Research on Defensive Strategy Selection in Network Security

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Abstract

Security analysis and attack-defense modeling are effective method to identify the vulnerabilities of information systems for proactive defense. The attack graph model reflects only attack actions and system state changes, without considering the perspective of the defenders. To assess the network information system and comprehensively show attack and defense strategies and theirs cost, a defense graph model is proposed. Compared with the attack graph, the model makes some improvements. Defense graph will be mapped to the attack and defense game model, in order to provide a basis for active defense policy decision. What's more, a generation algorithm of defense graph is proposed. A representative example is provided to illustrate our models and generation algorithm.

Keywords: *Network Security, Active Defense, Attack-Defense Game Model*

1. Introduction

Existing computer network information systems are deployed on multiple platforms [1-3], run numerous application software and support plentiful linkage patterns. Inevitably there will have some security vulnerabilities and faults. Network attacks tend to be diversified and integrated [4-5]. Due to limitations of resources and capability, network administrator can't eliminate drawbacks and defends all attacks neither. Network information security defenders always feel at loss and get in dilemma between information security investment and the best defense [6-18]. How to strike balance between information security risk and investment is a problem which needs consider defense cost effectiveness, making the most appropriate decisions with limited resources to reach "moderate security". That is a matter of selecting the optimal network security defense measures. Existing security model lacks description of the dynamic gaming between attack and defense, which can't reflect accurately the dynamic interaction and status evolution between attacker and defender in the system [19-28].

Here we talk about the complication of selecting the best defending strategies for network security. It defines formally the problem of choosing the best defensive strategies for network security, which are described with mathematical function [29-40]. Then, it gives the construction and solving method of selection function. Markov decision process has been successfully applied to search the optimal strategy by single intelligent agent under multiple states. Because of that, we can combine matrix type offensive and defensive game model and Markov decision process to get a random attack-defense game model which can be used to search dynamically the optimal attack-defense strategy by such a few rational intelligent agents under many offensive and defensive states. Random gaming [41-48] can be regarded as a state machine making game system shift from one status to the other with combined efforts of all players. Likewise, network system can be regarded as a state machine, which makes system change its status with co-action of offensive and defensive on target conflicts. The objective of attacker is to destroy the security attribute of network system. Defender prevents attacker from impairing secure

attributes. System state change is not certain, moving from one state to another in a probability manner. Hence it's reasonable to depict network offence and defense conflict problem with random game model. In the static offense and defense game model, two sides search the best offensive and defensive strategy with static model in single state circumstances, no consideration of the dynamic state evolution or transition of offense and defense status. In this case, we propose random offensive and defensive game model which portrays the dynamic variations of network security offense and defense conflict and can solve the problem of selecting the best prevention strategy. The network attack and defense sides are modeled as a 2-person non-cooperative attack and defense random game model. It describes formalized definition and constituting elements of the model. Use attacker's privilege state on network entity components as element of offense and defense random game model; model the dynamic changes of network attack and defense states and predict attack behaviors and decide the best defending strategy. Next it presents the best defense strategy selection algorithm based on random offense and defense game model. Through discussion of network instances, we demonstrate the model and algorithm both work effectively on attack strategy prediction and optimal active defense [49-50].

2. Formalized Description of the Optimal Defense Strategy Selection

In network security management, the defender is perplexed by the defense strategy selection problem. What is the optimal defense strategy? A defensive strategy can reduce attack risk and loss but meanwhile defense cost is increased. How to weigh them and how to get the optimal defense strategy? The selection of strategy not only considers the cost and also network asset criticality and potential attack. For single attack, the defense decision needs choose a strategy which realizes the minimum defense cost; for multi-step and multiple attacks, some defending strategy is workable for one attack action but not for others. On that regard, we need consider the effectiveness of defense strategy for specific attack and the operation cost and negative influences. Besides, the happening probability of every attack strategy is unknown. How to guarantee defense tactics being the optimal and expected integrated defending cost being the lowest is a too complicated issue.

Based on above analysis, we can define the optimal defense strategy selection problem as one function: $f_{selection} = (C, A, D, G) \rightarrow D'$; where each element is defined as follows:

C: entity component collection of protected network information system; entity component $c \in C$ can be host, router, firewall; each entity component is composed of part or more of software, hardware, data and service, *e.g.* Web server which runs HTTP service.

A: information aggregation of possible attack, happening attack and on the way. For network entity component $c \in C$, c has vulnerability which may be utilized by attacker; so it's required to recognize possible attack, occurrent attack and incoming attack $a \in A$ as to protect C.

D: collection of defending strategies taken by defensive system, *e.g.* attack against Ftp Buffer overflow vulnerability; defending strategy $d=(\text{close Ftp service})$, $d \in D$.

G: collection of offensive and defensive game models, such as matrix type offensive and defensive game model, random attack and defense game model AD SG introduced in next part, choose different game model according to specific network offensive and defensive situation.

D' : collection of optimal defending tactics taken by defense system, $D' \subseteq D$

$f_{selection}$ is mapping from network security situation (C, A, D, G) to the optimal defense strategy D' . For any i, j , if $(C_i, A_i, D_i, G_i) \rightarrow D'_i$, $(C_j, A_j, D_j, G_j) \rightarrow D'_j$, if $(C_i, A_i, D_i, G_i) = (C_j, A_j, D_j, G_j)$ then definitely $D'_i = D'_j$. Give network information

system entity component collection C; determine attack information aggregation A through vulnerability analysis and invasion detection mechanism; analyze A and C and determine defending strategy collection D; choose suitable attack and defense game model G as per network attack-defense and requirement; with relative information about A, C, and D, construct the offense and defense game model G.

3. Offense and Defense Random Game Model

In this part we introduce matrix type offensive and defensive game model and Markov decision-making process. Markov decision process has been successfully used to search the optimal strategy by single intelligent agent under multiple states. By combining matrix type offense and defense game model and Markov decision-making process, we can have the random offense and defense game model used to dynamically find the best attack-defense strategy by many rational attack-defense intelligent agents in multiple offense and defense states.

3.1. Matrix Type Attack-Defense Game

Matrix type Attack-Defense Game (ADG) is a three tuple $ADG=(N,S,U)$, where,

1. $N=(P_1, P_2, \dots, P_n)$ is a set of players in the game of attack-defense. Participants are the main body of decision making and policy makers.
2. $S=(S_1, S_2, \dots, S_n)$ is a set of strategies for the attack-defense. $\forall i \in n, S_i \neq \emptyset$. $S_i=(S_1^i, S_2^i, \dots, S_m^i)$ is the strategy set of offense and defense P_i .
3. $U=(U_1, U_2, \dots, U_n)$ is a collection of the revenue function of the attack-defense. $\forall i \in n, U_i$ is the function of the offensive and defensive P_i .

3.2 Markov Decision-Making Process

Markov decision-making process is a dynamically optimized method built in the Markov process. Markov decision-making process has the basic thinking: transfer the state change of system to a Markov process to deal with; for every state in Markov process, decision-maker can take different actions according to various states and decision actions; decision-maker can gain certain revenue, which can be negative, meaning it suffers a loss. Markov decision process aims to find a strategy through which a proper decision action is taken in different states to make the ultimate benefit maximum or minimum. Markov decision process (MDP) [51] is a tetrad (S, A, T, R) ; S is state collection; A is system behavior collection; T is state transition function and R is revenue function. Mark R as profit value gained by system shifting state s to s' with the use of action a ; mark T as probability of system moving state s to s' with the use of action a .

3.3 Attack-Defense Random Game Model

We extend single state of matrix type attack-defense. game model to multiple states and single intelligent agent in Markov decision-making process to many. By combining the two, we give out attack-defense random game model, defined as follows:

Definition: Attack-defense random game model (ADRG) is a 7 tuple $ADRG=(N, S, A, D, P, U_a, U_d)$, where,

$N=\{A_{attacker}, D_{defender}\}$ is collection of players joining offense and defense game. If the number of attacker is ≥ 2 , it means distributive collaborative attack; if the number of defending system is ≥ 2 , it means collaborative protection by several defending system. Here we study when $n=2$, one attacker and one defender. Merge a couple of attackers and defenders and they can be seen as single attacker and defender.

$S = (S_1, S_2, \dots, S_n)$ A is an attack-defense random game state set.

$A = (a_1, a_2, \dots, a_M)$ is an attacker action set. An attacker in the game state S_k attack action set $A_k \subset A$

$D = (d_1, d_2, \dots, d_N)$ A is a set of defensive actions. The defender in the game state S_k protective action set $D_k \subset D$

$P: S \times A \times D \times S \rightarrow [0,1]$ is the state transition probability function of the attack-defense random game.

$U_k: S \times A \times D \times S \rightarrow R, k = a, d$ is a set of utility function.

The benefit relationship between attacker and defender includes zero-sum and nonzero-sum. Choose zero sum or non-zero sum game model based on different network environment and attack-defense situation. In the course of network attack-defense game, the relationship between attacker and defender decides that either party won't notify the other of any strategy decision or they reach agreement. The relationship is always non-cooperative and antagonistic. Therefore the above model is a non-cooperative attack-defense. random game model. Markov decision making process is single intelligent agent's multi-state model; matrix type attack-defense. game model is single-state model of multiple intelligent agents.

3.4. Attack-defense. Random Game State

We look network security state as attack-defense. random game state collection. Network security state describes network entity components' hardware and software resource attribute, connectivity, and user or attacker's ability to access the whole network. Security state change is caused by attack-defense. action pair (a_i, d_j) , in the form of file modification, system configuration variation, executable program running, attacker's privilege elevation *etc.* attack-defense random game state can be represented by a directed graph $G = (S, E)$, where S is graph's point set; each point represents a game state; E is collection of edges, meaning the transition relation of attack-defense. game state. Figure 1 illustrates game state and the transition relation by citing example of state graph which contains three game states $S = (S_1, S_2, S_3)$. In Figure1, state can mutually transit; but in some specific network environments, not all states can mutually transit. In it, $p_{ij}(a_i, d_j)$ marking between different states means the transitional possibility of game state changing from state i to state j under the action of attack-defense. strategy pair (a_i, d_j) .

Figure 1. Example of ADRG's state

4. Defense Strategy Selection Algorithm based on Attack-Defense Random Game Model

Given (C, A, D, G) , where $G = ADRG = (N, S, A, D, P, U_a, U_d)$. Because there are many states in the game of attack-defense. Shapley iterative method can be used to solve the value $v = (v_1, v_2, \dots, v_k)$ of offensive and defensive random game and its optimal attack-defense strategy. Defense strategy selection algorithm based on attack-defense random game model is as shown:

Algorithm1. Defense strategy selection algorithm based on attack-defense random game model

Input: $(C, A, D, G), \delta$
Output: Optimal attack-defense strategy $\pi^{a*}, \pi^{d*} = D'$

1. By C, A, D to build a random game of attack-defense $G=ADSG$
2. Arbitrary initial vector $v^0 = (v^0(1), v^0(2), \dots, v^0(K))$
3. Repeat
4. For every game state $S \in S_k$ do
5. For all s_{ij}^k do
6. With v_l instead of s_l
7. End for
8. Calculation $v_k^{r+1} = Val(u_{ij}^k + \sum_{l=1}^K p_{ij}^{kl}(a_i, d_j)v_l^r)$
9. End for
10. For every game state $S \in S_k$ do
11. $v_k \leftarrow Val(S_k)$
12. End for
13. Until $|v_k^{r+1} - v_k^r| < \delta, \forall S \in S_k$
14. For every game state $S \in S_k$ do
15. $(\pi_k^a, \pi_k^d) = Slove(S_k)$
16. End for
17. Return $\pi^{a*} = (\pi_k^a), \pi^{d*} = (\pi_k^d)$

5. Experimental Analysis and Results

5.1. Network Topology Structure

Assuming that there is a typical network topology, the attack host is located in the external network, it is shown in Figure2. The protected network information system entity component set $C = \{\text{Attacker Host, Smtip Server, Ftp Server, Data Server}\}$.

Figure 2. Topology of Example Network

The firewall separates the target network from external network, the firewall rules and the connection information are shown in Table 1. Target system vulnerability information is shown in table 2.

Table 1. Connectivity in Example Network

Source	Destination	Service	Action
All	Smtip Server	Ftp, Smtip	Allow
All	Ftp Server	Ftp, Ssh	Allow
Smtip Server	Database	Oracle	Allow
Ftp Server	Data Server	Oracle	Allow

Table2 Vulnerability in servers

Host	Vulnerability	CVE ID	Effect
Smtip Server	Ftp .rhost	2011-0547	User privilege
Ftp Server	Ftp .rhost	2011-0547	User privilege
	Sshd Buffer overflow	2013-2421	User privilege
Data Server	Oracle TNS Listener	2012-0965	User privilege

5.2 Description of Attack-Defense Random Game State

Attacker's offense and control of the network are manifested in the control of network entity components, *i.e.* the acquisition of privilege by the attacker for entity components. We now introduce by expressing network security state as accessing ability of attacker to each network entity component, *i.e.* privilege; and network security state as attack-defense. random game state collection. Attack action leads to change of network security state, *i.e.* the state change of attacker's privilege for each component. Generally, we can define attacker's privilege state collection per actual network system environment. Here attacker's privilege state includes: no privilege, remote access privilege, local user privilege, and root privilege, which from low to high is no privilege<remote access privilege<local user privilege<root privilege.

Assume attacker has root privilege to invade host and launch attack but can't implement simultaneously multiple attack actions, with acquiring root privilege of Data Server as its goal. According to firewall rules, in Smtip Server and Ftp Server, attacker has the lowest remote access privilege and unable to access data server. However vulnerability exists in various components and they're dependent, attacker can utilize associated weakness to make multi-step attack and elevate privilege to get root privilege of Data Server, as described hereunder: in state S_1 , attacker has root privilege to assault host; it can utilize respective vulnerability of Smtip Server and Ftp Server to launch Ftp.rhosts attach and obtain the local user privilege to arrive in state S_2, S_3 . Since they're connected with Data Server, attacker uses them as springboard to employ Oracle TNS Listener's weak point to get Data Server's root privilege and reach state S_5 . Besides, attacker can use Ftp Server's weakness Sshd Buffer overflow to make attack to get

privilege of Ftp Server to reach state S_4 ; then, with the connection with Data Server, attacker utilizes Oracle TNS Listener's loophole to get root privilege of Data Server to reach state S_5 . The directed graph $G=(S, E)$ is shown for attack-defense random game model. It is shown in Figure3. Game state $S = (S_1, S_2, S_3, S_4, S_5)$, each state is described as shown in Table 3.

Figure 3. Attack-Defense Random Game State Graph

Table 3. Description of Random Game State

State	Description
S_1	Root privilege on Attacker Host
S_2	User privilege on Ftp Server
S_3	User privilege on SmtP Server
S_4	User privilege on Ftp Server
S_5	Root privilege on Data Server

5.3 Optimal Defense Strategy Selection

With algorithm 1, we can solve out the state value of each attack-defense random game and the best attack-defense strategy, the value of each matrix type game model S_i is calculated by Gambit method; finally the optimal attack-defense strategy is:

$$\pi^{a*} = (\pi_1^{a*}, \pi_2^{a*}, \pi_3^{a*}, \pi_4^{a*}), \pi^{d*} = (\pi_1^{d*}, \pi_2^{d*}, \pi_3^{d*}, \pi_4^{d*})$$

In game state S_1 , attacker takes the best offensive strategy: choose attack action a_1 in the probability 0.3; choose attack action a_2 in the probability 0.27; choose action a_3 in the probability 0.43. In this state from the perspective of attacker, attack action a_1, a_2, a_3 works basically the same to the whole attack process, no big difference between cost and gain. For a_3 , the expectant revenue is high, so it's highly possible to take action a_3 . For defender, the best defending tactics is: choose defensive action d_1 in the probability 0.39, d_4 in 0.47 and d_6 in 0.14. In the game state S_2, S_3, S_4 , both take pure strategy, which conforms to the actual attack-defense situation. For attacker, in game state S_2, S_3, S_4 , there are only two options: attack or non-attack. Only the attack action is taken, can attacker achieve it purpose. So attacker makes attack in the probability 1. For defender, also in the state mentioned above, d_8 can yield the biggest revenue; therefore defender

chooses it in the probability 1. The expected return value of each game state is shown in table 4.

Table 4. Expected Payoff of Game State

Game state	S_1	S_2	S_3	S_4	S_5
Payoff of Attacker	364.5	64	64	64	40
Payoff of Defender	-364.5	-64	-64	-64	-40

Figure 4 and Figure5 describe the attack and defense strategy of the two sides in the game state S_1 probability change process. Gradually convergence tends to stable strategy to achieve the offensive and defensive Nash equilibrium.

Figure 4. Probability of Attack Strategies in S_1

Figure 5. Probability of Defense Strategies in S_1

According to significances of Nash equilibrium in game theory, only defender sticks to its own Nash equilibrium strategy, may the system be impaired to the minimum extent during attack. The Nash strategy is obtained by analysis method of attack-defense. random game model provides solution to defender for active defense by selecting the

optimal defending tactics. In actual application, security preventive measures can be taken based on network environment, security requirement and investment for security. If security prevention investment resource is limited, Nash equilibrium strategy is option. Moreover, properly increase defending investment to prevent all attack strategies as to reinforce network information system security.

6. Conclusion

In view of the complexity of network security optimal defense strategy selection, the formal definition of network security is the most selection of optimal defense strategy. In this paper, the static matrix model and the Markov decision process are extended, and the formal definition of a random game model is presented. The model can describe the dynamic change of network security attack and defense, in order to find the best offensive and defensive strategy for both offensive and defensive states. The experimental results show that the proposed model and algorithm are effective in attack strategy prediction and optimal active defense.

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