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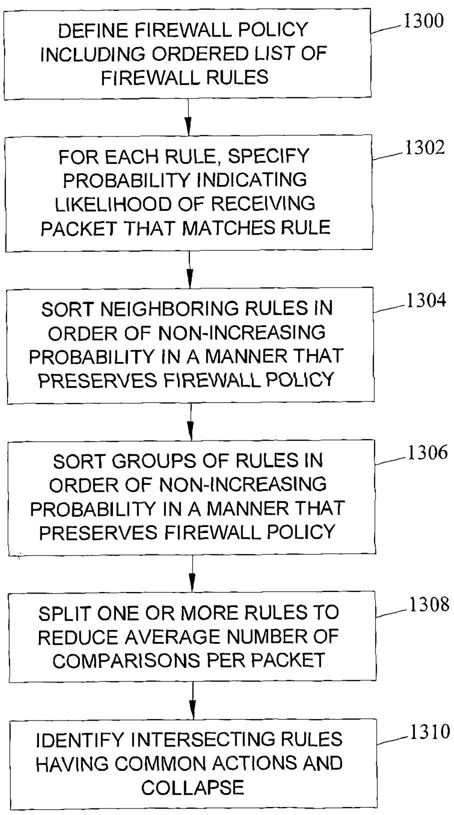

(57) Abstract: Methods, systems, and computer program products for firewall policy optimization are disclosed. According to one method, a firewall policy including an ordered list of firewall rules is defined. For each rule, a probability indicating a likelihood of receiving a packet matching the rule is determined. The rules are sorted in order of non-increasing probability in a manner that preserves the firewall policy.

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TITLE

METHODS, SYSTEMS, AND COMPUTER PROGRAM PRODUCTS FOR NETWORK FIREWALL POLICY OPTIMIZATION

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Serial No. 60/665,664, filed March 28, 2005; the disclosure of which is incorporated herein by reference in its entirety.

GOVERNMENT INTEREST

This invention was made with Government support under Grant No. DE-FG02-03ER25581 awarded by U.S. Department of Energy, Mathematical and Computational Information Sciences Division. The U.S. Government has certain rights in the invention.

TECHNICAL FIELD

The subject matter described herein relates to optimizing polices for network firewalls. More particularly, the subject matter described herein relates to methods, systems, and computer program products for optimizing performance of network firewalls.

BACKGROUND ART

Network firewalls remain the forefront defense for most computer systems. Guided by a security policy, these devices provide access control, auditing, and traffic control [3, 30, 31]. A security policy is a list of ordered rules, as seen in Table 1, that defines the action to perform on matching packets. For example, an accept action passes the packet into or from the secure network, while deny causes the packet to be discarded. In many implementations, the rule set is stored internally as a linked list. A packet is sequentially compared to the rules, starting with the first, until a match is found; otherwise, a default action is performed [30, 31]. This is referred to as a first-match policy and is used in many firewall systems including the Linux firewall implementation iptables [25].

No.	Proto.	Source IP	Source Port	Destination IP	Destination Port	Action	Prob.
1	UDP	1.1.*	*	*	80	deny	0.01
2	TCP	2.*	*	1.*	90	accept	0.02
3	UDP	*	*	1.*	*	accept	0.10
4	TCP	2.*	*	1.*	20	accept	0.17
5	UDP	1.*	*	*	*	accept	0.20
6	*	*	*	*	*	deny	0.50

Table 1: Example Security Policy Consisting of Multiple Ordered Rules

Traditional firewall implementations consist of a single, dedicated machine, similar to a router, that sequentially applies rules to each arriving packet. However, packet filtering represents a significantly higher processing load than routing decisions [24, 29, 31]. For example, a firewall that interconnects two 100 Mbps networks would have to process over 300,000 packets per second [30]. Successfully handling these traffic loads becomes more difficult as rule sets become more complex [4, 22, 31]. Furthermore, firewalls must be capable of processing even more packets as interface speeds increase. In a high-speed environment (e.g. Gigabit Ethernet), a single firewall can easily become a bottleneck and is susceptible to DoS attacks [4, 9, 13, 14]. An attacker could simply inundate the firewall with traffic, delaying or preventing legitimate packets from being processed.

One approach to increase firewall performance focuses on improving hardware design. Current research is investigating different distributed firewall designs to reduce processing delay [4, 9, 22], and possibly provide service differentiation [11]. Another approach focuses on improving performance via better firewall software [6, 7, 12, 16, 17, 24]. Similar to approaches that address the longest matching prefix problem for packet classification [8, 10, 25, 28], solutions typically represent the firewall rule set in different fashions (e.g. tree structures) to improve performance. While both approaches, together or separate, show great promise, each requires radical changes to the firewall system, and therefore are not amenable to current or legacy systems.

Accordingly, there exists a need for improved methods, systems, and computer program products for network firewall policy optimization.

SUMMARY

The subject matter described herein includes methods, systems, and computer program products for network firewall policy optimization. According to one method, a firewall policy including an ordered list of firewall rules is defined. For each rule, a probability indicating a likelihood of receiving a packet matching the rule is defined. Neighboring rules are sorted in order of non-increasing probability in a manner that preserves the firewall policy.

As used herein, the term “firewall” refers to a logical entity that is adapted to filter packets at the ingress and/or egress portions of a network based on a policy. The term “firewall” is intended to include systems that block packets from entering or leaving a network and systems that perform intrusion detection and intrusion protection functions for packets entering or leaving a network. Thus, the methods and systems described herein for firewall policy optimization can be used to optimize policies for intrusion detection and intrusion protection firewalls.

The subject matter described herein includes a method to improve firewall performance and lower packet delay that can be applied to both legacy and current systems. In one implementation, a firewall rule set may be re-ordered to minimize the average number of rule comparisons to determine the action, while maintaining the integrity of the original policy. Integrity is preserved if the reordered and original rules always arrive at the same result. To maintain integrity, a firewall rule set may be modeled as a Directed Acyclical Graph (DAG), where vertices are firewall rules and edges indicate precedence relationships. Given this representation, any linear arrangement of the DAG is proven to maintain the original policy integrity. Unfortunately, determining the optimal rule order from all the possible linear arrangements is proven to be *NP*-complete, since it is equivalent to sequencing jobs with precedence constraints for a single machine [15]. Although determining the optimal order is *NP*-complete, a heuristic will be described below to order firewall rules that reduces the average number of comparisons while maintaining integrity. Simulation results show the proposed reordering method yields rule orders that are comparable to optimal; thus, provides a simple means to significantly improve firewall performance and lower packet delay.

The subject matter described herein for network firewall policy optimization may be implemented using any combination of hardware, software, or firmware. For example, the subject matter described herein may be implemented using a computer program product comprising computer executable instructions embodied in a computer readable medium. Exemplary computer readable media suitable for implementing the subject matter described herein include disk memory devices, chip memory devices, programmable logic devices, application specific integrated circuits, and downloadable electrical signals. In addition, a computer program product that implements the subject matter described herein may be implemented using a single device or computing platform or may be distributed across multiple devices or computing platforms.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the subject matter described herein will now be explained with reference to the accompanying drawings of which:

Figure 1A is a block diagram of a rule list Directed Acyclical Graph (DAG) for the firewall rules in Table 1;

Figure 1B is a linear arrangement of firewall rules corresponding to the original rule order;

Figure 2A is a policy DAG representing a reordered version of the firewall rule set in Figure 1 after sorting;

Figure 2B is a policy DAG for the rule set illustrated in Table 1 illustrating an optimal rule order;

Figure 3A is a graph illustrating average numbers of packet comparisons versus intersection percentage for different orderings of a firewall policy;

Figure 3B is a graph illustrating the percent difference in average numbers of packet comparisons between sorted and optimal sortings of a firewall policy;

Figure 4A is a graph of percent difference comparisons between original and sorted versions of a firewall policy;

Figure 4B is a graph illustrating the performance impact of considering rule intersection and actions in performing firewall rule sorting;

Figure 5A is a table illustrating a firewall policy before sorting;

Figure 5B is a table illustrating a sorted version of the firewall policy of Figure 5A;

Figure 6A is a policy trie representation of the firewall policy of Figure 5B;

Figure 6B is a table representing the firewall policy of Figure 5A after TCP and UDP sub-trie rotation;

Figure 7A is a policy trie illustrating the splitting of rule r_5 into rules r_{5a} and r_{5b};

Figure 7B is a table illustrating the firewall policy of Figure 5A after splitting rule r_5 into rules r_{5a} and r_{5b};

Figure 8A is a graph illustrating firewall performance with and without rule splitting;

Figure 8B is a graph illustrating locations and probabilities where splitting is better;

Figure 9A is a policy DAG of a firewall rule set;

Figure 9B is a policy DAG illustrating compression of rules r_1 and r_5;

Figure 10A is a policy DAG of a firewall rule list;

Figure 10B is an original policy trie before sorting;

Figure 10C is a policy trie illustrating the firewall rules after rotating sub-tries T_1 and T_2;

Figure 11A is a policy DAG illustrating a firewall policy;

Figure 11B is a policy trie illustrating firewall rules of the policy before sorting;

Figure 11C is a policy trie illustrating the firewall policy after exchanging nodes r_1 and r_2 and nodes r_7 and r_8;

Figure 11D is a policy trie illustrating the firewall policy after exchanging sub-tries T_3 and T_4;

Figure 11E is a policy trie illustrating the firewall policy after exchanging sub-tries T_1 and T_2;

Figure 12A is a policy DAG illustrating an original order for a firewall policy;

Figure 12B is a policy DAG illustrating a sorted version of the firewall policy of Figure 12A after exchanging neighbors;

Figure 12C is a policy DAG illustrating a sorted version of the firewall policy after exchanging lists L_1 including rules r_1 and r_3 and lists L_2 including rules r_2 and r_4;

Figure 13 is a flow chart illustrating exemplary steps for network firewall policy optimization according to an embodiment of the subject matter described herein;

Figure 14 is a block diagram illustrating exemplary components of a system for firewall policy optimization according to an embodiment of the subject matter described herein; and

Figure 15 is a block diagram illustrating a plurality of firewall nodes for implementing a firewall policy according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION OF THE INVENTION

Modeling Firewall Security Policies

As described above, a firewall rule set, also known as a firewall policy, is traditionally an ordered list of firewall rules. Firewall policy models have been the subject of recent research [1, 2, 16]; however, the primary purpose is anomaly detection and policy verification. In contrast, the policy model described in this herein is designed for firewall performance optimization and integrity. Firewall performance refers to reducing the average number of comparisons required to determine an action, while integrity refers to maintaining the original policy intent. Although improving the worst-case performance is important, it is not possible without changing the list-based representation [16, 24].

Firewall Rule and Policy Models

In the examples described herein, a rule *r* is modeled as an ordered tuple of sets, $r = (r[1], r[2], ..., r[k])$. Order is necessary among the tuples since comparing rules and packets requires the comparison of corresponding tuples. Each tuple $r[l]$ is a set that can be fully specified, specify a range, or contain wildcards '*' in standard prefix format. For the Internet, security rules are commonly represented as a 5-tuple consisting of: protocol type, IP source address, source port number, IP destination address, and destination port number [30, 31]. Given this model, the ordered tuples can be supersets and subsets of each other, which forms the basis of precedence relationships. In addition to the prefixes, each filter rule has an action, which is to accept or deny. However, the action will not be considered when comparing packets and rules. Similar to a rule, a packet (IP datagram) d can be viewed as an ordered k-tuple $d = (d[1], d[2], ..., d[k])$; however, ranges and wildcards are not possible for any packet tuple.

Using the previous rule definition, a standard security policy can be modeled as an ordered set (list) of n rules, denoted as $R = \{r_1, r_2, ..., r_n\}$. A packet d is sequentially compared against each rule r_i starting with the first, until a match is found ($d \Rightarrow r_i$) then the associated action is performed. A match is found between a packet and rule when every tuple of the packet is a subset of the corresponding tuple in the rule.

Definition Packet d matches r_i if

$$d \Rightarrow r_i \qquad \text{iff} \qquad d[l] \subseteq r_i[l], \qquad l = 1, ..., k$$

The rule list R is comprehensive if for every possible legal packet d a match is found using R. Furthermore, two rule lists R and R' are equivalent if for every possible legal packet d the same action is performed by the two rule lists. If R and R' are different (e.g. a reorder) and the lists are equivalent, then the policy integrity is maintained.

As previously mentioned, a rule list has an implied precedence relationship where certain rules must appear before others if the integrity of the policy is to be maintained. For example consider the rule list in Table 1. Rule r_1 must appear before rules r_3 and r_5, likewise rule r_6 must be the last rule in the policy. If for example, rule r_3 was moved to the beginning of the policy, then it will shadow [2] the original rule r_1. However, there is no precedence relationship between rules r_2 and r_4 given in Table 1. Therefore, the relative ordering of these two rules will not impact the policy integrity and can be changed to improve performance. The present example assumes that the original policy is free from any anomalies. Likewise, when a policy is reordered to improve performance it should not introduce any anomalies, which will occur if precedence relationships are not maintained. As a result, a model is needed to effectively represent precedence relationships.

Modeling Rule List Precedence Relationships

The precedence relationship between rules in a policy will be modeled as a Directed Acyclical Graph (DAG) [23, 18]. Such graphs have been successfully used to represent the relative order of individual tasks that must take place to complete a job (referred to as a task graph model). Since certain rules must appear before others to maintain policy integrity, this structure is well suited for modeling the precedence of firewall rules. Let $G = (R, E)$ be a rule list DAG for a rule list R, where vertices are rules and edges E are the precedence relationships (constraint). A precedence relationship, or edge, exists between rules r_i and r_j, if $i < j$, the actions for each rule are different, and the rules intersect.

Definition The intersection of rule r_i and r_j, denoted as $r_i \cap r_j$ is

$$r_i \cap r_j = (r_i\,[l] \cap r_j\,[l]), \qquad l = 1, ..., k$$

Therefore, the intersection of two rules results in an ordered set of tuples that collectively describes the packets that match both rules. The rules r_i and r_j intersect if every tuple of the resulting operation is non-empty. In contrast, the rules r_i and r_j do not intersect, denoted as $r_i \not\cap r_j$, if at least one tuple is the empty set. Note the intersection operation is symmetric; therefore, if r_i intersects r_j, then r_j will intersect r_i. The same is true for rules that do not intersect.

For example consider the rules given in Table 1, the intersection of r_1 and r_3 yields (UDP, 1.1.*, *, 1.*, 80). Again, the rule actions are not considered in the intersection or match operation. Since these two rules intersect, a packet can match both rules for example d = (UDP, 1.1.1.1, 80, 1.1.1.1, 80). Furthermore, the actions of the two rules are different. Therefore, the relative order must be maintained between these two rules and an edge drawn from r_1 to r_3 must be present in the rule list DAG, as seen in Figures 1A and 1B. More particularly, Figure 1A illustrates a rule list DAG for the rules in Table 1. Figure 1B illustrates a linear arrangement of the rules in Figure 1A. In Figures 1A and 1B, the vertices represent rules, the circles represents an accept rules, and the squares represents deny rules. Edges that connect the vertices represent precedence requirements. As can be seen from Figure 1B, because of the edge between rules r_1 and r_3, precedence between rules r_1 and r_3 must be maintained. In contrast consider the intersection of rules r_3 and r_5. These two rules intersect, indicating packets belonging to the set (UDP, 1.*, *, 1.*, *) would match both rules. However, it does not matter which of the two rules a packet matches first, since the action is the same for both rules. Therefore, an edge does not exist between rules r_3 and r_5 in the diagram. Similarly, rules r_2 and r_4 do not intersect due to the fifth tuple (destination port). A packet cannot match both rules indicating the relative order can change; therefore, an edge will not exist between them.

The match operation can be used to identify precedence relationships, but it cannot do so in every case. Consider a partial-match example [1], where r_a = (UDP, *, 80, 10.*, 90, accept) and r_b = (UDP, 10.*, 80, *, 90, deny). The intersection of r_a and r_b is (UDP, 10.*, 80, 10.*, 90); therefore a packet, such as d = (UDP, 10.10.10.10, 80, 10.10.10.10, 90), can match both rules. If r_a appears before r_b then the packet d is accepted, but if r_b occurs before r_a then d is rejected. As a result, the order of r_a and r_b in the original policy must be maintained. However, the match operation is unable to identify the precedence in this example. A partial match exists in between rules r_3 and r_5 in Table 1, but as previously discussed an edge does not exist between the rules since the actions are the same.

Using the rule list DAG representation a linear arrangement is sought that improves the firewall performance. As depicted in Figure 1B, a linear arrangement (permutation or topological sort) is a list of DAG vertices where all the successors of a vertex appear in sequence after that vertex [23]. Therefore it follows that a linear arrangement of a rule list DAG represents a rule order, if the vertices are read from left to right. Furthermore, it is proven in the following theorem that any linear arrangement of a rule list DAG maintains integrity.

Theorem Any linear arrangement of a rule list DAG maintains integrity.

Proof Assume a rule list DAG *G* is constructed from the security policy *R* that is free of anomalies. Consider any two rules r_i and r_j in the policy, where $i < j$. If an edge between r_i and r_j in *G* does not exist, then a linear arrangement of *G* can interchange the order of the two rules. An edge will not exist if the rules do not intersect; however, a reorder will not affect integrity since a packet cannot match both rules. Shadowing is not introduced due to the reorder since the intersection operation is symmetric. An edge will not exist if the two rules intersect but have the same action; however, a reorder will not affect integrity since the same action will occur regardless of which rule is matched first. If an edge does exist between the rules, then their relative order will be maintained in every linear arrangement of *G*; thus maintaining precedence and integrity.

Rule List Optimization

As described above, it is important to inspect packets as quickly as possible given increasing network speeds and QoS requirements. Using the rule list DAG to maintain policy integrity, a linear arrangement is sought that minimizes the average number of comparisons required. However, this will require information not present in the firewall rule list. Certain firewall rules have a higher probability of matching a packet than others. As a result, it is possible to develop a policy profile over time that indicates frequency of rule matches (similar to cache hit ratio). Let $P = \{p_1, p_2, ..., p_n\}$ be the policy profile, where p_i is the probability that a packet will match rule *i* (first match in the policy). Furthermore, assume a packet will always find a match, $\sum_{i=1}^{n} p_i = 1$; therefore *R* is comprehensive. Using this information, the average number of rule comparisons required is

$$E[n] = \sum_{i=1}^{n} i \cdot p_i \quad (1)$$

For example, the average number of comparisons required for the rule set in Table 1 is 5.03.

Given a rule list DAG $G = (R, E)$ and policy profile $P = \{p_1, p_2, ..., p_n\}$ a linear arrangement π of G is sought that minimizes Equation 1. In the absence of precedence relationships, the average number of comparisons is minimized if the rules are sorted in non-increasing order according to the probabilities [26], which is also referred to as Smith's algorithm [27]. Precedence constraints cause the problem to be more realistic; however, such constraints also make determining the optimal permutation more problematic.

Determining the optimal rule list permutation can be viewed as job scheduling for a single machine with precedence constraints [15, 21]. The notation for such scheduling problems is $\alpha|\beta|\gamma|\delta$, where α is the number of machines, β is the precedence (or absence of) which can be represented as a DAG, γ is a restriction on processing time, and δ is the optimality criterion [15]. Determining the optimal rule order is similar to the $1|\beta|1|\sum \omega C_i$ scheduling problem, or optimality criterion, where ω is a weight associated with a job (for example, importance) and C_i is the completion time. As previously noted, the $1|||\sum \omega C_i$ problem can be solved in linear time the using Smith's algorithm [27], which orders jobs according to non-decreasing $\frac{t_i}{\omega}$ ratio, where t_i is the processing time of job i. In this case set $t_i = 1$ and $\omega = p_i\ \forall i$. However, Lawler [19] and Lenstra et al. [21] proved $1|\beta|1|\sum \omega C_i$ to be NP-complete via the linear arrangement problem, which implies determining the optimal firewall rule order is also NP-complete. Note, determining the number of possible permutations has been proven to be NP-hard [5].

Theorem $1|\beta|1|\sum \omega C_i \propto$ *Determining the optimal order of a firewall rule list*

Proof Consider the $1|\beta|1|\sum \omega C_i$ problem. Each of n jobs J_i, $i \in I$, has to be processed without preemption on a single machine that can handle at most one job at a time. For each $i \in I$, let ω be the associated weight. Furthermore, let $G = (V, E)$ be a DAG that represents the precedence order of the jobs J_i. Assume the processing time of each job equals 1 time unit, the weights to be $0 \leq \omega \leq 1$ such that $\sum \omega = 1$, and β, which is G, to be a rule list DAG. In this case, the optimization criterion $\sum \omega \cdot C_i$ is the same as $\sum p_i \cdot i$, which is given in equation 1. Clearly, the optimal firewall rule ordering problem has a solution if and only if $1|\beta|1|\sum \omega C_i$ has a solution. Therefore, determining the optimal permutation of firewall rules is *NP*-complete.

Exemplary Rule Sorting Algorithm

Although determining the optimal rule permutation was proven to be *NP*-complete, reducing the average number of comparisons required to process a packet remains an important objective. As previously discussed, a sorting algorithm must maintain the precedence relationships among rules. Of course an exhaustive search is possible if the number of rules is small (generate and test all possible topological orders); however as proven in the previous section, this is not feasible with a realistic rule list.

One exemplary algorithm starts with the original the rule set, then sorts neighboring rules based on nonincreasing probabilities. However, an exchange of neighbors should never occur if the rules intersect and have different actions. This test preserves any precedence relationships in the policy. For example, the following sorting algorithm uses such a comparison to determine if neighboring rules should be exchanged. Note a_i denotes the action associated with the i^{th} rule.

```
done = false
while(!done)
    done = true
    for(i = 1; i <n; i++)
        if(p_i < p_i+1 AND (r_i ⋔̸ r_i+1 OR a_i == a_i+1))then
            exchange rules, actions, and probabilities
            done = false
        endif
    endfor
endwhile
```

Other sorting algorithms are possible if the completion time of the sort is an issue; however, the method presented is easy to implement and only requires a simple neighbor comparison. Assume the match probabilities for the rule list given in Table 1. Applying the sorting algorithm to this rule list results in the ordering depicted in Figure 2A, which has 10% fewer comparisons on average. However when using the algorithm, it is possible that one rule can prevent another rule from being reordered. For example, rule r_1 prevents rule r_5 from being placed closer to the beginning of the rule set. However, if both rules r_1 and r_5 are placed closer to the beginning of the policy while maintaining their relative order, the average number of comparison will be further reduced, 15% fewer. This is the optimal order for the 6 rule set, which is depicted in Figure 2B. Although this simple sorting algorithm is unable to move groups of rules, it can still improve the performance of the firewall system. Its effectiveness is measured experimentally in the next section.

Experimental Results

In this section, the average number of rule comparisons required after sorting the rules is compared with average number of comparisons required using the original order and the optimal order. Note the optimal rule ordering was determined via an exhaustive search. As a result, it was not feasible to determine the optimal ordering once the number of rules equaled 15 given the number of permutations to consider. Two different variations of the rule sorting method described in the preceding section were implemented. The difference between the methods was the comparison used to determine if neighboring rules should be exchanged. The first sorting algorithm exchanged neighboring rules if they were out of order and did not intersect. The if-condition was as follows.

if ($p_i < p_{i+1}$ **AND** $r_i \not\pitchfork r_{i+1}$) **then**

Therefore, rule actions were not considered and the method will be referred to as *non-action sort*. The second sorting method did consider the rule action (as described in the preceding section) and will be referred to as *action sort*. The comparison between the two sorting algorithms will indicate the importance of considering rule actions when ordering rules.

In the first experiment, lists of 10 firewall rules were generated with random precedence relationships. The match probability of each rule was given by a Zipf distribution [20], which assigns probabilities according to the rank of an item. For this simulation, the last rule had the highest probability which is consistent with most policies (last rules are more general). As a result, the original order yields the worst average number of comparisons. The intersection percentage measured the percentage of rules that intersect in the policy. This metric gives a value for the dependency level in the policy; however note, rule action is not considered when calculating this metric. Rules were equally likely to have an accept or deny action and the results (average number of rule comparisons) for a particular intersection percentage were averaged over 1000 simulations.

Results of the first experiment are given in Figures 3A and 3B. More particularly, Figure 3A is a graph illustrating the average number of packet comparisons versus intersection percentage for the original rule sorting, the non-action sort, the action sort, and the optimal sort. Figure 3B is a graph illustrating the percent difference in the average number of comparisons required between the sorted and optimal firewall policy configurations. The average number of comparisons required was lower for the sorted and the optimal lists when the intersection percentage was low, as seen in Figure 3A. This was expected since there is a large number of possible rule permutations (few edges in the DAG). When the intersection percentage approached 100%, the values converged to the number required for the original list. This is due to the limited number of possible rule orders, only one order in the extreme case. The percent difference between the sorted and optimal order is shown in Figure 3B. At zero intersection percentage the sorted and optimal orders are equal, since any ordering is possible. Similarly at an intersection percentage of 100, the sorted and optimal orders are equal since only one order is possible. Between these two extremes, the action sorting algorithm remains close to the optimal value. In contrast, the non-action sort had a maximum difference of 33%.

The benefit of rule sorting on larger policies is also of interest; however as previously described, it was not possible to determine the optimal ordering once the number of rules approaches 15. Therefore, the second experiment used larger rule sets, but only compared the original order and the sorted orders. The number of rules ranged from 10 to 1000, while the matching probabilities and intersection percentages were the same as the previous experiment. The results of this experiment are depicted in Figure 4A. The sorted rule sets always performed equal to or better than the original order, while the action sort consistently performed better than the non-action sort. As noted in the previous experiment, the percent difference is very large given few intersections (e.g. 80% decrease for 1000 rules with 0% dependency), but approaches zero as all the rules intersect. As the number of rules increases, sorting is increasingly beneficial, although only at low intersection percentages. The benefit of sorting drops more significantly as the intersection percentage increases with larger rule sets. This is primarily due to the low matching probabilities of each rule, which requires a complete reordering to have a significant impact on the average number of comparisons. As a result, large rule sets can benefit from sorting if the intersection percentage is low.

The impact of considering rule actions when sorting is illustrated in Figure 4B. In this experiment lists of 1000 rules were generated, where the intersection percentages ranged from 0% to 100% and the percentage of rules with the same action varied from 50% to 100%. The performance of the action sort to the original list was then compared. As the percentage of rules with the same action increased, the percent difference (reduction) in the average number of comparisons also increased. This is due to the increased number of permutations possible when the rule actions are increasingly the same (fewer edges in the rule list DAG to consider). This is depicted in Figure 4B where a policy with a 100% intersection percentage can significantly reduce the number of comparisons (80% reduction) if all the rules have the same action. This performance increase is not possible with the non-action sort. Therefore, considering the rule action increases the number of possible rule orders, thereby providing more possibilities to improve firewall performance.

Conclusions

Network firewalls enforce a security policy by comparing arriving packets to a list of rules. An action, such as accept or deny, is then performed on the packet based on the matching rule. Unfortunately packet filtering can impose significant delays on traffic due to the complexity and size of rule sets.

Therefore, improving firewall performance is important, given network Quality of Service (QoS) requirements and increasing network traffic loads.

The sections above describe rule ordering methods to improve the performance of network firewalls. Assuming each rule has a probability of a packet matching, firewall rules should be sorted such that the matching probabilities are non-increasing. This reduces the average number of comparisons and the delay across the firewall. However, a simple sort is not possible given precedence relations across rules. It is common in a security policy that two rules may match the same packet yet have different actions. It is this precedence relationship between rules that must be maintained to preserve integrity. The method described above uses Directed Acyclical Graphs (DAG) to represent the precedence order rules must maintain. Given this representation, a topological sort can be used to determine the optimal order (minimum average number of comparisons); however, the examples above prove this problem to be *NP*-complete (similar to job scheduling for a single nonpreemptive machine with precedence constraints). As an alternative, a simple sorting method was introduced that maintained the precedence order of the rules. Simulation results indicate this method can significantly reduce the average number of comparisons required and is comparable to optimal ordering.

Several areas exist for future research in optimizing firewall rule lists. The sorting method proposed above is based on a simple algorithm. Although it can offer an improvement over the original rule order, algorithms that can move groups of rules could provide a larger reduction in the average number of comparisons. The effect of stateful firewalls should also be addressed in future research. Security can be enhanced with connection state and packet audit information. For example, a table can be used to record the state of each connection, which is useful for preventing certain types of attacks (e.g., TCP SYN flood) [30, 31]. The impact of such rules on the firewall needs to be investigated and whether sorting can be done on-line to reflect temporal changes. In addition, more research is needed to determine more accurate probability distributions for packet matching and dependency percentages.

Given this information, better algorithms can be designed and more realistic simulations can be performed.

Trie-Based Network Firewall Optimization Methods and Rule Splitting

Overview

As described above, while assuring firewall policy integrity is critical, performance is equally important given increasing network speeds and traffic volumes. Firewall processing delay can be reduced via hardware as well as policy optimization, where rules are manipulated to reduce the number of comparisons. For a given firewall installation, it can be determined that certain security rules have a higher probability of matching a packet than others. As a result, it is possible to develop a *policy profile* over time that indicates frequency of rule matches (similar to cache hit ratio). Given this information, trie-based methods are described herein to minimize the average number of comparisons required per packet. Although most firewall systems still utilize an ordered list representation, the proposed enhancements still are applicable to current firewall systems since a policy trie can be converted into an ordered list using an inorder traversal.

Rule Sorting

As described above, rule sorting of neighboring rules based on ascending probabilities in a manner that considers rules intersection and rule actions can be used to improve firewall performance by reducing the number of packet comparisons. The methods described above use Directed Acyclic Goal Graphs (DAGs) to represent firewalls. The methods described in this section will use the rule sorting algorithms in combination with policy trie representations to perform sorting of groups of rules in a manner that improves firewall performance.

In this example, it is assumed that a security policy contains a list of n ordered rules, $\{r_1, r_2, ..., r_n\}$. In addition, let p_i represent the probability that a packet will match rule i (first match in the policy). Therefore, the policy is comprehensive, which means every packet will have a match, if $\sum_{i=1}^{n} p_i = 1$.

Using this information, the average number of rule comparisons required can be calculated as

$$E[n] = \sum_{i=1}^{n} i \cdot p_i$$

The average number of comparisons is minimized if the rules are sorted in non-ascending order according to the probabilities. However, this can only be achieved if the sorting algorithm considers the probabilities and whether one rule is a superset of another. For example, sorting algorithms must use the following comparison to determine if neighboring rules should be interchanged Note, a_i denotes the action associated with the i^{th} rule.

if ($p_i < p_{i+1}$ **AND** $r_i \not\cap r_{i+1}$ **OR** $a_i == a_{i+1}$)) **then**

Sorting rules in this fashion can have positive impact on the average number of comparisons required. Figure 5A is a table illustrating a firewall policy prior to rule sorting. The expected number of comparisons for the policy of Figure 5A is 4.26 comparisons per packet. Figure 5B is a table illustrating the firewall policy of Figure 5A after sorting using the above-described algorithm. In Figure 5B, the expected number of comparisons per packet has been reduced to 3.94. Thus, using the method described above, the number of comparisons per packet can be reduced by 8%.

However, it can be seen from Figures 5A and 5B that one rule can prevent another rule from being reordered. For example in Figure 5B, rule r_1 prevents rule r_4 from being placed closer to the beginning of the rule set. However, if both rules r_1 and r_4 are placed closer to the beginning of the policy while maintaining their relative order, the average number of comparison will be reduced.

To solve this problem, rule sets can be sorted a using policy tries. First, the rule list is converted into an equivalent policy trie. Each sub-trie will have an associated probability $\bar{p}$ that is average probability (hit-ratio) of the rules comprising the sub-trie. Sub-tries can be rotated around their parent node to increase performance, using the method described earlier. Since the policy trie (or equivalent rule set) is tested from left to right, rotation should occur if the probability of the right sub-trie is greater than the left sub-trie. As a result, the average number of comparisons required will be reduced and the policy integrity is maintained. Figure 6A is a trie representation of the rules in Figure 5B. Figure 6B is a table representing resulting rule set after rotating the TCP and UDP sub-tries. The TCP sub-trie in Figure 6A has an expected packet matching probability of 0.095 while the UDP sub-trie has an expected packet matching probability of 0.155. Thus, the UDP sub-trie and the TCP sub-trie should be rotated so that the UDP sub-trie becomes the left sub-trie and the TCP sub-trie becomes the right sub-trie. In the table illustrated in Figure 6B, which lists the ordering of the rules after rotating the sub-tries, the average number of comparisons per packets has been reduced to 3.70.

Rule Splitting

Rule splitting takes a general rule and creates more specific rules that collectively perform the same action over the same set of packets. Here, rule splitting is used to reduce the average number of comparisons. For example in Figure 7A, rule r_5 is split into two separate rules, r_{5a} for UDP and r_{5b} for TCP. Figure 7B is a table corresponding to the policy trie of Figure 7A. Once the rules are positioned based on their probabilities and their relation to other rules, the average number of rule comparisons is reduced to 2.98 (after sort, trie rotation, and splitting) which is a 30% less.

It many not be advantageous to split a general rule since it adds another rule to the policy. For example, assume a policy contains 20 rules where the first 19 rules have the same probability. Assume the last rule can be split and the new specific rule has a probability that is $\frac{3}{4}$ of the last rule. The impact of the probability of the last rule and the location of the new split rule, m, is depicted in Figures 8A and 8B. More particularly, Figure 8A is a graph illustrating the average number of comparisons for firewalls with and without rule splitting. Figure 8B is a graph illustrating average number of comparisons versus different locations of the new rule and probabilities. The average number of comparisons is reduced as the split rule is located closer to the first rule (surface decreases as m approaches one). Furthermore, splitting yields better results when the general rule has a high probability. However as illustrated in Figure 8B, the closer the specific rule is to the location of the original rule the average number of comparisons increases, which is the penalty of adding one more rule to the policy.

The effect of splitting a single rule can be described mathematically as follows. Consider n rules where rule r_n can be split into rules $r_{n,1}$ and $r_{n,r}$ (whose union is the original rule). In addition, assume the split rule $r_{n,1}$ will be located at the m^{th} position ($1 \leq m < n$), while rule $r_{n,r}$ will remain at the n^{th} location. The goal is to determine the best location m, which yields a lower average number of comparisons as compared to the original rule set. This can be defined mathematically in the following formula.

$$\sum_{i=1}^{n} i \cdot p_i > \sum_{i=1}^{m-1} i \cdot p_i + m \cdot p_{n,l} + \sum_{i=m}^{n-1} (i+1) \cdot p_i + (n+1) \cdot p_{n,r}$$

The left side of the inequality is the average number of comparisons for the original rule set. The right hand side of the inequality is the average number of comparisons with the specific rule at location m. If it is assumed that the rules located between m and n have an equal probability (denoted as p) the previous equation can be solved for m.

$$m < \frac{n \cdot p - n \cdot p_n + (n+1) \cdot p_{n,r}}{p - p_{n,l}}$$

The new rule must be located between the first and m^{th}; however, its final location will depend on the relationship with the other rules (cannot be placed before any rule for which it is a superset). This result can be applied iteratively to multiple rules and repeatedly to the same rule.

Rule Optimization for QoS

In the preceding sections, optimizing the entire security policy has been discussed. However, it may be desirable to optimize the rules for a certain type of traffic, in order to reduce the average number of comparisons this traffic encounters. This can be done by organizing the policy trie via traffic classification, then optimizing the sub-tries. The result is an ordering where the rules for the most important traffic are tested first.

Network Firewall Optimization Using Rule Compression

Another method for network firewall optimization is referred to as rule compression. Given a security policy R, one objective in optimizing firewall performance is to reduce number of rules in the policy while maintaining the original integrity. A method for reducing the number of rules called *rule compression*, which combines and replaces two rules in the policy will now be described. Although compression does reduce the number of rules, it can only be done if the integrity of the original policy is maintained.

Consider two rules r_i and r_j in policy R, where r_i appears before r_j. The two rules can be compressed if and only if the following conditions are true

1. The two rules intersect, $r_i \cap r_j \neq \emptyset$ (an edge between r_i and r_j exists in the policy DAG) (Tuples that are proper subsets and supersets are considered. Compression may still occur if the rules do not intersect or are adjacent in the set space, the resulting rule may contain ranges.)
2. The action of r_i and r_j is the same.
3. Rule r_i is not dependent on any rule r_k that is directly or indirectly dependent on r_j (only one path from r_i to r_j exists in the policy DAG).

The result of compression is a new rule, $r_{i,j}$ whose tuples are the union of the corresponding tuples of rules r_i and r_j. The new rule $r_{i,j}$ replaces both r_i and r_j in R; however, the location of $r_{i,j}$ in R may require the relocation of other rules. Let D_j be the ordered set of rules that appear after r_i that directly or indirectly depend upon r_j. The new rule is placed at the original location of r_i in R and the rules D_j are placed before $r_{i,j}$.

For example, consider the policy given in Table 2. It is possible to compress rules r_1 and r_5, creating the new rule $r_{1,5}$ =[TCP, *, *, 2.*, *, accept]. The ordered set D_j in this example consists of the rules r_3 and r_4. As a result, the new rule $r_{1,5}$ is placed at the original location of r_1 while the rules in D_j are placed before the new rule. Figures 9A and 9B respectively illustrate the original policy DAG for Table 2 and the policy DAG after rules r_1 and r_5 are compressed.

No.	Proto.	Source IP	Source Port	Destination IP	Destination Port	Action
1	TCP	1.1.*	*	2.2.*	*	accept
2	TCP	1.*	*	*	80	deny
3	TCP	3.3.*	*	*	80	accept
4	TCP	3.*	*	*	*	deny
5	TCP	*	*	2.*	90	accept

Table 2: Example Policy Consisting of Multiple Ordered Rules

Theorem *Compressing rules r_i and r_j of policy R will maintain integrity if the three conditions are met and method described is used.*

Proof Before r_i and r_j are compressed, relocate the rules D_j immediately before r_i and D_i. This relocation will maintain integrity due to the third requirement for compression (no rule in D_i can be dependent on any rule in D_j). Now place r_j directly after r_i. This relocation will not affect integrity since no rule in D_i can have an edge to r_j (again, due to the third condition). Compressing the neighboring rules r_i and r_j creates $r_{i,j}$. This does not affect integrity since the resulting rule only matches the packets that match r_i or r_j in the original policy. Therefore, the result is the compression of rule r_i and r_j , and the integrity of the policy is maintained.

Determining if Compression Should Occur

Although compression may be possible, it may not improve the performance of the policy due to the relocation of rules. Compression should only occur if the average number of comparisons required for the new policy R_c is less than the original policy R; therefore, $E[R_c] < E[R]$.

Firewall Rule Sub-Trie and Sub-List Ordering

Policy Sub-Trie Ordering

Additional methods for firewall optimization are referred to as firewall sub-trie and sub-list ordering. Given a policy trie *T*, it may be desirable to order all sub-tries such that the average number of tuple comparisons is reduced and policy integrity is maintained. Consider a policy trie *T* that contains sub-tries T_i and T_j having the same parent node, as seen in Figures 10A-10C. Let P_i denote the sum of the probabilities of the rules contained in sub-trie *i*, while C_i denotes the number of comparisons required to completely traverse sub-trie *i* (which is equal to the number of branches). In order to reduce the average number of tuple comparisons, sub-tries that share the same parent node should be ordered such that the following two conditions are observed.

1. Sub-tries that share a parent node are ordered such that the P_i values are non-ascending (higher match probabilities occur first, from left to right).
2. If sub-tries that share a parent node have the same probability (P_i equals P_j), then order the sub-tries such that the C_i values are non-descending (sub-tries consisting of fewer comparisons occur first, from left to right).

These conditions are recursively applied throughout the policy trie as seen in Figures 11A-11D. However, these conditions do not necessarily maintain policy integrity.

Consider a group of *n* sub-tries that share the same parent node that are numbered sequentially from left to right. Consider any two non-intersecting sub-tries T_i and T_{i+k} in this group that are out of order. If two sub-tries do not intersect, denoted as $T_i \not\pitchfork T_j$, then no rule in one sub-trie will intersect with any rule in the other sub-trie, $r_k \not\pitchfork r_l, \forall r_k \in T_i, \forall r_l \in T_j$. The following *integrity condition* must be observed when reordering the sub-tries. The two sub-tries can be exchanged (rotated about the parent) if and only the sub-tries T_i through T_{i+k-1} do not intersect with T_{i+k} and the sub-tries T_{i+1} through T_{i+k} do not intersect with T_i. Similar to finding the linear sequence of a policy DAGs, these conditions maintain the policy trie integrity. This is observed in Figure 10A, where no edge exists between any rule in T_1 and T_2. More particularly, Figure 10A is a policy DAG of a six-rule firewall list. Figure 10B is a policy trie representation of the firewall rule list represented by Figure 10A. In Figure 10B, the average number of tuple compares required per packet is 5.5. Figure 10C illustrates the policy trie after rotating sub-tries T_1 and T_2. In Figure 10C, the average number of tuple compares required is 4.5. In Figures 10A-10C, the following probabilities are assumed:

$P_1 = 0.5$

$C_1 = 4$

$P_2 = 0.5$; and

$C_2 = 2$.

The average number of tuple comparisons is an estimate based on the longest trie path.

Using the conditions for comparing and ordering, the following sorting algorithm sorts neighboring sub-tries that share the same parent node.

```
m = a parent node in T
done = false
while(!done)
   done = true
   for each sub-trie Ti having parent m AND a right neighboring sub-trie
      if((Pi < Pi+1 AND (Pi == Pi+1 AND Ci > Ci+1)) AND Ti ∩̸ Ti+1) then
      interchange Ti and Ti+1
      done = false
      endif
   endfor
endwhile
```

Figures 11A-11D illustrate policy trie rotation for an eight-rule firewall policy. More particularly, Figure 11A illustrates the policy DAG representation of an eight-rule firewall policy. Figure 11B is a policy trie representation of the original firewall policy. In this example, ordering occurs in three stages, starting at the bottom level and moving towards the top level of the trie. In Figure 11C, the leaves are ordered at the lowest level. More particularly, nodes r_1 and r_2 are exchanged with nodes r_7 and r_8. The average number of tuple compares for the ordering represented by Figure 11C is 10.45. In Figure 11D, the sub-tries on the second lowest level (T_3, T_4, T_5, and T_6) are ordered. More particularly, Figure 11D illustrates the policy trie after exchanging sub-tries T_3 and T_4. The average number of tuple compares for the representation in Figure 11D is 10.275. In Figure 11E, the sub-tries on the second highest level, (T_1 and T_2) are ordered. Figure 11E illustrates the final ordering after exchanging T_1 and T_2. In the policy trie of Figure 11E, the average number of tuple compares required is 6.775. The average number of tuple comparisons is an estimate based on the longest trie path.

Policy Sub-List Ordering

The preceding section describes conditions for sorting policy sub-tries, which allow the exchange of groups of rules (sub-tries). The same conditions can be applied to list based policies, where sub-lists are ordered to improve the average number of rule comparisons.

In the sections above relating to rule sorting, a method is described to exchange neighboring rules in a list-based security policy, as seen in Figure 12B. However, it was observed that when ordering rules in this fashion it is possible that one rule can block the exchange of another. If groups of rules were allowed to be exchanged the average number of rule comparisons could be further reduced.

Given a policy list L, it may be desirable to order all sub-lists such that the average number of rule comparisons is reduced and policy integrity is maintained. Consider a policy list L that contains sub-tries L_i and L_j. Let P_i denote the sum of the probabilities of the rules contained in sub-list i, while C_i denotes the number of rules in sub-list i. In order to reduce the average number of rule comparisons, sub-lists should be ordered such that the following two conditions are observed.

1. Sub-lists are ordered such that the P_i values are non-ascending (higher match probabilities occur first, from left to right).
2. If sub-lists have the same probability (P_i equals P_j), then order the sub-lists such that the C_i values are non-descending (sub-lists consisting of fewer comparisons occur first, from left to right).

These conditions are applied throughout the policy list; however as with policy tries, these conditions do not necessarily maintain policy integrity.

Consider a group of n sub-lists that are numbered sequentially from left to right. Consider any two non-intersecting sub-lists L_i and L_{i+k} in this group that are out of order. If two sub-lists do not intersect, denoted as $L_i \pitchfork L_j$, then no rule in one sub-list will intersect with any rule in the other sub-list, $r_k \pitchfork r_l, \forall r_k \in L_i, \forall r_l \in L_j$. The following *integrity condition* must be observed when reordering the sub-lists. The two sub-lists can be exchanged if and only if the sub-lists L_i through L_{i+k-1} do not intersect with any rule in L_{i+k} and sub-lists L_{i+1} through L_{i+k} do not intersect with L_i. Similar to finding the linear sequence of a policy DAGs, these conditions maintain the policy trie integrity. For example, consider the sub-lists $L_1 = \{r_1, r_3\}$ and $L_2 = \{r_2, r_4\}$ given in Figure 12B. No edge exists between any rule in L_1 and L_2. The two sub-lists are out of order with respect to P and should be exchanged. The resulting list is given in Figure 12C. Figure 12A illustrates the original policy order and results in an average number of rule comparisons of 3.4. In the sorted version in Figure 12B, the average number of rule comparisons is 3.3. In Figure 12C, the average number of rule comparisons has been reduced to 2.7. Using the conditions for comparing and ordering, the following sorting algorithm sorts neighboring sub-lists.

```
done = false
while(!done)
   done = true
   for each sub-list Li having a right neighboring sub-list
      if ((Pi < Pi+1 OR (Pi == Pi+1 AND Ci > Ci+1)) AND Li ⋔ Li+1)then
         interchange rules and probabilities
         done = false
      endif
   endfor
endwhile
```

Summary of Firewall Policy Optimization Techniques and Methods

As stated above, the methods and systems described herein for a network firewall policy optimization can be implemented using any combination of hardware, software, and/or firmware. Alternatively, the steps for firewall policy optimization can be performed manually with the number of rules being optimized is small enough. Figure 13 is a flow chart illustrating an exemplary process for firewall policy optimization according to an embodiment of the subject matter described herein. Referring to Figure 13, in block **1300**, a firewall policy including an ordered list of firewall rules is defined. In block **1302**, for each rule, a probability indicating a likelihood of receiving a packet that matches each rule is specified. In block **1304**, neighboring rules are sorted in order of non-increasing probability in a manner that preserves firewall policy. In block **1306**, groups of rules are sorted in order of non-increasing probability in a manner that preserves firewall policy. For example, any of the policy-trie-based methods described above may be used. In block **1308**, one or more rules are split to reduce the number of average packet comparisons. In block **1310**, intersecting rules having common actions are identified and collapsed into single rules.

As described above, the subject matter described herein may be implemented in hardware, software, and/or firmware. In one implementation, the subject matter described herein for firewall policy optimization may be implemented on a general purpose computing platform. Figure 14 is a block diagram of a general purpose computing platform including software for firewall policy optimization according to an embodiment of the subject matter described herein. Referring to Figure 14, computing platform **1400** may be a general purpose computer, such as a personal computer, that includes a microprocessor **1402**, memory **1404**, and I/O interfaces **1406**. Microprocessor **1400** may be any suitable microprocessor, such as any of the Intel or AMD families of microprocessors. Memory **1404** may include volatile memory for running programs and persistent memory, such as one or more disk storage devices. I/O interface **1406** may include interfaces with I/O devices, such as user input devices and output devices.

In the illustrated example, software that may be resident in memory **1404** includes a firewall policy editor **1408** and a firewall policy optimizer **1410**. Firewall policy editor **1408** may allow a user to define a firewall policy. For example, firewall policy editor **1408** may allow a user to define a firewall policy by specifying different rules. The rules may be specified in a graphical manner, for example using policy DAGs as described above. Alternatively, firewall policy editor **1408** may allow a user to input rules in a tabular manner, as illustrated in any of the tables described herein. Firewall policy optimizer **1410** may implement any or all of the firewall policy optimization techniques to order rules entered via firewall policy editor **1408** in a manner that preserves policy integrity and that enhances firewall performance.

A firewall rule set that is optimized using the subject matter described herein may be implemented on any firewall system that includes one or more firewalls. For example, an optimized firewall rule set according to embodiments of the subject matter described herein may be implemented using any of the hierarchical, multi-node firewall systems described in commonly assigned, co-pending U.S. patent application no. 11/316,331, filed December 22, 2005, the disclosure of which is incorporated herein by reference in its entirety. Figure 15 illustrates an example of a multi-node firewall system suitable for implementing the firewall rules according to an embodiment of the subject matter described herein. Referring to Figure 15, a plurality of firewall nodes **1500**, **1502**, **1504**,and **1506** may collectively implement any of the optimized firewall policies described herein. For example, the firewall nodes may collectively implement different portions of a firewall policy data structure including an ordered list of firewall rules. A firewall policy engine **1508** resident on each firewall node may filter packets using its local portion **1510** of the firewall policy data structure. A control node **1512** may include a firewall policy optimizer **1514** that measures the average number of comparisons per packets for the current rule configuration and may dynamically reorder the rules to reduce the average number of comparisons per packet. For example, firewall policy optimizer **1514** may utilize any of the methods described herein to rearrange rules and improve firewall performance. Rules may be tested for rearrangement at user-specified intervals or when average number of packet comparisons increases by a user-specified amount.

References

The disclosure of each of the following references is hereby incorporated herein by reference in its entirety.

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It is to be understood that, if any prior art publication is referred to herein, such reference does not constitute an admission that the publication forms a part of the common general knowledge in the art, in Australia or any other country.

In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

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It will be understood that various details of the invention may be changed without departing from the scope of the invention. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

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CLAIMS

The claims defining the invention are as follows:

1. A method for producing a performance optimized firewall policy, the method comprising:
   (a) defining a firewall policy including an ordered list of firewall rules;
   (b) for each rule, defining a first match probability indicating the likelihood that the rule will be the first match for a given packet;
   (c) sorting neighboring rules in order of non-increasing probability for the first match probabilities and in a manner that preserves the firewall policy; and
   (d) sorting groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy, wherein at least one of the groups of two or more rules includes a first rule that prevents a second rule in the group from being moved, within the group, closer to a beginning of the ordered list that implements the firewall policy and wherein sorting the groups of rules includes moving the first and second rules closer to the beginning of the ordered list while maintaining their relative position.

2. The method of claim 1 wherein sorting neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy includes rearranging the rules if a first rule has a lower probability than a second rule and the first rule is not a subset of the second rule with a different action.

3. The method of claim 1 comprising sorting groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy.

COMS ID No: ARCS-372276 Received by IP Australia: Time (H:m) 11:49 Date (Y-M-d) 2012-06-06

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4. The method of claim 3 wherein sorting groups of two or more rules in a manner that preserves firewall policy includes assigning each group of rules to a sub-trie in a policy trie, computing a sum of packet matching probabilities for rules in each sub-trie, and, in response to determining that a first sub-trie has a lower sum than a second sub-trie, rotating the first and second sub-tries about a common parent so that rules in the second sub-trie will be applied before the rules in the first sub-trie in the firewall policy.

5. The method of claim 4 comprising, in response to determining that the first and second sub-tries have equal sums, determining whether the second sub-trie has an lower number of branches than the first sub-trie, and, in response to determining that the second sub-trie has a lower number of branches than the first sub-trie, rotating the first and second sub-tries about a common parent so that the rules in the second sub-trie will be applied before the rules in the first sub-trie in the firewall policy.

6. The method of claim 3 wherein sorting groups of two or more rules in a manner that preserves the firewall policy includes:
   (a) identifying first and second sub-lists of rules in the ordered list of firewall rules, the first sub-list preceding the second sub-list in the ordered list of firewall rules;
   (b) determining a sum of packet matching probabilities for each of the first and second sub-lists;
   (c) determining whether the first and second sub-lists intersect; and
   (d) in response to determining that the sum of the packet matching probabilities for the second sub-list is greater than the sum of the packet matching probabilities for the first sub-list and that the first and second sub-lists do not intersect, switching the order of the first and second sub-lists in the ordered list of firewall rules.

7. The method of claim 6 comprising, in response to determining that the sums of the packet matching probabilities for the first and sub-lists are

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equal, determining whether the second sub-list has a lower number of rules than the first sub-list, and, in response to determining that the second sub-list has a lower number of rules than the first sub-list, switching the order of the first and second sub-lists in the ordered list of firewall rules.

8. The method of claim 1 comprising splitting at least one of the firewall rules to reduce an average number of comparisons required per received packet.

9. The method of claim 1 comprising identifying intersecting rules having a common action and collapsing the rules into a single rule representing a union of the intersecting rules.

10. The method of claim 1 wherein sorting neighboring rules includes sorting rules such that comparisons for a particular class of packets are reduced.

11. The method of claim 1 comprising assigning the rules to vertices in a directed acyclical graph (DAG), determining precedence relationships between the rules, assigning the precedence relationships to edges that connect the vertices in the DAG, and wherein sorting the neighboring rules in order of non-increasing probability in a manner that preserves the firewall policy includes sorting the neighboring rules in a manner that preserves the precedence relationships represented by the DAG.

12. The method of claim 1 wherein the rules comprise intrusion detection rules.

13. The method of claim 1 wherein the rules comprise intrusion protection rules.

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14. A system for firewall policy optimization, for implementing the steps of any one of claims 1-13.

15. A network firewall comprising:
    (a) a firewall policy data structure for storing an ordered list of firewall rules;
    (b) a firewall policy engine for implementing a firewall policy by comparing packets to the rules in the order specified by the firewall policy data structure; and
    (c) a firewall policy optimizer for optimizing performance of the network firewall by reordering the rules in a manner that reduces an average number of rule comparisons per packet and that preserves the firewall policy, wherein the firewall policy optimizer is further configured to sort groups of two or more rules in order of non-increasing probability in a manner that preserves the firewall policy, wherein at least one of the groups of two or more rules includes a first rule that prevents a second rule in the group from being moved, within the group, closer to a beginning of the ordered list that implements the firewall policy and wherein sorting the groups of rules includes moving the first and second rules closer to the beginning of the ordered list while maintaining their relative position.

16. The network firewall of claim 15 wherein the firewall policy optimizer is adapted to measure average number of comparisons per packet for a rule ordering specified by the firewall policy data structure and to dynamically re-order to rules to reduce the average number of comparisons per packet.

17. A computer program product comprising computer executable instructions embodied in a computer readable medium which, when executed on one or more computing devices or platforms, performs steps in accordance with any one of claims 1 - 13.

18. A method for producing a performance optimized firewall policy, the method substantially as herein described with reference to the accompanying drawings.

19. A network firewall substantially as herein described with reference to the accompanying drawings.

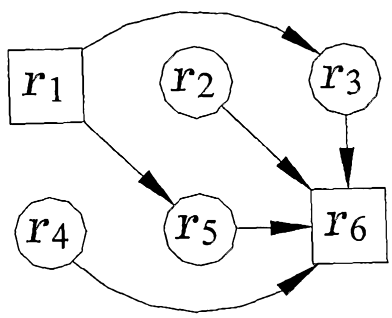

FIG. 1A

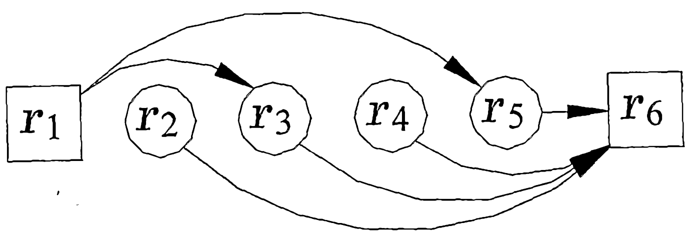

FIG. 1B

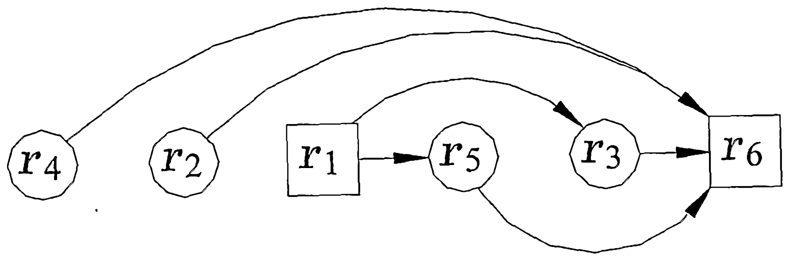

FIG. 2A

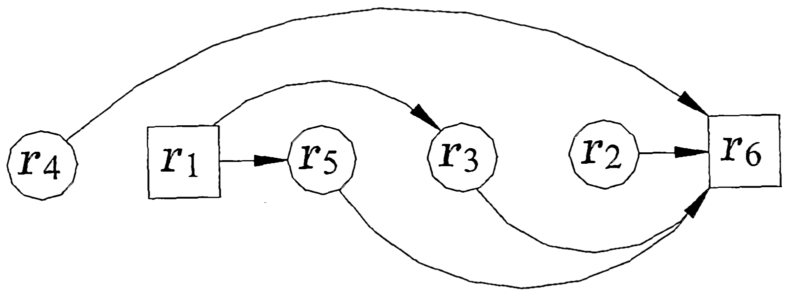

FIG. 2B

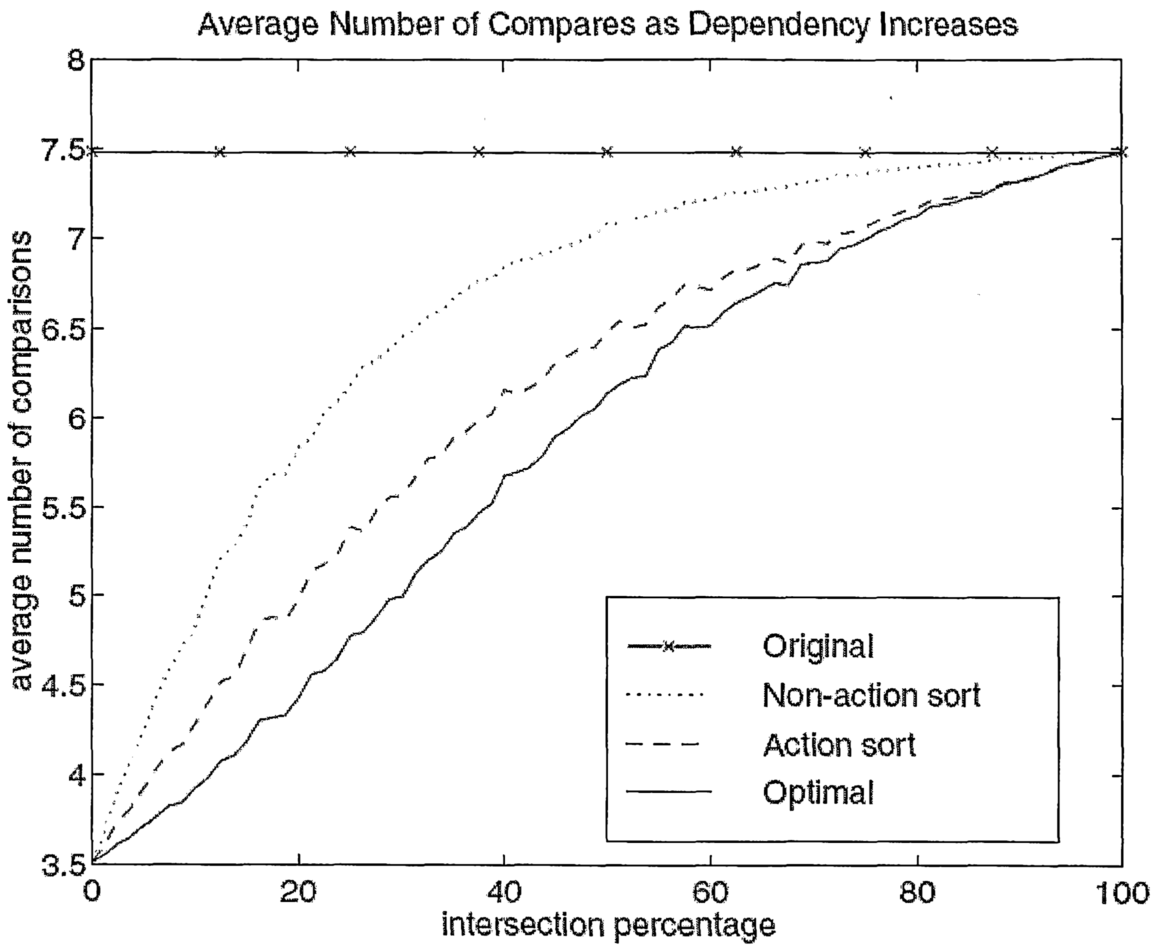
Average Number of Compares as Dependency Increases
average number of comparisons
intersection percentage
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
0
20
40
60
80
100
Original
Non-action sort
Action sort
Optimal

FIG. 3A

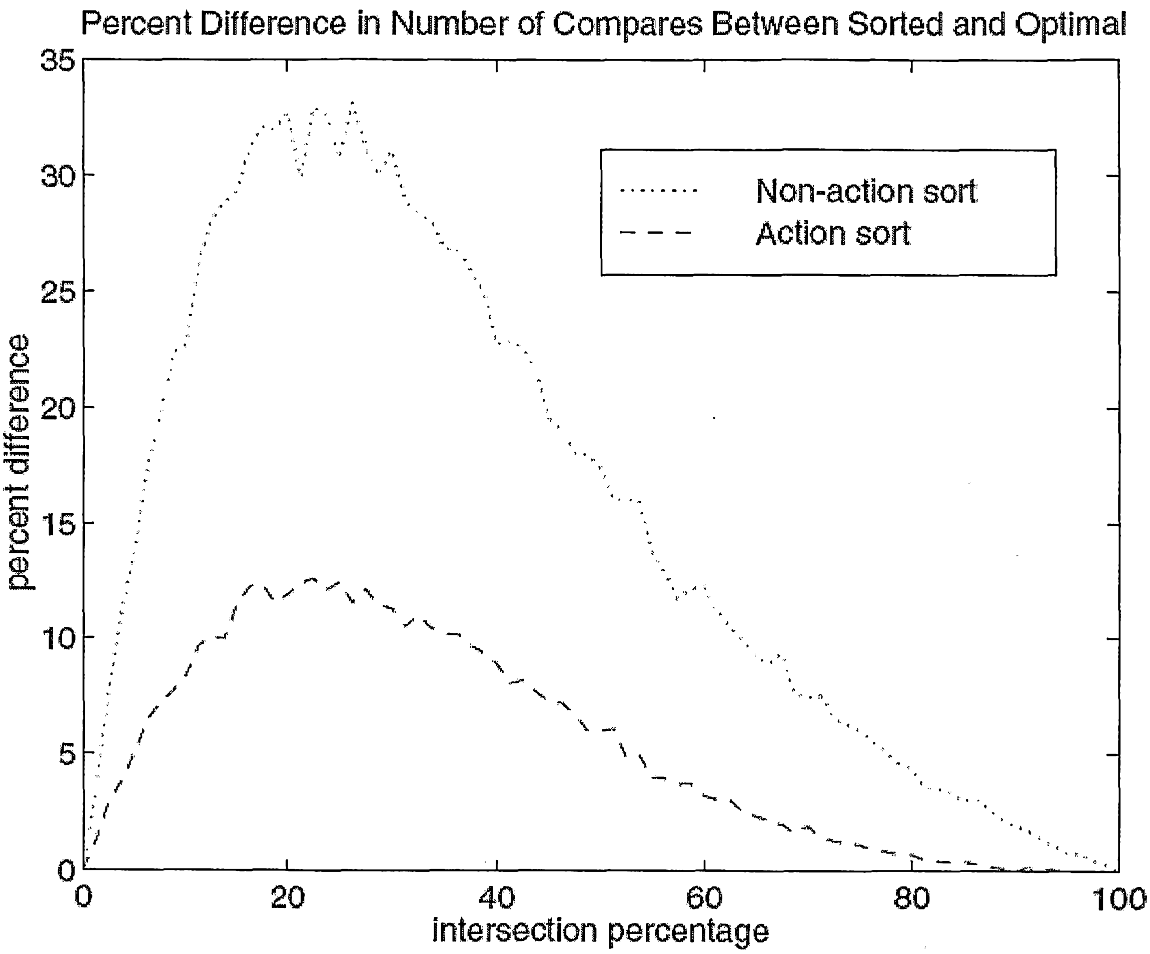
Percent Difference in Number of Compares Between Sorted and Optimal
Non-action sort
Action sort
percent difference
intersection percentage
0
5
10
15
20
25
30
35
0
20
40
60
80
100

FIG. 3B

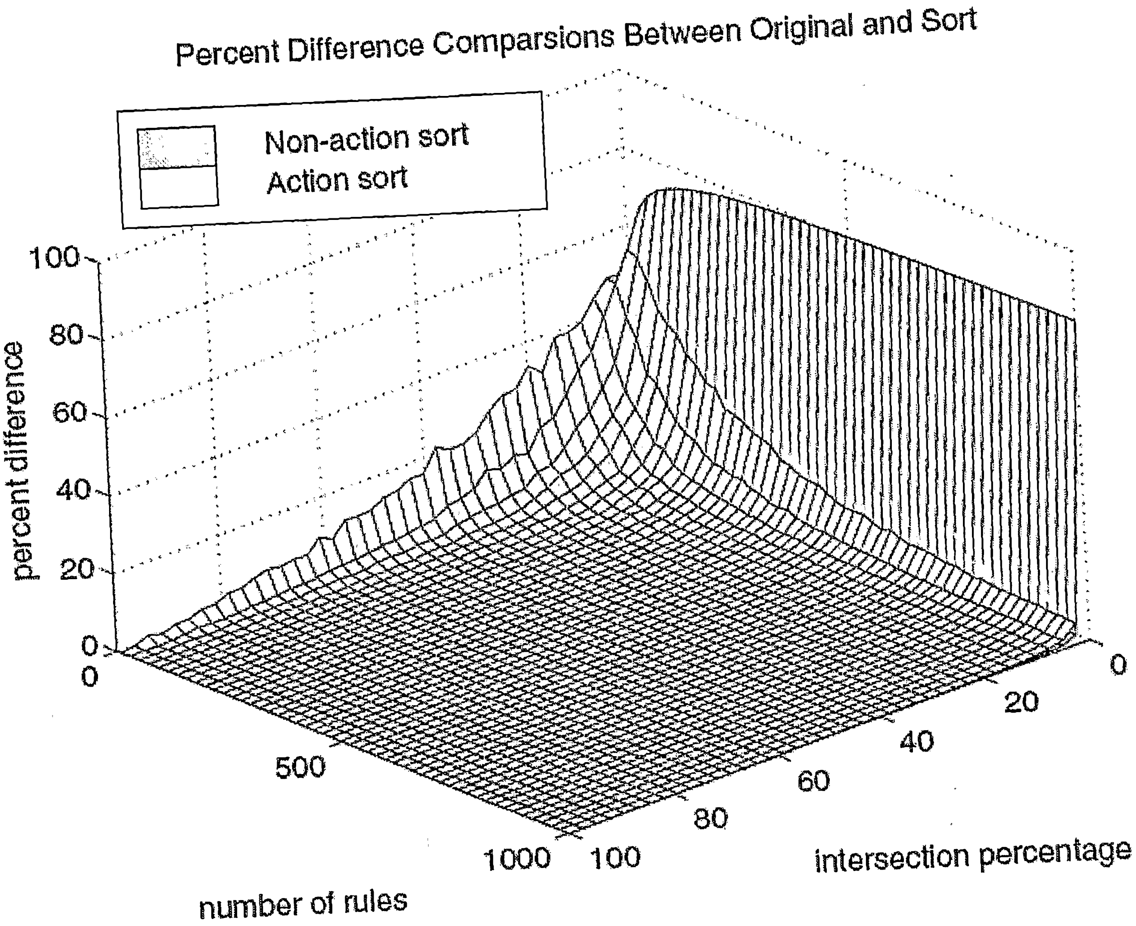
Percent Difference Comparsions Between Original and Sort
Non-action sort
Action sort
percent difference
100
80
60
40
20
0
0
500
1000
number of rules
100
80
60
40
20
0
intersection percentage

FIG. 4A

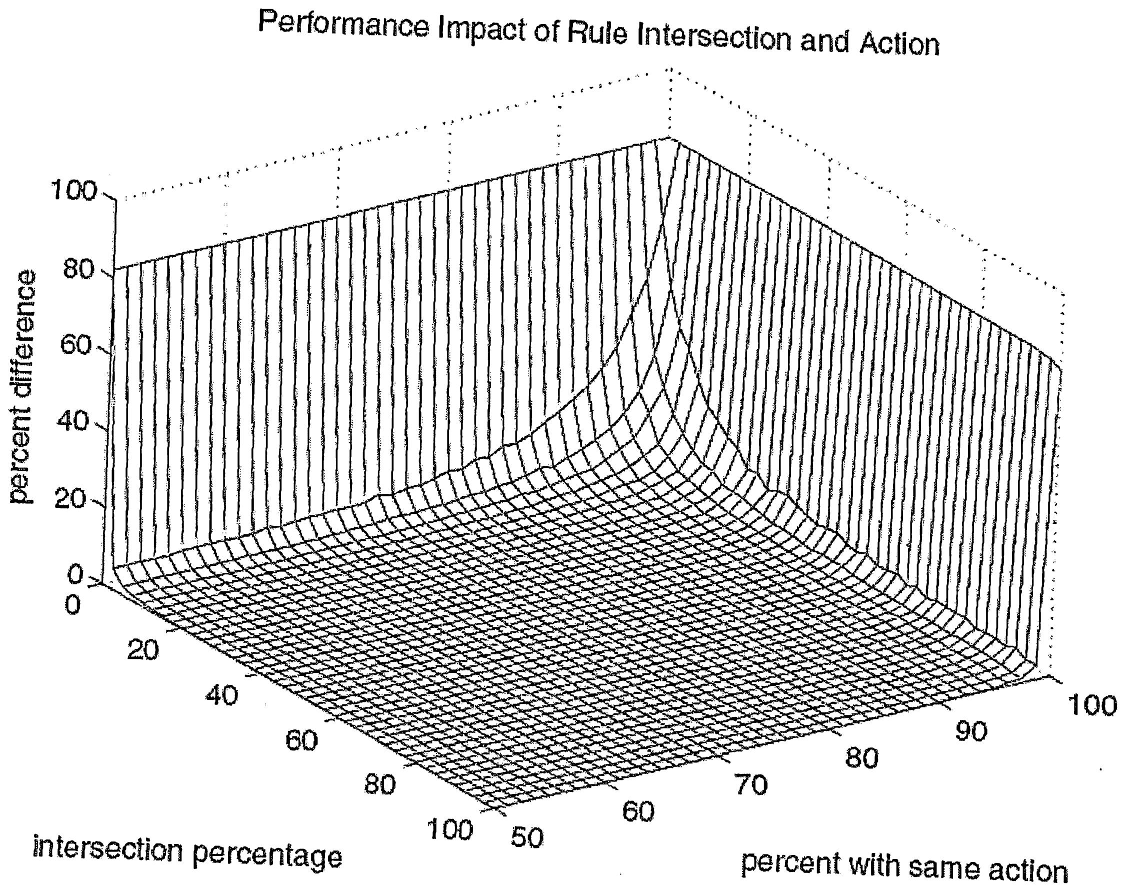
Performance Impact of Rule Intersection and Action
percent difference
100
80
60
40
20
0
0
20
40
60
80
100
intersection percentage
50
60
70
80
90
100
percent with same action

FIG. 4B

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 5A

r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 5B

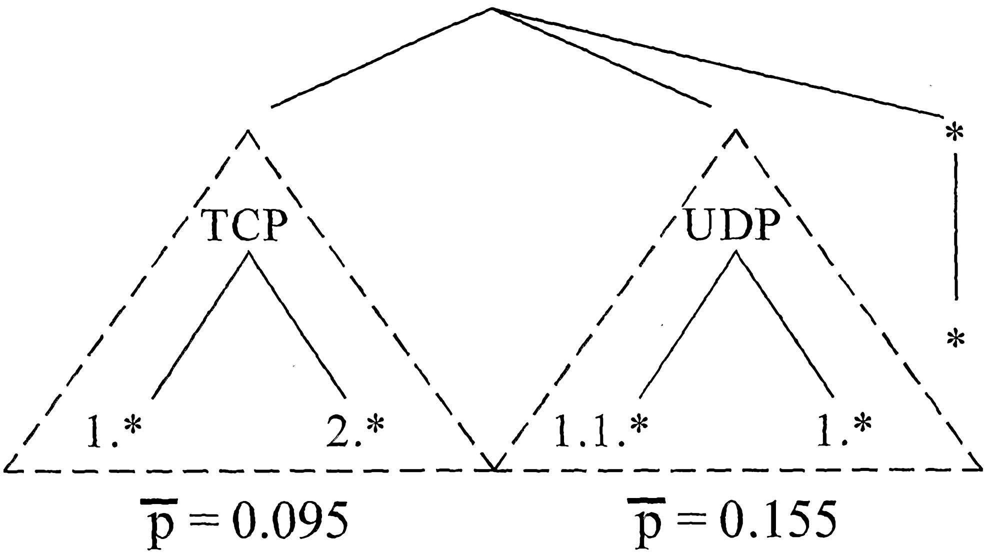

FIG. 6A

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	DENY)	$p_4 = 0.30$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_5	(*,	*,	DENY)	$p_5 = 0.50$

FIG. 6B

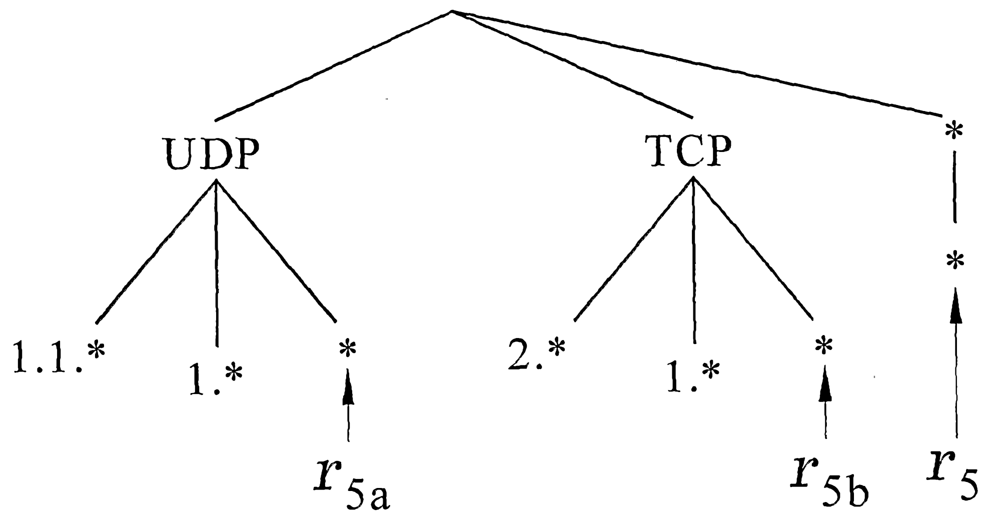

FIG. 7A

r_1	(UDP,	1.1.*,	ACCEPT)	$p_1 = 0.01$
r_4	(UDP,	1.*,	ACCEPT)	$p_4 = 0.30$
r_{5a}	(UDP,	*,	DENY)	$p_{5a} = 0.47$
r_3	(TCP,	2.*,	ACCEPT)	$p_3 = 0.17$
r_2	(TCP,	1.*,	ACCEPT)	$p_2 = 0.02$
r_{5b}	(TCP,	*,	DENY)	$p_{5b} = 0.03$

FIG. 7B

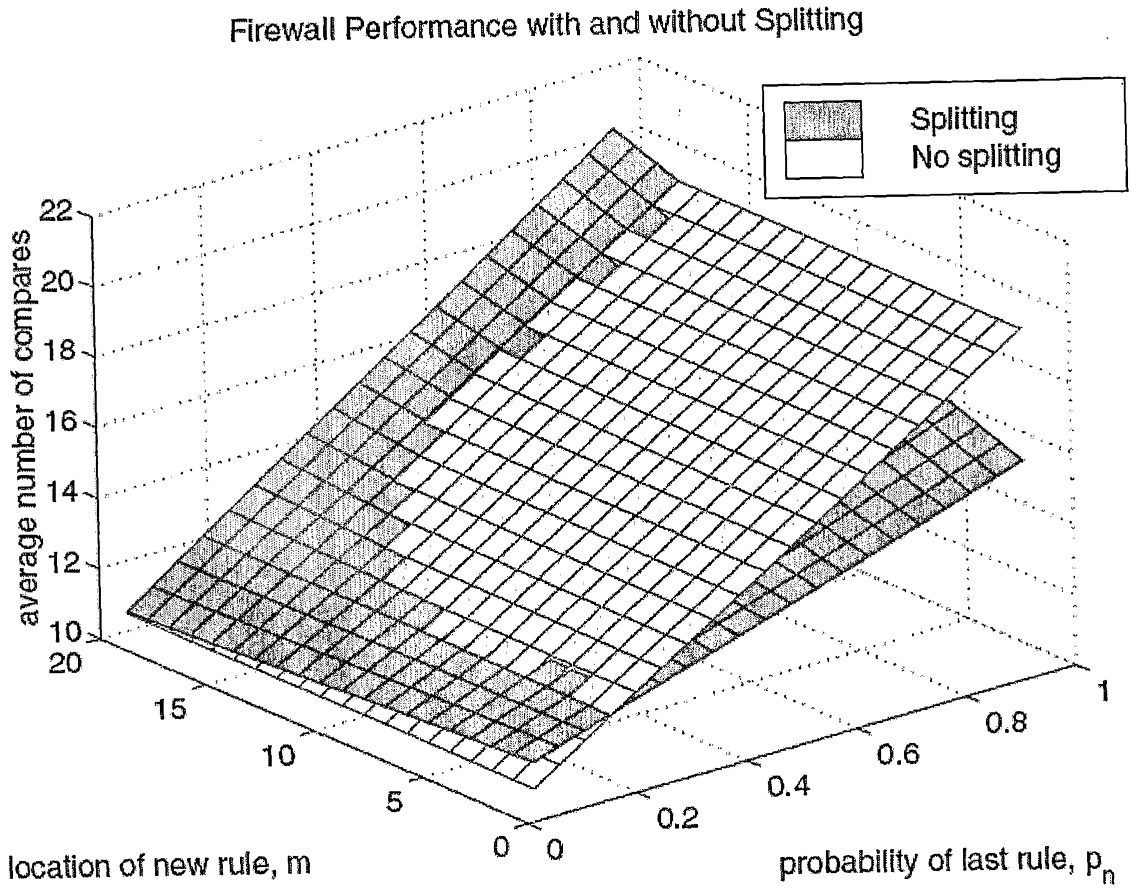
Firewall Performance with and without Splitting
Splitting
No splitting
average number of compares
22
20
18
16
14
12
10
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
location of new rule, m
probability of last rule, p_n

FIG. 8A

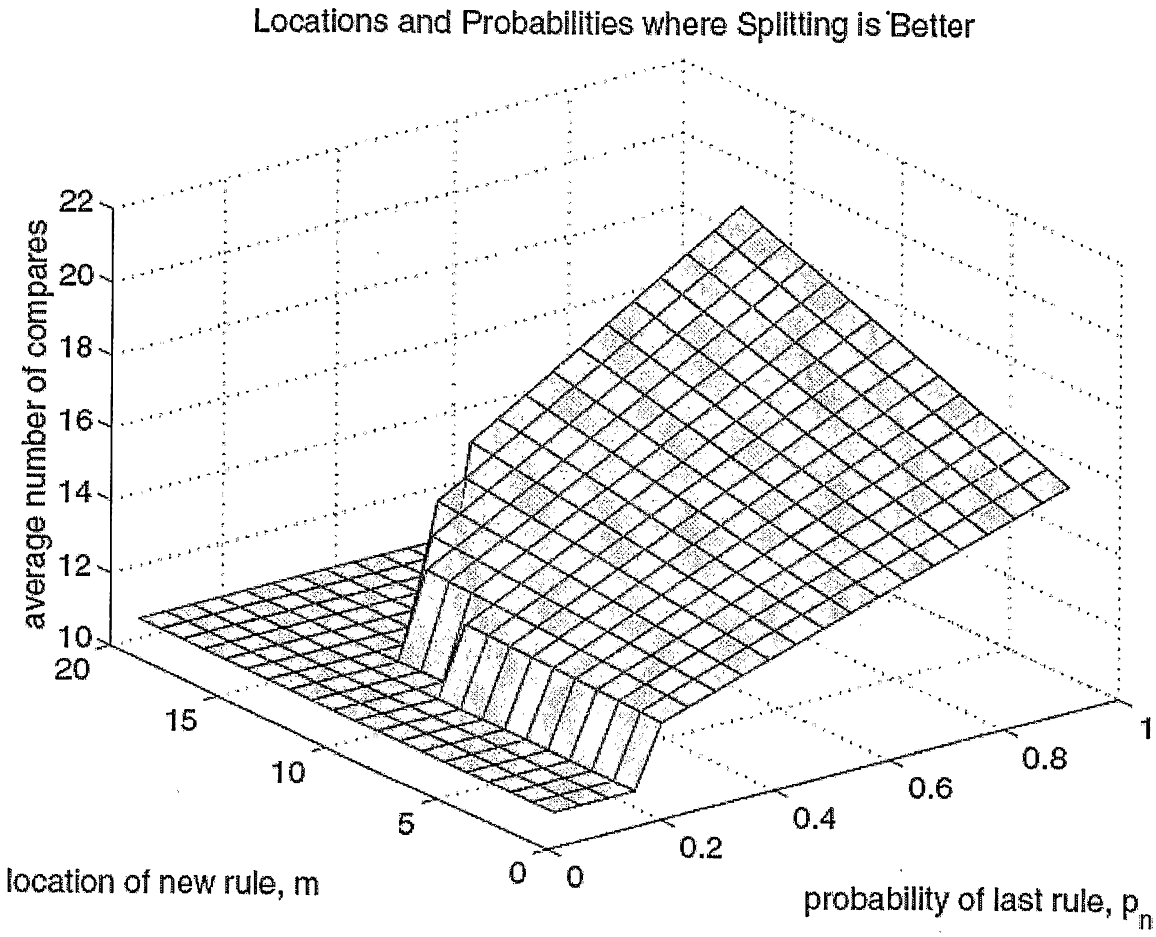
Locations and Probabilities where Splitting is Better
average number of compares
22
20
18
16
14
12
10
20
15
10
5
0
location of new rule, m
0
0.2
0.4
0.6
0.8
1
probability of last rule, p_n

FIG. 8B

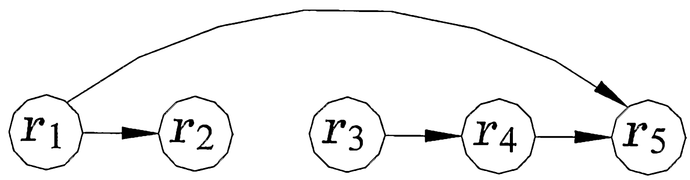

FIG. 9A

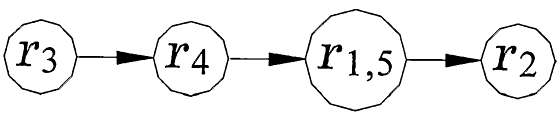

FIG. 9B

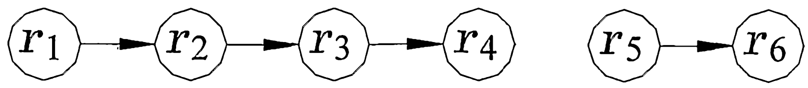

FIG. 10A

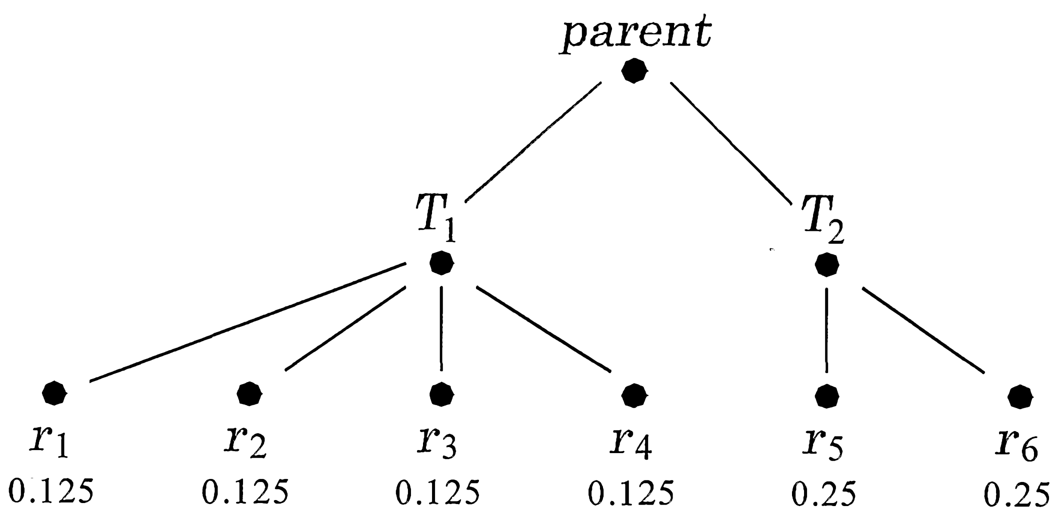

FIG. 10B

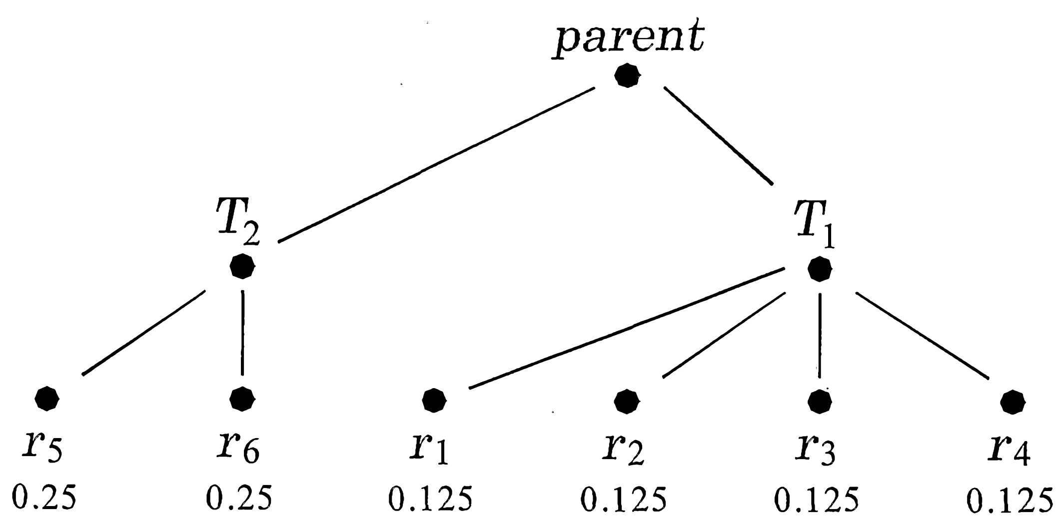

FIG. 10C

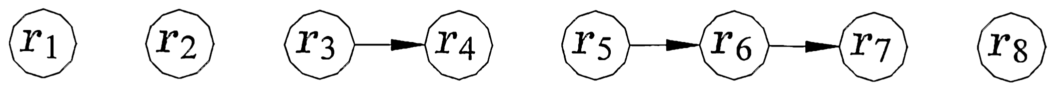

FIG. 11A

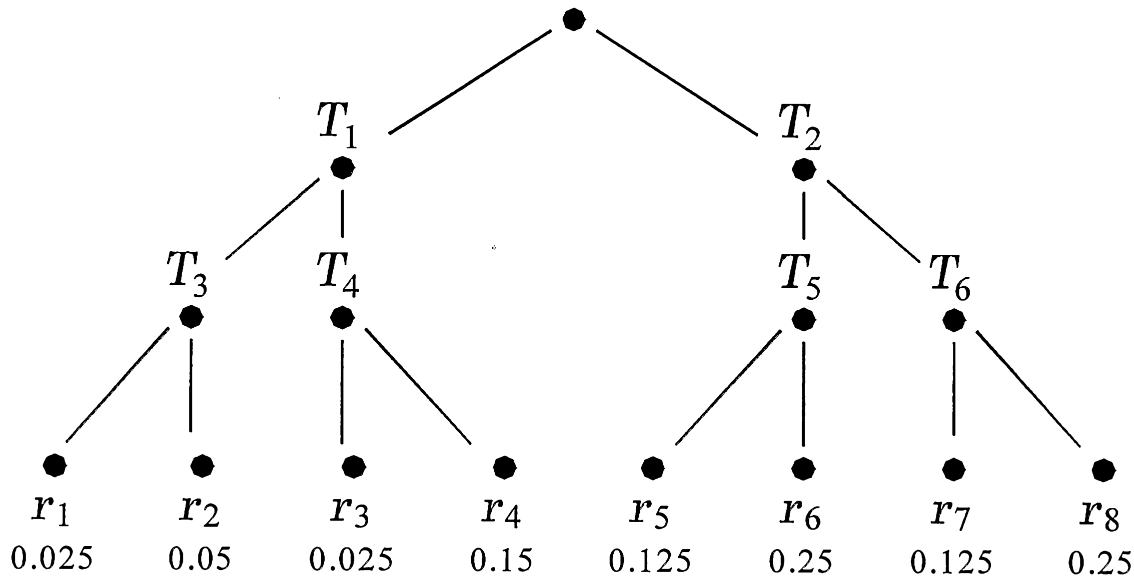

FIG. 11B

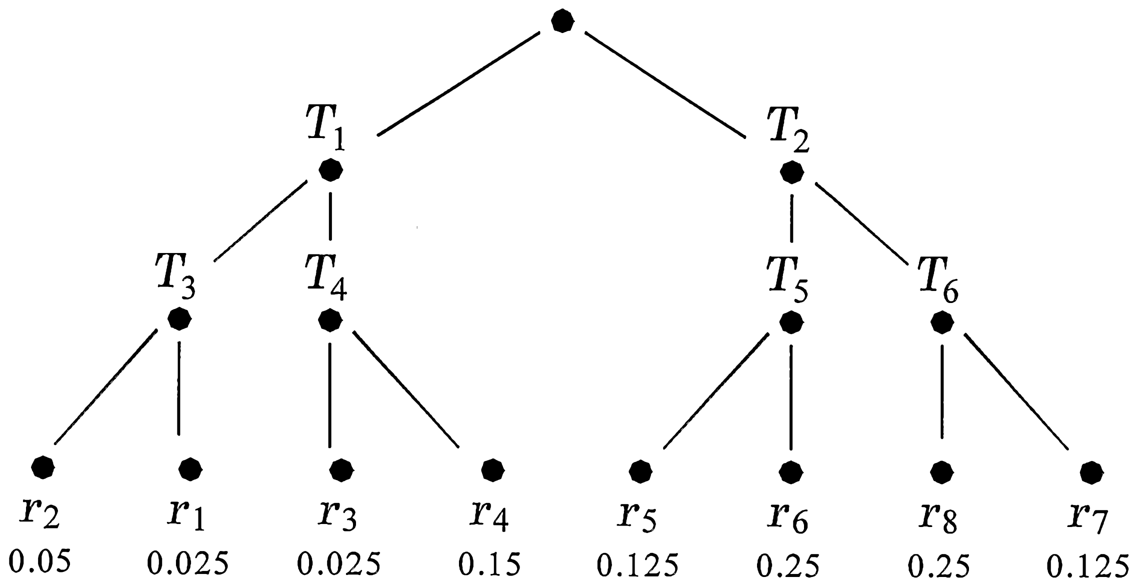

FIG. 11C

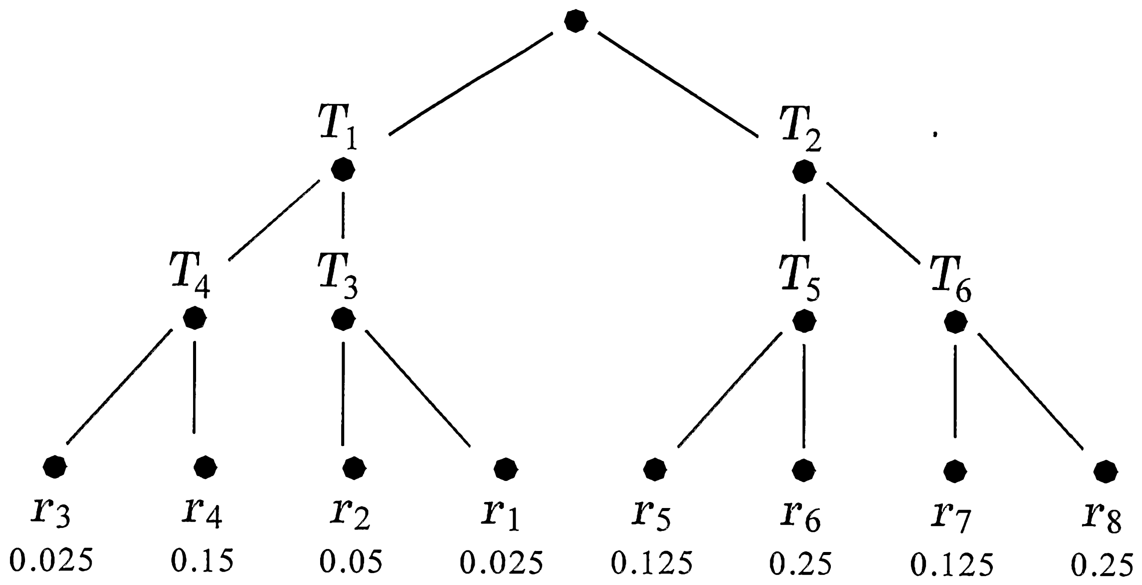

FIG. 11D

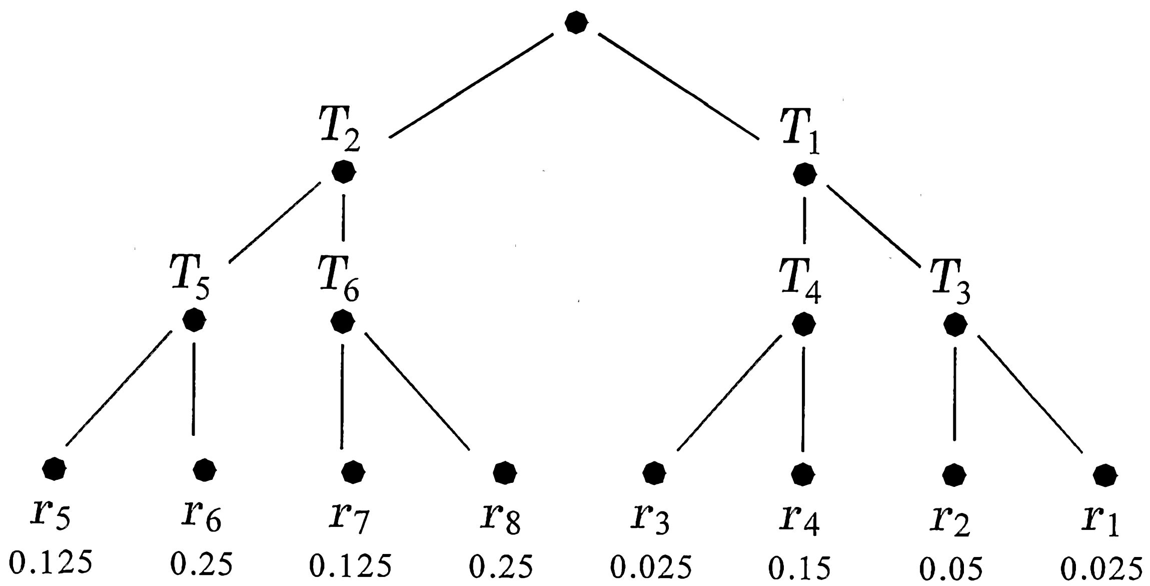

FIG. 11E

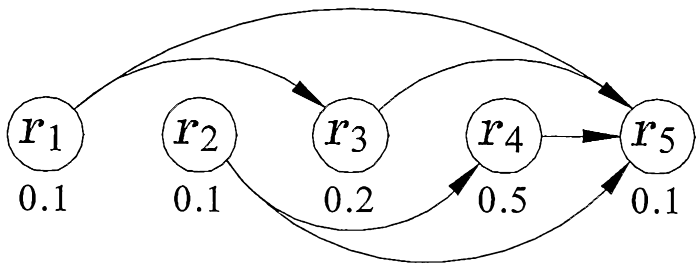

FIG. 12A

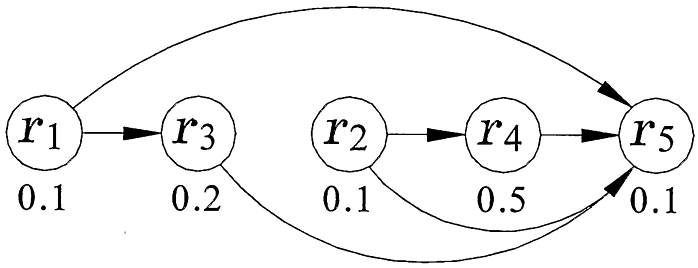

FIG. 12B

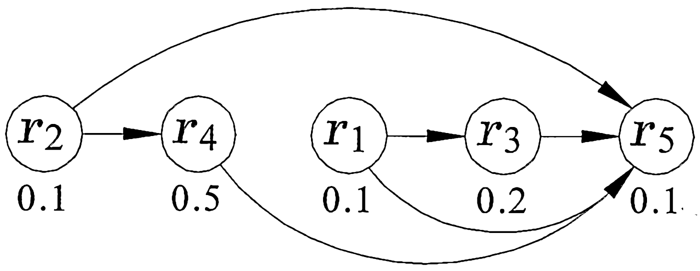

FIG. 12C

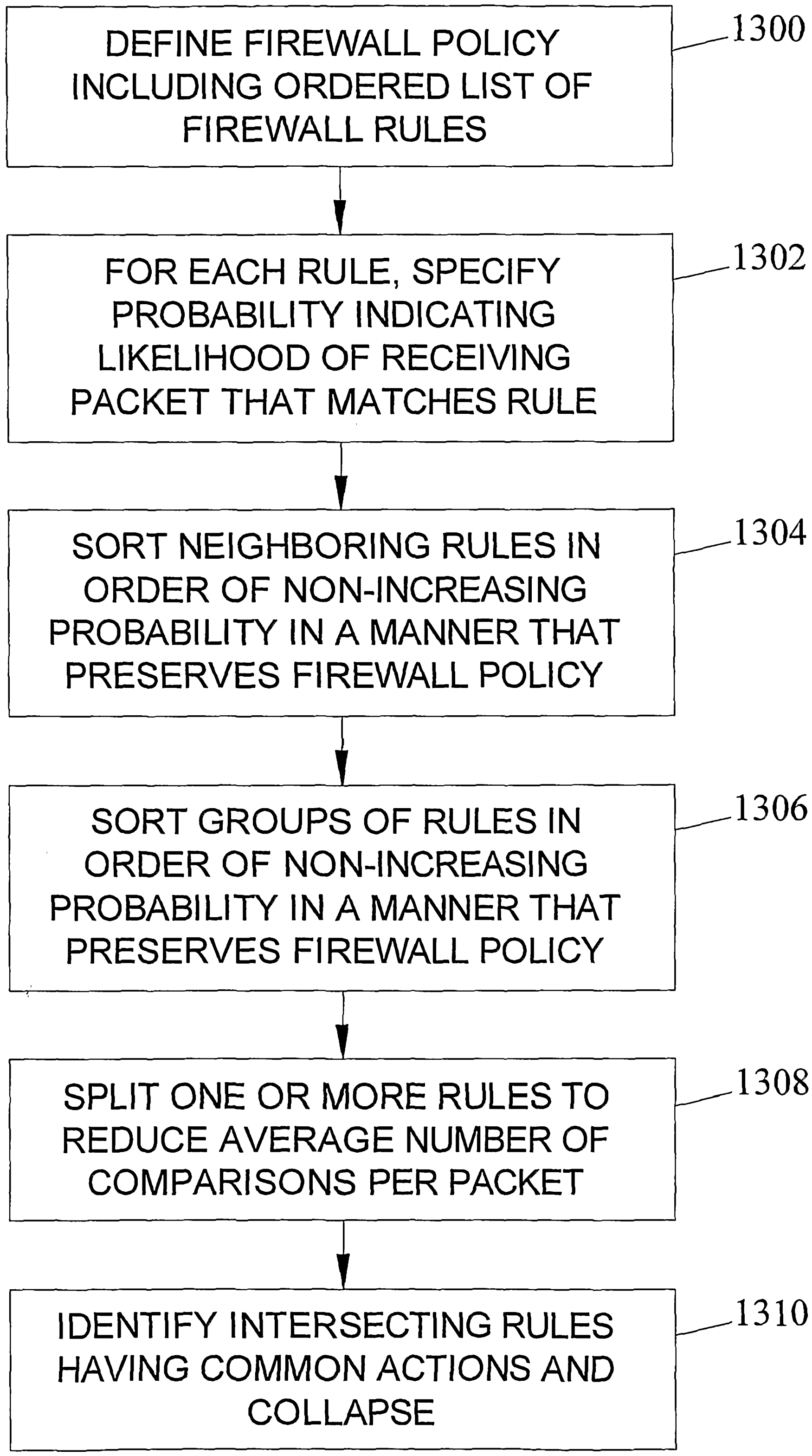
DEFINE FIREWALL POLICY INCLUDING ORDERED LIST OF FIREWALL RULES
1300
FOR EACH RULE, SPECIFY PROBABILITY INDICATING LIKELIHOOD OF RECEIVING PACKET THAT MATCHES RULE
1302
SORT NEIGHBORING RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1304
SORT GROUPS OF RULES IN ORDER OF NON-INCREASING PROBABILITY IN A MANNER THAT PRESERVES FIREWALL POLICY
1306
SPLIT ONE OR MORE RULES TO REDUCE AVERAGE NUMBER OF COMPARISONS PER PACKET
1308
IDENTIFY INTERSECTING RULES HAVING COMMON ACTIONS AND COLLAPSE
1310

FIG. 13

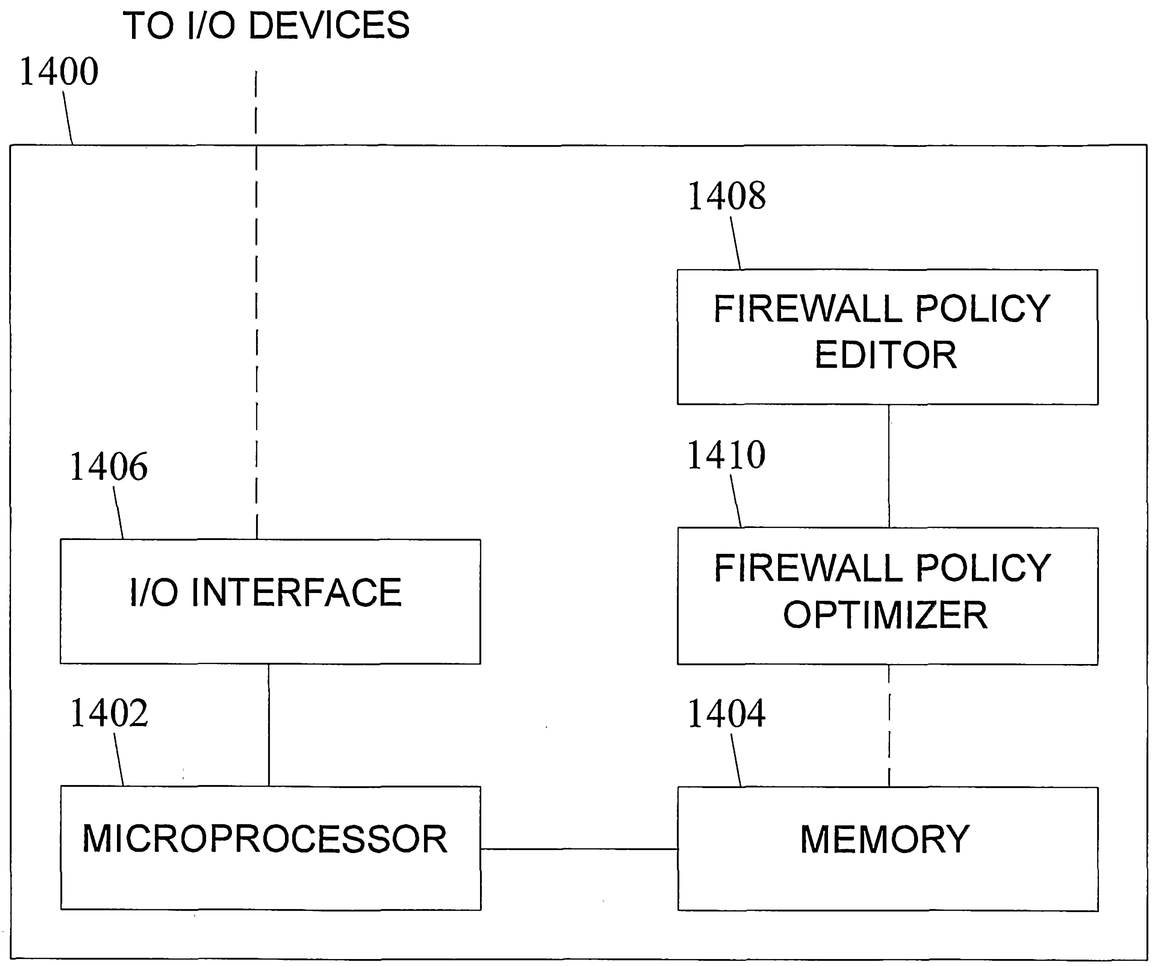
TO I/O DEVICES
1400
1408
FIREWALL POLICY EDITOR
1410
FIREWALL POLICY OPTIMIZER
1406
I/O INTERFACE
1402
MICROPROCESSOR
1404
MEMORY

FIG. 14

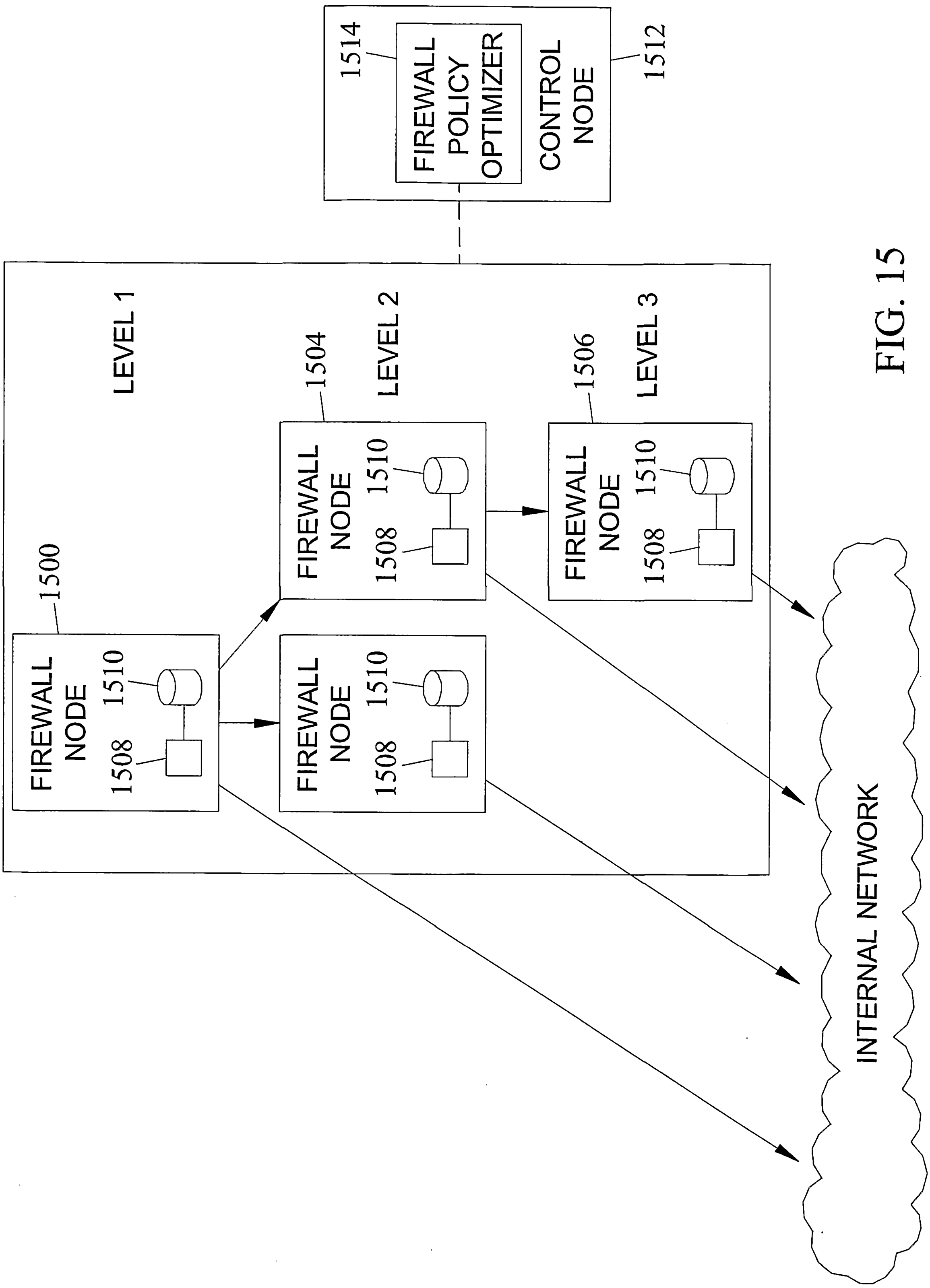
FIREWALL POLICY OPTIMIZER
1514
CONTROL NODE
1512
LEVEL 1
LEVEL 2
LEVEL 3
FIREWALL NODE
1500
1504
1506
1508
1510
INTERNAL NETWORK

FIG. 15