Conditional Probability Voting Algorithm Based on Heterogeneity of Mimic Defense System

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About the paper

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Abstract

1. In recent years network attacks have been increasing rapidly, and it is difficult to defend against these attacks, especially attacks at unknown vulnerabilities or backdoors.
2. As a novel method, Mimic defense architecture has been proposed to solve these cyberspace security problems by using the principle of dynamic heterogeneous redundant variants.
3. Choosing appropriate variants and voting algorithm according to heterogeneities of these variants become the key issue of designing mimic defense architecture.
4. This paper analyzes the system failure probability and scalability of 3 different voting algorithms- MHA, MVA, CPVA, and decide which one is the best.

Variants

Mimic defense system can be considered a restrict version of N-variant systems, because it adopts the basic idea of running multiple variants of the same program in parallel.

1. Variants are usually composed of a series of components, such as CPU, operating system, middleware, application, etc.
2. Each component is composed of several modules. For example, the application can be divided into module 1, module 2,. . ., module M, etc.
3. A module is atomic, and its implementations are different from each other.
4. Each variant can be represented by a module implementation vector $z^i = ({g_1}^i {g_2}^i ... {g_N}^i)$, where N is the number of modules contained in a variant and each module may have several implementations.

Variants

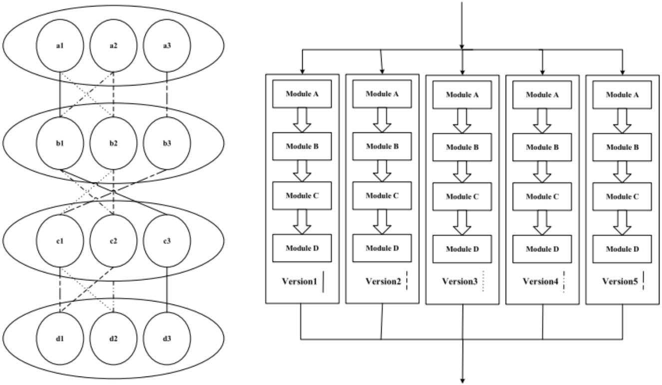


Figure: A typical mimic defense instance

Variants

The mimic defense system shown in above figure can be described by a matrix as shown below.

$$\begin{pmatrix} z^1 \\ z^2 \\ z^3 \\ z^4 \\ z^5 \end{pmatrix} = \begin{pmatrix} a_1 & b_1 & c_3 & d_3 \\ a_2 & b_2 & c_2 & d_1 \\ a_1 & b_2 & c_1 & d_2 \\ a_2 & b_1 & c_2 & d_2 \\ a_3 & b_3 & c_1 & d_1 \end{pmatrix}$$

Heterogeneous Variants

1. Mimic defense system requires the variants to be heterogeneous to each other, not just applications, but also including CPU, OS, middleware and so on.
2. For a large system which is common in mimic defense system, it is hard to realize totally heterogeneous.

There are mainly three kinds of algorithms to choose variants:

1. maximum heterogeneous algorithm (MHA)
2. optimal mean distance algorithm (OMDA)
3. random seeds scheduling method

Heterogeneous Variants

2-level similarity

Suppose there are three variants (1, 2, 3), the 2-level similarities are referred to the similarities for 1&2,1&3,2&3. The sum of similarities is lower, the system is considered to be safer.

1. As the number of working variants grows, 2-level similarity become less important.
2. Heterogeneity will reach max when there are 3 variants in the mimic system, and the heterogeneity will drop as variants number increase more than 3.

Classic Model

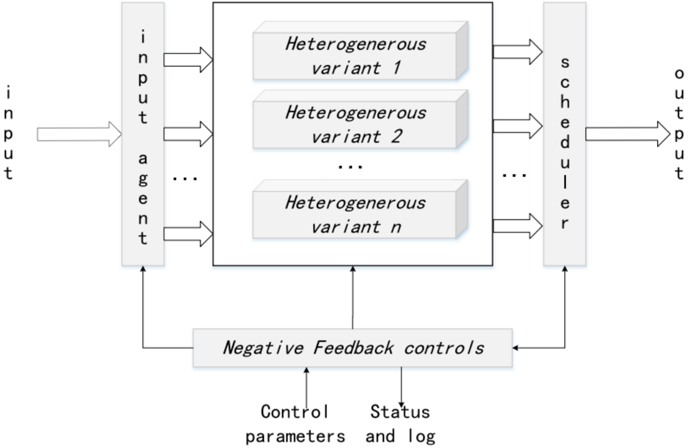


Figure: Classic model of mimic defense architecture

Assumptions

1. Input agent, Scheduler, and Feedback controller are safe from network attacks.
2. Each vulnerability/backdoor of the system have the same probability being attacked.
3. When the high-level vulnerability/backdoor is attacked, the variants who share the vulnerability will generate the same output.
4. Only one vulnerability / back door can be attacked at a time, and the attacked variant will be cleaned in a short time.

The probability of successfully attacking each module is β_i , which should satisfy $\sum_i \sum_{\psi_i} \beta_i = 1$, ψ_i is the number of implementations for module i.

Binary Division Vectors

Module diversity ψ_i

The implementation number of the module g_i, which can be calculated by formula $|\bigcup_i {g_k}^i|$. Implementation set is $(a_1 a_1 a_1 a_2 a_3)^T$, then union the contents and get the set $\{a_1 a_2 a_3\}$, which contain 3 elements, so the diversity of module a is 3.

Binary division vector ${\eta_i}^k$

1. In a module, divide the same implementations into one group and other implementations into another group, and use a vector to represent. Assign corresponding values in the vector of the same implementations to 1 and others to 0.
2. For example, the implementation of g_1 is $(a_1 a_1 a_1 a_2 a_3)^T$, then there are 3 binary division vectors for module g_1, the binary division vector of a_2 is $(00010)^T$, a_3 is $(00001)^T$, a_1 is $(11100)^T$.

Binary Division Vectors

Complement binary division vector $\sim\eta_i^k$

which is reversing every element in the binary division vector. Based on the binary division vector $(11100)^T$ of module implementation a_1, reverse all the elements in it, and its complement vector will be $(00011)^T$.

Isomorphic number of binary division vector $\lambda_i{}^k$

The number of elements whose value is equal to 1. There are three 1 in the binary division vector of module implementation a_1, which is $(11100)^T$, then there are three a_1, and Isomorphic number of $(11100)^T$ is 3.

Maximum heterogeneous algorithm

1. It is based on 2-level similarity.
2. *system failure probability* $= \frac{\textit{no. of similarities}}{\textit{no. of vulnerabilities}}$.
3. $$\begin{pmatrix} z^1 \\ z^2 \\ z^3 \\ z^4 \\ z^5 \end{pmatrix} = \begin{pmatrix} a_1 & b_1 & c_3 & d_3 \\ a_2 & b_2 & c_2 & d_1 \\ a_1 & b_2 & c_1 & d_2 \\ a_2 & b_1 & c_2 & d_2 \\ a_3 & b_3 & c_1 & d_1 \end{pmatrix}$$
4. system failure probability $= \frac{0+1+1+0+1+2+1+1+1+0}{9} = \frac{8}{12} = \frac{3}{4}$

Important Property

1. If there are T executions in the mimic defense system, there will be atleast 1 implementation whose isomorphic number is not less than $\left\lfloor \frac{T+1}{2} \right\rfloor$.
2. In order to reduce the failure probability of mimic defense system, add different implementation of a module or balance the same implementation of a module so that its maximum implementation is less than $\left\lfloor \frac{T+1}{2} \right\rfloor$.

Majority voting algorithm

1. Divide the variants by their results, put variants with the same result into a group G_k . According to the hypothesis only one vulnerability/backdoor is attacked at a time, so there are usually 2 groups, suppose they are G_1 and G_2.
2. If $|G_1| > |G_2|$, then select the result of G1 as the final output; otherwise, select the result of G2 as the final output.
3. Clean the variants which have been arbitrated to be abnormal.

Majority voting algorithm

1. V_g = NULL
2. for i = 1: N
3. for k = 1: ψ_i
4. If($\lambda_i{}^k \geq \lfloor \frac{T+1}{2} \rfloor$)
5. add i in V_g
6. endfor
7. endfor
8. msum = 0
9. for each index in U_g
10. msum = msum + β_k
11. endfor

Conditional probability voting algorithm

1. The variants which generated the same results are divided into one group G_k , generally there are only two groups, assumed as G_1 and G_2.
2. If there is the same implementation of one module in both G_1 and $G2$, the same module implementation in the G_1 and G_2 need to be removed, then we can get two eliminated sets G_1' and G_2', that is $(z^i - \bigcap\limits_{j \subset G_2} z^j)$ and $(z^i - \bigcap\limits_{j \subset G_1} z^j)$.
3. If there are multiple implementations of one module in G_1' or G_2', we use intersection to eliminate different module implementations, we can get two eliminated sets G_1'' and G_2'', that is $\bigcap\limits_{i \subset G_1} (z^i - \bigcap\limits_{j \subset G_2} z^j)$ and $\bigcap\limits_{i \subset G_2} (z^i - \bigcap\limits_{j \subset G_1} z^j)$.

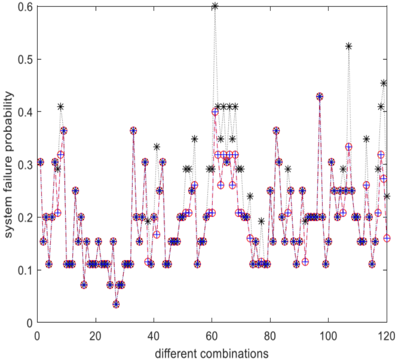
Conditional probability voting algorithm

4. Calculation β_{G_1} and β_{G_2}, $\beta_{G_1} = \sum_k \beta_k$, if k $\in \bigcap\limits_{i \subset G_1} (z^i - \bigcap\limits_{j \subset G_2} z^j)$, $\beta_{G_2} = \sum_k \beta_k$, if k $\in \bigcap\limits_{i \subset G_2} (z^i - \bigcap\limits_{j \subset G_1} z^j)$.
5. If $\beta_{G_1} > \beta_{G_2}$, the result of G_2 shall be used, otherwise, the result of G_1 shall be used.
6. Clean the abnormal variants which have generated wrong result.

Conditional probability voting algorithm

1. G_u = NULL
2. for i = 1: N
3. for k = 1: ψ_i
4. if($\lambda_i{}^k \geq \lfloor \frac{T+1}{2} \rfloor$)
5. G_u = union(G_u,$\eta_i{}^k$)
6. endif
7. endfor
8. endfor
9. csum = 0
10. $G_L = G_S$ = NULL
11. for each vctorl in G_u
12. for i = 1: N
13. for k = 1: ψ_i
14. if(vctorl == $\eta_i{}^k$)
15. add i in G_L
16. else if($\sim$vctorl==η_i^k)
17. add i in G_S
18. endif
19. endfor
20. endfor
21. lsum = ssum = 0
22. for each k in G_L
23. lsum = lsum + β_k
24. endfor
25. for each k in G_S
26. ssum = ssum + β_k
27. endfor
28. if *lsum* < *ssum*
29. csum = csum + lsum
30. else
31. csum = csum + ssum
32. endif
33. endfor

Results for 3-variants experiment



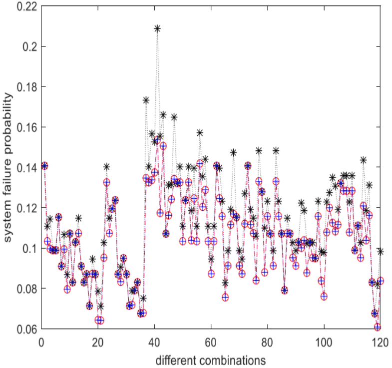


Figure: System failure probabilities of MHA, MVA and CPVA when N=10 M=5 and N=100 M=10

Results for 5-variants experiment

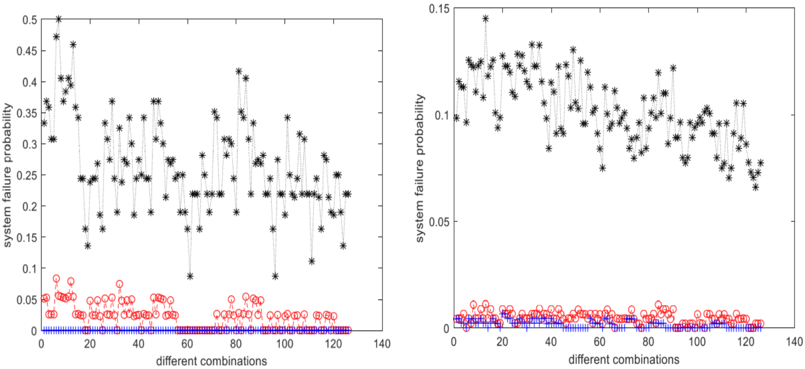


Figure: System failure probabilities of MHA, MVA and CPVA when N=10 M=10 and N=100 M=10

Results for scalability experiment

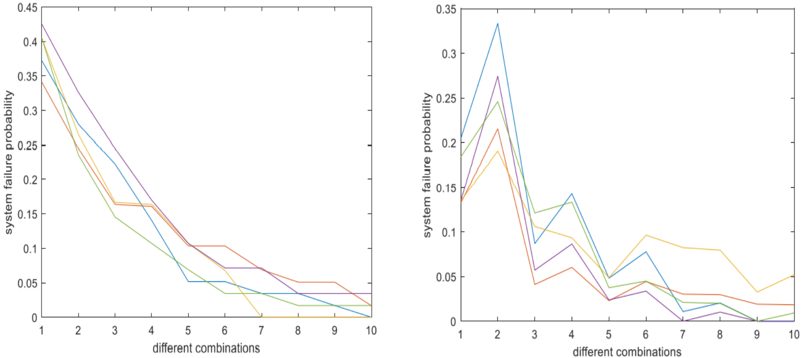


Figure: System failure probabilities of CPVA and MVA with variants increase

Performance analysis

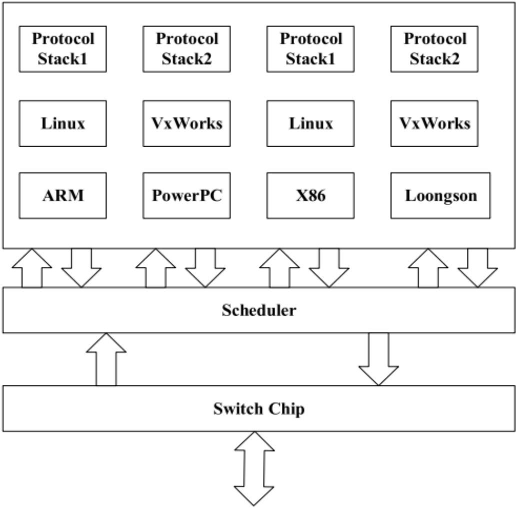


Figure: Mimic defense architecture for control panel of ethernet switch.