# Managing Security for the Cyber-Space - From Smart Monitoring to Automated Configuration

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# Managing Security for the Cyber-Space – From Smart Monitoring to Automated Configuration –

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# 1

# Introduction

## 1.1 Research Context

This Habilitation Degree manuscript gives an overview of some of my major research activities performed in the area of network and service management over the past few years.

During my PhD thesis, I started to perform research by investigating and implementing new monitoring methods and techniques for supporting mobile ad-hoc networks [30]. At that time period, these networks were a particularly disruptive networking environment characterized by self-configuring capabilities and spontaneous deployments from mobile devices without requiring any pre-existing fixed infrastructure. The major challenge was to adapt and to make more flexible the network management plane, in order to cope with the properties of these dynamic networks, where nodes may cooperate or not at their will. The research efforts have first focused on building a dedicated information model for ad-hoc networks. We have then reorganized the management plane based on a probabilistic scheme. Instead of considering the whole network, the approach consisted in only selecting nodes that have both a high presence and a strong connectivity with their neighborhood, in order to establish management clusters. Finally, we have adapted management operations, in the context of performance monitoring using filtering techniques, and in the context of fault detection relying on information theory.

At IBM Research, I worked on change management in virtualized infrastructures, in the team of Prof. Joe Hellerstein and Dr. Alexander Keller at Hawthorne Heights, New York. We have proposed the architecture and implementation of a novel workflow-driven provisioning system for application services, such as multi-tiered systems. These services need to be dynamically provisioned to accommodate rapid changes in the workload patterns. This, in turn, requires a highly automated service provisioning process, for which we were able to leverage a general-purpose workflow language, called BPEL4WS, and its execution engine. While the concept of cloud computing was not yet born, we have successfully integrated a workflow-based change management system with a commercial service provisioning system that allowed the execution of automatically generated change plans as well as the monitoring of their execution. In addition to publications, these research efforts have led to an international patent.

My postdoctoral period at the Oslo Metropolitan University took place in the research team of Prof. Mark Burgess, where I worked on new management strategies for autonomic systems. Autonomic computing advocates greater decentralization of autonomy and only weak coupling of components through cooperative communication. It makes traditional server-state and least-connection inapplicable or inefficient. Our efforts on pull-based mechanisms have showed that relaxing the desire for mandatory control of servers using a central controller, and instead allowing

them to cooperate voluntarily through only weak coupling, is not the disadvantage that skeptics imagine; quite the opposite, it has the potential to exceed the performance of a push-based solution, while maintaining better security for each component. In addition to publications, this work has contributed to the integration of new performance metrics into the commonly-used Cfengine configuration management tool, which is developed in this research team, as well as in a dedicated company for the commercial part.

In 2007, I joined as an Associate Professor the TELECOM Nancy School of Engineering in Computer Science, part of the Lorraine INP Collegium, at the University of Lorraine, France, and became a permanent staff member of the RESIST (formerly MADYNES) research team led by Prof. Olivier Festor and then by Prof. Isabelle Chrisment, at the Loria / Inria Nancy Grand Est laboratory. The team activities are focused on network and service management, which is typically organized into five functional domains (FCAPS) which stand for Fault Management, Configuration Management, Accounting Management, Performance Management, and Security Management. Since then, my research efforts, that will be presented in this manuscript, have been centered on novel monitoring and configuration methods and techniques for the functional domain of security management.

## 1.2 Contributions

Figure 1.1 gives a high-level view on my research activities and their context. These network and service management activities contribute to security management for the cyberspace, in particular the current and new Internet, with the large-scale deployment of the Internet of Things, and the multiplication of services offered by cloud infrastructures. They are structured into three main axes: (1) smart monitoring for low-resource networks, (2) assessment and remediation of vulnerabilities, and (3) automated configuration of virtualized resources.

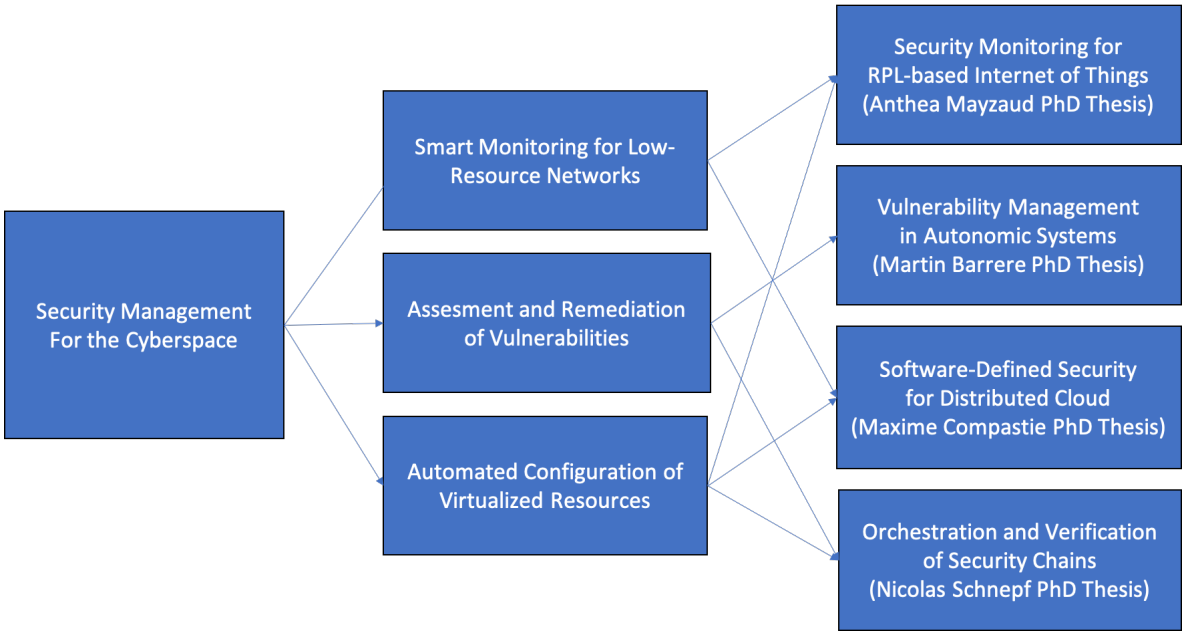


FIGURE 1.1 – Overview of research activities on security management

### Smart Monitoring for Low-Resource Networks

A first important axis concerns the investigation of smart monitoring methods capable to cope with low-resource networks, in particular in the context of the Internet of Things. The growing interest for connected objects has resulted in the large scale deployment of Low-power and Lossy Networks (LLN) such as home automation systems. These networks are strongly constrained in terms of resources (memory, power and processing) and communicate using unstable links with high error rates and low throughputs. In this context, existing routing protocols for wired networks and for ad-hoc networks do not cope with all these constraints. More precisely, the IETF RoLL working group has proposed a new routing protocol called RPL based on IPv6 and specially designed for these environments. The RPL protocol is however exposed to a large variety of internal and/or external attacks such as resource consuming attacks, interception or loop building attacks. The deployment of security mechanisms may also be quite expensive in terms of resources. Therefore, LLN networks present new challenges in terms of monitoring and security. During the PhD thesis of Anthéa Mayzaud [130], we proposed a security-oriented monitoring approach for addressing the trade-off between security and cost in the Internet of Things. In a first stage, we assessed security threats faced by these networks. In particular, we identified and classified attacks targeting RPL networks through a dedicated taxonomy. We also quantified the consequences of two major attacks called DAG inconsistency attacks and version number attacks causing over-consumption of node resources. The obtained results showed the importance of addressing them to preserve RPL-based infrastructures. In a second stage, we focused our work on security solutions for RPL-based Internet of Things. We proposed a strategy for addressing DAG inconsistency attacks and evaluated it through experiments. In order to detect more complex attacks such as version number attacks and to complement our node-level approach, we designed a security-oriented distributed monitoring architecture for RPL networks. This solution allowed us to preserve constrained nodes energy by performing monitoring and detection activities on dedicated nodes. We showed the feasibility of our approach by implementing a prototype able to detect both DAG inconsistency and version number attacks. We quantified the performance and the cost of this architecture and the detection modules.

### Assessment and Remediation of Vulnerabilities

A second major axis consists in the assessment and remediation of vulnerabilities. The massive deployment of computing devices over disparate interconnected infrastructures has dramatically increased the complexity of network management. Autonomic computing has emerged as a novel paradigm to cope with this challenging reality. By specifying high-level objectives, autonomic computing aims at delegating management activities to the networks themselves. However, when changes are performed by administrators and self-governed entities, vulnerable configurations may be unknowingly introduced. Vulnerabilities constitute the main entry point for security attacks. Hence, self-governed entities unable to protect themselves will eventually get compromised and consequently, they will lose their own autonomic nature. In that context, vulnerability management mechanisms are vital to ensure safe configurations, and with them, the survivability of any autonomic environment. During the PhD thesis of Martin Barrere [34], we targeted the design and development of novel autonomous mechanisms for dealing with vulnerabilities and reducing the exposure to attacks. The contributions concerned autonomic assessment strategies for device-based vulnerabilities and extensions in several dimensions, namely: distributed vulnerabilities (spatial), past hidden vulnerable states (temporal), and mobile security assessment (technological). The spatial dimension permits to cover vulnerabilities that may involve several

devices on a distributed topology. Vulnerability assessment is traditionally performed over individual network devices, independently of each other. Sometimes, however, two or more devices combined together may produce a vulnerable network state that host-based approaches are not able to detect. The temporal dimension focuses on past-hidden vulnerable states. Vulnerability assessment activities usually analyze new security advisories only over current running systems. However, a system compromised in the past by a vulnerability unknown at that moment may still constitute a potential security threat in the present. Indeed, a backdoor installed by an attacker for instance, may remain in the system even though the original vulnerability has been eradicated. The technological dimension aims at reducing the assessment workload in the case of mobile devices, considering a probabilistic cost-efficient technique integrated into a client-server architecture. In addition, we worked on vulnerability remediation methods to autonomously bring networks and systems into secure states. The remediation activity should not generate new vulnerable states on the system. We therefore proposed a formalization of the remediation decision process as a SAT problem, in order to prevent the occurrence of new vulnerabilities when corrective operations are applied.

### Automated Configuration of Virtualized Resources

A third axis is dedicated to automating configuration of virtualized resources for supporting security objectives. During the PhD thesis of Maxime Compastié [71], we considered a software-defined security approach for configuring distributed clouds. More specifically, we showed to what extent such programmability facilities can contribute to the protection of distributed cloud services, through the generation of secured unikernel images. These ones are instantiated in the form of lightweight virtual machines, whose attack surface is limited and whose security is driven by a security orchestrator. In that context, we defined a logical architecture supporting the programmability of security mechanisms in a multi-cloud and multi-tenant context. It permits to align and parameterize these mechanisms for cloud services whose resources are spread over several providers and tenants. We then introduced a method for generating secured unikernel images in an on-the-fly manner. It permits to lead to specific and constrained resources, that integrate security mechanisms as soon as the image generation phase. These ones may be built in a reactive or proactive manner, in order to address elasticity requirements. We also extended an orchestration language, so that is possible to generate automatically secured resources, according to different security levels in phase with the orchestration. Complementarily, during the PhD thesis of Nicolas Schnepf [168], we investigated the configuration of security chains. These chains are typically external to the resources to be protected, and may be composed of several security functions, such as firewalls, intrusion detection systems, and data leakage prevention mechanisms. To configure these security chains, it is important to have an adequate model of the patterns that resources (e.g. end user applications) exhibit when accessing the network. We proposed an automated method for learning the networking behavior of resources using algorithms for generating finite state models. These models can be exploited for inferring SDN policies ensuring that applications respect the observed behavior. Such policies can be formally verified and deployed on SDN infrastructures in a dynamic and flexible manner. In particular, our system infers a high-level representation of the security functions, which can be translated into a concrete implementation in the Pyretic language for programming software-defined networks. We showed that the generated chains satisfy several desirable properties such as the absence of black holes and loops, and that they are consistent with the underlying security policy. Further correctness properties of the chains can be verified using our Synaptic checker based on symbolic model checking and SMT solving.

## 1.3 Manuscript Organization

This manuscript presents a set of contributions in the area of security management addressing the main axes mentioned above. It is structured into four main chapters, complemented by the conclusion chapter.

The first chapter synthesizes research efforts on security monitoring for the Internet-of-Things, performed in the context of the PhD thesis of Anthéa Mayzaud [130], with the design of novel methods and techniques able to cope with the specific properties of these environments, and taking benefits from protocol piggybacking mechanisms.

The second chapter describes research efforts on vulnerability management for autonomic systems, performed in the context of the PhD thesis of Martin Barrère [34]. The presented methods exploit the knowledge provided by configuration vulnerability descriptions, in order to assess the presence of vulnerabilities and select adequate counter-measures.

The third chapter relates to research efforts on software-defined security for distributed clouds, performed in the context of the PhD thesis of Maxime Compastié [71]. The proposed solutions contribute to automate the building and configuration of virtualized resources with a low attack surface in cloud infrastructures.

The fourth chapter is about research efforts on orchestration of security chains, performed in the context of the PhD thesis of Nicolas Schnepf [168]. The approach enables automating the generation and parametrization of these security chains, from an analysis of the networking behaviors of resources.

The last chapter provides conclusions and details research perspectives.

# 6

# Conclusions and Perspectives

## 6.1 Conclusions

The different contributions detailed in this manuscript are the results of research activities developed in the RESIST research team, which aims at designing, implementing and validating novel models, algorithms and tools to make networked systems elastic and resilient so as to enhance their scalability and security, assuming users, applications and devices whose volume and heterogeneity will continue to increase. The team activities are structured according to four main research axes, namely Monitoring, Experimentation, Analytics and Orchestration, as illustrated on Figure 6.1. Softwarization of networks and data analytics are key enablers to design intelligent methods to orchestrate – i.e. configure in a synchronized and distributed manner – both network and system resources. In particular, intelligent orchestration should leverage relevant data for decision-making using data analytics. Input data reflecting the past, current and even future (predicted) states of the system have to be used for building relevant knowledge. Two approaches can then be pursued to generate knowledge and to validate orchestration decisions [17]. First, a running system can be monitored in vivo. Second, in vitro experimentation in a controlled environment (simulators, emulators and experimental platforms) is helpful to reproduce a running system with a high reliability and under different hypotheses. Monitoring and experimentation are therefore steered and configured through orchestration according to two intertwined loops. As highlighted on the figure, our contributions can be mapped to these team research axes.

### Security Monitoring for RPL-based Internet-of-Things

The first contribution is focused on security monitoring for low-power and lossy networks, in the context of the PhD thesis of Anthéa Mayzaud, and mainly relates to the Monitoring and Analytics research axes. Such IoT networks are strongly constrained in terms of resources (memory, power and processing) and communicate using unstable links with high error rates and low throughputs. The IETF RoLL working group has proposed a new routing protocol called RPL based on IPv6 and specially designed for these environments. We have started by assessing security threats targeting the RPL protocol through the identification and classification of attacks and have proposed a dedicated taxonomy. We have analyzed the impact of two RPL specific attacks which are the DAG inconsistency and the version number attacks and showed the importance of addressing them. We have then presented a local strategy to detect and mitigate DAG inconsistency attacks in RPL networks and evaluated its performance and costs. We have designed a security-oriented monitoring architecture in order to complement our node-level approach and address more complex attacks. In a passive and distributed manner, this

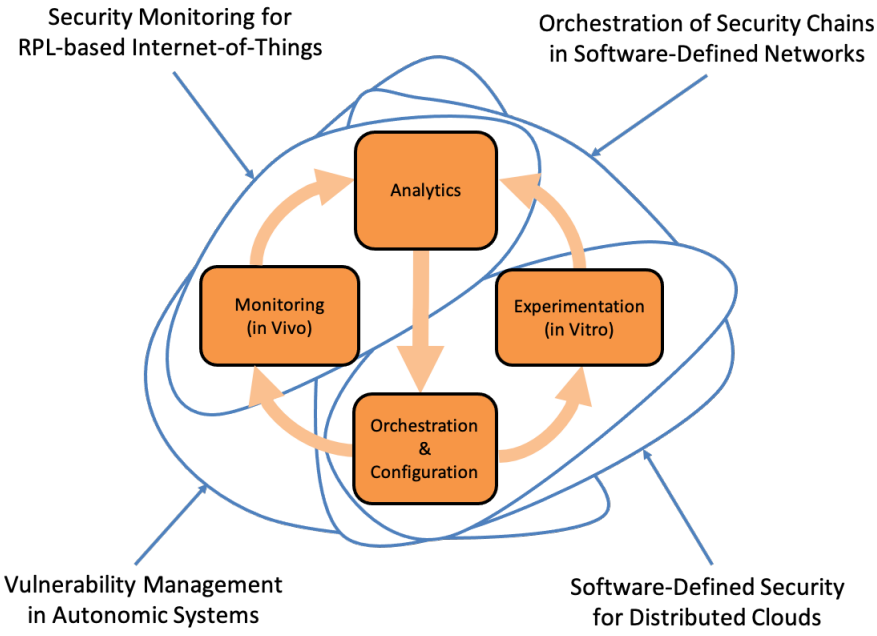


FIGURE 6.1 – Research contributions according to the four main axes of our RESIST team.

solution preserves constrained node resources, by exploiting RPL mechanisms such as the multi-instance feature and by relying on higher-order devices which implement detection modules responsible for identifying the considered security attacks. We have evaluated this architecture through extensive series of experiments and discussed the placement of monitoring nodes in that context. These works performed in the framework of the Flamingo European Network of Excellence, in collaboration with Jacobs University of Bremen, have shown the benefits of protocol piggybacking and dynamic adaptation in order to build a lightweight security-oriented monitoring solution for RPL-based IoT networks.

### Vulnerability Management in Autonomic Systems

The second contribution concerns vulnerability management in autonomic systems, in the context of the PhD thesis of Martin Barrère, and mainly relates to the Analytics and Orchestration research axes. Vulnerability management is a major challenge to secure autonomic environments whose changes dynamically operated on their configuration may increase the attack exposure. We have proposed to automate vulnerability assessment by integrating vulnerability descriptions (expressed with the OVAL language) into the autonomic management plane. By translating these security advisories into Cfengine policy rules, autonomic agents deployed across the network become able to analyze their own security exposure and to generate alerts. We have then extended this solution according to three dimensions. We have first addressed distributed vulnerabilities, which correspond to situations where two or more devices under specific conditions may present safe states, but when combined across the network, a vulnerable state arises (spatial dimension). We have then covered the case of past hidden vulnerabilities, by considering an historization of the system configurations from which the vulnerability assessment can be performed to detect past compromissions (temporal dimension). We have also designed a probabilistic solution to lightweight the assessment costs over mobile devices with constrained resources (technological dimension). We have finally worked on vulnerability remediation

mechanisms in order to automate the selection of corrective actions using SAT solving, and to enable collaborative strategies addressing distributed vulnerabilities. These works carried out in the context of the Univerself European project, in collaboration with Alcatel-Lucent Bell Labs, have shown the benefits of automating vulnerability assessment and remediation for maintaining safe configurations in autonomic environments.

### Software-Defined Security for Distributed Clouds

The third contribution is about software-defined security for distributed clouds, in the context of the PhD thesis of Maxime Compastié, and mainly relates to the Orchestration and Experimentation research axes. Cloud infrastructures facilitate the provisioning and access to multiple computing resources that require to be efficiently protected, considering the fact that these resources may be distributed over different datacenters, and shared amongst multiple tenants using virtualization technologies. We have first conducted a comparative analysis of virtualization models with regard to cloud protection, and infered several recommendations for our security approach. In particular, we have shown that unikernel-based virtualization provides interesting properties to sanitize the source code and restrict the attack surface, while generating lightweight virtual machines. We have then designed a general software-defined security architecture supporting different abstraction levels to cope with distribution and multi-tenancy, that serves as a basement to our solution, and has been validated based on several use-case scenarios provided by a network operator. We have complemented this architecture with a framework enabling the generation of unikernel cloud resources that comply with security requirements and embed security mechanisms at the earliest stage, as soon as the building of resource images. We have also extended the TOSCA orchestration language to drive such a generation according to different security levels, using our software-defined security architecture. These works developed in the context of the Inria-Orange joint lab, in collaboration with Orange research teams, have shown the benefits of rethinking the security management lifecycle in order to minimize the attack surface, with configuration changes resulting in the systematic rebuilding of cloud resource images in the extreme case.

### Orchestration of Security Chains in Software-Defined Networks

The fourth contribution is centered on the orchestration of security chains in software-defined networks, in the context of the PhD thesis of Nicolas Schnepf, and mainly relates to Orchestration and Analytics axes. Network programmability contributes to the flexible building and deployment of security chains for protecting smart devices, such as Android smartphones. It is of major importance to properly configure and verify them to prevent any inconsistencies that could impact on security itself. We have first worked on the automated synthesis of security chains that satisfy by construct correctness properties. For that purpose, we have considered a methodology for profiling the networking behavior of Android applications, and building behavioral models using aggregation and automata learning algorithms, whose performances have been compared in terms of accuracy and simplicity. Based on the obtained models and their properties, we have designed and exploited a rule-based inference system to produce a high-level representation of security chains and their security functions, that are then automatically translated into a concrete implementation deployable in a SDN infrastructure. Complementarily, we have investigated verification and optimization techniques for such security chains that may also be manually specified or updated by network operators. In particular, we have proposed and implemented a security chain checker that supports the rewriting of a set of security chains into different for-

mal specifications that are then interpretable by commonly-used verifiers from SMT solving and model checking areas. These works performed in collaboration with the Veridis INRIA research team have shown the benefits of formal verification to support the building and orchestration of security chains in software-defined networks.

## 6.2 Research Program

We propose to pursue these research efforts on security automation, according to three main axes, namely (1) ensemble learning methods for smart monitoring, (2) automated security orchestration for composite services, and (3) verified AI-based security management, as illustrated on Figure 6.2. They come within the scope of future network infrastructures, that are characterized by ever-increasing capabilities, in particular in terms of agility, scalability, and automation, as already suggested by the latest deployments of 5G networks and services [19].

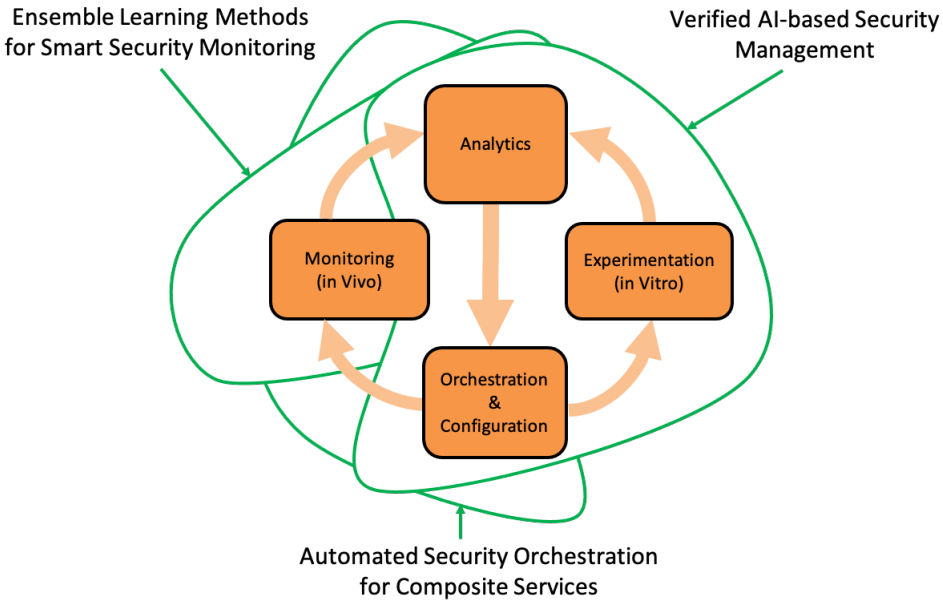


FIGURE 6.2 – Research program with respect to the four main axes of our RESIST team.

### Ensemble Learning Methods for Smart Security Monitoring

Security monitoring is challenged by the multiplication and heterogeneity of technologies, protocols and devices that constitute current and future network infrastructures. Learning methods have shown their benefits for building behavioral models from dedicated training datasets, such as network flows and configuration records. These models are then used to identify similarities or deviations characterizing normal behaviors or specific security attacks. For instance, we have already considered them for assessing the network traffic generated by applications running on Android devices, or for parameterizing specific detection methods applied to IoT devices in collaboration with Jacobs University Bremen (Germany) [136]. However, the performance obtained for a given learning method may significantly vary depending on the nature of considered data, which also depends on the strategies that are used for the collection, aggregation and preprocessing of these data, and on the scenarios that are analyzed. In that context, the objective of

our first axis is to investigate ensemble learning methods for enhancing security monitoring. Each learning method has its own advantages and drawbacks, and none of them may outperform the others in all cases. This phenomenon is particularly true with the diversity of monitoring data to be addressed for the applications of future networks, with ever-richer communication technologies. Ensemble learning strategies consist in simultaneously using several learning methods, and combining their results, instead of relying on only one of them. This implies an additional cost to be taken into consideration, but tends to increase the detection performance, and to improve the robustness against adversarial obfuscation techniques.

A typical example for this first axis on ensemble learning methods for smart security monitoring can be given with the case of large-scale heterogenous IoT systems. These latter integrate numerous protocols, platforms and equipments, to support the growing development of smart services, including services for critical and sensitive areas such as industry, transportation and healthcare. The sophistication of security attacks against these systems is increased with the development of advanced persistent threats (APT), such as *Stuxnet* worms against nuclear centrifuges or *Industroyer* malwares against power electric grids, taking the form of multi-step scenarios, that often use to their benefits the complexity of IoT systems, in order to remain as furtive as possible. The detection of these scenarios requires to take into account the attack strategy, the heterogeneity of resources and technologies on which it may rely over time, and the causal relationships amongst its different phases. While different IoT architectures including security modules and features, such as proposed by Carnegie Mellon University (USA) [137] or ARM (UK) [20], have been proposed in the literature, security cannot be guaranteed without failure or only by-design to prevent these attacks, in particular for such evolving ecosystems. Ensemble learning methods have already shown their benefits in many functional areas. For instance, research groups such as Umea University (Sweden) [184], have explored them for supporting fault diagnosis. They also offer promising perspectives to improve attack detection at an early stage in IoT infrastructures, by exploiting complementary learning techniques, such as probabilistic, statistical, proximity-based, and isolation-based methods. However, their usage should not only impact on data analytics, but also on the whole security monitoring process, from the placement and configuration of probes in the network infrastructures to the generation of indicators and alerts, that then serve to orchestrate counter-measures and properly mitigate these advanced attacks.

### Automated Security Orchestration for Composite Services

Future infrastructures, leveraged by advances on softwarization, will constitute ever more efficient integration platforms, enabling a higher degree of programmability and automation, in phase with continuous development and delivery strategies, such as those promoted by DevOps and Infrastructure-as-Code initiatives [23]. The growing maturity of orchestration languages already contribute to the building and deployment of composite services. These services typically rely on virtualized resources provided by cloud infrastructures (such as software components and virtual machines) and may be complemented by physical resources (such as connected objects and cyber-physical systems). The orchestration languages permit to specify their structure based on the different resources that compose the service, as well as the relationships that exist amongst them. The objective of our work is to automate the orchestration of security for such composite services, by exploiting and extending the knowledge provided by their specifications. We have already showed the benefits of extending such orchestration languages to drive the building of unikernel-based resources characterized by a low attack surface, in collaboration with Orange [75]. The specified resources and their relationships may provide substantial information

to identify potential vulnerabilities affecting composite services, to enable an adequate placement of security mechanisms, and more generally to improve the resiliency of such services with respect to security attacks. In particular, the relationships include horizontal dependencies, such as two interconnected resources located on different nodes (e.g. a web server and a database server), and vertical dependencies, such as a resource running over another resource (e.g. a web server running over an operating system). This structural information should be taken into account for supporting security automation, and the extension of orchestration languages should be considered for defining different orchestrated security levels, and expressing alternative security mechanisms in order to efficiently adapt to contextual changes. These changes include new security risks that may be identified, collaboratively or not, by cyber threat intelligence, using dedicated tools such as the MISP sharing platform [189] supported by CIRCL (Luxembourg) or the DDoS clearing house [180] developed by SIDN labs (The Netherlands).

A typical example for this second axis on automated security orchestration can be given with the case of cloud composite services and the migration of their resources. The latter may be deployed across different infrastructures owned by one or several cloud provider(s), and are subject to changes over time. This dynamics increases the complexity of management tasks and may lead to potential vulnerabilities that may compromise the resources, or even the whole cloud composite service. In particular, the cold and hot migrations of cloud resources are currently facilitated by recent advances on virtualization techniques, permitting to transfer one or several resource(s) of a cloud composite service from a given provider (or a given infrastructure) to another one. This process is often motivated by performance and cost objectives, with regard to cloud properties, such as scalability, rapid elasticity and on-demand self-service. However, it may impact on the security of cloud composite services and increase their exposure to security attacks. The changes that affect the migrated resources may involuntarily generate vulnerabilities that are exploitable by cybercriminals to cause critical damages, including disclosure of information, data loss and data tampering. It is important to support these migrations with the automated orchestration of adequate security counter-measures. These counter-measures may rely on two categories of security: endogenous mechanisms, such as deploying dedicated security patches, that directly impact internally on the considered resources, or exogenous mechanisms, such as adding new firewall security rules, using different security functions offered externally by cloud providers. Current research efforts typically focus only on one of these categories at a time. For instance, Institut Mines-Telecom (France) [150] have shown how to dynamically generate access control models and policies for different tenant domains, by considering exogenous mechanisms and leveraging network function virtualization (NFV). Some other research groups, such as Ghent University (Belgium) and UFRGS (Brazil) [54], have looked more specifically on the integrity of service function chaining in NFV environments. We believe that orchestration languages provide an interesting and extensible support to partially share security-related information through the usage of trusted third-parties, and to enable an efficient and complementary exploitation of endogenous and exogenous counter-measures, in order to cope with security management issues induced by resource migrations.

### Verified AI-based Security Management

Future networks and services will also require further coordination amongst distributed intelligences to enable better operational performance and security amongst networked infrastructures. Artificial intelligence and machine learning are extensively considered for enhancing and automating the different management functional areas, including security management. They help to better identify current and new security threats, and to provide faster responses to security

incidents and attacks, and this being performed over distributed environments. However, their full exploitation is often conditioned by explainability and verification properties, that should ensure the decision-making processes are kept trustful and transparent, and are fully controllable by human administrators and operators. In that context, the objective of the third axis is to bridge the gap between artificial intelligence and verification techniques to support security management automation. We have already investigated management solutions based on verification techniques, such as SAT solving and model checking, to prevent configuration vulnerabilities that may involuntarily occur when changes are operated on the infrastructures in a manual or automated manner [35]. These techniques might also be combined with artificial intelligence methods, in order to guarantee formal verification properties, and improve the decision-making processes. Such an integration may typically be considered for supervised and semi-supervised learning methods, in order to support the preliminary training phase, where the labeling of data might be improved by exploiting the results given by verification techniques. It may also be envisioned for reinforcement learning methods, in order to give verification feedbacks to algorithms that are responsible for exploring different actions and learning from past experiences based on the observations that are performed on the managed system. In the meantime, the considered verification techniques as well as the formal models on which they rely, may in turn benefit from machine learning techniques with respect to their parameterization. Research efforts have already been done at UC Berkeley (USA) [167] to establish the foundations of verified artificial intelligence. They specify the semantic behavior of autonomous industrial systems (e.g. self-driving cars), and then verify that several invariants are guaranteed when AI-based operations are performed. However, they only focus on safety considerations, and do not exploit the knowledge currently provided by security databases and repositories.

A typical example for this third axis on verified AI-based security management can be given with the case of moving target defense (MTD) techniques, that aim at confusing attackers through the reconfiguration of the network infrastructures to be protected. These techniques consist in dynamically changing the available attack surface, by modifying the different resources and parameters of the considered infrastructures, such as the migration of virtual machines, the shuffling of IP addresses, the changes with respect to software product versions, or even the redefinition of functional interfaces. The introduced dynamics impact on the reconnaissance activities, that are performed at the first phase of the cyber kill-chain, by preventing the consolidation of knowledge, regarding the targets and tactics to be considered for performing security attacks, such as accurate identification of entry points and precise software fingerprinting. Methods based on artificial intelligence are currently investigated to support moving target defense strategies, as highlighted by Prof. Gabi Dreo from the CODE Research Institute (Germany) [96]. They automatically determine and schedule the movements to be applied on the infrastructures at different layers. For instance, game theoretic approaches such as developed by Carnegie Mellon University (USA) [129] formalize moving target defense strategies as a two-player game between a defender that continuously shift the system with reconfiguration costs, and an attacker that spends efforts to find new attacks or to try to make past attacks work, the concept of Nash equilibrium being used to establish the defender optimal stationary strategy. The different movements that are applied to the system should not follow any reconfiguration patterns that could be predictable by the attackers. However, this leads to explore new configurations over time that may potentially introduce vulnerabilities on the infrastructure. The changes that are decided by security automation methods based on artificial intelligence, and that may affect different resources distributed over the network, have therefore to be efficiently driven or checked by verification techniques, in order to maintain a minimal attack surface of the considered system.

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# Glossary

**6LoWPAN** - IPv6 Low-power Wireless Personal Area Network.
**AI** - Artificial Intelligence.
**AMI** - Advanced Measurement Infrastructure.
**AMPL** - A Mathematical Programming Language.
**AMQP** - Advanced Message Queuing Protocol.
**API** - Application Programming Interface.
**AT** - Adaptive Threshold.
**CNF** - Conjunctive Normal Form.
**CoAP** - Constrained Application Protocol.
**CoMI** - CoAP Management Interface.
**CPU** - Central Processing Unit.
**CSP** - Cloud Service Provider.
**CTL** - Computation Tree Logic.
**CVC** - Cooperating Validity Checker.
**CVE** - Common Vulnerabilities and Exposures.
**CVSS** - Common Vulnerability Scoring System.
**DAG** - Directed Acyclic Graph.
**DAMON** - Distributed Architecture for MONitoring mobile network.
**DAO** - Destination Advertisement Object.
**DAO-ACK** - Destination Advertisement Object Acknowledgement.
**DoS** - Denial of Service.
**DDoS** - Distributed DoS.
**DIO** - DODAG Information Object.
**DIS** - DODAG Information Solicitation.
**DNS** - Domain Name System.
**DODAG** - Destination Oriented Directed Acyclic Graph.
**DOVAL** - Distributed OVAL.
**DPI** - Deep Packet Inspection.
**DT** - Dynamic Threshold.
**EPMOSt** - Energy-efficient Passive MOnitoring System.
**FP** - False Positive.
**FPR** - False Positive Rate.
**FW** - Firewall.
**GSP** - Global Security Policy.
**IEEE** - Institute of Electrical and Electronics Engineers.
**IETF** - Internet Engineering Task Force.
**IDS** - Intrusion Detection System.
**ILP** - Integer Linear Programming.

**IOS** - Cisco Internetworking Operating System.
**IoT** - Internet of Things.
**IPS** - Intrusion Prevention System.
**JSON** - JavaScript Object Notation.
**KVM** - Kernel-based Virtual Machine.
**LLN** - Low-power and Lossy Network.
**MANET** - Mobile Ad-hoc NETwork.
**MIB** - Management Information Base.
**MISP** - Malware Information Sharing Platform.
**MMU** - Memory Management Unit.
**MOP** - Mode Of Operation.
**MP2P** - Multipoint-to-Point.
**MTD** - Moving Target Defense.
**NETCONF** - NETwork CONFiguration protocol.
**NFV** - Network Function Vitualization.
**OS** - Operating System.
**OVAL** - Open Vulnerability and Assessment Language.
**P2MP** - Point-to-Multipoint.
**P2P** - Point-to-Point.
**P4** - Programming Protocol-Independent Packet Processors.
**PAP** - Policy Administration Point.
**PDP** - Policy Decision Point.
**PEP** - Policy Enforcement Point.
**PMSW** - Passive Monitoring System for WSN.
**RAM** - Random-Access Memory.
**RIP** - Routing Information Protocol.
**RoLL** - Routing Over Low-power and Lossy networks.
**RPL** - Routing Protocol for Low-power and lossy networks.
**SAT** - Satisfiability.
**SCAP** - Security Content Automation Protocol.
**SDK** - Software Development Kit.
**SDN** - Software-Defined Networking.
**SDSec** - Software-Defined Security.
**SFC** - Service Function Chaining.
**SIP** - Session Initiation Protocol.
**SMT** - Satisfiability Modulo Theories.
**SNMP** - Simple Network Management Protocol.
**SNTS** - Sensor Networks Troubleshooting Suite.
**SO** - Security Orchestrator.
**SVN** - Subversion (Control Version System).
**TLS** - Transport Layer Security.
**TLSP** - Tenant-Level Security Policy.
**TN** - True Negative.
**TOSCA** - Topology and Orchestration Specification for Cloud Applications.
**VM** - Virtual Machine.
**VMM** - Virtual Machine Monitor.
**VNF** - Virtual Network Function.
**WAN** - Wide Area Network.

**WSN** - Wireless Sensor Network.
**XACML** - eXtensible Access Control Markup Language.
**XCCDF** - eXtensible Configuration Checklist Description Format.
**XML** - eXtensible Markup Language.
**YOUNG** - YOung Unikernel Generator.

# Abstract

The Internet has become a great integration platform capable of efficiently interconnecting billions of entities, from simple sensors to large data centers. This platform provides access to multiple hardware and virtualized resources (servers, networking, storage, applications, connected objects) ranging from cloud computing to Internet-of-Things infrastructures. From these resources that may be hosted and distributed amongst different providers and tenants, the building and operation of complex and value-added networked systems is enabled. These systems are however exposed to a large variety of security attacks, that are also gaining in sophistication and coordination. In that context, the objective of my research work is to support security management for the cyberspace, with the elaboration of new monitoring and configuration solutions for these systems. A first axis of this work has focused on the investigation of smart monitoring methods capable to cope with low-resource networks. In particular, we have proposed a lightweight monitoring architecture for detecting security attacks in low-power and lossy networks, by exploiting different features provided by a routing protocol specifically developed for them. A second axis has concerned the assessment and remediation of vulnerabilities that may occur when changes are operated on system configurations. Using standardized vulnerability descriptions, we have designed and implemented dedicated strategies for improving the coverage and efficiency of vulnerability assessment activities based on versioning and probabilistic techniques, and for preventing the occurrence of new configuration vulnerabilities during remediation operations. A third axis has been dedicated to the automated configuration of virtualized resources to support security management. In particular, we have introduced a software-defined security approach for configuring cloud infrastructures, and have analyzed to what extent programmability facilities can contribute to their protection at the earliest stage, through the dynamic generation of specialized system images that are characterized by low attack surfaces. Complementarily, we have worked on building and verification techniques for supporting the orchestration of security chains, that are composed of virtualized network functions, such as firewalls or intrusion detection systems. Finally, several research perspectives on security automation are pointed out with respect to ensemble methods, composite services and verified artificial intelligence.



**Keywords:** Security Management, Cyberspace, Monitoring, Configuration.

## Résumé

L'Internet est devenu une formidable plateforme d'intégration capable d'interconnecter efficacement des milliards d'entités, de simples capteurs à de grands centres de données. Cette plateforme fournit un accès à de multiples ressources physiques ou virtuelles, allant des infrastructures cloud à l'internet des objets. Il est possible de construire et d'opérer des systèmes complexes et à valeur ajoutée à partir de ces ressources, qui peuvent être déployées auprès de différents fournisseurs. Ces systèmes sont cependant exposés à une grande variété d'attaques qui sont de plus en plus sophistiquées. Dans ce contexte, l'objectif de mes travaux de recherche porte sur une meilleure gestion de la sécurité pour le cyberespace, avec l'élaboration de nouvelles solutions de monitorage et de configuration pour ces systèmes. Un premier axe de ce travail s'est focalisé sur l'investigation de méthodes de monitorage capables de répondre aux exigences de réseaux à faibles ressources. En particulier, nous avons proposé une architecture de surveillance adaptée à la détection d'attaques dans les réseaux à faible puissance et à fort taux de perte, en exploitant différentes fonctionnalités fournies par un protocole de routage spécifiquement développé pour ceux-ci. Un second axe a ensuite concerné la détection et le traitement des vulnérabilités pouvant survenir lorsque des changements sont opérés sur la configuration de tels systèmes. En s'appuyant sur des bases de descriptions de vulnérabilités, nous avons conçu et mis en œuvre différentes stratégies permettant d'améliorer la couverture et l'efficacité des activités de détection des vulnérabilités, et de prévenir l'occurrence de nouvelles vulnérabilités lors des activités de traitement. Un troisième axe fut consacré à la configuration automatique de ressources virtuelles pour la gestion de la sécurité. En particulier, nous avons introduit une approche de programmabilité de la sécurité pour les infrastructures cloud, et avons analysé dans quelle mesure celle-ci contribue à une protection au plus tôt des ressources, à travers la génération dynamique d'images systèmes spécialisées ayant une faible surface d'attaques. De façon complémentaire, nous avons travaillé sur des techniques de construction automatique et de vérification de chaînes de sécurité, qui sont composées de fonctions réseaux virtuelles telles que pare-feux ou systèmes de détection d'intrusion. Enfin, plusieurs perspectives de recherche relatives à la sécurité autonome sont mises en évidence concernant l'usage de méthodes ensemblistes, la composition de services, et la vérification de techniques d'intelligence artificielle.



**Mots-clés:** Gestion de la sécurité, Cyberespace, Monitorage, Configuration.