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Nicol et al.

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(54) ANALYSIS OF DISTRIBUTED POLICY RULE-SETS FOR COMPLIANCE WITH GLOBAL POLICY

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(51) **Int. Cl.**
G06F 17/00 (2006.01)
H04L 29/06 (2006.01)

(52) **U.S. Cl.** **726/1**; 726/25; 709/224

(58) **Field of Classification Search** 726/1, 25
See application file for complete search history.

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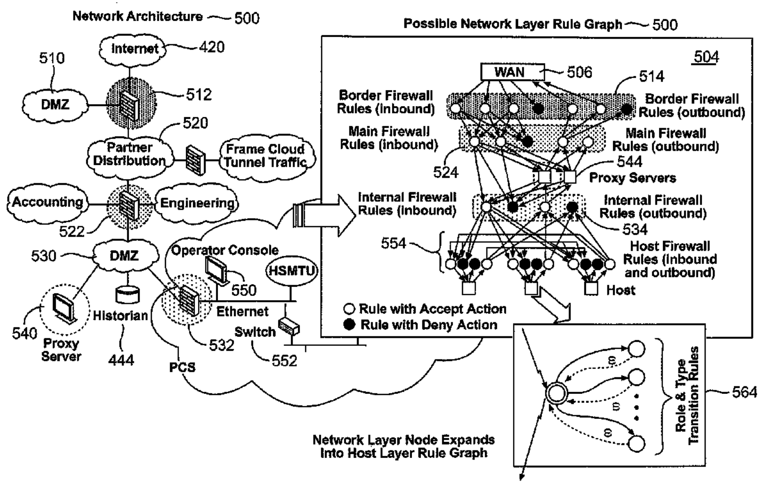
(57) **ABSTRACT**

A method for analysis of distributed device rule-sets for compliance with global policies includes enabling an administrator to specify a network topology with intercommunicating elements and parameters required to secure the intercommunication with access control elements of the network topology; establishing connections to the access controls elements to capture a snapshot configuration of device rule-sets of the access control elements; enabling the administrator to specify a set of global access constraints with reference to the access control elements; enabling the administrator to select between exhaustive analysis and statistical analysis; conducting the selected analysis to determine violations by the device rule-sets that fail to comply with the set of global access constraints, wherein statistical analysis quantitatively characterizes a level of compliance without conducting analysis of all potential network paths; and providing results of the selected analysis to the administrator through a graphical user interface (GUI) as the results are obtained.

34 Claims, 9 Drawing Sheets


Network Architecture 500
Internet 420
510
DMZ
512
520
Partner Distribution
Frame Cloud Tunnel Traffic
Accounting
Engineering
522
530
DMZ
Operator Console
HSMTU
550
Historian
Ethernet Switch
540
Proxy Server
444
PCS
532
552
Possible Network Layer Rule Graph 500
504
WAN 506
514
Border Firewall Rules (inbound)
Border Firewall Rules (outbound)
Main Firewall Rules (inbound)
Main Firewall Rules (outbound)
524
544
Proxy Servers
Internal Firewall Rules (inbound)
Internal Firewall Rules (outbound)
534
554
Host Firewall Rules (inbound and outbound)
Host
○ Rule with Accept Action
● Rule with Deny Action
Role & Type Transition Rules
564
Network Layer Node Expands Into Host Layer Rule Graph

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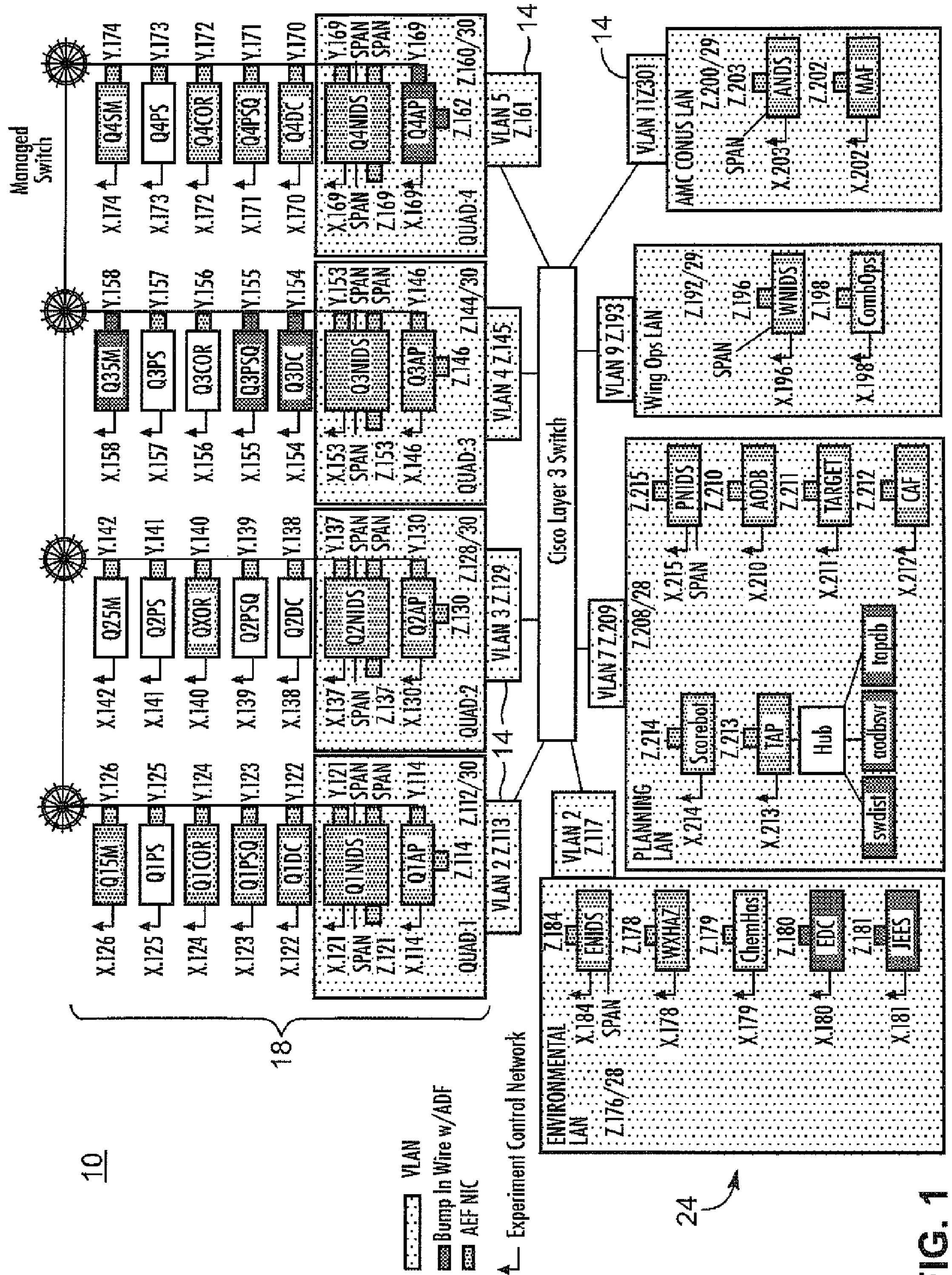
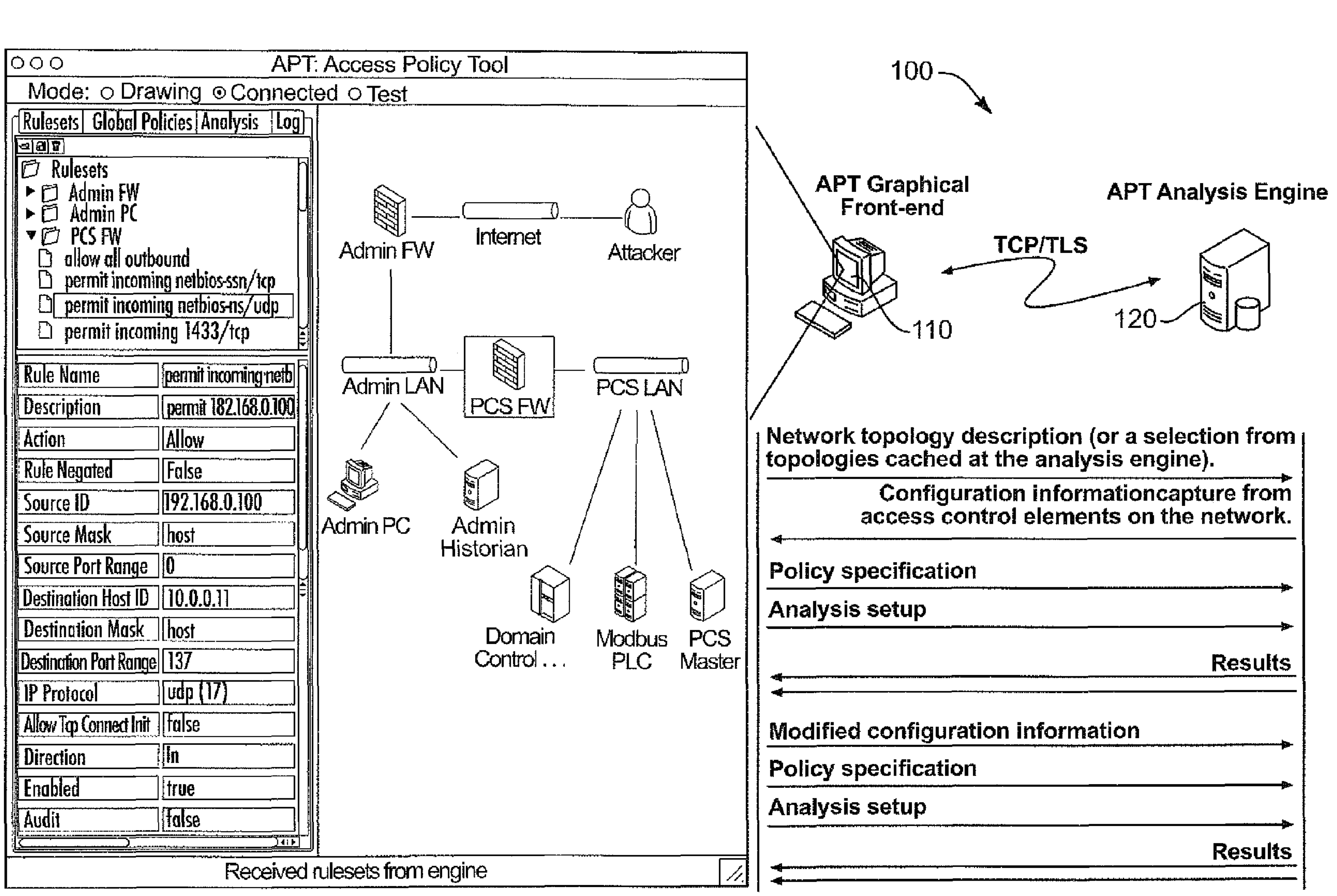

10
VLAN
Bump In Wire w/ADF
AEF NIC
Experiment Control Network
Managed Switch
18
14
24
Cisco Layer 3 Switch
QUAD:1
QUAD:2
QUAD:3
QUAD:4
VLAN 2 Z.113
VLAN 3 Z.129
VLAN 4 Z.145
VLAN 5 Z.161
VLAN 2 Z.117
VLAN 7 Z.209
VLAN 9 Z.193
VLAN 11 Z.201
Q1SM
Q1PS
Q1COR
Q1PSQ
Q1DC
Q1NIDS
Q1AP
Q2SM
Q2PS
QXOR
Q2PSQ
Q2DC
Q2NIDS
Q2AP
Q3SM
Q3PS
Q3COR
Q3PSQ
Q3DC
Q3NIDS
Q3AP
Q4SM
Q4PS
Q4COR
Q4PSQ
Q4DC
Q4NIDS
Q4AP
SPAN
ENVIRONMENTAL LAN
Z.176/28
ENIDS
WXHAZ
ChemHas
EDC
JEES
PLANNING LAN
Z.208/28
Scorebot
TAP
Hub
swdist
aodbsvr
tapdb
PNIDS
AODB
TARGET
CAF
Wing Ops LAN
Z.192/29
WNIDS
CombOps
AMC CONUS LAN
Z.200/29
ANDS
MAF

FIG. 1



Rule Name	permit incoming netb
Description	permit 182.168.0.100
Action	Allow
Rule Negated	False
Source ID	192.168.0.100
Source Mask	host
Source Port Range	0
Destination Host ID	10.0.0.11
Destination Mask	host
Destination Port Range	137
IP Protocol	udp (17)
Allow Tcp Connect Init	False
Direction	In
Enabled	true
Audit	false

Received rulesets from engine

Network topology description (or a selection from topologies cached at the analysis engine).

Configuration informationcapture from access control elements on the network.

Policy specification

Analysis setup

Results

Modified configuration information

Policy specification

Analysis setup

Results

FIG. 2

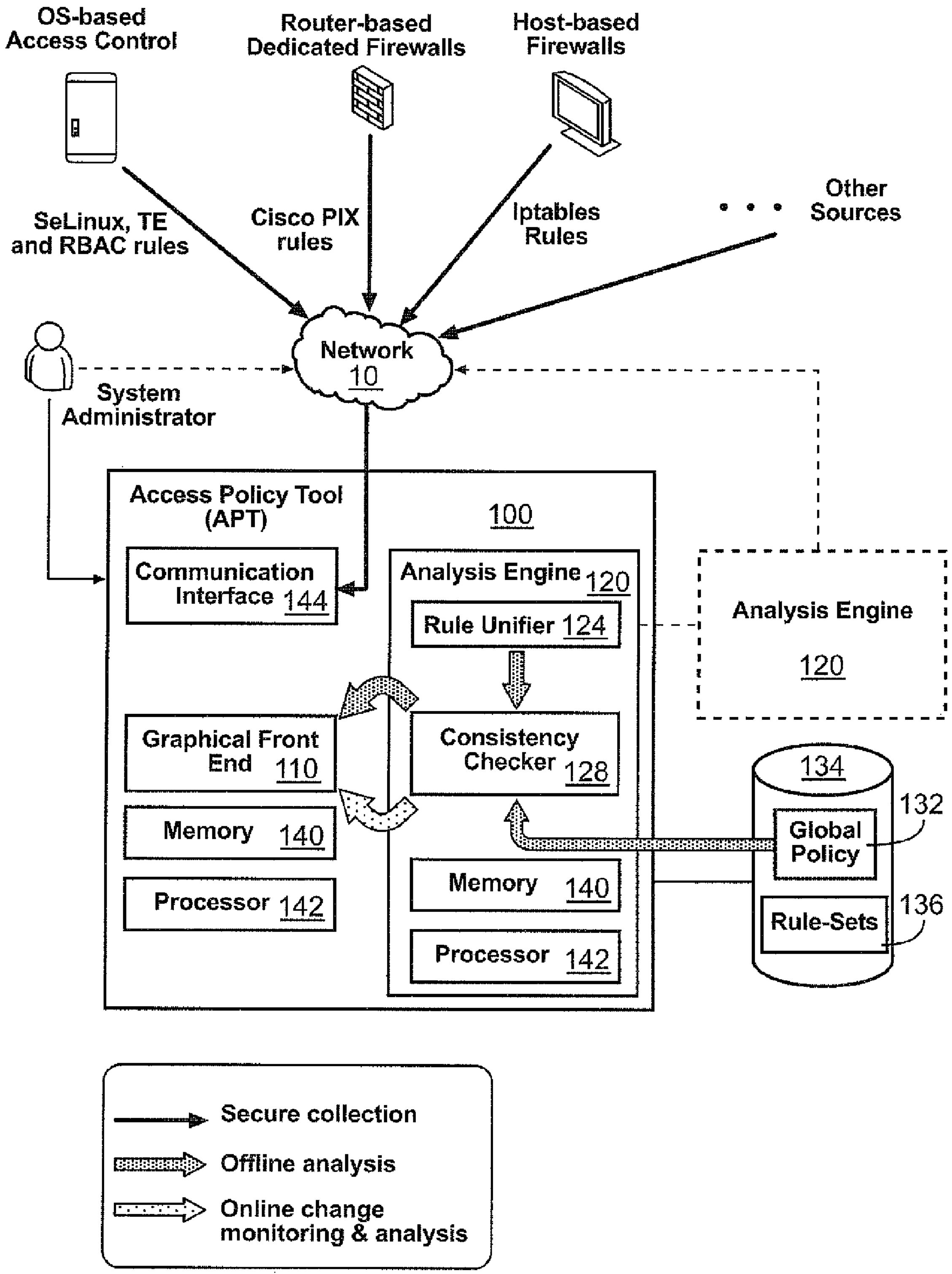
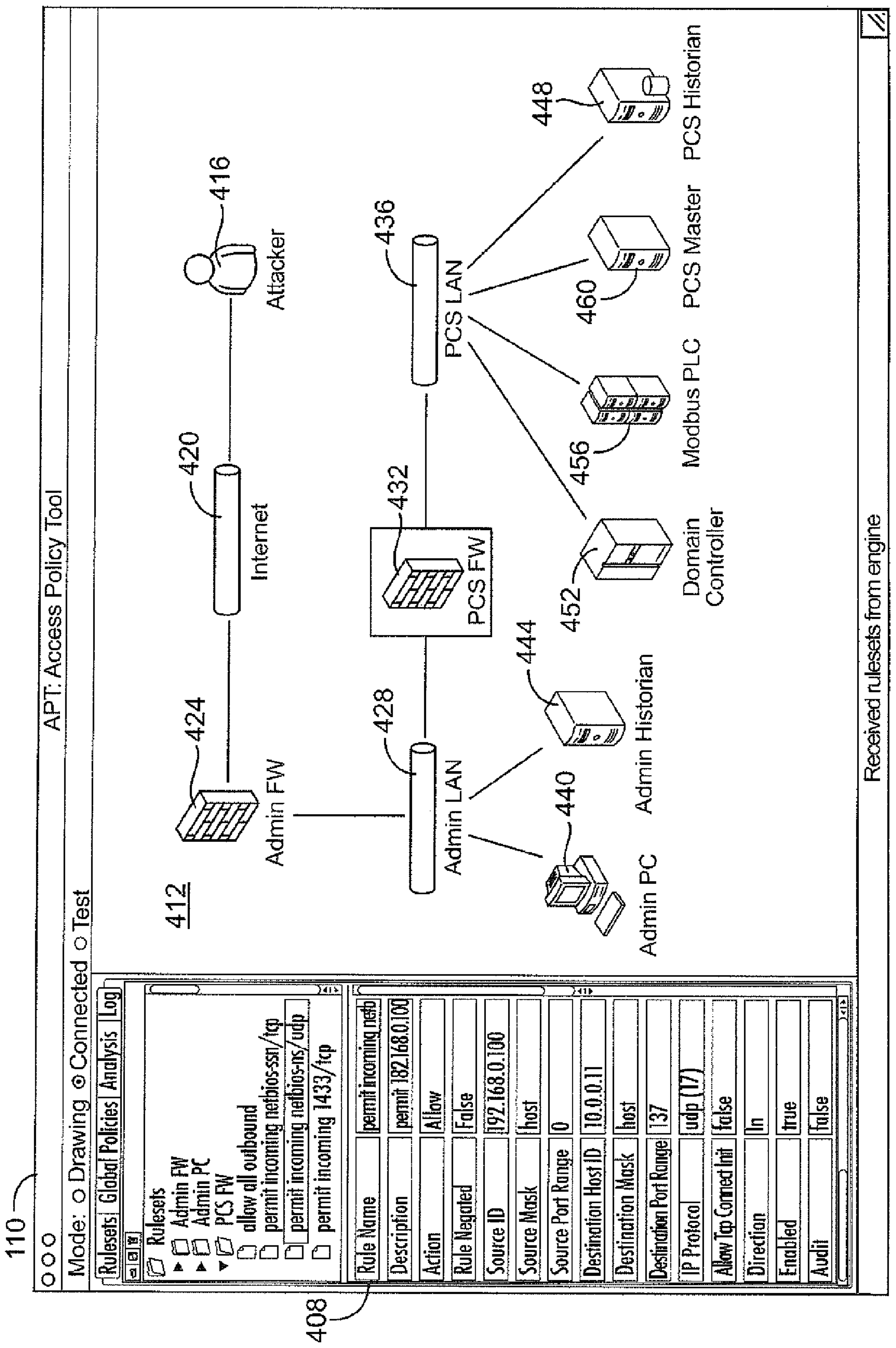

OS-based Access Control
Router-based Dedicated Firewalls
Host-based Firewalls
SeLinux, TE and RBAC rules
Cisco PIX rules
Iptables Rules
Other Sources
Network 10
System Administrator
Access Policy Tool (APT)
100
Communication Interface 144
Analysis Engine 120
Rule Unifier 124
Analysis Engine 120
Graphical Front End 110
Consistency Checker 128
134
132
Global Policy
Memory 140
Memory 140
Processor 142
Rule-Sets
136
Processor 142
Secure collection
Offline analysis
Online change monitoring & analysis

FIG. 3



Rule Name	permit incoming netb
Description	permit 182.168.0.100
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Rule Negated	False
Source ID	192.168.0.100
Source Mask	host
Source Port Range	0
Destination Host ID	10.0.0.11
Destination Mask	host
Destination Port Range	137
IP Protocol	udp (17)
Allow Tcp Connect Init	false
Direction	In
Enabled	true
Audit	false

FIG. 4

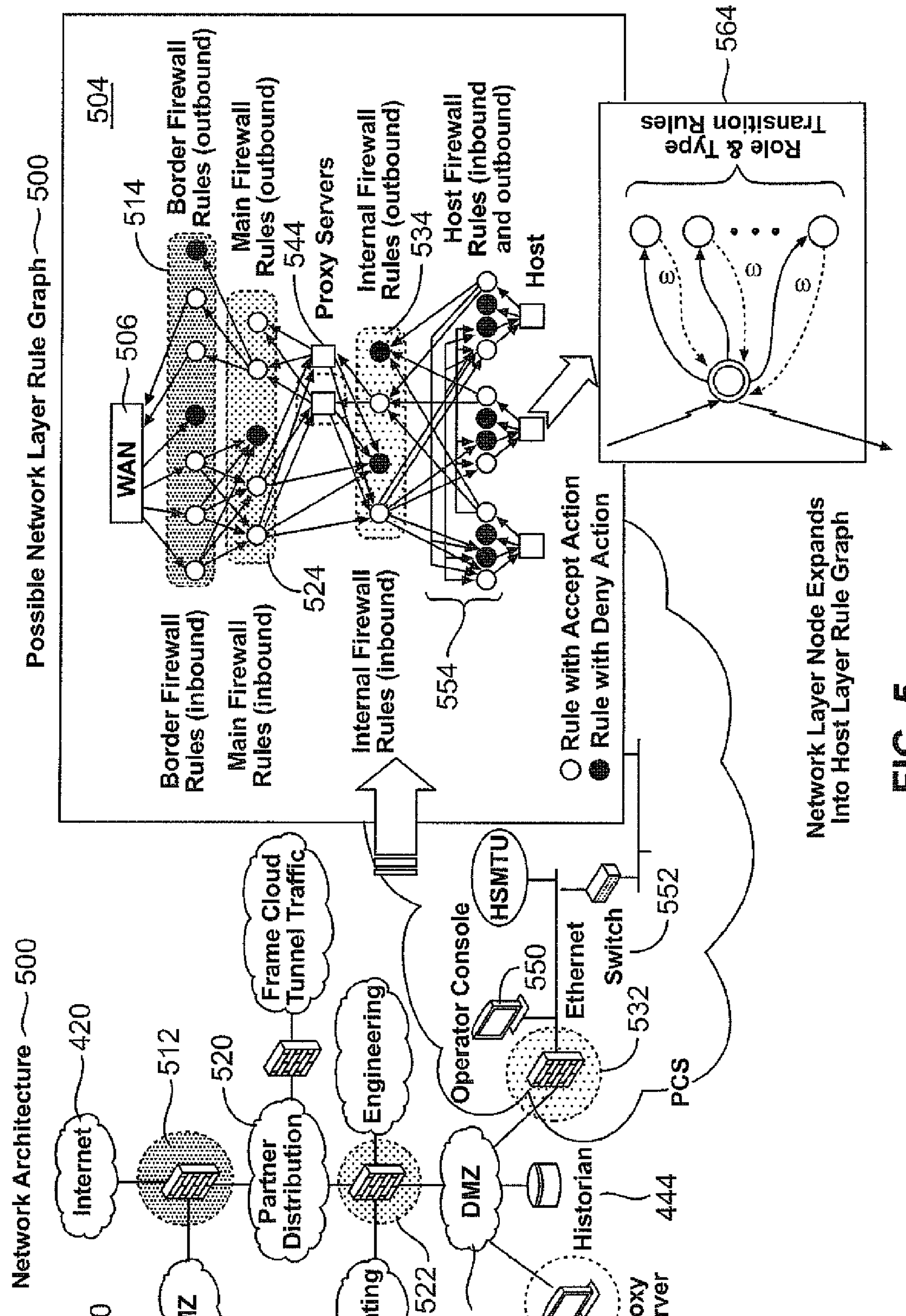

Network Architecture 500
Internet
420
512
520
DMZ
510
Partner Distribution
Frame Cloud Tunnel Traffic
Engineering
Accounting
522
DMZ
530
Historian
444
Proxy Server
540
Operator Console
550
PCS
532
Ethernet Switch
552
HSMTU
Possible Network Layer Rule Graph 500
504
WAN
506
514
Border Firewall Rules (outbound)
Main Firewall Rules (outbound)
544
Proxy Servers
Internal Firewall Rules (outbound)
534
Host Firewall Rules (inbound and outbound)
Host
Border Firewall Rules (inbound)
Main Firewall Rules (inbound)
524
Internal Firewall Rules (inbound)
554
○ Rule with Accept Action
● Rule with Deny Action
ε
ε
ε
Role & Type Transition Rules
564
Network Layer Node Expands Into Host Layer Rule Graph

FIG. 5

600

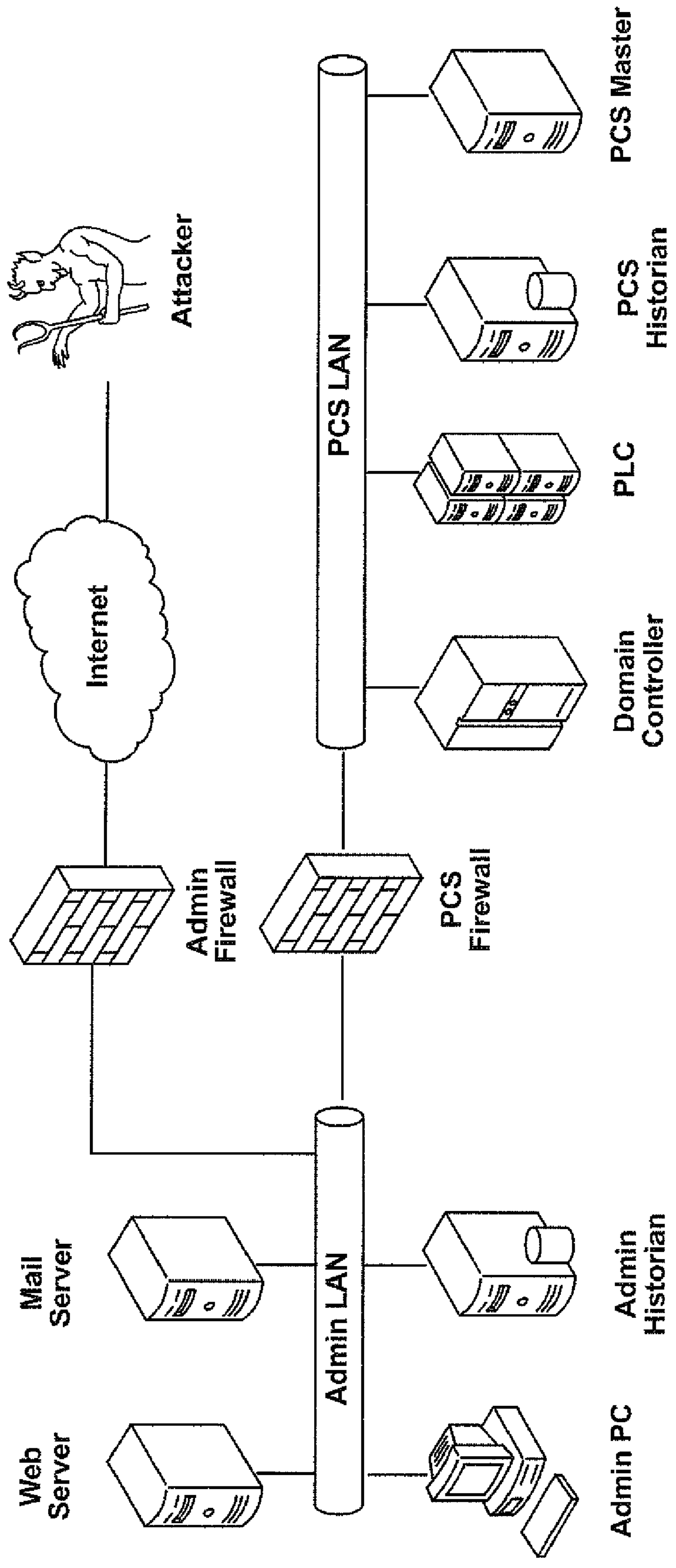

Web Server
Mail Server
Admin LAN
Admin PC
Admin Historian
Admin Firewall
PCS Firewall
Internet
Attacker
PCS LAN
Domain Controller
PLC
PCS Historian
PCS Master

FIG. 6A

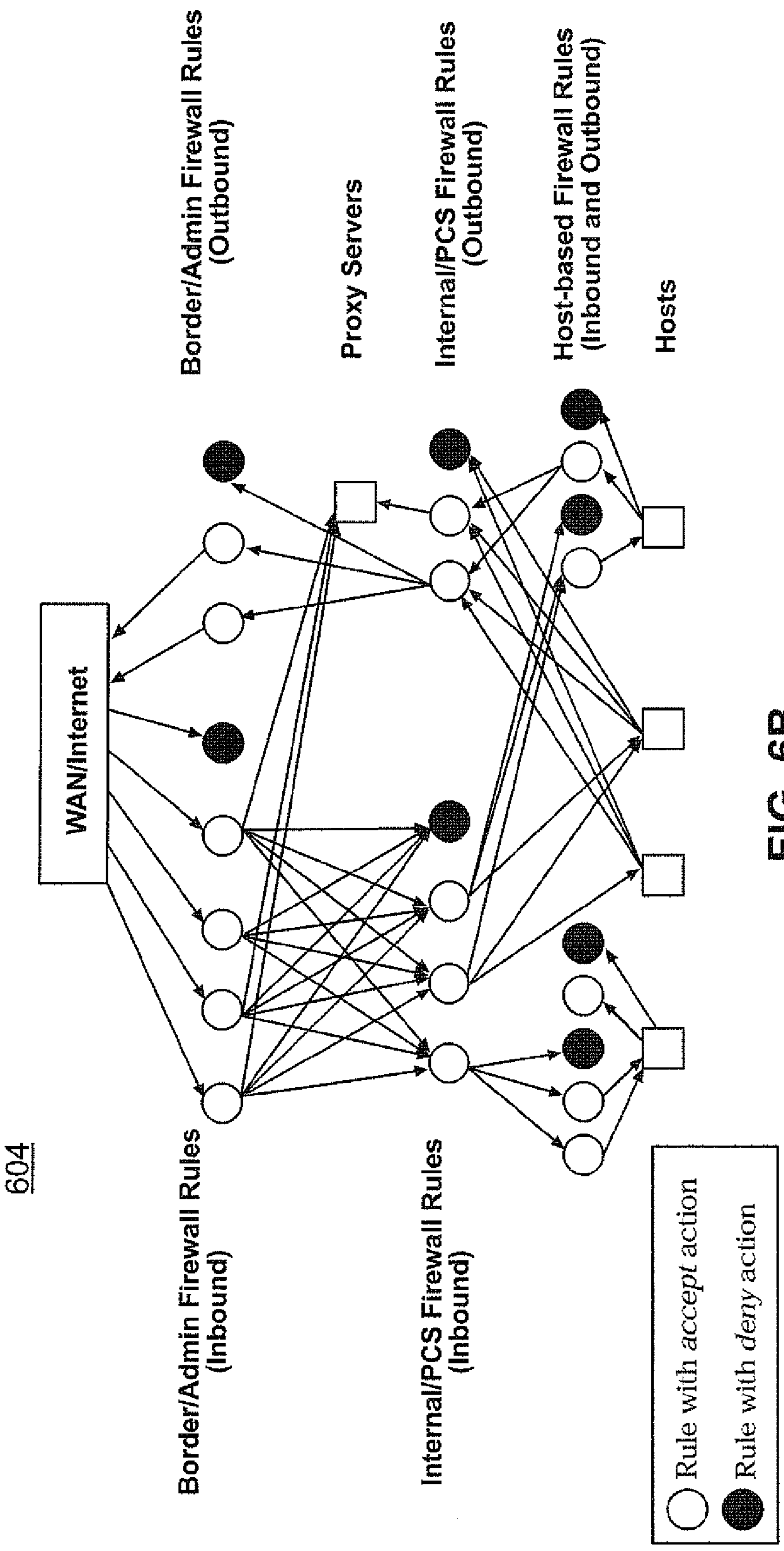
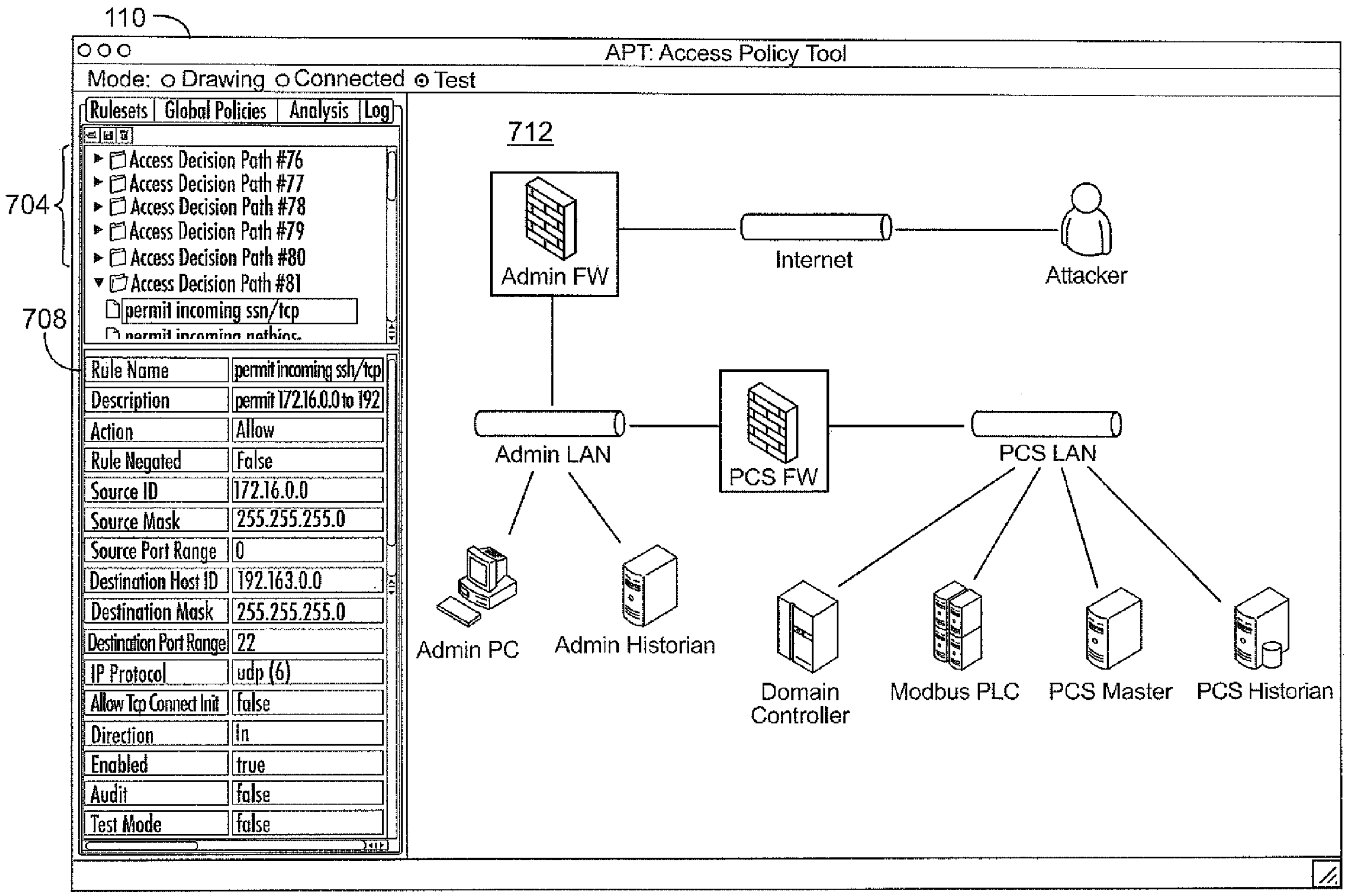

604
WAN/Internet
Border/Admin Firewall Rules (Outbound)
Proxy Servers
Internal/PCS Firewall Rules (Outbound)
Host-based Firewall Rules (Inbound and Outbound)
Hosts
Border/Admin Firewall Rules (Inbound)
Internal/PCS Firewall Rules (Inbound)
○ Rule with *accept* action
● Rule with *deny* action

FIG. 6B



▸ Access Decision Path #76
▸ Access Decision Path #77
▸ Access Decision Path #78
▸ Access Decision Path #79
▸ Access Decision Path #80
▾ Access Decision Path #81
permit incoming ssn/tcp
permit incoming nothing

Rule Name	permit incoming ssh/tcp
Description	permit 172.16.0.0 to 192
Action	Allow
Rule Negated	False
Source ID	172.16.0.0
Source Mask	255.255.255.0
Source Port Range	0
Destination Host ID	192.163.0.0
Destination Mask	255.255.255.0
Destination Port Range	22
IP Protocol	udp (6)
Allow Tcp Connect Init	false
Direction	In
Enabled	true
Audit	false
Test Mode	false

FIG. 7

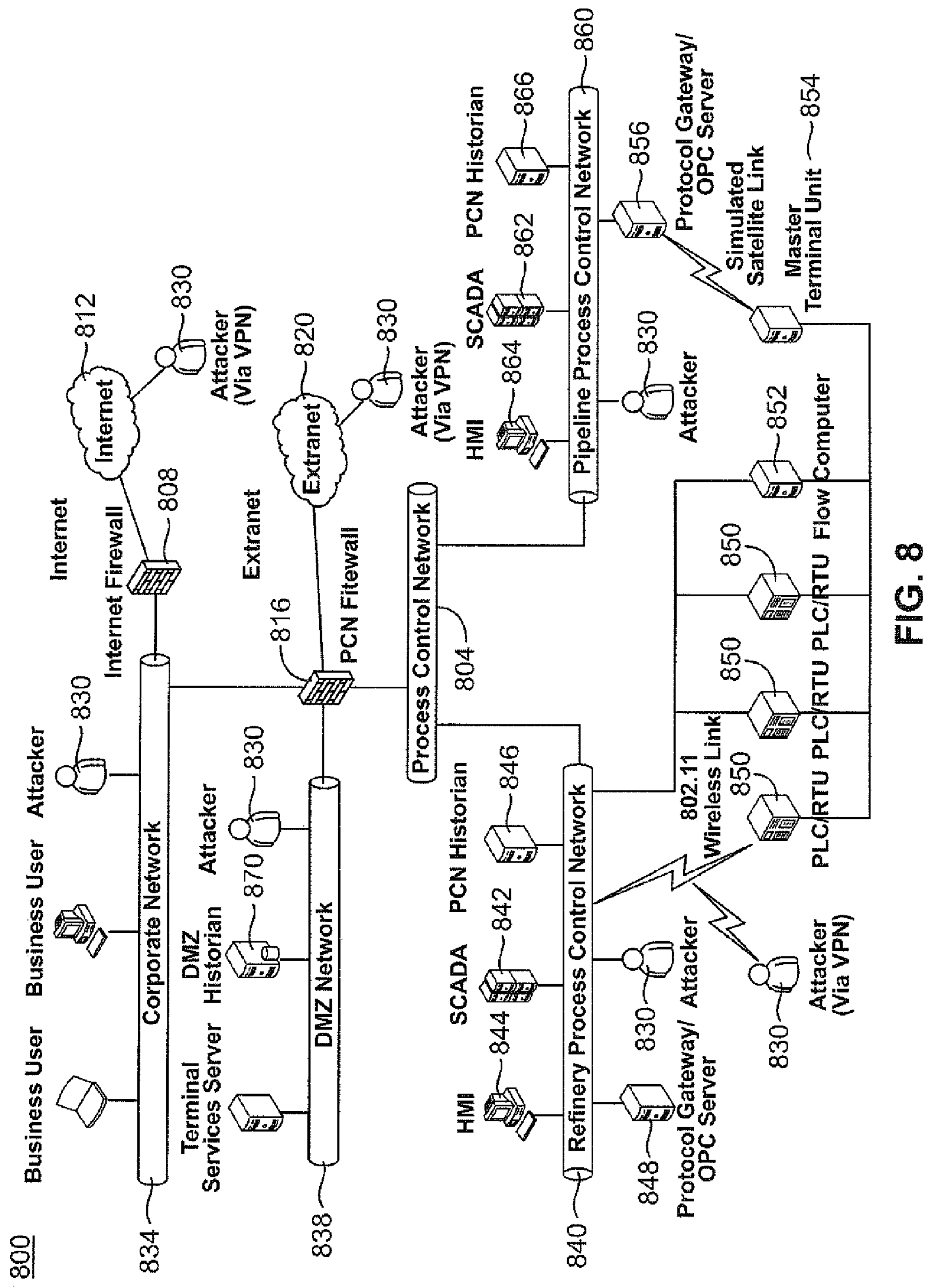

800
Business User
Business User
Attacker
830
Internet
Internet Firewall
808
Internet
812
830
Attacker (Via VPN)
834
Corporate Network
Terminal Services Server
DMZ Historian
870
Attacker
830
838
DMZ Network
816
PCN Fitewall
Extranet
Extranet
820
830
Attacker (Via VPN)
Process Control Network
804
HMI
864
SCADA
862
PCN Historian
866
860
Pipeline Process Control Network
Attacker
830
856
Protocol Gateway/ OPC Server
Simulated Satellite Link
Master Terminal Unit
854
852
Flow Computer
850
PLC/RTU
850
PLC/RTU
850
PLC/RTU
802.11 Wireless Link
840
Refinery Process Control Network
HMI
844
SCADA
842
PCN Historian
846
848
Protocol Gateway/ OPC Server
830
Attacker
830
Attacker (Via VPN)

FIG. 8

ANALYSIS OF DISTRIBUTED POLICY RULE-SETS FOR COMPLIANCE WITH GLOBAL POLICY

RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application 60/941,132, filed May 31, 2007, which is herein incorporated by reference.

FEDERALLY SPONSORED RESEARCH

This invention was made with Government support under Contract Number CNS-0524695 awarded by the National Science Foundation (NSF). The United States Government has certain rights in the invention.

TECHNICAL FIELD

The present disclosure relates to methods and a system for analyzing distributed policy rule-sets for compliance with global policies, and more particularly to finding the source of errors that cause noncompliance with the global policies.

BACKGROUND

Networked systems are used in a large number of settings, including several critical infrastructure systems, such as chemical plants; electric power generation; transmission and distribution; water distribution networks; waste water treatment; and enterprise networks, used in many mission-critical business settings. The emerging scenarios and the likely trends for the future of critical networked systems demand that the problem of securing these systems receive immediate attention, especially in the context of controlling access to the critical elements of the system over the communication networks. Given the mission-critical nature of a significant number of large networked information systems, it is important to ensure their protection against cyber-attacks, which, in a worst-case scenario, could result in loss of life, or in massive financial losses through loss of data, actual physical destruction, misuse, or theft.

A modern networked system includes a variety of devices and mechanisms to control access to its resources. These access control mechanisms include, but are not limited to: (1) router-based dedicated firewalls, such as the Cisco PIX series; (2) host-based firewalls, which could be based in software (such as iptables in Linux®, the inbuilt firewall in Windows XP® or Vista®, and popular products from Symantec® and McAfee® for Windows®) or hardware (such as 3Com's Embedded Firewall NICs); (3) operating-system-based mechanisms, such as discretionary access control in Linux® or Windows®, or more sophisticated mechanisms such as the mandatory access control in NSA's SELinux and similar functionality provided for Windows® by the Cisco® Security Agent; and (4) middleware-based mechanisms, such as the Java® Security Manager, that provide for specification and enforcement of fine-granularity access control policies for Java programs.

All these distributed and layered mechanisms can interact in complex ways that can lead to subtle errors and mask problems. It can be difficult to discern the global picture that emerges from the local configurations of these myriad access control elements. As a result, it is not surprising that misconfigurations of these mechanisms are a major source of security vulnerabilities. In fact, a recent study suggests that most firewalls (the most popular access control mechanism) suffer

from misconfigurations. It is important for the administrators of computer networks to have ways to make sure that high-level specifications of such system access constraints are reflected in the actual configurations of the access control mechanisms spread throughout the system. Furthermore, if the implementation of policy (device configurations) is not in compliance with the specification, a diagnosis to locate the root causes of the problem would be useful.

BRIEF DESCRIPTION OF THE DRAWINGS

A more particular description of the disclosure briefly described above will be rendered by reference to the appended drawings. Understanding that these drawings only provide information concerning typical embodiments and are not therefore to be considered limiting of its scope, the disclosure will be described and explained with additional specificity and detail through the use of the accompanying drawings.

FIG. **1** is a diagram showing a representative network of the kind analyzed by the system and methods disclosed herein.

FIG. **2** is a diagram that provides an overview of the tool architecture available to an administrator accessing a graphical front-end of an Access Policy Tool (APT) system to perform comprehensive analysis of the access control policy implementation in a large networked system.

FIG. **3** is a system diagram that gives an operational overview of the APT system, which includes the graphical front-end and an analysis engine.

FIG. **4** is an example portion of a user graphical front-end for accessing rule-sets in the APT system.

FIG. **5** shows an example network topology on the left and a corresponding possible multi-layered rule graph on the right as represented by a consistency checker of the APT system.

FIGS. **6**A and **6**B are, respectively, another example network topology diagram and a corresponding multi-layered rule graph as represented by the consistency checker of the APT system.

FIG. **7** is an example portion of a user graphical front-end for accessing rule graph analysis as performed by the APT system.

FIG. **8** shows an experimental test bed developed at the Sandia National Labs to represent a networking infrastructure at a typical Oil and Natural Gas (ONG) operator with an emphasis on the protection of the process control network (PCN).

DETAILED DESCRIPTION

In the following description, numerous specific details of programming, software modules, user selections, network transactions, database queries, database structures, etc., are provided for a thorough understanding of various embodiments of the systems and methods disclosed herein. However, the disclosed system and methods can be practiced with other methods, components, materials, etc., or can be practiced without one or more of the specific details.

In some cases, well-known structures, materials, or operations are not shown or described in detail. Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. The components of the embodiments as generally described and illustrated in the Figures herein could be arranged and designed in a wide variety of different configurations. The order of the steps or actions of the methods described in connection with the disclosed embodiments may be changed as would be apparent to those skilled in the art. Thus, any order appearing in the Figures, such as in flow charts or in the Detailed Description is for illustrative purposes only and is not meant to imply a required order.

Several aspects of the embodiments described are illustrated as software modules or components. As used herein, a software module or component may include any type of computer instruction or computer executable code located within a memory device and/or transmitted as electronic signals over a system bus or wired or wireless network. A software module may, for instance, include one or more physical or logical blocks of computer instructions, which may be organized as a routine, program, object, component, data structure, etc., that performs one or more tasks or implements particular abstract data types.

In certain embodiments, a particular software module may include disparate instructions stored in different locations of a memory device, which together implement the described functionality of the module. Indeed, a module may include a single instruction or many instructions, and it may be distributed over several different code segments, among different programs, and across several memory devices. Some embodiments may be practiced in a distributed computing environment where tasks are performed by a remote processing device linked through a communications network. In a distributed computing environment, software modules may be located in local and/or remote memory storage devices.

This disclosure describes an Access Policy Tool (APT) (**100** in FIG. **2**), developed in answer to the needs described above. The APT analyzes the security policy implementation for conformance with the global security policy specification. It integrates policy rules (i.e., configuration information) from a large variety of sources typically found in a modern network and provides for a detailed offline analysis, as well as dynamic online analysis of incremental configuration changes for detection of policy implementation holes during operation. For increased usability and ease of managing information, the tool includes a graphical front-end.

Access Control in Networks

FIG. **1** is a diagram showing a representative network **10** of the kind analyzed by the system and methods disclosed herein. The network "**10**" will be variably referred to herein as a network system **10** to be analyzed, and is not specific only to FIG. **1**, which is but an example of such a network **10**. Firewalls, which may be implemented in hardware or software, are critical assets in the protection of a network. A firewall **14** or other network device is configured through its rules (collectively referred to as a rule-set), which it can use to mold and shape the traffic that crosses it. A firewall **14** or other device matches the incident network traffic against its rules, using traffic characteristics such as the source of origin, intended destination, and communication protocol, and either forbids or allows the traffic to pass through depending on the action indicated by the matching rule. Note that the servers or computers shown in FIG. **1** include a mixture of different operating systems, including SELinux, WindowsXP Professional, RedHat, Solaris 8, and Windows 2000.

As shown in FIG. **1**, a typical setting usually contains a distributed firewall **14** implementation, wherein traffic may need to pass through more than one firewall to transit the network **10**. In such a setting, the firewalls **14** can be used to divide the network into secure zones that limit user and application access between zones. For example, network traffic between a process control system (PCS) **18** and a business network **24** can be restricted to that which is required (including restrictions on the direction of flow). Examples of a business network **24** in FIG. **1** include environmental, planning, wing ops, or AMC CONUS local area networks (LANs).

Most companies configure firewalls to a "deny all, permit none" setting with a few exceptions. However, in reality, there are no generic rules that fit all situations, and the specific architecture of the system (e.g., the use of demilitarized zones (DMZ)) dictates how the rules should be configured for effective security at a particular site. Firewalls may further support "stateful" rules that keep track of roles in a transport control protocol/internet protocol (TCP/IP) session and only allow traffic that is consistent with the past history of the session indicated in the network packet. In addition, firewalls may provide network address translation (NAT), which creates a mapping between the IP addresses and port numbers used in the interior of the network and a (common) IP address and port number offered to the outside network.

In addition to dedicated, router-based firewalls, host-based firewalls may also exist. These are implemented in either software or hardware. Software-based firewalls, such as iptables in Linux® and several commercial ones available for Windows® of Microsoft, Redmond, Wash., are implemented in the host operating system. Hardware-based firewalls, such as 3Com's Embedded Firewall (EFW) PCI card, are implemented on the network interface card (NIC) itself, and as a result, those firewalls are tamper-resistant to cyber-attackers who might gain control of the operating system on a host.

There are published guidelines (e.g., the National Infrastructure Security Coordination Center (NISCC) guide to good practices in firewall deployment) to facilitate the development of unique rule-sets for the different firewalls at an operating site, but they are fairly generic and have to be customized by network system administrators to the specific needs of their sites.

A finer-grained access control is provided by mechanisms available on the operating system and middleware levels. They might include discretionary built-in mechanisms for managing permissions for local objects (such as files) and privileges of the processes that are present in the default installations of popular operating systems like Linux® and Windows®. In security-conscious settings, however, especially for networks managing critical infrastructure, hardened versions of the traditional operating systems have been increasingly adopted. These include SELinux (developed by the NSA), which is a secure version of the Linux® operating system. It can be configured using a large number of policy files that can be compiled into the Linux® kernel. It makes it possible to restrict the processes on a machine so that they run within domains that are isolated from each other, with explicit rules in the policy files governing transition between domains (i.e., change in privilege). It can control the ability of applications and user classes/roles to access not just file objects, but also network sockets and other applications. Policies are typically specified using type enforcement and role-based access control mechanisms. Similar functionality for Windows® operating systems can be provided through third-party software, such as the Cisco® Security Agent.

An increasing number of handheld and embedded devices that liaison with networked systems are based on, or at least support, Java®. The Java® Security Manager provides fine-grained access control similar to SELinux for the Java® Virtual Machine, and adds another avenue for access policy implementation.

The complexity of implementing an access control policy through configuration of a large number of distributed devices and the risk of conflicts among these devices has spawned a significant amount of work. However, the majority of the work focuses on internal consistency among rules of a single firewall. A conflict detection tool for distributed firewall systems has been described in E. Al-Shaer and H.

Hamed, *Discovery of Policy Anomalies in Distributed Firewalls*, In *Proceedings of the IEEE INFOCOM*, volume 4, pages 2605-2616, March 2004. But, this conflict detection tool only checks for certain kinds of syntactic errors, such as overlapping rules, and not for semantic errors with respect to a specification of the intent. Furthermore, none of the work takes into account the collective fine-grained access control provided by the network-based mechanisms (e.g., firewalls) and host-based mechanisms (e.g., SELinux policies). Also, none of the above work has been applied to and optimized for specific classes of networks.

Another vector of research effort has attempted to focus on automatic generation of consistent policy implementation (at devices) from formal description of global policy. Among the commercial solutions, Cisco® provides Cisco® Works, a suite of products that enable top-down firewall policy management. The suite includes a firewall management center to manage configurations, a secure policy manager to generate policies from higher-level specifications, and Mars, for log/audit analysis. Those solutions provide for rule-set specification and top-down management, and do not help with validation of existing implementations. They are also largely limited to firewalls, and, even there, to certain brands and models of firewalls. Furthermore, they require specification of detailed and exhaustive global security policy. For most current network system administrators, the ability to check existing configurations against policy specifications that indicate intended high-level behavior is likely of more utility.

Analysis Framework

FIG. **2** is a diagram that provides an overview of an Access Policy Tool (APT) **100** architecture available to an administrator (or user) accessing a graphical front-end **110** of the APT **100** (variably referred to herein as the APT system **100**) to perform comprehensive analysis of the access control policy implementation in a large networked system **10**. FIG. **2** also describes the interaction between the APT graphical front-end **110** and an analysis engine **120** of the APT **100** during the analysis process. The following begins with a summary of features of the Access Policy Tool (APT) **100** followed by a description of several specific aspects in more detail in the subsequent, separately titled sections.

The graphical front-end **100** or user interface (GUI) of the APT **100**, which may be written in Java® Swing, runs independent of the analysis engine **120**, which may be written in C++, with the two ends communicating securely via TCP. This makes it possible to deploy the analysis engine **120** as an appliance that can be plugged into a suitable spot in the network **10**, with the front-end **110** being used as a management console that users of the tool **100** (such as a system administrators) can run from their workstations. The analysis engine **120** can be configured with basic information about the topology of the network **10** on which the APT **100** is deployed and parameters for secure access to the various constituent devices. With that input, it can securely obtain a snapshot of the security configuration (e.g., rule-sets for the firewalls or policy files for SELinux installations).

The configuration information obtained may be translated into an extensible markup language (XML) (or another appropriate language) schema designed to be able to handle a variety of types of information. The configuration information, together with the topology, is used to generate a specialized data structure called a multi-layered rule graph. Each node in the rule graph represents a possible access decision in the network **10** (e.g., a rule in a Cisco® PIX firewall that incoming traffic might match), with paths representing possible sequences of access decisions. The APT system **100** can enumerate the possible attributes of the traffic and user classes that can traverse a path in the rule graph (i.e., the attributes of the traffic that can undergo the sequence of access decisions represented by the path), and those attributes can be checked against a specification of global access policy for potential violations. Various efficient data structures and algorithms are used for representation and manipulation of the traffic attribute sets. The data structures involve representing the related multi-layer rule graphs compactly, and support rapid traversal thereof as will be explained in more detail below.

The APT **100** can perform a comprehensive, exhaustive analysis, wherein the rule graph data structure is analyzed in its entirety and all possible violations of the specified access policy are enumerated and suitably highlighted in the front-end's graphical display. When the network **10** size makes an exhaustive analysis impossible, the APT **100** supports a statistical analysis to quantitatively characterize the conformance of the policy implementation to the specification of the global access policy (GAP). It does so using a set of statistical techniques known as importance sampling, backed by appropriate mathematical constructs as well as analytical (or empirical) proofs of variance reduction. As a result, a fairly accurate estimation of the security posture can be obtained with only a very limited (and hence, fast) exploration of the rule graph data structure. The APT **100** will also support dynamic online analysis of incremental changes to security configurations for detection of policy implementation holes that may be introduced during the operation of the network **10**. In that mode, changes can be automatically detected by the APT **100**, and fast analysis can be performed using the results from the previous comprehensive analysis and the localized nature of the new changes.

APT Architecture

Accordingly, the analysis tool **100** has two independent components: (1) the graphical front-end **110** (or the management console) that system administrators can run from their workstations and use to provide information about the basic network topology, specify specifications of the global access policy (GAP) (or subsets thereof and set up analyses; and (2) the analysis engine **120**, which captures the network **10** system state and analyzes that information with respect to policy specifications.

As indicated in FIG. **2**, the two components of the tool communicate securely over the network using TCP and/or transport layer security (TLS) protocols. This segregation of functionality makes it possible to use the analysis engine **120** to be used as an appliance that can be plugged into a suitable spot in the network **10** from which it can establish secure connections to the access control elements present on the network **10**, and capture the relevant configuration information. The actual interface between the tool **100** and the user front-end **110** can then be freely placed where it is convenient for the administrator.

As shown in FIG. **2**, the administrator first provides a description of the network topology using the graphical front-end **110**. That can be done using the easy-to-use drawing tools included with the front-end **110**. The information to provide includes all the relevant access control elements (firewalls, proxy servers, wireless access points such as displayed in FIG. **1**); details for each element, such as its IP addressees) and parameters that the analysis engine **120** can use to establish secure connections to the element to capture its configuration; and all the network interactions between the listed elements. Entities can be grouped together to indicate subnetworks and LANs, and properties can be specified for such groupings.

XML may be used as the underlying language for internal representation for most of the information in the tool, which provides the added benefit of being able to interface with third-party tools and applications simply by providing wrappers that output the XML conforming to schemas of the APT **100**. The front-end **110** converts the visual topology representation provided by the administrator to an internal XML representation. It is also possible to browse and select from the list of topology descriptions previously cached topologies remotely at the analysis engine **120**. In either case, once the topology is decided, the information is sent over the network **10** to the analysis engine **120**.

The analysis engine **120** uses the received information to securely obtain the snapshot of the access control policy implementation, in the form of configuration files from the various devices indicated in the topology description (described in more detail below with reference to “Analysis Engine Intervals”). The analysis engine **120** also indexes and caches the topology description and captured configuration information. The captured information from all the different sources may then converted to a unified XML schema, and the resultant XML is sent back to the front-end, where the administrator can now highlight various elements in the topology diagram and look at their current configurations (e.g., rule-sets for a firewall). Note that the unified schema functions for firewall devices, but not for some host-based policies such as those found in SELinux. These host-based policies and rules may be expressed in XML and sent to the engine **120** separately and in a different format from the unified rules.

The administrator then specifies the global access constraints, which are a subset of the possible comprehensive security policy. Global access constraints indicate some intended behavior against which the administrator wishes to check the policy implementation for compliance. The administrator uses the graphical front-end **110** to specify constraints for the various elements or groupings of elements, and the APT **100** considers their conjunction, applying conflict resolution rules in the event that two constraints yield conflicting access decisions. The individual constraints can express positive as well as negative assertions about the nature of traffic, roles, user-classes, or applications that can access a particular grouping of resources (hosts, specific files or applications, and so forth). In other words, events and/or errors that should never happen, as well as things that must be allowed, may be expressed by the APT **100**.

For example, in a process control system (PCS) where the tightly controlled isolation of the process control network (PCN) is a key to security, using the APT's graphical front-end **110**, the APT **100** can specify global access constraints indicating that the hosts in the PCN should be accessible from each other. But, the APT **100** also specifies that only specially designated hosts (historians) should be accessible from outside the PCN, and that even they should be accessible only on very specific protocol ports and only by certain classes of users (say, managers and system administrators) accessing from a particular sub-network. Once the constraints are specified, they are converted into an internal XML representation. This further gives the administrator the freedom to use third-party technologies, such as a variety of modal logics, to specify the global access constraints.

The next step for the administrator is to set up the analysis. The administrator can select either an exhaustive analysis or a statistical analysis, each of which has certain configuration parameters that need to be provided. Once that is done, the front-end sends the policy specification and setup information for the analysis to the analysis engine **120**. The analysis engine **120** sends back the results as it obtains them, giving the administrator the option to abort the analysis at any stage and do post-analysis on the partial results. The administrator can manipulate, filter, and/or navigate through the results, and if any violations are found, can visualize the problem and diagnose the key misconfigurations behind the violations.

A variety of post-analysis techniques are available in the front-end **110** to help the administrator identify the root causes of the violations. Once the administrator has some possibilities in mind, hypothetical changes can be analyzed using the front-end: the administrator can make proposed changes to the configuration of various elements (e.g., modify, delete, or reorder certain rules), and the new information will be sent to the analysis engine **120**, which then performs a quick re-analysis to see if the hypothetically modified configuration information now conforms to the specification of the access policy. This feature can also be used to check planned changes in configuration for compliance quickly before they are actually rolled out.

Analysis Engine Internals

FIG. **3** is a system diagram that gives an operational overview of the APT system **100**, which includes the graphical front-end **110** and the analysis engine **120**. The analysis engine **120** may further include a rule unifier **124** and a consistency checker **128**. A global policy **132**, including access control constraints, may be stored in a database **134** or other memory storage. The database **134** may also store a plurality of rule-sets **134** that are obtained from secured devices located within an administrator-specified network topology. The global policy **132** may be made available in XML to the consistency checker **128** of the APT **100** so that it may be analyzed with reference to the access policy implementation of the network **10** devices, which is provided by the rule unifier **124**. As discussed previously, the analysis engine **120** may be designed as a portable appliance that may be located at any location (shown in dashed lines) throughout the network **10**. Accordingly, the analysis engine **120** may include its own processing power and storage capabilities.

The APT **100** may be implemented as a computer, server, mobile device, or one or more computing devices. Accordingly, the APT **100** may also include a memory **140**, a processor **142**, and a communication interface **144** that are coupled to each other and that electrically communicate with the front-end **110**, the analysis engine **120**, and the database **134**, e.g., through a system bus (not shown). The communication interface **144** communicates with the network **10** to send and receive data communication from access control elements thereon.

The graphical front-end **110** supplies the analysis engine **120** with information about the network topology and the parameters for establishing secure network connections with the access control elements of the topology. Examples of such parameters include keys for establishing VPN connections to Cisco® PIX firewalls and a guest username/password for establishing secure shell (SSH) connections to Linux®/SELinux hosts. Using the supplied information, the analysis engine **120** can establish connections and obtain the relevant configuration information, hence capturing a snapshot of the access policy implementation, e.g., with the network-wide compilation of device rule-sets. The configuration information can take many forms depending on the mechanisms and devices being used to enforce access control. The configuration information may consist of custom rule descriptions for different kinds of firewalls, SELinux type and role transition policies, and/or Java® Security Manager policies, and/or other host-based access control policies.

The APT **100** integrates (or combines) policy rules from a large variety of such sources. A unified XML schema has been developed that captures the essence of the union of all the classes of access control mechanisms that one is likely to encounter in a modern information technology (IT) network **10**. The analysis engine **120** includes modules that convert the policy rules (configuration information) from the different sources (with the exception of host-based policies such as SELinux discussed above), with the rules from each source in their own custom language, into XML (or other common language) conforming to the unified schema. That allows for easy extensibility as support for new access control mechanisms and devices can be added by simply writing the translation modules for those devices. The host-based policies and rules (such as SELinux) may be expressed in XML and sent to the engine **120** separately and in a different format from the unified rules.

In the APT's offline analysis mode, it is not necessary to tightly integrate the analysis engine **120** with the system being analyzed, and if needed, the analysis engine **120** can be directed to read in the configuration snapshot that has been collected offline a priori and placed locally on the file system. In the online analysis mode, the analysis engine **120** either periodically checks with access control devices for any changes in configuration, or is specifically directed towards those changes by the administrator via the front-end **110**.

FIG. **4** is an example portion of a user graphical front-end **110** for accessing rule-sets **136** in the APT system **100**. The various rule-sets **136** may be browsed through for review, and updated, if need be, manually. Note that the administrator may click on a specific rule that is tied to one of the network devices (or access control elements), after which the detailed information for that rule is displayed for viewing or alteration in the below left window **408**. The topology being analyzed is shown a right window **412** of the front-end **110**; the network devices of the topology correspond to the rule-sets **136**.

The below left window **408** includes detailed information that may be changed or updated through the user front-end **110**. From the top to the bottom, the below left window **408** may include, but is not limited to: (1) a rule name, preferably something helpful for tracking; (2) a description, which adds detail to what the rule does, for instance, permit 192.168.0.100; (3) an action, which can be to allow or deny, for instance; (4) a field to indicate whether or not the rule is negated, for instance by operation of another rule through the same network **10**; (4) a source ID address, which is an internet protocol (IP) address from which traffic is allowed, and may include a range of IP addresses (FIG. **7**) to create a bit pattern of IP addresses affected by the global access policy; (5) a source mask, here "host," or an indication of the network mask to use with the source ID address; (6) a source port range, which may include more than one port; (7) a destination host ID address or range of IP addresses to which traffic is allowed to be sent; (8) a destination mask; (9) a destination port range, which may include more than one port; (10) IP protocol or protocols that are supported; (11) a field that indicates whether or not to allow a TCP connection to be initialized; (12) a direction of the traffic (in or out); (13) a field that allows an administrator to enable/disable the rule; and (14) an audit field to enable auditing of rule changes.

In the right window **412** is the topology of the network **10** being analyzed, and the one displayed is only exemplary. The topology indicates the position of an attacker **416** through an internet **420**. The attacker **416** has to get through an administrative firewall (FW) **424**, through an admin LAN **428**, and then through a PCS **432** to gain access to a PCS LAN **436**. An administrative PC **440** and an administrative historian **444** are located on the administrative LAN **428** side of the firewalls (**424**, **432**). The administrative historian **444** is configured so that it can read through the PCS FW **432** to read a PCS Historian **448** off the PCS LAN **436**. Network devices that also communicate through the PCS LAN **436** include a domain controller **452**, a Modbus programmable logic controller (PLC) **456**, and a PCS master server **460**. Similar network devices and topologies are further exemplified through this disclosure, but description thereof will not be repeated as the APT system **100** is designed to analyze any topologic network **10**.

Consistency Checker

With further reference to FIG. **3**, the consistency checker **128** forms the core of the analysis engine **120**. It takes as input the XML representations of the collective configuration information from the various devices and of the formal specification of the access constraints provided by the front-end **110**, and sets up an analysis based on the parameters supplied by the administrator (using the front-end **110**). As described with reference to the "APT Architecture," the output, in the form of the list of violations, is sent back to the front-end **110**. In the online mode, if an intrusion detection and alert correlation system has been deployed on the network **10**, the results may also be forwarded to that system in the form of an alert.

FIG. **5** shows an example network topology **500** on the left and a corresponding possible multi-layered rule graph **504** on the right as represented by a consistency checker **128** of the APT system. The network topology **500** and the configuration information (policy rules) from the access control devices (or network layer nodes) are internally represented by the consistency checker **128** using a specially constructed data structure called a multi-layered rule graph **504**. FIG. **5** shows a simplified representation of a possible two-layered rule graph for the network shown on the left. The "multi-layer" designation is due to the fact that the analysis of the network topology **500** is spread through at least two hierarchal levels of traffic flow, e.g., operating systems of network devices, firewalls at the network level, and perhaps up to Java virtual machine (VM) level, for example. Additional layers may also be introduced as sub-networks of the network topology **500** in which the sub-network is treated as a single layer for the purpose of one or more rule-sets.

For instance, in the network topology **500** of FIG. **5**, the internet **420** is represented by the WAN layer **506** of the network layer rule graph **504** at right. A demilitarized zone (DMZ) **510** is created between firewalls **512**, which may be represented by the border firewall rules layer **514** at right. The DMZ **510** is boxed in by firewalls **512** except for a cut-outs or proxies through which traffic is specifically allowed. A partner distribution **520** of network devices represents those network devices that the APT system **100** can analyze through permissive accessibility to the same. Additional firewalls **522** may be located throughout various locations of the network topology **500** and together may be represented by the main firewall rules layer **524** at right. These firewalls **522** may further secure traffic from various sub-networks such as displayed: accounting, engineering, or frame cloud tunnel traffic that is configured to send traffic specific to particular applications.

Furthermore, another DMZ **530** may be positioned just before the locations of host servers or devices, and which communicates with an internal firewall **532**. The internal firewall **532** may be represented by the internal firewall rules layer **534** at right. Any proxy server **540** or historian **444** may be represented by the proxy servers layer **544** at right. The operator console **550** and the switch **552** may include host firewalls of software and/or hardware and may be represented by the host firewall rules layer **554** at right, in the multi-layer rule graph **504**.

The rules in the multi-layer rule graph **504** are represented by circles (or network nodes) that either have an accept action or a deny action. If a network data packet has characteristics that match a source destination according to a first rule, then an accept action (or deny action), whichever applies, is executed to either pass the packet on through the network **500** or to deny further movement. If the rule is inapplicable to the data packet characteristics, then a second rule is checked, which can be located in another network layer, and so forth through all the rules such that the data packet is appropriately acted upon. If no rules apply to the data packet, the default action is usually to deny the data packet further passage through the network **500**. A bottom right inset **564** depicts how a network layer node expands into a host layer rule graph, and reference thereto will be made below.

FIGS. **6**A and **6**B are, respectively, another example network topology diagram **600** and a corresponding multi-layered rule graph **604** as represented by the consistency checker **128** of the APT system **100**.

The rule graph (FIGS. **5** and **6**B) captures the network interconnectivity and data flow among the policy enforcement rules. In the top-level, or the network-layer, rule graph, there are nodes that correspond to devices that accept traffic and other nodes that correspond to rules in devices through which traffic passes. A firewall (dedicated or host-based) is represented by as many nodes as it has rules, with both inbound and outbound rules being presented, and a host (terminal or proxy) is represented by just one node. For instance, a node representing rule r_j in firewall F_m directs an arc to a node representing rule r_j in firewall F_n if the action (access control decision) associated with the rule r_j is to accept, and a network packet that is thus accepted can be received (in accordance with the network topology) by firewall F_n. A node representing a proxy host (that allows for traffic to pass through it) has both incident and outgoing arcs.

Nodes representing hosts may further expand into a lower-level rule graph **564**. FIG. **5**, bottom right, shows a potential host-layer rule graph **564** (modeled as a directed graph with labeled edges) representing the SELinux policy rules for one of the hosts in the network-layer rule graph. The arcs in this rule graph change the security contexts and/or the permissions of various objects present on the host. Paths through this rule graph represent ways by which processes in the operating system can copy data through different contexts, and be made available to different readers. These paths show how a data object can be received from the network, pass through different processes and contexts, and then be retransmitted into the network, using (potentially) different owners, different permissions, and different network ports.

The overall strategy used by the consistency checker **128** is to analyze paths from traffic sources to terminal nodes in the rule graph. A terminal node may be a rule associated with a "deny" action, a destination, or an exit from the system. A path describes a possible sequence of access policy decisions applied to all traffic that traverses the corresponding devices in the network. The analysis approach is built around the observation that knowing which rules in the system make decisions about a piece of traffic tells us something about the attributes of that piece of traffic A network packet arriving from the Internet may in principle carry any source address, any destination address, and any protocol. If the packet is accepted by a particular rule in the border firewall, then it is inferred that its attributes do not satisfy the preconditions of the earlier rules in the firewall's rule-set, but do satisfy the preconditions of the rule that it matched. Every time a rule recognizes traffic, it refines the attributes of the traffic to reflect the constraining influence of the rules against which the traffic was tested at the firewall. Given a path in the rule graph, the consistency checker **128** can compute successive refinements of the attribute set of traffic, user classes and object permissions that can possibly traverse that path. At each stage along a path, the current attribute set is matched against the formal specification of the access constraints to confirm whether it is in violation.

FIG. **7** is an example portion of a user graphical front-end **110** for accessing rule graph analysis as performed by the APT system **100**. Note that access decision paths **704** are listed as are those paths that violate at least one rule-set. In the "Likely Root Causes" option, details of the likely reasons for path violation are listed. As in FIG. **4**, details of a selected path (and associated rule) are listed in a below left window **708**. When a path **704** is selected, if it is in violation of a global access policy, the details displayed in window **708** indicate the node where the error is being caused, the rule being violated, and other relevant tracking information. Additionally, the network topology that is under analysis is shown in the right part **712** of the window of the user front-end **110**.

Exhaustive Analysis

In the exhaustive analysis mode, the consistency checker **128** analyzes the multi-layered rule graph **504**, **604** for the system in its entirety, considering each piece of configuration information collected and all potential paths therethrough. It then produces a complete list of sequences of access decisions (e.g., firewall rules or SELinux transition rules) that can result in traffic that violates one or more of the global access constraints. The analysis can be directed to use a specific starting point as the initial source of the traffic (e.g., a particular host, a wide area network (WAN), or the Internet); if a starting point is not specified, all the hosts in the topology are considered starting points in turn.

The data structures for rule graphs and traffic attribute sets, and the algorithms to manipulate them, contribute to successful analysis performance. A number of optimizations are used for analysis speed-up. They include the use of multidimensional interval trees for representing the network traffic component of the attribute sets and custom set data structures for efficient representation of the discrete component of the attribute sets (e.g., security contexts or object permissions). Also used is the intelligent caching of results of analyses of sub-paths to minimize repeated computations.

Whether the analysis is performed online or offline, the APT **100** may enable an administrator to choose between exhaustive or statistical analysis based on the administrator's desired level of analysis and in light of the complexity or extensiveness of the network **10**, and thus of the multilayered rule graph **504**, **604**. The APT **100** may also automatically determine the likely resources required for an exhaustive analysis, and make a recommendation on behalf of the administrator to use statistical analysis in lieu of exhaustive analysis where the latter is seen as the default choice. The APT **100** may also make a choice on behalf of the administrator to conduct a statistical analysis where the time required to conduct an exhaustive analysis would be unacceptably too much time, e.g., beyond a threshold level such as 24 hours or the like. As will be discussed, statistical analysis can be much quicker and may provide acceptable results in terms of finding violations of the GAP.

Statistical Analysis

When the networked system **10** (considered together with the relevant components of the IT network) being analyzed is large and deep, the sheer combinatorics of the possible interactions among the access control devices and mechanisms may render a comprehensive exhaustive analysis computationally impossible. The underlying rule graph **504**, **604** would simply contain too many paths to allow an exhaustive exploration, especially when the actual paths of interest (i.e., the violations) form a very small subset of the set of all possible paths through the rule graph **504**, **604**. This is also especially the case where the APT **100** is capable of providing such defense in depth, or in other words, capable of providing access control analysis and violation detection through the many depth layers of the network **10**.

To handle this challenge, the APT **100** incorporates an advanced statistical analysis mode. The statistical analysis produces a sample, and likely incomplete, set of policy violations, and a quantitative estimate of the remainder. The latter may take the form of estimates of the total number of violations, the average number of rules (or other access decisions) in a violation, or the probability that there are no violations given that none were discovered after the analysis was performed for a specified amount of time.

The APT tool **100** obtains statistically valid estimates of such quantitative measures without actually exploring the entire rule graph **504**,**604**. It does so through repeated and random exploration of an extended version of the rule graph **504**, **604** to sample a few paths, using mathematically formulated heuristics to guide the choice at each step of the exploration towards the likely sources of policy violation. The desired set of metrics is calculated for each sampled path; importance sampling is employed to remove the bias introduced by the guidance heuristic and obtain unbiased estimators of the metrics. As the analysis continues, the administrator can watch the progress of the analysis, including the convergence of the chosen set of metrics using the graphical front-end **110**. The process can be continued until a user-specified relative error bound is reached or a user-specified fraction of the rule graph **504**, **604** has been explored. The administrator can also abort the analysis at any time.

The concept of importance sampling can be illustrated by a simple example. Let X be a random variable with probability density function p. Consider estimating the probability, γ, that X is in some subset A of R. The probability γ can be expressed in terms of an indicator random variable $1_{\{X\epsilon A\}}$, whose behavior depends on X's behavior. If one samples from X's distribution and observe x, then the indicator's value is 1 when for xϵA and is zero otherwise. Hence, the probability of X being in A can be expressed as $\gamma=E_p\lfloor 1_{\{X\epsilon A\}}\rfloor$, where the subscript p denotes the dependence of the expectation on X's distribution. The naive approach for estimating γ by simulation would be to generate N samples, $X_1, X_2, \ldots, X_N$, using the density p, and then use

$$\hat{\gamma}N = \frac{1}{N}\sum_{i=1}^{N} l_{\{X_i\in A\}}$$

as an unbiased estimator of $\gamma(E_p[\gamma N]=\gamma)$. The width of the confidence interval around $\hat{\gamma}_N$ will be proportional to the standard deviation $\sqrt{\gamma(1-\gamma)/N}$. For the estimate to be meaningful, the magnitude of $\hat{\gamma}_N$ needs to be significantly larger than the window of uncertainty around it, i.e., the ratio of sampling standard deviation to a mean needs to be small. If A corresponds to a rare event, i.e., γ is very small, the relative error of the estimate, defined as the standard deviation of the estimate divided by its mean, RE_N, is approximately $1/\sqrt{\gamma N}$. It is unbounded as $\gamma\rightarrow 0$. In order to minimize relative error, the sample size (N) must be large, and the probability γ should also be large. Another view is that for a given γ and target relative error, one must increase N to achieve that relative error.

Importance Sampling

Importance sampling is a way of achieving small relative error using significantly smaller N than this standard approach calls for. Defined is another probability density function p'(x), with p'(x)>0 for all xϵA such that p(x)>0. Then, $\gamma=E_{p'}\lfloor 1_{\{x\epsilon A\}}L_{p'}(X)\rfloor$, where $L_{p'}$ is the likelihood ratio, i.e., $L_{p'}(x)=p(x)/p'(x)$, and the subscript in the expectation denotes sampling using density p'. The term p' is used to generate N samples, $X_1, X_2, \ldots, X_N$, and

$$\hat{\gamma}N = \frac{1}{N}\sum_{i=1}^{N} l_{\{X_i\in A\}}L_{p'}(X_i)$$

is an unbiased estimator of γ. Thus, it is possible to estimate γ by simulating use of a different probability density and then unbiasing the output by multiplying it by the likelihood ratio. The sampling with a different density is usually referred to as a "change of measure" and p' is called the "importance sampling density." It can be shown that to reduce the variance of the estimator $\hat{\gamma}_N$, one may make the likelihood ratio p(x)/p'(x) small on the set A. Since p is a given, this means that one should choose a p' such that p'(x) is large on A, i.e., the change of measure makes A likely to occur. Another factor in the choice of the appropriate change of measure, especially with regard to the feasibility of simulation using the new estimator, is the cost of generating the samples.

Note that the above discussion on importance sampling also applies easily to the construction of metric estimators. If W(x) is a metric whose value depends on xϵA, one can estimate $\alpha=E_p\lfloor W(X)1_{\{X\epsilon A\}}\rfloor$ using exactly the same technique.

The importance sampling approach to metric estimation for use in the APT **100** has been formalized to follow model-based penetration testing. The mathematical formalism is largely identical; however, as is always the case with importance sampling, the heuristics for change of measure are different as they must exploit domain knowledge.

Now briefly described is one approach. It must be understood that all randomness in this formulation comes from the randomness of sampling, not from the system itself. If a path through a rule graph is chosen randomly, that can say something about the probability of the traffic description at the end of the path having certain properties or metrics, but the probability is with respect to the randomness used in choosing the path. The path chosen is like the random variable X in the example above, and the statement that the path has some property (such as reflecting deviation from global policy) is like an indicator $I_{\{XinA\}}$. Probability measure p reflects the random selection of rules that define the path.

Given a partial path already sampled, the action of randomly sampling to find the next rule is a matter of identifying all rules that might next legitimately be applied (i.e., in devices reachable from the output traffic of the last rule applied) and choosing from among these. Of course, not all rules in the reachable devices will apply, so some computation is done to identify legitimate extensions. With an importance sampling approach, a probability distribution is selected that biases the sampling towards rules that may lead us along paths that contribute most heavily to whatever measure is being estimated. Rules likely involved in conflicts, or nearer to the resources specified in the global policy, are excellent candidates for biasing when the measure has higher value on problem paths.

The formulation for estimating the total number of paths through the rule graph **504**, **604** that satisfy some property of interest (e.g., deviation from global policy) is now described. Traversing a path in the rule graph is traversing a state space, where states are either firewall rules $<r_i^n>$ (which notation states that rule r_i on firewall F_n matches the traffic attributed presented to F_n, and would be the rule chosen if a packet from that attribute space were chosen), or (for a multi-layer node) a host action that supports the transfer of data from one context to another, or from one user to another. In both cases arcs indicate movement of data across a network or within the policy space of a host system. Let S denote the (finite) set of all states in the model. Let S_0 denote the set of initial states, i.e., the set of legal states in which the currently matching rule is in the rule-set of the first firewall in the path of a traffic source.

The term "sample sequence" is used to denote any infinite sequence $\{s_t, i>0\}$, where each $s_t \in S$. There is no supposition of any kind of structure other than each element of the sequence is drawn from S. The term "valid prefixes" is used to describe legitimate complete paths in the rule graph, starting in S_0 and terminating in a final security decision (e.g., firewall denies, or a host accepts). "Legitimate" here means that there exists a packet with attributes such that the firewall rules force it to traverse that path.

Suppose one is interested in valid prefixes that satisfy some property (e.g., they end in the violation of the global policy). V is defined to be the set of all valid prefixes with this property, and members of V are referred to as "interesting prefixes." Let a sample space, Ω, be the set of all sample sequences. A probability measure P on Ω is defined such that all sample sequences are equally likely. Now, each state in S can be assigned a digit in the number system with base |S| as a unique identifier. A random variable X on Ω is defined that maps a sample sequence to a real number $(0.d_1d_2d_3 \ldots)_{|S|}$, where d_i is the identifier of the i^{th} state in the path. Hence, X provides a one-to-one correspondence between Ω and [0,1]. Therefore, P, X is uniformly distributed over [0,1], and has a probability density function p(x)=1 if x∈[0,1] and 0 otherwise. Henceforth, the subscript |S| is dropped and all real numbers are in base |S|.

The set of all sample sequences with the interesting prefix $(0.d_1d_2 \ldots d_l)$ form a closed interval of length $|S|^{-l}$ starting at $(0.d_1d_2 \ldots d_l)$. Given an interesting prefix ν, this interval is denoted by l_v, and its length by l_v. Notice that if ν, W∈V, then $I_v \omega I_w = \emptyset$. It can be seen that $A = \cup_{v \in V} I_v$ forms a finite union of disjoint intervals. Hence, the total probability of A is the sum of probability masses associated with the constituent intervals, each of which is simply the length of the interval since p(x)=1 on [0,1]. Due to the sheer size of Ω, this total probability would be very small and membership in V would be a rare event under P.

The objective of this formulation is the construction of an unbiased estimator of the total number of interesting prefixes (i.e., |V|=T). A function $W:[0,1] \rightarrow Z_+$ is defined that takes the value $|S|^l$ for all points in an interval corresponding to an interesting prefix of length l, and is zero elsewhere. Therefore,

$$
\begin{aligned}
E_p[W(X)] &= E_p[W(X) l_{\{X \in A\}}] \qquad (1)\\
&= \int_{\infty}^{\infty} W(x) l_{\{x \in A\}} p(x)\, dx \\
&= \int_{x \in A} W(x) p(x)\, dx \\
&= \sum_{v \in v} \left(\int_{x \in I_v} W(x) p(x)\, dx \right)
\end{aligned}
$$

-continued

$$
\begin{aligned}
&= \sum_{v \in v} \left(\int_{x \in I_v} |S|^{l_v}\, dx \right) \\
&= \sum_{v \in v} \left(|S|^{l_v} \int_{x \in I_v} dx \right) \\
&= \sum_{v \in v} |S|^{l_v} |S|^{-l_v} = |v| = T,
\end{aligned}
$$

where the introduction of summation is possible because A is a finite union of disjoint l_v's. Hence, |ν| is estimated by estimating $E_p[W(X)]$. As described earlier, the standard unbiased estimator for T would be

$$\hat{T}_N = \frac{1}{N} \sum_{j=1}^{N} W(x_i),$$

where $X_1, X_2, \ldots, X_N$ are N random samples drawn from [0,1] (or, equivalently, from Ω) with density p(x). However, since W(X) is non-zero only on the rare set A, the variance of the estimator would be very large for any reasonable value of N. The problem is well-suited to the application of importance sampling techniques.

The following algorithm can be used to generate sample points in [0,1] under the new measure.

IMP-Sampling-Algorithm

1. Initialization: Create a variable s of type state and initialize its static components with information about network connectivity and other properties of the initial setup of the system being modeled. Initialize p_{curr} to 1, l_{curr} to 0, and Attr to all possible packet attributes.

2. Pick a Transition. Generate the list L of available rules on all firewalls accessible from the current host (initially outside the network) that have not yet been traversed.

a. If L is not empty and Attr is not empty: (i) Assign a non-zero probability to each available rule using some heuristic, while ensuring that the probabilities sum up to 1. (ii) Pick one of the available rules based on the probabilities assigned above. This choice determines the current digit of the sample. Let q be the probability that was assigned to the chosen rule. (iii) Update (constrain) the Attr according to the rule chosen above (and the rules in the chosen firewall that did not match). (iv) Update p_{curr} by multiplying its current value by q. (v.) Increment l_{curr} by 1. (v) Check Attr to see if global policy is violated. If yes, then the process has reached a goal state, and exits with an indication of success, along with the current value of p_{curr} and l_{curr}; otherwise, the process goes back to the beginning of step (ii.)

b. Else: Exit with an indication of failure because the current sample is not in A.

The above algorithm either returns an interesting prefix, along with the length of the prefix and the probability mass associated with the prefix under the new probability density, or indicates that the sample is not an interesting prefix. In case an interesting prefix is chosen, the returned probability mass is distributed uniformly in the interval corresponding to the valid prefix. A similar process is done in case of an indication of failure. Hence, at this stage a sample point exists in [0,1]. These considerations result in a new probability density function p'(x). This is a valid change of measure, and the value of p'(x) for $x \in I_v$ for some interesting prefix ν is

$$p'(x) = \frac{p_v}{\text{size\_of\_I}_v} = \frac{p_v}{||S|^{-l_v}|} = \left(\prod_{j=1}^{l_v} q_i^v\right)|S|^{l_v}, \tag{2}$$

where p_v is the probability of choosing the valid prefix v.

Despite the large numbers symbolically expressed above (e.g., $|S|^{l_v}$), the actual computations used in estimating $E_p[W(X)]$ can be done involving much smaller values, avoiding the risk of round-off and precision errors. It can be shown that the variance of the above estimator is proportional to

$$\frac{1}{N}\left(\sum_{v\in v} \frac{1}{\prod_{j=1}^{l_v} q_i^v} - T^2\right). \tag{3}$$

It is obvious from the above equation that the variance changes greatly with the heuristic used to decide the q_i^v's, i.e., the heuristic that chooses the next firewall rule to match at any stage of the sampling algorithm.

As systems being analyzed grow in size and sophistication, it is anticipated that the APT's statistical analysis mode will become increasingly relevant, providing the tool with superior scalability.

Experimental Evaluation

In this section, demonstrated is the efficacy of the APT **100** by using it to verify the access control policy implementation in a variety of settings. Test cases exist that are relatively small in size, such as a networking system typically found in a process control setting, and that show how the exhaustive analysis can be used to weed out misconfigurations of access control devices. This disclosure then demonstrates the APT's (**100**) scalability through the use of statistical analysis for analyzing a much larger system **10** that is beyond the capability of the exhaustive analysis. In all the experimental evaluations described below, APT's analysis engine was running on an AMD AthlonXP-64 3700+ machine with 2 GB of RAM.

FIG. **8** shows an experimental test bed developed at the Sandia National Labs to represent a networking infrastructure **800** at a typical Oil and Natural Gas (ONG) operator with an emphasis on the protection of a process control network (PCN) **804**. The network contains two dedicated Cisco® PIX firewalls, each with 15 rules; one firewall **808** secures traffic to/from an internet **812** and the other, a PCN firewall **816** to secure traffic in/out of an extranet **820**. Out of the 17 hosts in the network **800**, five have host-based firewalls (iptables in Linux). All the hosts run the stock versions of the Windows® or Linux® operating systems (i.e., only discretionary access control mechanisms are present, and mandatory access control such as that provided by SELinux is not present). The rule-sets for the various firewalls were populated based on the settings found at a number of actual ONG sites.

A plurality of attackers **830** have potential access or starting points at their displayed locations. A corporate network **834** is located on the other side of the firewall **808** from the internet **812** and on the other side of the PCN firewall **816** from the extranet **820** and the PCN **804**. A DMZ network **838** is located on the other side of the PCN firewall **816** from the corporate network **834**, from the extranet **820**, and from the PCN **804**. The PCN **804** directly communicates with a refinery PCN **840**, which connects to a supervisory control and data acquisition (SCADA) computer **842**, a human machine interface (HMI) **844**, a PCN Historian, **846**, and a protocol

gateway/open connectivity via open standards (OPC) data access server **848**. The refinery PCN **840** also communicates wired or wirelessly to a plurality of programmable logic controllers (PLCs)/remote terminal units (RTUs) **850**, to a flow computer **852**, and to a master terminal unit **854**. The master terminal unite **854** may also communicate with a protocol gateway/OPC data access server **856** over a simulated satellite link.

The PCN **804** directly communicates, or includes as a sub-network, a pipeline PCN **860**. The pipeline PCN **860** directly communicates with a SCADA **862**, an HMI **864**, a PCN historian **866**, and with the protocol gateway/OPC data access server **856**. Note that the attackers **830** may access a number of points, whether from in front of or behind the firewalls **808**, **816**, wired or wirelessly. Again, this was an experimental ONG test bed, exemplary only of the types of topologies that the APT system **100** can analyze.

The global access constraints (GAPs) were defined, using APT's graphical front-end **110**, to emphasize the tightly controlled isolation of the PCN **804** from the rest of the IT network **800**. In particular, the GAPs specified that the hosts in the PCN **804** could access each other; however, only one (the PCN Historian **846**, **866**) could be accessed from outside the PCN **804**. The PCN Historian **846**, **866** could be accessed from (and only from) a "sysadmin" class user via a DMZ Historian **870** and from a "manager" class user from a host in the corporate network **834**. APT's graphical front-end **110** facilitated easy specification of these constraints, which were subsequently translated into the underlying XML representation of the global policy.

The APT's (**100**) analysis engine **120**, using the information about the network topology provided by the front-end **110**, automatically and securely captured the configuration snapshot of the system network **10**. An exhaustive analysis of the network system **10** was then performed. The analysis identified a total of 83 paths (sequences of firewall rules) in 10 seconds. The APT tool **100** was then instructed to perform a post-analysis on the results to further pinpoint the root causes of the violations. The post-analysis, based on frequency of occurrence in the list of violations, identified two rules, one in each of the two Cisco® firewalls **808**, **816** acting in series, as the likely source of the violations. It further identified the attributes of the traffic that they are allowing to pass and also indicated the subset of the global access constraints that the traffic was violating.

Using the graphical front-end **110**, it is possible to test hypothetical modifications to the highlighted rules and perform quick re-evaluation to discover the appropriate changes that resulted in zero violations of the policy specification (GAP). As is evident from this experiment, the exhaustive analysis functionality of the APT **100** was very useful for a reasonably small network. A complete analysis of the test bed network **800** indicated that the rule graph for the system had about 230,000 paths. Hence, the number of violations not only helps identify and correct misconfigurations, but also, when viewed in the context of the total number of ways traffic could traverse through the system **10**, can serve as a quantitative measure of the system's security posture.

The APT **100** was also used to analyze the sample scripts used in the evaluation of the "Firewall Policy Advisor" by Al-Shaer and Hamed. All the misconfigurations in their sample scripts were captured. See E. Al-Shaer and H. Hamed, *Discovery of Policy Anomalies in Distributed Firewalls, Proceedings of the IEEE INFOCOM*, volume 4, pages 2605-2616, March 2004. Note that the APT's functionality is a superset, since the disclosed analysis is not limited to the analysis of relations between just two firewalls, and the APT system **100** can check for inconsistencies (due to the use of multi-dimensional interval trees) as well as explicit policy violations.

The scalability of the APT tool **100** was explored by testing it on the example setup (**10**) shown in FIG. **1**. This test bed represents an intrusion-tolerant publish-subscribe system **10** developed as part of a DARPA-funded research effort. The system **10** contains more than 40 hosts, all with hardware NIC-based firewalls (more than 20 rules per firewall); 8 Cisco® PIX firewalls; and 29 of the hosts running SELinux, each with four (4) or more process domains. As can be imagined, the configuration of the large number of access control elements in this system in adherence to the global security policy is an extremely complicated task.

The global access constraints were set to emphasize tightly controlled access to the "System Manager" group of machines (the top row of four (4) machines in FIG. **1**). These machines could access one another in very specific ways (to run Byzantine fault-tolerance algorithms) and could be accessed by only a very small set of other machines and only by processes from specific domains on those machines. Again, APT's graphical front-end **110** and underlying XML schema was used for the specification of the global access constraints.

A rule was then deliberately misconfigured in the hardware NIC-based firewall for one of the system manager machines, allowing for traffic that would result in the violation of the global policy. The exhaustive analysis was able to identify the resulting **263** violations and pinpoint the root cause in about 140 seconds (focusing primarily on the firewall rules, and not on the host-based access control mechanisms). Note that the total number of paths in the rule-graph for this system network **10** is huge, which explains the time taken by the analysis.

The problem was then made more complex by introducing problems in two firewalls; a Cisco® PIX dedicated firewall, and the hardware NIC-based firewall for one of the system manager machines, such that the violations only occur in the access decision sequences that include both the rules. The exhaustive analysis, again limited to firewall rules, identified 155 violations and the two modified rules in about 200 seconds. However, when the host-based access control mechanisms were also included in the analysis, the exhaustive analysis could not complete even after running for more than 3 hours, setting the stage for demonstrating increased scalability provided by the statistical analysis.

As described earlier, the APT's (**100**) statistical analysis can provide a sample set of violations and an estimate of the remainder. In this case, the APTO **100** uses the total number of violations as the quantitative estimate of the remainder. The biasing heuristic used for guiding importance sampling is based on shortest distance, i.e., it assigns higher weight to those access decisions that would guide the traffic closest (in network topology sense) to the hosts that are included in the specification of the global policy. Stopping criteria for the sampling was set at 500,000 samples or 5% relative error with 95% confidence, whichever was achieved first.

Statistical analysis on the test bed network **10** of FIG. **1** for the one-rule misconfiguration example above resulted in an answer in under 10 s (with the relative error convergence being the stopping criterion). The analysis estimated 255 violations, which is within 3% of the exact answer obtained from exhaustive analysis.

For the example with two misconfigured rules, the statistical analysis obtained an answer within 4% of the exact answer in about 10 s when only firewall rules are being

analyzed, and about 25 s when host-based access control mechanisms are also being modeled.

Another example was tested where in addition to the two misconfigured rules, also introduced was a misconfiguration in the SELinux policy for the host with misconfigured host-based firewall, such that the global policy was now violated only when all three access control points were included. Again, the exhaustive analysis could not produce the complete list of violations after running for more than 3 hours, but the statistical analysis was able to provide an estimate with a 10% confidence interval (number of samples analyzed being the stopping criterion) in about 1 minute. Additional accuracy required a disproportionate increase in the time required for the analysis. Obtaining an estimate with a 5% confidence interval required the analysis to run for about 5 minutes.

Hence, one can observe that statistical analysis allows the APT **100** to analyze fairly complex systems within reasonably short periods of time. The tool's performance can likely be improved further with use of better biasing heuristics.

Deployment of a large number of distributed and layered access control mechanisms, such as firewalls, is the staple solution to the problem of enforcing security policy. Hence, it is preferable to ensure that all the access control mechanisms work collectively in harmony, and that their complex interactions do not mask subtle errors, introducing security vulnerabilities. The Access Policy Tool (APT) **100** provides a way for network system administrators and security experts to analyze their security policy implementation (configuration of various devices on their network) for conformance with a global security specification. The APT **100** features ease of information management through a graphical front-end **110**, offline as well as online analysis of the compliance of a configuration with the desired or intended behavior, and scalability through the use of statistical techniques for the estimation of security posture. Those capabilities allow the gain of confidence in the implementation before actual deployment, making it possible to reason about policy at an increased level of abstraction, and permit system administrators to detect policy holes created during operational use of a system.

While specific embodiments and applications of various methods and systems for automatic verification of distributed and layered security policy implementations have been illustrated and described, it is to be understood that the disclosure claimed herein is not limited to the precise configuration and components disclosed. Various modifications, changes, and variations apparent to those of skill in the art may be made in the arrangement, operation, and details of the methods and systems disclosed.

The embodiments may include various steps, which may be embodied in machine-executable instructions to be executed by a general-purpose or special-purpose computer (or other electronic device). Alternatively, the steps may be performed by hardware components that contain specific logic for performing the steps, or by any combination of hardware, software, and/or firmware.

Embodiments may also be provided as a computer program product including a machine-readable medium having stored thereon instructions that may be used to program a computer (or other electronic device) to perform processes described herein. The machine-readable medium may include, but is not limited to, floppy diskettes, optical disks, CD-ROMs, DVD-ROMs, ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, propagation media or other type of media/machine-readable medium suitable for storing electronic instructions. For example, instructions for performing described processes may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals embodied in a carrier wave or other propagation medium via a communication link (e.g., network connection).

The invention claimed is:

1. A computer-implemented method for analysis of distributed device rule-sets for compliance with global policies, the method executable by a computer having a processor and memory, comprising:

receiving from an administrator a network topology with a plurality of reachable, intercommunicating elements and associated parameters required to secure the intercommunication with one or more access control elements of the network topology;

establishing connections to the access control elements to capture a snapshot configuration of device rule-sets of the one or more access control elements;

receiving from the administrator a set of global access constraints with reference to the plurality of access control elements;

generating a multi-layered rule graph that captures network interconnectivity and data flow among the intercommunicating elements, where each of a plurality of nodes in the multi-layered rule graph represents a possible access decision by an access control element and paths of the multi-layered rule graph represent sequences of access decisions;

conducting statistical analysis using model-based importance sampling of the multi-layered rule graph to determine violations by the device rule-sets that fail to comply with the set of global access constraints, the importance sampling quantitatively characterizing a level of compliance with the global access constraints without conducting analysis of all potential paths of the multi-layered rule graph; and

providing results of the statistical analysis to the administrator through a graphical user interface (GUI) of the computer as the results are obtained so that the administrator can watch the progress of the analysis.

2. The method of claim **1**, wherein the plurality of access control elements include network resources, and wherein enabling the administrator to specify a set of global access constraints comprises enabling the administrator to set a global access constraint for a group of the network resources.

3. The method of claim **1**, further comprising:

converting the device rule-sets of the one or more access control elements into a software language format;

integrating the converted device rule-sets into a schema of the software language format for presentation to the administrator through the GUI; and

integrating the administrator-specified global access constraints into the unified software language schema of the converted device rule-sets.

4. The method of claim **1**, further comprising:

enabling the administrator to abort the analysis; and

enabling the administrator to perform a post-analysis on any partial or complete results throughout the analysis process.

5. The method of claim **4**, wherein the post-analysis comprises:

enabling the administrator to make hypothetical changes to the configuration of the device rule-sets for the plurality of access control elements; and

enabling the administrator to select from at least one of exhaustive analysis and statistical analysis to analyze the changed configuration.

6. The method of claim **1**, further comprising:

checking, for consistency, the configuration represented by the snapshot of the plurality of access control elements together with the administrator-specified global access constraints.

7. The method of claim **1**, further comprising:

enabling the administrator to select exhaustive analysis;

analyzing the multi-layered rule graph for the network topology in its entirety, considering each piece of configuration information collected; and

producing a complete list of sequences of access decisions that indicates one or more paths taken through the multi-layered rule graph that violates a global access constraint.

8. The method of claim **7**, wherein analyzing the multi-layered rule graph comprises:

obtaining data structures and traffic attribute sets for the multi-layered rule graph that enable rapid traversal thereof, and algorithms to manipulate the data structures and attribute sets;

using multi-dimensional interval trees to represent a network traffic component of the attribute sets;

using custom set data structures to represent discrete components of the attribute sets;

labeling a plurality of edges in the multi-layered rule graph, each label describing all traffic that is admitted by a rule corresponding to an edge source node and being analyzed by a rule corresponding to a terminal node; and

using intelligent caching of results of analyses of sub-paths to minimize repeated computations.

9. The method of claim **1**, wherein upon the administrator selecting the statistical analysis, the method further comprising:

conducting repeated and random exploration of an extended version of the multi-layered rule graph to sample a number of paths to construct unbiased statistical measures of compliance;

using the importance sampling to guide the random selection towards paths likely to be sources of violation of the global access constraints to reduce variance in the compliance measures; and

calculating a desired set of metrics for traffic represented by each explored path.

10. The method of claim **9**, where calculating a desired set of metrics includes calculating unbiased metrics estimators to remove a bias introduced by the importance sampling, further comprising:

calculating a quantitative estimate of a remainder of the unexplored paths of the multi-layered rule graph; and

analyzing the sampled paths of the multi-layered rule graph with the unbiased metrics estimators to form an estimate of the total number of paths therethrough that violate a specified global access constraint.

11. A system for analyzing distributed policy rule-sets for compliance with global policies, the system comprising:

a graphical user interface (GUI) through which an administrator specifies a network topology with a plurality of reachable, intercommunicating elements and associated parameters required to secure the intercommunication with one or more access control elements of the network topology;

an analysis engine in communication with the GUI and with the plurality of elements, the analysis engine including a processor operable to unify a plurality of device rule-sets associated with the one or more access control elements, and to convert the device rule-sets into a software language format presentable to the administrator through the GUI; and

a memory to store an administrator-specified global access policy (GAP) that includes a plurality of global access constraints with reference to the plurality of elements, and to store the plurality of access policy rules;

wherein the processor is operable to:

generating a multi-layered rule graph that captures network interconnectivity and data flow among the intercommunicating elements, where each of a plurality of nodes in the multi-layered rule graph represents a possible access decision by an access control element and paths of the multi-layered rule graph represent sequences of access decisions;

conduct statistical analysis using model-based importance sampling of the multi-layered rule graph to determine violations by the device rule-sets that fail to comply with the GAP, the importance sampling quantitatively characterizing a level of compliance with the GAP without conducting analysis of all potential paths of the multi-layered rule graph; and

provide results of the selected compliance analysis in real time to the GUI for viewing by the administrator as the results are obtained.

12. The system of claim **11**, wherein the processor is operable to convert the GAP into the software language format and analyzes compliance of the one or more access control elements in accordance with the GAP.

13. The system of claim **11**, wherein the processor is operable to select, on behalf of the advertiser, the at least one of exhaustive analysis and statistical analysis based on a determined level of resources required to conduct a full exhaustive analysis.

14. The system of claim **11**, wherein the processor is operable to analyze the network topology to capture a snapshot configuration of the device rule-sets affiliated therewith, and wherein the processor is operable to convert the configuration into a schema of the software language for presentation through the GUI.

15. The system of claim **14**, wherein the processor is operable to:

index and cache in the memory the snapshot configuration of the device rule-sets of the network topology; and

while the analysis engine is disconnected from communication with the plurality of intercommunicating elements, to access the cached snapshot configuration of the converted device rule-sets to analyze compliance of the one or more access control elements in accordance with the GAP.

16. The system of claim **14**, wherein the analysis engine comprises:

a consistency checker that, together with the processor, is operable to analyze the snapshot configuration of the device rule-sets based on the administrator-specified parameters, and return to the GUI a list of violations thereof with at least one global access constraint for reference by the administrator.

17. The system of claim **16**, wherein the consistency checker generates the multi-layered rule graph that captures network interconnectivity and data flow among the plurality of intercommunicating elements, and wherein the processor is operable to integrate the GAP into the software schema for purposes of the compliance analysis, where each of a plurality of nodes in the multi-layered rule graph represents a possible access decision by an access control element.

18. The system of claim **11**, wherein the processor is operable to:

enable the administrator, through the GUI, to abort the analysis; and

enable the administrator to perform a post-analysis on any partial or complete results throughout the compliance analysis.

19. The system of claim **18**, wherein the processor is operable to:

enable the administrator, through the GUI, to make hypothetical changes to the configuration of the device rule-sets for the plurality of elements; and

enable the administrator to select from at least one of exhaustive analysis and statistical analysis to analyze the changed configuration.

20. The system of claim **17**, wherein in response to the administrator selecting the exhaustive analysis, the processor operable to:

analyze the multi-layered rule graph for the network topology in its entirety, considering each piece of configuration information collected; and

produce a complete list of sequences of access decisions that indicates one or more paths taken through the multi-layered rule graph that violates a global access constraint of the GAP by all traffic to which that sequence of access decisions applies.

21. The system of claim **20**, wherein the processor is operable to:

obtain data structures and traffic attribute sets for the multi-layered rule graph that enable rapid traversal thereof, and algorithms to manipulate the data structures and attribute sets;

use multi-dimensional interval trees to represent a network traffic component of the attribute sets;

use custom set data structures to represent discrete components of the attribute sets;

label a plurality of edges in the multi-layered rule graph, each label describing all traffic that is admitted by a rule corresponding to an edge source node and being analyzed by a rule corresponding to a terminal node; and

use intelligent caching of results of analyses of sub-paths to minimize repeated computations.

22. The system of claim **17**, wherein in response to the administrator selecting the statistical analysis, the processor operable to:

conduct repeated and random exploration of an extended version of the multi-layered rule graph to sample a number of paths to construct unbiased statistical measures of compliance;

use importance sampling to guide the random selection towards paths likely to be sources of violation of the global access constraints to reduce variance in the compliance measures; and

calculate a desired set of metrics for traffic represented by each explored path.

23. The system of claim **22**, where to calculate a desired set of metrics the processor operable to calculate unbiased metrics estimators to remove a bias introduced by the importance sampling, where the processor is further operable to:

calculate a quantitative estimate of a remainder of the unexplored paths of the multi-layered rule graph; and

analyze the sampled paths of the multi-layered rule graph with the unbiased metrics estimators to form an estimate of the total number of paths therethrough that violate a specified global access constraint of the GAP.

24. The system of claim **11**, wherein the one or more access control elements comprise a plurality of firewalls.

25. A non-transitory computer readable medium including machine-readable instructions executable by a processor that causes a computer including the processor and memory to perform the operations of:

enabling an administrator to specify a network topology with a plurality of reachable, intercommunicating elements and associated parameters required to secure the intercommunication with one or more access control elements of the network topology;

establishing connections to the access control elements to capture a snapshot configuration of device rule-sets of the one or more access control elements;

enabling the administrator to specify a set of global access constraints with reference to the plurality of access control elements;

generating a multi-layered rule graph that captures network interconnectivity and data flow among the intercommunicating elements, where each of a plurality of nodes in the multi-layered rule graph represents a possible access decision by an access control element and paths of the multi-layered rule graph represent sequences of access decisions;

conducting statistical analysis using model-based importance sampling of the multi-layered rule graph to determine violations by the device rule-sets that fail to comply with the set of global access constraints, the importance sampling quantitatively characterizing a level of compliance with the global access constraints without conducting analysis of all potential paths of the multi-layered rule graph; and

providing results of the selected analysis to the administrator in real time through a graphical user interface (GUI) as the results are obtained so that the administrator can watch the progress of the analysis.

26. The computer readable medium of claim **25**, wherein the plurality of access control elements include network resources, and wherein enabling the administrator to specify a set of global access constraints comprises enabling the administrator to set a global access constraint for a group of the network resources.

27. The computer readable medium of claim **25**, further comprising performing the operation of:

automatically selecting, on behalf of the advertiser, at least one of exhaustive analysis and statistical analysis based on a determined level of resources required to conduct a full exhaustive analysis.

28. A computer-implemented method for analysis of distributed device rule-sets for compliance with global policies, the method executable by a computer having a processor and memory, comprising:

receiving from an administrator a network topology with a plurality of reachable, intercommunicating elements and associated parameters required to secure the intercommunication with one or more access control elements of the network topology;

establishing connections to the access control elements to capture a snapshot configuration of device rule-sets of the one or more access control elements;

receiving from the administrator a set of global access constraints with reference to the plurality of access control elements;

generating a multi-layered rule graph that captures network interconnectivity and data flow among the intercommunicating elements, where each of a plurality of nodes in the multi-layered rule graph represents a possible access decision by an access control element and paths of the multi-layered rule graph represent sequences of access decisions;

receiving a selection to perform model-based statistical analysis to determine violations by the device rule-sets that fail to comply with the set of global access constraints, where statistical analysis quantitatively characterizes a level of compliance without conducting analysis of all potential paths of the network topology;

conducting the statistical analysis by selecting a probability distribution that biases sampling paths having device rule-sets that increase the likelihood of discovering violations of the global access constraints in the device rule-sets of sampled paths; and

providing results of the statistical analysis to the administrator as the results are obtained.

29. The method of claim **28**, where the snapshot configuration of the device rule-sets is received from the administrator.

30. The method of claim **28**, where the statistical analysis further comprises:

conducting repeated and random exploration of an extended version of the multi-layered rule graph to sample a number of paths to construct unbiased statistical measures of compliance;

using importance sampling to guide the random selection towards paths likely to be sources of violation of the global access constraints to reduce variance in the compliance measure; and

calculating a desired set of metrics for traffic represented by each explored path.

31. The method of claim **30**, where calculating a desired set of metrics includes calculating unbiased metrics estimators to remove a bias introduced by the importance sampling, further comprising:

calculating a quantitative estimate of a remainder of the unexplored paths of the multi-layered rule graph; and

analyzing the sampled paths of the multi-layered rule graph with the unbiased metrics estimators to form an estimate of the total number of paths therethrough that violate a specified global access constraint.

32. The method of claim **28**, further comprising:

enabling the administrator to abort the analysis;

enabling the administrator to perform a post-analysis on any partial or complete results throughout the analysis process;

enabling the administrator to make hypothetical changes to the configuration of the device rule-sets for the plurality of access control elements; and

enabling the administrator to conduct again the statistical analysis to analyze the changed configuration.

33. The method of claim **28**, further comprising:

presenting the results to the administrator through a graphical user interface (GUI) of the computer; and

enabling the administrator, through the computer and while viewing the results in the GUI as the results are obtained, to manipulate, filter, or navigate through the results and to visualize a violation once the violation is detected, thereby enabling real-time diagnostic of one or more misconfigurations of a configuration of the device rule-set of one or more control access elements.

34. The method of claim **33**, further comprising:

accepting one or more proposed modifications to the device rule-sets; and

sending the proposed modifications to an analysis engine of the computer to perform the statistical analysis again to verify whether the proposed modifications would resolve one or more of the misconfigurations.

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CERTIFICATE OF CORRECTION

Page 1 of 1

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APPLICATION NO.	: 12/128445
DATED	: June 26, 2012
INVENTOR(S)	: David M. Nicol et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Add after "awarded by the National Science Foundation (NSF)" in Column 1, Line 15:
-- and under Contract Number DE-OE0000097 awarded by the Department of Energy (DOE) --

Signed and Sealed this
Third Day of April, 2018

Andrei Iancu

Andrei Iancu
Director of the United States Patent and Trademark Office