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.

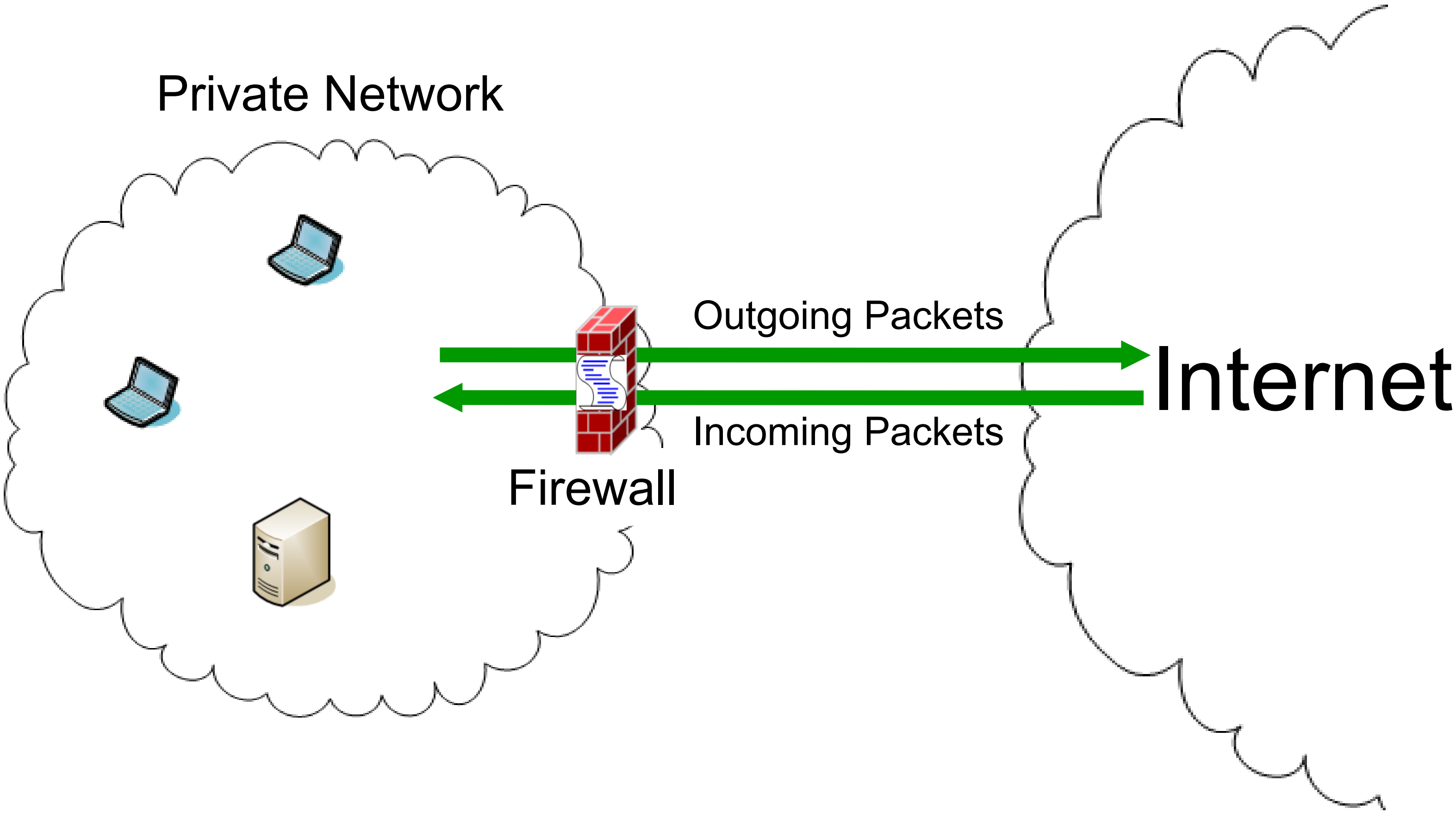
- We invent methods for fixing firewall policies automatically.
  - We first model 5 types of faults.
  - For each type of faults, we develop an algorithm to fix them.
  - Given a faulty firewall policy, we propose a systematic method to fix the faults automatically using the 5 algorithms.

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



Background – Firewall Policies

- 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

	Src IP	Dst IP	Src Port	Dst Port	Protocol	Decision
r_1	1.2.3.*	192.168.1.1	*	25	TCP	Accept
r_2	1.2.3.9	192.168.1.1	*	25	*	Discard
r_3	*	*	*	*	*	Discard

Packet

Src IP	Dst IP	Src Port	Dst Port	Protocol	Payload
1.2.3.5	192.168.1.1	78	25	TCP	

- 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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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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Fault Model of Firewall Policies (1/2)

- We propose a fault model that includes five types of faults

(1) Wrong order: the order of firewall rules is wrong.

	Src IP	Dst IP	Src Port	Dst Port	Protocol	Decision
r_1	1.2.3.*	192.168.1.1	*	25	TCP	Accept
r_2	1.2.3.9	192.168.1.1	*	25	*	Discard

Correction technique: Order Fixing

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

r^*

	Src IP	Dst IP	Src Port	Dst Port	Protocol	Decision
r_1	1.2.3.*	192.168.1.1	*	25	TCP	Accept
r_2	1.2.3.9	192.168.1.1	*	25	*	Discard

Correction technique: Rule Addition

(3) Wrong predicates: the predicates of some rules are wrong.

	Src IP	Dst IP	Src Port	Dst Port	Protocol	Decision
r_1	1.2.3.*	192.168.1.1	*	25	TCP	Accept

Correction technique: Predicate Fixing

Fault Model of Firewall Policies (2/2)

(4) Wrong decisions: the decisions of some rules are wrong.

	Src IP	Dst IP	Src Port	Dst Port	Protocol	Decision
r_1	1.2.3.*	192.168.1.1	*	25	TCP	Accept
r_2	1.2.3.9	192.168.1.1	*	25	*	Discard

Correction technique: Decision Fixing

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

	Src IP	Dst IP	Src Port	Dst Port	Protocol	Decision
r_1	1.2.3.*	192.168.1.1	*	25	TCP	Accept
~~r_2~~	~~1.2.3.9~~	~~192.168.1.1~~	~~*~~	~~25~~	~~*~~	~~Discard~~
r_3	*	*	*	*	*	Discard

Correction technique: Rule Deletion

Each operation of these five techniques is called a modification.

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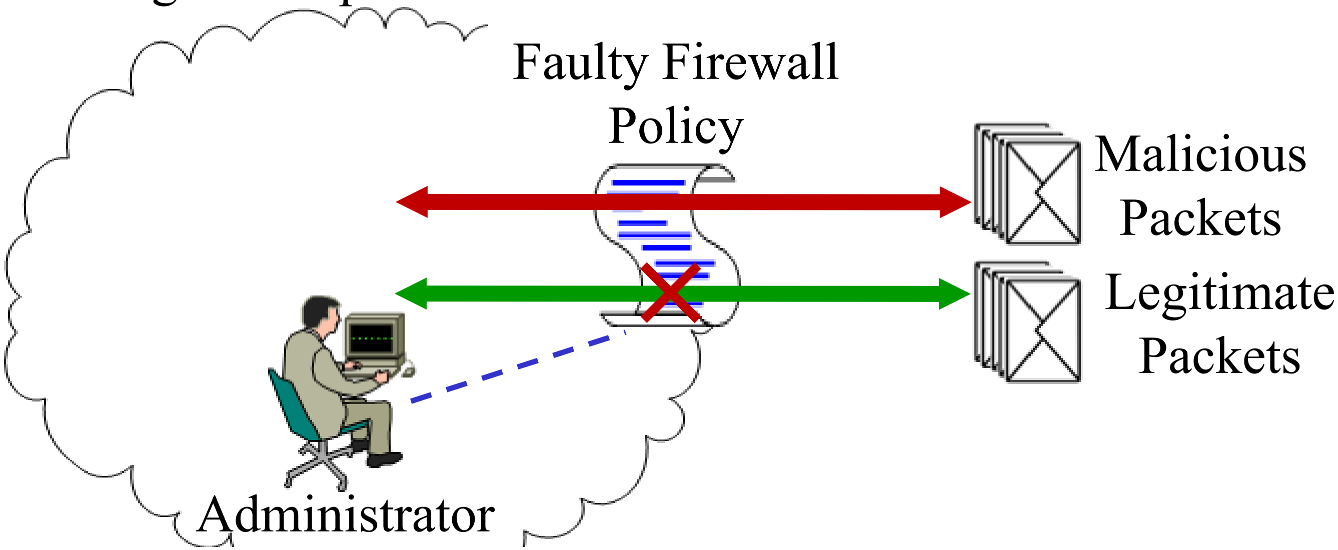
Detection of Faulty Firewall Policies

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



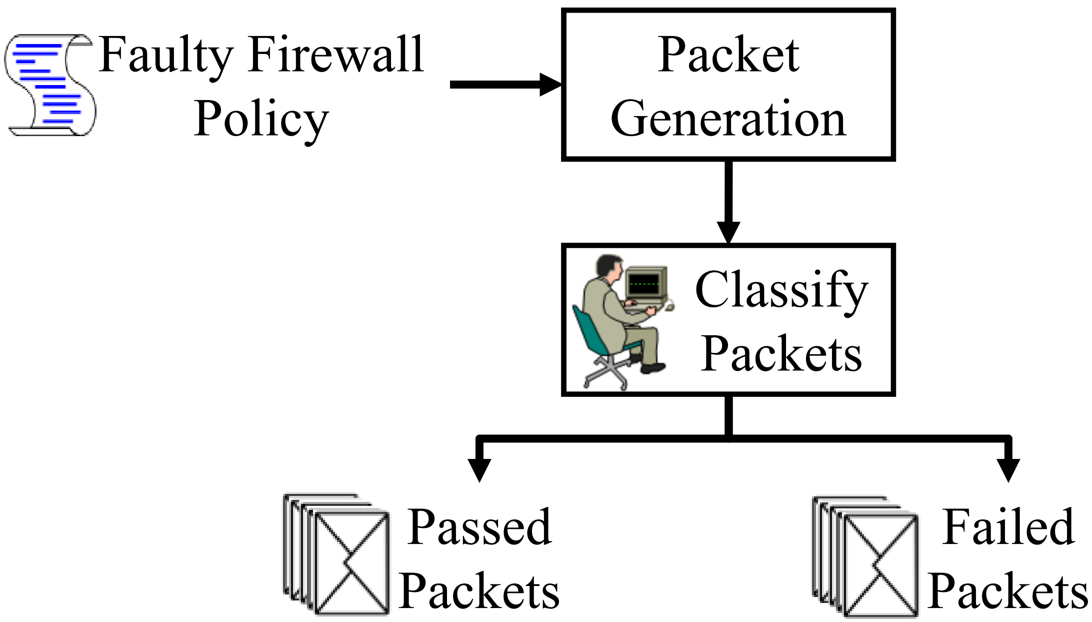
- These packets cannot provide enough information about the faults
  - The number of these observed packets is typically small
- Bruteforce testing every possible packets needs 2^{104}
- How to generate test packets for faulty firewall policies?

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.



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 modifition, 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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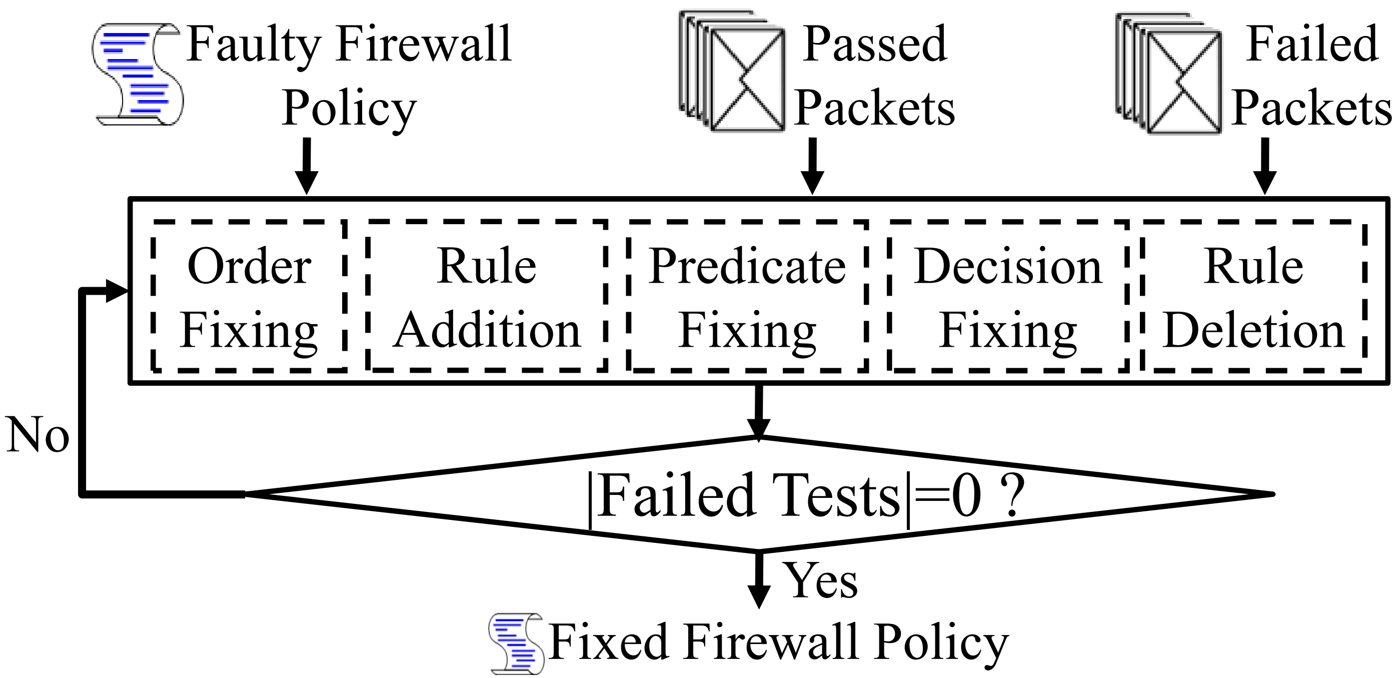
Automatic Correction of Firewall Policy Faults

- 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|.



Running Example

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

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

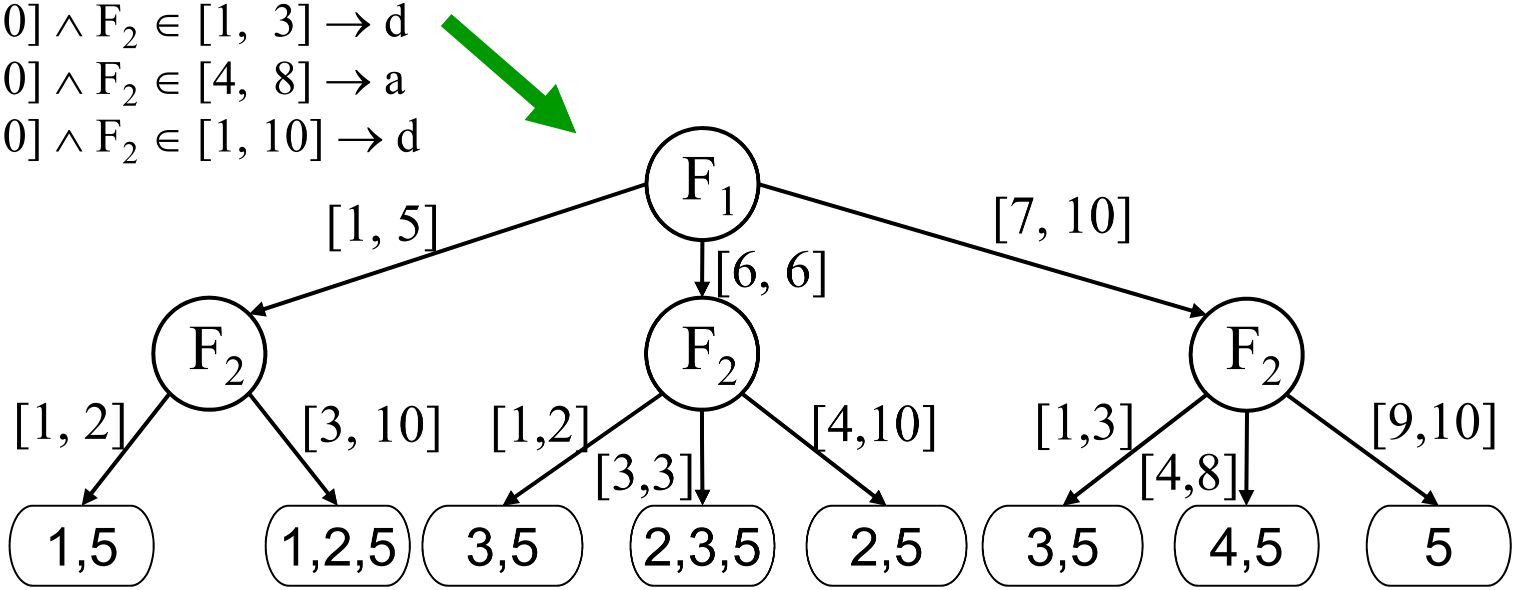
$p_6: (6, 3) \rightarrow d$
$p_7: (7, 9) \rightarrow a$
$p_8: (8, 5) \rightarrow d$

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.

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

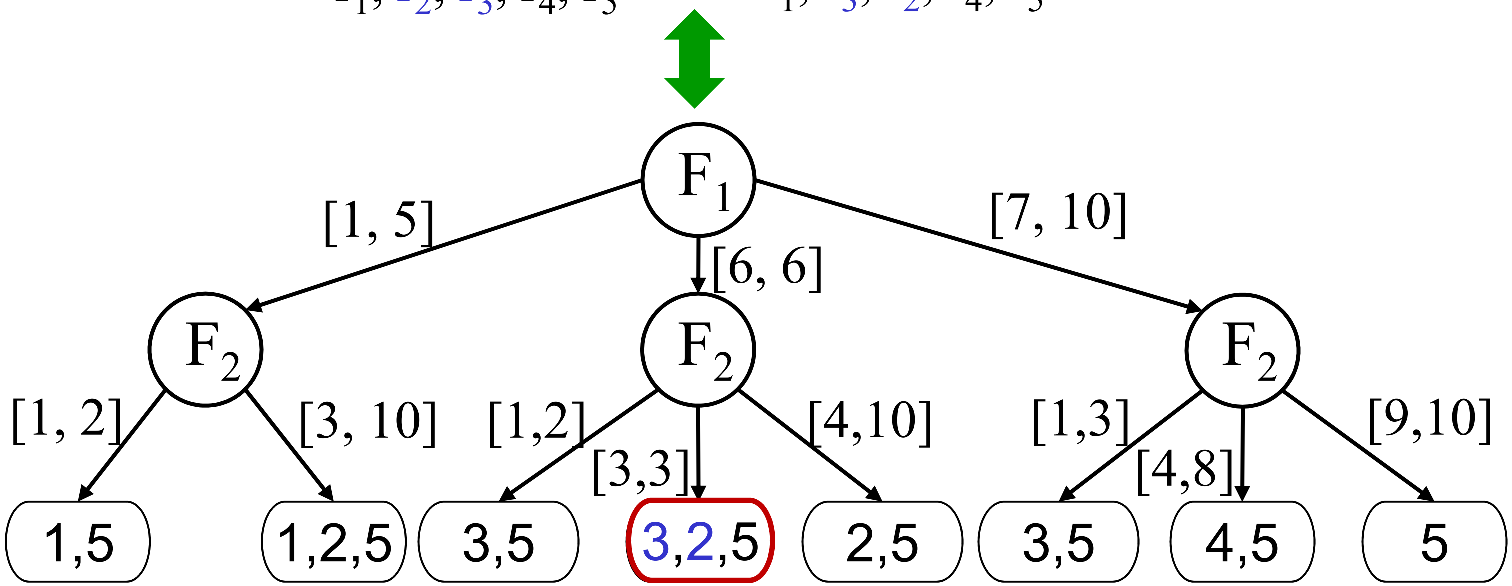


Order Fixing (2/2)

- 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

$$\langle r_1, r_2, r_3, r_4, r_5\rangle \Rightarrow \langle r_1, r_3, r_2, r_4, r_5\rangle$$



- 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) → d to a passed test

Rule Addition

- Bruteforce 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

$r^*: F_1 \in [\ ,\ ] \wedge F_2 \in [\ ,\ ] \rightarrow dec$	$p_7: (7, 9) \rightarrow a$	$p_6: (6, 3) \rightarrow d$	$p_8: (8, 5) \rightarrow d$
$r_1: F_1 \in [1, 5] \wedge F_2 \in [1, 10] \rightarrow a$			
$r^*: F_1 \in [\ ,\ ] \wedge F_2 \in [\ ,\ ] \rightarrow dec$	$p_7: (7, 9) \rightarrow a$	$p_6: (6, 3) \rightarrow d$	$p_8: (8, 5) \rightarrow d$
$r_2: F_1 \in [1, 6] \wedge F_2 \in [3, 10] \rightarrow a$		$p_6: (6, 3) \rightarrow d$	
$r^*: F_1 \in [\ ,\ ] \wedge F_2 \in [\ ,\ ] \rightarrow dec$	$p_7: (7, 9) \rightarrow a$		$p_8: (8, 5) \rightarrow d$
$r_3: F_1 \in [6, 10] \wedge F_2 \in [1, 3] \rightarrow d$			
$r^*: F_1 \in [\ ,\ ] \wedge F_2 \in [\ ,\ ] \rightarrow dec$	$p_7: (7, 9) \rightarrow a$		$p_8: (8, 5) \rightarrow d$
$r_4: F_1 \in [7, 10] \wedge F_2 \in [4, 8] \rightarrow a$			$p_8: (8, 5) \rightarrow d$
$r^*: F_1 \in [\ ,\ ] \wedge F_2 \in [\ ,\ ] \rightarrow dec$	$p_7: (7, 9) \rightarrow a$		
$r_5: F_1 \in [1, 10] \wedge F_2 \in [1, 10] \rightarrow d$			

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

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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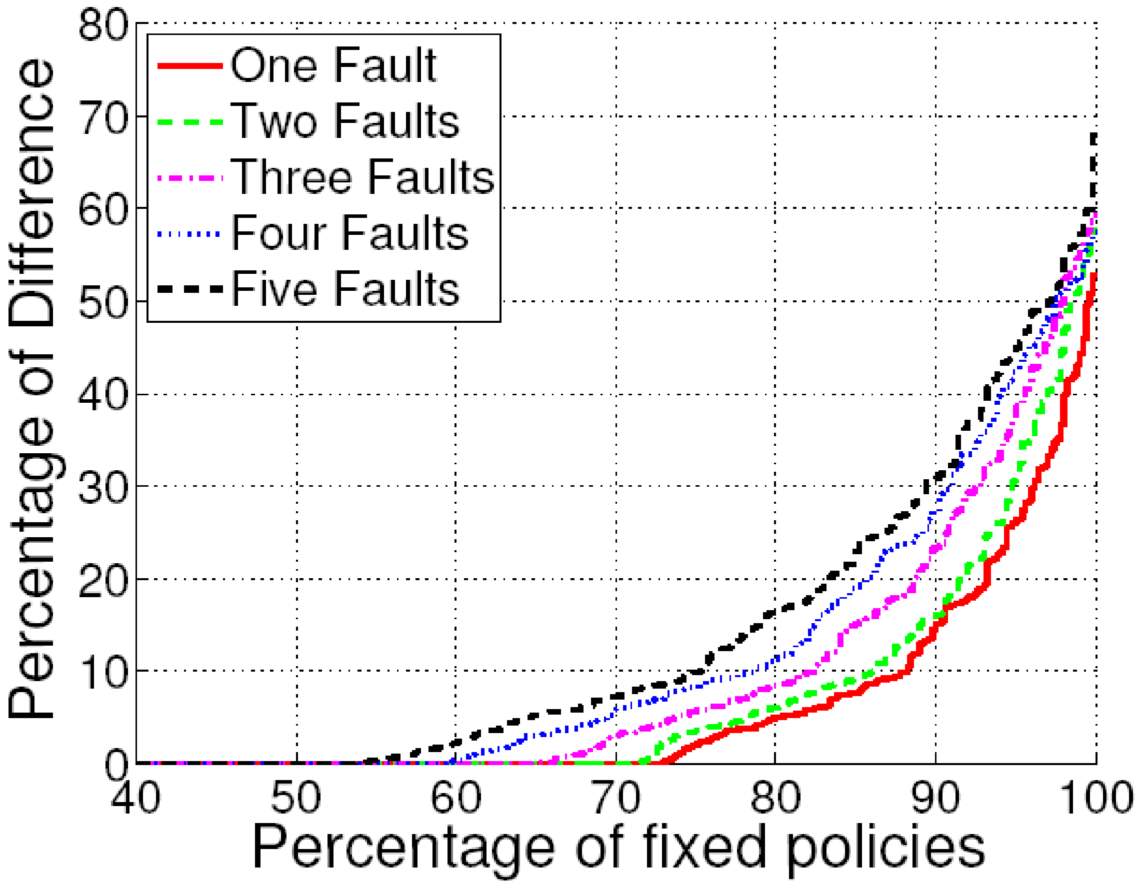
Effectiveness (1/4)

- For wrong decision faults

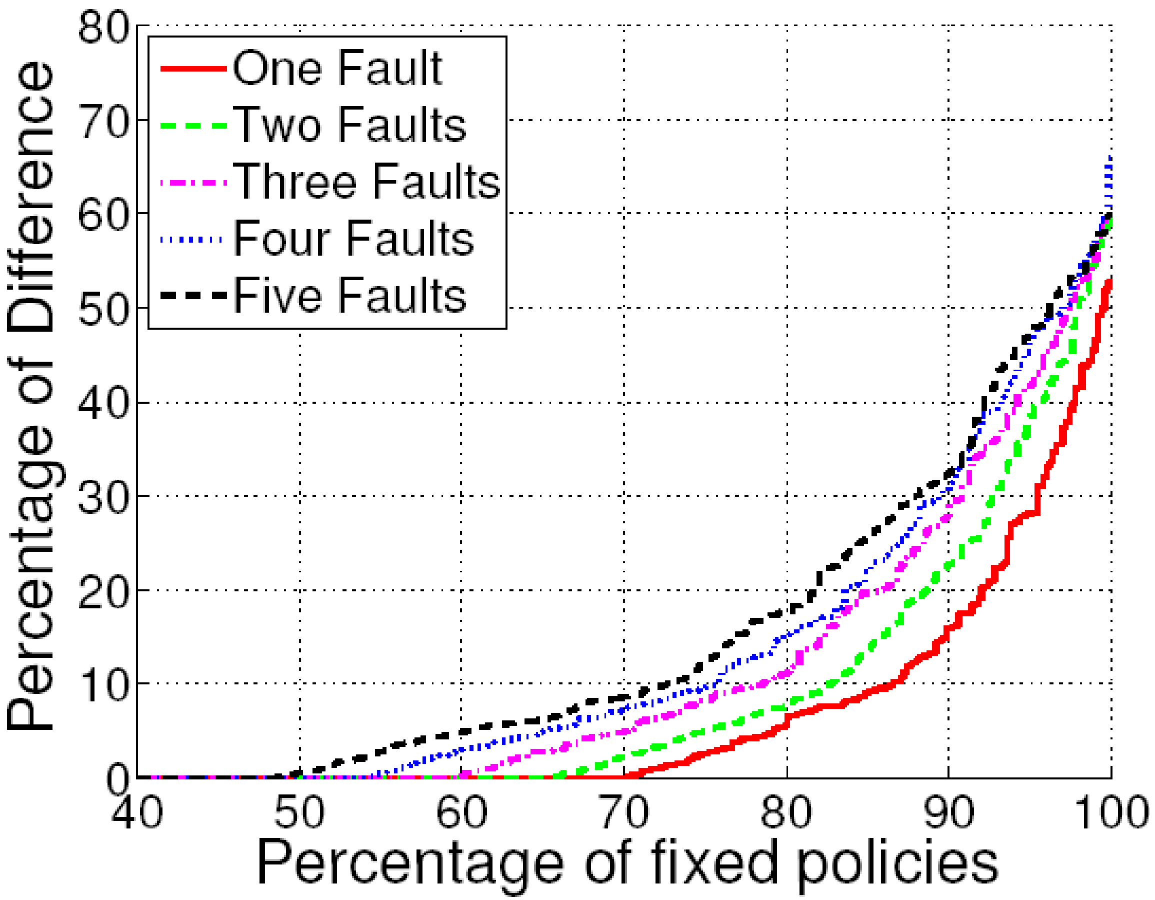
  The percentages of fixed policies that are equivalent to their corresponding real-life policies are 73.5%, 68.8%, 63.7%, 59.3%, and 53.8%, respectively.



Effectiveness (2/4)

- For wrong order faults

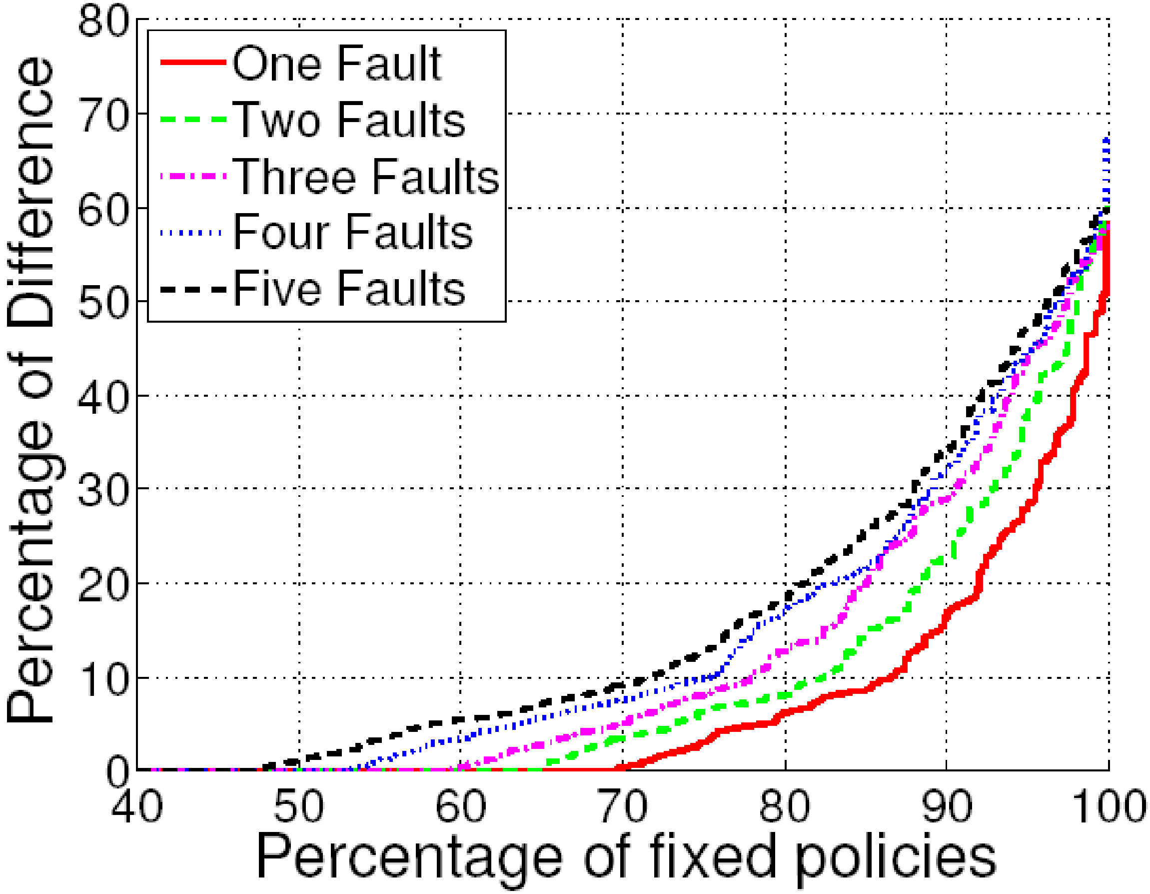
  The percentages of fixed policies that are equivalent to their corresponding real-life policies are 69.7%, 64.2%, 59.7%, 54.3%, and 48.9%, respectively.



Effectiveness (3/4)

- For wrong extra rule faults

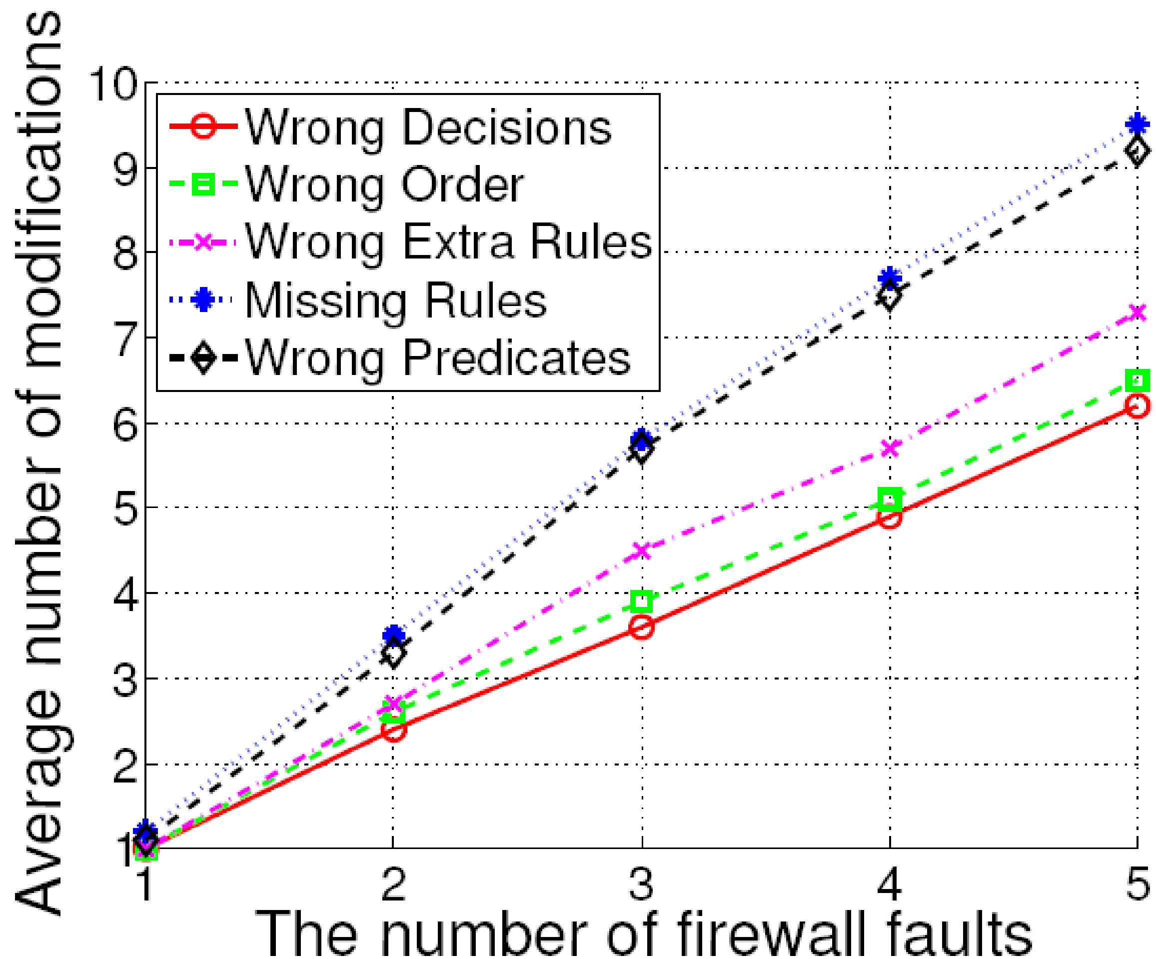
  The percentages of fixed policies that are equivalent to their corresponding real-life policies are 68.3%, 63.5%, 59.3%, 53.2%, and 47.3%, respectively.



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!