Agile Virtualized Infrastructure to Proactively Defend Against Cyber Attacks

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***Abstract*—DDoS attacks have been a persistent threat to network availability for many years. Most of the existing mitigation techniques attempt to protect against DDoS by filtering out attack traffic. However, as critical network resources are usually static, adversaries are able to bypass filtering by sending stealthy low traffic from large number of bots that mimic benign traffic behavior. Sophisticated stealthy attacks on critical links can cause a devastating effect such as partitioning domains and networks. In this paper, we propose to defend against DDoS attacks by proactively changing the footprint of critical resources in an unpredictable fashion to invalidate an adversary's knowledge and plan of attack against critical network resources. Our present approach employs virtual networks (VNs) to dynamically reallocate network resources using VN placement and offers constant VN migration to new resources. Our approach has two components: (1) a correct-by-construction VN migration planning that significantly increases the uncertainty about critical links of multiple VNs while preserving the VN placement properties, and (2) an efficient VN migration mechanism that identifies the appropriate configuration sequence to enable node migration while maintaining the network integrity (e.g., avoiding session disconnection). We formulate and implement this framework using SMT logic. We also demonstrate the effectiveness of our implemented framework on both PlanetLab and Mininet-based experimentations.**

I. Introduction

Network robustness is essential for service availability and quality of service against increasingly common cyber threats, such as DDoS [1]. The indispensable nature of these services for today's world make them mission critical and any disruption to them could be catastrophic. A DDoS attack can be either direct or indirect. In direct DDoS, the attack traffic is sent directly to the victim destinations to flood the last mile link. In indirect DDoS, the attack traffic is sent to the geographical neighbors of the victim destinations to flood critical links in the network shared between the neighbors and the victims. We concern ourselves with indirect DDoS attacks. Existing DDoS mitigation techniques [2], [3] try to defend by filtering out attack traffic. However, as the attacks are going more stealthy (like sending low traffic per bot to mimic normal user) [1], distinguishing benign from attack is not feasible in most cases. Nonetheless, a common prerequisite of all link-based DDoS attacks is to identify critical target(s) through reconnaissance (e.g., small set of links carrying most of the traffic [1], [4]). If the critical nature of such targets is changed to non-critical, before the attack can be launched then the attack can be rendered useless to the adversary.

Virtual networks (VNs) [5]–[10] are envisioned to provide such flexibility within a communication infrastructure. When VNs are deployed, physical (substrate) resources can be dynamically allocated to a service (VN placement) and if a physical resource is rendered unavailable, due to fault or attack, it can be replaced with a different resource to ensure service availability (VN migration). We call the capability to perform VN migration in an orchestrated fashion to deceive or evade attacker as *VN agility*. Even though virtualization has now been offered as a commercial service through companies posing central authority [11], [12], the existing VN placement techniques [6]–[10] do not provide for VN agility because (1) they are simply static (no migration support), and (2) the existing placement control mechanisms are attack-unaware. Apart from providing one time resource assignment for the VN, no technique considers migration as a proactive defense to evade reconnaissance or DDoS attacks. Therefore, this static status quo of VN placement still enables an adversary to discover and plan devastating DDoS attacks. In this paper, we propose an agile VN framework that proactively defends against sophisticated DDoS attacks without requiring the distinguishing of attack from benign traffic. We achieve this by actively reassigning the VN to new threat safe physical resources without disrupting the service or violating the VN properties.

Persistent cyber threats demand continuous VN movement which requires a provably correct-by-construction VN placement technique to ensure intact service functionality at all times. Our first contribution is in developing such VN placement technique as a constraint satisfaction problem using Satisfiability Modulo Theory [13] based formal methods. We adopt the same VN placement requirements used in the literature [6]–[10] and define them formally as constraints in the model.

Proactive defense requires identifying critical resources that can be replaced with non-critical resources to evade attack. Our VN framework is generic for all link-based DDoS and reconnaissance attacks. But to show the effectiveness of our approach, we use Crossfire attack [1] as a case study for our threat model. Because, it is the most devastating and stealthy attack to-date. Furthermore, we experimentally calculate the Crossfire reconnaissance time to set a time bound within which

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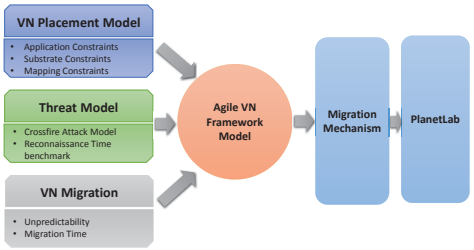


Fig. 1. Abstract model diagram

the critical only migration should take place to evade the attack successfully. This is our second contribution in the paper.

The purpose of agility is to frequently replace potentially discovered critical substrate with *valid* new threat safe resources such that (1) the selection process of the new resources is unpredictable by the adversary, and (2) the migration to these new resources will be faster than the reconnaissance time of the adversary. This, therefore, will constantly invalidate the adversary assumptions about the VN placement, discovered in the reconnaissance phase and this is our third contribution. All these constraints are formally defined as a part of the agile VN framework model using SMT [13]. Advanced SMT solvers such as Z3 [14] and Yices [15] can solve tens of thousands of constraints and millions of variables [13]. Therefore, our approach is scalable to large networks with multiple VNs.

The fourth contribution is in developing a migration mechanism that executes VN migration strategy generated by the framework on a virtualized physical network. It handles all the logistics of the movement including the exact sequence/schedule of the steps to be executed in order to complete the move and the timing of such steps. We use PlanetLab [16] as our virtualized infrastructure and extend the functionality of an existing PlanetLab based controller, PL-VNM [17], to implement our migration mechanism. We use this PlanetLab implementation to rigorously evaluate the effectiveness of this framework. We also use simulation and Mininet-based experiments to evaluate other features (like scalability) which were not possible on Planetlab.

Our proposed solution only requires provision in the network to have redundant paths that can be used to switch critical role to non-critical. Furthermore, the proposed framework model can be extended by adding more functional, security or threat related constrainst.

In the rest of the paper, we explain related work in Section II followed by our approach in Section III. Threat modeling is explained in Section IV followed by agile migration in Section V. The migration mechanism and evaluation are presented in Section VI and Section VII, respectively.

II. Related Work

The existing DDoS remedies, all requiring the ability to distinguish attack traffic from benign, can be divided into two major categories, infrastructure based and virtual network based approaches. Some infrastructure based approaches proposed adding authentication bits in packet headers to assist routers drop attack traffic [18]–[20]. Others, suggested routers to signal each other through a signaling protocol to filter DDoS traffic [21]–[23]. The major limitation of these approaches is to expect major changes in existing hardware and network protocols, which is hard to come by. The VN based approaches [2], [24]–[28] suggest deploying a secret virtual layer on top of the substrate to route traffic only through designated routers. For example Akamai's SiteShield service [3], SOS [2], [28] and Mayday [24] use a shared secret (e.g., IP of the target) to route traffic through specialized routers. The major shortcoming with such approach is that if the secret (virtual layer) is revealed then the adversary can bypass the virtual network to directly flood the target. Some countermeasure approaches [2], [24] were also proposed preventing malicious overlay components to disclose shared secret, but they require expensive mechanisms such as anonymous routing. However, none of these approaches can counter the Crossfire attack [1] because this attack does not directly attack the target.

For VN agility, the work done in [7] focuses on one time VN placement but allows a limited moving of ensemble of VNs deployed on the substrate under resource contention. The work in [29] considers VN link reconfiguration in response to changes in traffic demands. That work does not allow moving the placement of the virtual components. Recent work [30] has developed and implemented a scheme for moving a single virtual router in a virtualized separated router environment. This work has recently been used in [31] to design entire network migration mechanisms. A recent effort [32] has also considered this VN migration withsoftware defined networks (SDN). All these recent work deals with low level migration configuration functions with no investigation of strategy and higher-level mechanism questions.

An alternative solution would be to dilate (spread) the critical footprint by dividing the traffic equally across all available routes. Major shortcoming of such approach will be a significant increase in the power consumption [33] and network management cost of the network. Also, it would require changing routing protocols as they automatically converges to a power-law (shortest path) based path logic after a failure.

III. Agile VN Framework

The objective of agile VN framework is to develop a migration strategy that determines *what* resources should be reassigned and, *where* and *when* migration should take place to defy hostile environment. In the following of the paper, we explain all the modules of agile VN framework, as in Figure 1.

A. Modeling VN Placement

The VN placement is all about finding the best combination of substrate (physical) resources satisfying all the requirements of one or more services, where each service will have its own VN. These requirements are enforced as constraints of the VN placement model, explained in the following. Let the substrate network be a directed graph, $G =< C, L >$, where C is the set of all components (any network device) and L is the set of all links. Similarly, let υ be a VN placed for a service. By definition, VN placement is about connecting a

source to a destination through a network path, that satisfies all constraints. This path can further be restricted to pass through one of more designated components (e.g., components capable of hosting virtual routers). But in environments such as SDN,all components are considered the same. Our model is applicable to both scenarios. A source can be an ingress router, some aggregating node (like proxy node) or some corporate office [11] in the network. Similarly, a destination can be an egress router, some aggregating node (like proxy) or the actual destination (e.g., web server or data center). And, C_{src} is the set of all source components in the network and C_{dst} is the set of all destination components. Both components represent a small fraction of the network size. Then, the VN placement is about finding optimal paths between these source-destination pairs. Where u_i represents such a source-destination pair, $u_i =< c_j, c_k >$ and $u_i \in U = \{C_{src} \times C_{dst}\}$. The shortest distance between any node c_i to a destination node c_j is represented as d_{ij}, where, $c_j \in C_{dst}$. And, b_{ik} is a Boolean variable, which is true if component c_k is carrying the traffic for a source-destination pair u_i. I_{c_j} is the set of neighboring components of c_j and κ_j is the traffic capacity of a node c_j. Deploying a VN for a service requires the estimated traffic that needs to be handled by the network, e.g., between a corporate office to a data center[1] and λ_i is the estimated traffic load of a pair u_i. All thresholds in our model are represented as $T^{(.)}$.

The following placement model assigns substrate resources to multiple VNs. Let A be the set of all VNs, i.e., $A = \{\upsilon_1, \upsilon_2, \ldots, \upsilon_m\}$. Then, the binary assignment variable b_{ij} will be updated as, $b_{ij}^{\upsilon_l}$, which means, node c_j is assigned to pair u_i of VN υ_l. For the simplification of notations and understanding, we explain the VN placement modeling for one VN in the following section.

From the existing literature [6]–[10] we are using following requirements as constraints of our model.

1) Reachability Constraints: According to this constraint, data generated from a source must reach the destination. Assuming that each node will forward the traffic, this constraint is about connecting components so that from source to destination there is a connected path. This constraint is formally defined as: $b_{ij} \rightarrow \bigvee_{\exists c_k \in I_{c_j}} (b_{ij} \wedge b_{ik})$ which says, if a node is selected i.e., b_{ij} is true, then it must be connected to one of its neighboring components. In other words, a node receiving traffic must forward this to one of its neighboring component. However, forwarding a packet to one of the neighboring components does not guarantee packet delivery to the destination. So, in this constraint we need to add a sense of direction from source to destination. This sense can be added by using the distance from the current node to the destination node. The updated reachability constraint is defined in the following as: $b_{ij} \rightarrow \bigvee_{\exists c_k \in I_{c_j}} ((b_{ij} \wedge b_{ik}) \wedge (d_{kl} < d_{jl}))$ where, d_{jl} is the distance from node c_j to destination node c_l of the pair $u_i =< ., c_l >$. Now, what if the next node is itself the destination node, then traffic must not be forwarded to any other node. This completes the reachability constraint and the final version of this constraint is as follows:

$$b_{ij} \rightarrow (c_j \in C_{dst}) \vee \bigvee_{\exists c_k \in I_{c_j}} ((b_{ij} \wedge b_{ik}) \wedge (d_{kl} < d_{jl})) \quad (1)$$

Although, we assume mostly stable routing because according to [1] 72% of links tend to be stable. However, our model can be incrementally updated to recalculate placement in case of topology changes.

2) Load Satisfaction Constraint: According to this constraint, every node along the path must be able to carry traffic load of the pair assigned to it. In practical, this decision must be made by comparing traffic load with leftover capacity of the node. If the aggregate traffic supported by node c_j is σ_j, which is calculated in the Section III-A5, then formal definition of this constraint is as followed:

$$\forall u_i \in U, c_j \in C, b_{ij} \rightarrow (\kappa_j - \sigma_j) \geq \lambda_i \quad (2)$$

3) Middle-ware Device Constraint: An application might require some specialized service from the substrate (e.g., the IPSec, etc.). Mostly, only a handful of components can provide such requested feature. This constraint ensures that the VN traffic must go through such specialized node. Let $C_{sp} \subset C$ be a set of such specialized components. Then, for a pair u_i we enforce this constraint by explicitly setting the node assignment variable b_{ij} to true, where, $c_j \in C_{sp}$. The formal definition is as followed:

$$\exists c_j \in C_{sp}, b_{ij} \quad (3)$$

The VN placement model, as a whole, will automatically connect this component with other components to satisfy all constraints.

4) Quality of Service Constraint: For simplicity, we assume relatively homogeneous network where hop count can be proportional to network latency. This assumption has been widely used in existing literature [34].

$$\forall u_i \in U, (\sum_{c_j \in C} b_{ij}) \leq T^{qs} \quad (4)$$

where, T^{qs} is the affordable delay threshold for any pair in the system. It can be the same for the entire system or different for each VN. In addition, our framework allows for more complex constraints to define bounded delays.

5) Node Stress Constraint: According to this constraint, each node must have some leftover capacity to accommodate the traffic fluctuations due to load dynamics or uncertainty. Therefore, the leftover capacity can ensure to handle such incorrect traffic load estimations. This is formally defined as:

$$\forall c_j \in C, \{(\kappa_j - (\sum_{u_i \in U} b_{ij} * \lambda_i)) \geq T^{lo}\} \quad (5)$$

where, $\sum_{u_i \in U} b_{ij} * \lambda_i$ is the aggregate traffic σ_j at node c_j and T^{lo}, is the leftover capacity threshold set for each component. This can be provided as a percentage of the capacity of a node.

[1]In a commercial products like Virtela [11] and Aryaka [12], they expect to estimate this traffic as well.

6) Pair Mapping Constraint: According to this constraint, each pair must be assigned some substrate resources. This is formally defined as:

$$\forall u_i \in U, \sum_{\forall c_j \in C} b_{ij} > 1 \tag{6}$$

7) Loop Avoidance Constraint: According to this constraint, a substrate component cannot be assigned to a pair twice because this would create a loop within the path. Our model enforces this by checking how many links are enabled for each component? In the model, a link is represented logically as $b_{ij} \wedge b_{ik}$, i.e., both components c_j and c_k are assigned to u_i and they are connected. If the number of links are more than 2, this means there is a loop. E.g., $c_j \wedge c_k$ and $c_k \wedge c_i$, if $c_i \wedge c_j$, this makes a loop that is not allowed. It is formally defined as follow:

$$\forall u_i \in U, c_j \in C, (\sum_{\forall c_k \in I_{c_j}} (b_{ij} \wedge b_{ik} \rightarrow 1)) \leq 2 \tag{7}$$

In this equation the condition is not modeled as exactly equal to 2 but less than or equal to 2. It is because, the source and destination components will have only one link.

IV. Modeling Threat

The planning phase of all link-level DDoS attacks is to perform network reconnaissance to identify critical components. For proactive defense, we have to model this reconnaissance attack and incorporate it as a module of the agile VN framework. This module proactively identifies potential targets so that these can be replaced with threat safe components to evade attacks. Our framework can handle general classes of link-level DDOS and reconnaissance attacks. It is general enough to consider new attack by only updating threat model to reflect new logic of identifying critical components without changing any other parts of the framework in Figure 1. However, in this paper we are using the most devastating and stealthy DDoS attack to-date, i.e., Crossfire [1] as a case study threat model.

In the Internet, data connectivity follows power law distribution [4], which means a small set of links carry most of the traffic. The Crossfire attack identifies such links that carry most of the traffic to the victim. Then, it selects a list of surrounding public servers (decoy servers) that share these links with the target. The attack uses botnets to send enough traffic to these selected decoy servers that it throttles the shared links, thus causing denial of service to the victim, indirectly. The static critical status quo of these links enables the adversary to launch such attack.

Under the hood of a Crossfire attack, bots send traceroute probes to all victim machines and decoyer servers. As opposed to manually searching decoy servers in the original attack, we use the geographical coordinates of the victim and select initial set of decoy servers who are within certain miles from the victim. We use geographical database *GeoLite* [35] to get all such coordinates and use geographical distance formula [36] to calculate distance. The final set of decoy servers is selected after observing the sharing of infrastructure between victim

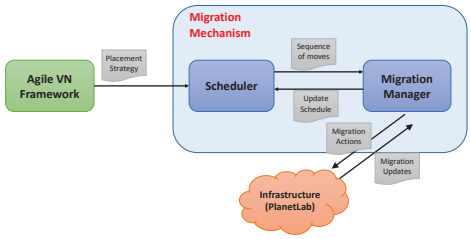


Fig. 2. Migration Mechanism on PlanetLab

and decoy servers. Let the set of bots be O, decoy servers be Y and victim machines be V. Each traceroute probe provides a data path, and P is the set of all paths from bots to decoy servers and victim machines. And, P^Y and P^V are the set of paths from bots to decoy servers and victim machines, respectively, i.e., $P = \{P^Y \bigcup P^V\}$. A path is simply a set of components, i.e., $p_=\{c_1, c_2, \ldots, c_n\}$, where, $c_n \in C$ is from Section III-A. All those paths that do not share anything between victim and decoy servers are removed from the set, i.e., $P' = \{\neg\exists p_i \in P^Y, p_j \in P^V, p_i \cap p_j = \emptyset\}$.

For a packet to be delivered successfully from origin to destination, every component along the path must forward the packet. Let $F(.)$ be a Boolean function, which is true if the component successfully forwards the packet and false otherwise. This path forwarding property can be expressed as a logical formula as, $F(p_i) = \bigwedge_{c_j \in p_i} F(c_j)$. However, from the adversary's perspective, she just has to compromise any single component along the path to violate the forwarding property of the path. Let $B(.)$ be a Boolean function that is true if a component along the path is compromised and false otherwise. Now, the same path forwarding property can be flipped to formulate path breaking property, which says a path is broken if any component along the path is compromised, i.e., $B(p_i) = \bigvee_{c_j \in p_i} B(c_j)$. Due to limited resources of the adversary, compromising the entire network may not be a possibility. Therefore, the model must also be equipped with a choice to disrupt any path or not based on the budget of the adversary. This choice is added as a binary variable χ in the path breaking property, i.e., $B(p_i) = \bigvee_{c_j \in p_i} B(c_j) \rightarrow \chi_i$. The value of this choice variable, χ, will be one if the path can be broken or zero otherwise. This all depends upon the budget of the adversary. We can extend this path breaking property for the entire network to find a set of components, if broken, can cause the desired devastation in the network. Its formal definition is as follows:

$$B(P') = \bigwedge_{p_i \in P'} B(p_i) = \bigwedge_{p_i \in P'} \{ \bigvee_{c_j \in p_i} B(c_j) \rightarrow \chi_i \} \tag{8}$$

This formula provides a list of components, if attacked, can inflict the desired devastation. This is an NP complete problem and we formalize it as a SAT [13] problem. Normally, the adversary has limited budget (cost) in terms of attack traffic that can be generated to throttle components. Therefore, finding only those components that can be throttled with that budget is the prime focus of adversary. Let $|B(.)|$ be a function that provides number of true components in Equation 8. If the

adversary does not know the capacity of target components, then cost will represent the number of components that can be throttled assuming them to have same capacity. This constraint is encoded as follows:

$$|B(P')| \leq Cost \tag{9}$$

$$\sum_{\forall p_i \in P'} \chi_i \leq T^{dv} \tag{10}$$

where T^{dv} is the desired disruption of the adversary. If we assume that the adversary has the leftover capacity information of each component then the Equation 9 can be optimized. This last assumption is optional and we do not use this in our implementation.

$$\sum_{\forall c_j \in C} ((\kappa_j - \sigma_j) * B(c_j)) \leq Cost \tag{11}$$

During reconnaissance attack, the adversary cannot afford to send too much traffic to decoy servers or victim machines to avoid detection. Therefore, by simply adding more bots will not guarantee that the reconnaissance attack will complete in small time window. The experiments explained in Section VII-B5 provide the reconnaissance time benchmark of this attack model.

a) Defender's View vs. Attacker's View: When an adversary runs a traceroute probe for a target machine, she views the same data plane that is deployed during the VN placement for the service running on that target machine. Similar observation is made in [1] that bots probing a target from the Internet would end up viewing the same critical footprint with respect to the target. Therefore, the threat model discussed in this section can be viewed as both defender's and attacker's perspective of potential targets. Because the decoy server information is public and available to both. Similarly, the adversary would rely on bots to decoy server relation and the defender would rely on source to decoy server relation to identify critical components. Bots and sources are logically the same just with different roles. In Section VII-B6, we have demonstrated this fact using simulation to show that both see the same components as potential targets.

V. Modeling Threat Aware Migration

The purpose of agility is to replace critical components with only new threat safe components. Following are the two constraints that ensure threat safe agility.

A. Migration Disturbance Constraint

Simply replacing critical components with randomly selected new distinct resources is not enough because the adversary can start building a dictionary of learned critical components of the network. So, if we only move to distinct components then next time the adversary will not consider previously learned critical components and this will reduce the sample space for the adversary to find new critical targets. Instead, we assign a random counter to a component once flagged as critical. This component cannot be reused in the next iterations of migration unless its counter is expired[2]. This uniformly distributes the reuse probability of the components in the upcoming iterations, leaving adversary to keep guessing. Let R be the set of critical nodes and h_j is a Boolean variable. If it is true, this means component c_j was selected as a critical node. And, q_j is the index of the iteration in which the component c_j was selected as a critical component. And, β_j is the number of iterations (counter) for component c_j before it can be repeated. Now, the original assignment variable b_{ij} will be constrained to assign only allowed resources in the next placement. This constraint is formally defined in the following equation.

$$\forall u_i \in U, c_j \in C, b_{ij} \wedge ((q_j = 0) \vee ((t+1) - q_j > \beta_j \rightarrow h_j)) \tag{12}$$

Where, $t+1$ represents the index of the next iteration.

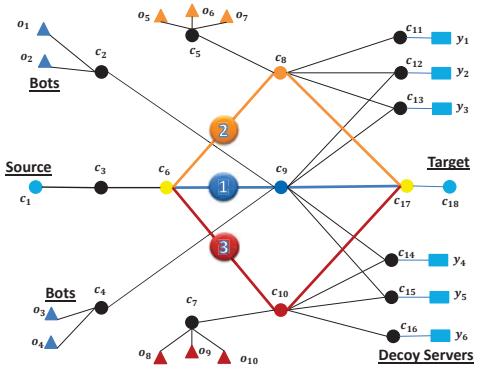


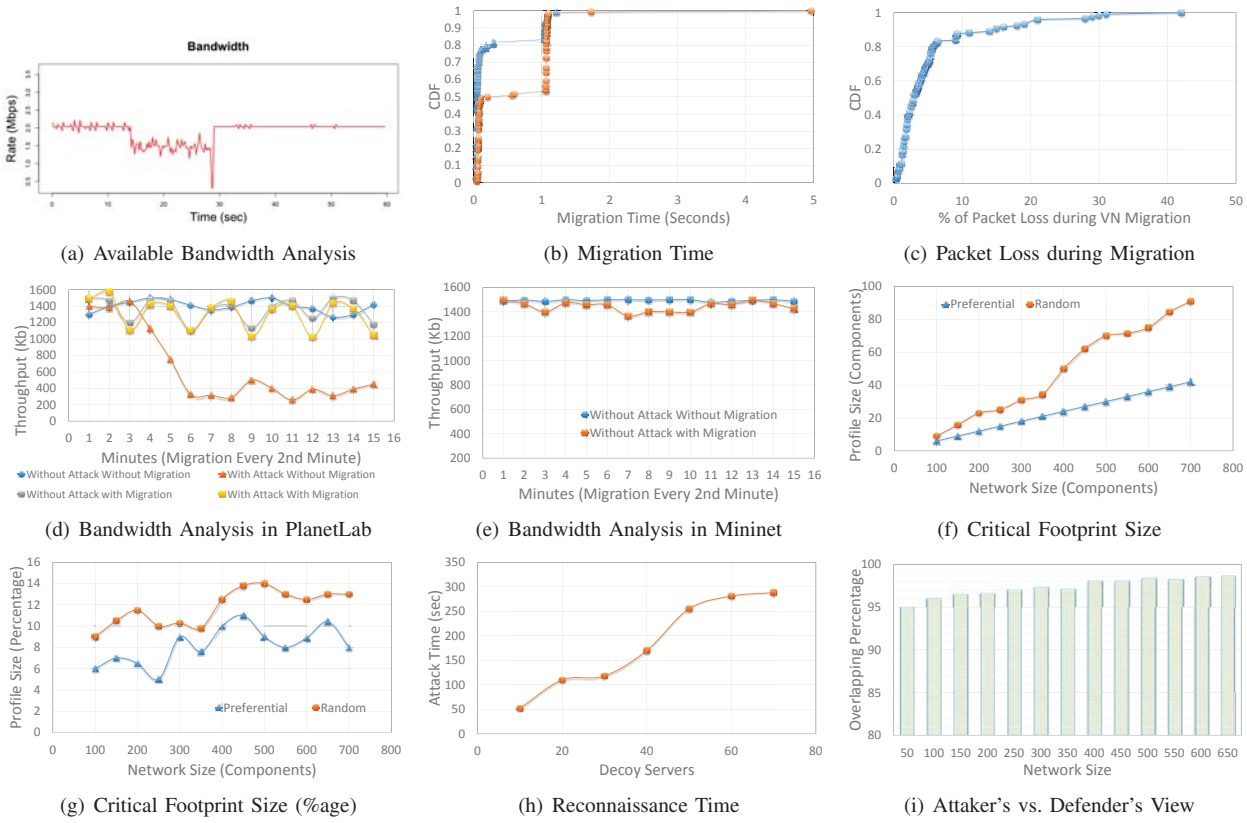
Fig. 3. Topology diagram of the experiments

B. Migration Distance Constraint

Migration should complete before the adversary can finish reconnaissance and launch the attack. During migration [30] following steps take place, 1) setting up tunnels between current and new components, 2) copying control plane from old to new components, 3) populating data plane in the new component, and 4) establishing routes between the new components and the neighbors of the old components. In our implementation on PlanetLab, we use controller based architecture [17] like in Software Defined Networking (SDN). In such architecture, the relative positions of the current and new components do not matter. Instead, control plane resides at the controller, which populate the forwarding plane in the new components by sending control packets carrying forwarding rules. The controller already has established tunnels with each network component. So, the migration time will be calculated as: how much time will it take to send control packets from the controller to the new substrate components. Let α_j be the distance from the controller to a component c_j, τ be the time spent per hop and b_{ij}^t, where t represents the index of the iteration of migration. Now, we can define our migration distance constraint as:

$$[\sum_{\forall u_i \in U} \{ \sum_{\forall c_j, c_k \in C} ((b_{ij}^t \wedge b_{ik}^{t+1}) \wedge (j \neq k)) \rightarrow \tau * \alpha_k \}] < \omega \tag{13}$$

[2]After each iteration, the counter is decremented by one.



(a) Available Bandwidth Analysis (b) Migration Time (c) Packet Loss during Migration

(d) Bandwidth Analysis in PlanetLab (e) Bandwidth Analysis in Mininet (f) Critical Footprint Size

(g) Critical Footprint Size (%age) (h) Reconnaissance Time (i) Attaker's vs. Defender's View

Fig. 4. These diagrams present the effectiveness and disruptiveness of agility results.

where, b_{ij}^{t+1} represents the assignment of component c_j to pair u_i in the new placement. To quantify this equation, we use calculations from our PlanetLab experiments. In our PlanetLab experiments, we observed the average traceroute probe time to be almost $250ms$ and the average path length observed is almost 10 hops. We use these measures to develop following heuristics. The traceroute time represents a round trip time, so, one way time will be $125ms$. This means it takes almost $13ms$ per hop along the path. Assuming the controller can initiate populating forwarding tables at once for all nodes, then using a more conservative hop time i.e., $\tau = 20ms$ we can calculate the migration distance in Equation 13. We assume that the size of forwarding tables is the same and bandwidth from controller to node will remain the same. Therefore, we do not need to put these as the part of the model as they are not going to change for different controller-node pairs.

VI. Migration Mechanism

The migration mechanism executes VN migration strategy generated by the framework on a virtualized physical network. Given the destination for a particular VN to be moved, it handles all the logistics of the movement including the exact sequence/schedule of the steps to be executed in order to complete the move and the timing of such steps. It is also responsible for interacting with specific substrate and its virtualization technology to accomplish the move. There are two main parts of the mechanism (in Figure 2), (1) the *scheduler* is responsible to determine exact sequence of moves based on the input migration strategy from the agile VN framework while the *configuration manager* implements and executes these steps on the infrastructure like PlanetLab [16]. It reserves resources needed during the migration, sending signals to virtual nodes ordering them to start their moves, keeping track of the health of the migration via monitoring, and requesting dynamic adjustments to the migration schedule if necessary. We have used PlanetLab as our testbed to implement migration mechanism because it offers a unique geographically distributed virtualized infrastructure. Instead of developing the entire mechanism from scratch, we leverage an existing PlanetLab based controller, PL-VNM [17]. This controller offers the core migration functionality and implements single virtual node migration[3]. An abstract level view of our extensions to PL-VNM are briefly described as follows.

A. Implementing VN Placement

We have implemented our VN placement module inside the controller.The controller can perform two key tasks, (1) given a substrate topology of PlanetLab, the controller finds the initial suitable placement, and (2) using the threat model it generates a migration strategy to initiate a threat aware migration.

B. Implementing Threat Model

We have implemented the Crossfire threat model as the part of the controller. For a complete threat simulation, we

[3]Due to limited space, we skip the technical details of our controller extensions and implementation.

designate different PlanetLab nodes (allocated to us) as bots and decoy servers manually. As each node might be located in a different country, there is no way to automating the decoy server selection using geographical coordinates. The threat module instructs these bots to send traceroute probes to each decoy server and collects the path information to identify the critical footprint. Then, the bots are instructed to start sending attack traffic using already configured UDP based iperf.

C. Implementing Partial Migration

The controller was lacking the partial VN migration capability. In the existing implementation, all end users connect to specialized nodes that are called gateways. These gateways were responsible to switch from old substrate to new substrate. This method was used to migrate entire VN from one substrate to another. Our framework requires each node to act as a gateway, as any node can be flagged as critical. Once a node is identified as critical, all of its neighboring nodes must act as gateways to move traffic away from this critical node. We have extended the role of each node to act as a gateway in the controller.

VII. Implementation and Evaluation

We have used PlanetLab, simulation and Mininet-based experiments to perform a rigorous evaluation.

A. Experiment Setup Discussion

1) PlanetLab based Experiment Setup: The experiment topology that we have developed within the PlanetLab is showed in Figure 3. In our experiments, we classify the components into four categories: 1) fixed components, the components that do not change during migration, black ones in the figure; 2) Gateway components, that switch traffic between new and previous components, respectively. These are the yellow components c_6 and c_{17} in the figure; 3) Critical components, that are needed to be changed, these are c_9, c_8 and c_{10} in migration step 1, 2 and 3, respectively; 4) Origin and sink components in the network, e.g., c_1, c_{18} and y_1 are the source, the destination and the decoy server components, respectively.

The same color of bots, components and links in Figure 3 represents that these were active during the same migration iteration. For example, during iteration 1, the component c_9 was selected as critical (only one carrying traffic to the target) and only bots o_1 through o_4 were activated in the attack because these are the only bots sharing critical component c_9 with the destination. Similarly, the path from source c_1 to destination c_{18} was $\{c_3, c_6, c_9, c_{17}\}$ and as the links between c_6 to c_9 and from c_9 to c_{17} were carrying the traffic during iteration 1, they all have the same color. Another pivotal concept observable in this example is that the changing of the critical footprint also changes the association between bots and decoy servers. This means that the adversary has to repeat reconnaissance to learn this new association again.

TABLE I
Migration Overhead

Network Size	Preferential Network		Random Network	
	No. of Rules	No. of MBs	No. of Rules	No. of MBs
100	60000	145.2	90000	217.8
150	90000	217.8	157500	381.15
200	120000	290.4	230000	556.6
600	360000	871.2	750000	1815

TABLE II
Depth of Defense

East Coast	West Coast	Europe
4	5	4

2) Simulation based Experiment Setup: We have used BRITE [37] to generate topologies with random connectivity and power law based preferential connectivity. In each topology, a small fraction of nodes (5%) with least degree are designated as sources and destinations. The shortest paths between these nodes simulate network data plane. First, VN placement module finds different placement, second, threat model finds critical footprint in each placement. We randomly select least degree nodes as bots and near by nodes to destination (based on hop distance) as decoy server for the threat model. We use $Z3$ theorem prover to formulate a constraints satisfaction model [14]. The $Z3$ is a state-of-the art theorem prover from Microsoft Research and it is used to check the satisfiability of logical formulas over one or more theories. We have used a machine with Core i7, 2.4 GHz processor and 8GB RAM to run all the simulation based experiments.

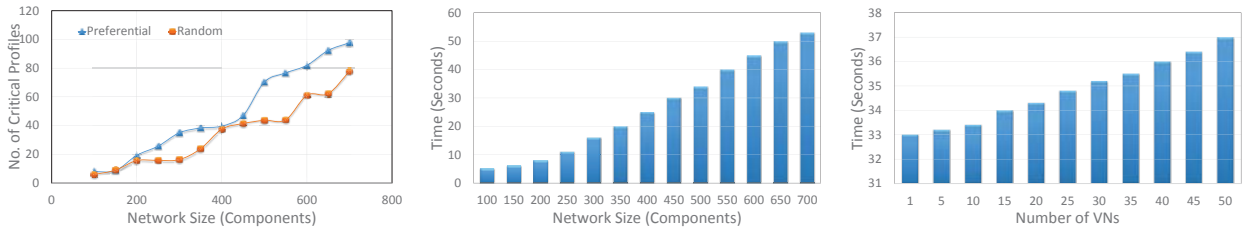
3) Mininet-based Experiment Setup: Mininet-based experiments are used to observe packet loss during the migration. We have used POX as a reference controller for Mininet. We create similar topology as in Figure 3, but without any bots and decoy servers. We have extended the POX controller by adding a switching module for our implementation. We have used the iperf functionality built-in the Mininet to observe packet loss during switching.

B. Agile VN Framework Evaluation

1) Evaluating Depth of Defense: The depth of defense measures the over provisioning available in terms of alternate routes and placements available in the Internet. Alternate route provisioning is measured using PlanetLab experiments and alternate VN placements is calculated by simulation. In our simulation, we let the model calculate all possible placements for each network type and size, and results are showed in Figure 5(a). The results demonstrate that in every network, we always have a decent number of alternate VN placements available, e.g., almost 100 for a network of size 700 nodes, and that increases with the increasing size of the network.

To calculate the depth of defense in terms of alternate routes, we selected three PlanetLab university sites, from East Coast of USA, West Coast of USA and Europe[4]. Then, we select 100

[4]Due to anonymous submission, we are not disclosing this information.



(a) Depth of Defense (b) Time w.r.t. Network Size (c) Time w.r.t. Multiple VNs

Fig. 5. This diagram shows Migration overhead, Framework scalability results.

PlanetLab nodes scattered through the world to send traceroute probes to these university sites. Each probing node sent exactly 6 probes (following same model as in [1]). After extracting the paths from these probes, we calculate alternate routes by simply identifying the minimum number of links that need to be broken to compromise all paths. The results showed in Table II demonstrate that there are always 4 to 5 alternate paths available to each destination. Now, as commercial overlay virtualization providers [11], [12] are in the picture, exhibiting central authority, this over provision will be more because in probing we do not necessarily view all links e.g., backup links.

2) Evaluating the Evasion Effectiveness: In evaluating evasion effectiveness experiment on topology in Figure 3, we calculated link bandwidth between source (c_1) and destination (c_{18}) nodes using TCP based Iperf. It was observed sometimes as 2.0 Mbps and sometimes 1.6 Mbps due to bandwidth limit enforced by PlanetLab, results are showed in Figure 4(a). At around 13^{th} second, the Crossfire attack was launched from bots o_1 through o_4 that crippled the available bandwidth by limiting it to 300 Kbps within seconds. At time 27^{th}, the agility module of the PL-VNM is activated to initiate evasion through migrating to a different path and that instantly restored the bandwidth back to 2.0 Mbps. We let this experiment run for sometimes to calculate the migration time in switching between nodes. The results in Figure 4(b) show that the migration time stayed around 1 to 2 seconds which is way better than the reconnaissance time observed in Figure 4(h). During these experiments we kept the SSH channel open between the controller and the nodes.

3) Evaluating the Disruptiveness of Migration: We design an experiment on PlanetLab using the same topology from Figure 3 to analyze the packet loss caused by the migration. Without any attack, we let the controller keep migrating between nodes in every 2 minutes and we calculated the average bandwidth available in each minute. The cumulative distributed function (CDF) results in Figure 4(c) show only 5% packet loss for almost 85% of the times and higher for just 15% of the times. Further investigation revealed that PlanetLab uses unicast reverse path forwarding. It matches the arriving interface of the packet with the departure interface, if it does not match, it simply drops packets. That is why all in-flight packets were lost every time the migration happens. This is the limitation with PlanetLab architecture and there is nothing that can be done. Therefore, we tested the same migration experiment in a more migration friendly virtualized infrastructure, i.e., Mininet. The combined results in PlanetLab and Mininet experiments, under all possible scenarios, are presented in Figure 4(d) and Figure 4(e), respectively. And the Mininet results in Figure 4(e) clearly show that there is almost no or minimal packet loss observed during migration. This proves that if the network is supportive of the migration then packet loss will not be an issue.

4) Evaluating the Overhead of Migration: Because on PlanetLab such large scale experiments were not possible, we have calculated migration overhead in terms of nodes to be migrated and extra traffic to be generated with simulation. Figure 4(f) and 4(g) demonstrate the overhead results in terms of the size of critical footprint and its percentage w.r.t. the network size respectively, for different networks. We have used both types of networks (preferential and random) to evaluate the critical footprint size. For networks with preferential connectivity, the size of critical profile represents around $5-10\%$ of the network, whereas, for random network this percentage is $9-14\%$. Intuitively, preferential connectivity based networks have a smaller critical footprint than random ones.

The amount of overhead traffic is calculated by multiplying average routing table size, which is 24.4 MB or $10K$ rules [30], with the number of components to be migrated. Results with different network sizes are showed in Table I. For a network of 100 nodes, in both preferential and random networks, overhead traffic size is only 145 MB and 217 MB, respectively. For a large network of the size 600 nodes, it is 871 MB and 1.8 GB for preferential and random networks, respectively. In large networks, this amount of traffic is not significant because of the over provisioning for handling DDoS traffic amounting to hundreds of GB, e.g., in 2014, CloudFair's customer was hit with a massive 400 Gbps DDoS attack [38]. Furthermore, reconnaissance in large networks also takes more time and this helps to reduce the frequency of migration.

5) Benchmarks of Reconnaissance Time: The VN agility is bounded by reconnaissance time, which we calculate through a PlanetLab experiment. In this experiment, we host a web server on one of the USA based university node of PlanetLab and select 10 to 70 decoy server around that university. We use only one PlanetLab node as bot to perform reconnaissance because, in actual Crossfire reconnaissance, each node has to perform same amount of probing. Furthermore, increasing bots will not increase time because of limited probing traffic that can be sent to decoy servers and targets to avoid detection. The results in Figure 4(h) show that even for a small scaled exper-

iment with just 70 decoys, it took us 5 minutes to complete reconnaissance, that provide a big margin to maneuver.

6) Evaluating Attacker's View vs. Defender's View: We use simulation environment, explained in Section VII-A2, to calculate disparity, if any, between the defender's view and the attacker's view of the critical footprint. They both view the same network data plane and decoy server information is publicly available. We start by finding critical footprint sets, firstly, by just using bots (for attacker) and secondly, by just using sources (for defender). Then, we calculate overlapping ratio of two sets. The results in Figure 4(i) clearly show that almost 95% of the time both end up selecting the same critical footprint that coincide the finding of the existing literature [1].

7) Evaluating Scalability: We tested the scalability of our approach in terms of time complexity by varying the size of the networks and number of VNs within a network. The results of varying network size and number of VNs are showed in Figure 5(b) and Figure 5(c) respectively. The time complexity increases linearly with network size and for network of the size 700 components, it is well below one minute. Whereas, it does not change much by just increasing the number of VNs within same network e.g., it changes from 33 seconds to 38 seconds for one VN to 50 VNs in a network of size of 500.

VIII. Conclusion

All DDoS attacks focus only on a small set of critical network components. If we can change the role of these critical components to non-critical ones, we can evade DDoS attacks. Virtual networks provide this flexibility by dynamically assigning and reassigning physical resources to a service. In this paper, we have proposed a correct-by-construction agile VN framework that proactively defended against sophisticated DDoS attacks like Crossfire by actively reassigning the VN to new threat safe physical resources and without breaking the service or violating the VN properties. We have implemented that framework on PlanetLab and our experiments showed the effectiveness of restoring the downgraded bandwidth (80%) due to DDoS attack by migrating to a threat safe placement in just seconds. Furthermore, the existing provision of redundant paths in the Internet, $4 - 5$ as found in our experiments, is enough to defend against large scale DDoS attack.

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