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(54) **AUTOMATED EXTRACTION AND CLASSIFICATION OF MALICIOUS INDICATORS**

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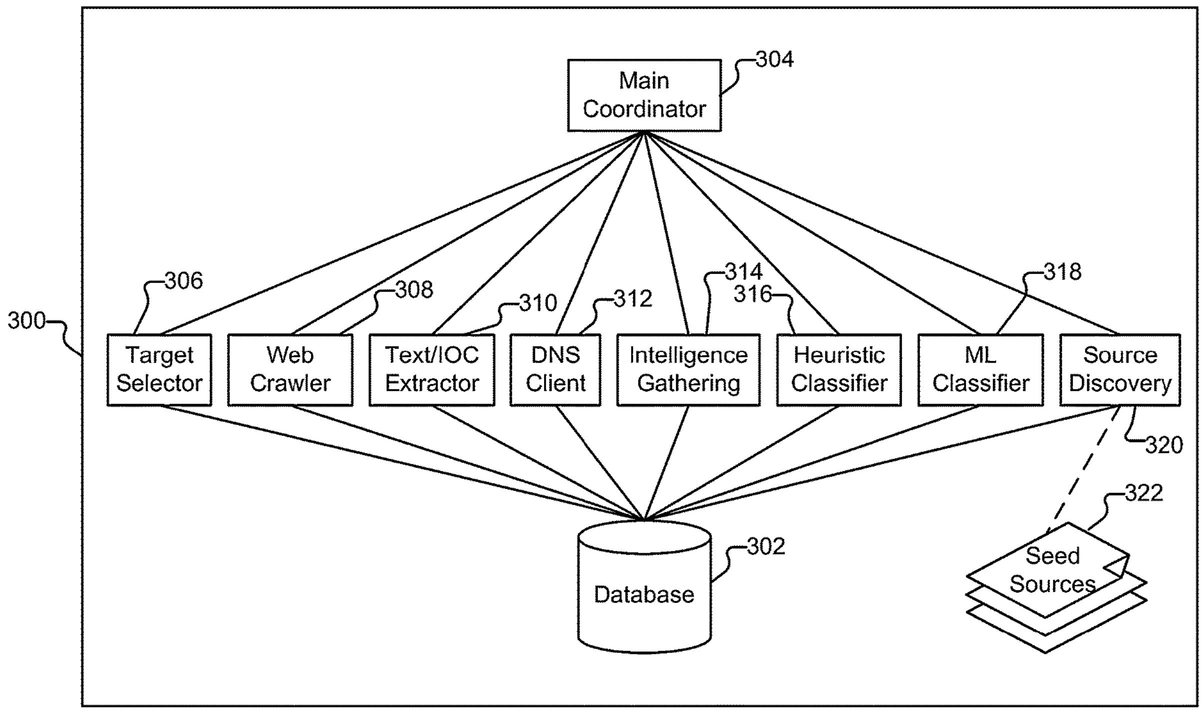
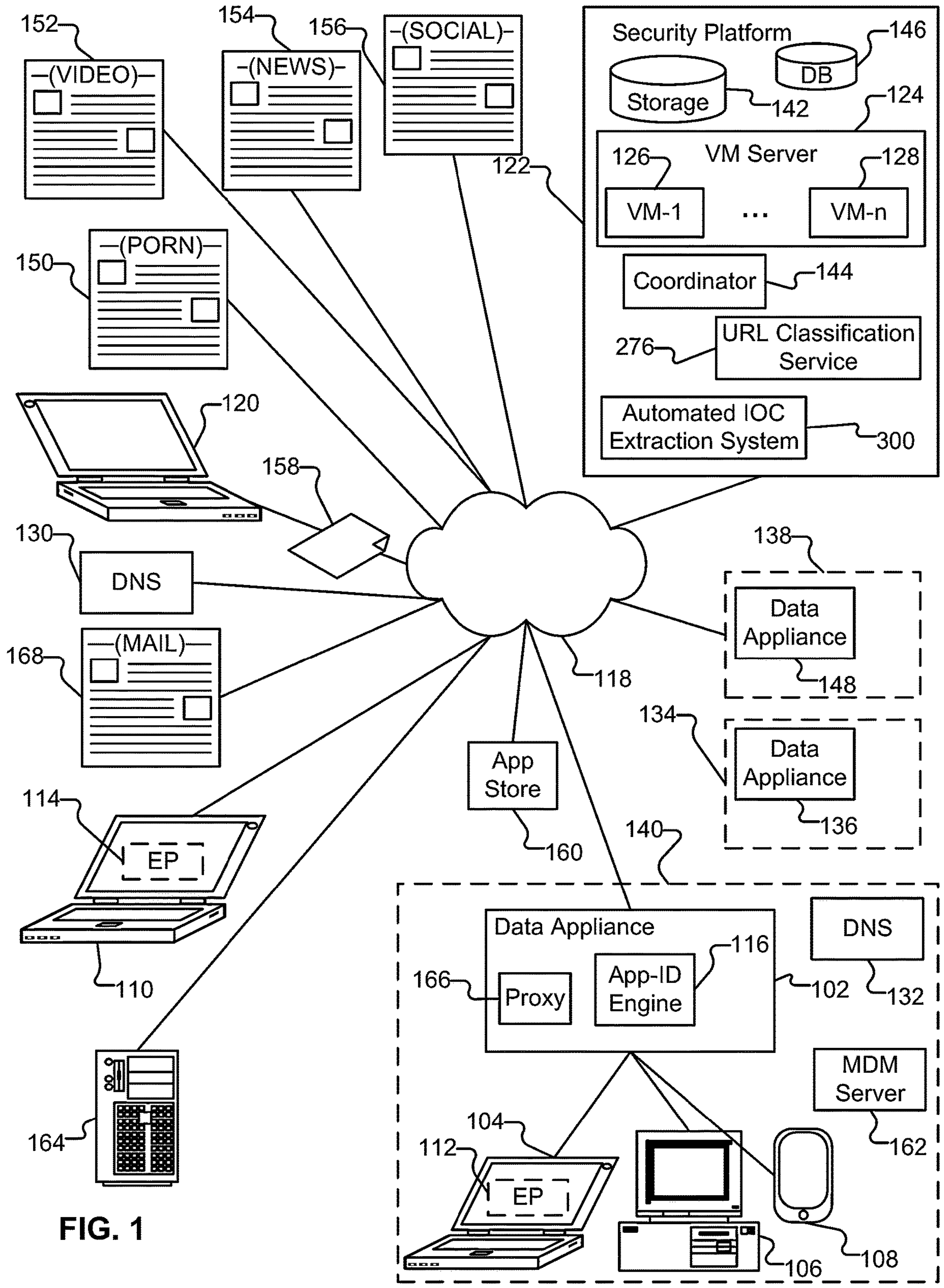
CPC ***H04L 63/1416*** (2013.01); ***G06N 5/025*** (2013.01); ***G06N 20/00*** (2019.01)

(57) **ABSTRACT**

Techniques for generating actionable indicators of compromise (IOCs) are disclosed. A set of potential sources for IOCs are received. One or more candidate IOCs are extracted from at least one source included in the set of potential sources. An actionable IOC is automatically identified from the one or more candidate IOCs. The actionable IOC is provided to a security enforcement service.





152
(VIDEO)
154
(NEWS)
156
(SOCIAL)
Security Platform
146
DB
Storage
142
124
VM Server
126
128
VM-1
...
VM-n
122
150
(PORN)
Coordinator
144
276
URL Classification Service
Automated IOC Extraction System
300
120
158
130
DNS
138
Data Appliance
148
168
(MAIL)
118
134
Data Appliance
136
114
EP
App Store
160
140
110
Data Appliance
116
166
Proxy
App-ID Engine
102
DNS
132
MDM Server
162
104
112
EP
164
106
108

FIG. 1

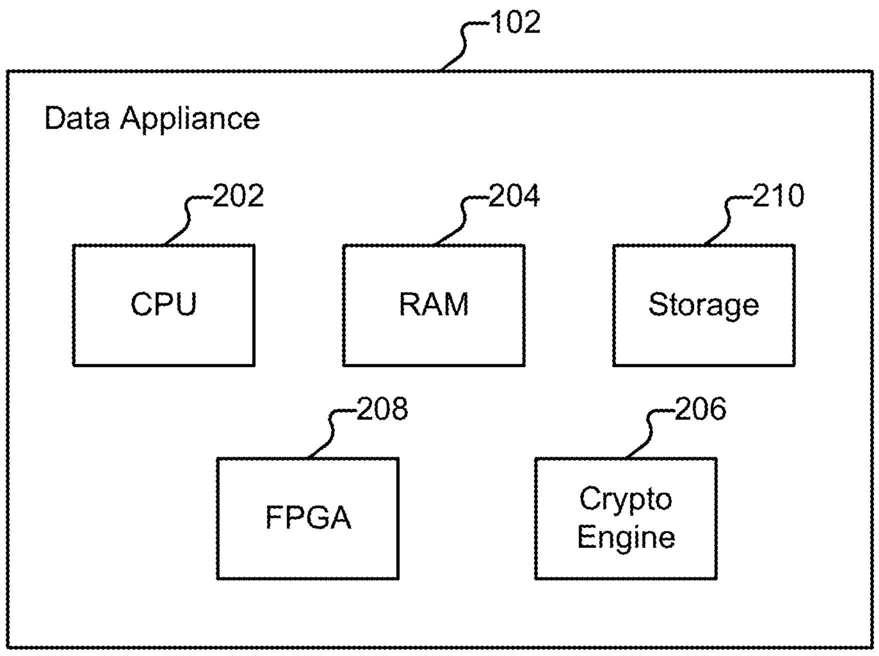

102
Data Appliance
202
CPU
204
RAM
210
Storage
208
FPGA
206
Crypto Engine

FIG. 2A

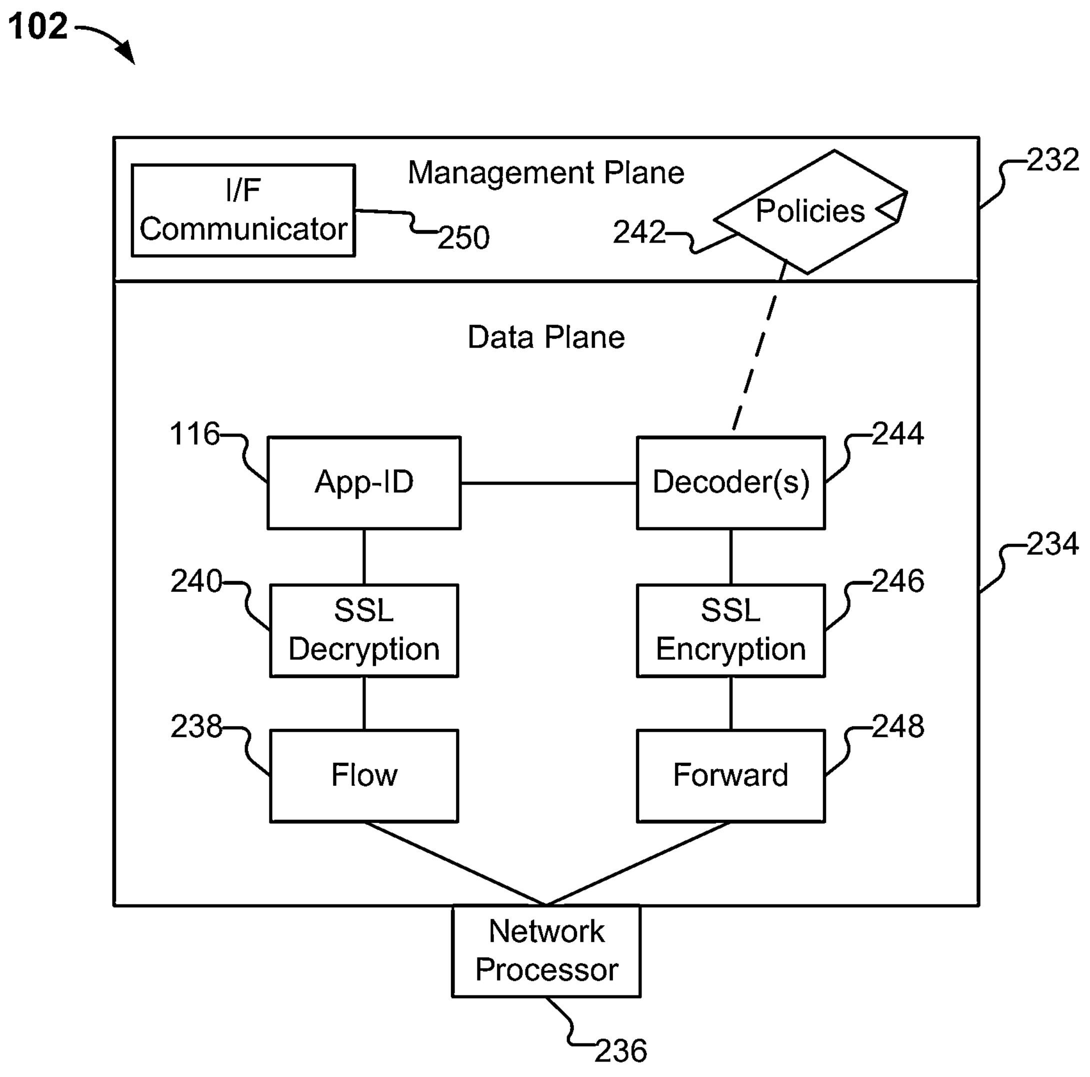

102
Management Plane
I/F Communicator
250
Policies
242
232
Data Plane
116
App-ID
Decoder(s)
244
234
240
SSL Decryption
SSL Encryption
246
238
Flow
Forward
248
Network Processor
236

FIG. 2B

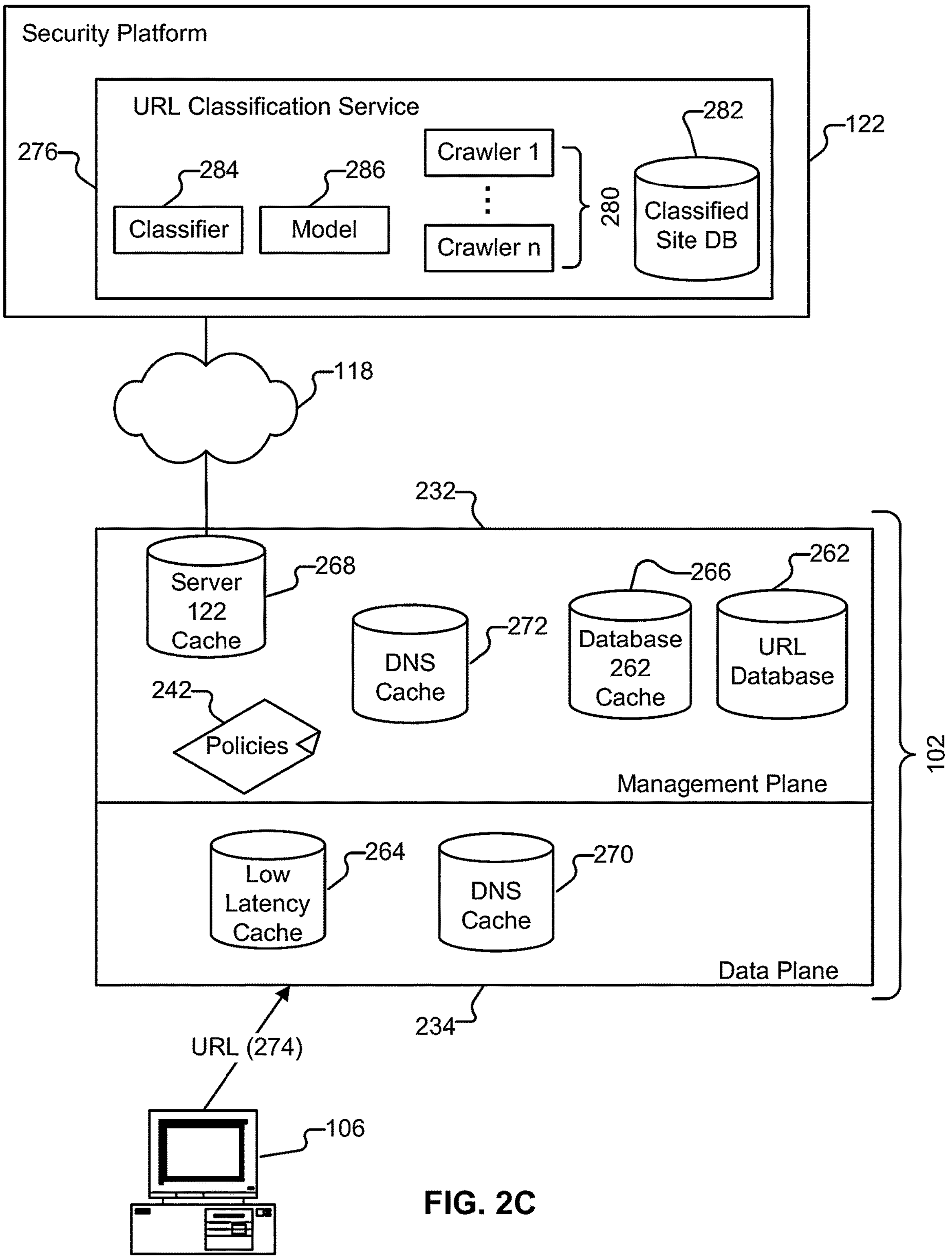
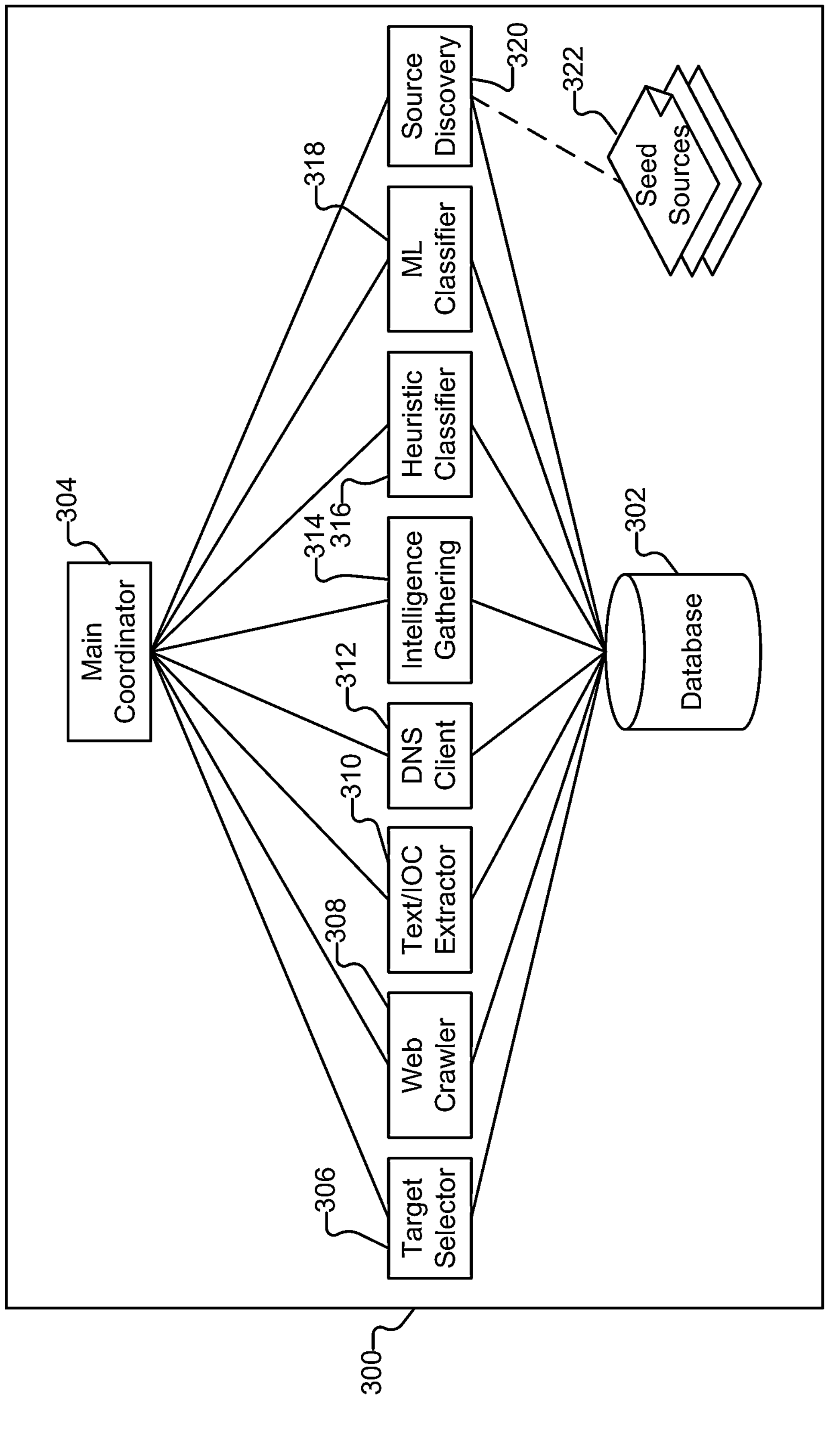

Security Platform
URL Classification Service
276
284
Classifier
286
Model
Crawler 1
Crawler n
280
282
Classified Site DB
122
118
232
Server 122 Cache
268
DNS Cache
272
Database 262 Cache
266
URL Database
262
242
Policies
Management Plane
102
Low Latency Cache
264
DNS Cache
270
Data Plane
234
URL (274)
106

FIG. 2C



300
304
Main Coordinator
306
Target Selector
308
Web Crawler
310
Text/IOC Extractor
312
DNS Client
314
Intelligence Gathering
316
Heuristic Classifier
318
ML Classifier
320
Source Discovery
322
Seed Sources
302
Database

FIG. 3

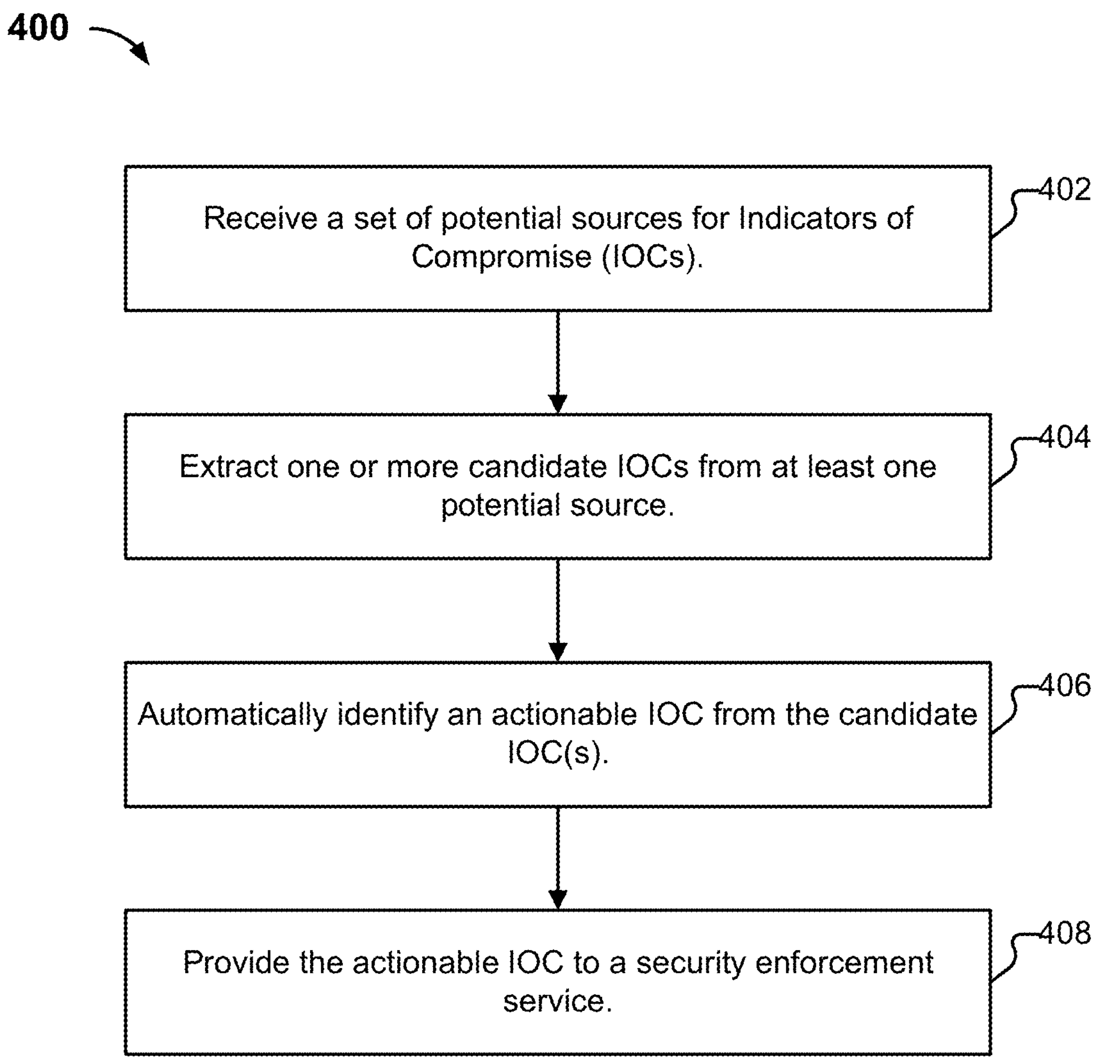
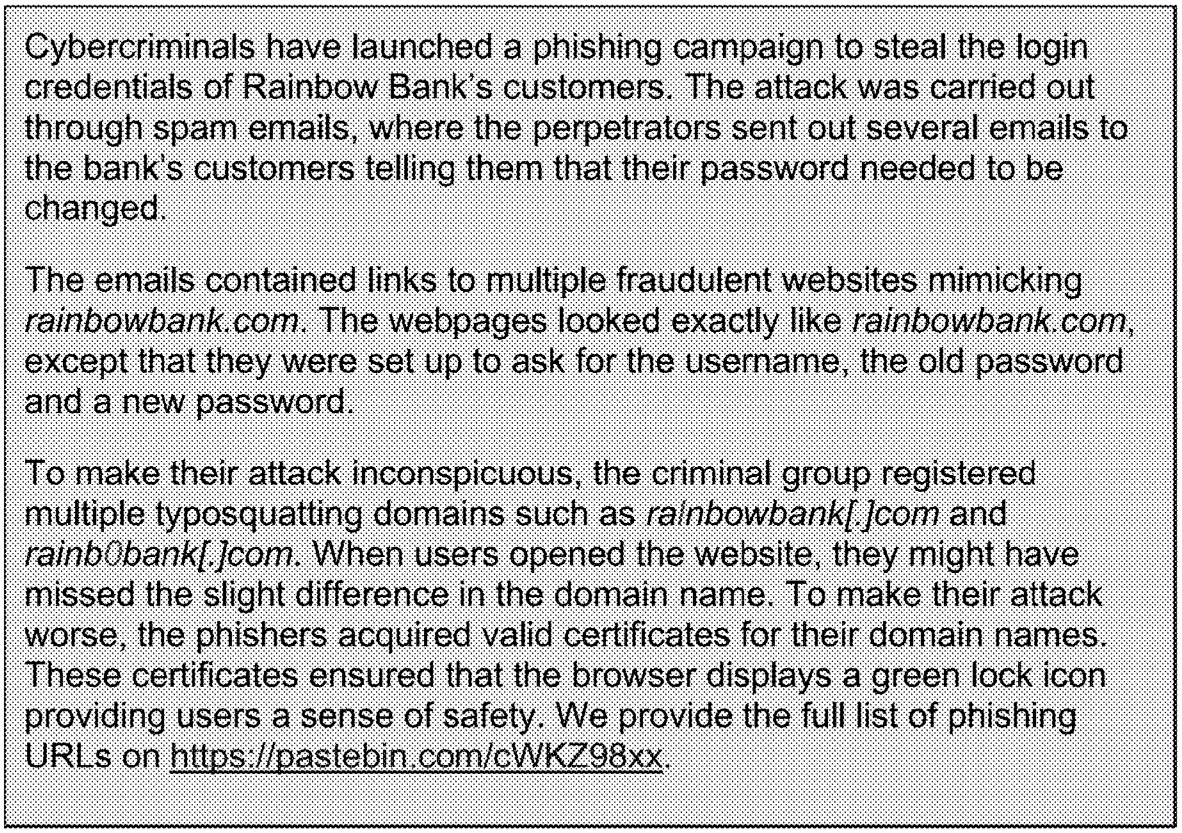

400
Receive a set of potential sources for Indicators of Compromise (IOCs).
402
Extract one or more candidate IOCs from at least one potential source.
404
Automatically identify an actionable IOC from the candidate IOC(s).
406
Provide the actionable IOC to a security enforcement service.
408

FIG. 4

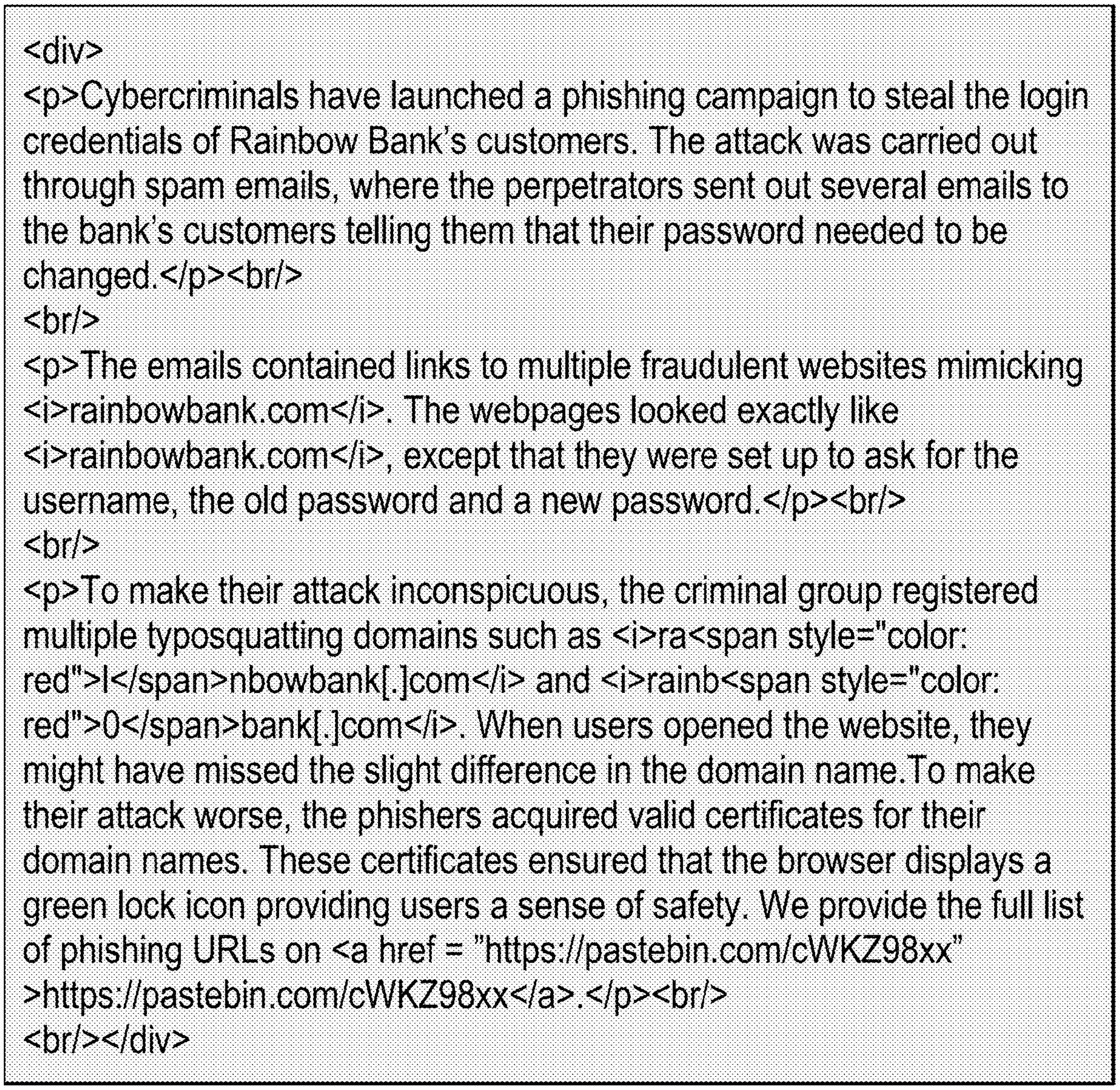


Cybercriminals have launched a phishing campaign to steal the login credentials of Rainbow Bank's customers. The attack was carried out through spam emails, where the perpetrators sent out several emails to the bank's customers telling them that their password needed to be changed.

The emails contained links to multiple fraudulent websites mimicking *rainbowbank.com*. The webpages looked exactly like *rainbowbank.com*, except that they were set up to ask for the username, the old password and a new password.

To make their attack inconspicuous, the criminal group registered multiple typosquatting domains such as *raınbowbank[.]com* and *rainb0bank[.]com*. When users opened the website, they might have missed the slight difference in the domain name. To make their attack worse, the phishers acquired valid certificates for their domain names. These certificates ensured that the browser displays a green lock icon providing users a sense of safety. We provide the full list of phishing URLs on https://pastebin.com/cWKZ98xx.

FIG. 5A



```
<div>
<p>Cybercriminals have launched a phishing campaign to steal the login
credentials of Rainbow Bank’s customers. The attack was carried out
through spam emails, where the perpetrators sent out several emails to
the bank’s customers telling them that their password needed to be
changed.</p><br/>
<br/>
<p>The emails contained links to multiple fraudulent websites mimicking
<i>rainbowbank.com</i>. The webpages looked exactly like
<i>rainbowbank.com</i>, except that they were set up to ask for the
username, the old password and a new password.</p><br/>
<br/>
<p>To make their attack inconspicuous, the criminal group registered
multiple typosquatting domains such as <i>ra<span style="color:
red">l</span>nbowbank[.]com</i> and <i>rainb<span style="color:
red">0</span>bank[.]com</i>. When users opened the website, they
might have missed the slight difference in the domain name.To make
their attack worse, the phishers acquired valid certificates for their
domain names. These certificates ensured that the browser displays a
green lock icon providing users a sense of safety. We provide the full list
of phishing URLs on <a href = ”https://pastebin.com/cWKZ98xx”
>https://pastebin.com/cWKZ98xx</a>.</p><br/>
<br/></div>
```

FIG. 5B

AUTOMATED EXTRACTION AND CLASSIFICATION OF MALICIOUS INDICATORS

BACKGROUND OF THE INVENTION

[0001] Nefarious individuals attempt to compromise computer systems in a variety of ways. As one example, such individuals may embed or otherwise include malicious software ("malware") in email attachments and transmit (or cause the malware to be transmitted) to unsuspecting users. When executed, the malware compromises the victim's computer. Some types of malware will instruct a compromised computer to communicate with a remote host. For example, malware can turn a compromised computer into a "bot" in a "botnet," receiving instructions from and/or reporting data to a command and control (C&C) server under the control of the nefarious individual. One approach to mitigating the damage caused by malware is for a security company (or other appropriate entity) to attempt to identify malware and prevent it from reaching/executing on end user computers. Another approach is to try to prevent compromised computers from communicating with the C&C server. Unfortunately, malware authors are using increasingly sophisticated techniques to obfuscate the workings of their software. Accordingly, there exists an ongoing need for improved techniques to detect malware and prevent its harm.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] Various embodiments of the invention are disclosed in the following detailed description and the accompanying drawings.

[0003] FIG. **1** illustrates an example of an environment in which policies are enforced.

[0004] FIG. **2**A illustrates an embodiment of a data appliance.

[0005] FIG. **2**B illustrates logical components of an embodiment of a data appliance.

[0006] FIG. **2**C illustrates an embodiment of a data appliance.

[0007] FIG. **3** illustrates an embodiment of an automated indicator of compromise extraction system.

[0008] FIG. **4** illustrates an embodiment of a process for generating actionable indicators of compromise.

[0009] FIG. **5**A illustrates a portion of user-visible text.

[0010] FIG. **5**B illustrates source code corresponding to the text shown in FIG. **5**A.

DETAILED DESCRIPTION

[0011] The invention can be implemented in numerous ways, including as a process; an apparatus; a system; a composition of matter; a computer program product embodied on a computer readable storage medium; and/or a processor, such as a processor configured to execute instructions stored on and/or provided by a memory coupled to the processor. In this specification, these implementations, or any other form that the invention may take, may be referred to as techniques. In general, the order of the steps of disclosed processes may be altered within the scope of the invention. Unless stated otherwise, a component such as a processor or a memory described as being configured to perform a task may be implemented as a general component that is temporarily configured to perform the task at a given time or a specific component that is manufactured to perform the task. As used herein, the term 'processor' refers to one or more devices, circuits, and/or processing cores configured to process data, such as computer program instructions.

[0012] A detailed description of one or more embodiments of the invention is provided below along with accompanying figures that illustrate the principles of the invention. The invention is described in connection with such embodiments, but the invention is not limited to any embodiment. The scope of the invention is limited only by the claims and the invention encompasses numerous alternatives, modifications and equivalents. Numerous specific details are set forth in the following description in order to provide a thorough understanding of the invention. These details are provided for the purpose of example and the invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the invention is not unnecessarily obscured.

I. Overview

[0013] A firewall generally protects networks from unauthorized access while permitting authorized communications to pass through the firewall. A firewall is typically a device, a set of devices, or software executed on a device that provides a firewall function for network access. For example, a firewall can be integrated into operating systems of devices (e.g., computers, smart phones, or other types of network communication capable devices). A firewall can also be integrated into or executed as one or more software applications on various types of devices, such as computer servers, gateways, network/routing devices (e.g., network routers), and data appliances (e.g., security appliances or other types of special purpose devices), and in various implementations, certain operations can be implemented in special purpose hardware, such as an ASIC or FPGA.

[0014] Firewalls typically deny or permit network transmission based on a set of rules. These sets of rules are often referred to as policies (e.g., network policies or network security policies). For example, a firewall can filter inbound traffic by applying a set of rules or policies to prevent unwanted outside traffic from reaching protected devices. A firewall can also filter outbound traffic by applying a set of rules or policies (e.g., allow, block, monitor, notify or log, and/or other actions can be specified in firewall rules or firewall policies, which can be triggered based on various criteria, such as are described herein). A firewall can also filter local network (e.g., intranet) traffic by similarly applying a set of rules or policies.

[0015] Security devices (e.g., security appliances, security gateways, security services, and/or other security devices) can include various security functions (e.g., firewall, anti-malware, intrusion prevention/detection, Data Loss Prevention (DLP), and/or other security functions), networking functions (e.g., routing, Quality of Service (QoS), workload balancing of network related resources, and/or other networking functions), and/or other functions. For example, routing functions can be based on source information (e.g., IP address and port), destination information (e.g., IP address and port), and protocol information.

[0016] A basic packet filtering firewall filters network communication traffic by inspecting individual packets transmitted over a network (e.g., packet filtering firewalls or first generation firewalls, which are stateless packet filtering firewalls). Stateless packet filtering firewalls typically inspect the individual packets themselves and apply rules based on the inspected packets (e.g., using a combination of a packet's source and destination address information, protocol information, and a port number).

[0017] Application firewalls can also perform application layer filtering (e.g., application layer filtering firewalls or second generation firewalls, which work on the application level of the TCP/IP stack). Application layer filtering firewalls or application firewalls can generally identify certain applications and protocols (e.g., web browsing using HyperText Transfer Protocol (HTTP), a Domain Name System (DNS) request, a file transfer using File Transfer Protocol (FTP), and various other types of applications and other protocols, such as Telnet, DHCP, TCP, UDP, and TFTP (GSS)). For example, application firewalls can block unauthorized protocols that attempt to communicate over a standard port (e.g., an unauthorized/out of policy protocol attempting to sneak through by using a non-standard port for that protocol can generally be identified using application firewalls).

[0018] Stateful firewalls can also perform state-based packet inspection in which each packet is examined within the context of a series of packets associated with that network transmission's flow of packets. This firewall technique is generally referred to as a stateful packet inspection as it maintains records of all connections passing through the firewall and is able to determine whether a packet is the start of a new connection, a part of an existing connection, or is an invalid packet. For example, the state of a connection can itself be one of the criteria that triggers a rule within a policy.

[0019] Advanced or next generation firewalls can perform stateless and stateful packet filtering and application layer filtering as discussed above. Next generation firewalls can also perform additional firewall techniques. For example, certain newer firewalls sometimes referred to as advanced or next generation firewalls can also identify users and content (e.g., next generation firewalls). In particular, certain next generation firewalls are expanding the list of applications that these firewalls can automatically identify to thousands of applications. Examples of such next generation firewalls are commercially available from Palo Alto Networks, Inc. (e.g., Palo Alto Networks' PA Series firewalls). For example, Palo Alto Networks' next generation firewalls enable enterprises to identify and control applications, users, and content—not just ports, IP addresses, and packets—using various identification technologies, such as the following: APP-ID for accurate application identification, User-ID for user identification (e.g., by user or user group), and Content-ID for real-time content scanning (e.g., controlling web surfing and limiting data and file transfers). These identification technologies allow enterprises to securely enable application usage using business-relevant concepts, instead of following the traditional approach offered by traditional port-blocking firewalls. Also, special purpose hardware for next generation firewalls (implemented, for example, as dedicated appliances) generally provide higher performance levels for application inspection than software executed on general purpose hardware (e.g., such as security appliances provided by Palo Alto Networks, Inc., which use dedicated, function specific processing that is tightly integrated with a single-pass software engine to maximize network throughput while minimizing latency).

[0020] Advanced or next generation firewalls can also be implemented using virtualized firewalls. Examples of such next generation firewalls are commercially available from Palo Alto Networks, Inc. (e.g., Palo Alto Networks' VM Series firewalls, which support various commercial virtualized environments, including, for example, VMware® ESXi™ and NSX™, Citrix® Netscaler SDX™, KVM/OpenStack (Centos/RHEL, Ubuntu®), and Amazon Web Services (AWS)). For example, virtualized firewalls can support similar or the exact same next-generation firewall and advanced threat prevention features available in physical form factor appliances, allowing enterprises to safely enable applications flowing into, and across their private, public, and hybrid cloud computing environments. Automation features such as VM monitoring, dynamic address groups, and a REST-based API allow enterprises to proactively monitor VM changes dynamically feeding that context into security policies, thereby eliminating the policy lag that may occur when VMs change.

II. Example Environment

[0021] FIG. **1** illustrates an example of an environment in which policies are enforced. Included in the environment are two Domain Name System (DNS) servers (**130** and **132**). Typically, when attempting to access a URL, a web browser (e.g., executing on a client device) forwards a request to a DNS server (e.g., DNS server **130**) to resolve the domain name of the URL into a corresponding (Internet Protocol (IP) address. In response to receiving a valid IP address for a requested domain name, the client can connect to a corresponding content server (e.g., site **152**) using the IP address to request a desired resource. The content server responds with the requested resource if the requested resource is available at the content server or responds with an error message or with a redirect to another content server if the requested resource is not available at the content server.

[0022] Also shown in FIG. **1** is an example enterprise network **140** which belongs to an entity hereinafter referred to as ACME Corporation. Enterprise network **140** includes an enterprise DNS server **132**. Enterprise DNS server **132** is configured to resolve enterprise domain names into IP addresses, and is further configured to communicate with one or more external DNS servers (e.g., DNS server **130**) to resolve domain names. Also included within enterprise network **140** are example client devices **104-108**, which are a laptop computer, a desktop computer, and a tablet (respectively). Laptop **104** and desktop computer **106** are owned by ACME, and tablet **108** is personally owned by an ACME employee hereinafter referred to as Alice. Client device **110** is a laptop computer located outside of enterprise network **140**.

[0023] Client devices, such as client devices **104-110** can each execute a variety of applications. The term "application" is used throughout the Specification to collectively refer to programs, bundles of programs, manifests, packages, etc., irrespective of form/platform. An "application" (also referred to herein as a "sample") can be a standalone file (e.g., a calculator application having the filename "calculator.apk" or "calculator.exe") and can also be an independent component of another application (e.g., a mobile advertisement software development kit (SDK) or library embedded within the calculator app).

[0024] "Malware" as used herein refers to an application that engages in behaviors, whether clandestinely or not (and whether illegal or not), of which a user does not approve/would not approve if fully informed. Examples of malware include Trojans, viruses, rootkits, spyware, hacking tools, keyloggers, etc. One example of malware is a desktop application that collects and reports to a remote server the end user's location (but does not provide the user with location-based services, such as a mapping service). Another example of malware is a malicious Android Application Package .apk (APK) file that appears to an end user to be a free game, but stealthily sends SMS premium messages (e.g., costing $10 each), running up the end user's phone bill. Another example of malware is an Apple iOS flashlight application that stealthily collects the user's contacts and sends those contacts to a spammer.

[0025] Other forms of malware can also be mitigated using the techniques described herein (e.g., ransomware). And, while examples provided throughout the Specification generally refer to malicious applications, techniques described herein can also be used in various embodiments with respect to other kinds of applications (e.g., adware, goodware, etc.). In some cases, an end user of an application (e.g., Alice) may approve of functionality provided by an application, while another entity (e.g., ACME) may not. As two examples, Alice may intentionally have gambling applications or pornographic-themed applications installed on her tablet **108**. In contrast, ACME may have corporate policies prohibiting employees from using enterprise network **140** for such applications. As will be described in more detail below, ACME can enforce policies against the use of such applications within enterprise network **140**.

[0026] Techniques described herein can be used in conjunction with a variety of platforms (e.g., desktops, mobile devices, gaming platforms, embedded systems, etc.) and/or a variety of types of applications (e.g., Android .apk files, iOS applications, Windows PE files, Adobe Acrobat PDF files, etc.).

[0027] Data appliance **102** (also included within enterprise network **140**) is configured to enforce policies regarding communications between client devices, such as client devices **104** and **106**, and nodes outside of enterprise network **140** (e.g., reachable via one or more external networks collectively depicted as network cloud **118**). One example of a policy is a rule prohibiting any access to site **150** (a pornographic website) by any client inside enterprise network **140**. Another example of a policy is a rule prohibiting access to social networking site **156** by clients between the hours of 9 am and 6 pm. Yet another example of a policy is a rule allowing access to video streaming website **152**, subject to a bandwidth or other consumption constraint. Yet another example of a policy is one that logs the time spent by employees using social networking sites (e.g., where there is an understanding that employees will sometimes visit such sites throughout the workday, but should limit such activities to fifteen minutes per day). Policies can be made to apply to all devices equally, and can also be applied at more granular levels. For example, access to social networking site **156** can be permitted to anyone in the ACME marketing department (e.g., users having associated group identifiers indicating their affiliation with the marketing department), and unfettered bandwidth for use with video streaming website **152** can be granted to specific users (e.g., the CEO), to groups of users (e.g., the ACME sales department), and/or to individual/groups of clients (e.g., prohibiting access to video streaming site **152** on production servers). Access to sites (e.g., news site **154**) can be explicitly permitted (e.g., a rule allowing access to site **154** via URL ("www.examplenews.com") or category ("NEWS")), and can also be permitted by virtue of not being prohibited (e.g., "access to any site not prohibited is allowed," e.g., allowing access to web mail site **168** without needing to explicitly name the site in the rule).

[0028] Other types of policies can also be enforced, such as ones governing traffic shaping, quality of service, and/or routing (e.g., with respect to a given domain, a pattern including a domain (e.g., *.examplenews.com), a category associated with a domain, other hostname-associated information (e.g., URL), IP address range, etc.). Yet other examples of policies include security policies such as ones requiring the scanning for threats in incoming (and/or outgoing) email attachments, screening of website content, scanning files exchanged through instant messaging programs, and/or other file transfers. In some embodiments, data appliance **102** is also configured to enforce policies with respect to traffic that stays within enterprise network **140**.

[0029] In various embodiments, data appliance **102** executes a DNS proxy service **166** (described in more detail below). When a client device (e.g., client device **108**) attempts to communicate with a network resource (e.g., video streaming website **152**), a DNS request is received by DNS proxy service **166**, which provides a response back to client device **108**. As applicable, the response is cached by data appliance **102**.

[0030] In various embodiments, other devices are also included in enterprise network **140**, such as a mobile device management (MDM) server **162**, which is in communication with data appliance **102**. MDM server **162** communicates with mobile devices to determine device status and to report (e.g., periodically) such mobile device status information to data appliance **102**. MDM server **162** can be configured to report the presence of malicious applications installed on client devices, and/or can be configured to receive indications of which applications are malicious (e.g., from data appliance **102**, from security platform **122**, or combinations thereof). In some embodiments, data appliance **102** is configured to enforce policies against client devices based on information received from MDM server **162**. For example, if a client device is determined to have malware installed on it (or other types of unapproved applications), data appliance **102** (working in cooperation with MDM server **162**) can deny the client device access to certain enterprise resources (e.g., an Intranet) while allowing other client devices (which do not have malware installed on them) access to those resources.

[0031] Although illustrated as a single element in FIG. **1**, enterprise network **140** can comprise multiple networks, any/each of which can include one or multiple data appliances or other components that embody techniques described herein. For example, the techniques described herein can be deployed by large, multi-national companies (or other entities) with multiple offices in multiple geographical locations. And, while client devices **104-108** are illustrated in FIG. **1** as connecting directly to data appliance **102**, it is to be understood that one or more intermediate nodes (e.g., routers, switches, and/or proxies) can be and typically are interposed between various elements in enterprise network **140**.

[0032] An embodiment of a data appliance is shown in FIG. 2A. The example shown is a representation of physical/hardware components that are included in data appliance **102**, in various embodiments. Specifically, data appliance **102** includes a high performance multi-core Central Processing Unit (CPU) **202** and Random Access Memory (RAM) **204**. Data appliance **102** also includes a storage **210** (such as one or more hard disk drives or solid state storage units), which can be used to store policy and other configuration information, as well as other information such as signatures and hostname/URL categorization information. In various embodiments, data appliance **102** stores (whether in RAM **204**, storage **210**, and/or in other appropriate locations) information used in monitoring enterprise network **140** and implementing disclosed techniques. Examples of such information include application identifiers, content identifiers, user identifiers, requested URLs, IP address mappings, etc. Data appliance **102** can also include one or more optional hardware accelerators. For example, data appliance **102** can include a cryptographic engine **206** configured to perform encryption and decryption operations, and one or more Field Programmable Gate Arrays (FPGAs) **208** configured to perform matching, act as network processors, and/or perform other tasks.

[0033] Functionality described herein as being performed by data appliance **102** can be provided/implemented in a variety of ways. For example, data appliance **102** can be a dedicated device or set of devices. The functionality provided by data appliance **102** can also be integrated into or executed as software on a general purpose computer, a computer server, a gateway, and/or a network/routing device. In some embodiments, at least some services described as being provided by data appliance **102** are instead (or in addition) provided to a client device (e.g., client devices **104** or **110**) by software executing on the client device (e.g., endpoint protection applications **112** and **114**).

[0034] Whenever data appliance **102** is described as performing a task, a single component, a subset of components, or all components of data appliance **102** may cooperate to perform the task. Similarly, whenever a component of data appliance **102** is described as performing a task, a subcomponent may perform the task and/or the component may perform the task in conjunction with other components. In various embodiments, portions of data appliance **102** are provided by one or more third parties. Depending on factors such as the amount of computing resources available to data appliance **102**, various logical components and/or features of data appliance **102** may be omitted and the techniques described herein adapted accordingly. Similarly, additional logical components/features can be included in embodiments of data appliance **102** as applicable. One example of a component included in data appliance **102** in various embodiments is an application identification engine **116** which is configured to identify an application (e.g., using various application signatures for identifying applications based on packet flow analysis). For example, application identification engine **116** can determine what type of traffic a session involves, such as Web Browsing—Social Networking; Web Browsing—News; SSH; and so on.

[0035] FIG. 2B is a functional diagram of logical components of an embodiment of a data appliance. The example shown is a representation of logical components that can be included in data appliance **102** in various embodiments. Unless otherwise specified, various logical components of data appliance **102** are generally implementable in a variety of ways, including as a set of one or more scripts (e.g., written in Java, python, etc., as applicable).

[0036] As shown, data appliance **102** comprises a firewall, and includes a management plane **232** and a data plane **234**. The management plane is responsible for managing user interactions, such as by providing a user interface for configuring policies and viewing log data. The data plane is responsible for managing data, such as by performing packet processing and session handling.

[0037] Network processor **236** is configured to receive packets from client devices, such as client device **108**, and provide them to data plane **234** for processing. Whenever flow module **238** identifies packets as being part of a new session, it creates a new session flow. Subsequent packets will be identified as belonging to the session based on a flow lookup. If applicable, SSL decryption is applied by SSL decryption engine **240**. Otherwise, processing by SSL decryption engine **240** is omitted. Decryption engine **240** can help data appliance **102** inspect and control SSL/TLS and SSH encrypted traffic, and thus help to stop threats that might otherwise remain hidden in encrypted traffic. Decryption engine **240** can also help prevent sensitive content from leaving enterprise network **140**. Decryption can be controlled (e.g., enabled or disabled) selectively based on parameters such as: URL category, traffic source, traffic destination, user, user group, and port. In addition to decryption policies (e.g., that specify which sessions to decrypt), decryption profiles can be assigned to control various options for sessions controlled by the policy. For example, the use of specific cipher suites and encryption protocol versions can be required.

[0038] Application identification (APP-ID) engine **116** is configured to determine what type of traffic a session involves. As one example, application identification engine **116** can recognize a GET request in received data and conclude that the session requires an HTTP decoder. In some cases, e.g., a web browsing session, the identified application can change, and such changes will be noted by data appliance **102**. For example a user may initially browse to a corporate Wiki (classified based on the URL visited as "Web Browsing—Productivity") and then subsequently browse to a social networking site (classified based on the URL visited as "Web Browsing—Social Networking"). Different types of protocols have corresponding decoders **244**. Based on the determination made by application identification engine **116**, the packets are sent to an appropriate decoder **244**. Decoder **244** is configured to assemble packets (which may be received out of order) into the correct order, perform tokenization, and extract out information. Decoder **244** also performs signature matching to determine what should happen to the packet. As needed, SSL encryption engine **246** can re-encrypt decrypted data. Packets are forwarded using a forward module **248** for transmission (e.g., to a destination).

[0039] As also shown, policies **242** are received and stored in management plane **232**. Policies can include one or more rules, which can be specified using domain and/or host/server names, and rules can apply one or more signatures or other matching criteria or heuristics, such as for security policy enforcement for subscriber/IP flows based on various extracted parameters/information from monitored session traffic flows. As also shown in FIG. 2B, an interface (I/F) communicator **250** is provided for management communications (e.g., via (REST) APIs, messages, or network protocol communications or other communication mechanisms.

[0040] FIG. 2C illustrates an embodiment of a data appliance. As previously explained, in various embodiments, data appliance **102** includes a management plane **232** and a data plane **234**. The management plane is responsible for managing user interactions, such as by providing one or more user interfaces for configuring policies (**242**), reporting problems, and viewing log data. The data plane is responsible for managing data, such as by performing packet processing (e.g., to extract URLs) and session handling. In various embodiments, a scheduler is responsible for managing the scheduling of requests (e.g., as presented by data plane **234** to management plane **232**, or as presented by management plane **232** to a remote security platform **122**).

URL Filtering

[0041] As mentioned above, one task performed by data appliance **102** is URL filtering. Specified in data appliance **102** is a set of policies **242**, some of which govern the types of websites that ACME employees may access, and under what conditions. As one example, included in data appliance **102** is a policy that permits employees to access news-related websites. Another policy included in data appliance **102** prohibits, at all times, employees from accessing pornographic websites. Also included in data appliance **102** is a database (**262**) of URLs and associated categories (e.g., with bing.com being categorized as a "search engine" and with gmail.com being categorized as "web mail"). Other information can also be associated with the URLs in database **262** instead of or in addition to category information, and that other information can be used in conjunction with policy enforcement.

[0042] In some embodiments, database **262** (or at least some portions thereof) is provided by a third party, such as through a subscription service. In such a scenario, it is possible that instead of the URLs being directly stored in database **262**, a transformation is applied to the URLs prior to storage. As one example, MD**5** hashes of URLs can be stored in database **262**, rather than the URLs themselves. The URLs stored in database **262** (or transformations thereof) represent the top n URLs for which access is most likely to be sought by users of client devices, such as client device **104**, where n can be configured based on the computing and other resources available to data appliance **102**. As one example, an embodiment of database **262** includes 20 million URLs and is stored in storage **210**. Database **262** can be periodically refreshed/maintained, such as by security platform **122** transmitting daily (or another timescale) database updates to data appliance **102** (e.g., as a content package).

[0043] In various embodiments, data appliance **102** includes various caches (e.g., **264-272**), loaded into RAM **204**. In some embodiments, all or some of caches **264-272** are omitted from data appliance **102** and the processing described herein is adapted accordingly. In other embodiments, additional caches are included in data appliance **102**, as applicable. Additional details regarding components shown in FIG. **2**C are provided below.

[0044] When a user of client device **106** (an employee referred to hereinafter as "Bob") attempts to engage in activities such as web surfing, communications from and to client device **106** pass through data appliance **102**. As one example, suppose Bob has launched a web browser application on client device **106** and would like to visit an arbitrary web page. Data appliance **102** is configured to evaluate the URL of the site Bob would like to visit (e.g., URL **274**) and determine whether access should be permitted.

[0045] Suppose Bob would like to visit site **154**, the website of a national newspaper, and enters that URL into his browser ("www.examplenews.com"). In some embodiments, the URL (**274**) is evaluated by data appliance **102** as follows. In the first stage of the evaluation, the data plane (**234**) consults cache **264** for the presence of URL **274** (the results of which are indicative of whether data appliance **102** has previously received a request to access site **154** within cache resource constraints). If the URL is present in cache **264**, the associated category that is also stored in cache **264** is used to enforce any applicable policies **242** (e.g., allowing Bob access to site **154**). If the URL is not present in cache **264**, a temporary entry is inserted into cache **264** indicating that the URL is being resolved. As one example, a URL being resolved is assigned a temporary category of "UNRESOLVED." Additional requests received by data appliance **102** for access to site **154** (e.g., received from another user such as "Charlie," a user of client device **104**) will be queued pending the resolution. In various embodiments, a timeout condition is placed on UNRESOLVED entries included in cache **264**, such that if the entry is not updated within a specified period of time, the entry is removed.

[0046] Assuming URL **274** remains unresolved, data plane **234** sends a request to management plane **232** for an evaluation of URL **274**. URL **274** is transformed as applicable (e.g., an MD**5** hash of URL **274** is computed). For the remainder of the discussion of this example, no distinction will be made between a URL and the MD**5** (or other transformation) of a URL, to aid in clarity. It is to be assumed that if database **262** stores MD**5** hashes, the queries performed against (and corresponding operations) it will be performed using MD**5** (or other applicable) transformations of URLs.

[0047] In some embodiments, cache **266** is evaluated for the presence of URL **274** (indicative of whether database **262** was previously queried for URL **274** within cache resource constraints). Suppose URL **274** is not present in cache **266**. A query of database **262** is performed using URL **274**. If it is assumed that URL **274** is present in database **262**, the corresponding category NEWS is returned and ultimately provided to data plane **234**, which will update the entry in cache **264** by changing the UNRESOLVED category to NEWS. The category will be used by the firewall to enforce any applicable rules. In this case, for example, Bob's attempt to access URL **274** with his browser would be permitted (his session would not be terminated by data appliance **102**), because his request is associated with an attempt to access a NEWS site, which is a permissible use. Cache **266** is also updated to include the returned category and URL **274** (i.e., its MD5 hash).

[0048] Now suppose that a query of database **262** for URL **274** fails. The next phase of evaluation performed by the management plane is to consult cache **268** to see if URL **274** is present therein. Cache **268** is associated with queries performed by data appliance **102** against a set of one or more remote URL classification services. As with the previous phases, if URL **274** is present in cache **268**, the corresponding category (e.g., "NEWS") will be returned as a result and can be used by the firewall in policy enforcement (and included in cache **264**). If URL **274** is also absent in cache **268**, one or more remote URL classification services, such as URL classification service **276**, are queried.

[0049] In some embodiments, the URL classification service is an Amazon Cloud URL query server, which queries URL category information using a Trie structure lookup. In some embodiments, the URL classification service is made available by the provider of the contents of database **262**, and contains URL information that supplements the information included in database **262** (e.g., by including many millions of additional URLs and corresponding categories). As one example, URL classification service **276** can be provided by security platform **122** (e.g., as component **276**). A URL classification service can also be under the control of the owner of data appliance **102** or any other appropriate party. Further, a set of multiple URL classification services can be queried by data appliance **102**, whether in parallel, in sequence (e.g., if a first queried URL classification service has no results, data appliance **102** contacts a different URL classification service), selectively, etc.

[0050] In various embodiments, URL classification service **276** is implemented using commodity server-class hardware. URL classification service **276** can also be constructed using a scalable, elastic architecture, and may comprise several distributed components, including components provided by one or more third parties (e.g., using Amazon Web Services, Microsoft Azure, and/or Google Cloud Platform). Further, when URL classification service **276** is referred to as performing a task, such as storing data or processing data, it is to be understood that a sub-component or multiple sub-components of URL classification service **276** (whether individually or in cooperation with third party components) may cooperate to perform that task. Functionality described herein as being provided by URL classification service **276** can be implemented in a variety of ways, including as a set of one or more scripts (e.g., written in Java, python, etc., as applicable).

[0051] URL classification service **276** uses a set of crawlers **280** to crawl sites (e.g., sites **150-156**), extract metadata/content, and store information associated with the crawled sites in database **282**. Examples of tools that can be used to crawl/extract content from sites include PageDump (WebKit), HtmlUnit, and jsoup. Database **282** is, in various embodiments, implemented using MongoDB. Example tables that can be included in database **282** are a crawl queue (of sites to be crawled), a crawl log (a history of sites crawled), a classification result (e.g., a to-publish category, invalid site, or no category), and a crawl content report (e.g., a summary of crawled sites, language, and number of pages crawled). The information extracted for a site (e.g., title, description, body text, keywords, inlinks, outlinks, language, etc.) is used (e.g., by classifier **284**) to generate a feature vector (or set of feature vectors, as applicable). One example of a feature is whether or not any of the outlinks of a site lead to sites known to be classified as ADULT sites. Other example features variously include features related to body text, features related to metadata, features related to incoming links, and features related to the URL itself.

[0052] In various embodiments, different features included in a feature vector are used in conjunction with different types of machine learning approaches incorporated into a classification model, such as model **286**. Examples of such machine learning approaches include Naive Bayes, support vector machines, random forest, logistic regression, and gradient descent boosting trees. Classifier **284** uses a model, such as model **286**, to classify a given site (e.g., as NEWS, ADULT, etc.) based on its associated feature vector. In various embodiments, a model such as model **286** is trained using a training set of manually labeled websites. As one example, sites such as netflix.com, hulu.com, and youtube.com (well known to provide video streaming services) can be included in the training set (labeled as "video streaming"). Categorizations determined using model **286** are stored in database **282**. The contents of database **282** can be used for a variety of purposes, including generating database **262**, and responding to queries.

[0053] In the event that URL **274** is also absent from URL classification service **276** (and any additional URL services available to data appliance **102** as applicable), a category of UNKNOWN will be returned and appropriate policies applied, based on the category, such as by blocking access to URL **274**. Cache **264** can also be updated by switching the temporary category of UNRESOLVED to UNKNOWN. As with cache **266**, cache **268** is updated based on results returned by URL classification service **276**. In some embodiments, URLs with UNKNOWN categorization have a timeout, thus allowing for resolution of the categorization during a subsequent request.

Security Platform

[0054] Returning to FIG. **1**, in various embodiments, security platform **122** is configured to provide a variety of services (including to data appliance **102**), including analyzing samples (e.g., of documents, applications, etc.) for maliciousness, categorizing applications, categorizing domains/URLs/URIs, etc.

[0055] Suppose a malicious individual (using system **120**) has created malware **158**. The malicious individual hopes that a client device, such as client device **104**, will execute a copy of malware **158**, compromising the client device, and causing the client device to become a bot in a botnet. The compromised client device can then be instructed to perform tasks (e.g., cryptocurrency mining, or participating in denial of service attacks) and to report information to an external entity, such as command and control (C&C) server **164**, as well as to receive instructions from C&C server **164**, as applicable.

[0056] Suppose data appliance **102** has intercepted an email sent (e.g., by system **120**) to client device **104** to which a copy of malware **158** has been attached. As an alternate, but similar scenario, data appliance **102** could intercept an attempted download by client device **104** of malware **158** (e.g., from a website). In either scenario, data appliance **102** determines whether a signature for the file (e.g., the email attachment or website download of malware **158**) is present on data appliance **102**. A signature, if present, can indicate that a file is known to be safe (e.g., is whitelisted), and can also indicate that the file is known to be malicious (e.g., is blacklisted).

[0057] If a signature for malware **158** (e.g., an MD5 hash of malware **158**) is included in the set of signatures, data appliance **102** can prevent the transmission of malware **158**

to client device **104** accordingly (e.g., by detecting that an MD5 hash of the email attachment sent to client device **104** matches the MD5 hash of malware **158**). Security platform **122** can also provide to data appliance **102** a list of known malicious domains and/or IP addresses, allowing data appliance **102** to block traffic between enterprise network **140** and C&C server **164** (e.g., where C&C server **164** is known to be malicious). The list of malicious domains (and/or IP addresses) can also help data appliance **102** determine when one of its nodes has been compromised. For example, if client device **104** attempts to contact C&C server **164**, such attempt is a strong indicator that client **104** has been compromised by malware (and remedial actions should be taken accordingly, such as quarantining client device **104** from communicating with other nodes within enterprise network **140**).

[0058] If no signature for an attachment is found, in various embodiments, data appliance **102** is configured to provide the file for static/dynamic analysis, to determine whether it is malicious and/or to otherwise classify it. As one example, data appliance **102** can send a copy of malware **158** to security platform **122** for analysis. Security platform **122** can also (or instead) obtain copies of applications for evaluation from sources other than data appliance **102** (e.g., data appliances **136** and/or **148**), and/or from other types of sources, such as a software distribution platform (also referred to herein as an “app store”) **160**. Example embodiments of app store **160** include Google Play, iOS App Store, Windows Store, and Amazon Appstore. In various embodiments, analysis of malware **158** is performed at least partially on premise (e.g., within enterprise network **140**). And, analysis described herein as being performed by security platform **122** can also be performed, at least partially, by a malware analysis module included in data appliance **102**.

[0059] Security platform **122** stores copies of received samples in storage **142** and analysis is commenced (or scheduled, as applicable). One example of storage **142** is an Apache Hadoop Cluster (HDFS). Results of analysis (and additional information pertaining to the applications) are stored in database **146**. In the event an application is determined to be malicious, data appliance **102** can be configured to automatically block the file download based on the analysis result. Further, a signature can be generated for the malware and distributed (e.g., to other data appliances such as data appliances **136** and **148**) to automatically block future file transfer requests to download the file determined to be malicious.

[0060] In various embodiments, security platform **122** comprises one or more dedicated commercially available hardware servers (e.g., having multi-core processor(s), 16G+ of RAM, gigabit network interface adaptor(s), and hard drive(s)) running typical server-class operating systems (e.g., Linux). Security platform **122** can be implemented across a scalable infrastructure comprising multiple such servers, solid state drives, and/or other applicable high-performance hardware. Security platform **122** can comprise several distributed components, including components provided by one or more third parties. For example, portions or all of security platform **122** can be implemented using the Amazon Elastic Compute Cloud (EC2) and/or Amazon Simple Storage Service (S3). Further, as with data appliance **102**, whenever security platform **122** is referred to as performing a task, such as storing data or processing data, it is to be understood that a sub-component or multiple sub-components of security platform **122** (whether individually or in cooperation with third party components) may cooperate to perform that task. As one example, security platform **122** can optionally perform static/dynamic analysis in cooperation with one or more virtual machine (VM) servers, such as VM server **124**.

[0061] An example of a virtual machine server is a physical machine comprising commercially available server-class hardware (e.g., a multi-core processor, **8+** Gigabytes of RAM, and one or more Gigabit network interface adapters) that runs commercially available virtualization software, such as VMware ESXi, Citrix XenServer, or Microsoft Hyper-V. In some embodiments, the virtual machine server is omitted. Further, a virtual machine server may be under the control of the same entity that administers security platform **122**, but may also be provided by a third party. As one example, the virtual machine server can rely on EC2, with the remainder portions of security platform **122** provided by dedicated hardware owned by and under the control of the operator of security platform **122**. VM server **124** is configured to provide one or more virtual machines **126-128** for emulating client devices. The virtual machines can execute a variety of operating systems and/or versions thereof. Observed behaviors resulting from executing applications in the virtual machines are logged and analyzed (e.g., for indications that the application is malicious). In some embodiments, log analysis is performed by the VM server (e.g., VM server **124**). In other embodiments, analysis is performed at least in part by other components of security platform **122**, such as a coordinator **144**.

[0062] In various embodiments, security platform **122** makes available the results of its analysis of samples via a list of signatures (and/or other identifiers) to data appliance **102** (and/or to MDM server **162**) as part of a subscription. For example, security platform **122** can periodically send a content package that identifies malware apps (e.g., daily, hourly, or some other interval, and/or based on an event configured by one or more policies). An example content package includes a listing of identified malware apps, with information such as a package name, a hash value for uniquely identifying the app, and a malware name (and/or malware family name) for each identified malware app. The subscription can cover the analysis of just those files intercepted by data appliance **102** and sent to security platform **122** by data appliance **102**, and can also cover signatures of all malware known to security platform **122** (or subsets thereof, such as just mobile malware but not other forms of malware (e.g., PDF malware)).

[0063] In various embodiments, security platform **122** is configured to provide security services to a variety of entities in addition to (or, as applicable, instead of) an operator of data appliance **102**. For example, other enterprises, having their own respective enterprise networks **134** and **138**, and their own respective data appliances **136** and **148**, can contract with the operator of security platform **122**. Other types of entities can also make use of the services of security platform **122**. For example, an Internet Service Provider (ISP) providing Internet service to client device **110** can contract with security platform **122** to analyze applications which client device **110** attempts to download. As another example, the owner of client device **110** can install software **114** on client device **110** which communicates with security platform **122** (e.g., to receive content packages from security platform **122** and transmit applications to security platform **122** for analysis).

III. Automated Extraction and Classification of Malicious Indicators

[0064] Detecting online criminal activity can be challenging for a variety of reasons, including the diversity of malicious activities and the scale of the problem, where billions of potential indicators of compromise (IOCs) such as Internet Protocol (IP) addresses, domain names, Uniform Resource Locators (URLs), and file hashes (e.g., SHA256 or MD5) may exist and be usable to identify and stop malicious activity. To help address the seemingly insurmountable task of identifying IOCs, security researchers often share their discoveries with one another. Unfortunately, such information sharing among researchers is not standardized or centralized, posing two main challenges to researchers. The first challenge is how to locate sources of publicly shared potential IOCs. The second challenge is that, without a universal definition of IOC, malicious IOCs may be intermingled with benign indicators.

[0065] To address these and other problems, in various embodiments, security platform **122** includes an automated IOC extraction system **300** that can collect and classify IOCs automatically. As will be described in more detail below, IOC extraction system **300** curates existing and discovers new IOC sources, crawls those sources and extracts potential IOCs, collects IOC intelligence, and classifies IOCs. As used herein, a "true IOC," "confirmed IOC," "malicious IOC," and/or "actionable IOC" is an IOC that can be used to block malicious/other undesirable activities. A "candidate IOC" or "potential IOC" is one that has not yet been determined to be usable to stop malicious/other undesirable activities. A "false IOC" is a candidate IOC that is subsequently determined to be benign (or not otherwise usable to stop malicious/other undesirable activities).

A. Example Architecture

[0066] Automated IOC extraction system **300** supports both manual and automated addition of various IOC sources, including websites, blogs, RSS feeds, Twitter posts, and/or threat intelligence sharing platforms. As one example, system **300** can identify new sources by leveraging TF-IDF based scoring to decide if a source is a publisher of malicious IOCs. An initial seed of sources can be used to build a term frequency model of the natural language present in known computer security related IOC sources and to build an inverse document frequency representing documents in general. In the example of Twitter, a search API can be used to find potentially useful sources which can then be evaluated using the average TF-IDF score of feeds to decide whether a given feed should be added as a source.

[0067] Each type of source (e.g., blog or Twitter) is crawled with an applicable stateful crawler that maintains a visit history for each source individually and stores collected content in a raw format for processing. When the web crawler encounters a link, it can be added to a crawl queue. System **300** extracts user-readable text from the collected raw content (e.g., HTML, PDF, DOCX, etc.). Using natural language processing, the text is converted into a list of sentences. Candidate IOCs (URLs, domain names, IP addresses, email address, file hashes, etc.) are extracted from the list of sentences. The sentence (or other surrounding text) from which a given candidate IOC is extracted is referred to as the IOC's "context," which can be used to locate interesting computer security terms related to the IOC. Additional information related to the candidate IOC is also collected, such as blocklists that the IOC appeared in and DNS records associated with the IOC, and can be used to assist in determining whether the candidate IOC is an indicator of abuse by itself In various embodiments, system **300** leverages both a heuristic ruleset based classifier, and a machine learning classifier to decide whether a potential IOC is actionable (i.e., can be used for blocklisting by itself). Both classifiers rely on features based on the IOC's context, attributes of the source, and additional intelligence gathered about the IOC (described in more detail below). The output of system **300** can be used in a variety of ways (e.g., providing a list of IOCs to URL classification service **276**, to data appliance **102**, etc.).

[0068] FIG. **3** illustrates an embodiment of an automated IOC extraction system. System **300** is modular, with each component working separately and modules depending on each other through data stored in central database **302** (or, as applicable, via RAM). One example of database **302** is a relational database (e.g., MySQL) for data persistence. Database **302** can be normalized to make sure that the same content is not stored multiple times. In various embodiments, for each source (e.g., blog website, Twitter account, etc.), the crawling state (URLs visited and URLs to visit) is stored in a JSON format (e.g., as a byte array or other appropriate way).

[0069] Main coordinator **304** orchestrates when and how each module is run, and multiple instances of a particular module (e.g., web crawler **308**) may be run simultaneously. Components of system **300** can be implemented in a variety of ways (e.g., as a set of scripts authored in an appropriate programming/scripting language such as Java or python and using applicable libraries such as the NLTK python library for natural language processing, the Requests python library for scraping websites, and scikit-learn for machine learning).

[0070] Target selector **306** is configured to select and prioritize sources (e.g., URLs, RSS feeds, and Twitter accounts) to be crawled. It caps the number of resources that crawlers visit in a certain time frame for a specific source. Web crawler **308** crawls targets selected by target selector **306**. It collects all online documents found visiting a particular URL. Examples of documents include text, HTML, PDF, DOCX, XLSX, pictures, and other types of files. Web crawler **308** also visits URLs that may not be part of a source. As one example, IOCs are frequently posted to the site www.pastebin.com, which web crawler **308** may also visit.

[0071] Text/IOC extractor **310** comprises multiple parts. First, it extracts text from files collected by web crawler **308**. It can handle different file formats (e.g., HTML, PDF, etc.). Second, it leverages natural language processing (NLP) to retrieve sentences from text. Third, it reverse defangs and retrieves candidate IOCs from the sentences using regular expressions, and fourth, it validates whether the candidate IOCs are valid domain names, IP addresses, email addresses, etc. Browsers and other web and email clients often make URLs, IP addresses, email addresses, and/or domain names clickable. IOCs are often intentionally made unclickable to stop readers from inadvertently visiting dangerous resources, a process referred to as "defanging." An example of a defanged URL is "hXXPs[:]//malicious.url[.]com/install.exe." When a defanged IOC is encountered, system **300** can reverse the defanging process ("reverse defanging") to obtain the original IOC.

[0072] DNS client module **312** queries DNS to find resource records (e.g., IP address and name servers) associated with candidate IOCs. These resource records can be leveraged to identify if a candidate IOC is truly an IOC. Intelligence gathering module **314** queries online resources about candidate IOCs. As one example, this module queries blocklists to find out whether a candidate IOC is included on such lists. The information collected can be used to determine whether a candidate IOC is a true IOC.

[0073] Heuristic classifier **316** includes a set of rules to decide whether a candidate IOC should be deemed a true IOC or not. Suppose a candidate IOC is classified as a true IOC. In that case, it will be included in the different services (e.g., offered by security platform **122**) to block malicious activities (e.g., URL filtering and DNS security services). If a candidate IOC is not classified as a true IOC, then it can be sent to other maliciousness detectors (e.g., malware/phishing detectors). The heuristic classifier leverages a subset of the features that machine learning classifier **318** uses. For example, it leverages knowledge of whether an IOC was defanged, was included in third-party blocklists (e.g., as can be determined by querying VirusTotal or other appropriate source), what DNS resource records the DNS client collected, the type of the IOC (e.g., URL, domain, IP), and whether the context included certain words indicating that the source authors thought this IOC to be malicious. A candidate IOC that appears on multiple blocklists and is defanged is likely to be malicious. Therefore, an example rule could be if a candidate IOC is defanged, and it appears on more than three blocklists, then it is a true IOC.

[0074] An advantage of a machine learning classification is that it can automatically learn a large number of rules based on a large set of features that would be untenable for humans. A disadvantage of machine learning is that it depends on the availability of labeled data. A heuristic classifier can be used to hardcode important rules based on expert knowledge. A variety of techniques can be used to implement machine learning classifier **318**. As one example, a random forest model can be used.

[0075] Machine learning classifier **318** is involved in three main tasks. The first task is feature extraction (e.g., how many sources mentioned the IOC, the age of the IOC, whether the IOC was defanged), for example, from the context of IOCs, the candidate IOCs themselves, and any external intelligence collected.

[0076] In various embodiments, features used by machine learning classifier **318** can be grouped into the following categories: features specific to the IOC string, the sources the IOC was mentioned in, the context sentences, the context contents (e.g., blog posts or tweets), and a set of external features.

[0077] IOC Textual Features: The goal of textual features is to understand how a candidate IOC looks. Often, these features are indicative of malice themselves. For example, complex domains and URLs might be constructed to trick users. These features are derived directly from the IOC string. Examples of such features include:

- **[0078]** Character length of the IOC
- **[0079]** Type of the IOC (e.g., domain, IP, URL, email address, hash) integer encoded
- **[0080]** Number of domain levels
- **[0081]** Number of URL path levels
- **[0082]** Length of the URL query field
- **[0083]** Was it extracted as part of a longer IOC (e.g., domain/IP part from URL)

[0084] Source Features: Source features represent how the security community at large thinks about an IOC. The more sources that mention a defanged IOC, the more likely it is that the IOC is malicious. Examples of such features include:

- **[0085]** The number of times the IOC was mentioned defanged across all sources
- **[0086]** The unique number of techniques used to defang the IOC across all sources
- **[0087]** Methods used to defang the IOC across all sources, one-hot encoded
- **[0088]** The number of source types an IOC was mentioned in (e.g., blog, Twitter, RSS)
- **[0089]** Source Distribution related features: These features are calculated four times, once for the source, once for the affiliation. For both, it is also calculated only when the IOC was defanged:
  - **[0090]** The maximum number of times the IOC was mentioned in one source/affiliation
  - **[0091]** The total number of times the IOC was mentioned in sources/affiliations
  - **[0092]** Max in one source/affiliation divided by total mentions to see if an IOC is mentioned in one source/affiliation much more than in others
  - **[0093]** The total number of sources/affiliations the IOC was mentioned in

[0094] Sentence features: Some sentence features also represent how the security community, in general, thinks about an IOC. Other sentence features represent whether a given sentence likely talks about a real IOC. For an IOC, each context sentence (and contents) can be considered, that is, all sentences (and contents) where the IOC was mentioned. For example, if a URL IOC is found in a sentence with the word "phishing," it might indicate that the URL is a phishing URL. Similarly, if a sentence contains many candidate IOCs, then it is more likely that this sentence is about true IOCs. Examples of such features include:

- **[0095]** One-hot encoding of computer, network, or security-related keywords found in the context sentences. Examples of such words include: "cookies," "download," "data," "malware," and "C2."
- **[0096]** One-hot encoding of the token types found in the sentences
- **[0097]** Minimum, average, and maximum values of the following features among context sentences:
  - **[0098]** Sentence length
  - **[0099]** Ratio of letters to all characters
  - **[0100]** Ratio of special terms
  - **[0101]** Ratio of IOCs
  - **[0102]** Number of ways IOCs were defanged
  - **[0103]** Number of IOCs
  - **[0104]** Number of defanged IOCs

[0105] Content features: Content features are similar to sentence features, but they are calculated for entire posts (or otherwise across a document). For example, the average number of IOCs present in context contents (instead of context sentences) for a given IOC is calculated. Context content features are calculated the same way as for context sentences.

[0106] External features: Features collected from external sources, which might help decide if a candidate IOC is a true IOC, can also be leveraged. As one example, the stable Alexa rank of candidate IOCs can be used as popular domains are not likely to be true IOCs. Alexa ranks domain names based on popularity. Alexa ranks of domain names can be collected and a determination can be made of whether the domains maintain their ranks for a long time period as a stable Alexa rank. The number of blocklists an IOC candidate was included in can also be considered. DNS client **312**'s output indicates if a domain is non-existent (NX), which would also make it likely that it is a true IOC. Finally, the age of domain names can be considered, as new domains are more likely to be malicious.

[0107] A second task performed by machine learning classifier **318** is model selection. This includes training a classifier model (e.g., random forest) on labeled data. An example of labeled data is a list of candidate IOCs where it is known whether they are true or false IOCs. The labeled data can be split into three parts: training, development, and validation sets. The training data can be used to help the classifier learn the difference between true and false IOCs. However, there are many hyperparameters that the classifier cannot learn (e.g., in the case of random forest, the maximum allowed depth of the trees or the number of features that can be used for each tree). The development dataset can be used to see how different settings of hyperparameters affect the classifier's performance. One approach is to consider how good a classifier's recall is for a predefined precision (e.g., 0.99). Recall is a measure of the percent of true IOCs that the classifier can find (the number of true positives divided by the number of true positives plus false negatives). A true positive is where a candidate IOC is classified as a true IOC and was indeed a true IOC. A false negative is where a candidate IOC is classified as a false IOC but was in fact a true IOC. Precision is a measure of how often the classifier correctly determines that a candidate IOC is a true IOC (e.g., the number of true positives divided by the number of true positives plus false positives). Precision is important in limiting the number of false positives. A false positive is where a candidate IOC is erroneously classified as a true IOC when it was a false IOC. The validation set can be used to make sure that the classifier did not overfit on the training and development datasets and that it can be used in practice with good performance. The final task is using a selected model to classify new candidate IOCs as true or false IOCs. True IOCs can then be included in the different services offered by security platform **122** to block malicious activities, as with heuristic classifier results.

[0108] In various embodiments, automated IOC extraction system **300** also includes an automatic source discovery module **320**. It leverages a manually curated set of seed sources **322** and online information to discover new sources automatically. Source discovery module **320** achieves this in two steps. First, sources that are related to security are aggressively included. Second, sources that do not yield valuable information are removed. Different techniques can be leveraged for different kinds of sources. In the case of blogs, for example, a search engine can be used to locate security blogs, and then database **302** can be searched to determine how often sources (starting with the seed) have linked to these blogs. If multiple sources are linked to a given blog, it can be included in the list of sources. In the case of Twitter, user accounts that are followed by seed sources (e.g., accounts of security researchers, security companies, etc.) can be identified and included (e.g., the ones that are followed by the highest number of sources, are followed by a threshold number of seed accounts, etc.). Unfortunately, aggressively including many sources can lead to an ineffective system to collect IOCs over time. One way to address this issue is to periodically run source evaluation. If it is determined that a source did not recently provide actionable IOCs, the source can be removed. The source can be automatically added back to system **300** at a later time (if applicable) through subsequent automatic discovery.

B. Example Processing

[0109] FIG. **4** illustrates an embodiment of a process for generating actionable indicators of compromise (e.g., IOCs that can be provided to a production security enforcement system and used to prevent harm). In various embodiments, process **400** is performed by security platform **122**, and in particular by automated IOC extraction system **300**. Process **400** begins at **402** when a set of potential sources for indicators of compromise (IOCs) is received. As one example, target selector **306** receives a set of potential sources at **402**. At **404**, one or more candidate IOCs is extracted from at lest one of the potential sources. As one example, web crawler **308** and text/IOC extractor **310** collectively extract a set of candidate IOCs at **404**. At **406**, an actionable IOC is automatically identified. As an example, such identification can be performed at **406** by heuristic classifier **316** and/or machine learning classifier **318**. Finally, at **408**, the actionable IOC is provided to a security enforcement service. As one example, an actionable IOC is provided by automated IOC extraction system **300** to URL classification service **276**. As another example, an actionable IOC is provided by automated IOC extraction system **300** to data appliance **102** (e.g., via a subscription service provided by security platform **122**). Various remediation techniques described above (e.g., preventing client **104** from communicating with a domain, quarantining client **106** if it is determined that client **106** has communicated with the domain, etc.) can be taken based on the IOC.

1. Blog Post Example

[0110] Suppose that one source included in seed sources **322** is a blog called "Malware Busters." A file for the source (a seed file) contains the name of the blog and a URL to the main page of the blog: "www.malwarebusters.com." When target selector **306** is called, it will load the seed file and save the URL of the main page with the name of the blog to database **302**. Two lists are maintained for each source: "visited URLs" and "URLs to visit." Initially, the "URLs to visit" will include a single link—to the main page (www.malwarebusters.com). And, initially, the "visited URLs" list will be empty, and is maintained to make sure that the same blog posts are not visited multiple times. The exception is the main page of the blog, which is revisited periodically (e.g., every day).

[0111] Next, multiple web crawlers **308** in parallel will begin retrieving URLs from the "URLs to visit" list. In this example, starting with www.malwarebusters.com, they will download the main page of the blog and add all the URLs referencing blog posts to the "URLs to visit" list. They will continue visiting these URLs until a daily cap is reached.

Suppose that one of the pages crawled is a post about a phishing campaign that targets a bank, "Rainbow Bank." The page is located at http://malwarebusters.com/posts/rainbowphishing.html. An example of a portion of user-visible text from the page is shown in FIG. **5**A. The corresponding source code for the page excerpt is shown in FIG. **5**B. When web crawler **308** visits the page, it will first save the raw HTML file with HTML, JavaScript, and CSS code. It will also process the HTML file and retrieve links from it, such as "https://pastebin.com/cWKZ98xx" in two cases only: if the URL is part of the blog site or the domain portion is in a predefined list such as "pastebin.com." The retrieved links are then added to the "URLs to visit" list.

[0112] Text/IOC extractor **310** will start by extracting the user-visible text as seen in FIG. **5**A. Then, it will split the text into sentences using NLP. While the crawlers save the raw HTML files, this module will save the user-visible text and the extracted sentences to database **302**. Next, using regular expressions, extractor **310** will search for defanging and will reverse defang candidate IOCs, taking note of where and what kind of defanging took place in the sentences. (In this example, "ralnbowbank[.]com" will be transformed to "ralnbowbank.com".) After defanging, another set of regular expressions is used to look for candidate IOCs and extract them, noting their position in the sentence. Before saving them to database **302**, a check is made to see if they are valid domain names, URLs, IPs, and/or email addresses. After this step, the output looks similar to the following table:

IOC	Defanging Type	Type	Is Child	Related Sentences
rainbowbank.com	none	domain	no	sent3, sent4
ralnbowbank.com	[.]	domain	no	sent5
rainb0wbank.com	[.]	domain	no	sent5
pastebin.com	none	domain	yes	sent9
https://pastebin.com/cWKZ98xx	none	URL	no	sent9

[0113] Next, DNS client module **312** will query the IP address and the name server record of the domains found. Intelligence gathering module **314** will find that ralnbowbank.com is present on four blocklists while rainb0wbank.com is not present in any blocklists. It will also find that both domains are relatively new.

[0114] Heuristic classifier **316** will then process the candidate IOCs. For example, heuristic classifier **316** will classify ralnbowbank.com as a true IOC as it has appeared on multiple blocklists, it was defanged, it appears with the word "typosquatting," and it is a domain name. Therefore, ralnbowbank.com will be included in security services to be blocked when visited by users or connected to by machines. Candidate IOCs rainbowbank.com, pastebin.com, and https://pastebin.com/cWKZ98xx are in a whitelist. Thus, they will be deemed as false IOCs. Another example of a domain that can be included in such a whitelist is "docs.google.com." Many benign documents are reachable via docs.google.com, as are some malicious documents. By including "docs.google.com" in a whitelist, system **300** can be prevented from inadvertently generating an actionable IOC that would block all documents reachable via docs.google.com (as opposed to a more fine-grained URL pointing at a specific document or user account which could be an acceptable actionable IOC such as docs.google.com/kj235kjsdf78235kasrfh).

[0115] Suppose that in the case of rainb0wbank.com, heuristic classifier **316** is unable to decide if it was a true or a false IOC; therefore, it will send it for further analysis (e.g., to machine learning classifier **318** and/or other detectors (e.g., a phishing detector)).

[0116] For machine learning classifier **318**, multiple kinds of features will be extracted about rainb0wbank.com. Some example features include the ratio of IOCs to text in the context sentences, the number of defanged IOCs, the number of blogs mentioning and defanging the IOC, and the number of IOCs in the entire blog post. As machine learning classifier **318** finds that most defanged IOCs at malwarebusters.com are true IOCs and that rainb0wbank.com was also mentioned on another site (tocatchaphisher.xyz), it will classify it to be a true IOC.

2. Twitter Example

[0117] In this example, suppose that the Twitter account of a known security researcher, Alice (@sec_alice123), is included as a source for automated IOC extraction system **300**. Alice tweets the following message: "We found some very tricky ransomware hosted on compromised sites. I attached a picture of related IOCs. They seem to be part of a social engineering campaign. When users download them, kaboom! Their files are encrypted." Included with the tweet is an image containing the following defanged URLs:

[0118] hXXps[:]//antivirus.victim[.]site/download/me/clean-your-pc.exe?id=dr524lkr0dl and

[0119] hXXp[:]//virus-cleaner.victim2[.]site/remove/malware/removal.exe?ref=m37x8l2la

[0120] The process of extracting the IOCs is similar to the example as described above. However, this time the attached picture needs to be separately downloaded so that the text can be extracted using optical character recognition (OCR). In the case of these two URLs, machine learning classifier **318** might find that they are true IOCs since they are defanged, the URLs are complex (they have several components and are relatively long), and the text to IOC ratio is high in the text extracted from the picture.

[0121] Although the foregoing embodiments have been described in some detail for purposes of clarity of understanding, the invention is not limited to the details provided. There are many alternative ways of implementing the invention. The disclosed embodiments are illustrative and not restrictive.

What is claimed is:

1. A system, comprising:

a processor configured to:

receive a set of potential sources for Indicators of Compromise (IOCs);

extract one or more candidate IOCs from at least one source included in the set of potential sources;

automatically identify an actionable IOC from the one or more candidate IOCs; and

provide the actionable IOC to a security enforcement service; and

a memory coupled to the processor and configured to provide the processor with instructions.

2. The system of claim **1** wherein the processor is further configured to identify a new potential source to add to the set of potential sources.

3. The system of claim **1** wherein extracting the one or more candidate IOCs includes is determining whether a URL was defanged.

4. The system of claim **3** wherein providing the actionable IOC includes reverse defanging the URL.

5. The system of claim **1** wherein extracting the one or more candidate IOCs includes performing optical character recognition on an image.

6. The system of claim **1** wherein the processor is configured to periodically crawl the set of potential sources.

7. The system of claim **1** wherein automatically identifying the actionable IOC includes analyzing the one or more candidate IOCs using a rule-based classification.

8. The system of claim **1** wherein automatically identifying the actionable IOC includes analyzing the one or more candidate IOCs using a machine learning-based classification.

9. The system of claim **1** wherein automatically identifying the actionable IOC includes excluding as a candidate IOC a whitelisted domain.

10. The system of claim **9** wherein the domain is whitelisted based at least in part on a popularity metric.

11. The system of claim **1** wherein at least one candidate IOC comprises a domain.

12. The system of claim **1** wherein at least one candidate IOC comprises a URL.

13. The system of claim **1** wherein at least one candidate IOC comprises an IP address.

14. The system of claim **1** wherein at least one candidate IOC comprises an email address.

15. The system of claim **1** wherein at least one candidate IOC comprises a hash.

16. The system of claim **1** wherein at least one processor is further configured to prune the set of potential sources.

17. The system of claim **1** wherein the processor is configured to prune a source included in the set of potential sources based at least in part on whether an actionable IOC was previously obtained from the source.

18. A method, comprising:

receiving a set of potential sources for Indicators of Compromise (IOCs);

is extracting one or more candidate IOCs from at least one source included in the set of potential sources;

automatically identifying an actionable IOC from the one or more candidate IOCs; and

providing the actionable IOC to a security enforcement service.

19. A computer program product embodied in a non-transitory computer readable medium and comprising computer instructions for:

receiving a set of potential sources for Indicators of Compromise (IOCs);

extracting one or more candidate IOCs from at least one source included in the set of potential sources;

automatically identifying an actionable IOC from the one or more candidate IOCs; and

providing the actionable IOC to a security enforcement service.

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