significantly reduced. As we discussed in Section III, we showed how to obtain optimal system configurations under expected attack strategies and intensities. However, obtaining optimal configurations under all attack and recovery scenarios is not always possible. Based on our findings in the paper, we however propose a set of design guidelines to enhance performance under all general scenarios. (i) The design feature configurations should be flexible and adaptive to achieve high performance under different intensities of attacks. (ii) When attack information is unknown, moderate number of layers and mapping degree, and increasing node distribution are recommended to sustain a more than acceptable level of performance. (iii) When break-in attacks dominate, more layers and smaller mapping degrees are recommended. When congestion-based attacks dominate, less layers and larger mapping degrees are better. (iv) System recovery is always helpful to improve system performance under attacks. Under intense break-in attack, system recovery with large mapping can always help sustain a more than acceptable level of performance.

As part of future work, we propose to design SOFS system that is resilient to attacks while maintaining QoS. Also, the impacts of our work extend beyond DDoS attack defense. There are several other applications where a structure present, enables better service delivery. These include Multicasting, Real-time delivery, File Sharing systems etc. As modeled in this paper, attackers can cause significant damages to performance by exploiting knowledge of the structure already present in these systems. We believe that our work is a first step towards designing the features of resilient overlay architectures under intelligent attacks. Analyzing the resilience of such systems under intelligent attacks will also be a part of our future work.

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