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(54) **METHOD TO PREVENT ROOT LEVEL ACCESS ATTACK AND MEASURABLE SLA SECURITY AND COMPLIANCE PLATFORM**

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G06F 21/55 (2013.01)
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CPC ***G06F 21/554*** (2013.01); ***G06F 21/54*** (2013.01); ***H04L 41/5019*** (2013.01);
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(58) **Field of Classification Search**
CPC .. G06F 21/554; G06F 21/54; G06F 2221/034; G06F 2221/2115;
(Continued)

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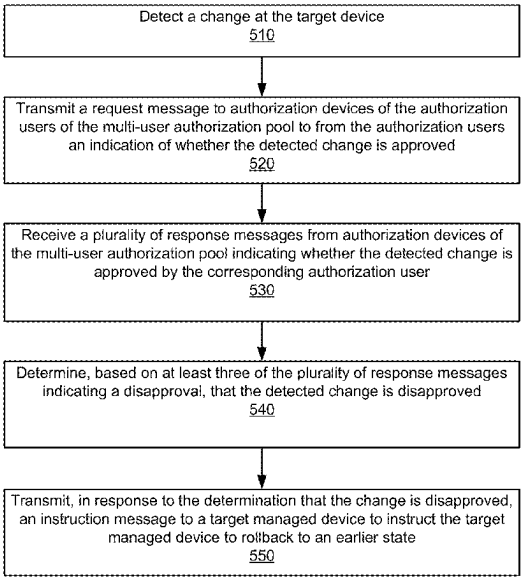
(57) **ABSTRACT**

A compliance monitor measures metrics regarding one or more managed devices in a network. The compliance monitor generates a log based on the information detected by the measurement trackers and to transmit a report based on the generated log to a recipient. The compliance monitor also initiates one or more security actions based on the one or more measurement trackers indicating that a measured metric exceeds an associated threshold measurement value.

20 Claims, 7 Drawing Sheets



Related U.S. Application Data

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(60) Provisional application No. 62/865,080, filed on Jun. 21, 2019, provisional application No. 62/865,083, filed on Jun. 21, 2019.

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H04L 9/40	(2022.01)
H04L 41/5019	(2022.01)
H04L 43/065	(2022.01)
H04L 43/16	(2022.01)

(52) **U.S. Cl.**

CPC ***H04L 43/065*** (2013.01); ***H04L 43/16*** (2013.01); ***H04L 63/1433*** (2013.01); ***H04L 63/1491*** (2013.01); *G06F 2221/034* (2013.01)

(58) **Field of Classification Search**

CPC G06F 2221/2127; G06F 2221/2139; G06F 21/552; G06F 21/57; H04L 41/5019; H04L 43/065; H04L 43/16; H04L 63/1433; H04L 63/1491; H04L 63/1441; H04L 41/5009; H04L 63/1408

See application file for complete search history.

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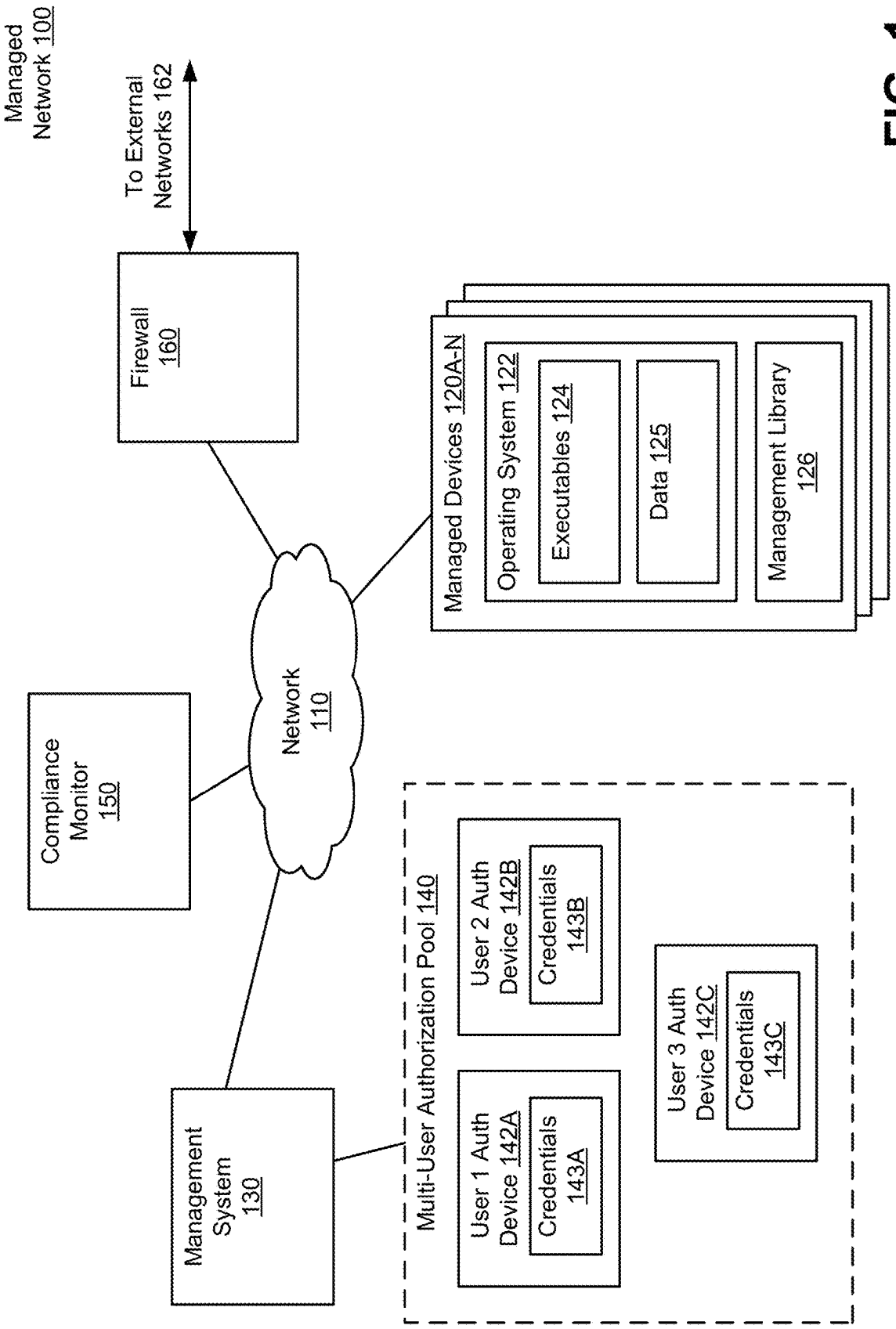
Managed Network 100
To External Networks 162
Firewall 160
Network 110
Compliance Monitor 150
Management System 130
Multi-User Authorization Pool 140
User 1 Auth Device 142A
Credentials 143A
User 2 Auth Device 142B
Credentials 143B
User 3 Auth Device 142C
Credentials 143C
Managed Devices 120A-N
Operating System 122
Executables 124
Data 125
Management Library 126

FIG. 1

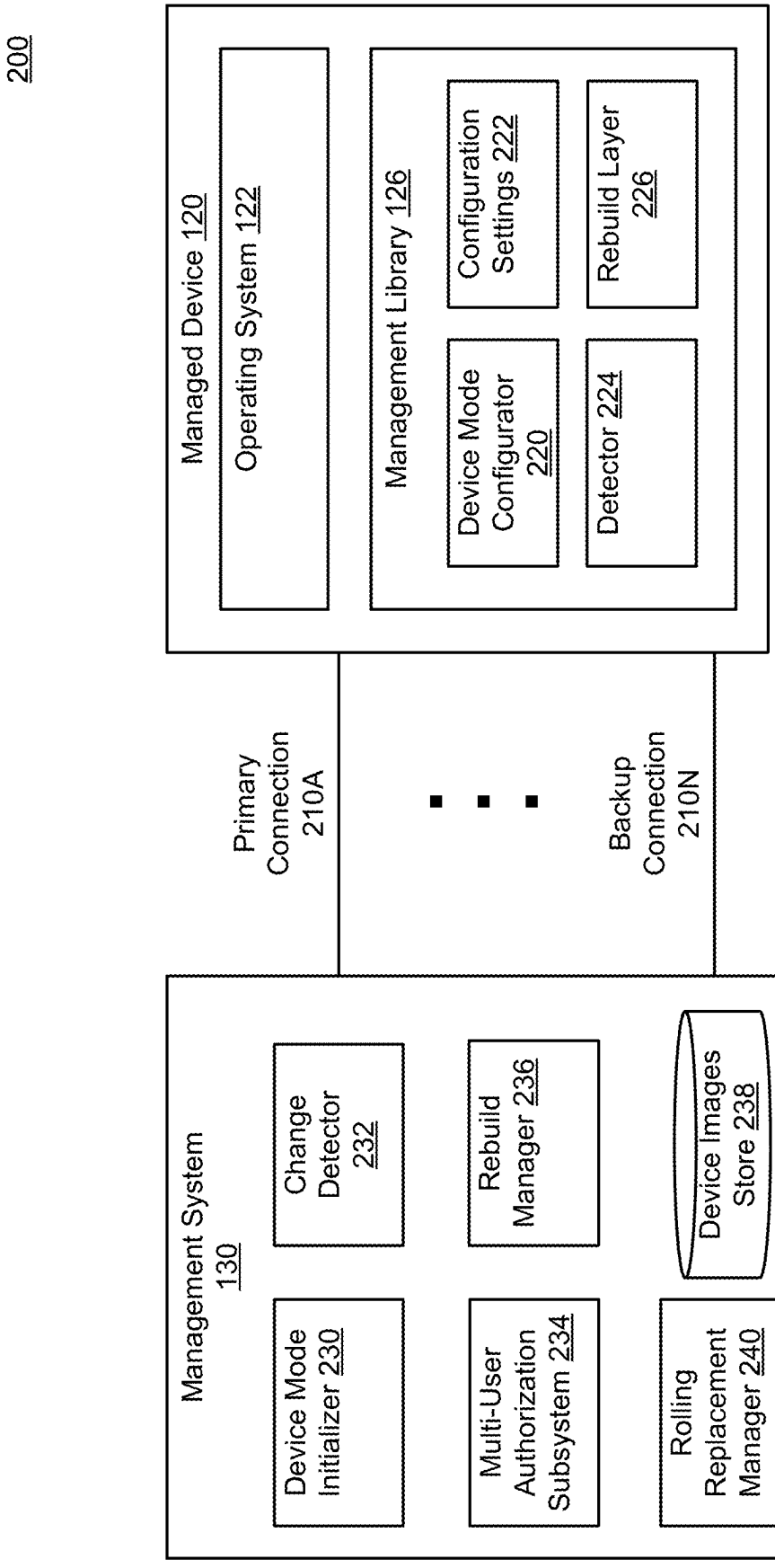
200
Managed Device 120
Operating System 122
Management Library 126
Device Mode Configurator 220
Configuration Settings 222
Detector 224
Rebuild Layer 226
Primary Connection 210A
Backup Connection 210N
Management System 130
Device Mode Initializer 230
Change Detector 232
Multi-User Authorization Subsystem 234
Rebuild Manager 236
Rolling Replacement Manager 240
Device Images Store 238

FIG. 2

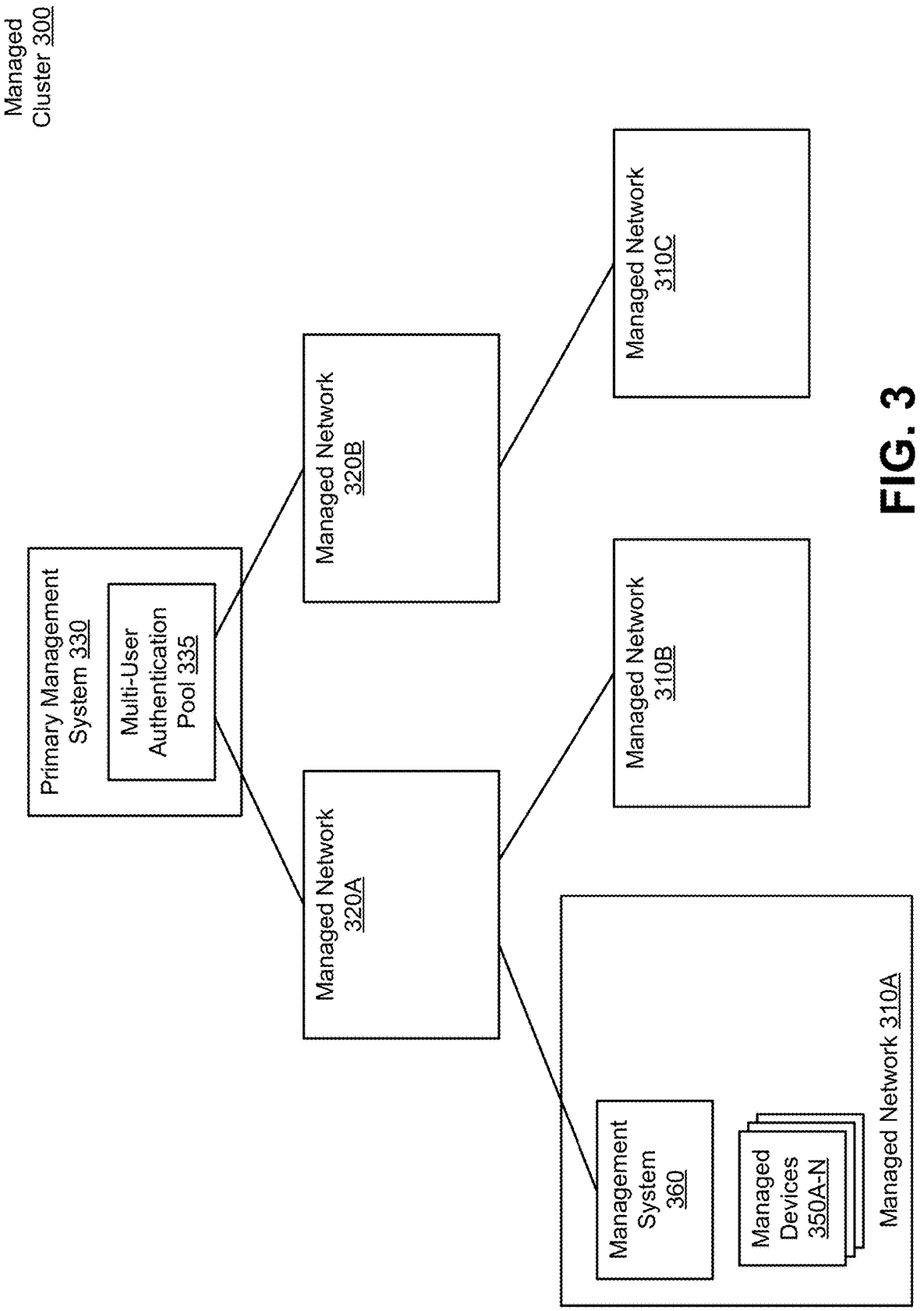
Managed Cluster 300
Primary Management System 330
Multi-User Authentication Pool 335
Managed Network 320A
Managed Network 320B
Managed Network 310A
Management System 360
Managed Devices 350A-N
Managed Network 310B
Managed Network 310C

FIG. 3

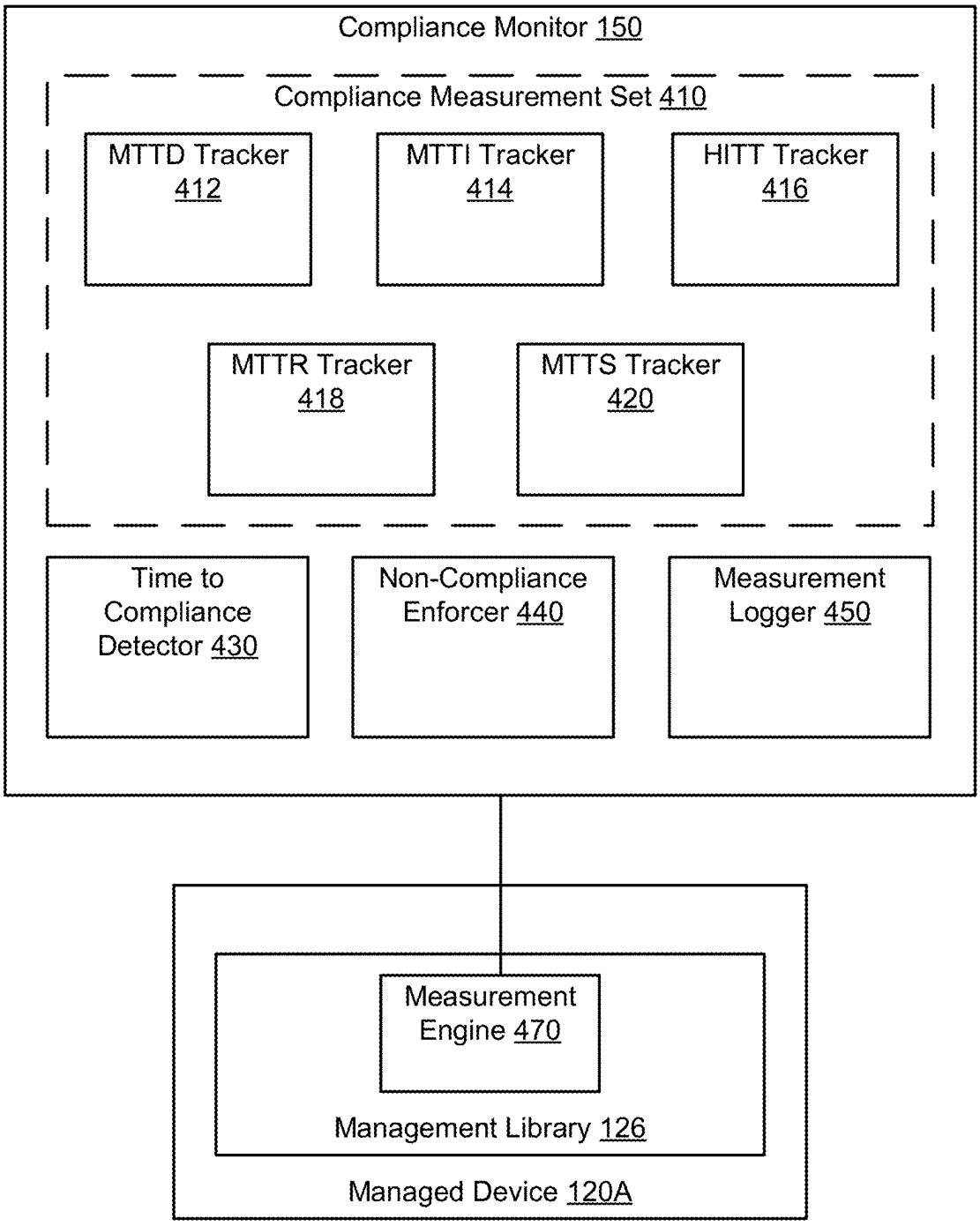
Compliance Monitor 150
Compliance Measurement Set 410
MTTD Tracker 412
MTTI Tracker 414
HITT Tracker 416
MTTR Tracker 418
MTTS Tracker 420
Time to Compliance Detector 430
Non-Compliance Enforcer 440
Measurement Logger 450
Measurement Engine 470
Management Library 126
Managed Device 120A

FIG. 4

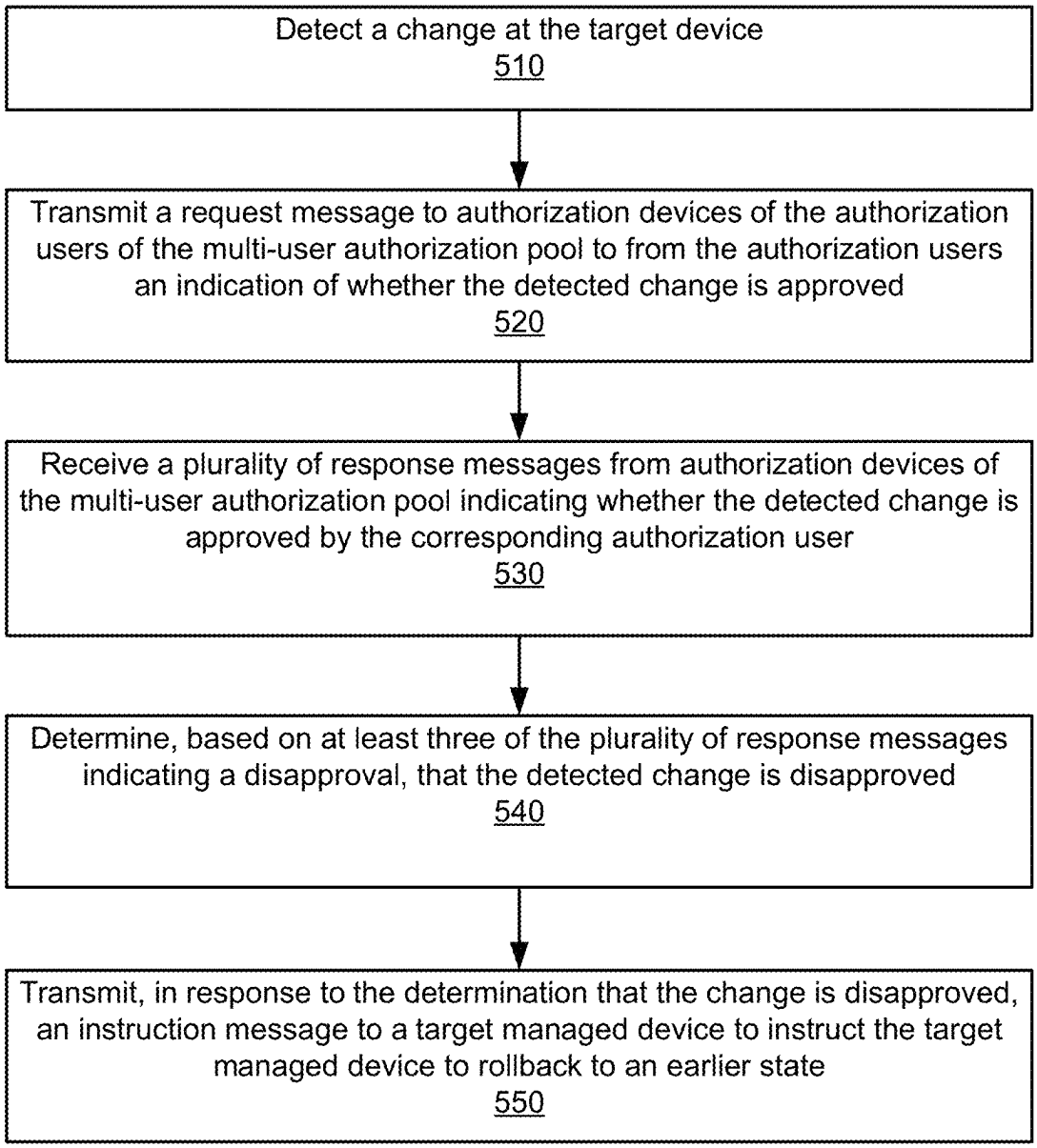
Detect a change at the target device
510
Transmit a request message to authorization devices of the authorization users of the multi-user authorization pool to from the authorization users an indication of whether the detected change is approved
520
Receive a plurality of response messages from authorization devices of the multi-user authorization pool indicating whether the detected change is approved by the corresponding authorization user
530
Determine, based on at least three of the plurality of response messages indicating a disapproval, that the detected change is disapproved
540
Transmit, in response to the determination that the change is disapproved, an instruction message to a target managed device to instruct the target managed device to rollback to an earlier state
550

FIG. 5

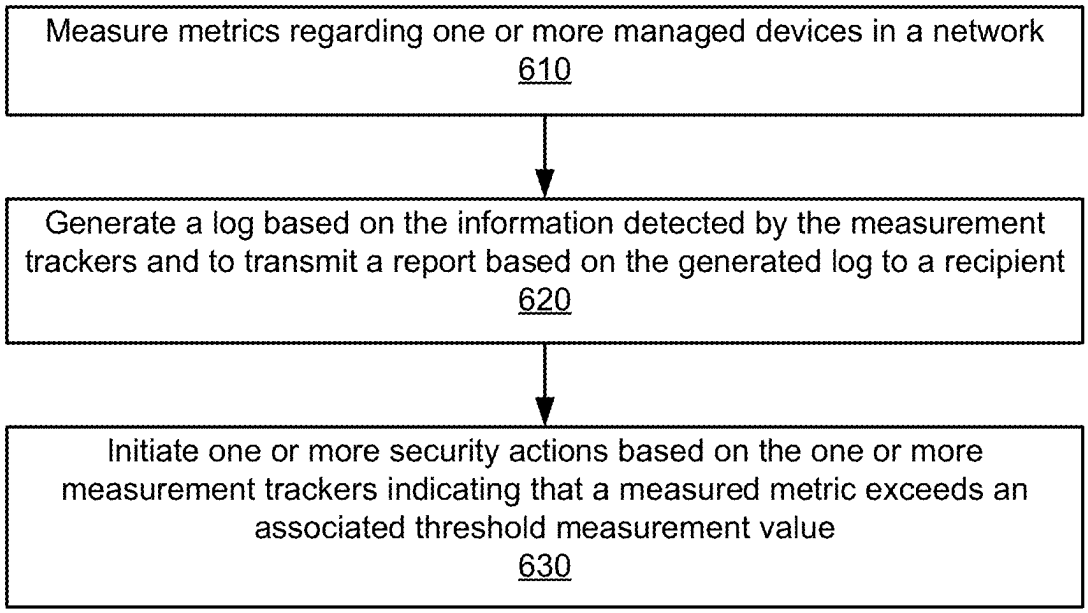
Measure metrics regarding one or more managed devices in a network
610
Generate a log based on the information detected by the measurement trackers and to transmit a report based on the generated log to a recipient
620
Initiate one or more security actions based on the one or more measurement trackers indicating that a measured metric exceeds an associated threshold measurement value
630

FIG. 6

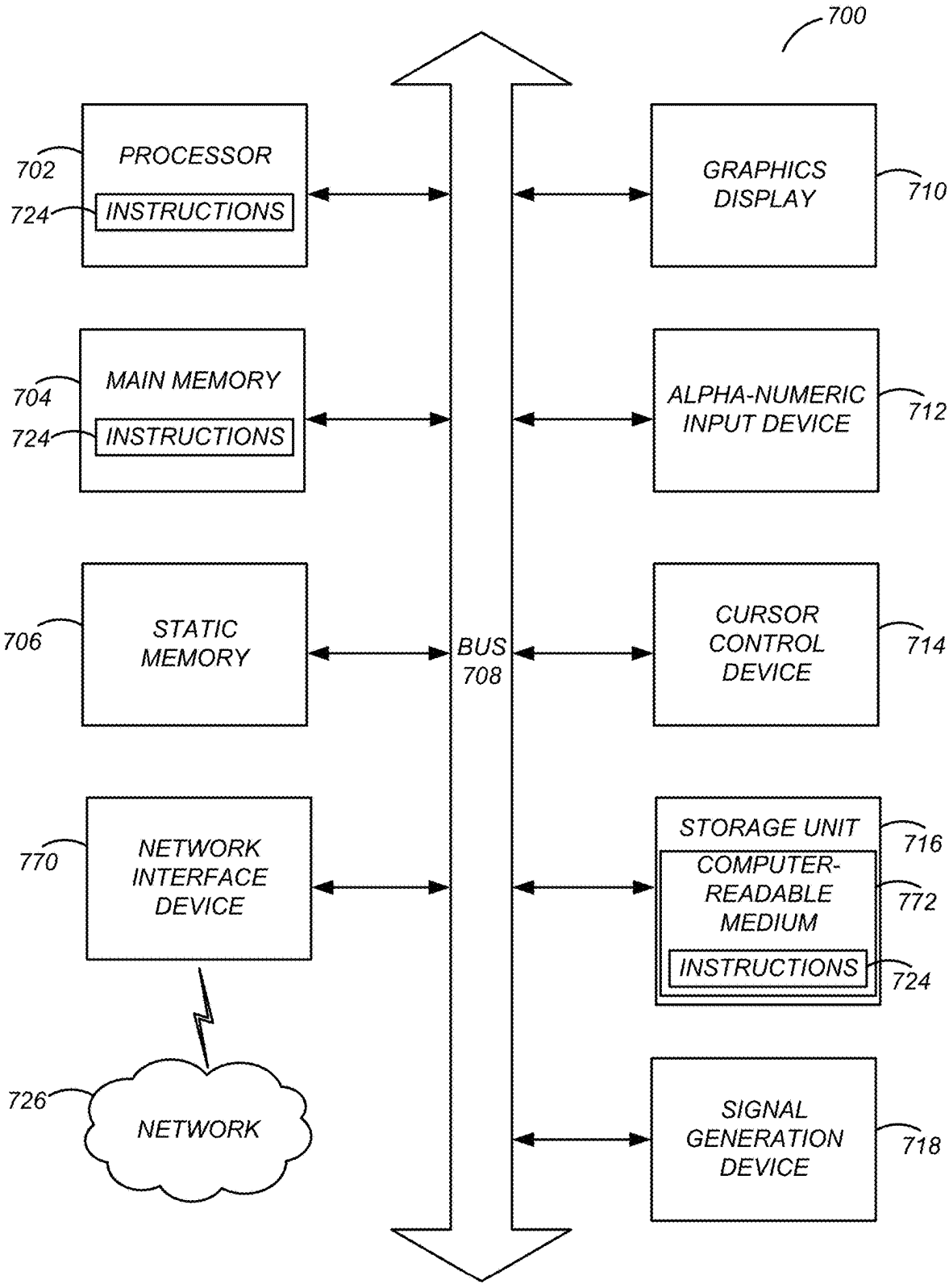
700
PROCESSOR
702
INSTRUCTIONS
724
MAIN MEMORY
704
INSTRUCTIONS
724
STATIC MEMORY
706
NETWORK INTERFACE DEVICE
770
NETWORK
726
BUS
708
GRAPHICS DISPLAY
710
ALPHA-NUMERIC INPUT DEVICE
712
CURSOR CONTROL DEVICE
714
STORAGE UNIT
716
COMPUTER-READABLE MEDIUM
772
INSTRUCTIONS
724
SIGNAL GENERATION DEVICE
718

FIG. 7

METHOD TO PREVENT ROOT LEVEL ACCESS ATTACK AND MEASURABLE SLA SECURITY AND COMPLIANCE PLATFORM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation application of U.S. patent application Ser. No. 18/308,388, filed Apr. 27, 2023, which is a continuation application of U.S. patent application Ser. No. 16/907,302, filed Jun. 21, 2020, which claims priority to U.S. Prov. App. No. 62/865,083, filed Jun. 21, 2019, and U.S. Prov. App. No. 62/865,080, filed Jun. 21, 2019, each of which is incorporated by reference.

BACKGROUND

An administrative or root account has full control over a device, operating system (OS) or applications executing on a system. When an administrator logs into a machine the administrator's user account is placed with a "admin or administrator" group account with privileges to perform such operations and duties for being an administrator. When a malicious attacker breaks into an operating system or application, they may attempt to gain this administrative privilege using the administrative account, in order to be able to clean up tracks and perform all necessary changes needed to perform whatever actions against the device or network they would like.

Furthermore, contemporary computer networks are constantly compromised. Multiple attack vectors exist, and multiple mitigation methods have been implemented to avoid or recover from these attacks. However, the entity which owns a system of computers often times lack insight into attack against their computers. For example, in many cases, administrative personnel can only provide an estimate of the timeframe of an attack after it has occurred, as has been seen in notices by companies to their customers of prior successful acts by malicious actors to access sensitive or confidential data. Therefore, what is lacking is a method of controlling root access to a device to detect and recover from attacks as well as a method of measuring the timeframe during which various attacks occur and the timeframe to recover from these attacks.

Therefore, what is lacking is a system to be able to prevent root attacks and to measure compliance within a system of devices.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** illustrates a managed network for monitoring root-level attacks and measuring compliance on managed devices, in accordance with an embodiment.

FIG. **2** is a block diagram that illustrates a detailed view of the management system and managed device with management library of FIG. **1**, in accordance with an embodiment.

FIG. **3** is a block diagram illustrating a centrally managed cluster of managed networks **310**, in accordance with an embodiment.

FIG. **4** is a block diagram that illustrates the compliance monitor of FIG. **1** in further detail, in accordance with an embodiment.

FIG. **5** is a flow diagram illustrating a process for monitoring and preventing root level attacks, in accordance with an embodiment.

FIG. **6** is a flow diagram illustrating a process for measuring compliance on a set of managed devices, in accordance with an embodiment.

FIG. **7** is a block diagram illustrating an example computing device, in accordance with an embodiment.

The figures depict, and the detail description describes, various non-limiting embodiments for purposes of illustration only.

SUMMARY

Disclosed herein is a management system that detects an changes at the target device. The management system transmits a request message to authorization devices of the authorization users of the multi-user authorization pool to from the authorization users an indication of whether the detected change is approved. The management system receives a plurality of response messages from authorization devices of the multi-user authorization pool indicating whether the detected change is approved by the corresponding authorization user, and based on at least three of the plurality of response messages indicating a disapproval, that the detected change is disapproved. In response to the determination that the change is disapproved, an instruction message is sent to a target managed device to instruct the target managed device to rollback to an earlier state.

Further disclosed herein is a compliance monitor that measures metrics regarding one or more managed devices in a network. The compliance monitor generates a log based on the information detected by the measurement trackers and to transmit a report based on the generated log to a recipient. The compliance monitor also initiates one or more security actions based on the one or more measurement trackers indicating that a measured metric exceeds an associated threshold measurement value.

DETAILED DESCRIPTION

The figures (FIGS.) and the following description relate to preferred embodiments by way of illustration only. One of skill in the art may recognize alternative embodiments of the structures and methods disclosed herein as viable alternatives that may be employed without departing from the principles of what is disclosed.

Reference will now be made in detail to several embodiments, examples of which are illustrated in the accompanying figures. It is noted that wherever practicable similar or like reference numbers may be used in the figures and may indicate similar or like functionality. The figures depict embodiments of the disclosed system (or method) for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles described herein.

Overview

A system can be implemented that prevents a root or administrative user or group to make undesired or unauthorized changes on an operating system (OS). Instead, the overall management now needs to meet critical scenarios of having multiple users in a real-time policy driven system to handle any and all changes that are executed at the OS or remote level. No unauthorized changes will be granted without multiple users signing off on those changes.

When a hacker takes ownership of a computer he escalates and figures out the administrator password. When he logs in with the administrator password today, he can then go in and open up any firewall rule changes. The rule changes in the OS are captured and applied because the administrator has full control over the machine to make those changes. When hitting apply, the OS kernel has no choice and accepts those changes within the local OS. However, a monitoring service within the machine as well as external to the machine will trigger a change state and immediately roll back the changes as it is not matching a known good state of the machine. Those rollback changes will be forced and an alert is transmitted to a security system where now a security operations center may be alerted to the changes. Once alerted, the security system may transmit alerts and/or messages to multiple users on a multiple custody approval list, who can then either accept the changes. Alternatively, if the changes are not accepted, the system may log the change as an intrusion and trigger a warning, alert, or sensor.

A challenge also arises in the case of system upgrades and patches. Typically, a root user is permitted at any time to accept patch changes, as the root user has the privileges to perform any action on the system. However, this will enable hackers to make changes to a core OS without getting noticed within the millions of changes that can take place during a patch upgrade. This makes it impossible to do file based change management to any platform to detect the changes in real-time. However, in one embodiment, to prevent this from occurring, a security system is implemented to only allow these changes in a different process and strictly disallow any changes to take place to an OS that is in a production state. All changes must be controlled and approved through the users in the multiple custody approval list, such that not even the administrator alone can apply changes to the production systems. This allows for the security system to detect any changes and reduce the false negative and false positive errors.

In the event where the malicious attacker attempts to disable any local monitoring services of the computer, the security system is capable of detecting the change (e.g., the local monitoring service may fail to send a heartbeat signal to the security system, or may be unresponsive to pings). Upon detecting the change, the security system may initiate a rebuild of the computer, by wiping and reinstalling the software layer on the computer (e.g., via a rebuild routine stored on firmware or other location inaccessible to the hacker). This rolls the system back to the original state.

Rollbacks are controlled centrally to what is the known good state. By having multiple copies (3+) of the known good state signature, when one copy falls out of state, then others force it back into state. A root user can change the state but it can only change its local copy. If any change performed centrally via approval by the users on the multiple custody approval list, this changes the multiple copies of the good state signature. Therefore, only by changing all copies will the system accept the change. Furthermore, the other copies are not stored within the computer for which the malicious attacker has access. This prevents the attacker from being able to access those copies of the signature.

The multiple user custody approval system requires multiple users to sign off within dashboard user interfaces presented to these users via the security system. The approval system may also include special groups. For example, in a security operations center there may be 12 operations people working and ⅔ of these may be needed to approve any changes. However, the operations lead and/or the customer may additionally be required to provide a final approval.

When all users on the multiple custody approval list (e.g., 3 users) approve the changes, the computer is in an Authorized Release State (ARS). In addition, the computer may be placed in an Authorized Provisioning State (APS). This state allows for multiple changes to take place while not requiring the users on the multiple custody approval list to approve each change. Instead, all changes are made, and then the computer is switched to the ARS state so that all the changes can be signed off at once. The APS state tracks all the changes still but doesn't force a lock down on the machine or rollback changes in real-time.

In addition, the computer may be placed in an Authorized Maintenance State (AMS). This is where builds are done and testing is performed. This state is used as for non-tracking state purposes and generally used for servers waiting to receive a configuration to be deployed to them. These computers are typically in an inventory available pool before an application is applied. Patches are applied in this state and fresh OS are built in this state.

To prevent any attacks to the approving users on the multiple custody approval list, the security system uses IP (Internet Protocol) signing scenarios where the approval must be done within certain IP restrictions as well as password and keys to be used. Therefore, if a user tried to approve from an IP on the Internet which is not on the allowed list of IPs the security system would trigger a sensor that the user approval is form an invalid network source. Even if a VPN (virtual private network) was available it can be locked to not grant the approval.

Furthermore, a new set of measurements and technologies can be used to counter the problem faced in today's environments. These new measurements do not exist today and any combination of these units together will enable new levels of "Security Service Level Agreements" that can actually be measured and reported on. This also enables new levels of security reporting for any type of compliance scenario measurable reports. It enhances all new levels of security and can expose how well or weak a current technology has been deployed within an existing environment.

In some embodiments, these include the following measurements:

- MTTD=Mean Time To Detection: A core technology to measure the time a hacker has been attached to a network to the time the detection system can detect the hacker. This may comprise a counter that is measured in seconds. MTTD is one of the most challenging scenarios the world has faced today. The measurement calculates the time a connection has been established or application has been applied to a machine where the damages to OS (operating system)/Application/Database or service has been in a state. The technology can dynamically change its state based on MTTD time leveraging its other key patents. SLAs can be built from this new measurement technology. Counters designed in this state can be analyzed further with machine learning and also trigger other software elements like logging, alerts, scripts, reports, and correlated machine learning of various source IPs, macs, WWNs, protocols and more.
- MTTI=Mean Time To Isolation: A core technology to measure the time after a hacker has been detected to the time it takes to isolate the hacker from performing further damage against the environment resources. This may comprise a counter that is measured in seconds.

This measurement calculates the time of detection to time of isolation where all connected states and resources are filtered down to prevent hackers from getting access to resources during their compromised state. The calculated time from known problem to isolation should be near real-time but in today's technology, the reaction time is all manual and human driven. This technology will enable automated responses to real-time hacking from millions of sources at the same time. Making the defense against automated or machine driven attacks useless against the real-time counters and responses based on the results of the counters. The counters are dynamic per application or OS type. It is purpose built learning in real-time to respond to groundhog day. The time to isolate is a key counter in measuring response time of a hacked event. The actions performed by this new measurement tool also responds in real-time to hackers' actions making the attack managed faster than any comparable technology in the market today. SLAs can be built from this new measurement enabling stronger defenses against hackers.

HITT=Hacker Investigation Tracking Time: A tracker to determine a length of time for a hacker to remain at the system, due to honeypots and other lures, while recording the actions of the hacker and tracing his source. This may comprise a counter that is measured in seconds. This measurement calculates the time a hacker has been isolated to the time either a hacker is kicked out or has simply left. This new level of measurement also contributes to tricking the hacker to stay engaged with more bogus data by dynamically presenting fake data to capture the audience of the hacker to stay engaged while other resources are used to record and trace the hacker's tracks. The new measurement tool also enables new levels of SLAs based on time in sub seconds scenarios. For example, a counter measurement is 30.6 seconds but could be measured in milliseconds.

MTTR=Mean Time To Repair: After a hacker has either left or has been kicked out, the measured time to repair the OS/Application/Database. This may comprise a counter that is measured in seconds.

MTTS=Mean Time to Service: The recovery time of a service needs to be measured in case of a service disruption of an OS/App compromise. This measurement calculates the time a service is offline as well as a component (VM, containerized system, physical machine or other) is not available to respond to session requests. The MTTS primarily monitors and manages the service availability and uptime metrics. It contributes to the overall machine learning elements with its data outputs.

These measurement trackers, or counters, can measure the detection times described above can be enabled via a secure service to any OS on any application integration. Counters are tunable based on combination of sensors but not limited to the following: 1) OS/application build completion; 2) when the system it is put into service and accepting traffic for users or requests; 3) application specific or service specific sensors (e.g., the counter is triggered to start upon some specific application process); 4) to user login; 5) to file system access, port access, log entry, integrity checker, simple uptime clock; 6) or others. User activity/system automation activity may also part of the measurable counters. Sensors can be integrated with each other or existing 3rd party sensors or counters.

In one embodiment, the counters are started from the time an OS has been provisioned or restored to a known good state. Once it is placed into an available pool for service the connectivity to the OS has been currently placed in the "Available" pool for service. In another embodiment, the counters are dynamically initialized and assigned based on tunable algorithms to measure any combination of the above times. These initializations may be local to a system, centralized, or distributed across multiple systems, and may be implemented using a security key.

In another embodiment, the counters may be initialized based on the triggered honeypot and fake resources placed on the system as a track. For example, fake folders within the OS which would normally no be accessed during normal operations may be accessed by a bot or human during a malicious attack. Additional honeypots may be in the form of user accounts. For example, a system may have 10+ user accounts where 6 of them will be honeypots that are sensors that trigger counters. If any of these fake user accounts are accessed, then the system will determine that a hacker has accessed the system. Root access may also be classified as one of the sensors. Admins are part of the root group but the root as well as other admin accounts may all be sensors that trigger a roll, SLA monitor, state of the machine issue and counter to start.

In another embodiment, once in the in service pool, the counters may be started. Each connection to the OS/APP are profiled and measured. Sensors built into the counter can be triggered.

In another embodiment, any modifications of the system may trigger one or more of the counters to initiate. In some cases, the system may not allow patching inline while the OS is in service. This allows too many changes to the file system and components of the OS to cause too many false negatives and false positives to be detected (which may trigger the counter). Instead, patches may occur offline, to reduce the number of detected false negatives and false positives. This allows accuracy to reach 99%+.

The system may be monitored externally to determine whether to trigger the counters, by having an external system monitor the local system via allowed access through a firewall or other load balancers. The control time or access time may also be monitored remotely.

In one embodiment, the counters may be stopped, i.e., detect the termination or end of the event, when the OS is powered off or based on dynamic ACLs (access control lists) indicating resource access based on sensors triggered. For example, connections to a database are dynamically removed if root login is detected in the local webserver and is trying to make changes to the OS.

In the case of the use of honeypot resources, an access to these files or resources may trigger an action response, such as an isolation of the system, and would set the system into a hacked state. This would ultimately cause the OS to be completely rebuilt and the hacker caught in the dynamically generated honeypot OS. The counter may be terminated after the rebuilding, as the hacking incident is over after the rebuild. The rebuilding of the OS may include the wiping of the existing software layer on the system and the re-imaging, rebuilding, and/or reinstallation of the software layer to an original state. The uptime of the OS in the rolling system is tuned to the application. An example lifetime of an OS is usually capped around 30 min max but can be as short as 10 seconds. If the lifetime of the OS standard configuration is 10 seconds and the measured SLA on the service is 30 seconds then the actual rolling time will be 20 seconds. The OS is rebuilt based on the SLA, thus forcing all threats that

are in the OS to become irrelevant as they need to be executed within that SLA period. All traffic from malicious activity may be analyzed via a machine learning algorithm to detect specific patterns to further determine information related to the attack.

The system may support contextual machine learning to stop counters as well as allow control over the devices as dynamic calls to the host or firmware (e.g., BIOS) of the system to reboot the server, or if the system is a virtual machine (VM) would reboot the VM, or if the system is a container in a containerized environment, to rebuild the container. In either of these cases access to the system by the hacker is terminated and thus the hacker cannot perform any further attacks within that SLA time. As the rebuild of the servers allows for a shortened time period for access, a hacker cannot cause additional damage to the system.

One example application of such counters is for a system that handles credit card transactions. In such an application, the SLA thresholds indicating a desired maximum time for any of the mean times indicated above may be based on the calculated transaction time of each transaction. A machine learning or other algorithm may be applied to determine the min and max transaction times of the credit card transactions, and the SLA may be built dynamically around these measurements to set the maximum and/or minimum times for TTD, TTI, TTC, TTH.

Nodes in a split session state may carry their counters forward. Having multiple nodes of the same memory/session state will carry the all SLA counters across physical devices. This will also help measure all forms of connection/session/replication activities.

The custom SLA counters can be monitored, picked up by any monitoring technology today which understands its designed output.

The SLA counters can be combined with other counters to improve on security posture and enable the advanced machine learning capabilities within and external machine learning processing as well.

The tools of MTTD, MTTI, MTTH, MTTS may generate logs, which can be consolidated. The log data performs the tracking of each tool's timeframe and measurements. The log data can be centralized like performance counters, which can then be analyzed in any database type for further analysis.

Measurable SLAs may be associated with reporting elements. The measurement counters will provide application aware points for customizing a min to max range based on an applications needs. The counter also can be used for generating events at all levels of the time interval.

Having these integrated counters can radically improve a security stance on compliance as these new counters can change the whole security compliance scenarios with now security measurable SLAs with measurable security compliance.

Security compliance is more of a process today which most companies are either in compliance or out of compliance based on a set of standards. The counters used above open up new levels of compliance as to now can be measured in real-time and not an external human driven process for verifying if a system or platform is in compliance. It opens up new levels of measurement at the compliance level counters where the detection time must be under a first time threshold and isolation time be under a second time threshold and hacking time (i.e., MTTH) be under a third predetermined time threshold. If these new counters are met and measured, then the system would be in compliance as measured. This is in contrast with traditional policies which are driven by human level questions, which do not perform any form of real-time measurement like the counters included above.

Furthermore, in traditional systems, the issue that was not considered was that these systems allowed a long period of time for the computing system and its OS to live in service. Due to this, these systems have to count all the time a potential attacker has been in the system. In contrast, by rebuilding the system as described above, this rolling system architecture reduces the mean times time down to seconds and minutes, which may be used to compute the SLA.

Additional details regarding these systems are described below with reference to FIGS. **1-7**.

Exemplary System

Figure (FIG. **1** illustrates a managed network **100** for monitoring root-level attacks and measuring compliance on managed devices, in accordance with an embodiment. As illustrated, FIG. **1** shows a network **110**, managed devices **120**A-N (generally referred to as managed device(s) **120**), a management system **130**, a multi-user authorization pool **140**, a compliance monitor **150**, and a firewall **160**. Although a certain arrangement and number of elements is shown here, in other embodiments the arrangement and layout of items differ. For example, the compliance monitor **150** and/or the firewall **160** may be components of the management system **140**. In one embodiment, one or more of the elements described here are implemented in a firmware, FPGA (field programmable gate array), integrated circuit, chip, SoC, or other hardware device.

The network **110**, which can be wired, wireless, or a combination thereof, enables communications among at least the elements shown, and may include the Internet, a LAN, VLAN (e.g., with VPN), WAN, or other network. In one embodiment, the networks **110** uses standard communications technologies and/or protocols, such as Secure Hypertext Transfer Protocol (HTTPS), Transmission Control Protocol/Internet Protocol (TCP/IP), Uniform Resource Locators (URLs), and the Doman Name System (DNS). In another embodiment, the entities can use custom and/or dedicated data communications technologies instead of, or in addition to, the ones described above. In one embodiment, all communications on the network **110** is monitored by the management system **130**. Therefore, any communication, whether secured, tunneled, plaintext, or otherwise, between the elements on the network **110** and other external networks may be gated by a firewall, such as firewall **160**. Using this method, the management system **130** may be able to monitor the activity on the network for any changes.

The managed devices **120**A-N are computing devices which communicate with each other and in some cases with devices on external networks via the network **110**. These devices may include any type of device capable of executing computer-readable instructions, and may have an architecture that includes components described below with reference to FIG. **7**. For example, these may include smartphones, IoT (Internet of Things) devices, wireless devices, smart speakers, wearable devices, tablets, virtual/artificial/mixed reality devices, desktop computers, laptops, server computers, wireless access points, routers, dumb terminals, and so on. The managed devices **120** may connect directly to the network **110** without passing through any intervening networks, or connect to the network **110** via an external network. This may be achieved using a secure communications method, such as a network tunnel (e.g., a VPN). In one embodiment, when the managed device connects via an

external network to the network **110**, all its communications with any network is monitored by the management system **130**.

In one embodiment, each managed device **120** may include an operating system (OS) **122** that may be used to execute executables **124**. Each managed device **120** may also include a management library **126** used to communicate with the management system **130** in order to monitor activity performed using the operating system **122** and executables **124** and to revert any changes that are detected during the use of the operating system **122**.

The operating system **122** for the managed device **120** is a set of computer-readable instructions that provides the basic system software used to manage computer hardware, hardware resources, software resources, and to provide a common interface and set of services for the executables **124** that are executed by the manage device **120**. Examples of operating systems include WINDOWS®, LINUX®-based operating systems, FreeBSD, OS X®, and so on. The executables **124** are also sets of computer readable instructions that can be executed by the managed device **120** via the operating system **122**, but which also communicate with the services and interfaces provided by the operating system **122** in order to function. The operating system **122** may also include data **125**, which represents non-executable computer-readable information that may be used to configure settings the operating system **122** and/or executables **124** and store user or other data (e.g., database files, media files, text files, etc.). Although the data **125** is shown to be part of the operating system **122**, some data **125** may be OS-agnostic and can be utilized even if a different operating system **122** were used for the managed device **120**. The computer readable instructions and information for the operating system **122**, executables **124**, and data **125** may be stored on storage media residing at the managed device **120** or at a remote location that can be accessed by the managed device **120** via the network **110**.

The operating system **122** has a kernel, which is a portion of the computer readable instructions of the operating system **122** that provide the core functionalities of the operating system **122**. This typically includes providing an interface to hardware resources, providing virtual memory interfaces, switching context between multiple executables **124** that are running on the operating system **122**, and providing various levels of security access to resources provided by the operating system **122**, such as access to files, hardware resources (e.g., network access, trusted platform module access, external I/O (input/output) access, and so on). The kernel typically restricts access based on a user permission scheme, whereby a root or administrative user has full access to all resources that the operating system **122** is capable of providing, while other users have different sets of more restrictive access to these resources. The access given to each user is their set of permissions. Each user is provided with a user account on the system, which the user can access via some credential authentication system (e.g., username/password, rotating token, biometrics). This user account, once accessed, provides the user with the aforementioned permissions. Users with more restrictive permissions cannot perform many undesirable actions on the operating system **122**, as they are restricted to access only a small subset of resources. However, an administrative, root, or system user account can perform many actions, some of which may be deemed unapproved. Access to the root account, if normally accessed by an authorized user, would not necessarily pose a security risk to the managed device **120**. However, if this same root account is accessed by a malicious user, either via a vulnerability in the code of the operating system **122** or by compromising the credential authentication of the authorized user of the root account, this poses a significant threat to the managed device **120**, as now the malicious user has unrestricted access to the managed device **120**, and potentially to other devices on the managed network **110** if the compromised user account used by the malicious attacker can be used to access other devices on the network. Similarly, using a system account, an unauthorized patch or upgrade to the operating system may occur which includes malicious code. The changes caused by these unrestricted user accounts may be unapproved and may result in negative consequences, such as stealing confidential information (e.g., data **125** that is confidential) from storage within the managed network **100**, creating a backdoor access within the network **110**, causing devices on the network **110** to cease functioning, and so on.

To mitigate these types of changes, each managed device **120** further includes a management library **126** to monitor the activities within the operating system **122** and, in the event that a change is detected, the management library **126** can remediate the change by, for example, rolling back the managed device **120** to a previously known good state. The management library **126** may perform this function by injecting one or more detection binaries executing as executables **124** within the operating system **122** which monitor the managed device **120** and operating system for any changes. If any changes fall outside an exception list of changes that are allowable/approved for the managed device **120**, the one or more detection binaries may transmit an alert/message to the management library **126** or to the management system **130** indicating that a change was detected. If the change is determined to be unauthorized, the management library **126** may revert any changes caused by the unapproved change. The management library **126** may determine that the change is unauthorized from a message received from the management system **130**. To revert the changes, the management library **126** may rollback the operating system **122**, and any associated executables **124** and data **125**, to an earlier state. This may be performed by replacing the current operating system **122**, including related executables **124** and data, with a previous image of the operating system **122**. The previous image of the system is an exact copy of an earlier state of the operating system **122**, executables **124**, and data **125** as was previously stored in the corresponding electronic storage, and which is in a known good state. This type of rollback prevents further malicious activity from occurring in the operating system **122** of the managed device **120**. Alternatively, the management library **126** performs a rollback the moment the change that falls outside the exception list is detected, and applies the change back to the managed device if it is determined to be approved. Additional details regarding the management library **126** are provided with reference to FIGS. **2-6** below.

The management system **130** receives messages of changes in any of the managed devices **120** on the network **110** from their management libraries **126** and instructs the management libraries **126** on the managed devices **120** with a message that includes instructions on how to respond to the change. As noted above, any indication of detected changes from the management library **126** may be transmitted to the management system **130**. These changes may be those that were not on an exception list. This message may be encrypted, possibly via a rotating key. In response, the management system **130** may determine, based on an exception list for that managed device **120**, whether the reported change is listed as an exception in the exception list. If the

change is listed in the exception list, the management system **130** may send a message to the management library **126** for that managed device **120** indicating to allow the change. The exception list may include rules regarding what types of accesses, to what degree/amount, and to what types of resources are acceptable. If, on the other hand, the reported change is not listed in the exception list, the management system **130** may send one or more messages to the multi-user authorization pool **140** to determine if that change is acceptable, i.e., to determine if the change is approved. In other embodiments, the management system **130** may instead transmit messages requesting approval from the multi-user authorization pool **140** for all received messages of possible changes from the managed devices **120**, without checking an exception list.

The multi-user authorization pool **140** is a set of authorization users who can approve or disapprove any reported changes from the managed device **120**. These authorization users may be administrators, system operators, customers, security experts, etc. Each authorization user of the multi-user authorization pool **140** may have an authorization device, such as the authorization devices **142**A-C (generally authorization devices **142**). Although three devices are shown here, in other embodiments the pool **140** can include a greater number of devices and associated users with approval authorization. These authorization devices **142** are computing devices (such as those described below with reference to FIG. **7**), and which themselves may be managed devices **120**. Each authorization device **142** can inform the user of the device with a description of the reported change via any one of a standard set of output devices (e.g., a display, audio output, wireless interface). The authorization device **142** can also receive input from the user to authenticate the user, e.g., via credentials **143**A-C, and to receive input from the user indicating whether the reported change is approved or disapproved. This input may be received via any one of a standard set of input devices (e.g., a keyboard, mouse, touchscreen). Each authorization device **142** may alert the user via some notification method (e.g., an audio, haptic, visual, or other output) that a change has been detected for a particular managed device **120**. The user may input their credentials **143** in order to authenticate themselves. These credentials may be similar to credentials used to authenticate users for a managed device **120**. They may include encryption keys, a certificate, biometrics, etc. The credentials may include a multi-factor authentication process. These credentials **143** may be transmitted for verification to the management system **130** or verified locally, after which the authorization device **142** outputs the description of the change to the user of the authorization device **142**. The authorization user, via the authorization device **142**, is presented with a description of the change. This might include log file information, a description of the access type, user account used to perform the access, a resource accessed, a specific error detected (e.g., loss of communication), and so on.

Each user of an authorization device **142** may have a set amount of time within which to approve a reported change, after which the management system **130** assumes by default that the user does not approve the change. Furthermore, a threshold number of users of authorization devices **142** must approve a change, before the management system **130** determines that that change is approved and instructs the management library **126** to allow the change to continue. If the threshold number of approvals is not reached, or if a threshold number of disapproval messages is received, then the management system **130** instructs the management library **126** to disapprove the change. This remediation may include, for example, rolling back changes as described previously. Alternatively, if the change is preemptively rolled back by the management library **126**, then the management library does not revert the change back. As an alternative, the management system **130** determines that the change is approved only if it receives approvals from a certain percentage of the users of the multi-user authorization pool **140**, and determines that the change is disapproved if it receives disapproval messages from a certain percentage of the users. In addition to transmitting a message to the management library **126** to rollback the system, the management system **130** may trigger other actions, such as to send a message to the firewall **160** to block external network access to the managed device **120** in which the change was detected, to instruct management libraries **126** of other managed devices **120** to block communications with the managed device **120** in question, and so on.

This process has many advantages. As more than one user is needed to approve any change deemed to be unapproved, the compromise of an authorization device **142** of any individual user who has approval capabilities does not compromise the entire system. Furthermore, as the system times out and disapproves any change if it does not receive the requisite number of approvals, it can continue to function even without continued user approvals and authorizations and continue to remain safe from attackers. Finally, as the approval process ultimately resides with a human, this avoids an issue where an automated approval system can perform an incorrect behavioral analysis of the reported change. An automated system can be targeted with vulnerabilities in order to deceive the system into determining that a change that is actually malicious is acceptable. For example, a resource access may be crafted in such a way that a heuristics or machine learning system determines that the pattern of access is similar to a normal access pattern, when in fact the access pattern is deliberately engineered to deceive the system and is actually malicious. By having a set of multiple human users approve any changes, both the attack vector of deceiving an automated behavioral analysis system, and the attack vector of compromising an individual administrative approval user's device, are mitigated. Additional details regarding the management system **130** and the multiple user/custody approval process is described below with reference to FIGS. **2**-**3** and FIG. **5**.

In one embodiment, the managed network **100** further includes a compliance monitor **150** to compute one or more trackers to determine a level of compliance of the managed network **100** with an SLA (service level agreement). Many compromises of organizational networks and devices are detected many months after the attack, which hinders the ability of forensics analysis, recovery of any stolen data (e.g., data **125**), and capture of the malicious attacker. Therefore, the ability to quickly track whether any SLA requirements have been violated is advantageous. The SLA here describes an agreement between the managed network **100** and any customers as to various measurable levels of service that the entity which manages/owns the managed network **100** aims to deliver to any of its clients. A violation of this SLA may indicate an unapproved change, such as an attack, has occurred on the managed network **100**. The compliance monitor **150** may track metrics associated with the SLA to determine if the SLA has been violated. The measurements that may be tracked include mean time of 1) detection of attack, 2) isolation of attack, 3) persistence of attacker in system, 4) repair to the system, 5) recovery time of a service, and 6) return to compliance with the SLA

metrics. In response to any one of the measurements exceeding a threshold value, the compliance monitor **150** may transmit a message to the management system **130**, which may in turn transmit a message to the multi-user authorization pool **140** as described above. If the management system **130** determines that the users of the multi-user authorization pool **140** disapprove of the reported violation of the threshold value, the management system **130** may initiate a remedial action upon the affected managed devices **120**, such as by rolling them back.

Using this method of compliance monitoring, the managed network **110** is able to ensure that the measured metrics in the system are guaranteed to stay within the SLA thresholds. If a tracked metric is measured to exceed a threshold which would trigger or eventually trigger an SLA violation, the system can take remedial action, such as rolling back affected systems, in a prompt manner. This ensures that SLA violations do not occur (or occur only very temporarily). This provides a service to customers that is more stable and resistant against attackers, which is desirable over existing systems in which an attack or other change may take many months to detect. Additional details regarding the compliance monitor **150** are described below with reference to FIGS. **4** and **6**.

In one embodiment, the managed network **100** also includes a firewall **160** which can manage network traffic directed to and exiting from the network **110** to external networks **162**. In one embodiment, the firewall **160** receives requests from the management system **130** to block network access (both inbound and outbound) by a managed device **120** to external networks **162**, in the case where the management system **130** determines that the managed device **120** is exhibiting a change that is unapproved. To block the network access, the firewall **160** may perform analysis on network packets and traffic, such as deep packet inspection, to determine the source and destination of network data to/from the external networks **162** (e.g., via network address, network port, other header information, payload information), and may drop any identified network traffic that are from the managed device **120** from which an unapproved change was detected, or directed to the same managed device **120**. In another embodiment, the firewall **160** may log the identified network traffic. The firewall **160** may also allow or selectively allow any identified network traffic to the destination based on instructions from the management system **130**, for example, in the event that the managed device **120** is a device configured to trace or attract malicious users, e.g., a honeypot.

In one embodiment, the firewall **160** itself is a managed device **120**, and includes a management library **126** which monitors changes in the operating system, executables, and data of the firewall **160** device itself to determine if any user is causing changes on the firewall **160** that is unapproved. If so, the management library **126** on the firewall **160** may transmit a message to the management system **130**, and in response, if the change is not approved, the management system **130** may cause the firewall **160** to rollback its operating system, executables, and data, similar to the process described above for the managed device **120**. In this fashion, the firewall **160** itself is also protected from any unauthorized root-level or other user attacks.

Example Management System

FIG. **2** is a block diagram that illustrates a detailed view **200** of the management system **130** and managed device with management library **126** of FIG. **1**, in accordance with an embodiment. FIG. **2** illustrates the management system **130** with a device mode initializer **230**, change detector **232**, multi-user authorization subsystem **234**, rebuild manager **236**, device images store **238**, and rolling replacement manager **240**. The management system **130** communicates with the management library **126** of the managed device **120** via one or more connections **210**A-N (generally referred to as connections **210**). These include a primary and various backup connections in the event of failure or compromise of a path.

The device mode initializer **230** initializes the managed device **120** to one of a number of different states, based on the requirements of the managed device **120** and based on approval from users of the multi-user authorization pool **140**. The device mode initializer **230** may receive a requisite approval from the multi-user authorization pool **140** to place the managed device **120** in one of the aforementioned states. This requisite approval may be approval by a threshold number of users, a threshold percentage of users, and/or approval by a special group of users within the pool. In response, the device mode initializer **230** configures the managed device **120** and management library **126** for the managed device **120** with configuration settings corresponding to that state.

In one embodiment, the managed device **120** can be in a release state, provisioning state, or maintenance state. These may be referred to as an Authorized Release State (ARS), Authorized Provisioning State (APS), and an Authorized Maintenance State (AMS), respectively.

In the release state, the device mode initializer **230** configures the managed device **120** to be in normal operating mode. This is a mode in which any changes detected at the managed device **120** trigger the management system **130** to request approval from a threshold number of users (e.g., at least 3 users) of the multi-user authorization pool **140**, as described above.

In the provisioning state, the device mode initializer **230** configures the management system **130** to allow changes to be made to the managed device **120** without constantly requesting approval from the multi-user authorization pool **140** for each change, although the management system **130** may still track any changes that are made. This state may be used when initially configuring, i.e., provisioning, the managed device **120**. When provisioning is completed, the device mode initializer **230** may be notified that the provisioning is completed (e.g., via an input from a user interface), and may request approval from a threshold number of users of the multi-user authorization pool **140** before converting the managed device **120** into the release state. Any changes logged during provisioning may be further reported to the users of the multi-user authorization pool **140** during this time for approval. Alternatively, the device mode initializer **230** may receive a message from a threshold number of users of the multi-user authorization pool **140** to convert the managed device **120** to the release state. This provisioning state may be used when a large number of changes need to be made to a managed device **120** during an initial phase.

The device mode initializer **230** may also receive a message to convert the managed device **120** into a maintenance state. In this state, no tracking is performed of the managed device **120** and no approvals are requested for any changes to the managed device **120**. To initiate this state, the device mode initializer **230** configures the management library **126** of the managed device to stop tracking of any changes. Furthermore, the device mode initializer **230** configures the management system **130** to ignore the managed device **120**. This state may be used for testing, configuration,

patching, and other maintenance tasks (performed by trusted individuals). In addition, in this state, the managed device **120** may also be cut off from the rest of the devices in the managed network **100**. Thus, this state may also be activated for a managed device **120** which is unresponsive or suspected to be compromised.

The change detector **232** detects any changes from the managed device **120**, either via the management library **126** on the device or via direct means. The change detector **232** may receive messages from the management library **126** of the managed device **120** regarding any change that is detected. Specifically, the change may be detected by the detector **224** of the management library **126**. In addition, the change detector **232** may detect changes with the managed device **120** directly. This may include detecting changes by analyzing the one or more connections **210** with the managed device **120**, and by analyzing the messages received from the detector **224** of the managed device **120**.

In one embodiment, the change detector **232** detects changes in the one or more connections **210** with the managed device. The management system **130** may in some cases maintain more than one connection, i.e., more than one logical or physical layer network paths, with the managed device **120**. For example, the management system **130** may connect to the managed device **120** using a wireless and two different wired connections, or may maintain more than one route to the managed device **120** (e.g., via different entries in a routing table for the network **110**). If the change detector **232** determines that any of these connections are disrupted, the change detector **232** may determine that a change has occurred. The change detector **232** may also receive one or more messages on these connections **210** from the managed device **120**. These messages may be heartbeat messages. The heartbeat message may furthermore be encrypted via a rotating key. Each connection may receive a different type of heartbeat message encrypted with a different rotating key. If the change detector **232** does not receive one or more heartbeat messages on any one connection, or if the heartbeat message is encrypted improperly (e.g., using the wrong rotating key), the change detector **232** may determine that a change has occurred.

The change detector **232** may also analyze other messages sent and received by the managed device **120** to determine if a change has occurred. This may include the messages from the managed device **120** that indicate an change was detected by the management library **126** of the device. These messages may be signed using a rotating key, authenticated using some known method, or be in a standard format. If the change detector **232** determines that the signature, authentication method, and/or format of the messages does not match an expected result, the change detector **232** may determine that a change is detected.

The change detector **232** may also analyze other changes made by the managed device **120** using the network. These changes may include messages sent or received by the managed device **120** using the network. The change detector **232** may have access to one or more network infrastructure devices, such as switches, routers, hubs, access points, and other network switching equipment, such as the firewall **160**, and can analyze the network traffic passing through these network infrastructure devices to extract messages that are sent and received by the managed device **120**.

The change detector **232** may also actively query the managed device **120** by sending network requests to the managed device **120**, e.g., via standard network protocols to determine if the response from the managed device **120** changes. If so, the change detector **232** detects that a change has occurred. For example, the change detector **232** may send an encrypted message to the managed device **120**, for which the management library **126** can respond to with a predetermined message that is encrypted based on or includes a secret that is not known to an illegitimate attacker (e.g., a private key value). If the change detector **232** determines that the response from the managed device **120** is changed from a predetermined response (e.g., it does not include the secret), then the change detector **232** may determine that a change is detected.

In another embodiment, the change detector **232** also queries the managed device **120** by accessing the managed device **120** remotely using a remote access protocol (e.g., Telnet, remote desktop, SSH). The change detector **232** may use this remote access to execute various commands and interface with the operating system **122** of the managed device **120** to perform a set of checks. If the response to these checks is changed from a predetermined set of responses (e.g., a query results in the wrong or no response), the change detector **232** may also determine that a change is detected at the managed device **120**.

If the change detector **232** determines that an change is detected, either by direct testing as described above or by receiving a message from the management library **126** of the managed device **120** indicating an change was detected, the change detector **232** may log the occurrence and send a message to the multi-user authorization subsystem **234** with a log of the change to determine if the change is approved. This message may include a description of the change exhibited by the managed device **120** as detected by the change detector **232** or received by the change detector **232** from the management library **126**.

In one embodiment, the change detector **232** does not report those changes to the multi-user authorization system **234** which match any exceptions within an exception list. The exception list includes a list of all changes which are already approved and thus do not require additional approval by sending the message to the multi-user authorization subsystem **234**. The changes may be defined using various rules that can be interpreted by the change detector **232** to determine the changes that excepted/excluded from requiring approval. These rules may indicate, for example, resource types, networks, files, protocols, file access, I/O access, application name, time range, user account, expected response, encryption type, and any other rules needed to define the pre-approved change. The exception list may be user defined or generated using machine learning means. In one embodiment, to generate the exception list, while the managed device **120** is in the provisioning state, changes made by the managed device **120** which are expected to occur during its normal operation are logged by the change detector **232**. These are subsequently recorded in the exception list, upon approval from the multi-user authorization pool **140** via the multi-user authorization subsystem **234**. These changes may include changes to a transaction log, temporary folder, external database, cache locations in memory, reads of web page files, etc. These are all changes which are expected to occur during the normal operation of the managed device **120**.

The multi-user authorization subsystem **234** queries the multi-user authorization pool **140** to determine if any detected change is approved by the users of the multi-user authorization pool **140**. To accomplish this, the multi-user authorization subsystem **234** may send messages to the authorization devices **142** of the authorization users of the multi-user authorization pool **140**. The multi-user authorization subsystem **234** may include with each message a

description of the change indicated in the no change and metadata, such as time of encounter, identification of the managed device **120** where the change was detected, user account in which the change was detected, and so on. The multi-user authorization subsystem **234** may receive responses from the one or more authorization devices **142** indicating whether the change is approved. The multi-user authorization subsystem **234** may ignore approval messages which are received from users in the multi-user authorization pool **140** which arrive from authorization devices **142** in which authentication failed for the authorization user (e.g., due to wrong credentials), or where the network addresses or other criteria for these authorization devices **142** do not match certain criteria. For example, the multi-user authorization subsystem **234** may only consider approval messages from an authorization device **142** when the authorization device **142** is connected to the network **110** without using a network tunnel and where it has a network address that is within the range of network addresses of the managed network **100**. The multi-user authorization subsystem **234** may also verify the credentials, authentication method, encryption, message signature, and/or certificate provided along with the message to determine whether the approval message is authentic and is from a user that is authorized to send approval/disapproval messages. In one embodiment, any deviation from the normal authentication process for a particular user of the multi-user authentication pool **140** may be reported to the other users in the pool for approval. If the requisite approval is not received, or a disapproval is received, the multi-user authorization subsystem **234** may remove or suspend the account of that particular user from being able to approve further changes, and/or instruct the rebuild manager **236** to rebuild the authorization device used by that particular user.

The multi-user authorization subsystem **234** determines if a requisite approval is provided for the change indicated in the change. This requisite approval may be a threshold number of the authorized users approving the change, a percentage of the total number of authorized users approving the change, and/or a particular subset of users of the authorized users (e.g., a team lead, manager, customer) approving the change. If the requisite approval is received, the multi-user authorization subsystem **234** may log the approval and transmit a message to the management library **126** to allow the change to continue/proceed. If the change is approved, the multi-user authorization subsystem **234** logs the approval and can additionally modify the exception list for the managed device **120** to include the change in the exception list for the managed device **120**. This may include modifying the exception list accessed by the change detector **232** at the management system **130** or the exception list at the management library **126** to include rules that match the change that was approved. For example, if the change included a particular set of network traffic, the multi-user authorization subsystem **234** may modify the exception list to indicate that network traffic having the type, header information, source, destination, and other characteristics matching that of the network traffic that was detected should be allowed as approved change. As another example, if the change included an access to a particular area of data (e.g., a particular database), then the multi-user authorization subsystem **234** may modify the exception list to include a rule to allow access by executables on the managed device **120** to that data.

Conversely, if the multi-user authorization subsystem **234** does not receive the requisite approvals within a set time period (e.g., 1 minute), then the multi-user authorization subsystem **234** may determine that the change is not approved and logs the disapproval. The multi-user authorization subsystem **234** may also determine that the change is disapproved if it receives a requisite number of disapprovals. For example, a threshold number of users, or a percentage of users, and/or a special group of users may transmit disapproval messages to the multi-user authorization subsystem **234**. In such a case, the multi-user authorization subsystem **234** may log the disapproval result and may indicate to the rebuild manager **236** that a rebuild of the managed device **120** is requested in order to repair the managed device **120** to prevent the change from occurring again.

The rebuild manager **236** restores the state of the managed device **120** to an earlier known good state in the event where an change is detected at the managed device **120** and where a requisite set of approvals is not received from the users of the multi-user authorization pool **140** for the change. The rebuild manager **236** may store a copy of the operating system **122**, including its executables **124** and data **125**, of the managed device **120** as a device image in the device images store **238**. The device image may not only include data related to the operating system **122** that is stored on non-volatile memory, but also data related to the operating system **122** that is in volatile memory, e.g., the state of the random access memory assigned to the operating system **122**. Each device image may be a 1:1 copy of the binary data comprising the operating system **122**, executables **124**, and data **125** of the managed device **120**. The rebuild manager **236** may receive the data for the device image from the management library **126** of the managed device **120** after the managed device is switched to the release state. Therefore, each time the managed device **120** is placed in a state for normal operations, a copy of the software and data for the managed device **120** may be stored as a device image by the rebuild manager **236** at the device images store **238**. The rebuild manager **236** may also generate a signature of the device image and mark that it is a device image of the managed device **120** in a known good state. Alternatively, device images may be marked as being in a known good state via a requisite approval from users of the multi-user authorization pool **140**.

The rebuild manager **236** may also store a copy of a device image each time a reported change receives the requisite approvals from the multi-user authorization pool **140**. These images may also be signed and marked. The rebuild manager **236** may also periodically record a device image of the managed device **120** to record regular changes that occur at the managed device **120**. Although the device images are shown to be stored at the management system **130**, in other embodiments the device images may be stored at the management library **126** to avoid unnecessary network usage from transferring of large amounts of data representing the device image.

When a change is detected by the change detector **232** which the multi-user authorization subsystem **234** determines is not approved by the users of the multi-user authorization pool **140**, the rebuild manager **236** may initiate a rollback of the managed device **120** to an earlier state using a device image recorded for that managed device **120**. The earlier state and the device image for that state records a state of the managed device **120** before the change was detected. Therefore, by using this earlier state device image on the managed device **120**, the change is reverted and the managed device **120** is restored to a known good state. The rebuild manager **236** sends instructions to the rebuild layer **226** of the management library **126** to initiate the rollback by

terminating all processes at the managed device **120**, and then by replacing the currently stored data associated with the operating system, executables, and data with the data from the earlier state device image. The rebuild manager **236** may instruct the rebuild layer **226** to identify the electronic storage on which the current data is stored, and to replace the data on that electronic storage with the data from the device image. The rebuild manager **236** may also restore the volatile storage of the managed device **120** to a state as stored in the device image. Subsequently, the rebuild manager **236** may instruct the rebuild layer **226** to boot up or start the operating system **122** of the managed device to resume operations. The rebuild manager **236** may also instruct the management library **126** to cause the managed device **120** to enter a release state. Subsequently, the rebuild manager **236** may indicate in a log that the rollback is completed in response to the change that was detected. The rebuild manager **236** may log the entire rollback process.

In some cases, the rollback is not successful. This may be due to some error in the process or when the managed device **120** is compromised. If this occurs, the rebuild manager **236** may send a message to the device mode initializer **230** to cause the managed device **120** to enter the maintenance state. In this state, normal communications with the affected managed device **120** is terminated. The rebuild manager **236** may also send a message to an administrator or one or more users of the multi-user authorization pool **140** indicating that a rollback failed and that the managed device **120** is in a maintenance state.

In one embodiment, the management system **130** also includes a rolling replacement manager **240** to periodically replace the current operating system **122**, executables **124**, and data **125** of the managed device **120** with a device image, which may be stored in the device images store **238** or at the management library **126**. The device image may be updated periodically to change passwords, encryption keys, add patches, and so on, such that the device image includes software that is up to date and less likely to be compromised using previously utilized attack vectors. Similar to the method performed by the rebuild manager **236**, the rolling replacement manager **240** instructs the rebuild layer **226** of the managed device **120** to replace the current software and data on the managed device **120** with the data and software from the selected device image. By regularly replacing the data of the managed device **120**, a malicious user is unable to gain a foothold in the system, as the system is frequently wiped clean and refreshed with a known good copy which does not include any modifications made by the attacker and which could be used to enter the system and cause any undesired change.

Turning now to the managed device **120**, the management library **126** on the managed device **120** may be separate from the operating system **122** of the managed device **120** in order to be able to rollback and/or rebuild the operating system **122** (along with the executables **124** and data **125**). The management library **126** may exist as a hypervisor, virtual machine manager, separate OS, firmware, etc. The management library **126** can also be rebuilt in the event that an change is detected. This may be achieved by having the management system **130** remotely access a low level firmware or other configuration utility of the managed device (e.g., a UEFI BIOS) to remove a current copy of the management library **126** software and to install a known good or updated version. Once installed, the management library **126** includes various elements to facilitate the monitoring of the managed device **120**. As shown, the management library **126** includes the device mode configurator **220**, configuration settings **222**, detector **224**, and the rebuild layer **226**.

The device mode configurator **220** on the management library **26** configures the managed device **120** based on the state indicated from the management system **130** for the managed device **120**. As noted above, these may be a release state, provisioning state, and maintenance state. In the release state, the device mode configurator **220** configures the detector **224** to detect all changes in the operating system **122** and to report any changes to the management system **130**. In the provisioning state, the device mode configurator **220** configures the detector **224** to detect all changes as well, but not to report any changes immediately. Instead, the device mode configurator **220** configures the detector **224** to report any changes that have occurred once the managed device is transitioned into the release state. Finally, in the maintenance state, the device mode configurator **220** configures the detector **224** to not detect any changes. For each state, the device mode configurator **220** may configure the operation of the detector **224** by storing settings for the detector **224** in the configuration settings **222**.

The detector **224** monitors changes in the managed device **120** and reports any changes to the change detector **232** of the management system **130**. To achieve this, the detector **224** may execute as a separate process outside the operating system (e.g., as a hypervisor, within firmware, etc.) or may execute as one or more executables (e.g., executables **124**) within the operating system. The detector **224** has access to monitor all changes performed on the operating system **122**.

A change on the operating system **122** may generally refer to any access, by a user account, to a resource provided by the operating system **122**. This access may differ from any previous behavior in the operating system **122**. The access may include read, write, transmission, receipt, execution, modification of permissions, changing of settings, and so on. A resource provided by the operating system includes any physical resource of the managed device **120** that the operating system **122** can expose, such as network resources, memory resources, input/output resources (e.g., keyboard, mouse, printer, display), processor resources (e.g., CPU, GPU, special purpose processors), storage resources, as well as any logical services provided by the operating system, such as services, libraries, application programming interfaces, drivers, hardware interfaces, and so on. The user account is a construct within the operating system, as described above with reference to the operating system **122** in FIG. **1**, that permits a user with credentials to access the user account certain permissions within the operating system **122** to perform certain types of access against certain resources provided by the operating system **122**. Although typically a user access a user account, in some cases the operating system itself may utilize a user account to perform various activities, such as upgrades or patches. Such a user account may be called a system account. A change may also include an omission or rejection of any access by a user of a resource. Thus, for example, where an access has occurred previously (e.g., the transmission of a heartbeat signal), the omission of this access at a later time is a change. As another example, where a device previously allowed access via a particular network connection, and now does not respond or refuses access, is a change.

The detector **224** monitors every change occurring within the operating system **122** using various application programming interfaces, system calls, shell scripts, shell commands, libraries, low level I/O monitoring, low level network monitoring, or using other methods. For each change that is

detected, the detector **224** may report this change to the change detector **232** of the management system **130**. This in turn triggers the multi-user approval process previously described and may cause a rebuild of the operating system. The detector **224** may also log any detected changes and may also log change that is not determined to be an non-excluded change as well.

In one embodiment, the detector **224** may not report every detected change to the change detector **232**. Instead, the detector compares the change to changes indicated in an exception list. This exception list may be similar to the exception list of the change detector **232**, and may be stored in the configuration settings **222**. The exception list indicates which changes, i.e., which types of access by which users against which resources, are exceptions that do not need to be reported to the change detector **232** and thus do not need approval by the multi-user authorization pool **140**. To initially configure the exception list, the management system **130** or management library **126** may be requested to perform an analysis of all previously logged changes of the managed device **120** during normal operation. This may occur during a provisioning state. After this analysis, a report of the most common or most frequent changes encountered may be provided. From this report, certain changes may be automatically selected based on frequency of encounter, access type, user account used, or some other factors and indicated to be part of the exception list. Alternatively, an administrator(s), such as the multi-user authorization pool **140**, may select those changes that should be included in the exception list. The exception list may also be generated in a similar fashion to the exception list described above for the management system **130**.

In another embodiment, the detector **224** detects changes not only occurring at the operating system **122**, but also at other components of the managed device **120** which are not the operating system **122**, such as the firmware (BIOS, UEFI), and reports any changes to these elements as well (although they may also be associated with an exception list).

The rebuild layer **226** rebuilds the operating system **122** using a stored device image in response to an instruction from the management system **130**. In response to either a request from the rebuild manager **236** or the rolling replacement manager **240**, the rebuild layer **226** may replace the current operating system **122** with a device image of the operating system **122** that is of a known good state, as described above with reference to the rebuild manager **236** and the rolling replacement manager **240**. The rebuild layer is not part of the operating system **122**, but exists outside the operating system (e.g., as a hypervisor, a part of the firmware, etc.). This allows it to manipulate the operating system **122** without itself being erased or removed. A user accessing the operating system **122** cannot access the rebuild layer **226**, even if that user has full user privileges, as the rebuild layer **226** exists in a layer outside of the operating system **122**. The rebuild layer **226** can erase any data stored within electronic storage and memory associated with the managed device **120**, and can halt any execution by a processor(s) of the managed device **120**. The rebuild layer **226** can write to the same electronic storage and memory, and can cause the processor(s) of the managed device **120** to enter a bootup sequence or to load and execute a particular set of instructions from the electronic storage. This allows the rebuild layer **226** to halt current execution, remove/replace the current operating system **122** with data from a device image, and then cause the processor(s) of the managed device **120** to boot up the newly imaged operating system **122**. The rebuild layer **226** may perform this operation in response to an instruction from the management system **130** to rebuild the system.

In one embodiment, instead of rebuilding the entire system by writing each block of the device image to the electronic storage, the rebuild layer **226** may determine a difference, or delta, between the current data stored in the electronic storage and the device image, and only write to the electronic storage those blocks of data that have changed from the device image such that they are reverted back to the data indicated in the device image. This may significantly reduce the time needed to roll back the operating system **122**. In another embodiment, the rebuild layer **226** may prepare a separate physical or logical volume of electronic storage which contains a prior device image which may be specified by the management system **130**. In response to a request from the management system **130** to roll back or rebuild the operating system **122**, the rebuild layer **226** may disconnect the managed device **120** (either logically or via a physical connection) from the current electronic storage and connect the managed device **120** to the separate volume that includes the already written device image. This allows instantaneous switching of the managed device **120** to the device image of known good state. After the switch, the rebuild layer **226** may rewrite the device image on the now offline physical/logical volume with the same device image of known good state (or with another device image provided or indicated by the management system **130**).

Exemplary Cluster

FIG. **3** is a block diagram illustrating a centrally managed cluster **300** of managed networks **310**, in accordance with an embodiment. In some cases, the management of the managed network may not simply be confined to a single organization or local network of devices, but may be spread among multiple organizations, each with their own managed network. In order to manage all these individual networks together, a managed cluster **300** is organized as shown. Here, instead of each managed network **310** or **320** having its own set of multi-user authorization pools, any changes detected by a management system, e.g., management system **360** from changes of the managed devices, e.g., managed devices **350**, in the managed network are instead reported to a managed network that is higher up in a hierarchy of managed networks. Thus, for example, managed network **310**A reports any changes to a management system of managed network **320**A. The other managed networks **310** report to at least one of the managed networks **320**, which in turn reports to another managed network further up in the hierarchy. Ultimately, all changes are reported to a primary management system **330**, which itself includes a multi-user authorization pool **335**. The function of this pool is similar to the multi-user authorization pool **140**, but instead of approving changes from activities on a single managed network, this pool may approve of changes across multiple ranks of managed networks. If the pool disapproves of a change, then the indication of the disapproval may be transmitted to each of the management systems of each of the managed networks to cause a rollback of any device that generated the change or remediation of any change that matches the disapproved change. On the other hand, if the change is approved, then this information is propagated to each of the managed networks in the managed cluster **300**. If approved, the change may also be added to an exception list for the relevant managed device or managed network where the change was detected. All communications between the net-

works are secured, e.g., via encryption, rolling encryption, or other means, such that fraudulent messages are not accepted between the different networks.

Each managed network may also detect changes in any managed networks for which they are a parent. For example, similar to the change detector **323** and the managed device **120** of FIG. **2**, each management system of each managed network may receive heartbeat signal from child networks, may probe child networks, may check connections to child networks, and so on, in order to detect any changes, such as rejection of a previously allowed connection, etc. If an change is detected in a child network which is not approved, the management system of the parent network may be able to cause a rollback of all components of the child network, including a rollback of the management system of the child network. This may be achieved similarly to the rollback of the operating system **122** of the managed device **120**. For example, the management system of the parent network may have access to a low level firmware or utility that allows it to transmit a device image to the computing device executing the management system in the child network in order to replace the software of the management system with the software in the device image which has a known good state of the management system for that child network. Furthermore, the parent network may periodically make device images of the management system software of the child network, as well as periodically rebuild the management system software of the child network.

Because each managed network is tightly coupled within the hierarchy, with ultimate control only allowed by the "ultimate" primary management system **330**, any attack on any component within the cluster **300** is easily detected and changes reverted using a rollback process. Furthermore, as only the users of the primary management system **330** can approve changes, any users with root or privileged access to any devices or systems within the various child networks will not be able to cause any permanent changes, as these changes are quickly reverted. If the primary system is compromised or taken offline, this also does not affect the cluster **300** as this simply means that no new changes are approved, but that the existing activity can continue to be allowed, allowing the entire cluster **300** to continue to operate.

Example Compliance Monitor

FIG. **4** is a block diagram that illustrates the compliance monitor **150** of FIG. **1** in further detail, in accordance with an embodiment. The compliance monitor **150** may be used, as described above, to determine whether the managed network **100** is in compliance with a previously agreed upon SLA, or service level agreement. In one embodiment, the compliance monitor **150** includes a compliance measurement set **410** including multiple trackers **412-420**, as well as a time to compliance detector **430**, non-compliance enforcer **440**, and measurement logger **450**. The compliance monitor **150** may be connected to a measurement engine **470** at the management library **126** of the managed device **120** to facilitate the measurement of the various SLA metrics by the trackers of the compliance measurement set **440**.

The compliance measurement set **410** includes multiple trackers which track various metrics of the managed network **110**. These metrics may be used to determine if the SLA is being met (i.e., enforced). In one embodiment, the compliance measurement set **410** includes a MTTD (mean time to detection) tracker **412**, a MTTI (mean time to isolation) tracker **414**, an HITT (hacker investigation tracking time) tracker **416**, a MTTR (mean time to repair) tracker **418**, and a MTTS (mean time to service) tracker **420**. The metric generated by each tracker is subsequently sent to the time to compliance detector **430**, non-compliance enforcer **440**, and measurement logger **450** for further processing. Although a particular arrangement of trackers is shown here, in other embodiments the compliance measurement set **410** may include a greater or fewer number of trackers based on the type of metrics which the SLA is intended to enforce.

The MTTD tracker **412** tracks the mean time taken by the managed network **100** between an attack from a malicious user to the detection of the attack, i.e., the time it takes to detect a change after that change occurs in the managed network **100**. These may only be changes which were not listed in an exception list. In order to determine this mean time, the MTTD tracker **412** may identify the occurrence of each change that is detected by the management system **130** and which was not given the requisite approval by the multi-user authorization pool **140**. For each of these events, the MTTD tracker **412** may further determine the specific change which occurred that was determined to be unapproved by accessing logs generated by the management system **130** and determine from the logged information when the change first occurred. For example, if the change is an access to some resource within the operating system **122**, the MTTD tracker **412** may determine when that access first occurred according to timestamps associated with any commands issued during the change, or timestamps associated with the resource that was accessed. The MTTD tracker **412** may find timestamps associated with issued commands in various system logs (e.g., a system call log). The MTTD tracker **412** may find timestamps associated with resources that are accessed in logs associated with the resource that was accessed, or based on a last accessed timestamp for that resource. For example, a network resource may include a log indicating network data that is sent/received and the timestamp of the transmissions. As another example, a file resource may include a filesystem timestamp indicating a last accessed timestamp. The MTTD tracker **412** computes for each of these incidents a difference in time between when the change detector **232** detected the event and reported it to the multi-user authorization pool **140**, and the timestamp associated with when the access first occurred for that change. This difference is the time to detection for this particular event. The MTTD tracker **412** may then determine a mean, rolling average (e.g., 5 hour rolling average), probability distribution, or other statistical analysis of the time to detection values for all detected change events. This is the mean time to detection (MTTD) metric. Alternatively, a mean time to detection may be computed for each individual managed device **120**. In such a case the mean time to detection for an individual managed device only includes an average of the time to detection for changes detected for that managed device **120**. A mean time to detection below a threshold (e.g., a threshold indicated in the SLA) may indicate that the managed network **100** is quickly detecting threats, which is desirable. Conversely, a longer mean time to detection may indicate that the managed network **100** is not properly detecting changes and improvements may be needed to speed up the detection.

The MTTI tracker **414** tracks a mean time to isolation for the managed network **100**. The mean time to isolation measures an average time taken between the detection of an change and the isolation or remediation of that change in the managed network **100**. This may only apply to changes which were not indicated in an exception list. To measure this value, the MTTI tracker **414** may identify instances

where the change detector **232** has detected an non-excluded change and where the change did not receive the requisite approval by the users of the multi-user authorization pool **140**. The MTTI tracker **414** may access logs generated by the change detector **232** to determine the timestamp at which the detection/identification of the change occurred. This may be the time at which the change detector **232** first identifies the change, before approval is submitted to the multi-user authorization pool **140**. The MTTI tracker **414** further tracks the timestamp of when a remediation of the change occurs. In this case, the remediation may be a rollback of the managed device **120** at which the change was detected. The MTTI tracker **414** may access the logs generated by the rebuild manager **236** to determine when the rollback is completed (or when the operating system **122** of the managed device **120** is halted). The difference between the timestamp of the detection and the timestamp of when the rollback is completed may be the time to isolation. The MTTI tracker **414** further determines a mean, rolling average (e.g., 5 hour rolling average), probability distribution, or other statistical analysis of the computed differences for each instance of detected change to determine the metric of mean time to isolation. Alternatively, the mean time to isolation may be computed for time to isolation events for each individual managed device **120**. This mean time to isolation may indicate how quickly the managed network **100** responds to a detected threat. A shorter mean time to isolation below a threshold (e.g., a threshold dictated in the SLA) may indicate that the response time of the managed network **100** is good. A longer mean time may indicate that the managed network **100** is taking too long to respond to threats and investigation is needed.

The HITT tracker **416** tracks a hacker investigation tracking time. This is a tracker that tracks the time a malicious user remains within the managed network **100** or within a single managed device **120**. To track this information, the HITT tracker **416** may determine, similar to the MTTD tracker **412**, a timestamp for a first instance of a disapproved change occurring at the managed network **100** or managed device **120**. The HITT tracker **416** further determines a user account associated with this change. The HITT tracker **416** determines, for that user account, whether it causes any additional disapproved changes. The HITT tracker **416** determines the last disapproved change caused by that user account. No further disapproved changes may occur either because the malicious user ceased their attack or because remediation occurred and the access was blocked (e.g., via a rollback). The HITT tracker **416** then determines a difference in time between the first disapproved change and the last disapproved change. This is the hacker investigation tracking time metric and indicates how long a malicious user remains at the managed network **100** or within a managed device **120**. The HITT tracker **416** may operate in conjunction with a honeypot system. A honeypot is an element on the managed network **100**, such as computing device, virtual machine, etc., that acts as a legitimate target for attack, but is in actuality a dummy target with resources that do not contain any actual valuable information. Such a honeypot is used to lure attackers. Thus, the hacker time to investigate metric may record how long a malicious user spends in accessing the honeypot resource.

This hacker time to investigate metric may be used to determine how long malicious attackers stay at the managed network **100**. A longer time value may be undesirable as this may indicate that the managed network **100** has multiple potential exploitable vulnerabilities which an attacker attempts to explore.

The MTTR tracker **418** tracks a mean time to repair for a managed device **120**. The repair of the managed device **120** refers to a remediation of the managed device due to change detected at the device which did not receive the requisite approval. Once repaired, the malicious attacker is "kicked out" of the managed network **100**. This repair process may include, for example, rollback of the device as described above. It may also include the execution of one or more repair tools at the managed device to revert any undesirable changes made due to the change. The MTTR tracker **418** may track this time to repair by accessing logs generated by the rebuild manager **236** for rebuilds of the managed device **120**. These logs may include information regarding when a rollback was started, and when the rollback was completed, i.e., when operating system **122** was halted, and when the operating system **122** was booted up after the known good device image was written to the electronic storage of the managed device **120** to replace the previous operating system **122** and related data. The MTTR tracker **418** determines a time to repair for the managed device **120** by determining a difference between when the rollback was completed and when the rollback was initiated. The MTTR tracker **418** may further determine a mean, rolling average (e.g., 5 hour rolling average), probability distribution, or other statistical analysis of this time to repair for each managed device that is repaired/rolled back in order to determine the mean time to repair metric. Alternatively, the MTTR tracker **418** may determine the mean time to repair for all managed devices **120** on the managed network **100**.

The MTTS tracker **420** tracks a mean time to recovery of a service provided by the managed network **100** to customers/clients of the organization responsible or having ownership of the managed network **100**. The MTTS tracker **420** may track an overall time that a service provided by a managed device **120** is unavailable due to the detection of a change at the managed device **120** and the repair of that device. Thus, this time may include a time period from the time of detection, until the time that the repair, e.g., a rollback, is completed and the managed device **120** is once again available to provide the service. The MTTS tracker **420** may compute this time by accessing logs generated by the change detector **232** and the rebuild manager **236** to determine a difference between a timestamp at which the rollback of a managed device is completed, and when the change detector **232** first detected the change that caused the eventual rollback. The MTTS tracker **420**, like the other trackers, may determine a mean or other statistical analysis of the various times to service recovery for all recorded service outages to generate the mean time to service metric for a particular service.

Although not shown here, the compliance measurement set **410** may include additional trackers to track other metrics related to a service level agreement. These metrics may be related to tracking the initialization and termination of certain processes (i.e., executables) executing on a managed device, user account login and logoff sessions, various file system accesses, network accesses, certain log entries, uptime checking, integrity checking, and so on. If an SLA necessitates a particular metric to be measured, a tracker may be initialized as part of the compliance measurement set **410** to track this metric.

The time to compliance detector **430** detects a time to compliance for the overall managed network **100**. The time to compliance detector **430** determines the period of time between when a managed network **100** falls out of compliance with the SLA, to when the managed network **100** comes back into compliance with the SLA. As noted, the

SLA requires that various metrics of the managed network **100** should be within some threshold bounds. For example, a mean time to detection may be required to be under 30 seconds. The time to compliance detector **430** may use the metrics measured by the trackers of the compliance measurement set **410** to determine when any of the tracked metrics exceed an agreed upon threshold indicated in the SLA, and to further determine an amount of time until the same tracker reports a metric value that is now within the threshold required by the SLA. This difference in time may be determined by the time to compliance detector **430** as the time to compliance. The time to compliance detector **430** may determine a mean, rolling average, probability distribution, or other statistical analysis of the different time to compliances that are computed for each instance where a metric exceeds a threshold required in the SLA in order to further determine a mean time to compliance for the managed network.

The non-compliance enforcer **440** performs various actions in response to any of the trackers of the compliance measurement set **410** or the time to compliance detector indicating a value that exceeds a threshold value required by the SLA or exceeds some other predetermined threshold value. The non-compliance enforcer **440** may select an action that depends upon the particular tracked metric that has exceeded the SLA-defined threshold. In the case of certain metrics, the non-compliance enforcer **440** may initiate a rollback/rebuild of the managed devices **120** which have metrics exceeding the threshold, when a threshold number of tracked metrics each exceed their SLA-defined thresholds, if a metric exceeds a threshold a multiple number of times over a time period, or if a metric exceeds a threshold for at least a minimum period of time. For example, if a mean time to repair metric of a managed device exceeds a threshold, this may indicate that a rollback of the device is not occurring quickly enough, and so in response the non-compliance enforcer **440** may request the management system **130** to initiate a rollback of this managed device **120**. As another example, if the time to compliance detector indicates that the time to compliance has exceeded the SLA-defined threshold for over a day, this may indicate a significant issue within the managed network **100**, such as a denial of service attack or other issue. In response, the non-compliance enforcer **440** may cause a rollback of all devices in the entire managed network **100**.

In other embodiments, depending on the metric that exceeds the threshold, the non-compliance enforcer **440** may perform other remedial actions. For example, the non-compliance enforcer **440** may cause a session for which change is detected, and for which a metric related to that session exceeds a threshold, to perform various security actions on the session, such as deep packet inspection, malformed packet detection, blocking session activity, and so on. The non-compliance enforcer **440** may escalate and add additional security actions as the metrics for that session continue to further exceed the threshold. In one embodiment, the non-compliance enforcer **440** may only respond to those changes which are not in an exception list.

In some embodiments, instead of comparing the metrics against SLA-derived thresholds, the non-compliance enforcer **440** may use machine learning or other statistical analysis methods to determine the threshold values. The non-compliance enforcer **440** may access historical metric values and determine based on this information a threshold value for each metric. For example, the non-compliance enforcer **440** may set a threshold for a metric to 150% of a 5 day rolling average of the metric's historical values.

Prior to performing any action, the non-compliance enforcer **440** may also transmit a message to the multi-user authorization pool **140** for approval of the action, similar to the process performed by the change detector **232** as described with reference to FIG. **2** when approving or disapproving a detected change.

The measurement logger **450** logs the metrics tracked by the trackers of the compliance measurement set **410**, e.g., trackers **412-420**, and by the time to compliance detector **430**. The measurement logger **450** may log this information over time. The measurement logger **450** may also log any remedial actions, such as rollbacks, security actions, and so on, which may have been performed against any of the managed devices **120** of the managed network. Upon request, the measurement logger **450** may also generate a report of these tracked metrics for the managed network **100** over time. Using this information, an administrator or other entity can determine the current and historical compliance rate, compliance level, and adherence to the SLA for the managed network. This also allows the entity to quickly determine whether the system is out of compliance and whether it needs any remedial action. With this advanced insight into the system, an organization can quickly determine if any issues have occurred on the network. This is advantageous and is in contrast with current systems, whereby an organization may only realize much later that their systems had been compromised, allowing an attacker to cause additional damage during this latent period where the attack was not yet detected. Subsequently this causes the organization to issue a letter or message to all affected users of their service indicating the oftentimes significant data breach or other issue. However, with the ability to quickly track these metrics and see the automated rollbacks that occur when the metrics exceed a threshold, the organization no longer has to face such a negative scenario.

Example Flows

FIG. **5** is a flow diagram illustrating a process for monitoring and preventing root level attacks, in accordance with an embodiment. In one embodiment, the operations described in the flow diagram are performed by the management system **130**. Although a certain set of operations is described herein, in other embodiments the arrangement and number of operations vary.

The management system **130** detects **510** a change at the target device. This may be achieved via the change detector **232** as described above with reference to FIG. **2**.

The management system **130** transmits **520** a request message to authorization devices of the authorization users of the multi-user authorization pool to from the authorization users an indication of whether the detected change is approved. This allows the management system **130** to determine whether that change should be allowed to continue or if some remedial action is needed.

The management system **130** receives **530** a plurality of response messages from authorization devices of the multi-user authorization pool indicating whether the detected change is approved by the corresponding authorization user. The management system **130** determines **540**, based on at least three of the plurality of response messages indicating a disapproval, that the detected change is disapproved. By soliciting approval/disapproval messages from at least three users at once, the system can avoid a single point of failure where a single user's system is compromised.

The management system **130** transmits **540**, in response to the determination that the change is disapproved, an

instruction message to a target managed device to instruct the target managed device to rollback to an earlier state.

FIG. **6** is a flow diagram illustrating a process for measuring compliance on a set of managed devices, in accordance with an embodiment. In one embodiment, the operations described in the flow diagram are performed by the compliance monitor **150**. Although a certain set of operations is described herein, in other embodiments the arrangement and number of operations vary.

The compliance monitor **150** measures **610** metrics regarding one or more managed devices in a network. These may be measured by any one of the trackers described above with reference to FIG. **4**. The compliance monitor generates a log based on the information detected by the measurement trackers and to transmit a report based on the generated log to a recipient. This may be performed, for example, by the measurement logger **450** described above. The compliance monitor **150** also initiates **630** one or more security actions based on the one or more measurement trackers indicating that a measured metric exceeds an associated threshold measurement value. These security actions may be performed by the non-compliance enforcer **440** as described above.

Computing Machine Architecture

FIG. **7** is a block diagram illustrating components of an example computing machine that is capable of reading instructions from a computer-readable medium and execute them in a processor (or controller). A computer described herein may include a single computing machine shown in FIG. **7**, a virtual machine, a distributed computing system that includes multiples nodes of computing machines shown in FIG. **7**, or any other suitable arrangement of computing devices. The computer described herein may be used by any of the elements described in the previous figures to execute the described functions.

By way of example, FIG. **7** shows a diagrammatic representation of a computing machine in the example form of a computer system **700** within which instructions **724** (e.g., software, program code, or machine code), which may be stored in a computer-readable medium for causing the machine to perform any one or more of the processes discussed herein may be executed. In some embodiments, the computing machine operates as a standalone device or may be connected (e.g., networked) to other machines. In a networked deployment, the machine may operate in the capacity of a server machine or a client machine in a server-client network environment, or as a peer machine in a peer-to-peer (or distributed) network environment.

The structure of a computing machine described in FIG. **7** may correspond to any software, hardware, or combined components shown in the figures above. While FIG. **7** shows various hardware and software elements, each of the components described in the figures above may include additional or fewer elements.

By way of example, a computing machine may be a personal computer (PC), a tablet PC, a set-top box (STB), a personal digital assistant (PDA), a cellular telephone, a smartphone, a web appliance, a network router, an internet of things (IoT) device, a switch or bridge, or any machine capable of executing instructions **724** that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines that individually or jointly execute instructions **724** to perform any one or more of the methodologies discussed herein.

The example computer system **700** includes one or more processors (generally, processor **702**) (e.g., a central processing unit (CPU), a graphics processing unit (GPU), a digital signal processor (DSP), one or more application specific integrated circuits (ASICs), one or more radio-frequency integrated circuits (RFICs), or any combination of these), a main memory **704**, and a static memory **706**, which are configured to communicate with each other via a bus **708**. The computer system **700** may further include graphics display unit **710** (e.g., a plasma display panel (PDP), a liquid crystal display (LCD), a projector, or a cathode ray tube (CRT)). The computer system **700** may also include alphanumeric input device **712** (e.g., a keyboard), a cursor control device **714** (e.g., a mouse, a trackball, a joystick, a motion sensor, or other pointing instrument), a storage unit **716**, a signal generation device **718** (e.g., a speaker), and a network interface device **720**, which also are configured to communicate via the bus **708**.

The storage unit **716** includes a computer-readable medium **722** on which is stored instructions **724** embodying any one or more of the methodologies or functions described herein. The instructions **724** may also reside, completely or at least partially, within the main memory **704** or within the processor **702** (e.g., within a processor's cache memory) during execution thereof by the computer system **700**, the main memory **704** and the processor **702** also constituting computer-readable media. The instructions **724** may be transmitted or received over a network **726** via the network interface device **720**.

While computer-readable medium **722** is shown in an example embodiment to be a single medium, the term "computer-readable medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, or associated caches and servers) able to store instructions (e.g., instructions **724**). The computer-readable medium may include any medium that is capable of storing instructions (e.g., instructions **724**) for execution by the machine and that cause the machine to perform any one or more of the methodologies disclosed herein. The computer-readable medium may include, but not be limited to, data repositories in the form of solid-state memories, optical media, and magnetic media. The computer-readable medium does not include a transitory medium such as a signal or a carrier wave.

Additional Considerations

Certain embodiments are described herein as including logic or a number of components, engines, modules, or mechanisms, for example, as illustrated in the above figures. Engines may constitute either software modules (e.g., code embodied on a computer-readable medium) or hardware modules. A hardware engine is a tangible unit capable of performing certain operations and may be configured or arranged in a certain manner. In example embodiments, one or more computer systems (e.g., a standalone, client or server computer system) or one or more hardware engines of a computer system (e.g., a processor or a group of processors) may be configured by software (e.g., an application or application portion) as a hardware engine that operates to perform certain operations as described herein.

In various embodiments, a hardware engine may be implemented mechanically or electronically. For example, a hardware engine may comprise dedicated circuitry or logic that is permanently configured (e.g., as a special-purpose processor, such as a field programmable gate array (FPGA) or an application-specific integrated circuit (ASIC)) to per-

form certain operations. A hardware engine may also comprise programmable logic or circuitry (e.g., as encompassed within a general-purpose processor or another programmable processor) that is temporarily configured by software to perform certain operations. It will be appreciated that the decision to implement a hardware engine mechanically, in dedicated and permanently configured circuitry, or in temporarily configured circuitry (e.g., configured by software) may be driven by cost and time considerations.

The various operations of example methods described herein may be performed, at least partially, by one or more processors, e.g., processor **702**, that are temporarily configured (e.g., by software) or permanently configured to perform the relevant operations. Whether temporarily or permanently configured, such processors may constitute processor-implemented engines that operate to perform one or more operations or functions. The engines referred to herein may, in some example embodiments, comprise processor-implemented engines.

The performance of certain of the operations may be distributed among the one or more processors, not only residing within a single machine, but deployed across a number of machines. In some example embodiments, the one or more processors or processor-implemented modules may be located in a single geographic location (e.g., within a home environment, an office environment, or a server farm). In other example embodiments, the one or more processors or processor-implemented modules may be distributed across a number of geographic locations.

Upon reading this disclosure, those of skill in the art will appreciate still additional alternative structural and functional designs for a similar system or process through the disclosed principles herein. Thus, while particular embodiments and applications have been illustrated and described, it is to be understood that the disclosed embodiments are not limited to the precise construction and components disclosed herein. Various modifications, changes, and variations, which will be apparent to those skilled in the art, may be made in the arrangement, operation and details of the method and apparatus disclosed herein without departing from the spirit and scope defined in the appended claims.

What is claimed is:

1. A method comprising:

receiving, from a plurality of devices in a managed network, first logged information describing activity of the plurality of devices in the managed network;

computing a first value for a security compliance metric for the managed network based on the received first logged information;

comparing, at a first time, the first value for the security compliance metric to a threshold value corresponding to the metric;

identifying the security compliance metric as being out of compliance based on the comparing of the first value to the threshold value;

receiving second logged information from the plurality of devices;

computing, at a second time later than the first time, a second value for the security compliance metric based on the second logged information;

comparing the second value for the security compliance metric to the threshold value corresponding to the security compliance metric;

determining that the security compliance metric that is in compliance based on the comparing of the second value to the threshold value;

computing a time to compliance for the managed network based on the first time, the second time, the first logged information, and the second logged information;

comparing the time to compliance to a threshold value; and

initiating, responsive to the time to compliance exceeding the threshold value, a security action.

2. The method of claim **1**, wherein the security action includes rolling back a state of a managed device to an earlier known good state.

3. The method of claim **1**, wherein the security compliance metric includes a mean time to isolation metric representing a mean time to an isolation of each device of the plurality of devices when a change is detected at the device.

4. The method of claim **1**, wherein the security compliance metric includes a hacker investigation time metric that tracks a time spent by a malicious attacker at a device of the plurality of devices.

5. The method of claim **4**, wherein the device is a honeypot designed to provide dummy resources for a malicious attacker to access, the dummy resources being attractive to the malicious attacker.

6. The method of claim **1**, wherein the security compliance metric includes a mean time to repair metric that represents a mean time to repair a device of the plurality of devices after a change is detected at the device.

7. The method of claim **1**, wherein the security compliance metric includes a mean time to service metric that represents a mean time to restore a service provided by the plurality of devices in the network after a disruption of the service caused by a change detected at a device of the plurality of devices.

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

selecting a security action of a plurality actions based on the identified security compliance metric; and

initiating, responsive to the time to compliance exceeding the threshold value, the selected security action.

9. The method of claim **1**, wherein computing the first value for the security compliance metric comprises:

computing the first value by a tracker corresponding to the security compliance metric.

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

transmitting a notification of the initiated security action to a user.

11. A non-transitory computer-readable medium storing instructions that, when executed by a processor, cause the processor to perform operations comprising:

receiving, from a plurality of devices in a managed network, first logged information describing activity of the plurality of devices in the managed network;

computing a first value for a security compliance metric for the managed network based on the received first logged information;

comparing, at a first time, the first value for the security compliance metric to a threshold value corresponding to the metric;

identifying the security compliance metric as being out of compliance based on the comparing of the first value to the threshold value;

receiving second logged information from the plurality of devices;

computing, at a second time later than the first time, a second value for the security compliance metric based on the second logged information;

comparing the second value for the security compliance metric to the threshold value corresponding to the security compliance metric;

determining that the security compliance metric that is in compliance based on the comparing of the second value to the threshold value;

computing a time to compliance for the managed network based on the first time, the second time, the first logged information, and the second logged information;

comparing the time to compliance to a threshold value; and

initiating, responsive to the time to compliance exceeding the threshold value, a security action.

12. The computer-readable medium of claim **11**, wherein the security action includes rolling back a state of a managed device to an earlier known good state.

13. The computer-readable medium of claim **11**, wherein the security compliance metric includes a mean time to isolation metric representing a mean time to an isolation of each device of the plurality of devices when a change is detected at the device.

14. The computer-readable medium of claim **11**, wherein the security compliance metric includes a hacker investigation time metric that tracks a time spent by a malicious attacker at a device of the plurality of devices.

15. The computer-readable medium of claim **14**, wherein the device is a honeypot designed to provide dummy resources for a malicious attacker to access, the dummy resources being attractive to the malicious attacker.

16. The computer-readable medium of claim **11**, wherein the security compliance metric includes a mean time to repair metric that represents a mean time to repair a device of the plurality of devices after a change is detected at the device.

17. The computer-readable medium of claim **11**, wherein the security compliance metric includes a mean time to service metric that represents a mean time to restore a service provided by the plurality of devices in the network after a disruption of the service caused by a change detected at a device of the plurality of devices.

18. The computer-readable medium of claim **11**, the operations further comprising:

selecting a security action of a plurality actions based on the identified security compliance metric; and

initiating, responsive to the time to compliance exceeding the threshold value, the selected security action.

19. The computer-readable medium of claim **11**, wherein computing the first value for the security compliance metric comprises:

computing the first value by a tracker corresponding to the security compliance metric.

20. The computer-readable medium of claim **11**, the operations further comprising:

transmitting a notification of the initiated security action to a user.

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