Review

Cyber-Physical Systems Resilience: State of the Art, Research Issues and Future Trends

Jose Moura 1* and David Hutchison 2

1 School of Technology and Architecture, ISCTE-Instituto Universitário de Lisboa, 1649-026 Lisbon, Portugal, and Instituto de Telecomunicações, 1649-026 Lisbon, Portugal (e-mail: jose.moura@iscte-iul.pt)
2 School of Computing and Communications, InfoLab21, Lancaster University, Lancaster LA1 4WA, U.K. (e-mail: d.hutchison@lancaster.ac.uk)
* Correspondence: jose.moura@iscte-iul.pt

Received: date; Accepted: date; Published: date

Abstract: Ideally, full integration is needed between the Internet and Cyber-Physical Systems (CPSs). These systems should fulfil time-sensitive functions with variable levels of integration with their environment, incorporating data storage, computation, communications, sensing, and control. There are, however, significant problems emerging from the convergence between CPS and Internet of Things (IoT) areas. The high heterogeneity, complexity, and dynamics of these resource-constrained systems bring new challenges to their robust and reliable operation, which implies the need for novel resilience management strategies. This paper surveys the state of the art in the relevant fields and, discusses the research issues and future trends that emerge. Thus, we hope to provide new insights into the management of resilient CPSs, formed by IoT devices, modelled by Game Theory, and flexibly programmed using the latest software and virtualization platforms.

Keywords: Cyber-Physical Systems / CPS; Internet of Things / IoT; game theory; software-defined networks; challenges and cyber-attacks; algorithms; resilience; resilient systems; self-awareness; robustness

1. Introduction

The digitization and connection of almost everything are making an enormous impact on every aspect of our daily lives. The Internet of Things (IoT) [1] is a very important underpinning technology for Cyber-Physical Systems (CPS) [2] that offer, at the network edge, embedded intelligence and smart actuation/control of peripheral actuators. Prominent examples of CPS include the intelligent grid, smart buildings, and next generation mobile devices. Because of the increasing importance of CPS in our society, these systems require strong protection against threats that can undermine their normal operation and consequently the quality of our lives [3][4]. These threats can be classified in two classes, viz. unplanned or planned. The unplanned system threats are typically due to natural disasters (e.g. earthquake) or non-intentional human errors. Planned system threats are typically associated with cyber-attacks. Whatever the origin of the threat, it is vitally important to deploy appropriate resilience strategies and mechanisms. A list of relevant system weaknesses against threats is available in [5]. This list includes low-level vulnerabilities in physical networking equipment using field programmable gate array (FPGA) devices, which may allow, as an example, an attacker to install and boot a malicious software image in a huge diversity of networking devices, such as routers, switches and firewalls [6].

The Oxford English dictionary defines resilience as “the capacity to recover quickly from difficulties”. This suggests that a resilient system in the face of some either known or unknown threat should contain features to deal adequately with the system performance degradation provoked by that threat; typically, these features will be to detect, absorb, recover and adapt [7]. After successfully detecting a threat, the system should have the ‘absorb’ feature to diminish the negative impact
induced by that threat. Following the threat occurrence, the system should recover its operation as quickly as possible to an acceptable level. Then, after the system threat has finished, the system should adapt its management policies and diminish even more than before the negative impact on the system in any future repetition of the threat. This set of management features [7] (i.e. detect, absorb, recover, and adapt) is used in our paper to assess the resilience of CPSs. Nevertheless, there are other alternatives, such as in [4] where the authors propose two types of management features; the first type is formed by short-term or reactive management activities, viz. defend, detect, remediate and recover. The second type is formed by long-term or proactive management activities, viz. diagnose and refine.

The high levels of heterogeneity, complexity, and dynamics of resource-constrained CPSs bring new challenges to their reliable operation, which imply the need for novel management strategies, using distinct technologies. In this paper, we explore Game theory (GT); this is a fundamental tool for modeling the threats and their interactions with these systems, enabling the design of automated protection mechanisms [8]. GT has been used to study mechanisms in the area of Advanced Persistent Threats (APTs) [9] as well as for enabling both safety and security in Cyber-Physical and IoT Systems [10]. The emerging CPS features [7] of detect, absorb, recover, and adapt are like the diverse stages of a theoretical dynamic game model that run in a sequential way, mediating the interactions among opponent players. Examples of opponent players are cyber-attackers versus cyber defenders (electronically), or nature versus self-healing mechanisms.

The fundamental steps to realize a resilient CPS are quantification, assessment and analysis, and enhancement of cyber resilience [11]. During the first step, the quantification phase should give a clear specification of the measurement metrics to evaluate the resilience level of a system. The second step assembles qualitative or quantitative inputs for a broad range of metrics that were identified in the previous step. On one hand, qualitative metrics are normally based on human review and judgment of systems, networks, or processes. On the other hand, quantitative metrics are obtained from modeling or simulating systems, networks, or processes. The system resilience is then assessed. If a system’s resilience is judged as inadequate, the next step is enhancing it. This is the goal of the third and last step by using either an appropriate initial design or proactive mitigation measures, or defensive (re)actions during a serious menace [11].

This paper studies the resilience of CPSs through the lens of real-world use cases, enhancing previous work [1][10][12][13][14][15][16], mainly focused in sub-topics of resilience such as privacy and security. Our contribution investigates effective management solutions to the novel challenges of CPSs, which are converging into a common platform, often labelled as Edge (or Fog) Computing. This set of technologies is formed by GT, Software-Defined Networking (SDN), Network Function Virtualization (NFV) and Machine Learning (ML). We discuss the available literature, highlight the advantages that the surveyed research areas could bring to CPSs for enhancing their resilience and robustness, and outline some future research areas. As a primary case study, we investigate the outcome of a repeated and dynamic game, analyzing how a CPS system can detect, absorb and recover from, and adapt to, threats. These goals should be achieved using available system resources for limiting the system deployment and maintenance costs. Despite these considerable constraints, CPS should fulfill time-sensitive functions with variable levels of integration with the environment, integrating distributed data storage, parallel computation, robust communications, ubiquitous sensing, and efficient control with devices and humans.

The paper has the following structure. Section 2 discusses related work. Section 3 describes some background to the remaining part of paper, namely pertinent scenarios in CPSs. Section 4 discusses the relevant factors to be aware of when the goal is to enhance the resilience of CPSs. Section 5 presents a basic case study. Section 6 outlines open research directions. Section 7 concludes the paper. The paper logical organization is visualized in Figure 1 with further detail on each paper sub-section.
2. Related Surveys

This section compares known related literature surveys at the time of writing. Table I summarizes related work in both relevant and similar research areas with resilient networked systems. As we can conclude, a vast amount of work, e.g. [17][9][10][14][18][15][16][19][20][21] has been done on studying and classifying published contributions to security aspects, but they lack a more holistic and complete revision than the security perspective by reviewing some other important areas, such as software-defined solutions for resilient CPSs operating in diverse use cases. We justify the classification of some surveys as constrained literature overviews, because (for example) some [19] present techniques for detection of DDoS attacks, while others [20] study machine learning solutions for intrusion detection. Also, [21] is focused on security control and attack detection but only for industrial CPSs. Further relevant and associated work [22] is focused on theoretical management models for networked systems, considering the need of the diverse players of the network to cooperate among themselves to enforce the optimum usage of the available network resources. Complementing this work, [23] argues that the management of networked systems should also have self-adaptability characteristics in the presence of serious system threats. In this way, the system structure as well as its operation can become more resilient against serious and persistent menaces against their normal operation. Aligned with this set of system self-capabilities, there are a set of work proposing machine learning techniques [20][24][25]. In a more detail way, [25] investigates how machine learning algorithms can be used in applications involving NFV and SDN. NFV virtualizes network functions and decouples these from the hardware. The main goal of NFV-based solutions is to automate network configuration as well as to provide system services in an elastic way. On the other hand, SDN can be very useful in Edge Computing to program, with some abstraction of the physical devices, the way the system is expected to operate. As an example, SDN can be used to divert computational-intensive tasks from resource-constrained mobile devices to more powerful servers located at the network edge. Hence, the battery autonomy of mobile devices is increased, and the results of the computational-intensive tasks are more quickly obtained. In addition, there are several important contributions also aligned with our current proposal but applied to a more specific use case, namely, network resource allocation for ultra-dense networking [26], mobile network planning with small cells [27], optimization of hybrid SDN networks [28], and management of faults in SDN-based [29] or vehicular networks with autonomous cars [30].

![Logical Roadmap Behind the Paper](image-url)
In addition, we have found valid contributions in sensing management for smart city monitoring [31], mobility of things or devices using several standards of low-power wide area networks [32], studying novel business models for resource management in 5G wireless networks [33], and analyzing datasets to predict and prevent security incidents [34].

From all the surveys we are aware of at the time of writing, we clearly identify [35], which broadly reviews the literature in terms of contributions to resilience applied to CPSs. The authors argue according to their experience that the most challenging issue for designing a resilient CPS is to deploy a real-time, closed-loop, networked control system completely immune against serious threats. These threats are caused by natural noise, which induces in the system packet loss and bit errors, as well as some internal or external cyber-attacks. They also discuss two medical case studies. The first is about the resilient integration of virtual reality and a robot device for restoring the corporal coordination and flexibility of persons with disabilities. The second study is about the design of a robust implantable medical device for physical-to-cyber health sensing and cyber-to-physical organ control. This survey published in 2016, it is naturally outdated, missing last relevant and related literature work. Our paper tries to overcome these shortcomings, and looks anew at the literature on reliable and flexible software-defined management solutions for resilient CPSs.

We argue that an effective way to fulfil the challenging requisites imposed by the successful management of CPSs is to orchestrate diverse technologies, such as GT, SDN, NFV, or ML. The next section offers a background discussion on these technologies, as well as on CPS scenarios and resilience requirements in systems formed by either physical or virtualized resources.

| Year | Survey | Area Covered | Covered Scope and limitations |
|------|--------|--------------|------------------------------|
| 2019 | [17]   | Security     | Reviews dependability and security for detection, diagnosis, and mitigation; but does not cover enabling technologies, nor applications |
| 2019 | [9]    | Security     | Focused on persistent security attacks against private and corporate networked systems. Lacks a more holistic discussion, focusing on networked system resilience. |
| 2018 | [10]   | Security     | Discusses work related to safety/security threat models for CPSs and IoT systems. Lacks a more holistic discussion than security by focusing on the resilience of networked systems. |
| 2017 | [14]   | Security     | Reviews the existing game-theoretic approaches for work limited to cyber security and privacy issues. They lack a more complete discussion than security by reviewing some other important areas, such as scenarios and software-defined solutions for resilient CPSs. |
| 2019 | [18]   | Security     | Discusses contributions constrained to security features introduced by NFV and SDN to monitor, protect, and react to IoT security threats. It is missing a more holistic discussion that includes security. |
| 2018 | [15]   | Security     | Reviews literature limited to privacy-preserving of content disseminated by vehicular networks. It is missing a more holistic discussion including data privacy. |
| Year | Paper ID | Area                  | Description                                                                                                                                                                                                 |
|------|----------|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2018 | [16]     | Security              | Discusses work constrained to security and privacy for smart city scenarios. They omit discussion about resilience aspects in other relevant scenarios: e.g. power grids, next generation mobile networks, and healthcare systems. |
| 2018 | [26]     | Resource Allocation   | Reviews the literature in terms of resource allocation but constrained to Ultra-Dense Networking. They did not discuss except for resource allocation other relevant system management mechanisms such as computation offloading, energy efficiency, and resilience in diverse use cases. |
| 2019 | [27]     | Mobile network planning with small cells | Investigates work restricted to traffic modelling and deployment issues for 5G/IoT scenarios, but did not discuss other relevant scenarios where the resilience management is notably important. |
| 2019 | [22]     | GT applied to multi-access edge computing | Surveys work restricted to theoretical model games for edge computing use cases. The paper lacks a discussion of software-defined solutions for resilient CPSs. |
| 2019 | [19]     | Security              | Surveys work constrained to DDoS attacks at the application layer. Lacks investigation of security at network layers.                                                                                      |
| 2019 | [20]     | Machine Learning Techniques | Surveys work restricted to Intrusion Detection, but does not investigate resilience and security.                                                                                                         |
| 2018 | [21]     | Security control and attack detection | The survey is restricted to industrial CPSs.                                                                                                                                                               |
| 2019 | [23]     | Resilience on self-organized network systems | Discusses networked systems in the intersecting areas of autonomic formation, self-organization, and resilience. Lacks coverage of theoretical model games to enforce resilience in networked systems. |
| 2016 | [35]     | CPS Resilience        | Surveys the literature in terms of contributions within the aspect of resilience. This survey is somewhat outdated, missing recent relevant and related literature work.                                          |
| 2018 | [21]     | Security              | The discussion is restricted to the security of CPSs.                                                                                                                                                      |
| 2019 | [24]     | Machine Learning      | This discussion is restricted to machine learning techniques applied to micro-grids for smart cities.                                                                                                    |
| 2019 | [25]     | Machine Learning      | Investigates machine learning techniques applied to SDN-based solutions. They lack a literature analysis in theoretical model games as well as software-defined solutions empowered by learning algorithms. |

| 2019 | 28 | Optimization of Hybrid SDN networks | Discusses various optimization strategies on networks joining traditional solutions with SDN-based ones. The discussion is driven by the perspectives of traffic engineering, resource saving, network control capacity, and network security. |
|------|----|------------------------------------|-------------------------------------------------------------------------------------------------|
| 2019 | 29 | Management of faults in SDN networks | Presents a systematic classification of faults in SDN networks and analyze their symptoms and causes. They discuss solutions for system monitoring, fault diagnosis, fault recovery and repair, and fault tolerance. |
| 2019 | 30 | Autonomous Cars | Reviews aspects of safety and reliability, computational resources, accuracy of object detection, sensors management, decision-making, actuation, security, and privacy. |
| 2019 | 31 | Smart City Infrastructure | Focuses on the sensing for smart city monitoring in terms of node deployment in the configuration phase and sensing management in the running phase, for smart city monitoring. |
| 2019 | 32 | Internet of Mobile Things | Addresses the mobility of the things or devices in several standards of low-power wide area networks. |
| 2018 | 33 | Business models | Studies Pricing Models for Resource Management in 5G Wireless Networks. |
| 2019 | 34 | Cybersecurity Incident Prediction | Surveys work that analyzed datasets to predict incidents induced by cyber-attacks. |

3. Background on Resilient Cyber-Physical Systems

The paper’s content is based on our outline of a resilient Cyber-Physical and IoT system that is shown in Figure 2. This shows the two major goals of the paper. The first goal is to investigate how GT can model a CPS with IoT applied to edge computing use cases. The second goal is to study how SDN-based solutions can be used to empower a Cyber-Physical and IoT System with extra capabilities, such as programming of management policies that enforce the system resilience against diverse threats, including system node failures. For that, our current view is about a software-defined system that combines diverse technologies. In this way, there is a viable solution to support dynamic cross-layer resilience decision making for CPSs. In the sub-sections below, the literature within the major areas shown in Figure 2 are revised, as follows: i) scenarios of Cyber-Physical Systems; ii) resilience requirements for Cyber-Physical Systems; iii) analysis of Cyber-Physical Systems; iv) software-defined Cyber-Physical Systems.

We initially define what means a system being resilient. Then, we discuss some important technologies that are very useful to sustain the resilient operation of Cyber-Physical Systems in diverse use cases. These use cases are related with power grids, smart buildings, next-generation mobile communication systems, healthcare systems, and precision farming systems.
3.1. Resilience Definition and Novel Management Challenges

The NIST\(^1\) definition of a Cyber-Physical System (CPS) is a commonly accepted one. According to that definition, CPSs are engineering-based systems offering a functionality strongly dependent on the interaction among computational and physical processes. This integration enables the deployment of emerging systems that our society can use in different ways. The literature also offers several definitions of resilience. The current paper adopts the definition of resilience as the system’s capability to maintain an acceptable level of service to its users despite the eventual occurrence of

\(^1\) NIST stands for National Institute of Standards and Technology, available in [https://www.nist.gov/](https://www.nist.gov/) (verified in 21/02/2019)
various faults and challenges to the system’s normal operation, where some issues could be completely new to the system architect [4].

CPSs show completely novel capabilities, including pervasiveness and intelligence. In parallel with the new benefits offered by CPSs, these systems also become more attractive to cyber-attackers because if the attacks are successful then important sectors of society could suffer significant losses. Consequently, the research community has dedicated recent notable efforts to address the novel threats against CPSs [21] by enhancing the management of resilience [36][37]. In addition, the relevant interplay between resilience and self-organization for the design of critical networked systems has been also investigated [23]. A potential outcome from all these efforts is to obtain a robust CPS [35].

The literature have a few contributions related with CPSs that immunize these systems against either already identified or potential threats in distinct usage scenarios, namely: power grid [12][38][39][40], Supervisory Control and Data Acquisition (SCADA) [13], smart buildings [41][24], vehicular [42][43][44] and mobile networks [45]. In the next sub-section, we detail the literature revision of CPS using a taxonomy based on their use cases.

3.2. Scenarios of Cyber-Physical Systems

The current sub-section discusses some relevant use cases in CPSs enhanced with the ever-developing model of the Internet of Things (IoT). It provides a concise and precise description of these scenarios, their basic requirements, and the novel challenges that these use cases present to the research and standardization communities. The scenarios discussed below involve power grids [12][46][47][48][49][50], smart buildings [51][52][53], next-generation mobile communication systems [54][55][56][57][58][59][60][61][62], healthcare systems [63][64][65][66][67], and precision farming systems [68][69][70][71].

Intelligent Power Grid Systems

Power systems are changing from centralized large facilities to fully distributed micro-size facilities, such as domestic electrical appliances composed by photovoltaic panels and DC/AC power inverters. At the same time, the full operation of the latest generation of microgrids depends massively on computerized systems. Consequently, that situation makes these systems increasingly exposed to cyber-attacks [12][46], which could create huge problems in our everyday lives.

Smart grids present great challenges to their efficient management due to the unpredictability of demand load and the reliability of data communications. The unpredictability of demand load is caused by many factors, not least to domestic electrical energy variation and most recently to the charging of electrical vehicles [72]. In addition, the reliability of data communications in smart grids could be adversely affected by perturbations that occur on some links, mainly on wireless links [73]. These perturbations can be induced by either cyber-attacks [74][75] or impairments on the communications medium [76][77][78]. The authors of [76] study the outage probability of a wireless link, considering the multipath fading, shadowing, and random path loss given the location distribution of smart meters. In [77], they prioritize the data transfer within a smart grid using a position-based quality-of-service (QoS)-aware routing protocol. Further, they propose a load-balancing mechanism to mitigate network congestion induced by many critical event messages. As an example, these event messages can be related to the high number of damages on the electrical physical infrastructure a big storm can cause.

Paper [79] proposes an incentive-based demand response algorithm for smart grids, which uses a deep neural network to overcome the future system uncertainties by finding out the initial unknown both prices and energy demands. In addition, the same algorithm also uses reinforcement learning to obtain the optimal incentive rates, considering the profits of both service provider and customers.

In a smart grid, several devices use wireless communications to transfer data. Most of these use industrial, scientific, and medical (ISM) radio band for channel communication. Since the ISM band is license-free, attackers can easily have access to that frequency band, trying to initiate a cyber-attack. A potential attack is the jamming attack that can disconnect important system devices such as smart meters, collectors of meter data, remotely controlled distribution automation devices, and GPS
antennas of phasor measurement units. Therefore, more work is needed to create resilient wireless communications among the diverse components of a smart grid.

The authors of [48] are concerned with the resilience of network control systems under communication delay attacks. These attacks force two wrong operational situations on the controlled system (e.g. power plant) due to either missing data or delayed data from the power plant status. In addition, this attack type can be made over encrypted messages by jamming the wireless communications used by the system control loop. So, the authors of [48] propose a solution to countermeasure a time delay attack. To implement that protection, their solution has a system state estimator. Then, the state predicted can be compared with the reported state of the power plant. In the case the two states show significant changes, then the controller uses the predicted state until the reported state is similar to the predicted one, when the controller uses again the reported state.

Further aspects that need more work in smart grids are anomaly detection systems and intrusion detection systems, particularly from insider attackers [12]. In addition, more investigation on coordinated cyber-attacks needs to be carried out. During a cyber-attack bogus data that is enforced by the attackers can affect the normal operation of a power plant. So, it is necessary to detect and remove as quickly as possible from the power grid supervision system all the bogus power plant status inserted by false data injection attacks [47]. The authors of [49] provide a detailed discussion of improvement strategies for the resilience of power systems. These strategies are classified based on two distinct perspectives. The first perspective analyzes the resilience of power systems considering the time-dimension. The second perspective enforces the robust operation of power systems, choosing adequate control actions. Additional discussion on these topics is found in [49]. A comprehensive review of false data injection attacks against power systems is available in [50].

Smart Building Systems

Considering the substantial price reduction in sensor nodes, these now can be used in novel applications, as is the case, for example, in modern smart buildings. The authors of [51][52] argue that IoT can be a catalyst for a full integration of building intelligent mechanisms with the system grids that connect each building. Hence, the people living within those buildings could benefit from greater comfort without paying more to the diverse utilities, e.g. electricity, gas, water, or even healthcare [52]. To achieve this, and particularly for the electrical scenario, all the intelligent control mechanisms existing within a building should operate in a completely coordinated way with the smart grid supplying that building. To make that coordination possible, open networking protocols should be used [51]. By open, we mean standard solutions that enable universal exchange of data over heterogeneous technological systems to fulfil a set of common goals.

The authors of [53] propose a population based algorithm for deciding about the places where sensors should be located to monitor the various pipes within a large building. Their results show that the proposed algorithm demonstrates good performance in relation to other algorithms inspired in nature. The results obtained also suggest that the system lifetime can be improved.

In [80] the authors propose a smart solution for buildings that learns and predicts optimum individual user-preferences towards the efficient energy control of personalized light. They argue that their proposal can achieve energy savings up to 72% when compared to the conventional lighting systems. Aligned with previous work, [81] proposes a flexible approach supported by deep learning that offers automatic adjustments to system/environment variations. The same approach also has an incentive mechanism based on gamification for improving the interaction between the building inhabitants and the building system that supervises and controls the infrastructure.

In [82] the authors propose a platform-based methodology for smart building design. The last platform reuses hardware and software on shared infrastructures, enables the fast prototyping of applications, and allows exploration of the design space to optimize the design performance. The paper illustrates the usage of the proposed platform via a case study on the design of on-demand heating, ventilation, and air conditioning systems.

More work is necessary in the area of smart building systems. In fact, the living comfort characteristics (temperature, humidity, air quality), energy (electrical or gas) efficiency, and building safety require the existence within each building of a software-defined management service
responsible to satisfy the new challenges imposed by modern buildings with a myriad of embedded sensors and actuators. This management service should be responsible for local control loops, send automatic messages to external public entities (e.g. in case of gas leakage or fire alarm), and recording the occurred building events for future analysis. After analyzing the data extracted from the building events, the management service, in a proactive way, could recommend some maintenance tasks in the building to improve the living comfort, reduce the energy consumption, increase the safety, or reduce the false-negative statistics of reporting failures.

Next Generation Mobile Systems

Considering the rapid evolution of mobile cellular technologies, including smart personal wireless devices, a set of new mobile applications is appearing [54]. These novel applications are mainly focused on fulfilling the requirements of users. For ensuring some positive experiences to end-users, service providers are moving their focus from Quality of Service (QoS) to Quality of Experience (QoE) in the way they aim to efficiently manage the available resources from their network infrastructures. Obviously, QoS is related with technical metrics such as packet loss, loss rate, delay, and jitter, whereas QoE must be what the user expects and gets. For next generation mobile systems (e.g. 5G), the authors of [54] comprehensively discuss the literature in terms of enhancing the user experience by means of supporting advances in the methods that assess the video quality and reflecting on how the QoE reported from users should be conveniently managed in upcoming usage scenarios. For further enhancements in QoE, the management of both network resources and offered services needs to be evolved by adopting solutions based on self-organization optimization. In this way, it is possible to efficiently support cognitive operations in cellular communications [55]. In addition, SDN and cloud technologies can be useful to allocate the required services to the best possible available system resources, enabling a more dense network management with smaller cells than before, and a more holistic management considering the cross-layer aspect of SDN operation [56]. The authors of [57] propose a potential game for sharing spectrum in 5G networks in a decentralized way and based on user QoE. The authors of [58] discuss the major challenges and future developments on Cyber-Physical Systems in vehicular networks, healthcare systems, and mobile education. In [59] are comprehensively investigated diverse architectures based on the integration of 5G cellular networks with the SDN model. The work in [60] develops a mobile solution that sends to an user a notification message, recommending that user to move from a location where the data rate is not enough for delay-sensitive applications to an alternative nearby location with much better data rate. In [61] a solution is proposed based on a local cluster of voluntary crowd-sensing devices that perform the parallel processing of raw sensor data on those edge mobile devices. The authors of [62] consider the scenario of a vehicular ad hoc network formed by vehicles on the road with some common interests which can form a platoon-based driving pattern. They comprehensively discuss the novel management challenges induced by the platoon-based driving in the vehicular network.

Further work is needed to manage the continuous convergence between the network operators and the cloud providers forming a common meet-in-the-middle place currently designated as edge (fog) computing. This convergence scenario is a win-win situation for all the players involved, including the end-users, as we now explain. The network operators need more services, processing, and storage resources from the cloud providers, including their experience in satisfying high volumes of data processing with a minimum set of computing/networking resources by orchestrating all these (physical/virtualized) resources in an elastic way. In the opposite direction, the cloud providers are interested in supplying the end-users with customized applications and with the highest possible quality. To satisfy these requisites, the proactive data caching at the network edge based on historical data popularity can be very useful to diminish the data access latency/jitter. The end-users aim the ubiquitous and reliable access to all the services they prefer to help them in every daily task. If the end-users are served in an adequate way then they will be satisfied, rewarding both network operators and service providers. In this context, novel business models using GT are needed.
Healthcare Systems

A large and rapidly growing percentage of people in most countries is elderly. There is huge pressure to devote enough medical and human resources to ensure a good quality of life. However, the commitment of enough resources is proving impossible by reason of both human and financial constraints. A popular approach to alleviate these pressures is to explore the adoption of IoT in medical service systems, enabling innovative solutions in healthcare [63]. There are important potential advantages of deploying IoT-based healthcare systems, namely: i) extract useful information for raw-data; ii) automation in terms of either improve patient health or promote preventive care; iii) enhance patient satisfaction and engagement with their treatment procedures; and iv) enhance the management of population health in a large scale with a suitable amount of resources. However, obstacles for adopting IoT in healthcare systems include issues with security and performance. As an example, for deploying IoT-based healthcare systems with excellent performance, there is a strong need to support real-time requirements. The authors of [64] propose a fog computing implementation to decrease latency substantially. This occurs because the data processing is made as close to the end-consumers as possible by leveraging virtualized containers on the network edge such as mobile base stations, gateways, network switches and routers. Additional deployment challenges of IoT-based healthcare systems are discussed in [83]. In addition, based on a thoroughly revision of the literature, [65] discusses the major advances healthcare systems embedding IoT-based smart devices. They also address the intelligent trend and future research directions in the field of IoT-based healthcare solutions.

The authors of [66] proposed a smart health system which includes a unified data collection layer for the integration of public medical resources and personal health devices. In addition, the same system has a cloud-enabled and data-driven platform for multisource heterogeneous healthcare data storage and analysis. Then, the system offers access interfaces for system developers and users.

A comprehensive analysis of authentication protocols which address the trade-off between securing implantable medical devices in terms of access rights and the safety of the patient in case of emergency is available in [67]. Moreover, they contrast the authentication protocols with respect to the cryptographic and security mechanisms implemented on the implant.

Healthcare applications can benefit from the deployment of the fog computing paradigm [84]. This could be aided by appropriate design innovations in the way the networked systems interoperate [85]. In addition, healthcare applications can offer low latency, distributed processing, context awareness, better scalability, fault tolerance, better security and privacy [64]. Cloud-based IoT systems [86], or fog-based [84] to reduce the access delay, seem to be promising solutions in healthcare due to the huge available capacity in data storage and data processing; the offloading of computationally intensive data analysis tasks from body sensor devices to fog servers, which could be containers, is feasible. In this way, the autonomy of battery-operated body sensors is increased, lessening the burden on patients as they will not so often need to recharge their body sensors. A taxonomy of CPSs for healthcare is available in [87]. They identify as open research challenges the issues related with security and privacy, autonomic decisions for loop control, and event prediction.

Precision Farming Systems

IoT-based solutions seem promising ways to modernize the vital area of agriculture and satisfy the increasing demand for food in our planet [71]. As an example, [68] proposes an IoT-based proposal for urban agronomy. The authors of [69] and [70] offer literature revision about IoT-based solutions to enhance the abundance and quality of crops or even improve the raising of animals for food and other products (i.e. agro-industrial cases). Nevertheless, all these enhancements should be made while taking special account of natural hazard conditions (e.g. frosty weather condition) as well as the eventual negative environmental impact that could arise from increasing the level of farming production, such as drought or pollution derived from fertilizers [70]. In addition, the use of IoT in agriculture will bring several positive outcomes such as, strong automation along the diverse steps from sowing to cropping, better adaptation to climate change, enhancing the precision of irrigation systems, increasing the production of energy from renewable sources, and enabling a more sustainable agriculture. Further information on these topics is provided in [71].
Further research work is needed in novel projects behind the smart city paradigm. In this context, software-defined cyber-physical systems eventually augmented with machine learning techniques can be very useful to efficiently automate the urban agriculture [68], making possible to produce new forms of food which should be compatible with the environment of the smart city.

3.3. Analysis of Cyber-Physical Systems

The analysis of a Cyber-Physical System is made using a theoretical model. A very popular tool to perform system analysis is Game theory (GT). It is a fundamental mechanism to study the various challenges and faults that could affect the system normal operation. GT can also enable the design of automated mechanisms to protect the major functionalities of the system [8]. We have revised the literature for theoretical models in Cyber-Physical Systems distributed in the next aspects: system resource allocation [22][26][78][88][89][90], system computation offloading [91][92][93], system energy efficiency [81][94][95], and system security [8][14][96][97][98][99][100].

A brief background in GT (non-cooperative, cooperative, and evolutionary games) applied to edge computing is available in [22]. It includes a comprehensive review of game theoretical contributions to wireless communication networks. They also discuss diverse issues that can be addressed by theoretical game models to optimize the network performance in some emerging multi-access edge computing scenarios. The authors of [26] offered an alternative literature revision in coalitional games among other alternative techniques, such as large-scale convex optimization, mean field game, stochastic geometry, and stochastic optimization. All these techniques can enable an optimized system resource allocation. In particular, mean field games can be applied to analyze scenarios with a large number of resources, devices and user types. The authors of [78] proposes a non-cooperative game theoretic model for the management of a smart grid’s demand considering the packet error rate in the game formulation. In [88] the authors describe a model for determining optimal resource allocation by combining GT with a multi-attribute utility model. It allows optimal allocation of the defender’s budget across potential identified system targets and, considering different types of countermeasures. The authors of [89] propose a hierarchical model between mobile operators and users. They offer a management solution for effective bandwidth slicing in software-defined 5G systems. Another recent contribution [90] investigates the workflow of scheduling resources on hybrid cloud environments. A hybrid cloud aggregates the resources of remote clouds with the ones of local clouds localized at the network edge. The authors propose a Vickrey–Clarke–Groves (VCG) auction to allocate optimal resources for multi-provider mobile applications running in hybrid clouds. They enhanced the reverse auction mechanism with a two-phase scheduling algorithm for utility grids, designated as Partial Critical Paths, which aims to minimize the application cost while satisfying the requisites of mobile users. Their model also incorporates a failure recovery mechanism to deal with uncertainties during the execution of mobile applications. Nevertheless, their simulated results needs to be validated in a real scenario with higher levels of uncertainty due to delay variation in both data processing and transmission.

Other relevant functional aspects in CPSs are data offloading [91] or computation offloading [92][93]. In [91] the authors outline a SDN-based controller enhanced with a game model based on a single leader and multiple followers for a 5G-based vehicular network. This solution aims to deal with high speed and traffic congestion within that network. It enables the vehicles to perform intelligent decisions for data offloading by using the network services of priority manager and load balancer, which route the traffic load in an efficient way even within a large network. Another contribution [92] considers a scenario of a heterogeneous cellular network. The authors propose a solution based on a two-stage auction to perform task transfer from macro cell users to small cells, which are relay network nodes for task execution. This alleviates the heavy burden of macro base stations by offloading computation from macro cell user equipment to small cell base stations or remote cloud. In [93] the authors propose a non-cooperative and distributed game among Industrial IoT devices with the assistance of Blockchain. Using Blockchain, the IoT devices could securely trade distributed resources with other untrusted peers. Their solution transfers heavy resource demanding tasks such as data processing as well as mining from IoT devices to the edge/cloud servers.
There are some literature contributions focused in either reducing the energy consumption [81] [94] or defeating jamming attacks [95]. The authors of [81] propose a social game aiming to incentivize building occupants to modify their behavior so that the overall energy consumption in their room is reduced. Aligned with this, [94] proposes a social game to guarantee energy efficiency for buildings. Interestingly, [95] uses energy harvesting as a countermeasure against a potential jamming attack. The harvested energy is extracted from the energy used by the attacker to jam the channel, and the former is consumed to increase the transmission power of benign traffic.

A significant amount of work was made to enhance the security of CPSs. The authors of [8] propose a theoretical model with three phases to defeat a Physical Intrusion in a critical infrastructure. Their focus is to countermeasure cyber-physical attacks against critical infrastructures, e.g. smart grids. In addition, [14] classifies the literature into two classes, viz. security and privacy. Then they discuss the work in terms of the GT model that each contribution has proposed to defeat the various cyber-security problems. The authors of [96] propose a hierarchical model that adjusts the strategies for enabling the selection of wireless channels in such a way that jamming attacks are avoided. The work in [97] investigates how GT can provide hints for supporting the robustness of the software that controls a CPS, such as a power grid or transportation system. They aim to eliminate the weaknesses of the software. Otherwise, these vulnerabilities could be explored by cyber-attackers, such as in the case of Stuxnet, a computer worm that was used to attack supervisory control and data acquisition (SCADA) systems. A SCADA system monitors and controls a set of industrial equipment. Another contribution [98] proposes stochastic games for protecting microgrids against cyber-attacks, and [99] applies a Bayesian game of incomplete information to implement cyber deception by means of Honeypot devices in IoT usage scenarios. The authors of [100] investigated a two-stage model game between a system protector and a system attacker, where the protector using mixed-strategies randomly chooses the network links to protect at each stage. In this way, although the attacker may be able to infer the probabilities that each link is protected, he/she is uncertain about which specific links have been protected. This uncertainty can demotivate the attacker to initiate the attack. Using their model, the protector can keep the amount of defensive resources either fully hidden from the attacker (i.e. secrecy strategy for the defender) or only a little information about the defensive resources is disclosed to the attacker for demotivating him (her) to initiate the attack (i.e. truthful disclosure). Their evaluation results suggest that secrecy strategy adopted by the protector allocates fewer resources to protect critical infrastructures against intentional attacks than the truthful disclosure strategy does. Nevertheless, they did not consider in their model the cost of implementing a mixed protection strategy.

This sub-section highlights GT’s relevance for discovering suitable management decisions to counteract the negative effects of various threats to the normal operation of a Cyber-Physical System (CPS). Table II summarizes the surveyed literature in theoretical model games applied to Cyber-Physical Systems, eventually in usage scenarios with IoT devices.

| Work | Goal | Outcome |
|------|------|---------|
| [26] | Classifies and revises the literature in coalitional games among other alternative techniques, such as large-scale convex optimization, mean field game, stochastic geometry, and stochastic optimization. | A comprehensive study on diverse techniques which are useful for resource allocation in ultra-dense networks |
| [22] | A brief background in game theory (non-cooperative, cooperative, and evolutionary games) applied to edge computing; a comprehensive review of game theoretical contributions to wireless communication networks. | Discusses diverse issues that can be addressed by theoretical game models to optimize the network performance in some emerging multi-access edge computing scenarios |
| [78] | The authors studied a non-cooperative multiagent game | Manages the demands of a group of smart grid users |
| Reference | Description |
|-----------|-------------|
| [88] | It proposes a solution for determining optimal resource allocation by combining game theory with a multi-attribute utility model. Allows optimal allocation of the defender’s budget across potential identified system targets and, considering different types of countermeasures. |
| [89] | Proposes a hierarchical model between mobile operators and users. The authors propose a management solution for effective bandwidth slicing in software-defined 5G systems. |
| [90] | Investigates a fault-tolerant method based on a reverse-auction mechanism augmented with a scheduling algorithm for hybrid cloud environments. The proposal aims to minimize the application cost while fulfilling the requirements of mobile users. It also offers a failure recovery mechanism to deal with the jitter issue associated with the processing of mobile applications and data transmission. |
| [91] | Proposes a SDN-based controller enhanced with a game model based on a single leader and multiple followers for a 5G-based vehicular network. Their proposed solution aims to deal with high speed and traffic congestion within that network. The proposed solution enables vehicles to perform intelligent decisions for data offloading by using the network services of a priority manager and load balancer, which route the traffic load in an efficient way even within a large network. |
| [92] | Considering a heterogeneous cellular network, the authors proposed a solution based on a two-stage auction scheme to perform task transfer from macro cell users to small cell base stations, which are relay network nodes for task execution. Their solution alleviates the heavy burden of macro base stations by offloading computation from macro cell user equipment to remote cloud or small cell base stations. |
| [93] | Investigates a multi-hop cooperative and distributed computation offloading algorithm that considers the data processing tasks and the mining tasks together for Blockchain-empowered industrial Internet of Things. The solution transfers heavy resource demanding tasks such as data processing as well as mining from IoT devices to the edge/cloud servers. |
| [81] | Proposes a social game aiming to incentivize building occupants to modify their behavior so that the overall energy consumption in their room is reduced. Energy efficiency in smart buildings. |
| [94] | Uses a social game with a robust utility learning. Energy efficiency at a smart building. |
| [95] | Proposes a zero-sum game between a pair of legitimate nodes and a malicious jammer. The harvested energy is extracted from the energy used by attacker to jam the channel, and the former |
| Reference | Summary |
|-----------|---------|
| [8]      | Theoretical model with three phases to defeat a Physical Intrusion in a critical infrastructure increases the transmission power of benign traffic. |
| [14]     | The authors have reviewed the literature looking for a set of diverse game models. Analyzes scenarios related with cyber-physical security, communication security, privacy. |
| [96]     | Proposes a Stackelberg (SE) model to investigate the channel selection problem in wireless communication networks when malicious jamming and co-channel interference among users are simultaneously considered. The model is enhanced by a hierarchical and learning-based channel selection algorithm that discovers the SE optimum game solution. |
| [97]     | Hybrid theoretical dynamic model of two intertwined games: a zero-sum differential game for robust control design at the physical layer and a stochastic zero-sum game between administrator and attacker for defense mechanisms design. Aims to build a resilient control system. |
| [98]     | The authors study is about stochastic games. To protect microgrids from cyber-attacks. |
| [99]     | Investigates a Bayesian game of incomplete information. The aim is to implement cyber deception by means of Honeypot devices in IoT usage scenarios. |
| [100]    | The authors investigate a two-stage model game between a system protector and a system attacker, where the protector using mixed-strategies randomly chooses the network links to protect at each time. Using their model, the protector can keep the amount of defensive resources either fully hidden from the attacker (i.e. secrecy strategy for the defender) or only a little information about the defensive resources is disclosed to the attacker for demotivating him (her) to initiate the attack (i.e. truthful disclosure). Evaluation results suggest that secrecy strategy adopted by the protector allocates fewer resources to protect critical infrastructures against intentional attacks than the truthful disclosure strategy does. Not considered in the model is implementation cost of a mixed protection strategy. |

### 3.4. Software-Defined Management of Cyber-Physical Systems

CPSs require the deployment of sensors and actuators devices at the network edge. CPSs also need to be supervised and controlled in a distributed way because of their complexity, heterogeneity, and geographical dispersion. In parallel, the Quality of Experience (QoE) of end-user (or end-machine) services should be also supported end-to-end, among diverse network domains. To address these requirements, within each network domain, a Software-Defined Networking (SDN) [101][102][103][104][105][29] system with three levels can be deployed. The top level is formed by Network Function Virtualization (NFV) services and a northbound Application Programming Interface (API). The intermediate level is composed by an SDN controller or multiple SDN controllers and Southbound API. The bottom level incorporates networking devices and agents associated with end-user terminals or end-‘things’.

The SDN controllers can support Quality of Service (QoS) only within a network domain. Although the SDN controller already has some abstraction from the hardware, that abstraction is limited, because the SDN controller typically contacts the OpenFlow switch-based devices and not the end-devices. Therefore, in these conditions it is very hard to support QoE. Considering these limitations, the communication over the network domains should be made at the top level, by means of east-west APIs used by NFVs. In this way, using the top-level, there is a higher abstraction level.
from the network infrastructure, and it enables powerful management interactions among the domains to assure a reliable QoE.

The literature offers several pieces of work that apply SDN for Moving Target Defense (MTD) network protection [106][107][108][109] in Cyber-Physical Systems. If a Cyber-Physical System is protected via MTD, then that system recurrently modifies its configuration to deter potential inspections by attackers into the ways the system is configured and operated. The authors of [110] propose to enhance SDN with NFV against penetration attacks. A penetration attack is perpetrated by a delivery method that transports a malign payload to the target system device. This malign payload can trigger on the target system device the execution of compromised code which can jeopardize the system normal operation. To circumvent the occurrence of a penetration attack on a specific system, that system should be comprehensively assessed to identify weaknesses that an attacker could exploit. This verification of potential system vulnerabilities is designated as penetration testing. In addition, the literature has a considerable number of SDN-based solutions to enhance diverse network features, such as network security [111][112][113], network communications [114][115][116], energy efficiency [117] and network lifetime [118].

The authors of [119] abstract the complexity of the physical world and present to a programmer an abstracted view of that physical world. Thus, the programmer can more easily create a system model, perform system debugging or explore the design space of various IoT applications. The abstracted view of the physical world is made by using the composition of several “accessors”, which are design patterns that serve as proxies for any ‘thing’ or service that may be either local or remote. The accessors offer a similar functionality to that offered by a web proxy, when a client, instead of downloading a web page from the remote web server, alternatively downloads it directly from the web proxy. The work in [120] reviews and discusses adaptation features for deploying scalable and autonomous communication systems by means of SDN and NFV, both enhanced by ML.

CPs are challenging to manage because of their high complexity. The complexity is due to both the internal operation of each system and the interdependence among systems. A possible way of managing these systems efficiently is to adopt some automatic control functions from natural systems that evolved to optimum operation modes with minimum energy consumption, ensuring the survivability of the species coevolving in those natural systems. Aligned with these important goals, artificial life (AL) is a research area that investigates natural systems related to chemistry and biology fields. According to the tool type used to perform the investigation in this area, there are three main types of AL: i) soft via simulation; ii) hard via actuators or sensors; iii) wet via biochemistry. We think AL techniques can be very powerful for evaluating and manage cyber-resilience in CPSs that show a highly dynamic behavior. A comprehensive coverage of AL techniques combined with self-organization system capabilities is in [121]. The evolutionary trend of AL is discussed in [122] and its relevant open issues are covered by [123].

Another area that can be easily associated with AL is artificial intelligence (AI), including deep learning [124][125][126][127][128][44], random neural networks with reinforcement learning [129], hierarchical learning models [96] or a very recent model designated as brain intelligence [130]. These contributions propose deep learning and other machine learning (ML) techniques for optimizing the model performance of high-complexity systems in a more efficient way than other legacy techniques. This efficiency gain occurs because ML techniques discover the optimum results of a system model with smaller convergence time, higher accuracy, and are better adjusted to significant system variations than other legacy techniques that optimize the same system. Another limitation of a legacy technique is it does not support learning, in opposition to what ML techniques guarantee as demonstrated in [124]. In addition, the authors of [130] suggest brain intelligence (BI) as a new technique in AI to solve some optimization problems that cannot be solved by other, weaker AI algorithms. To illustrate the benefits of using BI, they discuss its positive usage on emerging scenarios such as autonomous vehicles, health care, and industrial automation.

A comprehensive study for protecting wireless sensor networks against diverse cyber-attacks via learning algorithms is available in [55]. Another way to deploy learning is via either a hierarchical model using Stackelberg games [96] or deep-learning [128][44]. The work in [44] uses deep-learning to control the routing of data packets in vehicular Cyber-Physical Systems.
The authors of [129] investigated the routing optimization for software defined networks even in severe use cases. They aim to optimize the QoS of data flows using a cognitive routing engine. Nevertheless, the satisfaction of QoS requirements can be jeopardized when system resilience / security is missing, or even when the system has other limitations such as limited resources of energy, which is very relevant for scenarios involving IoT devices. Further work is clearly needed in this field.

The current sub-section highlights the great importance of investigating intelligent mechanisms to enhance the next generation of CPS [131] with new capabilities, e.g. self-awareness of resiliency against threats. These new system capabilities can guarantee appropriate performance levels in dynamic scenarios, offer energy harvesting, diminish the consumption of energy, detect and recover from system errors, and protect against cyber-attacks. The self-aware management we have just discussed is like the autonomic (self-organized) management of networked systems, which is investigated in [132]. Table III summarizes the surveyed literature on technologies that aim to enable self-aware programming of Cyber-Physical Systems.

| Reference | Background Technology / Open Issues | Scenario |
|-----------|-------------------------------------|----------|
| [101][102][103][104][105][29] | SDN | Diverse use cases from the literature |
| [106][107][108][109] | SDN | Moving Target Defense (MTD) network protection |
| [110] | SDN with NFV | Against penetration attack |
| [111][112][113] | SDN | Network security |
| [114][115][116] | SDN | Network communications |
| [117] | SDN | Energy efficiency |
| [118] | SDN | Network lifetime |
| [119] | Uses “accessors”: design patterns that serve as proxies for any ‘thing’ or local/remote service. | 5G IoT |
| [120] | SDN and NFV, both enhanced by ML | Adaptation features for deploying scalable and autonomous communication systems |
| [121] | Artificial Learning; self-organization system capabilities | Diverse use cases |
| [122] | Discusses the evolutionary trend of Artificial Learning | Diverse use cases |
| [123] | Covers relevant open issues | Diverse use cases |
| [124][125][126][127][128][44] | Deep-Learning | Diverse use cases |
| [96] | Hierarchical learning model | Defense against jamming attack |
| [130] | Brain intelligence | Diverse use cases |
| [55] | Learning algorithms | Protects Wireless sensor networks against cyber-attacks |
| [44] | Deep-learning | It controls the routing of data packets in vehicular Cyber-Physical Systems |
| [129] | Random neural networks with reinforcement learning | Cognitive routing in software defined networks |
| [131][132] | Machine learning; neural networks | Cyber-Physical Systems with embedded sensors and actuators managed in an autonomic way |
4. Relevant Factors for Enhancing System Resilience

System resilience depends on several key aspects [11]. These aspects are managing complexity, choosing topology, adding resources, designing for rapid recovery from flaws in a distributed system, controlling failure / threat, providing information buffering, preparing active agents, building agent capabilities, considering adversaries, and analyzing system risks.

As network complexity increases, then the network’s resilience may be reduced, because the failure of a specific network component may cause the failure of other components in a completely unexpected way. The last unpredictable network behavior may be caused by some unplanned paths within the network that were not recognized by the network administrator or designer. Such unexpected behavior is particularly relevant in multi-genre or interdependent networks. These networks have also distinct roles such as data communication, computing, data storage, or extract knowledge from raw data. Therefore, unless a high level of complexity is needed to support resilience functions directly, the network complexity level should be controlled or even reduced. Aligned with this context, the authors of [133] discuss the existence of dependencies in complex systems and how the effect of those dependencies in systems operation should be characterized and analyzed. The authors of [134] present a methodology to assess the cyber resiliency of a system controlling a specific geographical region. Their methodology can perform a system functional diagnosis identifying system parts that must be protected against cyber-threats, such as datacenters and communications networks. Otherwise, in the case when any of these system parts become exposed to a serious menace, the system performance can be seriously undermined.

The choice of the most adequate network topology used within a system can enhance the system’s resilience [135]. In addition, there are two types of network topologies, according to the used node degree distribution in each network. The first type of network topology is exponential node degree distribution; the second type is scale-free network. Some examples of the former type are wireless networks and mesh networks and, of the latter type, the World Wide Web (WWW) and power grids. Comparing the two previous types of network topologies, one can conclude: i) on the one hand, scale-free graphs are much more robust to random node errors than graphs with an exponential degree distribution; ii) while, on the other hand, scale-free graphs are much more vulnerable to cyber-attacks targeted to some high-degree nodes.

Providing crucial additional resources can improve the resilience of a system. As an example, within a power generation plant, when we increase the number of system nodes, the probability of a system failure can be reduced as well as a quicker service restoration after a system problem. In addition, the additional resources should have some distinct characteristics among them to create diversity within the system, avoiding the additional resources being affected exactly in the same way by a cyber-attack (e.g. a worm attack). So, combining new but slightly differentiated resources could create a more resilient system [136] but the system designer should be aware of the amount of system resources (e.g. energy, network nodes) being used to achieve the aimed level of system resiliency.

The correctness and performance of a fault-tolerant system depend on its underlying replication protocols. The authors of [137] propose a hybrid replication protocol that provides the high performance of memory-durable techniques while offering strong guarantees including disk-durable approaches. The key idea of their replication protocol is that the replication mode should depend upon the state the distributed system is in at a given time. In the common case, with many (or all) nodes up and running, the last solution runs in memory-durable mode, thus achieving excellent throughput and low latency; when nodes crash or become partitioned, the same solution transitions to disk-durable operation, preferably flash-based solid-state drive (SSD) disks, thus ensuring safety at a lower performance level.

The designer of a system should protect the system against cascaded failures. Such failures occur when a node failure triggers a neighbor node failure and so on. To avoid these sequential (cascading) failures, the dependencies among nodes should be planned to minimize the chance of a failure easily propagating via neighboring nodes [135]. In addition, the effect of human actions in the way a failure could propagate within a system should be also studied [138].
To offer robust and timely data access, despite scarce network resources, some resilient solutions based on network buffering are very attractive. As an example, network buffering has been used to restore link connectivity and network performance following topological changes in mobile ad hoc networks [139], as well as to diminish the data access delay in disruptive-tolerant networks [140].

To allow a system to absorb a specific failure or attack, recover from that issue, and adapt the system for mitigating that problem in the case it occurs again, it is necessary to deploy active agents, either human or artificial. When the active agents enforcing the system’s resilience are humans, they should be trained, prepared, and motivated to perform the functions of absorbing, recovering, and adapting from an eventual failure, as efficiently as possible [138]. Alternatively, artificial intelligence techniques [141] can be used to deploy artificial agents that, on one hand, carry actions to enforce the problem mitigation and the system recovery and, on the other hand, the same artificial agents maintain a required level of concealment, exercising a self-defense strategy against the adversaries, e.g. malware that aims to discover and destroy the artificial agents of a system.

Increasing the functional redundancy within the agents that manage a network can significantly enhance the resilience of network functions in case of a network perturbation, e.g. loss of some agents. Using functional redundancy, the system roles made by the lost agents are reallocated to others. Another advantage of having several agents performing the same function is increasing the system’s scalability against high levels of system demand. The authors of [142] describe a distributed decision algorithm supported by diverse SDN controllers to enhance the recovery mechanism from a problem. The authors of [143] review comprehensively the major principles and challenges for the design of smart Cyber-Physical Systems that can recover at run-time from unexpected faults or threats.

The system attacker specifically tries to defeat the absorption and recovery efforts of the resilience strategies in order to perpetrate the worst impact possible on the system’s normal operation. In this way, the system designer should protect the processes of absorption and recovery after a problem so that these processes are more robust against such malicious actions. The work in [144][145][136] proposes GT for identifying effective strategies to support system resilience against these sorts of cyber-threats.

Any resilience-enhancing measure can cause unanticipated effects, leading to an overall reduction in system resilience. Therefore, each resilience-enhancing measure should be analyzed to check if it could have a potential negative effect on the system operation. Thus, comparative analytical studies should be made with and without the measure being investigated. Ref. [146] offers a numerical resilience definition that allows system designers to assess in a more formal way how much the system resilience could change after a set of system alterations are performed. It can also compare the resilience between either distinct systems or various design options of the same system.

Table IV summarizes the relevant factors together with their goals to enhance the resilience of Cyber-Physical Systems, which were discussed in the current sub-section. Additionally, the reader can consult [17] to obtain an alternative set of attributes that a system should satisfy in order to become more resilient against diverse kinds of system faults namely errors, failures or attacks. Further, [29] classifies typical faults present in a SDN-based system.

The following section presents a case study where are given more details in how the resilience of a Cyber-Physical System can be supported and potentially enhanced.

**Table IV. Relevant Factors to Enhance the Resilience and Robustness of Cyber-Physical Systems**

| Reference | Factor | Goal |
|-----------|--------|------|
| [133][134] | Managing complexity | Network complexity level should be controlled or even reduced |
| [135] | Selecting system topology between exponential node degree distribution or scale-free graphs | Adjust the system robustness to being better prepared against either planned cyber-attacks or random errors |
Adding resources Diminishes the probability of a system failure; there is a tradeoff between increasing system robustness and the amount of system resources (e.g., energy consumption) to achieve that result

Fault-tolerance based on replication Enables a faster system recover from a threat

Controlling failure / threat Minimizes the chance of a failure easily propagates through the system

Providing network data buffering Enables faster system recover or diminishes the latency associated to data access

Incorporating specialized agents in the system Enhances the system with new capabilities, such as absorb a specific failure or attack, recover from that issue, and adapt to future repetition of that menace

Creating a resilient and flexible network of agents This enhances system robustness and scalability

Considering adversaries Supports system resilience against cyber-threats

Analyzing system risks Evaluates consequences on the system robustness after a system design change

5. Case Study of a Software-Defined Resilient Cyber-Physical System

This section discusses the design and analysis of a Cyber-Physical System (CPS) to enhance this with extra capabilities to detect, absorb and recover, and adapt against threats against the normal operation of each CPS [7]. We also discuss reactive and proactive CPS management methods.

5.1. System Design

The current sub-section discusses some design aspects that are important to consider in Cyber-Physical and IoT systems. Table V presents a four-layered hierarchical architecture that can detect, absorb and recover, and adapt to threats against CPSs [7]. The bottom layer of Table V measures, collects (typically inside a local IoT domain), and stores data obtained via either physical or virtualized devices. The detection and absorbing of threats against a CPS can be made via interface chip programming.

| Layer | Plane               | Domain  | CPS Activity [7] | Goals                                                                 | Tools                      |
|-------|---------------------|---------|------------------|----------------------------------------------------------------------|----------------------------|
| 4     | Intelligent management | Inter/Intra | Adapt          | Reasoning, orchestration, full abstraction, adjust management policies or intents | NFV, SDN, GT, ML           |
| 3     | Control             | Intra   | Adapt, recover   | Partial abstraction, topology, traffic                               | Software-Defined Controller with |
Table V presents the second layer of the architecture, where the link layer discovery and forwarding are performed. The table shows the mapping of edge devices to local device tables, queues, and OpenFlow rules, which support the functional block of the system under discussion.

The second layer of the architecture visualized in Table V aims to distribute a common pool of available resources, such as, communications, storage, processing, or services. This layer is typically responsible for a single intra-domain using devices that exchange data using a single communications protocol. The exchange of data is controlled by flow rules stored within local devices and queues to give differentiated QoS to flows. Alternatively, the QoS support can be deployed based on flow type (e.g., video streaming, interactive, best effort), enhancing the system scalability, because the same flow type can aggregate a large number of individual traffic flows.

The third layer of Table V aims to control the data plane topology and how the traffic should be transferred through the available topological links. The current layer uses SDN-based solutions to control a heterogeneous intra-domain communications infrastructure, formed by diverse area networks with distinct networking ranges, such as home, large building, or corporate enterprise.

The fourth and topmost layer of Table V is the management layer. It supports service discovery, service composition, service management, and service interfaces. First, the service discovery aims to verify if a required service is available within a specific system. Second, the service composition aggregates diverse services, coordinating among them, as if these services operate has only a single service. The service integration is useful in a scenario where to satisfy a specific system request then several system services need to be processed for that request in a pre-defined order. Third, the service management manages and determines the trust mechanisms to satisfy in a resilient way the service requests involving diverse internal services. Fourth and finally, the service interfaces are used to support interactions among all the provided services within the management layer. The last layer aggregates several approaches, such as GT, NFV, and SDN. The current layer also deploys a heterogeneous inter-domain communications infrastructure, formed by diverse area networks with distinct networking ranges, such as street, digital city, or wide area.

The topmost layer of our proposed architecture supports the functional requirements of either human users or agents. The application layer supports applications used within CPSs with embedded sensors and actuators including smart grid, smart transportation, smart cities, smart homes, smart farming, smart logistics, smart health care, smart logistics, or smart industries. These applications can be augmented appropriately by machine learning [147] or brain intelligence methods to refine management policies or intents. In addition, the diverse applications, using middleware [148][149] along with other more recent options, such as Blockchain smart contracts [150][151], should offer a secure management functionality to ensure a resilient and well-coordinated CPS operation. Using smart contracts, it is possible to deploy trustful roaming (peer to peer) services among nodes belonging to distinct network domains, avoiding the use of external communication entities to enforce security such as key distribution centers. Another advantage of using distributed smart contracts is higher robustness against network failures.

The next sub-section debates the modeling of a resilient CPS, managed by a set of services which run at the topmost layer and offer the functional characteristics of detecting, absorbing and recovering, and adapting from serious threats against a CPS’s normal operation.

5.2. Analysis of Event-triggered Reactive Management Model

This sub-section discusses the modeling of a solution to manage Cyber-Physical and IoT Systems. This solution has a four-layered design (see Table V). In addition, Figure 3 presents the major functional blocks of the system under discussion. Here, the CPS status is periodically being
monitored by the SDN controller via a Southbound API protocol such as OpenFlow (see message 1 in Figure 3). Then, the SDN controller, acting as an intermediary, exchange REST messages via Northbound API with topmost level system agents. Using these messages, the SDN controller reports status events associated to the CPS operation. These events are analyzed, classified and processed. The agent decision is derived from the processing of all the received events (see message 3 in Figure 3) and sent to the SDN controller. Finally, the SDN controller translates the received management decision in to flow rules that control the CPS physical infrastructure (see message 5 in Figure 3).

Event analysis: classification and processing
Event-triggered management decision

Layer 4: Service Management

Layer 3: SDN Controller

Layer 1: CPS

1- CPS status
2- CPS status (event)
3- Event processing
4- Management
5- Control

Figure 3. System Functional Blocks with monitor, classify, manage, and control messages

The agent processing represented in Figure 3 as “Layer 4: Service Management” is presented in Table VI, which is now briefly explained. Each individual agent estimates the system status from received event messages. The system status is the ratio between the \( \text{Quantity\_good\_events} \) and the \( \text{Quantity\_total\_events} \), both collected during a system time interval. There is also the estimator \( S_n \), which is the system status at instant “n”. This agent system status estimator with memory (i.e. configurable parameter \( \alpha \in [0, 1] \)) enables that agent to identify in the best way possible an eventual system anomaly and, after that, trying to react in a cooperative way to that problem. This means that the recover or adapt algorithm is executed by a specific agent if that agent decides to cooperate and if that choice has been randomly sorted out by the same agent – like tossing a coin for that. In addition, all the previous goals should be achieved by minimizing the usage of (heterogeneous) system resources (e.g. energy, bandwidth). Alternatively, the agent selfishly can select the defective strategy. As the players select their strategies to optimize the system status, then they observe how the system evolves by evaluating the next value for the local estimator of the system status, and the local processing in each agent is repeated as already explained. In parallel, the global system management is hopefully enhanced, increasing its robustness against any future threat.
Table VI. Agent Event-Triggered Reactive Management Algorithm

\[
S_0 = 1; \ \alpha = 0.8; n = 1
\]

While True do

- Collect, analyze, and classify CPS events occurred within last time slot

\[
S = \frac{\text{Quantity_good_events_within_last_time_slot}}{\text{Quantity_total_events_within_last_time_slot}}
\]

\[
S_n = S_{n-1} \ast \alpha + S \ast (1 - \alpha)
\]

if \( S_n > \text{threshold} \) then

- CPS system is ok; do nothing different from last action

else

- CPS system is not ok; play the cooperative / defective game

end if

\[
n = n + 1
\]
end for

As we just explained the cooperation among system players is a key aspect to enhance system resiliency. To support cooperation within a system there are some distinct theoretical games, such as: i) hierarchical model [152][89][153]; ii) evolutionary model [154]; iii) cluster-based model [155]; and iv) potential game model [57][156]. In addition to these games, there is a mechanism design (or reverse GT) solution normally designated as auction model [92][157], which finds the optimum system status with a convergence time lower than the one of a game [158]. In addition to the previous solutions, it is discussed below a non-cooperative model augmented by an external mechanism enforcing cooperation between players through iterated repetitions of that model. The cooperation within players is very important to put the system operating in a reliable way with a limited set of resources. To support the current discussion, it is considered an infinitely repeated Prisoner’s Dilemma (PD) game between two players. These players are two functional entities of a CPS and IoT system, i.e. containers, NFV, or specialized agents located at the topmost layer of the system. By specialized agents, we mean, as the system overlaps a specific threshold, each system agent detects it and cooperatively reacts to that, selecting either absorbing or adapting to that problem. Alternatively, the same agent can be selfish by does not do nothing to mitigate the detected problem.

Following we analyze a model involving two topmost layer management agents that can either cooperate or defect. In the current game, the discounted factor combined with a mechanism that is triggered by a player’s defection can enforce cooperation throughout players. The discounted factor (\( \leq 1 \)) multiplies the payoffs of the current stage, meaning that in future game stages the payoffs of previous rounds have less relevance.

Figure 4 shows the payoff matrix of an infinitely repeated PD game as well as the total (per player accumulated) payoff along the initial four runs of that game, considering distinct values for the discounted factor (i.e. delta= \([0,2,6,95]\)). A Grim Trigger methodology deals with the case of a defecting player. Two distinct strategies are analyzed. In the first case, both players cooperate, being rewarded with the social optimum payoff of 3 in every stage of the game, as shown in (1). In the second case, one player defects in the first stage to increase its initial payoff from 3 to 5. Nevertheless, the other player at the second stage retaliates against the former defecting player, also defecting. Consequently, both players get a payoff of 1, as shown in (2), after the initial stage.
The expression (3) evaluates the minimum value (i.e. 0.5) for the discounted factor (delta) to reflect in future a strong enough threat (in terms of payoff decrease) to a deviating player. Comparing the payoff trends of the two cases we have discussed in the previous paragraph, one can conclude for delta values of 0 (i.e. the game has only a single stage) and 0.2, which are both lower than 0.5, then the more convenient strategy for both players is always to defect (see Figure 4). The mutual defection occurs because the model gives to the players a solid evidence that they are playing the final round of the game. So, the players are normally tempted to defect as they cannot be penalized in the future. Alternatively, analyzing from Figure 4 the trends associated with the delta values of 0.6 and 0.95, which are both higher than 0.5, one can conclude that in the initial stages both players are tempted to defect; but after a threshold stage of the current game is passed, both players should always cooperate in their best interest. This threshold stage depends on the delta value (see Figure 4). In fact, as the delta value increases towards one that means the player (with that perspective of the game) learns is better to cooperate instead defecting in a faster way, i.e. after fewer stages counted from the game’s start. The opposite happens if for the same game the strategy is changed from Tit for Tat (Figure 4) to Slow Tit for Two Tats (Figure 5). From Figure 5 is perfectly visible that the need to cooperate occurs in later stages of the game when compared with the trend of Figure 4. The last result occurs because Tit for Two Tats is a forgiving strategy by which a player only defects after the opponent has defected twice in a row. This behavior is fairer than Tit for Tat in cases where the player, due to a network communication error or other limitation, perceived erroneously the previous opponent’s choice. Figure 6 shows the evolution of a population composed by the two types of players, during one thousand rounds. It was used the Moran process to keep the population size always at a constant value of one hundred players. For simulating that, we have used the Axelrod Python library\(^2\). The winning strategy was Slow Tit for Two Tats, suggesting Tit for Tat has a lower fitness function than the former one, confirming our previous analytic results.

\[
\text{Coop} = 3 + \delta + \delta^2 + 3 + \cdots = \frac{3}{1 - \delta} \tag{1}
\]

\[
\text{Def} = 5 + \delta + \delta^2 + 1 + \cdots = 5 + \frac{\delta}{1 - \delta} \tag{2}
\]

---

\(^2\) [https://github.com/Axelrod-Python/Axelrod](https://github.com/Axelrod-Python/Axelrod) (Verified in 2019/04/21)
\[
\frac{3}{1-\delta} \geq 5 + \frac{\delta}{1-\delta} \iff \delta \geq 0.5
\] (3)

Figure 5. Total Payoff Trend for a specific player involved in an Infinitely Repeated PD Game with a Grim Punishment Mechanism (Slow Tit for Two Tats) and Diverse Discounted Factors

Figure 6. Distribution of the Two Studied Types of Cooperative Behavior in a Constant Population of 100 Players during 1,000 Rounds (STFTT – Slow Tit for Two Tats; TFT – Tit For Tat)

Open research issues in discounted repeated games are: i) study scenarios with myopic information; ii) payoff variations (controlling defection); iii) considering a distinct delta per player; iv) triggering punishment only during a limited set of stages (i.e. forgiving after T stages following a deviating behavior); v) studying scenarios where the end of the game at the current round (with probability 1-delta) due to the absence of cooperation among players could alternatively be related to the probability of the occurrence of a serious system threat at the current round, stopping the system’s operation and the game.
5.3. Data-triggered Proactive Management Model

This sub-section briefly discusses how data analysis can also influence the CPS operation in a proactive way. Figure 7 visualizes the CPS flowchart showing the functional steps of collecting data about the CPS operation (status), analyzing data, selecting a management decision, and applying the management decision on the CPS. After this, more CPS data is collected again, and the previous process is repeated. The data analysis can be made using a machine learning technique to enhance the system management. In addition, the management decision of this data model should be conveniently coordinated with the event-triggered management decision of the agent discussed in sub-section 5.2. The coordination among the two management methodologies (reactive vs proactive) can be made by a Blockchain solution [159], using a suitable consensus algorithm. Consensus algorithms, such as Kalman-based distributed algorithms [160], can provide interesting distributed functionalities of both filtering the threats and manage CPSs to mitigate them (or even avoid them in the future). In this way, important network functions, e.g. firewall or Intrusion Detection/Prevention or honeypots, can be deployed pervasively within large networking edge domains.

![Figure 7. Data-triggered Management Model of a Cyber-Physical System](image)

6. Lessons Learned and Open Issues

Recent work in the CPS arena is on the design and programming of intelligent solutions that optimize the management of CPSs, orchestrating the available system resources in an abstracted, elastic and flexible way. This new context can support the model of detect-absorb-recover-adapt discussed in Section 5.1, inspired by [7]. This can be successfully applied to various CPS scenarios with networking infrastructures (see Table VII) for fulfilling the goals of energy efficiency, quality support, computation offloading, data offloading, and threat management.

**Table VII. Applying the model of detect/absorb and recover/adapt [7] to various CPS scenarios with networking infrastructures**

| Scenario | Goal | Detect (event-based) | Absorb and Recover (Control) | Adapt (Learn) |
|----------|------|----------------------|-----------------------------|---------------|
| Mesh network formed by IoT battery-operated devices | Routing with energy efficiency | Detect network devices with a low-level of battery via associated events messages | Do not select routing paths using network devices with low energy in their batteries | Balance the traffic load through diverse paths to guarantee a fair depletion of battery among all the network devices |
| Quality support                          | To guarantee that the packet delay is constrained to a maximum value | Event originated by a high packet delay | Select alternative path or discard some packets | Based on historical data analysis performs a proactive load balancing |
|-----------------------------------------|---------------------------------------------------------------------|----------------------------------------|-----------------------------------------------|---------------------------------------------------------------------|
| Computation offloading                  | Efficient usage of end-user device with limitations on computational resources | Events originated by high CPU utilization at end-user devices | End-user device with maximum CPU utilization during a specified time then moves the execution of some tasks to servers located at the network edge | Based on historical data analysis, performs proactive actions of computation offloading |
| Data offloading                         | Edge data caching based on spatio-temporal popularity               | Events originated by high end to end Round Trip Time between a request and its reply | Stores data replicas at diverse edge network nodes | Based on historical data analysis, performs a proactive data replication at selected network nodes |
| Threat management                       | Mitigation of system threats                                        | Events originated by threat detection; events are classified as “malign traffic” or “packet is lost” | If threat is “malign traffic” then “discard malign packets” elseif threat is “packet is lost” then “select an alternative and more robust path” | Based on historical data analysis for the detected threat, decides on the more convenient correction |

A recent contribution [161] proposes design automation and optimization methodologies for the realization of bio-molecular protocols using microfluidic biochips. Such microfluidic biochips combined with wearable (IoT) biosensors can improve medical diagnostics in several scenarios [83]. In [162] is discussed future directions in networked control systems, where the execution of delay-sensitive tasks, such as the control of robotized arms, can be automatically offloaded from remote systems to fog controller nodes, giving significant gains in the control accuracy of field devices.

Due to the high level of heterogeneity and complexity of diverse cyber-physical systems as well as the need for a high-level of interoperability, management solutions with “fusion-enabled” capabilities [85][163][164] have been proposed. These use distinct system architectures such as the Internet and Information Centric Networking (ICN) for efficiently sharing common resources via interoperability entities [85]. Alternatively, the same fusion-enabled capability can be applied to merge and process heterogeneous data from multiple sources [163][164]. The data fusion methods can be classified based on the data space of each use case, namely Cyber-Physical space fusion, Cyber-Social space fusion, or Cyber-Physical-Social space fusion [163]. Considering the most complex case, the authors of [163] discuss a Cyber-Physical-Social System that aims to predict multi-users’ mobility pattern by solving a cubical User-Spatio-Temporal probability arising from heterogeneous sensor data. To solve the stationary probability map, they refer to a tensor-based iterative algorithm to merge and process sensor data from multiple sources, namely time, space, and social network. The algorithm seems promising for the prediction accuracy and associated convergence time. In addition, other important aims are to perform data fusion securely as well as preserving the privacy of original data [164].
IoT devices produce a lot of data demanding a large amount of network resources, and the best-effort allocation of network resources may not be efficient. To overcome this, it will be interesting to investigate novel ways to manage system resources, such as network slicing [165]. Network slicing is a technique that allocates to each data flow a dedicated set of network resources, according to the specific QoS requirements of that flow. To scale out the system management solution instead of allocating network resources to individual data flows, the resources should be allocated to data flow types (e.g. video, gaming, best-effort). This is like the classic DiffServ QoS strategy that (per domain) classifies, marks, polices, and shapes the incoming traffic class. Network slicing can also support seamless flow handover among mobile access networks [166].

Future research in high-level preparedness against threats to CPSs should certainly include proactive and preventive maintenance using either discrete-time [167] or continuous-time control [168] of IoT systems, risk-based protection, short mitigation times, and fast recovery. The diverse aspects to be enhanced should be studied not only at system runtime but initially at its design [10], including the robustness of the physical infrastructure for avoiding weaknesses recently reported [6].

Table VIII compares the diverse modeling techniques discussed along the current work.

| Modeling Technique         | Advantage                                         | Disadvantage                                              |
|----------------------------|---------------------------------------------------|-----------------------------------------------------------|
| Hierarchical Model         | Can optimize simultaneously diverse system parameters | Exposures private data                                   |
| Evolutionary Model         | Very suitable for systems with incomplete information | High convergence time                                    |
| Cluster-Based Model        | Reward is shared among the elements of the same cluster | Not suitable for dynamic systems due to the high complexity to manage clusters |
| Potential Game Model       | The same function runs in each node to optimize system configuration | A local optimum could be found instead of the expected global optimum |
| Mean Field Model           | Can address large-scale and heterogeneous scenarios | Players are rational, indistinguishable, and influenced only by the average behavior of others |
| Non-Cooperative Model      | Highly suitable for dynamic systems with incomplete information | Players cannot learn (with no game repetition nor cooperation incentive) from past actions |
| Auction Model              | Low convergence time because the solution space is further reduced than in the case of GT | Every player should truthfully tell the system designer its intent; otherwise the model result is negatively affected |

Table IX summarizes some of the discussed literature divided into several topics that are highly relevant for resilient and robust CPSs incorporating IoT devices.

| Reference | Topic               | Scenario                  | Positive Outcome                                                                 |
|-----------|---------------------|--------------------------|----------------------------------------------------------------------------------|
| [59]      | Resource allocation | 5G cellular networks     | Discusses resource allocation for SDN based cellular network                      |
| [92]      | Resource allocation | D2D Heterogeneous networks | Presents a solution based on a two-stage auction scheme to perform task transfer from macro cell users to small cell base stations, which are relay network nodes for task execution |
| [26]      | Resource allocation | Ultra-dense networking    | Discusses the challenge of resource allocation for Ultra-Dense Networks            |
| [27] | Resource allocation | Small cells in 5G/IoT | Reviews proposals managing femtocells and applications in IoT environments |
| [147] | Resource management | Cellular and IoT networks | Reviews machine and deep learning techniques for resource allocation in wireless IoT, such as heterogeneous networks, MIMO and device-to-device communications, and non-orthogonal multiple access |
| [91] | Computation offloading | 5G software-defined vehicular networks | Efficient and scalable management of traffic routing |
| [22] | Multi-access | Edge computing | Discusses the optimization of the network performance in some emerging multi-access edge computing scenarios |
| [94] | Energy-aware | Smart buildings | Energy efficient management |
| [117][53] | Energy-aware | Wireless sensor networks | Energy efficient management |
| [118] | Energy-aware | Wireless body area networks | Optimizes QoS and energy efficiency |
| [81] | Energy-aware | Smart buildings | Reduces the overall energy consumption in the building |
| [95] | Security | Wireless communications | Mitigates jamming attacks using energy harvesting |
| [19] | Security | Web applications | Discusses proposals for protecting application layer of systems against DDoS |
| [20] | Security | Intrusion detection | Discusses machine learning techniques in detecting intrusive activities |
| [34] | Security | Incident prediction | It surveys data-driven solutions for predicting cybersecurity issues |
| [4] | Resilience | Communication networks | Analyzes security issues in CPS architecture, with risk assessment and techniques for secure CPS |
| [97] | Resilience | Control systems | Discusses game-theoretic methods that study the tradeoff between robustness, security, and resilience |
| [46][49] | Resilience | Power systems | Qualitative evaluation of smart grid architectures for urban scenarios; resilience improvement strategies |
| [29] | Fault management | Software-defined networks | Thoroughly discusses SDN fault management solutions |
| [137] | Fault management | Distributed systems | Performs replicated data updates |
| [143] | Fault management | Smart Cyber-Physical Systems | Run-Time Self-Adapted Systems |
| [85] | System integration | Interoperability between distinct network architectures | Rolling out of new architectures using incremental and disjoint approaches |
### 7. Conclusion

This paper has explored research reported in the literature on resilience properties for modern Cyber-Physical Systems supported by IoT. The presentation and discussions involved key use cases, notably power grids, smart buildings, mobile networks, healthcare, and agriculture. We reviewed the literature for solutions that aggregate GT, SDN/NFV, and multi-access edge computing for enhancing system resilience and maintaining normal system operation under distinct, serious and real threats. We also discussed system design and how SDN-based theoretical model algorithms can be used to optimize the systems’ operation with respect to well-identified goals such as energy efficiency, computation offloading, data offloading, management of flow quality, and IoT data quality. In addition, via both analytic and simulation results, strategies to enforce cooperation among the system players have been compared. Along the way, key topics for further investigation in this increasingly important research area have been identified, including self-organized (autonomic) management of system threats.

**Funding:** The work of Jose Moura was supported by Instituto de Telecomunicações, Lisbon, Portugal, under Grant UID/EEA/50008/2019.

**Acknowledgments:** Jose Moura acknowledges the support given by Instituto de Telecomunicações, Lisbon, Portugal. David Hutchison is grateful to colleagues in EU COST Action RECODIS (CA15127) for discussions about the resilience of communication systems.

### References

1. J. Lin, W. Yu, N. Zhang, X. Yang, H. Zhang, and W. Zhao, “A Survey on Internet of Things: Architecture, Enabling Technologies, Security and Privacy, and Applications,” *IEEE Internet Things J.*, vol. 4, no. 5, pp. 1125–1142, Oct. 2017.

2. B. Bordel, R. Alcarria, T. Robles, and D. Martín, “Cyber–physical systems: Extending pervasive sensing from control theory to the Internet of Things,” *Pervasive Mob. Comput.*, vol. 40, pp. 156–184, Sep. 2017.
J. Qin, M. Li, L. Shi, and X. Yu, “Optimal Denial-of-Service Attack Scheduling With Energy Constraint Over Packet-Dropping Networks,” IEEE Trans. Automat. Contr., vol. 63, no. 6, pp. 1648–1663, Jun. 2018.

J. P. G. Sterbenz et al., “Resilience and survivability in communication networks: Strategies, principles, and survey of disciplines,” Comput. Networks, vol. 54, no. 8, pp. 1245–1265, Jun. 2010.

Carnegie Mellon University, “CERT Vulnerability Notes Database.” [Online]. Available: https://www.kb.cert.org/vuls/bypublished/desc/. [Accessed: 10-Aug-2019].

Cisco, “Cisco Secure Boot Hardware Tampering Vulnerability.” [Online]. Available: https://tools.cisco.com/security/center/content/CiscoSecurityAdvisory/cisco-sa-20190513-secureboot. [Accessed: 10-Aug-2019].

E. B. Connelly, C. R. Allen, K. Hatfield, J. M. Palma-Oliveira, D. D. Woods, and I. Linkov, “Features of resilience,” Environ. Syst. Decis., vol. 37, no. 1, pp. 46–50, Mar. 2017.

S. Rass, A. Alshawish, M. A. Abid, S. Schauer, Q. Zhu, and H. De Meer, “Physical Intrusion Games—Optimizing Surveillance by Simulation and Game Theory,” IEEE Access, vol. 5, pp. 8394–8407, 2017.

A. Alshamrani, S. Myneni, A. Chowdhary, and D. Huang, “A Survey on Advanced Persistent Threats: Techniques, Solutions, Challenges, and Research Opportunities,” IEEE Commun. Surv. Tutorials, pp. 1–1, 2019.

M. Wolf and D. Serpanos, “Safety and Security in Cyber-Physical Systems and Internet-of-Things Systems,” Proc. IEEE, vol. 106, no. 1, pp. 9–20, Jan. 2018.

I. Linkov and A. Kott, “Fundamental Concepts of Cyber Resilience: Introduction and Overview,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 1–25.

C. C. Sun, A. Hahn, and C. C. Liu, “Cyber security of a power grid: State-of-the-art,” International Journal of Electrical Power and Energy Systems. 2018.

S. Nazir, S. Patel, and D. Patel, “Assessing and augmenting SCADA cyber security: A survey of techniques,” Comput. Secur., vol. 70, pp. 436–454, Sep. 2017.

C. T. Do et al., “Game Theory for Cyber Security and Privacy,” ACM Comput. Surv., vol. 50, no. 2, pp. 1–37, May 2017.

X. Wang et al., “Privacy-Preserving Content Dissemination for Vehicular Social Networks: Challenges and Solutions,” IEEE Commun. Surv. Tutorials, pp. 1–1, 2018.

M. Sookhak, H. Tang, Y. He, and F. R. Yu, “Security and Privacy of Smart Cities: A Survey, Research Issues and Challenges,” IEEE Commun. Surv. Tutorials, pp. 1–1, 2018.

D. Ratasich, F. Khalid, F. Geissler, R. Grosu, M. Shafique, and E. Bartocci, “A Roadmap Toward the Resilient Internet of Things for Cyber-Physical Systems,” IEEE Access, vol. 7, pp. 13260–13283, 2019.

I. Farris, T. Taleb, Y. Khettab, and J. Song, “A Survey on Emerging SDN and NFV Security Mechanisms
for IoT Systems,” *IEEE Commun. Surv. Tutorials*, vol. 21, no. 1, pp. 812–837, 2019.

[19] A. Praseed and P. S. Thilagam, “DDoS Attacks at the Application Layer: Challenges and Research Perspectives for Safeguarding Web Applications,” *IEEE Commun. Surv. Tutorials*, vol. 21, no. 1, pp. 661–685, 2019.

[20] P. Mishra, V. Varadharajan, U. Tupakula, and E. S. Pilli, “A Detailed Investigation and Analysis of Using Machine Learning Techniques for Intrusion Detection,” *IEEE Commun. Surv. Tutorials*, vol. 21, no. 1, pp. 686–728, 2019.

[21] R. Alguliyev, Y. Imamverdiyev, and L. Sukhostat, “Cyber-physical systems and their security issues,” *Comput. Ind.*, vol. 100, pp. 212–223, Sep. 2018.

[22] J. Moura and D. Hutchison, “Game Theory for Multi-Access Edge Computing: Survey, Use Cases, and Future Trends,” *IEEE Commun. Surv. Tutorials*, vol. 21, no. 1, pp. 260–288, 2019.

[23] S. Dobson, D. Hutchison, A. Mauthe, A. Schaeffer-Filho, P. Smith, and J. P. G. Sterbenz, “Self-Organization and Resilience for Networked Systems: Design Principles and Open Research Issues,” *Proc. IEEE*, vol. 107, no. 4, pp. 819–834, Apr. 2019.

[24] E. O’Dwyer, I. Pan, S. Acha, and N. Shah, “Smart energy systems for sustainable smart cities: Current developments, trends and future directions,” *Appl. Energy*, vol. 237, pp. 581–597, Mar. 2019.

[25] J. Xie et al., “A Survey of Machine Learning Techniques Applied to Software Defined Networking (SDN): Research Issues and Challenges,” *IEEE Commun. Surv. Tutorials*, vol. 21, no. 1, pp. 393–430, 2019.

[26] Y. Teng, M. Liu, F. R. Yu, V. C. M. Leung, M. Song, and Y. Zhang, “Resource Allocation for Ultra-Dense Networks: A Survey, Some Research Issues and Challenges,” *IEEE Commun. Surv. Tutorials*, pp. 1–1, 2018.

[27] F. Al-Turjman, E. Ever, and H. Zahmatkesh, “Small Cells in the Forthcoming 5G/IoT: Traffic Modelling and Deployment Overview,” *IEEE Commun. Surv. Tutorials*, vol. 21, no. 1, pp. 28–65, 2019.

[28] X. Huang, S. Cheng, K. Cao, P. Cong, T. Wei, and S. Hu, “A Survey of Deployment Solutions and Optimization Strategies for Hybrid SDN Networks,” *IEEE Commun. Surv. Tutorials*, pp. 1–1, 2018.

[29] Y. Yu et al., “Fault Management in Software-Defined Networking: A Survey,” *IEEE Commun. Surv. Tutorials*, pp. 1–1, 2018.

[30] R. Hussain and S. Zeadally, “Autonomous Cars: Research Results, Issues and Future Challenges,” *IEEE Commun. Surv. Tutorials*, pp. 1–1, 2018.

[31] R. Du, P. Santi, M. Xiao, A. V. Vasilakos, and C. Fischione, “The sensible city: A survey on the deployment and management for smart city monitoring,” *IEEE Commun. Surv. Tutorials*, pp. 1–1, 2018.

[32] W. Ayoub, A. E. Samhat, F. Nouvel, M. Mroue, and J. Prevotet, “Internet of Mobile Things: Overview of LoRaWAN, DASH7, and NB-IoT in LPWANs standards and Supported Mobility,” *IEEE Commun. Surv.
N. C. Luong, P. Wang, D. Niyato, Y.-C. Liang, Z. Han, and F. Hou, “Applications of Economic and Pricing Models for Resource Management in 5G Wireless Networks: A Survey,” *IEEE Commun. Surv. Tutorials*, pp. 1–1, 2018.

N. Sun, J. Zhang, P. Rimba, S. Gao, Y. Xiang, and L. Y. Zhang, “Data-driven cybersecurity incident prediction: A survey,” *IEEE Commun. Surv. Tutorials*, pp. 1–1, 2018.

F. Hu *et al.*, “Robust Cyber–Physical Systems: Concept, models, and implementation,” *Futur. Gener. Comput. Syst.*, vol. 56, pp. 449–475, Mar. 2016.

Y. Ashibani and Q. H. Mahmoud, “Cyber physical systems security: Analysis, challenges and solutions,” *Comput. Secur.*, vol. 68, pp. 81–97, Jul. 2017.

S. F. Mihalache, E. Pricop, and J. Fattahi, “Resilience Enhancement of Cyber-Physical Systems: A Review,” Springer, Cham, 2019, pp. 269–287.

J. Jarmakiewicz, K. Parobczak, and K. Maślanka, “Cybersecurity protection for power grid control infrastructures,” *Int. J. Crit. Infrastruct. Prot.*, vol. 18, pp. 20–33, Sep. 2017.

N. Moreira, E. Molina, J. Lázaro, E. Jacob, and A. Astarloa, “Cyber-security in substation automation systems,” *Renew. Sustain. Energy Rev.*, vol. 54, pp. 1552–1562, Feb. 2016.

X. Zhang, S. Zhu, J. He, B. Yang, and X. Guan, “Credit rating based real-time energy trading in microgrids,” *Appl. Energy*, vol. 236, pp. 985–996, Feb. 2019.

K. Rendón Rozo, J. Arellana, A. Santander-Mercado, and M. Jubiz-Diaz, “Modelling building emergency evacuation plans considering the dynamic behaviour of pedestrians using agent-based simulation,” *Saf. Sci.*, vol. 113, pp. 276–284, Mar. 2019.

J. Wang, J. Liu, and N. Kato, “Networking and Communications in Autonomous Driving: A Survey,” *IEEE Commun. Surv. Tutorials*, pp. 1–1, 2018.

J. Li, H. Cheng, H. Guo, and S. Qiu, “Survey on Artificial Intelligence for Vehicles,” *Automot. Innov.*, vol. 1, no. 1, pp. 2–14, Jan. 2018.

A. Jindal, G. S. Aujla, N. Kumar, R. Chaudhary, M. S. Obaidat, and I. You, “SeDaTiVe: SDN-Enabled Deep Learning Architecture for Network Traffic Control in Vehicular Cyber-Physical Systems,” *IEEE Netw.*, vol. 32, no. 6, pp. 66–73, Nov. 2018.

S. Zhong *et al.*, “Networking Cyber-Physical Systems: System Fundamentals of Security and Privacy for Next-Generation Wireless Networks,” Springer, Cham, 2019, pp. 1–32.

P. Eder-Neuhauser, T. Zseby, and J. Fabini, “Resilience and Security: A Qualitative Survey of Urban Smart Grid Architectures,” *IEEE Access*, vol. 4, pp. 839–848, 2016.

Q. Wang, W. Tai, Y. Tang, M. Ni, and S. You, “A two-layer game theoretical attack-defense model for a
false data injection attack against power systems,” *Int. J. Electr. Power Energy Syst.*, vol. 104, pp. 169–177, Jan. 2019.

[48] A. Sargolzaei, K. K. Yen, M. N. Abdelghani, S. Sargolzaei, and B. Carbunar, “Resilient Design of Networked Control Systems Under Time Delay Switch Attacks, Application in Smart Grid,” *IEEE Access*, vol. 5, pp. 15901–15912, 2017.

[49] A. Gholami, T. Shekari, M. H. Amirioun, F. Aminifar, M. H. Amini, and A. Sargolzaei, “Toward a Consensus on the Definition and Taxonomy of Power System Resilience,” *IEEE Access*, vol. 6, pp. 32035–32053, 2018.

[50] G. Liang, J. Zhao, F. Luo, S. R. Weller, and Z. Y. Dong, “A Review of False Data Injection Attacks Against Modern Power Systems,” *IEEE Trans. Smart Grid*, vol. 8, no. 4, pp. 1630–1638, Jul. 2017.

[51] D. Kolokotsa, “The role of smart grids in the building sector,” *Energy Build.*, vol. 116, pp. 703–708, Mar. 2016.

[52] A. Kumar, A. Singh, A. Kumar, M. K. Singh, P. Mahanta, and S. C. Mukhopadhyay, “Sensing Technologies for Monitoring Intelligent Buildings: A Review,” *IEEE Sens. J.*, vol. 18, no. 12, pp. 4847–4860, Jun. 2018.

[53] S. Varshney *et al.*, “Energy Efficient Management of Pipelines in Buildings Using Linear Wireless Sensor Networks,” *Sensors*, vol. 18, no. 8, 2018.

[54] M. Agiwal, A. Roy, and N. Saxena, “Next Generation 5G Wireless Networks: A Comprehensive Survey,” *IEEE Commun. Surv. Tutorials*, vol. 18, no. 3, pp. 1617–1655, 2016.

[55] Y. Xu, J. Wang, Q. Wu, Z. Du, L. Shen, and A. Anpalagan, “A game-theoretic perspective on self-organizing optimization for cognitive small cells,” *IEEE Commun. Mag.*, vol. 53, no. 7, pp. 100–108, Jul. 2015.

[56] M. Arslan, K. Sundaresan, and S. Rangarajan, “Software-defined networking in cellular radio access networks: potential and challenges,” *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 150–156, Jan. 2015.

[57] N. Zhang, S. Zhang, J. Zheng, X. Fang, J. W. Mark, and X. Shen, “QoE Driven Decentralized Spectrum Sharing in 5G Networks: Potential Game Approach,” *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 7797–7808, Sep. 2017.

[58] Y. Guo, X. Hu, B. Hu, J. Cheng, M. Zhou, and R. Y. K. Kwok, “Mobile Cyber Physical Systems: Current Challenges and Future Networking Applications,” *IEEE Access*, vol. 6, pp. 12360–12368, 2018.

[59] S. K. Tayyaba and M. A. Shah, “Resource allocation in SDN based 5G cellular networks,” *Peer-to-Peer Netw. Appl.*, pp. 1–25, May 2018.

[60] C.-C. Cheng, P.-C. Hsiu, T.-K. Hu, and T.-W. Kuo, “Oasis: A Mobile Cyber–Physical System for Accessible Location Exploration,” *Proc. IEEE*, vol. 106, no. 9, pp. 1744–1759, Sep. 2018.
[61] R. Dautov, S. Distefano, D. Bruneo, F. Longo, G. Merlino, and A. Puliafito, “Data Processing in Cyber-Physical-Social Systems Through Edge Computing,” *IEEE Access*, vol. 6, pp. 29822–29835, 2018.

[62] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, “A Survey on Platoon-Based Vehicular Cyber-Physical Systems,” *IEEE Commun. Surv. Tutorials*, vol. 18, no. 1, pp. 263–284, 2016.

[63] Boyi Xu, Li Da Xu, Hongming Cai, Cheng Xie, Jingyuan Hu, and Fenglin Bu, “Ubiquitous Data Accessing Method in IoT-Based Information System for Emergency Medical Services,” *IEEE Trans. Ind. Informatics*, vol. 10, no. 2, pp. 1578–1586, May 2014.

[64] A. A. Mutlag, M. K. Abd Ghani, N. Arunkumar, M. A. Mohammed, and O. Mohd, “Enabling technologies for fog computing in healthcare IoT systems,” *Futur. Gener. Comput. Syst.*, vol. 90, pp. 62–78, Jan. 2019.

[65] Y. YIN, Y. Zeng, X. Chen, and Y. Fan, “The internet of things in healthcare: An overview,” *J. Ind. Inf. Integr.*, vol. 1, pp. 3–13, Mar. 2016.

[66] Y. Zhang, M. Qiu, C.-W. Tsai, M. M. Hassan, and A. Alamri, “Health-CPS: Healthcare Cyber-Physical System Assisted by Cloud and Big Data,” *IEEE Syst. J.*, vol. 11, no. 1, pp. 88–95, Mar. 2017.

[67] R. Altwawy and A. M. Youssef, “Security Tradeoffs in Cyber Physical Systems: A Case Study Survey on Implantable Medical Devices,” *IEEE Access*, vol. 4, pp. 959–979, 2016.

[68] A. Ordonez-Garcia, M. Siller, and O. Begovich, “IoT architecture for urban agronomy and precision applications,” in *2017 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*, 2017, pp. 1–4.

[69] R. Gómez-Chabla, K. Real-Avilés, C. Morán, P. Grijalva, and T. Recalde, “IoT Applications in Agriculture: A Systematic Literature Review,” in *2nd International Conference on ICTs in Agronomy and Environment*, 2019, pp. 68–76.

[70] J. M. Talaver *et al.*, “Review of IoT applications in agro-industrial and environmental fields,” *Comput. Electron. Agric.*, vol. 142, pp. 283–297, Nov. 2017.

[71] A. Tzounis, N. Katsoulas, T. Bartzanas, and C. Kittas, “Internet of Things in agriculture, recent advances and future challenges,” *Biosyst. Eng.*, vol. 164, pp. 31–48, Dec. 2017.

[72] K. Zhou and L. Cai, “Randomized PHEV Charging Under Distribution Grid Constraints,” *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 879–887, Mar. 2014.

[73] P.-Y. Kong, “Wireless Neighborhood Area Networks With QoS Support for Demand Response in Smart Grid,” *IEEE Trans. Smart Grid*, vol. 7, no. 4, pp. 1913–1923, Jul. 2016.

[74] I. Stellios, P. KotzaniKolaou, M. Psarakis, C. Alcaraz, and J. Lopez, “A Survey of IoT-Enabled Cyberattacks: Assessing Attack Paths to Critical Infrastructures and Services,” *IEEE Commun. Surv. Tutorials*, vol. 20, no. 4, pp. 3453–3495, 2018.
[75] E. Benkhelifa, T. Welsh, and W. Hamouda, “A Critical Review of Practices and Challenges in Intrusion Detection Systems for IoT: Toward Universal and Resilient Systems,” *IEEE Commun. Surv. Tutorials*, vol. 20, no. 4, pp. 3496–3509, 2018.

[76] L. Zheng, N. Lu, and L. Cai, “Reliable Wireless Communication Networks for Demand Response Control,” *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 133–140, Mar. 2013.

[77] A. Abdrabou, “A Wireless Communication Architecture for Smart Grid Distribution Networks,” *IEEE Syst. J.*, vol. 10, no. 1, pp. 251–261, Mar. 2016.

[78] S. Belhaiza and U. Baroudi, “A Game Theoretic Model for Smart Grids Demand Management,” *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1386–1393, May 2015.

[79] R. Lu and S. H. Hong, “Incentive-based demand response for smart grid with reinforcement learning and deep neural network,” *Appl. Energy*, vol. 236, pp. 937–949, Feb. 2019.

[80] P. Kar, A. Shareef, A. Kumar, K. T. Harn, B. Kalluri, and S. K. Panda, “ReViCEE: A recommendation based approach for personalized control, visual comfort & energy efficiency in buildings,” *Build. Environ.*, vol. 152, pp. 135–144, Apr. 2019.

[81] I. C. Konstantakopoulos, A. R. Barkan, S. He, T. Veeravalli, H. Liu, and C. Spanos, “A deep learning and gamification approach to improving human-building interaction and energy efficiency in smart infrastructure,” *Appl. Energy*, vol. 237, pp. 810–821, Mar. 2019.

[82] R. Jia et al., “Design Automation for Smart Building Systems,” *Proc. IEEE*, vol. 106, no. 9, pp. 1680–1699, Sep. 2018.

[83] F. Firouzi, B. Farahani, M. Ibrahim, and K. Chakrabarty, “Keynote Paper: From EDA to IoT eHealth: Promises, Challenges, and Solutions,” *IEEE Trans. Comput. Des. Integr. Circuits Syst.*, vol. 37, no. 12, pp. 2965–2978, Dec. 2018.

[84] F. A. Kraemer, A. E. Braten, N. Tamkittikhun, and D. Palma, “Fog Computing in Healthcare–A Review and Discussion,” *IEEE Access*, vol. 5, pp. 9206–9222, 2017.

[85] C. Guimarães, J. Quevedo, R. Ferreira, D. Corujo, and R. L. Aguiar, “Exploring interoperability assessment for Future Internet Architectures roll out,” *J. Netw. Comput. Appl.*, vol. 136, pp. 38–56, Jun. 2019.

[86] S. B. Baker, W. Xiang, and I. Atkinson, “Internet of Things for Smart Healthcare: Technologies, Challenges, and Opportunities,” *IEEE Access*, vol. 5, pp. 26521–26544, 2017.

[87] S. A. Haque, S. M. Aziz, and M. Rahman, “Review of Cyber-Physical System in Healthcare,” *Int. J. Distrib. Sens. Networks*, vol. 10, no. 4, p. 217415, Apr. 2014.

[88] E. C. Paulson, I. Linkov, and J. M. Keisler, “A game theoretic model for resource allocation among countermeasures with multiple attributes,” *Eur. J. Oper. Res.*, vol. 252, no. 2, pp. 610–622, Jul. 2016.
Z. Zhou, L. Tan, B. Gu, Y. Zhang, and J. Wu, “Bandwidth Slicing in Software-Defined 5G: A Stackelberg Game Approach,” IEEE Veh. Technol. Mag., vol. 13, no. 2, pp. 102–109, Jun. 2018.

S. Meng, Q. Li, T. Wu, W. Huang, J. Zhang, and W. Li, “A fault-tolerant dynamic scheduling method on hierarchical mobile edge cloud computing,” Comput. Intell., p. coin.12219, May 2019.

G. S. Aujla, R. Chaudhary, N. Kumar, J. J. P. C. Rodrigues, and A. Vinel, “Data Offloading in 5G-Enabled Software-Defined Vehicular Networks: A Stackelberg-Game-Based Approach,” IEEE Commun. Mag., vol. 55, no. 8, pp. 100–108, Aug. 2017.

L. Chen, J. Wu, X.-X. Zhang, and G. Zhou, “TARCO: Two-Stage Auction for D2D Relay Aided Computation Resource Allocation in HetNet,” IEEE Trans. Serv. Comput., pp. 1–1, 2018.

W. Chen et al., “Cooperative and Distributed Computation Offloading for Blockchain-Empowered Industrial Internet of Things,” IEEE Internet Things J., pp. 1–1, 2019.

I. C. Konstantakopoulos, L. J. Ratliff, M. Jin, C. Spanos, and S. S. Sastry, “Smart building energy efficiency via social game: a robust utility learning framework for closing-the-loop,” in 2016 1st International Workshop on Science of Smart City Operations and Platforms Engineering (SCOPE) in partnership with Global City Teams Challenge (GCTC) (SCOPE - GCTC), 2016, pp. 1–6.

G. Rezgui, E. V. Belmega, and A. Chorti, “Mitigating Jamming Attacks Using Energy Harvesting,” IEEE Wirel. Commun. Lett., pp. 1–1, 2018.

F. Yao, L. Jia, Y. Sun, Y. Xu, S. Feng, and Y. Zhu, “A hierarchical learning approach to anti-jamming channel selection strategies,” Wirel. Networks, vol. 25, no. 1, pp. 201–213, Jan. 2019.

Q. Zhu and T. Basar, “Game-Theoretic Methods for Robustness, Security, and Resilience of Cyberphysical Control Systems: Games-in-Games Principle for Optimal Cross-Layer Resilient Control Systems,” IEEE Control Syst., vol. 35, no. 1, pp. 46–65, Feb. 2015.

L. Wei, A. I. Sarwat, W. Saad, and S. Biswas, “Stochastic Games for Power Grid Protection Against Coordinated Cyber-Physical Attacks,” IEEE Trans. Smart Grid, vol. 9, no. 2, pp. 684–694, Mar. 2018.

Q. D. La, T. Q. S. Quek, J. Lee, S. Jin, and H. Zhu, “Deceptive Attack and Defense Game in Honeypot-Enabled Networks for the Internet of Things,” IEEE Internet Things J., vol. 3, no. 6, pp. 1025–1035, Dec. 2016.

C. Zhang, J. E. Ramirez-Marquez, and J. Wang, “Critical infrastructure protection using secrecy – A discrete simultaneous game,” Eur. J. Oper. Res., vol. 242, no. 1, pp. 212–221, Apr. 2015.

E. Molina and E. Jacob, “Software-defined networking in cyber-physical systems: A survey,” Comput. Electr. Eng., vol. 66, pp. 407–419, Feb. 2018.

T. Bakshish, “State of the Art and Recent Research Advances in Software Defined Networking,” Wirel. Commun. Mob. Comput., vol. 2017, pp. 1–35, Jan. 2017.
D. Kreutz, F. M. V. Ramos, P. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, “Software-Defined Networking: A Comprehensive Survey,” Proc. IEEE, vol. 103, no. 1, pp. 14–76, 2015.

B. Dezfouli, V. Esmaeelzadeh, J. Sheth, and M. Radi, “A Review of Software-Defined WLANs: Architectures and Central Control Mechanisms,” IEEE Commun. Surv. Tutorials, pp. 1–1, 2018.

B. Nunes, M. Mendonca, X. Nguyen, K. Obrazcza, and T. Turletti, “A Survey of Software-Defined Networking: Past, Present, and Future of Programmable Networks,” Communications Surveys Tutorials, IEEE, vol. PP, no. 99. pp. 1–18, 2014.

P. Kampanakis, H. Perros, and T. Beyene, “SDN-based solutions for Moving Target Defense network protection,” in Proceeding of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks 2014, 2014, pp. 1–6.

A. Makanju, A. N. Zincir-Heywood, and S. Kiyomoto, “On evolutionary computation for moving target defense in software defined networks,” in Proceedings of the Genetic and Evolutionary Computation Conference Companion on - GECCO ’17, 2017, pp. 287–288.

A. Chowdhary, S. Pisharody, A. Alshamrani, and D. Huang, “Dynamic Game based Security framework in SDN-enabled Cloud Networking Environments,” in Proceedings of the ACM International Workshop on Security in Software Defined Networks & Network Function Virtualization - SDN-NFVSec ’17, 2017, pp. 53–58.

A. Chowdhary, S. Pisharody, and D. Huang, “SDN based Scalable MTD solution in Cloud Network,” in Proceedings of the 2016 ACM Workshop on Moving Target Defense - MTD’16, 2016, pp. 27–36.

Q. Zhao, C. Zhang, and Z. Zhao, “A decoy chain deployment method based on SDN and NFV against penetration attack.,” PLoS One, vol. 12, no. 12, pp. 1–23, 2017.

N. Sultana, N. Chilamkurti, W. Peng, and R. Alhadad, “Survey on SDN based network intrusion detection system using machine learning approaches,” Peer-to-Peer Netw. Appl., pp. 1–9, Jan. 2018.

Z. Fan, Y. Xiao, A. Nayak, and C. Tan, “An improved network security situation assessment approach in software defined networks,” Peer-to-Peer Netw. Appl., pp. 1–15, Sep. 2017.

X. Xu, S. Wang, and Y. Li, “Identification and predication of network attack patterns in software-defined networking,” Peer-to-Peer Netw. Appl., pp. 1–11, Jan. 2018.

X. Yin, L. Wang, and S. Jiang, “A hierarchical mobility management scheme based on software defined networking,” Peer-to-Peer Netw. Appl., pp. 1–16, Jan. 2018.

J. Xiao, S. Chen, and M. Sui, “The strategy of path determination and traffic scheduling in private campus networks based on SDN,” Peer-to-Peer Netw. Appl., pp. 1–10, Dec. 2017.

Z. Zhang, L. Ge, P. Wang, and X. Zhou, “Behavior Reconstruction Models for Large-scale Network Service Systems,” Peer-to-Peer Netw. Appl., pp. 1–12, Jan. 2018.
[117] S. Din, A. Paul, A. Ahmad, and J. H. Kim, “Energy efficient topology management scheme based on clustering technique for software defined wireless sensor network,” Peer-to-Peer Netw. Appl., pp. 1–9, Oct. 2017.

[118] T. Bai et al., “An optimized protocol for QoS and energy efficiency on wireless body area networks,” Peer-to-Peer Netw. Appl., pp. 1–11, Sep. 2017.

[119] C. Brooks et al., “A Component Architecture for the Internet of Things,” Proc. IEEE, vol. 106, no. 9, pp. 1527–1542, Sep. 2018.

[120] W. Kellerer, P. Kalmbach, A. Blenk, A. Basta, M. Reisslein, and S. Schmid, “Adaptable and Data-Driven Softwarized Networks: Review, Opportunities, and Challenges,” Proc. IEEE, vol. 107, no. 4, pp. 711–731, Apr. 2019.

[121] C. Gershenson, V. Trianni, J. Werfel, and H. Sayama, “Self-Organization and Artificial Life: A Review,” Apr. 2018.

[122] W. Aguilar, G. Santamaría-Bonfil, T. Froese, and C. Gershenson, “The Past, Present, and Future of Artificial Life,” Front. Robot. AI, vol. 1, p. 8, 2014.

[123] M. A. Bedau et al., “Open Problems in Artificial Life,” Artif. Life, vol. 6, no. 4, pp. 363–376, Oct. 2000.

[124] Z. M. Fadlullah et al., “State-of-the-Art Deep Learning: Evolving Machine Intelligence Toward Tomorrow’s Intelligent Network Traffic Control Systems,” IEEE Commun. Surv. Tutorials, vol. 19, no. 4, pp. 2432–2455, 2017.

[125] T. O’Shea and J. Hoydis, “An Introduction to Deep Learning for the Physical Layer,” IEEE Trans. Cogn. Commun. Netw., vol. 3, no. 4, pp. 563–575, Dec. 2017.

[126] S. Dorner, S. Cammerer, J. Hoydis, and S. ten Brink, “Deep Learning Based Communication Over the Air,” IEEE J. Sel. Top. Signal Process., vol. 12, no. 1, pp. 132–143, Feb. 2018.

[127] M. A. Alsheikh, S. Lin, D. Niyato, and H.-P. Tan, “Machine Learning in Wireless Sensor Networks: Algorithms, Strategies, and Applications,” IEEE Commun. Surv. Tutorials, vol. 16, no. 4, pp. 1996–2018, 2014.

[128] H. Li, K. Ota, and M. Dong, “Learning IoT in Edge: Deep Learning for the Internet of Things with Edge Computing,” IEEE Netw., vol. 32, no. 1, pp. 96–101, Jan. 2018.

[129] F. Francois and E. Gelenbe, “Towards a cognitive routing engine for software defined networks,” in 2016 IEEE International Conference on Communications (ICC), 2016, pp. 1–6.

[130] H. Lu, Y. Li, M. Chen, H. Kim, and S. Serikawa, “Brain Intelligence: Go beyond Artificial Intelligence,” Mob. Networks Appl., vol. 23, no. 2, pp. 368–375, Apr. 2018.

[131] S. Ozawa, “Computational Intelligence in the Time of Cyber-Physical Systems and the Internet of Things,” in Artificial Intelligence in the Age of Neural Networks and Brain Computing, Academic Press, 2019,
[132] M. A. Khan and H. Tembine, “Meta-Learning for Realizing Self-x Management of Future Networks,” IEEE Access, vol. 5, pp. 19072–19083, 2017.

[133] N. Evans and W. Horsthemke, “Analysis of Dependencies,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 93–106.

[134] N. Evans and W. Horsthemke, “Regional Critical Infrastructure,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 355–380.

[135] T. J. Moore and J.-H. Cho, “Applying Percolation Theory,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 107–133.

[136] D. J. Bodeau and R. D. Graubart, “Systems Engineering Approaches,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 197–220.

[137] A. Ramnatthan, A. Ganesan, J. Liu, A. C. Arpaci-Dusseau, and R. H. Arpaci-Dusseau, “Fault-tolerance, fast and slow: exploiting failure asynchrony in distributed systems,” in Proceedings of the 12th USENIX conference on Operating Systems Design and Implementation, 2018, pp. 391–408.

[138] G. Giacomello and G. Pescaroli, “Managing Human Factors,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 247–263.

[139] Shengbo Yang, Chai Kiat Yeo, and Bu-Sung Lee, “Toward Reliable Data Delivery for Highly Dynamic Mobile Ad Hoc Networks,” IEEE Trans. Mob. Comput., vol. 11, no. 1, pp. 111–124, Jan. 2012.

[140] W. Gao, G. Cao, A. Iyengar, and M. Srivatsa, “Cooperative Caching for Efficient Data Access in Disruption Tolerant Networks,” IEEE Trans. Mob. Comput., vol. 13, no. 3, pp. 611–625, Mar. 2014.

[141] N. Tandiya, E. J. M. Colbert, V. Marojevic, and J. H. Reed, “Biologically Inspired Artificial Intelligence Techniques,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 287–313.

[142] M. Curado et al., “Internet of Things,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 381–401.

[143] J. Tavcar and I. Horvath, “A Review of the Principles of Designing Smart Cyber-Physical Systems for Run-Time Adaptation: Learned Lessons and Open Issues,” IEEE Trans. Syst. Man, Cybern. Syst., vol. 49, no. 1, pp. 145–158, Jan. 2019.

[144] E. J. Colbert, A. Kott, and L. P. Knachel, “The game-theoretic model and experimental investigation of cyber wargaming,” J. Def. Model. Simul. Appl. Methodol. Technol., pp. 1–18, Aug. 2018.

[145] I. Kotenko, I. Saenko, and O. Lauta, “Modeling the Impact of Cyber Attacks,” in Cyber Resilience of Systems and Networks, Cham: Springer International Publishing, 2019, pp. 135–169.

[146] S. Musman, S. Agbolosu-Amison, and K. Crowther, “Metrics Based on the Mission Risk Perspective,” in
[147] F. Hussain, S. A. Hassan, R. Hussain, and E. Hossain, “Machine Learning for Resource Management in Cellular and IoT Networks: Potentials, Current Solutions, and Open Challenges,” *ArXiv e-prints*, vol. arXiv:1907, no. 08965v1, pp. 1–21, Jul. 2019.

[148] J. Rodriguez-Molina and D. M. Kammen, “Middleware Architectures for the Smart Grid: A Survey on the State-of-the-Art, Taxonomy and Main Open Issues,” *IEEE Commun. Surv. Tutorials*, vol. 20, no. 4, pp. 2992–3033, 2018.

[149] A. Farahzadi, P. Shams, J. Rezazadeh, and R. Farahbakhsh, “Middleware technologies for cloud of things: a survey,” *Digit. Commun. Networks*, vol. 4, no. 3, pp. 176–188, Aug. 2018.

[150] K. Wang, H. Yin, W. Quan, and G. Min, “Enabling Collaborative Edge Computing for Software Defined Vehicular Networks,” *IEEE Netw.*, vol. 32, no. 5, pp. 112–117, Sep. 2018.

[151] J. Xu, S. Wang, B. K. Bhargava, and F. Yang, “A Blockchain-Enabled Trustless Crowd-Intelligence Ecosystem on Mobile Edge Computing,” *IEEE Trans. Ind. Informatics*, vol. 15, no. 6, pp. 3538–3547, Jun. 2019.

[152] H. Zhang, W. Ding, J. Song, and Z. Han, “A Hierarchical Game Approach for Visible Light Communication and D2D Heterogeneous Network,” in *2016 IEEE Global Communications Conference (GLOBECOM)*, 2016, pp. 1–6.

[153] X. Li, C. Zhang, B. Gu, K. Yamori, and Y. Tanaka, “Optimal Pricing and Service Selection in the Mobile Cloud Architectures,” *IEEE Access*, vol. 7, pp. 43564–43572, 2019.

[154] L. Cheng and T. Yu, “Nash Equilibrium-Based Asymptotic Stability Analysis of Multi-Group Asymmetric Evolutionary Games in Typical Scenario of Electricity Market,” *IEEE Access*, vol. 6, pp. 32064–32086, 2018.

[155] S. Li, F. Fei, D. Ruihan, S. Yu, and W. Dou, “A Dynamic Pricing Method for Carpooling Service Based on Coalitional Game Analysis,” in *2016 IEEE 18th International Conference on High Performance Computing and Communications; IEEE 14th International Conference on Smart City; IEEE 2nd International Conference on Data Science and Systems (HPCC/SmartCity/DSS)*, 2016, pp. 78–85.

[156] X. Zhao, L. Li, S. Geng, H. Zhang, and Y. Ma, “A Link-Based Variable Probability Learning Approach for Partially Overlapping Channels Assignment on Multi-Radio Multi-Channel Wireless Mesh Information-Centric IoT Networks,” *IEEE Access*, vol. 7, pp. 45137–45145, 2019.

[157] Z. Zhou, H. Liao, B. Gu, K. M. S. Huq, S. Mumtaz, and J. Rodriguez, “Robust Mobile Crowd Sensing: When Deep Learning Meets Edge Computing,” *IEEE Netw.*, vol. 32, no. 4, pp. 54–60, Jul. 2018.

[158] T. Luo, S. S. Kanhere, J. Huang, S. K. Das, and F. Wu, “Sustainable Incentives for Mobile Crowdsensing: Auctions, Lotteries, and Trust and Reputation Systems,” *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 68–74, Mar. 2017.
[159] P. K. Sharma, M.-Y. Chen, and J. H. Park, “A Software Defined Fog Node Based Distributed Blockchain Cloud Architecture for IoT,” *IEEE Access*, vol. 6, pp. 115–124, 2018.

[160] D. Ding, Q.-L. Han, Z. Wang, and X. Ge, “A Survey on Model-Based Distributed Control and Filtering for Industrial Cyber-Physical Systems,” *IEEE Trans. Ind. Informatics*, vol. 15, no. 5, pp. 2483–2499, May 2019.

[161] M. Ibrahim and K. Chakrabarty, “Cyber–Physical Digital-Microfluidic Biochips: Bridging the Gap Between Microfluidics and Microbiology,” *Proc. IEEE*, vol. 106, no. 9, pp. 1717–1743, Sep. 2018.

[162] Y. Zhan, Y. Xia, and A. V. Vasilakos, “Future directions of networked control systems: A combination of cloud control and fog control approach,” *Comput. Networks*, vol. 161, pp. 235–248, Oct. 2019.

[163] P. Wang, L. T. Yang, J. Li, J. Chen, and S. Hu, “Data fusion in cyber-physical-social systems: State-of-the-art and perspectives,” *Inf. Fusion*, vol. 51, pp. 42–57, 2019.

[164] W. Ding, X. Jing, Z. Yan, and L. T. Yang, “A survey on data fusion in internet of things: Towards secure and privacy-preserving fusion,” *Inf. Fusion*, vol. 51, pp. 129–144, 2019.

[165] Y. Yiakoumis, K.-K. Yap, S. Katti, G. Parulkar, and N. McKeown, “Slicing Home Networks,” in *Proceedings of the 2Nd ACM SIGCOMM Workshop on Home Networks*, 2011, pp. 1–6.

[166] H. Zhang, N. Liu, X. Chu, K. Long, A.-H. Aghvami, and V. C. M. Leung, “Network Slicing Based 5G and Future Mobile Networks: Mobility, Resource Management, and Challenges,” *IEEE Commun. Mag.*, vol. 55, no. 8, pp. 138–145, Aug. 2017.

[167] R. Casado-Vara, F. Prieto-Castrillo, and J. M. Corchado, “A game theory approach for cooperative control to improve data quality and false data detection in WSN,” *Int. J. Robust Nonlinear Control*, vol. 28, no. 16, pp. 5087–5102, Nov. 2018.

[168] R. Casado-Vara, P. Novais, A. B. Gil, J. Prieto, and J. M. Corchado, “Distributed Continuous-Time Fault Estimation Control for Multiple Devices in IoT Networks,” *IEEE Access*, vol. 7, pp. 11972–11984, 2019.