Taxonomy and Effectiveness of Worm Defense Strategies

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June 2005
CMU-CS-05-156

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Abstract

While it is important to develop effective worm defense techniques, most previous work has focused on a single point in the design space. The sheer complexity and size of the design space of worm defense requires a more systematic study of the design space.

We give the first systematic investigation of the design space of worm defense system strategies. We accomplish this by providing a taxonomy of defense strategies by abstracting away implementation-dependent and approach-specific details and concentrating on the fundamental properties of each defense category. Our taxonomy and analysis reveals the key parameters for each strategy that determine its effectiveness. We provide a theoretical foundation for understanding how these parameters interact, as well as simulation-based analysis of how these strategies compare as worm defense systems. Finally, we offer recommendations based upon our taxonomy and analysis on which worm defense strategies are most likely to succeed. In particular, we show that a hybrid approach combining Proactive Protection and Reactive Antibody Defense is the most promising approach and can be effective even against the fastest worms such as hitlist worms. Thus, we are the first to demonstrate that it is possible to defend against the fastest worms such as hitlist worms.

Keywords: worms, worm propagation, defense strategy analysis, proactive protection, probabilistic protection, address space randomization, worm blacklisting, worm antibody, worm containment, automatic worm containment

1 Introduction

Internet worms can cause millions of dollars of damage by infecting hundreds of thousands of hosts in a short period of time [25, 16]. As a result, considerable research effort has been spent developing worm defense systems [12, 13, 17, 19, 20, 22, 23]. While most previous work focuses on a single isolated point in the design space of worm defenses, the sheer complexity and size of the design space of worm defense requires a more systematic and global-view approach. A global-view approach assists us in understanding the fundamentals of worm defense, identifying new directions and points in the design space, and developing more effective defense strategies.

Despite the importance, little research has been done in systematically analyzing the design space of worm defense systems. Previous work by Moore et al. [14] and Porras et al. [20] has systematically analyzed more than one point in the design space. Their studies were limited in scope because they analyzed only a few combinations of proposed worm defense techniques. A general and systematic framework that explores the entire worm defense landscape has been an open problem.

In this paper, we provide the first systematic study of the complete worm defense design space. We provide the first taxonomy of worm defense system strategies. Our taxonomy provides an abstract framework and categorizes worm defense strategies based upon fundamental implementation-independent and approach-generic factors. This abstract framework enables us to pinpoint the key factors of each defense category that determines its effectiveness.

We conduct theoretical modeling and analysis as well as simulation evaluations of the effectiveness of each defense category against various worms, including random scanning and hit-list worms. Our analysis reveals the fundamental strengths and weaknesses of each defense category which provide important insight in designing new systems.

Our analysis yields fresh observations that provide new view points to previous beliefs. For example, previous work investigated the limitations of diversity in hosts as a protection measure [21]. Our taxonomy and analysis gives insight into how diversity – an example of our Proactive Protection category – is an important and practical worm defense strategy in many circumstances. In particular, Proactive Protection is extremely important in defending against super-fast worms such as hit-list scanning worms [25] (Section 5 & 6.2).

As another example, rate limiting – an example of our Local Containment category – is an often proposed worm defense solution [26]. From our analysis, we are able to show that any Local Containment strategy is fundamentally limited in any realistic scenario where it is only partially deployed. For example, if $1/2$ of the internet deployed such a strategy, current worms are slowed down by only a factor of 2. Other strategies are likely more practical since they achieve a larger slowdown with a smaller fraction of deployment (Section 5).

Note that in this paper we focus on worm defense mechanisms that reduce the number or the speed at which hosts are infected. Other mechanisms that assist in recovery or cleanup after-the-fact are orthogonal to our goal, and could be used in conjunction with any defense mechanism to reduce the total cost of a worm infection.

Contributions. In this paper, we make the following contributions:

- We provide the first taxonomy of worm defense strategies. This taxonomy allows us to systematically analyze the design space of worm defense, and is useful for abstracting away approach-specific details and investigating the fundamental strengths and weaknesses of the different strategies. Our taxonomy shows each strategy has unique key factors that determine its effectiveness besides the standard false positive and false negative analysis.

- We propose a list of evaluation criteria to guide our analysis and evaluation of each defense category. We then conduct theoretical analysis of the effectiveness of each defense strategy in our taxonomy.

To confirm our theoretical analysis, we conduct simulation evaluations for each strategy category with two real worms (Slammer and CodeRed) as well as theoretical hit-list worms which are among the fastest worms [25]. Our simulation evaluation confirms our theoretical analysis. Our analysis provides the first comparison between overall worm defense strategies.

- We use our results to craft recommendations for which strategies show the most promise. We show that a combination of Proactive Protection and Reactive Antibody Defense is the most effective defense and shows promise even against the fastest worms such as hit-list worms.
- As part of our analysis of the fundamental limits of the defense strategies, we design and investigate a new class of worms, called brute-force worms, that specifically target the weakness of Proactive Protection strategies. We design defense systems capable of defending against brute-force worms (Section 6.1).

Organization We begin by considering the entire worm defense design space, which we divide into a taxonomy of related strategies (Section 2). We then provide a theoretical framework for each defense strategy in the taxonomy for both when employed alone and in combination (Section 3 & 4).

Next, to confirm our theoretical analysis, we perform simulation evaluation for the effectiveness of each category for real-world worms, CodeRed and Slammer, (Section 5), as well as faster worms such as hit-list worms (Section 6). We also develop a new smart worm against Proactive Protection defenses. We analyze the effectiveness of this worm, along with potential defenses (Section 6.1).

Finally, we use the result of our theoretic and simulation modeling to provide recommendations for new worm defense systems (Section 8). The recommendations show that a hybrid approach combining Proactive Protection and Reactive Antibody Defense is the best approach to stop tomorrow's smart worms.

2 Defense Strategies

In this section, we first propose a taxonomy of worm defense strategies. We then propose the evaluation criteria for worm defense strategies. The following sections make use of the taxonomy and evaluation criteria to analyze and compare the different strategy categories.

2.1 Defense Strategy Taxonomy

To systematically analyze the design space of worm defense strategies, we first observe that in order to defend against worm attacks, we can take two fundamentally different approaches: either protect vulnerable machines from incoming worm attacks, or contain a local infection from sending outgoing attacks to spread the worm (which we call Local Containment). Note that most proposed systems fall into the former category which we further divide into proactive defense which is not dependent on any specific worm (which we call Proactive Protection) and reactive defense which needs specific information about the worm outbreak to be effective. We then further divide the reactive defense into two subcategories based on whether the defense uses the information about the content of the traffic (which we call Reactive Antibody Defense) or the sender of the traffic (which we call Reactive Address Blacklisting) (Figure 1). We describe the four categories below:

Strategy 1: Reactive Antibody Defense. In immunology, an antibody is a protein generated in reaction to and acts against a specific antigen. Similarly, a Reactive Antibody Defense strategy automatically generates an inoculation in response to a worm that when applied will protect hosts from infection. An example of

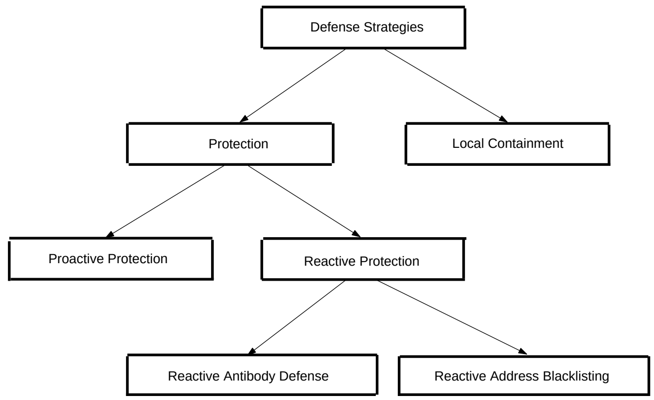


Figure 1: Worm Defense Strategy Taxonomy

such an antibody-based strategy is to automatically generate and deploy content-based signatures [12, 13, 14, 17, 19, 23] to filter out worm traffic. System patching is also a type of antibody [22][1].

Besides the standard false positive rate and false negative rate, a key factor determining the effectiveness of this strategy is the time it takes to create and disseminate the antibody, which we call the *reaction time*, denoted as δ_a. Intuitively, the longer it takes to create and disseminate the antibody, the more hosts a worm can infect.

Strategy 2: Reactive Address Blacklisting. Instead of generating a worm-specific antibody as a defense, another approach is to identify the infected machines and filter out packets from them to protect vulnerable hosts from their attacks. We call the list of host addresses that are infected and who therefore should be blocked [14] the *address blacklist*, and this defense strategy Reactive Address Blacklisting. [2]

Reactive Address Blacklisting differs from the Reactive Antibody Defense approach in that Reactive Address Blacklisting blocks worm infection attempts by recognizing that they are from infected (blacklisted) hosts, where Reactive Antibody Defense blocks worm infection attempts by recognizing that they are malicious packets irrespective of where they come from. While Reactive Antibody Defense is effective against a worm attack irrespective of where it comes from, Reactive Address Blacklisting can only be used to block out attacks from the hosts on the address blacklist (and will not be effective against attacks where address spoofing is possible such as UDP worm attacks). Thus, unlike Reactive Antibody Defense which only needs to create the antibody effective against the worm, the Reactive Address Blacklisting approach needs to identify each infected host as soon as it becomes infected and adds it to the address blacklist.

Similarly to the Reactive Antibody Defense approach, the effectiveness of Reactive Address Blacklisting is determined by the time for creating and installing the appropriate blacklists, which we call the reaction time, δ_b. Note δ_a in Reactive Antibody Defense is the reaction time to create and disseminate an antibody once the worm has started, while δ_b here is the reaction time to put a host on the (global) blacklist after it becomes infected.

Strategy 3: Proactive Protection. Instead of generating antibodies or blacklists reacting to a specific worm or infection attempt, another defense approach is to proactively harden the system to make it difficult for a worm to exploit vulnerabilities and successfully infect the host on any single attempt. We call this category of defense Proactive Protection. There are many different methods for proactively hardening a

[1]Similarly, port filtering could be a type of antibody defense, though most implementations suffer from poor accuracy due to the rough filtering granularity afforded by this method.

[2]We abstract away implementation details by assuming the blacklist is a single global list that is universally updatable.

system, including sandboxing, privilege separation, system call monitoring, etc. For a specific worm attack, a proactive protection mechanism may be completely effective in which case it will protect the vulnerable hosts from the attack (although some protection mechanisms work not by preventing a successful exploit of the vulnerability, but rather by preventing the exploit to do damage to or control the host); or the proactive protection may be only partially effective in which case it can only protect the host sometimes or in some cases. One specific example of the latter case is diversity-based approach, which delays infection of a vulnerable host by increasing the entropy of each individual host such that an internet worm on average needs multiple trials to compromise the host. For example, most exploits in worm attacks require knowledge of specific run-time internal states of the vulnerable host. Various *address-space randomization* techniques have been proposed to randomize run-time memory layout [1, 4, 5, 6, 8, 9, 28], preventing a worm from knowing the correct address a priori for a successful exploit. Other techniques such as pointer encryption [7], instruction set randomization [2, 3, 11, 24], password protection schemes, etc., also fall into this category as they make the system harder to attack by increasing the entropy of information needed for the attack to be successful. Note that the analysis in this paper only applies to the case of probabilistic Proactive Protection such as the diversity-based Proactive Protection.

The amount of entropy directly affects the probability p, called the *protection probability* , of a single worm exploit attempt succeeding in infecting a vulnerable host. Worms attacking hosts implementing Proactive Protection must make about $1/p$ exploit attempts to infect a host. The protection probability is thus the key factor determining the effectiveness of the Proactive Protection approach.

Note that one salient advantage of Proactive Protection is that it is a proactive defense always in place unlike a reactive measure. The defense is not based on any specifics of the vulnerability and does not need any triggered reaction to deploy to the vulnerable hosts. However, the defense only increases the work factor for a worm to successfully infect, and is not full-proof protection. Hence, eventually a long-term fix must be applied for permanent protection.

Strategy 4: Local Containment. A Local Containment strategy focuses on containing a locally infected machine from sending attack traffic to other potentially vulnerable hosts, e.g., filter based upon outgoing connections instead of the previous three approaches which focused on incoming connections. Local Containment strategies thus exemplify a "good neighbor" policy, where more good neighbors result in fewer worm attacks.

Scan rate throttling schemes such [26, 27] are the primary example of Local Containment. The throttle rate reduces the contact rate of current infections, thus slowing down the overall worm propagation speed.

The throttling rate is an important factor for containing the worm propagation speed, however, a more important factor is the deployment rate. As we will show in the next section, the effectiveness of Local Containment is proportional to the fraction of hosts deploying the defense, and consequently requires a very high deployment ratio in order to contain a worm outbreak. Even when deployed on 90% of the hosts and networks, i.e., 90% of the hosts and networks are good neighbors, it will not affect attacks coming from the other 10% of hosts and networks, and thus can only slow down the worm propagation by a factor of 10.

2.2 Evaluation Criteria

A worm defense strategy can be evaluated in two dimensions: how well it contains a worm outbreak vs. how many hosts participant in the defense. Let $N = N_p + N_{np}$ be the total number of vulnerable hosts, where N_p of the vulnerable hosts participate in the defense system (which we call *participating hosts*) and N_{np} do not (which we call *non-participating hosts*). Let $I(t) = I_p(t) + I_{np}(t)$ be the total number of infected hosts at time t, where $I_p(t)$ is the number of participating hosts infected and $I_{np}(t)$ the number of non-participating hosts infected.

Incremental Deployment. It is unrealistic to assume any scheme will be immediately and fully deployed overnight. The deployment ratio $\alpha = \frac{N_p}{N}$ is the number of vulnerable hosts participating in the protection strategy over the total number of vulnerable hosts. All other things being equal, strategies with lower α values are preferable since they require fewer participants to be effective.

Infection Factor. This factor measures the fraction of vulnerable hosts being infected at time t, which measures how well a worm defense system protects hosts from infection, with lower values indicates fewer hosts infected.

Worm defense strategy effectiveness can therefore be measured in two ways:

- **Overall Infection Factor:** The ratio of the number of hosts that are infected at a given time to the total number of vulnerable hosts, e.g., $\frac{I(t)}{N}$. When no hosts are infected the infection factor is 0%, while when all hosts are infected the infection factor is 100%. This is the most common measure of effectiveness.
- **Participation Infection Factor and Non-participation Infection Factor:** In a partial deployment scenario where only some hosts deploy the defense, the hosts and networks that deploy the defense (which we call *participating hosts*) may have a different likelihood of becoming infected than those that do not deploy the defense (which we call *non-participating hosts*). This difference, in fact, can be an important incentive to convince more hosts and networks to deploy the defense. To measure this difference, we propose two new effectiveness measures: the *participation infection factor (PIF)* as the ratio of the number of participating-hosts infected to the total number of participating hosts, e.g., $\frac{I_p(t)}{N_p}$; and the *non-participation infection factor (NPIF)* as the ratio of non-participating hosts infected to the total number of non-participating hosts, e.g., $\frac{I_{np}(t)}{N_{np}}$.
  If a defense approach incurs no difference in the likelihood of being infected between a participating host or a non-participating host, then the participation factor and the non-participation factor will be the same, which gives little incentive for hosts and networks to deploy the defense approach. For example, as our analysis in the next section shows, Local Containment gives no difference between the participation infection factor and the non-participation infection factor. On the other hand, a defense system with positive deployment incentive should give a much lower participation infection factor than the non-participation infection factor, as the case for Reactive Antibody Defense, Reactive Address Blacklisting, and Proactive Protection.

3 Theoretical Analysis of Worm Defense Strategies

In this section, we analyze the effectiveness of the different worm defense strategies in our taxonomy. We first review worm modeling background, and then give our theoretical analysis of the effectiveness of the different worm defense strategies. Our notation is summarized in Table 1.

3.1 Worm Modeling Background

Worm propagation can be well described with the classic Susceptible-Infected epidemic model [10]. The overall rate of new infections is given in this model by:

$$\frac{dI(t)}{dt} = \frac{\beta I(t)(N - I(t))}{N} \tag{1}$$

Equation 1 states the rate of new infections is equal to the product of the number of infected hosts, the average contact rate of each infected host (β), and the fraction of uninfected hosts.

We solve equation 1 for the number of hosts infected at time t ($I(t)$) with C initially infected hosts as:

α	Deployment ratio
β	Vulnerable host contact rate
β_1	Throttle rate
δ_a	Reaction time (Antibody)
δ_b	Reaction time (Blacklist)
p	Protection probability
t	Timestamp
C	# of initial infected hosts = $I(0)$

N	# of all vulnerable hosts
N_p	# of participating vulnerable hosts
N_{np}	# of non-participating vulnerable hosts
$I(t)$	# of hosts infected at time t
$I_p(t)$	# of participating hosts infected at time t
$I_{np}(t)$	# of non-participating hosts infected at time t
$\frac{dI(t)}{dt}$	Rate of new infections
$\frac{d^2I(t)}{dt^2}$	Acceleration of new infections

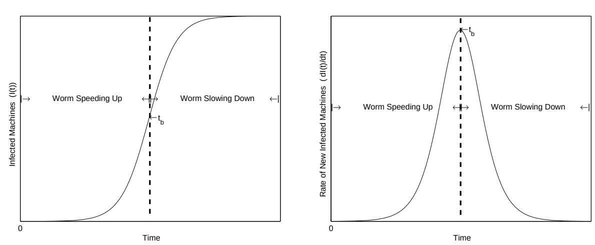
Table 1: Notation and Parameters Used in Our Analysis

$$I(t) = \frac{N}{1 + \frac{e^{-\beta t}(N-C)}{C}} \tag{2}$$

This shows that the worm contact rate β is the important factor for determining its propagation speed. We can also find the acceleration of a worm, given by:

$$\frac{d^2I(t)}{dt^2} = \frac{\beta^2 C e^{t\beta}(C-N)(C+Ce^{t\beta}-N)N}{\left(C(e^{t\beta}-1)+N\right)^3} \tag{3}$$

When a typical worm is first released, it will first undergo an acceleration phase because vulnerable hosts are easy to find. At some point the worm will slow down either because there are few uninfected vulnerable hosts left or the defense scheme makes them harder to infect. We call the point at which a worm begins to slow down the *breaking point* t_b. As shown in Figure 2, t_b is useful because it divides a worm's lifetime into two phases: acceleration and deceleration, and can be calculated as $\frac{d^2I(t)}{dt^2} = 0$. The t_b reference point is useful for many categories because it indicates whether the defense slows down a worm prior to its natural breaking point.



(a) Number of infections over time $I(t)$

(b) *Rate* of new infections over time $\frac{dI(t)}{dt}$

Figure 2: (a) shows infections as a function of time. (b) shows the rate of new infections. As shown, t_b divides the lifetime of a worm into two phases: acceleration and deceleration.

3.2 Effectiveness of Proactive Protection

We first analyze the effectiveness of Proactive Protection with full deployment ($I(t) = I_p(t)$). We can derive the time evolution of the number of infected hosts $I(t)$ with an average contact rate β and protection probability p as below:

$$\frac{dI(t)}{dt} = \frac{p\beta I(t)(N - I(t))}{N} \tag{4}$$

The solution to Equation 4 with C initially infected hosts is:

$$I(t) = \frac{N}{1 + \frac{e^{-p\beta t}(N-C)}{C}} \tag{5}$$

The above analysis shows that Proactive Protection slows down the worm propagation by a factor of $1/p$.

We now consider partial deployment ($I(t) = I_p(t) + I_{np}(t)$) where α fraction of the vulnerable hosts deploy Proactive Protection. We derive the time evolution of the number of infected hosts participating ($I_p(t)$) and not participating ($I_{np}(t)$) as:

$$\frac{dI_p(t)}{dt} = \frac{\beta\alpha p I(t)(N_p - I_p(t))}{N_p} \tag{6}$$

$$\frac{dI_{np}(t)}{dt} = \frac{\beta(1-\alpha)I(t)(N_{np} - I_{np}(t))}{N_{np}} \tag{7}$$

Equation 6 shows the worm infection rate for the α protected hosts is reduced by less than $\frac{1}{p}$ since non-participating infected hosts also contribute to protected host infections.

Since Proactive Protection is a proactive defense, one may wish to calculate the protection probability needed to ensure a given breaking point t_b. We calculate this as follows:

$$\frac{d^2}{dt^2}\left(\frac{N}{1 + \frac{e^{-p\beta t}(N-C)}{C}}\right)\Bigg|_{t=t_b} = 0 \tag{8}$$

By solving Equation 8 for p, we get:

$$p = \frac{ln\frac{N-C}{C}}{\beta t_b} \tag{9}$$

3.3 Effectiveness of Reactive Antibody Defense

We first analyze the effectiveness of Reactive Antibody Defense techniques with full deployment ($I(t) = I_p(t)$). Assuming the reaction time for generating and disseminating the (perfect) antibody is δ_a, we derive the time evolution of $I(t)$ as:

$$\frac{dI(t)}{dt} = \begin{cases} \frac{\beta I(t)(N-I(t))}{N} & \text{when } t \le \delta_a \\ 0 & \text{when } t > \delta_a \end{cases} \tag{10}$$

Equation 10 mirrors the idea that before an antibody is found all hosts are completely unprotected ($t \le \delta_a$), but after antibody is created and disseminated ($t > \delta_a$) no further infections occur. Therefore, antibody strategies should minimize δ_a.

The solution to Equations 10 with C initially infected hosts is:

$$I(t) = \begin{cases} \frac{N}{1+\frac{e^{-\beta t}(N-C)}{C}} & \text{when } t \leq \delta_a \\ \\ \frac{N}{1+\frac{e^{-\beta \delta_a}(N-C)}{C}} & \text{when } t > \delta_a \end{cases} \tag{11}$$

Now we consider partial deployment ($I(t) = I_p(t) + I_{np}(t)$) when α fraction of the vulnerable hosts are protected by Reactive Antibody Defense.

$$\frac{dI_p(t)}{dt} = \begin{cases} \frac{\beta\alpha I(t)(N_p - I_p(t))}{N_p} & \text{when } t \leq \delta_a \\ \\ 0 & \text{when } t > \delta_a \end{cases} \tag{12}$$

$$\frac{dI_{np}(t)}{dt} = \frac{\beta(1-\alpha)I(t)(N_{np} - I_{np}(t))}{N_{np}} \tag{13}$$

The solution to the system of differential equations is:

$$I(t) = \frac{N}{1 + \frac{e^{-\beta t}(N-C)}{C}} \text{when } t \leq \delta_a \tag{14}$$

$$I_p(t) = I_p(\delta_a) \text{ when } t > \delta_a \tag{15}$$

$$I_{np}(t) = \frac{I_p(\delta_a)A}{-1+A} + \frac{N_{np}A}{-1+A} - I_p(\delta_a) \text{ when } t > \delta_a \tag{16}$$

where

$$\begin{aligned} A &= e^{\frac{t\beta I_p(\delta_a)}{N_{np}} + t\beta - \frac{t\beta\alpha I_p(\delta_a)}{N_{np}} - t\beta\alpha - \frac{A_2 I_p(\delta_a)}{N_{np}A_1} - \frac{A_2}{A_1} + \frac{A_2\alpha I_p(\delta_a)}{N_{np}A_1} + \frac{A_2\alpha}{A_1}} \\ A_1 &= -I_p(\delta_a) - N_{np} + \alpha I_p(\delta_a) + \alpha N_{np} \\ A_2 &= -\delta_a\beta I_p(\delta_a) - \delta_a\beta N_{np} + \delta_a\alpha I_p(\delta_a) + \delta_a\alpha N_{np} + N_{np}\ln\left(-\frac{I_p(\delta_a) + I_{np}(\delta_a)}{N_{np} - I_{np}(\delta_a)}\right) \end{aligned}$$

The above analysis shows that given the reaction time δ_a, the deployment ratio has no influence on the protection of participating hosts. Non-participating hosts indirectly benefit from a larger deployment ratio after $t > \delta_a$. The reason is at this point uninfected participating hosts are effectively removed from the vulnerable population, resulting in a slower worm propagation.

3.4 Effectiveness of Reactive Address Blacklisting

We first analyze Reactive Address Blacklisting techniques with full deployment ($I(t) = I_p(t)$). The reaction time δ_b is the time to add a newly infected host to the global blacklist. We derive the time evolution of the number of infected hosts $I(t)$ as:

$$\frac{dI(t)}{dt} = \frac{\beta(I(t) - I(t-\delta_b))(N - I(t))}{N} \tag{17}$$

Now we consider the case when the Reactive Address Blacklisting is deployed to cover α fraction of the vulnerable hosts ($I(t) = I_p(t) + I_{np}(t)$).

$$\frac{dI_p(t)}{dt} = \frac{\beta\alpha(I(t) - I(t-\delta_b))(N_p - I_p(t))}{N_p} \tag{18}$$

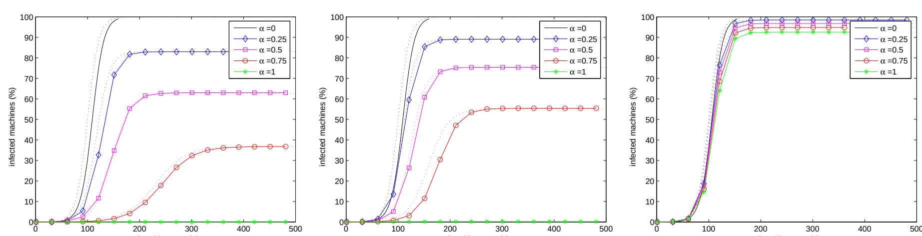
$$\frac{dI_{np}(t)}{dt} = \frac{\beta(1-\alpha)I(t)(N_{np} - I_{np}(t))}{N_{np}} \tag{19}$$

These equations quantify the intuition that a smaller reaction time slows down a worm's propagation.

Here, we briefly discuss the minimum reaction time required for an effective defense. Intuitively, if we can add a newly infected machine to the blacklist before it infects another machine, the Reactive Address Blacklisting defense may stop the exponential worm growth. Within each time unit the infected nodes can contact β vulnerable hosts. Thus, if the reaction time δ_b is faster than $\frac{1}{\beta}$, then the worm propagation to the hosts that deploy the defense can be effectively stopped. We call this threshold $\frac{1}{\beta}$ the *phase transition threshold*. On the other hand, if the reaction time δ_b is slower than $\frac{1}{\beta}$, then the worm propagation cannot be stopped and will eventually infect all the vulnerable hosts. Thus, the requirement for an effective Reactive Address Blacklisting is to ensure

$$\delta_b \leq \frac{1}{\beta} \tag{20}$$

To demonstrate the effect of the phase transition threshold, we depict in Figure 3 the influence of the reaction time on the effectiveness of Reactive Address Blacklisting, obtained from both theoretical analysis and simulation results. Note that the phase transition threshold, $\frac{1}{\beta}$, is about 10 seconds for Slammer. The graphs show that our theoretical analysis (dotted lines) match well our simulation results (solid lines). From the graphs, we can clearly see that the defense is effective when the reaction time is lower than $\frac{1}{\beta}$. In these cases, the number of infected machines for 100% deployment is close to zero. On the other hand, if δ_b is far higher, even 100% deployment of Reactive Address Blacklisting cannot stop the spread of worm.



(a) 5 sec.(S.L) (b) 10 sec.(S.L) (c) 30 sec.(S.L)

Figure 3: *The reaction time for Reactive Address Blacklisting* . We compare the effectiveness of the Reactive Address Blacklisting strategy against Slammer with different reaction times. The experimental data (solid lines) and the theoretical data (dotted lines) match well. When the reaction is low enough, as in (a) and (b), the number of infected machines for 100% deployment is very close to zero.

3.5 Effectiveness of Local Containment

We consider the case where α fraction of vulnerable hosts are covered by a Local Containment mechanism. The full deployment case is easily derived with $\alpha = 1$. Assume the throttling rate is β_1, i.e., an infected hosts covered by the Local Containment mechanism only has an effective contact rate of β_1. Let $\beta_2 = \beta_1\alpha + \beta(1-\alpha)$. Thus the worm propagation model is:

$$\frac{dI(t)}{dt} = \frac{\beta_2 I(t)(N - I(t))}{N} \tag{21}$$

The solution to Equation 21 with C initially infected hosts is:

$$I(t) = \frac{N}{1 + \frac{e^{(-\beta_2 t)}(N-C)}{C}} \tag{22}$$

Note that the best case is where β_1 is close to zero, i.e., $\beta_2 \doteq \beta(1-\alpha)$. Thus, even in the optimal local containment where the infected hosts covered by the Local Containment do not infect any other hosts, this defense approach can still only slow down the worm propagation by a factor of $1/(1-\alpha)$. For example, even if $\alpha = 50\%$, this defense approach can only slow down the worm propagation by a factor of two; and a deployment ratio of 90% can only slow down the worm propagation by a factor of 10.

4 Hybrid Defense Combinations

Defense strategies may be combined to create hybrid defense systems. In this section we analyze the effectiveness of hybrid worm defense systems.

4.1 Effectiveness of Combined Defenses

In this section we provide the theoretic framework for hybrids of two strategies. For brevity, we only give results for a fully deployed hybrid ($I(t) = I_p(t)$). Note the incremental deployment cases can be derived similar to proceeding sections by separating the participating and non-participating populations. The worm propagation models under different hybrid defense strategies, along with a short explanation of the effect, are given by:

- Proactive Protection + Reactive Antibody Defense:

$$\frac{dI(t)}{dt} = \begin{cases} \frac{p\beta I(t)(N-I(t))}{N} & \text{when } t \leq \delta_a \\ 0 & \text{when } t > \delta_a \end{cases} \tag{23}$$

  Proactive Protection slows down the number of hosts infected until the antibody can be created and disseminated.

- Proactive Protection + Reactive Address Blacklisting:

$$\frac{dI(t)}{dt} = \frac{p\beta(I(t) - I(t-\delta_b))(N-I(t))}{N} \tag{24}$$

  Proactive Protection makes it less likely an infected host will successfully infect another host before being added to the blacklist.

- Proactive Protection + Local Containment:

$$\frac{dI(t)}{dt} = \frac{p\beta_2 I(t)(N-I(t))}{N} \tag{25}$$

  Adding Local Containment to Proactive Protection yields the same effect as increasing p with Proactive Protection alone (and similarly for Proactive Protection).

- Reactive Antibody Defense + Reactive Address Blacklisting:

$$\frac{dI(t)}{dt} = \begin{cases} \frac{\beta(I(t)-I(t-\delta_b))(N-I(t))}{N} & \text{when } t \leq \delta_a \\ 0 & \text{when } t > \delta_a \end{cases} \tag{26}$$

  Reactive Address Blacklisting can help slow down the worm propagation before the anti-body can be generated and disseminated.

- Reactive Antibody Defense + Local Containment

$$\frac{dI(t)}{dt} = \begin{cases} \frac{\beta_2 I(t)(N-I(t))}{N} & \text{when } t \leq \delta_a \\ 0 & \text{when } t > \delta_a \end{cases} \tag{27}$$

  Local Containment slows down worm propagation until an antibody can be developed and disseminated.

- Reactive Address Blacklisting + Local Containment:

$$\frac{dI(t)}{dt} = \frac{\beta_2(I(t) - I(t-\delta_b))(N - I(t))}{N} \tag{28}$$

  Local Containment slows down worm propagation until an infected machine can be blacklisted.

4.2 Hybrid Considerations

Proactive Protection is a proactive strategy that can be deployed before a worm is ever released, and as a result is more synergistic when combined with Reactive Address Blacklisting or Reactive Antibody Defense strategies. The resulting hybrid affords hosts protection to a new worms while eventually providing complete protection after a new worm is released.

For example, Newsome and Song [19] proposes a hybrid approach using address space randomization and dynamic taint analysis. The address space randomization slows down a worm propagation on protected hosts, while the dynamic taint analysis is used to craft a signature antibody to filter out a worm.

The Reactive Address Blacklisting + Reactive Antibody Defense hybrid and Proactive Protection + Local Containment are less synergistic and therefore the combination seems less compelling. The analysis, however, may be useful for measurement purposes since the combinations may appear serendipitously, e.g., some sites deploy Reactive Address Blacklisting and some sites deploy Reactive Antibody Defense.

5 Comparison of Defense Strategies – Current Worms

To make the theoretical analysis in the previous sections more concrete, in this section we compare the different strategies for two real-world worms: one based upon CodeRed [16] and the other based upon Slammer [15]. Both CodeRed and Slammer scan hosts picked at random, and are representative of current worms on the internet. We show that the simulated results confirm our theoretical predictions. In the next section we extend our analysis to smarter worms.

5.1 Evaluation Setup

Simulation Setup. Our simulator is an extension of the Warhol Worm simulator [25] where we implemented different defense strategies. Complete connectivity is assumed within a 32-bit address space, with each link having a bandwidth between 14.4kbps and 4.5Mbps. Initial infected nodes, vulnerable nodes, and participant nodes are uniformly distributed.

Unlike in theoretical analysis discussed in Section 3 where a machine starts infecting others right after it is contacted by a worm, our simulation considers the *infection time* in order to make it more realistic. Infection time is the time taken to transfer a worm code from a machine to another. It depends on the bandwidth and the size of worm code. Due to the existence of infection time in our simulation, the worm propagation will be a little slower than that in theory.

CodeRed and Slammer Worms. The CodeRed worm, released in 2001, infected almost 360,000 Internet hosts over fourteen hours by exploiting a bug in the Microsoft IIS web server [16]. The Slammer worm, released in 2002, infected about 100,000 hosts within ten minutes by exploiting bugs in the Microsoft SQL server and the MSDE 2002 server [15]. We use CodeRed as an example of a worm with a modest contact rate (0.0005 hosts/sec) and Slammer as an example of a fast contact rate (0.093 hosts/sec), each of which employs random scanning to find vulnerable hosts [3]. Note that these contact rates are calculated from the data in [16, 15]. The sizes of worm code are also different. CodeRed TCP/IP packet is about 4kB while Slammer uses only 404 bytes.

Parameter Setup. In order to give a more concrete feeling to the analysis, we pick some concrete parameters to conduct simulation evaluations. In all our experiments unless otherwise noted, we use the following parameters. Although in the remaining sections we note when results may be drastically different with different parameter choices, the reader should always bear in mind the specific results provided are a result of the specific parameter values chosen.

In our simulations, for Proactive Protection, we choose the protection probability $p = 2^{-16}$ as in [21]. For the Reactive Antibody Defense strategy, we use two reaction time values to mimic the scan rate difference between CodeRed and Slammer: $\delta_a = 2$ hours for CodeRed and $\delta_a = 1$ minute for Slammer. Similarly, for Reactive Address Blacklisting, we set reaction time $\delta_b = 20$ minutes for CodeRed and $\delta_b = 30$ seconds for Slammer. For Local Containment, we set the throttling rate $\beta_1 = 1$ host/second.

5.2 Partial Deployment Strategy Comparison

Figure 4 shows the effectiveness of the four strategies – Proactive Protection, Reactive Antibody Defense, Reactive Address Blacklisting, and Local Containment– for defending against a CodeRed (a-d) and Slammer (e-h) outbreak. Each graph shows the evolution of the infected host population based upon 5 different incremental deployment (α) values: 0%, 25%, 50%, 75%, and 100%. The simulation results (solid lines in the graph) confirm our theoretical formulas (dotted lines).

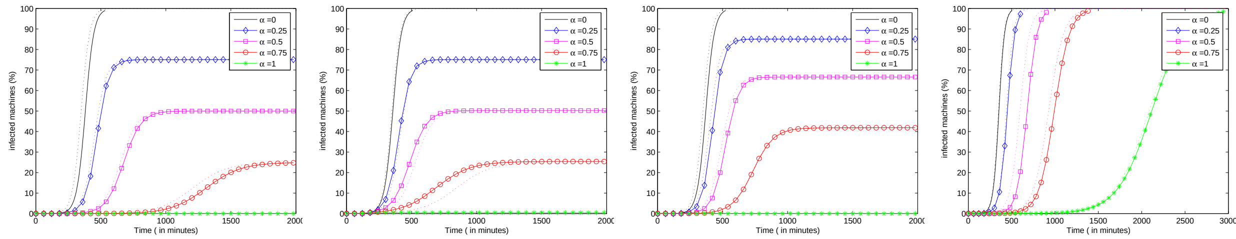
We see that under the simulation parameter, with Proactive Protection, Reactive Antibody Defense and Reactive Address Blacklisting, very few participating hosts are infected in the measured time period even with a small incremental deployment factor α. Note in the Proactive Protection scheme the slope is slightly increasing, and eventually after a long time all hosts will be infected. We also see that increasing α for Proactive Protection and Reactive Antibody Defense significantly decreases the total infected population. Local Containment only slows down the worm propagation.

5.3 Overall vs. Participation Infection Factor Analysis

In order to understand how participation influences the infection factors, we evaluate both participation infection factor (PIF) and non-participation factor (NPIF) (as defined in Section 2) for two different deployment ratios: 25% and 75%. Figure 5 shows the result of our theoretical analysis and simulation results for each strategy.

With the CodeRed worm (Figure 5 a-d), participants of Reactive Antibody Defense are completely protected and Proactive Protection participants are protected within the time period measured (there is a very slight upward slope in the graph that would continue to 100% with Proactive Protection), while all non-participants all become infected. These results demonstrate a strong motivation for hosts to participate in such strategies when possible. Reactive Address Blacklisting does an adequate job protecting participants, with about 40% infected. Everyone in a Local Containment strategy is infected within the time period measured, with no noticeable benefit for participants.

[3] Note that the contact rate $\beta = \frac{N}{2^{32}}$*scan rate.

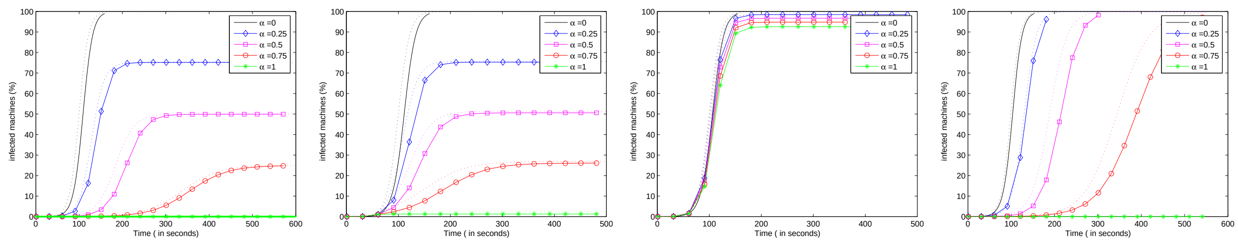


(a) Proactive Protection (C.R)

(b) Reactive Antibody Defense (C.R)

(c) Reactive Address Blacklisting (C.R)

(d) Local Containment (C.R)



(e) Proactive Protection (S.L)

(f) Reactive Antibody Defense (S.L)

(g) Reactive Address Blacklisting (S.L)

(h) Local Containment (S.L)

Figure 4: *Partial Deployment* Our simulation (solid lines) and theoretical (dotted lines) results for CodeRed (top) and Slammer (bottom) random scanning worms for each defense strategy. Each graph shows the infected host percentage over time for five different incremental deployment ratios (α). The theoretic predictions and experimental results match well.

The Slammer worm results (Figure 5 e-h) are similar to CodeRed for the Proactive Protection, Reactive Antibody Defense, and Reactive Address Blacklisting strategies. Local Containment participants do noticeably worse as the scan rate is much faster than the reaction time for adding hosts to the blacklist.

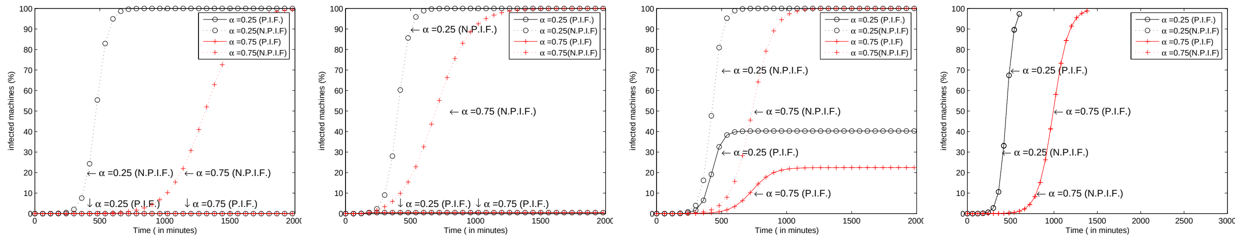
6 Comparison of Defense Strategies – Tomorrow's Smart Worms

In this section we investigate smart worms that may appear in the future. We first design a new kind of smart worm that targets Proactive Protection schemes, and analyze a proposed defense. We then use the same parameters as Section 5, except we change the worm to use a hit-list instead of random scanning. A hit-list worm knows *a priori* which hosts are vulnerable and does not waste time scanning non-vulnerable hosts [25].

6.1 Brute-force worms

Our analysis so far has indicated Proactive Protection is an effective defense strategy. However, Proactive Protection is vulnerable to a brute force attack in which a worm repeatedly attempts infection until a protected host is infected. If Proactive Protection were deployed tomorrow, we should expect worms to take advantage of this weakness.

We call worms that repeatedly attempt infection until success *brute-force worms*. With a uniform protection factor p, a brute-force worm will need to make about $\frac{1}{p}$ infection attempts before succeeding. Figure 6(a) shows the Proactive Protection defense against a normal Slammer worm outbreak, while Figure 6(b) shows the effectiveness against a brute-force Slammer worm.

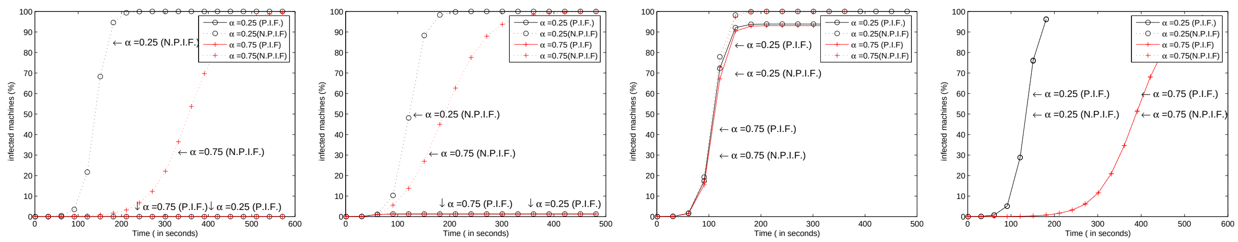


(a) Proactive Protection (C.R)

(b) Reactive Antibody Defense (C.R)

(c) Reactive Address Blacklisting (C.R)

(d) Local Containment (C.R)



(e) Proactive Protection (S.L)

(f) Reactive Antibody Defense (S.L)

(g) Reactive Address Blacklisting (S.L)

(h) Local Containment (S.L)

Figure 5: *Infection Factor* Figures a-f show both the non-participation infection factor (NPIF) and participation infection factor (PIF) for CodeRed and Slammer random scanning worms.

We can make a brute force worm smarter by allowing all worms to share a global list of discovered vulnerable hosts. We call such a worm a *Collaborative Brute-force Worm*. Figure 6(c) shows the effectiveness of Proactive Protection against a collaborative brute-force worm.

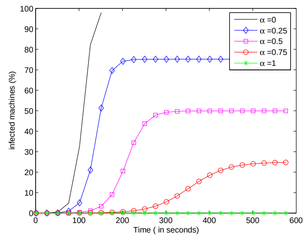
Hardened Proactive Protection. We create a Hardened Proactive Protection to combat brute-force and collaborative brute-force worms by augmenting each participating host a connection counter which is incremented on each failed infection attempt from a host. When the counter exceeds a *sensitivity threshold* R, the participating host no longer accepts new connections from that host.

We can derive the time evolution $I(t)$ for Hardened Proactive Protection with full deployment against the brute-force worm as:

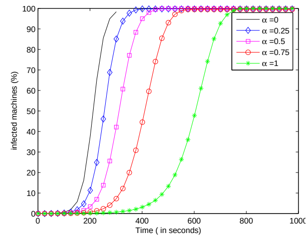
$$\frac{dI(t)}{dt} = \frac{\beta R p I(t)(N - I(t))}{N} \tag{29}$$

Figure 7 shows the effect of different sensitivity threshold values for the Hardened Proactive Protection against the brute-force Slammer worm. For all R values the number of infections over the first 500 seconds is about the same. After that, we see that smaller R values, i.e., the defense allows fewer failed infection attempts from a host, results in a slower growth rate. Note that for a brute-force worm using hit-lists, the defense result will be the same as shown in Figure 8 (a) & (e).

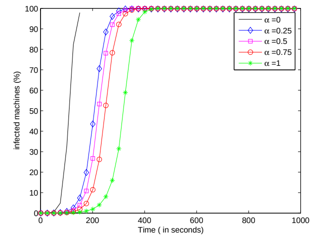
Figure 6(d-e) shows the result of Hardened Proactive Protection with $R = 10$ against a brute-force and collaborative brute-force Slammer worm. Note this worm uses fast scanning, and coordinates via a master global list of yet uninfected vulnerable hosts. Our results indicate Hardened Proactive Protection is effective even against such smart worms.



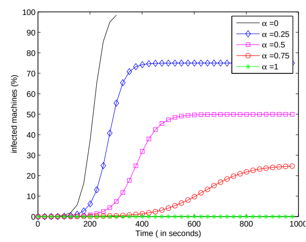
(a) Slammer vs. Proactive Protection



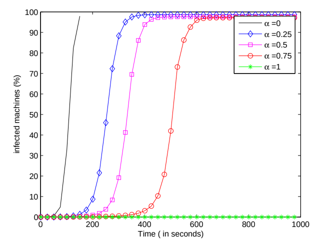
(b) Brute force worm vs. Proactive Protection



(c) Collaborative Brute force worm vs. Proactive Protection



(d) Brute force worm vs. Hardened Proactive Protection



(e) Collaborative Brute force worm vs. Hardened Proactive Protection

Figure 6: (a) shows the Slammer worm outbreak is controlled by Proactive Protection as in Section 4. (b) is a brute-force Slammer worm, which Proactive Protection can no longer control. (c) is a collaborative brute-force Slammer worm, which is even faster than the normal brute-force worm. (d) and (e) shows the hardened Proactive Protection strategy can control even the brute-force Slammer worm.

6.2 Hit-list Brute-force Worms

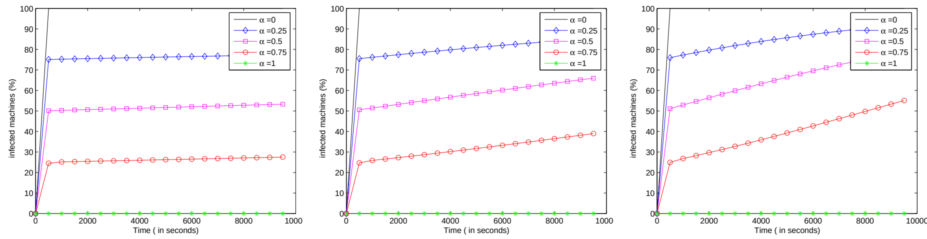
We analyze the effectiveness of each strategy against brute-force worms using a hit-list instead of random scanning. A hit-list worm knows all vulnerable hosts *a priori* and only scans those hosts appearing on the hit-list. Since infection is only attempted on vulnerable hosts, hit-list worms are one of the hardest to control [25]. Note that we combine the hit-list worm with the collaborative brute-force worm described in section 6.1 to make an even more aggressive worm against Proactive Protection.

Individual defense. Figure 8 shows the effectiveness of each individual strategy against a hit-list version of the brute-force Slammer and brute-force CodeRed worms, i.e., we use the same scanning rate as the Slammer and CodeRed worms except that all scan attempts in the hit-list version will reach vulnerable hosts.

Reactive Antibody Defense and Reactive Address Blacklisting strategies have little effect for both hit-list worms because the infection rate is faster than the reaction time values (δ_a and δ_b) we picked.

Due to the fast propagation speed of hit-list worms, implementations of these two strategies are not likely to provide fast enough reaction time to be effective against hit-list worms. Local Containment is also ineffective overall.

In this experiment, Proactive Protection clearly does the best job at controlling both worms. With CodeRed, Proactive Protection controls the worm with even small deployment factors for the time period measured (note there is a slight upward slope that would continue until 100% were infected), and further maintains a near-zero percent infection with 100% deployment for the entire time period measured. With Slammer, Proactive Protection delays infection for hosts much more substantially than the other defense



(a) R = 10 (b) R = 50 (c) R = 100

Figure 7: Effect of the sensitivity threshold on hardened Proactive Protection

approaches.

Hybrid defense. Figure 9 presents brute-force Slammer worm using hit-list scanning for Proactive Protection hybrid defenses. To see the influence of the synergy, we change the reaction time of Reactive Antibody Defense (δ_a) to be 30 seconds, instead of the previous 60 seconds. The reaction time of Reactive Address Blacklisting (δ_b) remains 30 seconds. We do not show other defenses because the exact graph is too dependent on the specific parameter choices to be meaningful.

The Proactive Protection + Reactive Antibody Defense hybrid provides the best protection of the considered schemes for both total effectiveness and largest gain as the partial deployment factor α increases. The kinks in the graph (e.g., at $t = 30$ where α = 0.25, 0.5, and 0.75) show where Reactive Antibody Defense takes over from Proactive Protection. Proactive Protection + Reactive Address Blacklisting performance is not terrible in either respect, though clearly secondary. The smoother graph for Proactive Protection + Local Containment is indicative of the trade-off between p and the scan rate threshold β_2 as discussed in Section 4.

7 Related Work

Moore et al. [14] is the most closely related work comparing defense systems. They analyze how the reaction time for content filtering and address blacklisting influences the number of infected machines. Their conclusion that reaction time is key for content filtering and blacklisting concurs with our results. Porras et. al. analyze a hybrid approach that combines rate limiting and "friends" [20]. Their results show that hybrid strategies do yield substantial improvements. Our work provides a more complete setting, along with more general theoretic and simulation results.

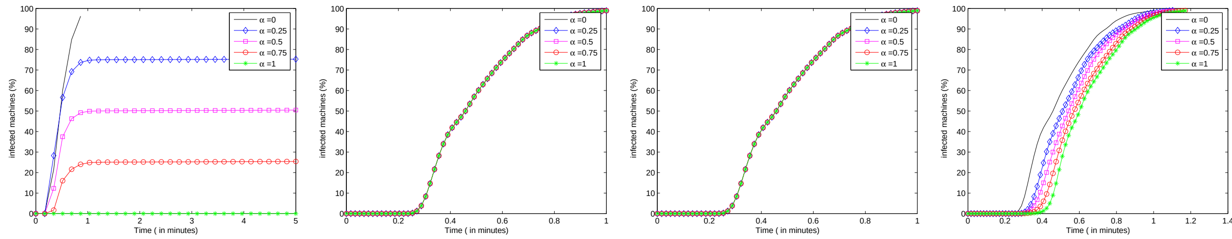
Many people have proposed systems for automatically creating content filters [12, 13, 14, 17, 19, 23]. This line of work can benefit from our theoretical analysis.

Address space randomization as been proposed by [1, 4, 6, 8, 9, 28]. Shacham et al. show the overall security of address randomization is suspect as a complete defense mechanism [21]. Our results, however, show address randomization can be an effective tool because it can slow down extremely fast spreading worms such as hit-list worms.

Zou models worm scan strategies using similar susceptible-infected models [29, 30]. Different worm scanning strategies can be plugged in to our taxonomy.

8 Conclusion and Recommendations

We provide the first systematic study of worm defense systems. We created a taxonomy consisting of four strategies: Proactive Protection, Reactive Antibody Defense, Reactive Address Blacklisting, Local Contain-

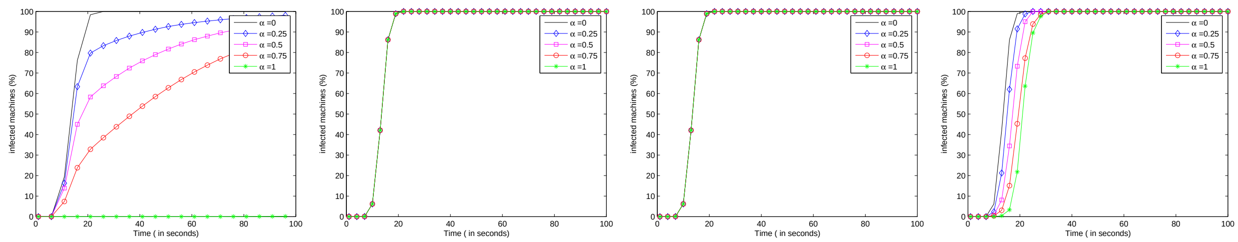


(a) Proactive Protection (C.R H.L.)

(b) Reactive Antibody Defense (C.R H.L.)

(c) Reactive Address Blacklisting (C.R H.L.)

(d) Local Containment (C.R H.L.)



(e) Proactive Protection (S.L H.L.)

(f) Reactive Antibody Defense (S.L H.L.)

(g) Reactive Address Blacklisting (S.L H.L.)

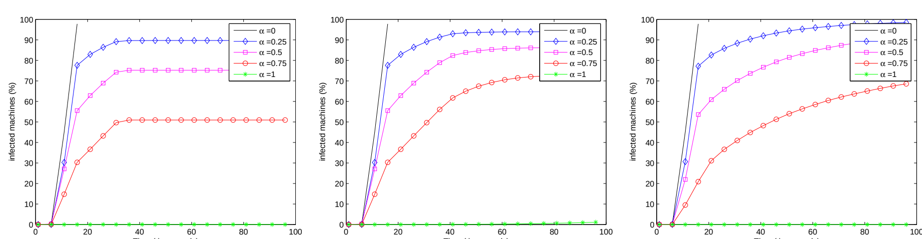
(h) Local Containment (S.L H.L.)

Figure 8: Effectiveness evaluation against the hit-list worms

ment. Our taxonomy reveals for each strategy the key factors that determine its effectiveness, and we provide theoretical analysis and simulation-based evaluation of the effectiveness of each defense category.

Our analysis also shows that the effectiveness of Local Containment requires very high deployment ratio. Even if half of the internet deploys the defense, it can only slow down the worm propagation by a factor of two. Thus, even though Local Containment may be a near-term approach in mitigating worm attacks to a limited extend, it is not likely to be a long-term promising approach as it does not provide the right deployment incentive and not strong defense.

Our analysis also shows that the effectiveness of Reactive Address Blacklisting is based on its reaction time to be short. However, since each newly infected host needs to be put onto the (global) blacklist quickly after it became infected, this offers a severe challenge to defend again fast-propagating worms. Thus, this



(a) Proactive Protection & Reactive Antibody Defense

(b) Proactive Protection & Reactive Address Blacklisting

(c) Proactive Protection & Local Containment

Figure 9: Hybrid defense against a Slammer worm using hit-list scanning with $\delta_a = \delta_b = 30$ seconds.

defense may be useful for slow-propagating worms, but is unlikely to be useful for fast-propagating worms.

Our analysis indicates a hybrid approach of Proactive Protection + Reactive Antibody Defense holds the most promise for protecting against new ultra-fast smart worms. For example, TaintCheck [19, 18] proposes using this hybrid combination. This hybrid is synergistic because Proactive Protection is a proactive, worm-agnostic defense that can be deployed before an outbreak, while Reactive Antibody Defense provides an eventual permanent fix once a worm is released.

Acknowledgement

The authors would like to thank Vern Paxson for his valuable discussion. The authors would like to thank Nicholas Weaver for providing his source code of his simulator to enable us to build our own simulator for the defense strategies described in this paper.

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