Programmable Data Gathering for Detecting Stegomalware

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***Abstract*—The "arm race" against malware developers requires to collect a wide variety of performance measurements, for instance to face threats leveraging information hiding and steganography. Unfortunately, this process could be time-consuming, lack of scalability and cause performance degradations within computing and network nodes. In this paper we propose to take advantage of the joint activities of two H2020 Projects, namely ASTRID and SIMARGL. To prove the benefits of the cooperation between the solutions developed by the two aforementioned projects, this paper reports a preliminary performance evaluation on the use of the extended Berkeley Packet Filter to gather data for detecting stegomalware.**

***Index Terms*—eBPF, syscall tracing, stegomalware, covert channels, detection.**

I. Introduction

Modern business models are increasingly demanding for more agility in the creation, operation and management of ICT services. To this aim, new computing paradigms are being progressively introduced, which leverage virtualization and cloud, as well as service-oriented architectures to interconnect software, devices, and data over a pervasive and seamless computing continuum encompassing different technological and administrative domains (i.e., IoT, data centers, and telco infrastructures). Despite of the benefits in terms of time-to-market and dynamicity, novel paradigms outdate the legacy security perimeter model and lead to additional threats [1].

The difficulty to effectively deploy cyber-security appliances in virtualized and cyber-physical systems is making cloud and network services the preferred target for a wide-range of novel attacks. As a matter of fact, the growing adoption of micro-services and service mesh architectures to implement large digital value chains creates interdependencies among software processes in different domains and paves the way for multi-vector attacks that combine together social engineering, malware, steganography, software bugs, and network vulnerabilities. The effective detection of threats in such scenarios requires to collect and correlate even apparently independent events from multiple subsystems, which is not possible for legacy standalone security appliances.

According to recent reports from cyber-security vendors, attacks are becoming ever more complex and stealthy, in order to elude well-known detection techniques based on signatures and behavioral patterns. As a paradigmatic example, steganography can be used to hide the presence of malicious code in digital media and network traffic is used as the carrier to covertly exfiltrate data or to stealthily orchestrate nodes of a botnet. Therefore, many recent attacks are difficult to detect and such a trend is expected to continue to grow [2].

Under this evolutionary scenario, programmatic access to data and events is an important requirement to improve the likelihood of detecting stealthy software and communications. In this paper, we show how research outcomes from complementary projects can be joined to this purpose. We consider the challenging scenario of detecting stegomalware in virtualized services, which encompass both cloud applications and network functions virtualization. The platform for lightweight and programmatic monitoring and inspection is taken from the ASTRID project[1], whereas SIMARGL[2] aims at developing scalable mechanisms to counteract novel malware endowed with steganographic techniques and crypto-lockers. While detection of network attacks has been largely discussed in the literature, information-hiding-capable threats pose new challenges, as they exploit bandwidth-scarce channels and their detection is a poorly generalizable process [3]–[5].

In more detail, we investigate the use of the programmable monitoring and inspection framework developed by ASTRID to collect data and measurements from virtualized environments, which are usually difficult to gather in an efficient way with existing tools. In addition, since the detection of steganographic threats is tightly coupled with the used carrier embedding the secret (e.g., the enumeration of sockets, the acquisition of a lock on a file or the manipulation of field within the header of a protocol), instrumenting virtual machines and network nodes without impacting their performances could be a hard and time-consuming task. To this aim, we leverage the extended Berkeley Packet Filter (eBPF), a framework integrated in the Linux kernel for the inspection of system calls, e.g., page faults and traffic stimuli [6]. Obtained measures can be then evaluated with toolkits envisaged in SIMARGL to reveal malware and hidden Command & Control (C&C) attempts or attacks targeting virtualized architectures.

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[1]AddreSsing ThReats for virtualIzeD services (ASTRID). URL: https://www.astrid-project.eu.

[2]Secure Intelligent Methods for Advanced Recognition of Malware and Stegomalware (SIMARGL). URL: https://simargl.eu.

Summarizing, the contributions of this paper are: *i*) the review of works enforcing security through virtualization; *ii*) the design of an architectural blueprint to integrate ASTRID and SIMARGL; *iii*) the identification of new threats taking advantage of steganography; *iv*) a preliminary experimental campaign on the use of eBPF to gather data for the detection of stegomalware.

The remainder of the paper is structured as follows. Section II reviews previous works on virtualization and security, while Section III deals with the architecture to combine the features of ASTRID and SIMARGL. Section IV portraits threats using steganography and Section V discusses technical aspects of the detection. Section VI showcases a preliminary performance evaluation on the use of eBPF to gather data for detecting stegomalware. Section VII concludes the paper and hints at some possible future developments.

II. Related Works

The use of virtualization to support security-related duties and the mitigation of attacks targeting virtual services have been already partially investigated in the literature. For instance, the approaches proposed in [7], [8] take advantage of an orchestrator for controlling pervasive and lightweight security hooks embedded in the virtual layers at the basis of cloud applications. The work in [9] discusses a mechanism to enhance a network hypervisor with new functions for implementing a flexible monitoring service. The proposed approach can ease the engineering of monitoring and security-related services, especially when in the presence of complex architectures based on micro services or cloud technologies. For the case of cybersecurity applied to networking, Deep Packet Inspection (DPI) is an important technique as it allows to evaluate several aspects of a flow, including alterations in the header at the basis of many covert channels [3], [10]. Indeed, network virtualization is often at the basis of large-scale scenarios where engines responsible of performing DPI can be deployed as software components on commodity hardware. To this aim, [11] proposes an approach for their dynamic placement to contain power consumptions and costs while delivering suitable degrees of scalability and performance. A more comprehensive framework is discussed in [12], where authors propose a virtualized security architecture to enforce integrity of virtual machines, isolate higher software layers, and provide adaptive network security appliances (e.g., intrusion detection systems and firewalls) encapsulated within virtual machines. Another important aspect concerns the definition and the implementation of effective orchestration policies. A possible idea could exploit meta-functions to dynamically construct security services able to satisfy various security requirements [13].

Concerning the detection of steganographic malware, at the best of our knowledge, there are not any works taking advantage of virtualization to gather data or neutralize attacks. In fact, literature abounds of works on the sanitization of carriers or the normalization of network traffic (see, e.g., references [5] and [3] and the references therein) but not any prior work investigates how a covert channel or a steganographic threat could be detect or prevented by means of virtualization. A variety of works address the security of virtualized architectures, but they mainly focus on the following classes of hazards [14]: access control of resources, DoS and DDoS attacks, virtualization to build the network infrastructure, and security management of virtualized assets. Even if the security risks caused by mobility, migration and hopping of virtual machines are well understood [15], steganographic threats are solely discussed without considering the overall architecture or the peculiarities of large-scale virtualized network scenario. Rather, they are addressed for very specific cases, e.g., colluding containers or virtual machines, but without gathering data via agents automatically deployed [10], [16].

III. A platform for SOCaaS

Following the general trend towards Everything-as-a-Service models (XaaS), ASTRID implements the concept of Security Operation Centres-as-a-Service (SOCaaS). Looking at the growing number of complementary appliances and the tighter integration required for the effective detection of stealthy threats in complex ICT systems, the ASTRID approach is based on the delivery of a common platform to run multiple security services. As depicted in Figure 1, the platform is conceived as a mediation layer between the detection and analysis logic and the physical and virtualization environments where cloud applications run. Differently from a bare Security Information and Event Management system (SIEM), which sends an overwhelming number of alerts to team members of the organization running the service/infrastructure, ASTRID enables security specialists to carry out deep analysis and investigation in a very flexible way, by selecting multiple complementary algorithms for each specific situation. The distinctive and innovative approach of ASTRID is the integration with software orchestration tools to automate the deployment and management of security agents, in order to overcome one of the main barrier to the adoption of SOC services.

Recent cybersecurity appliances and tools are quite flexible in the definition of the context to be collected (i.e., logs from specific applications, packet filters, event notifications, etc.), but are rather rigid in management. If a monitoring tool (e.g., a log collector or a packet classifier) is not available in the system, manual intervention from humans is required. In a similar way, reaction is often limited to traffic diversion, packet filtering, and changes in access rules. However, there is a little chance to automatically recover compromised systems, infrastructures, and services. In ASTRID, the integration with software orchestration tools will enable run-time management of virtual services, both to deploy additional inspection and monitoring processes and to trigger response and mitigation actions.

The deployment of capillary and pervasive security agents throughout the ICT infrastructure (network devices, servers, terminals of users, and smart things) is among the most critical issues for the realization of SOCs. ASTRID provides a set of

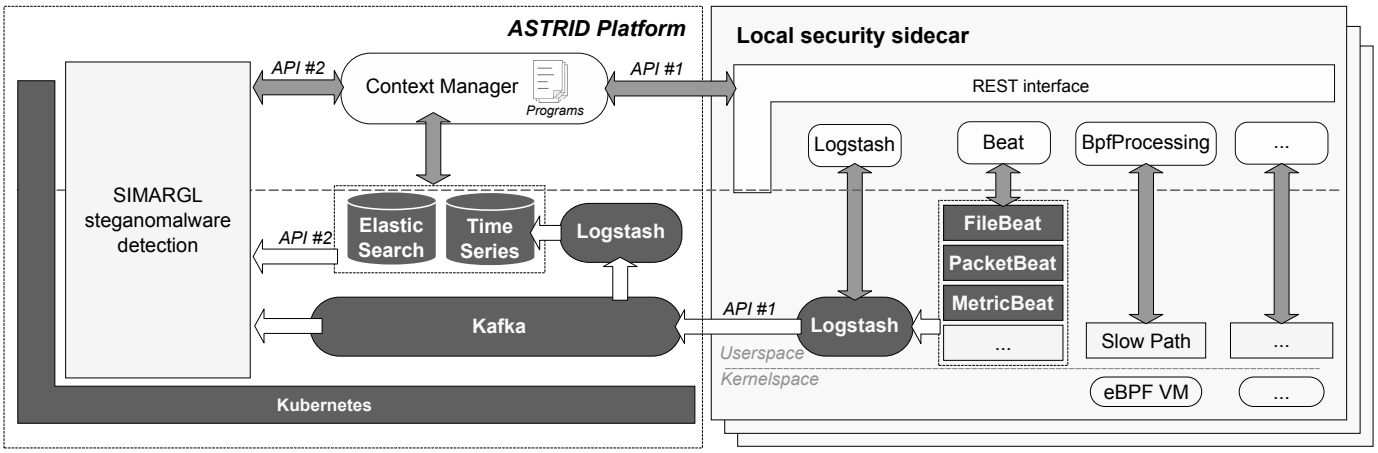


Fig. 1. Software architecture of the ASTRID platform.

security agents for collecting security-related information from the operating system, libraries, applications, and the network, hence fulfilling the need of different security algorithms for detection of intrusions, malware, and network anomalies. Moreover, agents can be used both for cloud applications and Network Functions Virtualization (NFV) services [17], [18].

The design used in ASTRID allows to disaggregate detection and analysis algorithms from the necessary hooks in the monitored system, but the resulting framework is not a full-fledged solution. Rather, it provides all architectural elements for programmatic access to the security context and adaptation of the security agents through programmability, but does not deliver the full stack of detection, analysis and assessment algorithms that are expected by security analysts. In this respect, it stands as a perfect platform to feed the SIMARGL toolkit in an effective way. Figure 1 shows the software architecture of the ASTRID framework integrated with the functionalities provided by SIMARGL. As shown, it includes local agents deployed in each virtual function as security sidecars and a centralized platform for collection and analysis of security-related data and measurements orchestrated over Kubernetes. The framework largely builds on the proven Elastic Stack framework, and extends it with an additional *beat* to run eBPF programs and a control/management plane. Through the Context Broker, it is possible to change the configuration of Elastic beats, load Logstash pipelines, and inject eBPF programs into the local environment. The Context Broker implements an abstraction of the service topology and current configuration of security agents allowing to know the type and structure of data that are delivered through Kafka. Additional elements are present in the framework to interact with software orchestration tools, to automate management and reaction operations, and to implement a graphical user interface, but they have been omitted for the sake of clarity (see [17], [18], for more details).

The needed data is provided to the SIMARGL toolkit by the ASTRID platform. Algorithms/software agents listen on the Kafka bus for notification of events and measurements, but they can also query the Timeseries database for historical data. The most important aspect is that such algorithms can define at run-time the needed measurements, and they can even load into ASTRID new eBPF programs for tailored data and statistics.

IV. Stegomalware and Emerging Threats

Despite a unique and precise definition is missing, the term *stegomalware* is used in SIMARGL to identify malware endowed with steganographic functionalities or able to exploit a covert channel [4]. In general, an attacker deploys steganography for the following use-cases.

Colluding Entities: they are those trying to create a covert channel to exchange data within the single host, mainly to bypass the security policies deployed in the underlying software and hardware layers, the guest OS or the hypervisor [5], [21]. Consequently, colluding applications implement a sort of unauthorized inter-process communication service between several software entities, for instance, virtual machines and containerized applications, as well as regular applications and processes. To exchange data, the typical approach set a local covert channel built by modulating the space available in the file-system, the CPU load or the state of TCP sockets. To detect such communications, two possible techniques can be used: monitor the syscalls handling the I/O or the access to the used carrier (e.g., a temporary file) or evaluate the sleep/wake patterns of processes as to identify those having overlapping behaviors, thus possibly colluding. In general, this attack can be used to exfiltrate data from an entity to another, e.g., to allow a containerized application handling sensitive data without network privileges to push the stolen information to another container with less constraints [16]. Moreover, virtual machines could also cooperate for reconnaissance purposes, such as to allow the malware to determine if it is confined on a honeypot or to map the underlying physical infrastructure [24].

Network Covert Channels: they allow to covertly transfer data by injecting the information within a network artifact

TABLE I
MEASURE OF INTEREST TO BE PERFORMED VIA ASTRID TO FEED THE SIMARGL TOOLKIT TO COUNTERACT STEGOMALWARE AND CRYPTLOCKERS.

Threat	Behavior of Interest	Sample Measures	Refs.
Colluding Applications	Activation statistic of processes or threads	stack trace of waker, total blocked time	[19], [20]
Colluding Apps. or Containers	Monitoring type and number of calls to VFS	type of VFS func, count	[16], [21]
Colluding Virtual Machines	Memory usage to infer anomalies	page cache hit/miss, read and write hit	[16], [22]
CC manipulating file-system	Processes that are performing disk I/O	type of op, disk, number of op	[3], [10], [19]
CC manipulating CPU	Time spent using the CPU	duration, count, load distribution	[3], [10], [19]
CC manipulating files	Reads and writes performed	reads, writes, r_kb, w_kb, type	[3], [10], [19]
CC enumerating sockets	TCP state change information	socket address, pid, cmd, state, duration	[3], [10], [19]
Miners, Cryptolockers and CC	Block disk I/O activity and performance	I/O latency, duration and count of operations	[4], [5]
Cryptolockers	Type of disk I/O operations and CPU usage	type of op, kbytes in R/W	[23]

acting as the carrier. To this aim, the sender can modulate the content of packets or alter some traffic features, e.g., he/she encodes information by manipulating the inter-packet time with proper delays. For the case of malware, network cover channels are typically used for: data exfiltration, implementation of a C&C infrastructure, development of cloaked transfer services for retrieving additional software components, botnet orchestration, and elusion of firewall rules [3], [5], [10].

Cycle-stealing threats, ransomware and cryptolockers. Despite their precise characterization is still an open problem, such threats share the aggressive usage of resources when attacking [25]. For instance, malicious code used for mining cryptocurrencies or orchestrating a botnet will impact on the average usage of computing or network resources, while the encryption of content stored on the file-system accounts for a significant volume of syscalls handling I/O operations. Therefore, being able to filter and monitor specific events within the kernel is a prime requirement for building effective indicators. This is even more important since many malware increase their stealthiness by adopting "time bomb" mechanisms triggering their execution after a predefined period of time. Such features reduce the chance of spotting the attack via a cause-effect observation (e.g., a lag in the graphical user interface due to excessive loads on the CPU) [26]. Similarly to the case of stegomalware, also cycle-stealing threats and ransomware require the access to different usage statistics, which are difficult to define *a priori*. A possible idea is to exploit abstract indicators, such as the used power [19]. Hence, being able to perform measurements "close" to the device driver or within the kernel is definitely important.

Another goal of SIMARGL is to develop detection methods for **obfuscation**, which is an umbrella term for many techniques enabling an application to look benign, even if endowed with malicious code. A prime class of methods embraces those using digital images as the carrier. For instance, some malware hides shell scripts by simply renaming them to mimic images (e.g., install.png) [27] or exploits steganography to embed malicious code within images, as well as configuration data, list of IP addresses to inspect or URL to contact for retrieving additional code as to implement multi-stage loading mechanisms [4].

Table I resumes the most popular attacks discussed in the literature, the behavior of interest, as well as some possible measurements to perform detection. For instance, in order to detect colluding applications or containers, a possible approach could monitor the behavior of the Virtual File System (VFS). In this case, by looking for the type of VFS functions called and their distribution it could possible characterizing the workload and spot anomalous bursts of operations. Other measures of interest could be those related to the I/O activity, such as the latency or the distribution of the size of the block of data (i.e., the block disk I/O). These values can provide relevant statistical indicators to detect miners or cryptolockers.

V. DETECTING STEGOMALWARE THROUGH ASTRID

The broad range of potential covert channels and carrier to be used for steganographic purposes make the detection of stegomalware a challenging task. As a matter of fact, stegomalware may leverage network packets, file system properties, memories and caches, CPU performance, and so on. Common detection mechanisms based on the analysis of log files and network statistics could be largely ineffective in this respect.

The detection of stegomalware requires temporal and spacial correlation of fine-grained system properties and actions. DPI can be used to spot anomalous usage of some header fields, while system tracing is required to analyze the behavior of the operating system. For example, by only narrowing the discussion to the most popular attacks targeting the single host/node, we can report the following considerations:

- Colluding Entities: typical attacks modulate the space available in the file-system, the CPU load or the state of TCP sockets. To detect them, two possible techniques can be used: *i*) monitor the syscalls handling the I/O or the access to the used carrier (e.g., a temporary file) or *ii*) evaluate the sleep/wake patterns of processes as to identify those having overlapping behaviors, thus possibly colluding.

TABLE II
EXAMPLES OF BCC TOOLS THAT CAN BE USED TO DETECT COVERT CHANNELS.

Attack	BCC tools
Colluding Applications	execsnoop, offwaketime, wakeuptime
Colluding Apps. or Containers	vfscount, vfsstat, biotop, ext4/xfs/zfsdist, ext4/xfs/xsflower, vfsreadlatency
Colluding Virtual Machines	cachestat, cachetop, biosnoop, bitesize, dcsnoop, dcstat, llcstat
CC manipulating file-system	biotop, biosnoop, bitesize, disksnoop, filteop
CC manipulating CPU	pidperscc, cachestat, cachetop, cpudist
CC manipulating files	filelife, filetop, filesnoop
CC enumerating sockets	tcpv4connect, opensnoop, solisten, tcpconnect, tcpstates, tcplife, tcpaccept, sofdsnoop
Miners, Cryptolockers and CC	biolatency, vfscount, biotop, biosnoop, funccount, funclatency, profile
Cryptolockers	biotop, biosnoop, bitesize

- Cryptolockers (or ransomware): in general, such threats generate a huge load on the filesystem to encrypt its content. Thus, monitoring operations on the I/O could be an effective indicator.

Several data sources are already present in the kernel to follow the execution of system calls and internal functions: *kprobes*[3], *uprobes*[4], *tracepoints*[5], *dtrace-probes* [28], and *lttng-ust*. Multiple tools are available to collect information from these tracing hooks (*ftrace*, *perf*, *sysdig*, *SystemTap*, *LTTng*), but eBPF is probably the most powerful framework for gathering data in the perspective of detecting information-hiding-capable threats. Specifically, there are no additional modules to install in the kernel, custom programs can be defined and attached to tracing hooks to do any kind of aggregation and lightweight processing. As a concrete example of the broad range of applicability of the eBPF framework, Table II lists existing programs from the BPF Compiler Collection[6] (BCC) that could be used to detect some well-known covert channels.

Put briefly, BCC is a toolkit for creating efficient kernel tracing and manipulation programs, and already includes several useful tools for tracing the most common features. Besides, it allows writing eBPF programs in C language and compiling them with LLVM. It also includes front-ends in Python and Lua. ASTRID improves this framework by feeding Elastic Stack with the output from eBPF programs.

This framework can be used to implement an effective suite of probes to gather the data needed by the SIMARGL toolkit for detecting stegomalware. Through ASTRID, investigation should start from eBPF programs to detect high-level indicators, while additional programs are then injected as soon as the scope is narrowed. Since there is no dependency on a specific set of programs, new programs can be implemented at runtime to cope with new or unknown covert channel and threats using information hiding.

VI. EXPERIMENTAL RESULTS

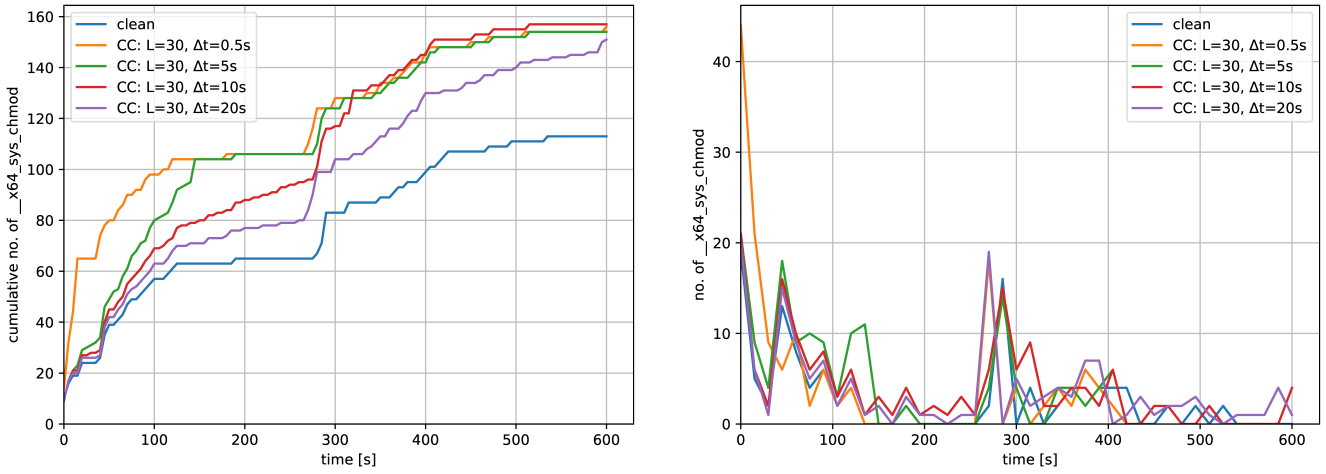
To prove the effectiveness of eBPF-based tracing, we selected a colluding applications threat where two endpoints exchange data through the chmod-stego technique. The chmod-stego is a covert channel that injects secrets in Unix file privilege numbers. The application is made of two peers, a sender and a receiver. The sender encodes data in the privilege of a set of files within a given directory, while the receiver listens for the specified file permissions and, according to changes, it decodes the secret message.

Since the chmod-stego technique is based on the manipulation of the file-system, the most straightforward way to design a detection strategy is by tracing the `__x64_sys_chmod` kernel function, which provides better indications than more generic I/O activity (e.g., read/write operations through `__x64_sys_read` and `__x64_sys_write`).

To validate such an idea, we investigated if and under what conditions a steganographic transmission could be detectable during system activity. We created an experimental setup composed of a Virtual Machine with Debian GNU/Linux 10 (buster) running the Linux kernel 4.20.9 and the aforementioned chmod-stego[7] steganographic method. A kernel compilation was run as the main system activity, which entails many I/O system calls and can be easily replicated for comparison. To gather data, a simple eBPF filter was injected to trace invocations of the `__x64_sys_chmod` kernel function and to report its relevant parameters, i.e., file and permissions, the Process ID (PID), and the Thread ID (TID).

We performed two different tests. The first aimed at evaluating the tradeoff between the steganographic bandwidth of the covert channel and its detectability. To this aim, we fixed the length L of the secret message to be transmitted and we varied the time between the transmission of two consecutive characters, denoted as Δt. Specifically, we conducted trials

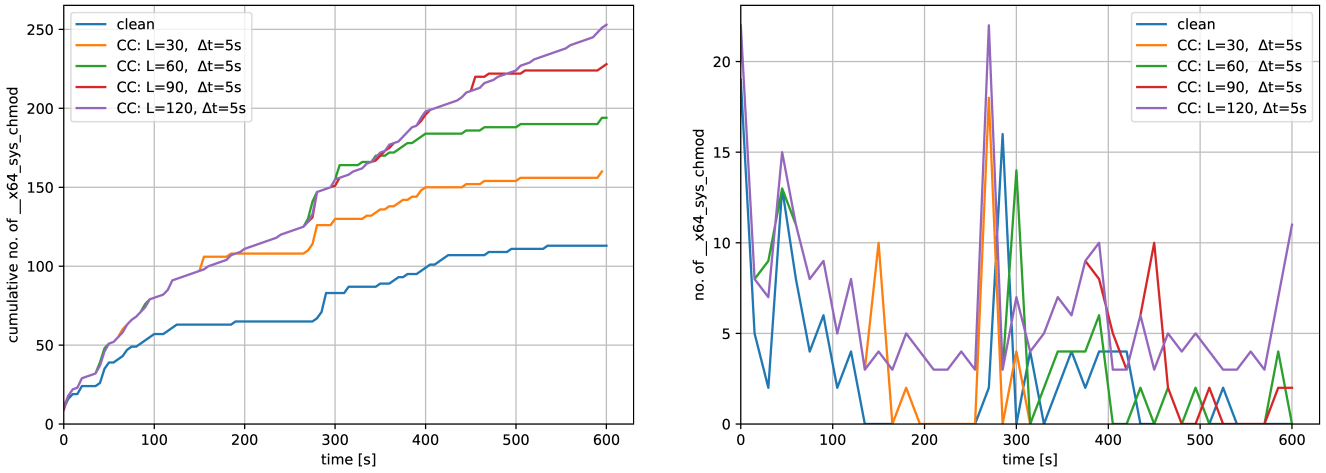
[3]https://lwn.net/Articles/132196/.
[4]http://www.brendangregg.com/blog/2015-06-28/linux-ftrace-uprobe.html.
[5]https://lwn.net/Articles/379903/.
[6]https://github.com/iovisor/bcc.
[7]https://github.com/operatorequals/chmod-stego.



(a) Cumulative time evolution

(b) Instantaneous time evolution

Fig. 2. Detected invocation of the `__x64_sys_chmod` kernel function with $L = 30$ and $\Delta t = 0.5, 5, 10, 20$ s.



(a) Cumulative time evolution

(b) Instantaneous time evolution

Fig. 3. Detected invocation of the `__x64_sys_chmod` kernel function with $\Delta t = 5$ s and $L = 30, 60, 90, 120$.

with $L = 30$ and $\Delta t = 0.5, 5, 10, 20$ s. In the second round of tests, we investigated the influence of the size of the data exchanged between the two colluding applications. Hence, we set $\Delta t = 5$ s and we performed trials with $L = 30, 60, 90, 120$ characters, which may be representative of the exfiltration of a PIN, a cryptographic key or the information of a credit card. In both tests, the "clean" configuration has been considered the one characterized by the load of traced kernel functions due to the compilation of the Linux kernel 5.5.5. All the trials lasted 10 minutes.

Figure 2 depicts the results of the first round of tests. As shown, the presence of an exchange of information through a covert channel (denoted as CC in the figure) affects both the number and the distribution of the `__x64_sys_chmod` kernel functions. Specifically, the higher the steganographic bandwidth (i.e., Δt decreases) the higher the load of `__x64_sys_chmod` kernel functions at the begin. In fact, higher transmission rates reduce the time needed to transmit the secret message. This can be viewed in Figure 2(b), where the instantaneous time evolution is shown. Similar results have been observed for the second set of experiments, which are showcased in Figure 3. In this case, the steganographic bandwidth is fixed and the length of the message is the unique factor that makes the transmission more or less detectable.

For what concerns detection, in general, channels with a higher steganographic bandwidth and longer messages are easier to detect. Indeed, they imply either sudden peaks or larger volumes of `__x64_sys_chmod` kernel functions. Clearly, on-line detection is not straightforward, because of the difficulty to find an effective decision rule able to discriminate between legitimate usage and the presence of hidden transmissions for different use cases. Luckily, for the case

of chmod-stego technique, a possible signature is given by a quick change in the volume of `__x64_sys_chmod` kernel functions at the end of the trials. This is due to the sender that restores the original file permissions, as to avoid the detection by common file system monitoring tools. Moreover, taking into account additional parameters available from tracing (e.g., the file names) can be used to further improve the likelihood of the detection. In this perspective, the SIMARGL toolkit will take into account multiple complementary indicators, possibly independent of the specific threat.

VII. Conclusions and Future Works

In this paper, we showcased how the framework developed within ASTRID can be used by the SIMARGL toolkit for the detection of novel threats, such as stegomalware and cryptlockers. To prove the effectiveness of this vision, we presented a preliminary performance evaluation on the use of the eBPF to collect variable of interests. The provided data can then be used to feed detection models or create datasets to train machine-learning-capable techniques.

Future works aim at refining the approach. In particular, the main objective is the definition of a more programmatic process to progressively narrow down the scope from generic indicators to fine-grained tracing of execution patterns for specific covert channels or information-hiding-capable threats. In this respect, ongoing research deals with the development of threat-independent signatures such as energy consumption, RAM usage patterns, and the time statistics of running processes.

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References

[1] R. Rapuzzi and M. Repetto, "Building situational awareness for network threats in fog/edge computing: Emerging paradigms beyond the security perimeter model," *Future Generation Computer Systems*, vol. 85, pp. 235–249, August 2018.

[2] K. Cabaj, L. Caviglione, W. Mazurczyk, S. Wendzel, A. Woodward, and S. Zander, "The new threats of information hiding: The road ahead," *IT Professional*, vol. 20, no. 3, pp. 31–39, 2018.

[3] S. Zander, G. Armitage, and P. Branch, "A survey of covert channels and countermeasures in computer network protocols," *IEEE Communications Surveys & Tutorials*, vol. 9, no. 3, pp. 44–57, 2007.

[4] W. Mazurczyk and L. Caviglione, "Information hiding as a challenge for malware detection," *IEEE Security & Privacy*, vol. 13, no. 2, pp. 89–93, 2015.

[5] ——, "Steganography in modern smartphones and mitigation techniques," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 1, pp. 334–357, 2014.

[6] S. Miano, M. Bertrone, F. Risso, M. Tumolo, and M. V. Bernal, "Creating complex network services with ebpf: Experience and lessons learned," in *2018 IEEE 19th International Conference on High Performance Switching and Routing (HPSR)*. IEEE, 2018, pp. 1–8.

[7] M. Repetto, A. Carrega, and G. Lamanna, "An architecture to manage security services for cloud applications," in *2019 4th International Conference on Computing, Communications and Security (ICCCS)*. IEEE, 2019, pp. 1–8.

[8] S. Covaci, M. Repetto, and F. Risso, "A new paradigm to address threats for virtualized services," in *2018 IEEE 42nd Annual Computer Software and Applications Conference (COMPSAC)*, vol. 2. IEEE, 2018, pp. 689–694.

[9] Y. Sun, S. Nanda, and T. Jaeger, "Security-as-a-service for microservices-based cloud applications," in *2015 IEEE 7th International Conference on Cloud Computing Technology and Science (CloudCom)*. IEEE, 2015, pp. 50–57.

[10] S. Wendzel, S. Zander, B. Fechner, and C. Herdin, "Pattern-based survey and categorization of network covert channel techniques," *ACM Computing Surveys (CSUR)*, vol. 47, no. 3, pp. 1–26, 2015.

[11] M. Bouet, J. Leguay, and V. Conan, "Cost-based placement of virtualized deep packet inspection functions in sdn," in *MILCOM 2013-2013 IEEE Military Communications Conference*. IEEE, 2013, pp. 992–997.

[12] J. Li, B. Li, T. Wo, C. Hu, J. Huai, L. Liu, and K. Lam, "Cyberguarder: A virtualization security assurance architecture for green cloud computing," *Future Generation Computer Systems*, vol. 28, no. 2, pp. 379–390, 2012.

[13] Z. Lin, D. Tao, and Z. Wang, "Dynamic construction scheme for virtualization security service in software-defined networks," *Sensors*, vol. 17, no. 4, p. 920, 2017.

[14] X. Luo, L. Yang, L. Ma, S. Chu, and H. Dai, "Virtualization security risks and solutions of cloud computing via divide-conquer strategy," in *2011 Third International Conference on Multimedia Information Networking and Security*. IEEE, 2011, pp. 637–641.

[15] H.-Y. Tsai, M. Siebenhaar, A. Miede, Y. Huang, and R. Steinmetz, "Threat as a service?: Virtualization's impact on cloud security," *IT professional*, vol. 14, no. 1, pp. 32–37, 2011.

[16] X. Gao, Z. Gu, M. Kayaalp, D. Pendarakis, and H. Wang, "Containerleaks: Emerging security threats of information leakages in container clouds," in *2017 47th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN)*. IEEE, 2017, pp. 237–248.

[17] M. Repetto, A. Carrega, and G. Lamanna, "An architecture to manage security services for cloud applications," in *4th IEEE International Conference on Computing, Communication & Security (ICCCS-2019)*, Rome, Italy, Oct., 10th–12th, 2019.

[18] ——, "Towards novel security architectures for network functions virtualization," in *IEEE Conference on Network Function Virtualization and Software Defined Networks (IEEE NFV-SDN)*, Dallas, Texas, USA, Nov., 12th–14th, 2019.

[19] L. Caviglione, M. Gaggero, J.-F. Lalande, W. Mazurczyk, and M. Urbański, "Seeing the unseen: revealing mobile malware hidden communications via energy consumption and artificial intelligence," *IEEE Transactions on Information Forensics and Security*, vol. 11, no. 4, pp. 799–810, 2015.

[20] M. Urbanski, W. Mazurczyk, J.-F. Lalande, and L. Caviglione, "Detecting local covert channels using process activity correlation on android smartphones," *International Journal of Computer Systems Science and Engineering*, vol. 32, no. 2, pp. 71–80, 2017.

[21] C. Marforio, H. Ritzdorf, A. Francillon, and S. Capkun, "Analysis of the communication between colluding applications on modern smartphones," in *Proceedings of the 28th Annual Computer Security Applications Conference*, 2012, pp. 51–60.

[22] Y. Zhang, A. Juels, M. K. Reiter, and T. Ristenpart, "Cross-vm side channels and their use to extract private keys," in *Proceedings of the 2012 ACM conference on Computer and communications security*, 2012, pp. 305–316.

[23] N. Scaife, H. Carter, P. Traynor, and K. R. Butler, "Cryptolock (and drop it): stopping ransomware attacks on user data," in *2016 IEEE 36th International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2016, pp. 303–312.

[24] P. Wang, L. Wu, R. Cunningham, and C. C. Zou, "Honeypot detection in advanced botnet attacks," *International Journal of Information and Computer Security*, vol. 4, no. 1, pp. 30–51, 2010.

[25] K. Liao, Z. Zhao, A. Doupé, and G.-J. Ahn, "Behind closed doors: measurement and analysis of cryptolocker ransoms in bitcoin," in *2016 APWG Symposium on Electronic Crime Research (eCrime)*. IEEE, 2016, pp. 1–13.

[26] R. Andriatsimandefitra and V. V. T. Tong, "Detection and identification of android malware based on information flow monitoring," in *2015 IEEE 2nd International Conference on Cyber Security and Cloud Computing*. IEEE, 2015, pp. 200–203.

[27] G. Suarez-Tangil, S. K. Dash, M. Ahmadi, J. Kinder, G. Giacinto, and L. Cavallaro, "Droidsieve: Fast and accurate classification of obfuscated

android malware," in *Proceedings of the Seventh ACM on Conference on Data and Application Security and Privacy*, 2017, pp. 309–320.

[28] B. M. Cantrill, M. W. Shapiro, and A. H. Leventhal, "Dynamic instrumentation of production systems," in *Proceedings of the annual conference on USENIX Annual Technical Conference (ATEC '04)*, June 2004.