First Step Towards Automatic Correction of Firewall Policy Faults

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What do we do here?

- Most firewall policies are poorly configured and contain faults. [Wool 2004 & 2010]
  - A coworker may mess up your firewall rules
  - Any modification may introduce firewall faults.

- We invent methods for fixing firewall policies automatically.
  - We first model 5 types of faults.
  - For each type of faults, we develop an algorithm to fix them.
  - Given a faulty firewall policy, we propose a systematic method to fix the faults automatically using the 5 algorithms.
Roadmap

- **Background**
  - Firewalls
  - Firewall Policies
  - Firewall Policy Faults

- **Technical Challenges**

- **Fault model of firewall policies**
  - Five types of faults

- **Problem formalization**

- **Our solution**

- **Experimental results**
Background – Firewalls

- A firewall checks all outgoing and incoming packets
- The firewall policy decides whether to accept or discard a packet
A firewall policy is usually specified as a sequence of rules.

Each rule consists of a predicate and a decision.

- A predicate typically includes five fields: source IP, destination IP, source port, destination port, protocol type.
- Typical decisions are accept and discard.

### Firewall Policy

<table>
<thead>
<tr>
<th>Src IP</th>
<th>Dst IP</th>
<th>Src Port</th>
<th>Dst Port</th>
<th>Protocol</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2.3.*</td>
<td>192.168.1.1</td>
<td>*</td>
<td>25</td>
<td>TCP</td>
<td>Accept</td>
</tr>
<tr>
<td>r1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.3.9</td>
<td>192.168.1.1</td>
<td>*</td>
<td>25</td>
<td>*</td>
<td>Discard</td>
</tr>
<tr>
<td>r2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Discard</td>
</tr>
<tr>
<td>r3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Packet

<table>
<thead>
<tr>
<th>Src IP</th>
<th>Dst IP</th>
<th>Src Port</th>
<th>Dst Port</th>
<th>Protocol</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2.3.5</td>
<td>192.168.1.1</td>
<td>78</td>
<td>25</td>
<td>TCP</td>
<td></td>
</tr>
</tbody>
</table>

### Conflict Resolution: first-match
Background – Firewall Policy Faults

- Most firewall policies are poorly configured and contain faults. [Wool 2004 & 2010]
- It is dangerous to have faults in a firewall policy. A policy fault
  - either allows malicious traffic to sneak into the private network
  - or blocks legitimate traffic and disrupts normal business processes
- A faulty policy evaluates some packets to unexpected decisions.
  - Such packets are called misclassified packets of a faulty firewall policy
- Manually locating and correcting firewall faults are impractical.
  - A firewall may consist of thousands of rules
- Automatically correcting firewall faults is an important problem.
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- Technical Challenges

- Fault model of firewall policies
  - Five types of faults

- Problem formalization

- Our solution

- Experimental results
Three Key Technical Challenges

- It is difficult to determine the number of policy faults and the type of each fault.
  - A set of misclassified packets can be caused by different types of faults and different number of faults.

- It is difficult to correct a firewall fault.
  - A firewall policy may consists of a large number of rules.
  - Each rule has a predicate over multi-dimensional fields.

- It is difficult to correct a fault without introducing other faults
  - Due to the first match, correcting faults in a firewall rule affects the functionally of all the subsequent rules.
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We propose a fault model that includes five types of faults:

1. **Wrong order:** the order of firewall rules is wrong.
   
   ![Example Rule 1](image)
   ![Example Rule 2](image)
   
   **Correction technique:** Order Fixing

2. **Missing rules:** some rules are missed in the firewall policy.

   ![Example Rule 1](image)
   ![Example Rule 2](image)
   
   **Correction technique:** Rule Addition

3. **Wrong predicates:** the predicates of some rules are wrong.

   ![Example Rule 1](image)
   
   **Correction technique:** Predicate Fixing
(4) Wrong decisions: the decisions of some rules are wrong.

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</thead>
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<td>192.168.1.1</td>
<td>*</td>
<td>25</td>
<td>TCP</td>
</tr>
<tr>
<td>r2</td>
<td>1.2.3.9</td>
<td>192.168.1.1</td>
<td>*</td>
<td>25</td>
<td>*</td>
</tr>
</tbody>
</table>

Correction technique: Decision Fixing

(5) Wrong extra rules: some rules are not needed in the policy.

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<td>*</td>
<td>25</td>
<td>*</td>
</tr>
<tr>
<td>r3</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

Correction technique: Rule Deletion

Each operation of these five techniques is called a modification.
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Detection of Faulty Firewall Policies

- A faulty firewall policy is detected when administrators find that the policy allows some malicious packets or blocks some legitimate packets.

- These packets cannot provide enough information about the faults. The number of these observed packets is typically small.

- Bruteforce testing every possible packets needs $2^{104}$

- How to generate test packets for faulty firewall policies?
Generating Test Packets for Faulty Policies

- We employ the automated packet generation techniques in [Hwang et al. 2008] to generate test packets.
- Administrators identify passed/failed tests automatically or manually.

According to security requirements for the firewall policy,
- If the decision of a packet is correct, administrators classify it as a passed test.
- Otherwise, administrators classify it as a failed test.

![Diagram showing the process of generating test packets from faulty firewall policy, classifying packets, and categorizing them as passed or failed packets.]

Passed Packets  Failed Packets
Problem Statement

- **Input:**
  1. A faulty firewall policy FW
  2. A set of passed tests PT, |PT|\( \geq 0 \)
  3. A set of failed tests FT, |FT|>0

- **Output:**
  A sequence of modifications \(<M_1, \ldots, M_m>\), where \(M_j\) (\(1 \leq j \leq m\)) denotes one modification, satisfies the following two conditions:
  1. After applying \(<M_1, \ldots, M_m>\) to FW, all tests in PT and FT become passed tests.
  2. No other sequence that satisfies the first condition has the smaller number of modifications than m.

- This is a global optimization problem and hard to solve because
  - a policy may consist of a large number of rules, and
  - different combinations of modifications can be made.
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Automatic Correction of Firewall Policy Faults

- We propose a greedy algorithm to address this problem.
  - For each step, we correct one fault in the policy such that $|PT|$ increases.
  - To determine which technique should be used, we try the five correction techniques and then find the one that maximizes $|PT|$.

![Diagram of firewall policy correction process with decision nodes for failed tests, rule fixing, additional rule, predicate fixing, decision fixing, and rule deletion.](image)
Running Example

\[ r_1: F_1 \in [1, 5] \land F_2 \in [1, 10] \rightarrow a \]
\[ r_2: F_1 \in [1, 6] \land F_2 \in [3, 10] \rightarrow a \]
\[ r_3: F_1 \in [6, 10] \land F_2 \in [1, 3] \rightarrow d \]
\[ r_4: F_1 \in [7, 10] \land F_2 \in [4, 8] \rightarrow a \]
\[ r_5: F_1 \in [1, 10] \land F_2 \in [1, 10] \rightarrow d \]

A faulty firewall policy

\[ p_1: (3, 2) \rightarrow a \]
\[ p_2: (5, 7) \rightarrow a \]
\[ p_3: (6, 7) \rightarrow a \]
\[ p_4: (7, 2) \rightarrow d \]
\[ p_5: (8, 10) \rightarrow d \]

A set of passed tests

A set of failed tests
Order Fixing (1/2)

- Swapping every two rules is computationally expensive.
  - There are \((n-1)(n-2)/2\) pairs of rules that can be swapped
- We use all-match firewall decision diagrams (all-match FDDs) [Liu et al. 2008] as the core data structure.
  - Any firewall policy can be converted to an equivalent all-match FDD.

\[
\begin{align*}
r_1: & \quad F_1 \in [1, 5] \land F_2 \in [1, 10] \rightarrow a \\
r_2: & \quad F_1 \in [1, 6] \land F_2 \in [3, 10] \rightarrow a \\
r_3: & \quad F_1 \in [6,10] \land F_2 \in [1, 3] \rightarrow d \\
r_4: & \quad F_1 \in [7,10] \land F_2 \in [4, 8] \rightarrow a \\
r_5: & \quad F_1 \in [1,10] \land F_2 \in [1, 10] \rightarrow d
\end{align*}
\]
All-match FDD has the following nice property.

Swapping two rules is equivalent to swapping the sequence numbers of the two rules in the terminal nodes of all-match FDD.

\[
<r_1, r_2, r_3, r_4, r_5> \Rightarrow <r_1, r_3, r_2, r_4, r_5>
\]

For the running example, this technique can find that swapping \(r_2\) and \(r_3\) can increase \(|PT|\) by 1.

- change the failed test \((6, 3) \rightarrow d\) to a passed test.
Rule Addition

- Brute-force addition for each position is computationally expensive
  - The number of possible rules that can be added for each position is $O(2^{204})$.
- The basic idea of rule addition is that for each position
  - Find all possible failed tests that can be corrected by adding a rule

\[
\begin{align*}
  r^*: F_1 &\in [\ , \ ] \land F_2 \in [\ , \ ] \rightarrow \text{dec} \\
  r_1: F_1 &\in [1, 5] \land F_2 \in [1, 10] \rightarrow a \\
  r^*: F_1 &\in [\ , \ ] \land F_2 \in [\ , \ ] \rightarrow \text{dec} \\
  r_2: F_1 &\in [1, 6] \land F_2 \in [3, 10] \rightarrow a \\
  r^*: F_1 &\in [\ , \ ] \land F_2 \in [\ , \ ] \rightarrow \text{dec} \\
  r_3: F_1 &\in [6, 10] \land F_2 \in [1, 3] \rightarrow d \\
  r^*: F_1 &\in [\ , \ ] \land F_2 \in [\ , \ ] \rightarrow \text{dec} \\
  r_4: F_1 &\in [7, 10] \land F_2 \in [4, 8] \rightarrow a \\
  r^*: F_1 &\in [\ , \ ] \land F_2 \in [\ , \ ] \rightarrow \text{dec} \\
  r_5: F_1 &\in [1, 10] \land F_2 \in [1, 10] \rightarrow d \\
\end{align*}
\]

- Compute a rule that matches the maximum number of failed tests
  - For adding a rule between $r_1, r_2$, we can compute $F_1 \in [6, 8] \land F_2 \in [3, 5] \rightarrow \text{d}$ to correct two failed tests $p_6: (6, 3) \rightarrow \text{d}$ and $p_8: (8, 5) \rightarrow \text{d}$.
Evaluation Setup

- We generate faulty firewall policies from 40 real-life policies.
  - Each faulty policy contains one type of fault, and the number of faults ranges from 1 to 5.
  - For each faulty policy, we employed the packet generating technique [Hwang et al. 2008] and then classified them into passed and failed tests.
  - We applied our greedy algorithm to produce the fixed policy.

- Methodology
  - Difference ratio over FW_{real}, FW_{faulty}, and FW_{fixed}

\[
\frac{\Delta(FW_{real}, FW_{fixed})}{\Delta(FW_{real}, FW_{faulty})}
\]

- The average number of modifications
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Effectiveness (1/4)

- For wrong decision faults
  The percentages of fixed policies that are equivalent to their corresponding real-life policies are 73.5%, 68.8%, 63.7%, 59.3%, and 53.8%, respectively.
Effectiveness (2/4)

- For wrong order faults
  The percentages of fixed policies that are equivalent to their corresponding real-life policies are 69.7%, 64.2%, 59.7%, 54.3%, and 48.9%, respectively.
For wrong extra rule faults
The percentages of fixed policies that are equivalent to their corresponding real-life policies are 68.3%, 63.5%, 59.3%, 53.2%, and 47.3%, respectively.
Effectiveness (4/4)

- In terms the number of modifications
  The number of modifications of our approach is close to the minimum number.
Contributions

- Propose the first comprehensive fault model for firewall policies.
- Propose the first systematic approach that can automatically correct all or part of the misclassified packets of a faulty policy.
- Conduct extensive experiments on real-life firewall policies to evaluate the effectiveness of our approach.
Questions

Thank you!