

Analyzing Cooperative Containment of Fast Scanning Worms

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Abstract

Fast scanning worms, that can infect nearly the entire vulnerable population in order of minutes, are among the most serious threats to the Internet today. In this work, we investigate the efficacy of cooperation among Internet firewalls in containing such worms. We first propose a model for firewall-level cooperation and then study the containment in our model of cooperation using analysis and simulation. Our results suggest that, with moderate overhead, cooperation among Internet firewalls can provide 95% containment under 10% deployment while being resilient to 100-1000 malicious firewalls.

1 Introduction

Scanning worms that probe IP addresses to find vulnerable hosts are the most common worms today. Several recent worms, such as Slammer, Witty, CodeRed, and Blaster, fall in this category. Slammer, one of the fastest scanning worms seen so far, took less than 10 minutes to infect 90% of the Internet's vulnerable population [1]. Scanning worms that are more carefully designed using techniques discussed in [2] can accomplish infection even faster. This threat is further exacerbated by the possibility of worms that exploit unknown vulnerabilities. It is clear that automatic mechanisms are required to defend against these worms. Unfortunately, many existing defenses, like patching and address blacklisting, hold out little hope in containing novel fast worms [3].

An emerging approach that offers hope in containing such worms is a decentralized solution in which firewalls in various access networks exchange information amongst themselves to defend against worm attacks. Such a scheme may be easier to deploy compared to end-host based schemes [4–6], schemes that may require support from core routers [7, 8], or schemes that place the burden of analysis on a centralized infrastructure [9, 10]. Recent work [11–14] suggests that such *cooperation* may

contain fast worms, but an understanding of its efficacy and limitations on robustness is still lacking.

In this paper, we aim to fill this void by modeling cooperation in an abstract fashion, and then studying the containment in this model. In our model, the participants in the cooperative are Internet firewalls, each protecting an access network. Each firewall employs *local detection* to detect infection within its network. Once it detects an infection, it notifies other firewalls of the ongoing worm infection. We consider two forms of such notifications: *implicit* and *explicit* signaling. Firewalls that receive these signals are alerted to the worm attack and can then *filter* their incoming traffic based on these signals. Signaling between firewalls is the essence of cooperation, and our model of signaling captures and extends the salient features of existing schemes for cooperation. Moreover, this model integrates various known techniques for local detection [11, 15, 16] and filtering [4, 5, 17] into a framework for cooperation.

Our analytical results based on this model are as follows. First, we show that local detection and filtering without any signaling can contain scanning worms under certain regimes. Second, we characterize the dependence of the containment provided by cooperation on various worm and cooperation parameters. Our results indicate that the containment offered by cooperation drops linearly with the scan rate of the worm and the average time taken by the firewall to detect infection, and drops quadratically with the size of the vulnerable population. Third, our analysis quantifies the trade-off between the containment offered by cooperation and robustness to malicious participants. Our numerical results suggest that, even against the most virulent worm seen so far, cooperation among Internet firewalls can offer over 95% containment under 10% deployment while being resilient to about 100-1000 malicious firewalls.

Although we primarily study Internet-level cooperation among firewalls to contain scanning worms, our analytical approach can be applied to other scenarios as well:

to enterprise-level or Internet-level cooperation, to host-level or firewall-level cooperation, and to a limited extent for analyzing sophisticated worms like hit-list based worms. The downside of our analytical approach however is that there are inherent limitations in any tractable model amenable to analysis. Such a model, by necessity, cannot include all “real-life” details. Our model includes the main factors characterizing a worm attack and we use simulations to incorporate the effect of other factors in our results.

2 Modeling Cooperation

We consider the Internet to consist of N access networks that are connected to their ISPs through an access link. Each network is monitored by a firewall which analyzes traffic on its access link and exchanges information with other firewalls to contain worms. We focus on containment of fast random scanning worms in this work. Such worms perform a local topological scan followed by a global uniform random scan: an infected host first infects all hosts in its network and then probes external IP addresses uniformly at random to find more vulnerable hosts. Note that, in our model, a firewall cannot prevent infection from spreading within its network, since it may not even see local topological scans.

The main goal of cooperation is to maximize the containment metric C , defined as the fraction of vulnerable networks that escape infection during a worm attack. Other desirable features of a cooperative containment scheme include resistance to malicious participants, effectiveness under partial deployment, and scalability (*e.g.*, bandwidth overhead). We now describe our model of cooperation.

2.1 Framework for Cooperation

The main purpose of this framework is to define the design space of cooperation schemes in a simple manner suitable for analysis. Some points in this space correspond to existing schemes [11–13, 18, 19].

We begin by making two assumptions, which we will remove later: (a) all firewalls operate according to our protocol (b) all firewalls in the Internet participate in our cooperative. Firewalls participating in the cooperative perform three functions: local detection, propagation, and filtering.

Local Detection: A firewall uses local detection to determine whether its own network is infected by analyzing *outgoing* traffic. There are two advantages in analyzing outgoing traffic as opposed to analyzing incoming traffic. A firewall can maintain characteristics of its outgoing traffic using per-host state, unlike incoming traffic which

can be noisy due to background Internet traffic. Also, a decision made using incoming traffic can potentially be influenced by external malicious hosts sending traffic to the firewall’s network. However, analyzing outgoing traffic cannot aid a firewall in protecting its *own* network, since the characteristics of outgoing traffic change only *after* its network is infected. We use the term “detected firewall” to denote a firewall whose local detection scheme identifies infection within its network.

One can use existing techniques [5, 11, 15, 20] for local detection. These techniques identify infection by analyzing various characteristics of outgoing traffic, *e.g.*, number of unique destination addresses, connection failure rate, and packet payload.

Propagation: A detected firewall proceeds to notify other firewalls of its infection. These notifications include *filters* for identifying malicious packets. On receiving these notifications, these firewalls are said to be “alerted” to the attack. There are two forms of such notifications: *implicit* and *explicit*.

Implicit Signaling: A detected firewall sends implicit signals by *marking* all suspicious outgoing packets. Suspicious packets are identified using filters inferred by the filtering mechanism. Marking can be done by using bits in packet headers or by encapsulating suspicious packets within special headers. This marking serves two purposes. First, it informs the destination firewall that the packet is possibly malicious. The destination firewall can simply drop such packets or it can process them in a special manner (*e.g.*, send it to a hardened end-host for analysis). Thus, the decision to drop/process is delegated to the destination. Second, the destination firewall is notified that the source network is infected. This enables the destination firewall to install filters before its own network gets infected: this is the essence of cooperation.

Explicit Signaling: A detected firewall sends explicit notifications of its infection to other participating firewalls at some fixed rate E . We only consider schemes where signals are sent to randomly chosen participating firewalls. This naive method can easily be improved by, say, a publish-subscribe based system; however the security properties of such systems are harder to characterize.

In both types of signaling, note that a firewall can report only of its *own* infection; it cannot implicate other firewalls. This rules out *setup* attacks in which malicious firewalls make false accusations. We use a challenge-response protocol to verify that the originator of a signal is the infected firewall itself. Such a protocol also eliminates spoofing attacks by malicious end-hosts.

Filtering: We refer to a firewall that has been alerted by a signal as an *alerted* firewall. Such a firewall installs filters and drops malicious *incoming* traffic matching these filters. These filters are gathered from the sig-

nals it receives. Filtering is also used by a detected firewall during implicit signaling: only outgoing packets identified as malicious by the filter are marked.

A very simple filter could be based on port numbers: any traffic on alerted ports is dropped. More sophisticated filters can be inferred using known techniques, such as Autograph [17] which deduces signatures from packet payloads, and Vigilante [5], TaintCheck [4], which infer signatures by host-based mechanisms to track the flow of network data in a program.

To summarize, in our scheme, every firewall is in one of the following four states: normal, alerted, infected, and detected. Our model can also be extended to the case when multiple worms may be propagating. The filtering mechanism would infer filters for each propagating worm, and firewalls can maintain state and perform propagation on a per-worm basis.

2.2 Security

We now discuss the security of our model against malicious firewalls and evasive worms. First, in a cooperative framework, it is important to distinguish between a global Internet-wide attack and an infection localized to a small set of networks. Thus, if a small number of firewalls report that they have been infected, even if they are being truthful, this attack could simply be a localized one. Thus, a fundamental necessity in the cooperative framework is that a firewall should enter the alerted stage and install filters only if it receives signals from T distinct firewalls. Second, it is also necessary to defend against firewalls attempting to trigger false positives/negatives. Since the alerted state is entered only upon receiving T signals, our scheme can resist up to T malicious firewalls that trigger a false alarm. This design choice is also fundamental since it may be impossible to detect whether a notification sent by a firewall is a false alarm (*e.g.*, if a firewall originates traffic as if its own network had been infected). False negatives occur when a firewall deliberately/otherwise fails to report of its infection. We have also devised schemes to defend against such attacks [21], although we do not discuss them here.

Finally, cooperation should also be resilient to sophisticated worms that attempt to evade propagation (worms that evade local detection and filtering are beyond our scope). A worm could use pre-generated hit-lists [2] to ensure that most of its probes are successful, and also alter its scanning pattern over time to thwart propagation. In the limit, a worm could simply stop scanning after its firewall has entered the detected stage, since beyond this point, all its scans will be marked and cannot infect any new hosts. In this case, implicit signaling is completely ineffective. Explicit signaling will however continue to

perform well. We consider such a worm in Section 4.2.

2.3 Partial Deployment

Under partial deployment, the main limitation of our model is that it is not possible to prevent undeployed networks from getting infected eventually, since infected hosts in undeployed networks can always infect other undeployed networks. This limitation cannot be overcome without support from core routers. We therefore choose our metric for the partial deployment case as the containment among the *deployed* firewalls. As a baseline solution, our existing scheme for propagation works in this case as well. Only deployed firewalls perform detection and propagation: undeployed firewalls do not engage in local detection, propagation, or filtering. We also improved on this scheme using a technique called rerouting discussed in [21]; we omit details due to lack of space.

2.4 Discussion

There are three salient features in our model of cooperation. First, in our model, signals can be *verified* using a challenge-response mechanism. This makes the security properties of our model much easier to characterize as compared to existing work [13, 14]. Second, our model incorporates both forms of signaling, implicit and explicit, whereas existing work has dealt mainly with explicit signaling. There are trade-offs associated with both approaches; implicit signaling has lesser overhead and may be simpler to implement, but explicit signaling is necessary to contain smart worms. Finally, our model integrates the various techniques proposed for local detection and filtering in a framework for cooperation. Decoupling the various mechanisms used in cooperative containment also aids analysis, as will be seen in the following section.

3 Analyzing Cooperation

In this section, we analyze the containment metric C (the fraction of vulnerable networks that escape infection) of our cooperative model under three cases: all firewalls are deployed and operate according to the protocol (Section 3.2, 3.3,3.4), all firewalls are deployed but some of them may be malicious (Section 3.5), and finally under partial deployment (Section 3.6).

3.1 Worm and Network Model

We now introduce the assumptions and the parameters used in our analysis (parameter names are in bold type). In our worm model, an infected host first infects all vulnerable hosts in its own network in *zero* time, and then

proceeds to probe external addresses. The scanning rate of a fast worm is limited by access bandwidth, and hence we use the scanning rate “ s ” of a single *infected network* in our analysis. The probability of a successful probe “ p ” is the number of vulnerable hosts divided by the size of the IP address space. We denote the total number of vulnerable networks as “ N ”. We use the homogeneous cluster model, used for modeling Slammer victims in [1]. This assumes that the vulnerable hosts are uniformly distributed among all vulnerable networks.

For purposes of analysis, we assume that the time taken for an infected firewall to detect its infection is an exponential variable with mean “ t_d ”. This assumption is certainly not true for all local detection schemes, but considerably simplifies the analysis. Thus, our model includes several simplifications, such as the uniform distribution of vulnerable hosts. In the following results, the environment used for simulation exactly matches the one used in analysis, and thus, the simulation only serves as a validation for the analysis. We also simulated environments with non-uniform host distributions and network delays, and obtained similar results (not presented here for lack of space).

3.2 Effectiveness of Detection and Filtering

First, we analyze a simplified variant of our scheme without any propagation under complete deployment. Thus, there is no sharing of information between firewalls. In this variant, a firewall performs only local detection and filtering (once a firewall enters the detected stage, outgoing scans are marked and cannot infect any more hosts). Thus, the defense against a worm attack is that an infected host can effectively probe only until its firewall does not detect infection. The following lemma shows that such a simplified scheme is surprisingly effective under some conditions. We define λ as the expected value of the number of successful infections by an infected network before its firewall detects infection. λ can be written in terms of our parameters as $\lambda = spt_d$. We now state the following lemma without proof (for all proofs, see our technical report [21]).

Lemma 1 *If $(\lambda < 1)$, then as $N \rightarrow \infty$, the containment metric $C \rightarrow 1$. Further, if I_0 denotes the number of infected firewalls at time $t = 0$, for any N , $C \geq 1 - \frac{I_0}{(1-\lambda)N}$.*

Interestingly, the above lemma holds irrespective of the scanning strategy employed by the worm. The condition $\lambda < 1$ can be enforced by deploying firewalls at as fine a granularity as necessary. This can be used to control the effective scanning rate s and thus the parameter λ . Earlier worms like Blaster had low scan rates leading to low values of λ , and could have been controlled by

simple detection and filtering even if the firewalls were deployed at the level of class B networks. Recent worms like Slammer used much higher scan rates and require very fine grain deployment to enforce $\lambda < 1$.

Surprisingly, even if $\lambda > 1$, detection and filtering still provide some containment against a *random scanning* worm, although the effectiveness degrades rapidly with λ . The reason this occurs is that as the infection proceeds, it takes longer for a random scanning worm to find uninfected hosts, and thus the local detection schemes have a greater chance of throttling the infection.

Lemma 2 *If $(\lambda > 1)$, assuming $I_0 \ll N$, $C \geq 1 - \min_{k:k>1} (\frac{(k\lambda-1)(k+1)}{k\lambda(k-1)} - \frac{2*\log(k\lambda)}{(k-1)\lambda})$ against a random scanning worm (k is a variational parameter used in minimization).*

Our analytical results based on the above lemma indicate that detection and filtering provide about 40% containment at $\lambda = 1.5$ and about 20% at $\lambda = 2.0$. We show later that $\lambda = 2.0$ corresponds to the one of the most virulent worms seen so far.

3.3 Effectiveness of Implicit Signaling

In this section, we analyze the containment metric when implicit signaling is used along with detection and filtering under complete deployment. Denote the total number of deployed firewalls as n . We model the infection process as follows. At time t , denote by $n_i(t)$ the number of infected firewalls, by $n_d(t)$ the number of detected firewalls, and by $n_a(t)$ the number of alerted firewalls (the remaining firewalls are in the “normal” state). Note that $n_i(t)$ represents all infected firewalls, so $n_i(t) - n_d(t)$ is the number of infected firewalls that have not yet detected infection. A simple differential equation model for implicit signaling is as follows:

$$\frac{d}{dt}(n_i) = (n_i - n_d) \times s \times \frac{(n - n_i - n_a)}{N} \quad (1)$$

$$\frac{d}{dt}(n_d) = \frac{n_i - n_d}{t_d} \quad (2)$$

$$\frac{d}{dt}(n_a) = n_d \times s \times \frac{(n - n_i - n_a)}{N} \quad (3)$$

The first and third equations count the number of successful scans and alerts per unit time respectively. The second equation is based on the assumption of an exponential distribution for detection: the probability that an infected and undetected network identifies infection during time dt is equal to dt/t_d . We could not solve these equations exactly, so we present a closed-form upper bound:

Lemma 3 *For $\lambda > 1$ and $I_0 \ll N$, with implicit signaling, $C \geq 1 - \frac{(\log(N))t_d\sigma^2}{s} (\frac{1}{t_d\sigma} + 1)$ where $\sigma = (\lambda - 1)/t_d$ and $\lambda = pst_d$.*

By substituting for σ in the region $\lambda > 1$, the above lemma suggests that the containment metric decreases linearly with t_d and s and drops quadratically with p .

3.4 Effectiveness of Explicit Signaling

In the case of explicit signaling at rate E along with implicit signaling, the containment metric can be obtained by simply substituting $s = s + E$ in the denominator of Lemma 3 to obtain $C \geq 1 - \frac{\log(N)t_d\sigma^2}{s+E} \left(\frac{1}{t_d\sigma} + 1\right)$. Notice that the containment metric varies with the rate of explicit signaling as $1/(1 + E/s)$.

3.5 Effectiveness under Threshold T

In this case, a firewall enters the alerted state after receiving alerts from T distinct firewalls. Our differential equation model in Section 3.3 can be extended to model this case by adding $(T + 1)$ differential equations to track the number of firewalls that have received $0, 1, \dots, (T - 1), T$ alerts. This approach is however cumbersome even for low values of T . However, the lower bound on containment metric for the implicit signaling case (Lemma 3) can be applied to obtain:

Lemma 4 For $\lambda > 1$ and $I_0 \ll N$, the containment metric C obtained by implicit signaling is at least $1 - \frac{(\log(N)+(T-1)\log(\log(N)))t_d\sigma^2}{(s+E)} \left(\frac{1}{t_d\sigma} + 1\right)$ where $\sigma = \frac{\lambda-1}{t_d}$.

The main implication of this result is that the containment drops linearly with the threshold T . This quantifies the trade-off between the robustness of cooperation and the containment C .

3.6 Effectiveness under Partial Deployment

The differential equation model in Section 3.3 can be suitably modified by introducing a differential equation for the number of infected undeployed firewalls at time t . Unfortunately, we could not obtain a closed-form analytical bound (as in the complete deployment case). We numerically solve our differential equation model to evaluate cooperation under partial deployment.

4 Numerical Solutions

We now evaluate the containment offered by cooperation against worms of varying virulence and how this containment depends on the various mechanisms used in cooperation. Our results are obtained by two means: (a) numerical integration of the differential equation model (b) discrete-time event simulation to validate the analytical

method (marked ‘‘Sim’’ in our plots). The number of initial infected networks is set to 10 by default, and the simulation is run until all the networks are infected/alerted.

4.1 Default Parameters

In the following results, the default parameters are as follows. We used $p = 0.0005$ corresponding to a vulnerable population of about 2 million, twice that of Blaster, one of the most wide-spread worms. We set the scanning rate s as 20000 (the average scan rate of Slammer [1], one of the fastest worms so far). Thus, these settings correspond to one of the most virulent worms seen yet. The number of firewalls N was set to 100000 based on the number of observed BGP prefixes (obtained from routeviews.org). Thus, every network has an address space of 2^{15} and about 20 vulnerable hosts. Under these settings, the worm takes 0.6 seconds to infect 99% of all vulnerable hosts, assuming no network congestion. We set $t_d = 0.2s$ in our analysis and use implicit signaling for propagation. By default, we assume all networks are deployed. Note that $\lambda = 2$ under these settings, so as per Lemma 2, signaling is necessary for containment under these settings.

4.2 Varying Worm Virulence

We present results corresponding to three axes of worm virulence in order to evaluate the performance of cooperation against known worms and worms of the future.

Number of Vulnerable Hosts: The size of the vulnerable population is a key parameter of worm virulence, and we plotted the containment metric against this parameter in Figure 1(a). The number of vulnerable networks was kept constant, and the vulnerable population size was varied between 2 and 20 million hosts (corresponding to $p = 0.0005 - 0.005$). As suggested by the analysis, there is roughly a quadratic drop in C with p .

Scanning Rate: Figure 1(b) plots the containment metric against the worm scanning rate, since the propagation time of the worm is also influenced by this rate. The containment metric exhibits a slow linear drop with scanning rate of the worm. Since implicit signals are piggybacked on worm scans, faster the worm scanning rate, greater the effective signaling rate as well.

Number of Initial Seeds: Our analytical bounds assume that the set of hosts used to seed the infection is a small subset of the vulnerable population. This assumption may not be true if botnets (networks consisting of already infected zombie hosts) are used to seed a worm attack, given that botnets of up to 50000 hosts have been discovered. At one extreme, if all these hosts are in different networks, our results indicate 48.63% containment. At the other extreme, either all hosts within a net-

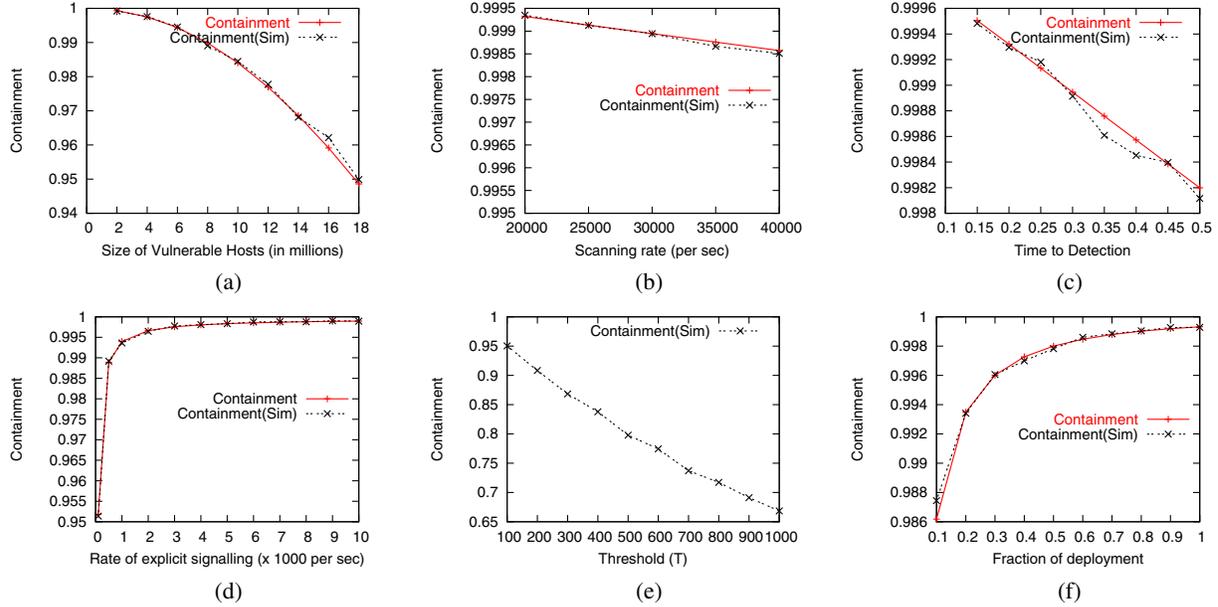


Figure 1: (a) Containment Vs. Size of vulnerable population (b) Containment Vs. Scanning Rate (c) Containment Vs. Time to detection (d) Containment Vs. Rate of Explicit Signaling (e) Containment Vs. Threshold T (f) Containment Vs. Deployment

work belong to the botnet or none of them do. In our settings, each network has 20 vulnerable hosts, which means that 2500 networks are under attacker control. In this case, cooperation provides 96.88% containment.

4.3 Varying Cooperation Parameters

This section presents results illustrating the impact of detection time t_d , signaling parameters (explicit signaling rate E and threshold T), and level of deployment, on containment.

Local Detection: Figure 1(c) illustrates the sensitivity of cooperation to local detection. As suggested by the analysis in the previous section, the dependence is roughly linear. Though the worm propagates in about $0.6s$, even with time to detection t_d as high as $0.5s$, cooperation performs very well. This might appear surprising, but note that $0.5s$ seconds is the *mean* time to detection, and with a finite probability, detection occurs before $0.5s$.

Rate of Explicit Signaling: The rate of explicit signaling corresponds to the overhead of cooperation, and we plotted containment metric obtained through explicit signaling for varying rates E (100-10000) in Figure 1(d). In obtaining this plot, only explicit signaling is used. The containment metric improves with the ratio E although the variation is very low.

Threshold T : Since the security of the scheme is determined by the threshold T (number of alerts required to transition to the alerted state), in Figure 1(e), we varied the threshold T from 100 to 1000 firewalls (0.1% to 1.0%

of the total number of firewalls). Since the differential equation model is cumbersome for threshold $T \gg 1$, we show only the results obtained through simulation. The containment drops by as much as 30%, and clearly T is the most sensitive of all the parameters we have considered so far. This means that in our model, cooperation is resilient to a small fraction of malicious firewalls, but cannot deal with large scale collusion (for example, when the worm infects firewalls).

Level of Deployment: Figure 1(f) shows the containment obtained under various levels of deployment. Cooperation continues to perform well even at deployment levels as low as 10%. The reason is that as soon as a certain fraction of deployed firewalls are infected, the propagation of alerts outpaces the worm scan rate.

5 Related Work

We classify related work into three main categories. The first includes works that analyze traffic at an end-host or a single observation point to detect worm attacks, *e.g.*, Vigilante [5], Throttling [15], TaintCheck [4], Threshold random walks [16, 20], Honeypot-based architectures. Any of these proposals can serve as a local detection scheme in our model (in a firewall or host-based cooperative). In general, host-based mechanisms can detect a wider class of worms, but involve a heavy deployment cost. The second category relies on inferring and deploying filters to contain worms *e.g.*, Autograph [17], Dynamic Quarantine [7]. Filter placement within the Internet core is necessary for most of these schemes. In

contrast, existing mechanisms for inferring filters can be used as filtering mechanisms in our model to achieve good containment without modifying core routers. The final category relates to proposed architectures for worm containment involving multiple vantage points. Architectures, such as [9], perform distributed data collection followed by centralized analysis. Decentralized designs include Hard Perimeters [11], Weaver et al [12], Domino [18]. In [11,12], data collection and analysis are performed by firewalls, while [18] splits these functionalities between satellites and an axis overlay. All participants are implicitly trusted in these proposals. Our model accomodates malicious participants by using simple verification along with a thresholding mechanism. Nojiri et al [13] handles malicious participants, but unlike our model, assumes the existence of apriori trust relationships among firewalls. Anagnostakis et al [14] proposes a signaling protocol very similar to our explicit signaling, but their focus is more on multiple propagating worms as against fast worms. Finally, Staniford et al [22] proposes an analytical model for worm containment, which however does not study cooperative containment.

6 Conclusion

In this work, we have discussed a framework for modeling cooperation in order to conduct a preliminary analysis of its efficacy, resilience and deployability. This framework is intended to be as general as possible, and to capture and extend the notion of cooperation proposed in recent work. The advantage of analyzing a general framework is that our results can be applied to cooperation in a wide-variety of scenarios: at the enterprise-level or Internet-level, at the host-level or firewall-level, and also to a limited extent for analyzing sophisticated worms like hit-list based worms. Our analysis can be used to decide if cooperation is necessary, and if so, can help tune local detection and signaling.

In an Internet-level cooperative of firewalls, our results indicate that cooperation can indeed be an effective solution to containing fast uniform scanning worms, and may also be effective against more sophisticated worms of the future. Cooperation can be made resilient to a small number of malicious participants (100-1000), and even at low levels of deployment (about 10%), effective containment can be achieved. As part of future work, we are working on hybrid protocols that use implicit signaling in the early stages of a worm, and switch to explicit signaling beyond a threshold.

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