

A Systems and Control Perspective of CPS Security

S. M. Dibaji, M. Pirani, D. Flamholz, A. M. Annaswamy, K. H. Johansson, and A. Chakraborty

Abstract—The comprehensive integration of instrumentation, communication, and control into physical systems has led to the study of Cyber-Physical Systems (CPS), a field that has recently garnered increased attention. A key concern that is ubiquitous in CPS is a need to ensure security in the face of cyber attacks. In this paper, we carry out a survey of systems and control methods that have been proposed for the security of CPS. We classify these methods into three categories based on the type of defense proposed against the cyberattacks: prevention, resilience, and detection & isolation. A unified threat assessment metric is proposed in order to evaluate how CPS security is achieved in each of these three cases. Also surveyed are risk assessment tools and the effect of network topology on CPS security. An emphasis has been placed on power and transportation applications in the overall survey.

Index Terms—cyber-physical systems, resilient control

I. INTRODUCTION

Motivated by concerns about sustainability, efficiency, and resiliency, several sectors including energy, transportation, water, and healthcare systems have witnessed significant advances in instrumentation, monitoring, and automation over the past decade. The resulting integration of information, communication, and computation with physically engineered systems demands a detailed investigation into the analysis and synthesis of Cyber-Physical Systems (CPS) so as to realize the desired performance metrics of efficiency, sustainability, and safety. The extensive and intricate presence of cyber components also introduces a vulnerability of unwanted access to these systems. The available communication technologies, referred to as SCADA (Supervisory Control and Data Acquisition), are witnessing significant advances, triggering a shift from protected, closed, and wired networks to open and wireless networks which, as a side effect, are more vulnerable to outside interference.

S. M. Dibaji, D. Flamholz, and A. M. Annaswamy are with the Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA, E-mails: (dibaji/aanna/flamholz)@mit.edu, M. Pirani and K. H. Johansson are with the Department of Automatic Control, KTH Royal Institute of Technology, Sweden, E-mails: mpirani@uwaterloo.ca and kallej@kth.se, and A. Chakraborty is with the Department of Electrical Engineering, North Carolina State University, Raleigh, NC, USA, E-mail: achakra2@ncsu.edu.

This, in turn, has led to a recent systematic investigation of security of CPS, various attack models, tools for analysis of CPS security, and most importantly, methods for ensuring resilience against cyber attacks. This paper surveys this emerging area and offers a systems and control-theoretic perspective to provide a snapshot of the current state of research in the field. For the purposes of this paper, we denote the term CPS security to include both security, which sometimes is used as a system property that corresponds to defense against attacks, and resiliency, the system property that corresponds to survival and recovery after the attack occurs.

The notion of security against unwanted intrusions and attacks can be traced back to the times of Caesar [1] and early warfare strategies. A technological intersection with this topic, however, has its origins in the proliferation of computers in the commercial sector. Grouped under the rubric of InfoSec, information security breaches were recognized to be central to the satisfactory performance of a system. In particular, three security breaches were often considered to be important for the protection of information [2]–[4]: Confidentiality, Integrity, and Availability which denote as an unauthorized information release, an unauthorized information modification, and an unauthorized denial of use of the information, respectively¹.

Given the central role that information plays in a feedback control system, the approaches to achieving CPS security can be grouped using the same taxonomy (see Fig. 1). A confidentiality breach can be viewed as the monitoring of information that is used to control the system, integrity breach as the corruption of the sensor data sent to the network for processing, and availability breach as either blocking, or delaying the information from the computational block to the actuation node in a system [6]–[9].

If protection against the security breaches above can be viewed as a defenders perspective, an attackers perspective can be considered as well, to address CPS security. Broadly speaking, cyber attacks have been

¹In the literature [5], security goals are also defined in the same manner but with a positive voice: Confidentiality is to maintain the secrecy of the important data, Integrity is to guarantee the fidelity of the data, and Availability is to ensure the accessibility of the data at the right time.

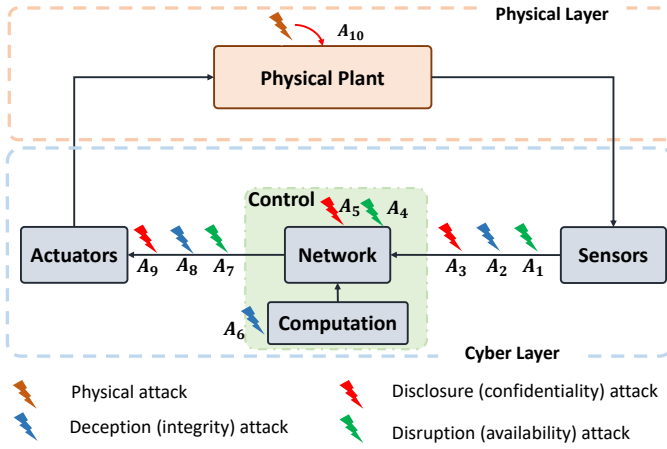


Fig. 1. Schematic figure of physical attacks, disclosure attacks, deception attacks, and disruption attacks on control systems

grouped under three headings, disclosure attacks, deception attacks, and disruption attacks [10], [11] denoted as DDD attacks in what follows (Fig. 1). Disclosure attacks refer to any intrusions that include eavesdropping [12]. Deception attack corresponds to the corruption of signals (e.g., a spoofing attack [13] and a false-data injection attack [14]), and a disruption attack corresponds to another active intrusion where the signal may either be blocked or delayed (e.g., Denial of Service [15]). These three attacks are not mutually exclusive—almost all deception attacks can be disruptive as well; disruption attacks need not necessarily coincide with a deception attack to achieve a more active action such as blocking or delaying. It is clear that there is a direct mapping between these three attack-models and the three security goals of confidentiality, integrity, and availability [10]. Both the CIA goals and the DDD attacks have been extensively analyzed in the literature for analysis and synthesis of CPS security over the past few years [10], [16].

In a well-designed control system where performance goals of accuracy, speed, and robustness are met, allowing cyber attacks to have an impact, let alone a significant one, seems like an impossibility. To the contrary, the number of attacks, as well as their impact on the underlying infrastructure, has been quite compelling. We summarize some of the major attacks on control systems in power and transportation infrastructures in the following section. Each of the major attacks is classified using the security breaches and attack models described above. The specific set of components compromised in the underlying feedback control loops is indicated in Fig. 1.

A. Examples of CPS Cyber-Attacks

In this subsection, we name a few of the most consequential attack scenarios that have occurred in industrial systems.

1) *Stuxnet*: Stuxnet was a cyber-physical attack on an Iranian uranium enrichment plant in 2011. In targeting a commercially available Programmable Logic Controller, operating under a narrow set of conditions, the attackers were able to ensure the attack reached its intended recipient with limited fallout. They inserted a Malware which would lie dormant in the system and go undetected [17], [18]. With such a stealthy presence, observing critical and confidential system data, the attacker observed key outputs of the system under stable conditions, and replayed those measurements to other monitoring sites of the network. Simultaneously, malicious actuation signals were injected into other critical actuation sites, resulting in a significant damage to a number of centrifuges [17]. In general, many cyber-attacks can remain undetected after insertion, for a significantly long period up to a year [18], [19]. Fig. 2 illustrates Stuxnet in a schematic form. One can view Stuxnet as a combination of deception and disclosure attacks.

2) *RQ-170*: In 2011, US operators lost control of an RQ-170 unmanned aerial vehicle (UAV) which subsequently landed in Iran. One speculation as to what caused this to occur is that Iranian forces jammed GPS communications followed by a spoof of GPS signals, thereby deceiving the drone into landing in the desired location [20]. In addition to this attack on a UAV, a number of studies have been carried out to show the potential threat of GPS spoofing on vehicles [21]. The RQ-170 attack can be viewed as a disruption attack followed by a deception attack.

3) *Ukraine Attack*: Traditional practice in power grids is to institute safeguards against physical faults [22] using protective devices. A singular departure from such occurrences happened in the Ukraine attack. This consisted of a series of attacks on Ukrainian power distribution networks causing outages as well as lasting damage in 2015. The first was introduced via phishing emails containing the Black Energy malware. Once it infiltrated the system, it enabled the attacker to steal critical data and study the system environment. This, in turn, enabled access to a more critical control level and allowed the spoofing of control commands [23]. That is, first there was a confidentiality breach, followed by an integrity breach. Finally, by overwriting the firmware in a few substations, the attacker was able to ensure remote inoperability of breakers, leading to an availability breach. In 2016, yet another attack was launched on a transmission station using the Crash Override malware.

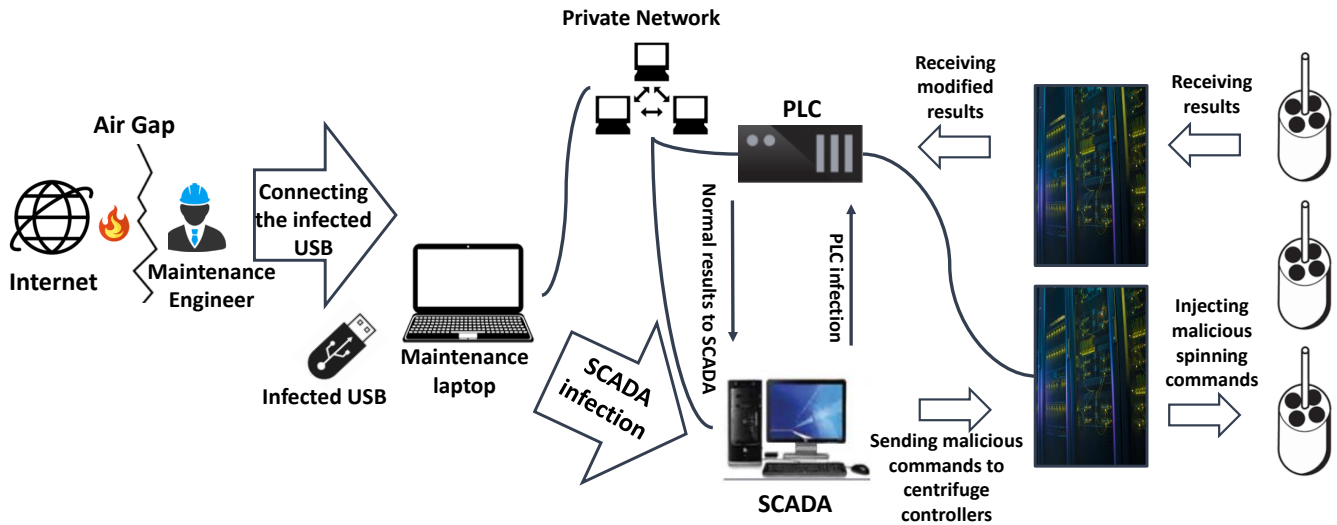


Fig. 2. Schematic figure of Stuxnet attack on nuclear enrichment facilities.

This malware could communicate directly with grid control software and its modular design enabled it to be modified to work for US or European grid protocols as well [24].

4) *Maroochy Attack*: In 2000, the Maroochy water services in Queensland, Australia, was attacked by a disgruntled employee. Motivated by revenge, he accomplished the attack by infiltrating the SCADA network of water services and altered the control signals. The attacker took control of 150 sewage pumping stations resulting in the evacuation of one million liters of untreated sewage, over a three-month period, into stormwater drains and on to local waterways [25]. This is clearly a deception attack/integrity breach on actuators.

5) *Jeep Hack*: Car hacking shows a large level of vulnerability that modern automotive systems seem to possess against adversarial actions. One of the examples was an (under control) attack on a Jeep which was driving in 70 mph on a highway in St. Louis, USA, where the car was hijacked remotely by attackers to show how various Electronic Control Units, from wiper to brake and engine systems, can be manipulated remotely through the cellular connection inside the vehicle [26]. Although this attack was set to be under control, it is claimed that remote car hacking can have life-threatening consequences for passenger vehicles in the future [27].

6) *Other Attacks*: The attacks listed above are by no means comprehensive. They are meant to be an overview of some of the major cyber-attacks that have had a noticeable impact on power and transportation infrastructures. The earliest cyber attack on critical infrastructure is reported to have occurred in 1982 when the sale of intentionally damaged control software to the Soviet

Union resulted in an explosion in Siberia [28]. Over the past five years, there have been several other cyber attacks on ground transportation infrastructures [29], the service industry, and the manufacturing industry to name a few (for a list of cyber-attacks refer to [30]–[32]). We have excluded physical attacks like the Metcalf sniper attack [33] that have occurred on a PG&E transmission substation in California leading to a large financial loss and pilot intended crash of Airbus [34]. Based on [35], two thirds of attacks have been initiated by phishing emails. A majority (70-80%) of attacks are abetted by insiders. 67% of the cyber threats are enabled by victim errors, 64% are directly introduced by hackers, and 38% by malware.

B. Current State of the Art in CPS Security

The FY 2019 US Presidents Budget includes \$15 billion of budget authority for cyber-security-related activities, a \$583.4 million (4.1 percent) increase above the FY 2018 Estimate [36], which indicates the level of attention being paid to this topic. As the problem of CPS security is of huge interest to the engineering community, it is not surprising that there is a large number of research investigations over the past decade. Earlier works such as [6]–[8], [37] brought to attention the fact that the topic of cyber-attacks is not of interest just to the cybersecurity community, but out of significantly broader interest. These works also demonstrated that component-wise solutions may not suffice, and instead, these threats must be analyzed from a comprehensive system and infrastructure perspective and that component-wise solutions may not suffice and need to be analyzed from system-wide and infrastructure-wide perspectives. Also as mentioned

above, DDD attacks have been discussed at length in [6], [38].

Issues of CPS security arise in a range of applications. On a daily basis, there are reports of cyberattacks in almost every sector that includes a cybercomponent. To give the readers a better sense of the impact of cyberattacks and the general problem of CPS security, in what follows, we expand on the impact in the context of power systems [28], [37], [39]–[55]. In particular, see [39] for definitions of security and [55] for a chapter on cybersecurity in smart grid control with comprehensive discussion on attacks by insiders and outsiders and countermeasures in a power system. The presence of a large number of subsystems in power systems implies that the impact of attacks vary significantly depending on where they occur. Broadly speaking, this impact can be summarized over the following three broad headings:

- 1) Transmission level: Attacks may happen in AGC control loops (generator governor control) [47], PSS, FACTS controller, and wide-area controllers [48]–[50]. Each of these cases may involve denial-of-service type attacks, hardware failures, control software failure, replay attacks, and data tampering attacks. Wide-area control is especially susceptible to attacks as substantive long-distance sensitive communication is required for WAC, opening up many vulnerable points for attackers to intrude through. For example, if the computation of the wide-area control signals is happening in a cloud, then attackers may cause DoS, data tampering and other such attacks to either degrade the closed-loop CPS performance or completely destabilize the system. Direct hardware attacks on the bare metal of the shared virtual computers used in the cloud for performing these computations, or software attacks on their data storage units and hypervisors, are also highly possible.
- 2) Distribution level: Attacks can happen in islanded microgrids, grid-connected microgrids, or networked microgrids [51]. Similarly, in a distribution-level power grid, an attacker may change the current and voltage setpoints of the power converters that connect the renewable resources to the grid to wrong values such that the power flow equations no longer have any feasible solution, forcing the grid to enter into an unsafe zone [53]. Another important point is that majority of communication protocols used for microgrid operation and control are executed using wireless communication, where security may be a serious concern. If this communication is hacked, and, as

a result, messages do not reach the microgrid controllers from supervisory management layer, then severe issues of frequency stability and voltage stability can arise.

- 3) Market level: False data injection in electricity markets has been investigated in [52], where a convex optimization problem is solved by the attacker to find which nodal price of Ex-Post market must be manipulated to maximize the financial profit of the attacker.

Similar to power systems, transportation systems experience a wide range of impact depending on the specific subsystem that is targeted. Unmanned aerial vehicles and their vulnerabilities are addressed in [56]. General transportation systems have been examined in [57]–[69], and industrial systems in [70]–[73]. As evidenced by the Jeep-Hack and Stuxnet examples, the impact of cyber-attacks can be significant, as they represent safety-critical infrastructures.

In addition to the above applications, CPS security has been investigated in [74] for protection methods in nuclear power plants, motivated by the cyberattack in 2014. In [75], a review on deception and disruption attacks in CPSs has been done. The importance of security in SCADA has been discussed in [70], [71] and in Modbus control systems in [72]. A survey on information and communication-based security aspects of industrial control systems is done by [76]. The repeated occurrence of the term *security* in the recent control systems survey [77] is another indicator of the importance of this topic.

C. Contributions of this Paper

The purpose of this paper is to present an overview of the research activities in the area of CPS security in two critical infrastructures, *power* and *transportation*. We provide this overview with two objectives in mind. The first is to provide a broad system and control perspective within which most of the research contributions to-date can be viewed. The second objective is to map these contributions to a CIA-taxonomy of security breaches and DDD-taxonomy of attack models. We accomplish both of these objectives in Section II, where all systems and control defense mechanisms are grouped under three headings of Prevention, Resilience, and Detection & Isolation, based on the underlying concept employed. A metric that quantifies CPS security is also proposed. A summary and suggestions for future research are included in Section IV.

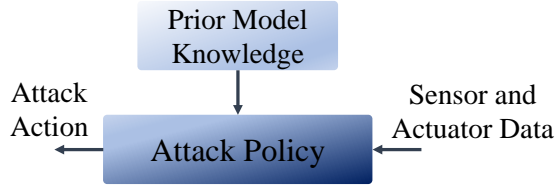


Fig. 3. Attacks differ from random faults in the sense that they *may* have access to the system model and may leverage this knowledge to harm more effectively.

II. SYSTEMS AND CONTROL METHODS FOR CPS SECURITY

With the overall importance of CPS security mentioned in the introduction, we now focus on the details of the intersection of this topic with closed-loop control systems. Given that control systems consist of key components such as sensors which measure key variables of interest and actuators that synthesize control inputs that help the system perform tasks of regulation and tracking, it is important the CPS security focuses on sensors and actuators. In addition to these components, another important component of a control system is a communication network often used to relay crucial information to relevant places. Therefore CPS security needs to include its focus not only on sensors and actuators but also the underlying communication network.

It is essential to model the adversary and its available resources. One such conceptual model is illustrated in Fig. 3. It should be noted that attacks on CPSs often are confused with the faults that may occur randomly and are oblivious of the system model. Attacks, unlike faults, through eavesdropping, publicly available knowledge, operator faults, and so on, may have access to the system model and make use of this knowledge to design smarter and more effective attacks [11]. This is one of the reasons that a system and control level of defense is required against such attacks. However, in order to develop a systematic set of methodologies that provides CPS security for control systems, one needs to begin with an analysis of the different type of attacks that are possible. Attack models that characterize the capabilities of the attacker, such as their computational power, the type of access they may have, the data they collect, and their collaborative capabilities are very much needed. One such model is developed in [38] which is based on the available resources to an attacker. These models need to be designed using questions such as the following: What are the points and signals that attackers have access to? What can they do precisely on the signals? What are their limitations? These must

be stated clearly in order to understand the logic behind the associated defense mechanisms, to understand the level of conservatism, to compare with other security mechanisms, and to improve the defense mechanisms². The DDD attack models mentioned in the introduction provide a starting point for such designs and form our primary focus in this paper. In Fig. 1, we indicate where these attacks can occur in a typical control system. This figure illustrates a high level so-called *attack surface*, i.e. the vulnerable points, in a CPS control structures. Each of these attacks is discussed further in what follows.

A. Attack Models

Disclosure Attacks: Disclosure attacks try to find access to informative signals or obtain some conclusive information about them. A successful disclosure attack may directly use or sell the obtained data or use them in order to extract other information about the system³. Disclosed, or indirectly interfered data, can also be used to design smarter attacks in the future. One of the reasons that disclosure attacks are, despite their simple definitions, more vital in security is that the detection of disclosure attacks usually take a long time, i.e. the attacks are in the so-called *zero days* mode. It has been proved that in some systems, the attacks that use the system's information, potentially gained via an initial disclosure attack, can destabilize the closed-loop system. Disclosure attacks may take place on either sensor measurements, control computations, or actuation signals, which are indicated in Fig. 1, respectively, by A_3 , A_5 , and A_9 .

Deception Attacks: Deception attacks or false data injection (FDI) are accomplished when the signals are somehow different from what their true value. They can occur in three distinct location of the closed-loop system (see Fig. 1): (i) Sensor attacks, which change the operating conditions ruining the fidelity of the measurements (A_2 in Fig. 1), (ii) Actuation attacks, which deviate the control signals from the values they have to be (A_8 in Fig. 1), and (iii) Computational attacks, which alter the control law (A_6 in Fig. 1). Deception attacks are the strongest attacks in terms of the level of damages they

²There is a wide spectrum of assumptions that can be made on attacks. Based on *Shannon's Maxim*, the enemy knows the system. The Shannon's paradigm is in contrast to *Security by Obscurity* in which the security is guaranteed by assumptions on the secrecy of the system's data [78]. The best security solutions are those that with the assumptions on which data are shared or under a direct access of the public (or non-trusted insiders), the attacks are defined thoroughly. This is done in computer security via *Access Control* tables [79].

³The latter is called *inference attacks* which are to infer the private information of a system using the access to some potentially legitimate parts of the system [80].

may create. For example, it is easy to imagine how a deception attack can quickly destabilize the closed-loop system.

Disruption Attacks: The intentional lack of information is classified in disruption attacks. Disruption attacks are also called *Denial of Service (DoS)* or *Jamming*. DoS attacks can be on sensor data (A_1), in the potential existent network for computing the control input (A_4) or on the actuation signals (A_7).

In addition to the above attacker perspective, a defender's perspective is important as well. One can argue that the focus of cyber-security [35] is from such a perspective and seeks to provide protection to a system by securing key components through firewall, encryption, etc. However, as the complexity of the overall system increases, it becomes difficult to ensure that a defense mechanism of the entire system can be guaranteed only through protection of every one of its individual components. Rather, a systems perspective is needed, which focuses on prevention of these attacks, and if attacks do occur, ensure that the system is resilient by containing the impact of these threats, and/or detect and isolate these threats and recover quickly. This is the focus of the next subsection.

B. Defense Mechanisms

In this paper, we characterize three defense mechanisms, employed either prior to, or during the occurrence of the attack, to ensure CPS security. In order to present these three mechanisms in a unified manner, we consider an overall threat assessment metric illustrated in Fig. 4. The variable $I(t)$ denotes the vulnerability of the underlying system. Our thesis is that in order to develop a comprehensive defense mechanism for security, all three components of prevention (to postpone the onset of an attack), resilience (to contain the maximum impact of the attack and operate as closely to normal as possible), and detection and isolation (to identify the source of the attack, isolate the corrupted subsystems, and restore the normal mode as quickly as possible) are equally important and have to be layered in. If the defense strategy relies on detection alone, then the threat of the same attack recurring is not minimized. In addition, in the interval between the onset of the attack and detection, the system could experience a significant damage. A good example of such a scenario is the Stuxnet [81]. Maroochy is also an outcome of the lack of detection and resilience mechanisms [25]. The absence of resilience in RQ-170 is apparent, as the control system was unable to defend against the spoofing attack. It could be viewed that preventive mechanisms are active prior to

the attack whereas resilience and detection and isolation mechanisms are invoked during the attacks and until the system is restored to normal operation.

Each of the three defense mechanisms represents a certain point of view of ensuring security and therefore corresponds to a certain control methodology and related systems tools. The goals, the tools used, and the resulting performance are therefore intimately connected with the defense mechanism. In the sections that follow, the control methodology, the tools, and the results reported in the literature are provided in detail.

1) *Prevention Mechanisms:* Methods in this category are to guard against disclosure attacks, which start from an infiltration stage to steal the vital information of the system and leverage them in future attacks. A simple example of this stage is through an insider (like the case in Maroochy attack) or *Advanced Persistent Threats (APTs)*, an attack in which the access of the system is given to an unauthorized user in a stealthy fashion for an extensive period of time [82]. We group defense mechanisms in this category into two cases, Cryptography and Randomization. The former is a long-standing topic with its underpinnings in computer science and extensively studied [83]. The latter, on the other hand, is grounded in control theory and has a rich history in robust control problems [84].

(i) Cryptography:

Cryptography is the science of constructing and analyzing protocols that prevent third parties or the public from reading private messages. Modern cryptography started after World War II making use of the concept of public key [85], Fig. 5 (a). The idea behind cryptography is to make sure that the data between sender and receiver cannot be revealed via an unauthorized user. Authentication can be checked with sharing the secure acknowledge messages. Fig. 5 (b) shows why making use of encryption and decryption is helpful in maintaining the confidentiality of data. However, if the eavesdropper has access to the points between decryptor and B, or encryptor and A, it can still read the message. As A and B can be any of three components, sensors, communication network, or actuators, shown in Fig. 1, this kind of attacks may take place in CPS. However, if a form of encryption that allows computation on ciphertexts is used, it can prevent the eavesdropper from accessing these messages. References [86] and [87] discuss a homomorphic cryptographic platform with closed-loop stability analysis to address. Applications of this method to secure transportation systems is discussed in [88]. A key management scheme for privacy issues in SCADA systems is also proposed in [89]. A polynomial-based scheme for a symmetric key generation in SCADA

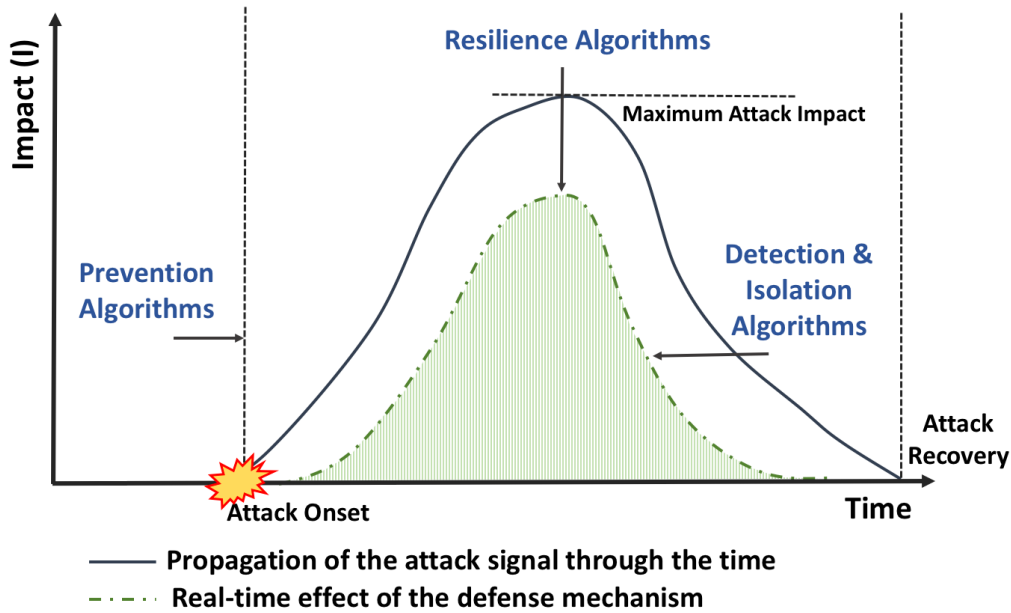


Fig. 4. Threat assessment of a CPS system and its reduction due to three defense mechanisms, based on prevention, resilience, and detection isolation. The variable I denotes a quantity of interest that signifies the system vulnerability.

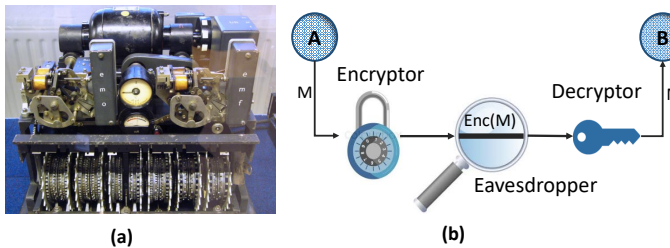


Fig. 5. (a) German Lorenz cipher machine, used in World War II to encrypt very-high-level messages, (b) Encryption and Decryption's roles in confidentiality.

is discussed in [90] and a cryptographic framework for the threats in cyber-physical systems is analyzed in [91]. Also [62] proposes a similarity technique between encrypted data to preserve the privacy of ride-sharing autonomous vehicles. Secure estimation with privacy assurance of the encoded data is discussed in [92].

(ii) Randomization:

Randomization as a defensive tool is utilized to confuse the potential attacker and has been proved useful whenever the predictability of the deterministic rules may be leveraged by the attackers to obtain key information of the system, potentially for conducting much more advanced attacks. Randomized algorithms have proved useful in a wide range of mathematical and algorithmic problems [93]. Randomization as a robust control tech-

nique has been proved useful in the last decade [84], [94]. Most of the techniques which aim to provide a confidentiality service use randomization of data. An example of masking the private data in the presence of an adversarial agent is [95]. The regular (non-adversarial) agents obtain the correct states and compute the average consensus using the masked data with a noise. A similar technique in a network of agents is proposed by [12] where the privacy of the states is preserved in an approximate manner. The latter method uses the differential privacy technique to tackle the problem [96], [97]. The idea there is to use an alternative randomized data set to maintain the main data set from confidentiality breaches. The idea of randomization has been proposed also in *adversarial machine learning* [98]. In [99], the idea of masking data to achieve the exact average consensus in the presence of an eavesdropper is proposed. [100] proposes a random gain selection method to secure the closed loop system against disclosure attacks on A_3 and A_9 .

2) *Resilience Mechanisms*: Resilience is a property defined as the ability to withstand and recover from severe stresses induced by natural stresses or deliberate attacks [101]–[104]. Resilience may not be an inherent property of the system and needs to be bestowed through a suitable design of the control system. A large number of the methods reported in the literature can be viewed

as a resilience-increasing mechanism. In what follows, we group these methods into four types, which include Game Theory, Mean Subsequence Reduced Algorithms, Trust-Based Approaches, and Event-Triggered Control.

(i) Game-Theoretic Methods:

A game-theoretic approach that provides resilience consists of trying to maximize the price of attacking a system or minimize the damage that an attacker can apply to the system. Game theory, in a nutshell, is an interaction between two or multiple players, where each player tries to optimize some objective function. The challenging part of games is that the objective function of a player depends on the choices of at least one other player in the game. Thus, each player can not optimize its objective independent of choices of other players.

There is a vast literature on game-theoretic approaches to the security and resilience of control systems since the past decade. These approaches vary depending on the structure of the cyber-physical system or based on the specific type of malicious action acting on the cyber layer. Each of these two approaches is discussed briefly as follows:

The first approach is to model the game for the security of CPS based on the structure of the cyber and the physical layers [105]–[113]. One of the common approaches is to define games in both physical and cyber layers. More formally, considering that in the physical layer, the evolution of the system is modeled with the following general dynamics

$$\dot{x}(t) = g(t, x, u, w, \eta(t, \alpha, \beta)), \quad (1)$$

where $g(\cdot)$ is a nonlinear function of the state x , the control action u , the disturbance effect w and $\eta(t, \alpha, \beta)$ which is a switching signal indicating the state of the cyber-layer. Here t is the time step and α and β are the actions of the attacker and defender in the cyber layer, respectively. Parameter η evolves in discrete time, e.g., Markov jump model, in the cyber-layer which makes the overall hybrid system shown in Fig. 6. The concept of *games-in-games* reflects two interconnected games, one in the physical layer and the other in the cyber layer. At the physical layer control system, a zero-sum differential game between the robust controller and the disturbance is used to design an \mathcal{H}_∞ controller for achieving robust performance for uncertain parameters or disturbances [114]. At the cyber layer defense system, a zero-sum stochastic game between a defender and an attacker is used to design an optimal cyber policy for ensuring system security [115].

Another approach is based on the type of the attack and malicious behaviour [116]–[120]. More particularly, in this case, depending on the type of adversarial or

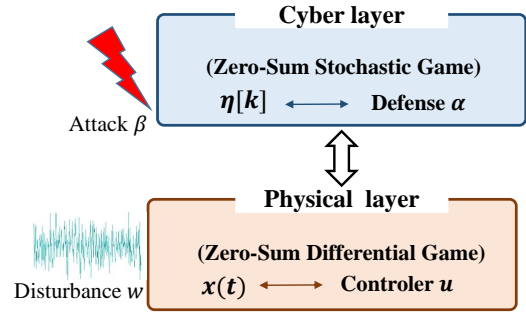


Fig. 6. Schematic figure of games in physical and cyber layers.

malicious behavior that is active or passive, an appropriate game strategy, e.g., Nash or Stackelberg, has been discussed. More specifically, the interaction between a jammer and a passive defender can be reasonably captured by a Stackelberg game in that the jammer is an active player who sends signals at an intended level to interfere with communication channels while the legitimate user rationally defends itself from such an attack. On the other hand, in the case where the defending user behaves actively or either side has an information advantage, the Nash equilibrium becomes a reasonable solution concept [121], [122]. Another example is eavesdropping action. As eavesdropping is a passive attack where an eavesdropper receives information that leaks from a communication channel, the behavior of an eavesdropper can be viewed as that of a follower in a Stackelberg game against a user who employs active defenses [123]. Recently, an attacker-defender game framework on networks with unknown topology is proposed in which the defender injects control inputs to reach a synchronization while attenuating the (worst case) attack signal from adversarial agents [124], [125].

In addition to the above game-theoretic approaches, other approaches have been proposed as well. For instance, the evolution of network control systems has been modeled as cooperative games [126] and the resilience of these cooperative games to the actions of adversarial agents or communication failures have been investigated. In [109], [127], [128] the effect of adversarial agents and communication failures on a cooperative game was discussed. Moreover, in [129] a zero-sum game for the problem of estimation under attacked sensors is suggested. In order to address the threats on cloud-based control systems, a signaling game is designed to model the trust between the defender and the threats [130], [131].

(ii) Mean Subsequence Reduced (MSR) Algorithms:

MSR is a resilient control approach in which at each time of the updates, the controller, in order to not get affected by the attacks, ignores the suspicious values and computes the control input. One of the well-known applications of MSR algorithms is against *Byzantine* threats. Byzantine nodes are the computational nodes that, in an adversarial manner, send inconsistent information to their neighbors [132]–[137]. Byzantine attacks have been investigated in the '80s in computer science (e.g., [134]). Recently, Byzantine consensus is getting revisited, again in the computer science community, to develop secure and reliable cryptocurrencies (see, e.g., [138]). MSR algorithms have been applied to distributed computational problems, including consensus [132], [133], [139], distributed state estimation [140], synchronization [136], clock synchronization [141], and distributed optimization [142]. MSR algorithms act as local filters, in which, by assuming that the maximum number f of malicious agents in the network is known, every node disregards f largest and f smallest values from its neighbors. Hence, there is no need to have a knowledge about the global topology⁴. In these studies, network-theoretic necessary and sufficient conditions for the convergence of MSR algorithms have been introduced. The critical property is called *graph robustness* which is a measure of connectivity within a graph and characterizes how well groups within the network are connected via multiple paths. Network robustness was first introduced by [132] for the resilient consensus of agents with first-order interaction dynamics. Graph robustness can be determined with linear programming [144] and in general was shown in [135] to be a computationally hard problem but can be obtained almost surely in random large networks.

(iii) Trust-Based Approaches:

Trust-based methods have been investigated for not only cyber-security but also general problems where some of the subsystems may be untrustworthy. References [145]–[147] have used a multi-agent approach in order to improve overall resilience. This strategy is equivalent to *redundancy-based approaches* in graphs and is based on the assumption that if the number of attacks is sufficiently small, correct information can flow through the paths formed by trusted nodes. Trust-based approaches have been investigated in [148], [149] to spread the information in a multi-agent system in the presence of adversarial nodes. An alternative way is to define a function of trust and update the trust value between the nodes as the system evolves. In such

approaches, the reliance and effects of each healthy node on its neighbors is a function of the trust value. A survey on how to use trust models in different network domains is [150]. Trust-based approaches have been used mainly for defense against deception attacks and more often in the context of sensor networks [151], [152] and in DC microgrid control [153].

(iv) Event-Triggered Control:

Based on how frequent the attacks occur, event-triggered control schemes instead of time-triggered schemes emerged as appropriate tools to increase the resilience of control systems (for an introduction to event-triggered control, refer to [154]). Sensor disruption attacks (also called jamming or DoS), in some time intervals, on measurements (A_1 in Fig. 1), are among the threats whose effects can be mitigated via appropriate event-triggered control policies. Event-triggered control techniques have been used to design the sequence of control inputs $u(t_k)$ in order to preserve the input to state stability of the closed-loop system. The DoS attacks in these works are limited by the frequency and length. The application of event-triggered control to the resilience of cyber-physical systems has been studied in [15], [155]–[158]. In these works, the control input is sample-and-hold in the time sequence of $t_k - t_{k-1} > \delta$ instead of periodic sampled-data systems. The triggering function to generate a new control input is based on the errors of state variables $x(t_k) - x(t)$. In addition to the case of disruption attacks, mitigating the effects of computational deception attacks (A_6 in Fig. 1) via event-triggered control techniques has been investigated [159], [160].

(v) Other Approaches:

In addition to the above four methods, resilience mechanisms have been proposed using a variety of other control methods. Reference [161], for instance, suggests a resilient control assuming that the probability of the disruption attacks at each time is at least partially known. A sliding mode control for the resilience against DoS attacks in nonlinear and chaotic systems has been proposed in [162]. An acknowledge-based cheating scheme is proposed in [163]. Another technique is [164], where it proposes a decomposition of Kalman filters as a weighted sum of local state estimates under sparse sensor deception attacks (A_2) into a more secure estimation framework. Another recent work is [100] where for defending against the deception attacks on the cyber layer, an information retrieval approach is hired so that the state feedback, at each time step, makes use of healthy and unattacked data. Finally, in [165], a Lyapunov stability method is employed for DoS attacks in wide-area control of power systems. In [100], a distributed information retrieval approach is proposed against the

⁴One reason that in such algorithms detection is not utilized is that detection-based approaches require global topology of the network and have a heavy computational burden on each node [143].

network deception attacks (A_6). Yet another tool used for obtaining resilience, mainly against disclosure attacks, is the use of privacy loss as a penalty component in the underlying cost function (e.g., [166]). By constructing an information theoretic measure, I , given by between two data sets X and Y ,

$$I(X; Y) = H(X) - H(X|Y), \quad (2)$$

where H is the entropy, to form the penalty component, the approach consists of the optimization of this cost function with and without the penalty component and evaluating the resulting trade-off.

3) *Detection and Isolation Mechanisms*: We now direct our attention to the third component illustrated in Fig. 1, detection & isolation. As the name suggests, this corresponds to a quick detection and isolation of the attack. These mechanisms, similar to the resilience described in Section II-C, get activated after the attack, and constitutes the bulk of the research in CPS security from the controls community. It should be noted that methods such as patch and pray [35], stemming from the computer science community, can be grouped under this category as well. This is commonly used in cybersecurity, and has to do with responding to existing threats and hoping that the results will deter future attacks.

A detection mechanism usually uncovers the existence of an attack by monitoring its effects on the outputs of the system. In addition to detecting the existence of an attack, stronger strategies can be proposed to *identify* (or *localize*) the set of nodes/signals that are attacked (e.g., [167], [168]). If the effect of the attacks signal cannot be traced by the outputs, they are called *covert* [11] or *stealthy* attacks [169]. The survey papers [73], [170] has reviewed some detection mechanisms for deception, as well as disruption attacks in cyber-physical systems. Detection tools stemming from the control-theoretic literature have been used primarily against deception attacks while in the computer-science literature have been employed for confidentiality attacks as well [5].

In what follows, we classify all detection & isolation methods proposed in the controls literature in to four categories which include Observer-Based Techniques, Watermarking, Baiting, and Learning-Based Anomaly Detection.

(i) Observer-based Techniques:

Observers in control systems are designed to estimate unmeasurable state variables. Detection can therefore be enabled using observers and a comparison between the resulting state estimates in the healthy and attacked cases, often termed *residues*. If the residues exceed a certain threshold, an alarm is activated [38]. A common

method used for designing such observers is geometric control theory [171], [172]. Termed Unknown Input Observers, the approach consists of using this method in the presence of unknown input that here it refers to the attacked inputs which cannot be relied upon. Another example can be found in [167], where deception and disruption attacks on both sensors and actuators are modeled as linear algebraic conditions for detection and identification of the attacked sets. Reference [167] also proposes centralized and distributed filters. The identification phase, in particular, is based on combinatorial search on all potential sets of attacks. The same ideas have been used in multi-agent systems in the presence of misbehaving nodes [143], [173], [174]. Moreover, [175] uses the same technique on sensor attacks (A_2 in Fig. 1) and analyzes the reachable sets of attacks. However, in these works, different matrices for prediction of the outputs and detection have to be used which take significant amount of memory and computational complexities. A scalable version of these works is [176] where attack-free sensors using a Satisfiability Modulo Theory (SMT) are identified with Luenberger observers.

A specific subcase of observers corresponds to the case when the underlying model is static. For example, if

$$z = Hx + e, \quad (3)$$

where H is the Jacobian matrix, z is the measurement, x is the state variables, and e is the measurement/modeling noise, the goal is to estimate x using z , in the presence of attacks, which may either be on the sensor z or on H . This problem is ubiquitous in power systems where measurements of either voltage or current are not possible everywhere in the network but have to be estimated [177]. For example, if deception attacks on sensors (e.g., A_2 in Fig. 1) occur, references [37], [178]–[181] propose a solution based on robust signal processing techniques such as Least Trimmed Squares (LTS) to minimize the residue. In general, the underlying idea here is to treating corrupted data and ignore them as outliers before doing the required analysis. Application of such works on Automatic Generation Control (AGC) and SCADA is studied in [182].

(ii) Watermarking:

The concept of Watermarking is often used to authenticate an entity. For example, a watermark on a piece of paper is effectively a signature that cannot be erased. This concept is used in the context of detection and isolation by constructing a suitable metric and a perturbation of the input signal such that the metric dropping below a certain threshold signals the presence of an attacker [183]. Particular success of the watermarking approach

has been reported in the context of replay attacks and is discussed below.

A replay attack corresponds to one where the attacker hijacks the sensors or eavesdrops for a certain amount of time and replays the same data over and over again. In particular, a recorded horizon of data, in normal conditions, is sent to the monitors of the operators so that the alarms would not be triggered and the operators are tricked into thinking that the closed-loop system is operating normally [81], [183]. Replay attacks are sometimes grouped under the category of disruption attacks as they cause the current data to become unavailable. Obviously they can also be viewed as a deception attack [73].

Replay attacks can be overcome using watermarking [19] by perturbing an optimal control input in a particular manner. In order to ensure that the controller does not become overly sub-optimal, [19] discusses methods to maximize the likelihood of attack detection while constraining the effect of the watermark on ideal system operation. An application of watermarking in SCADA networks is introduced in [184]. A watermarking-based approach to defend against replay attacks in multi-agent systems (A_6) is proposed in [185]. In [186], a multiplicative sensor based watermark is used to detect replay attacks on sensors. In [187], the same multiplicative watermarking technique is used to detect *routing attacks* where the wires of the sensors are intentionally swapped (A_2). Motivated by the replay attacks, [19], [188] posit a form of replay attacks on linear stochastic systems and propose a χ^2 -detection method to alert the system operator of the presence of an adversary conducting a replay attack.

The effects of watermarking on a more general set of sensor deception attacks is studied in [189]. It is also shown that a set of uncompromised actuators, each injecting its own added watermark signal, can be used to check the honesty of the sensors which should report back measurements that contain a history of the effect of watermarking. More specifically, [189] analyzes a number of systems including SISO (Single Input, Single Output) and MIMO (Multi-Input, Multi-Output) linear systems with Gaussian noise models and shows that the asymptotic behavior of a system with the watermark constrains the damage a sensor spoofing attacker can do without being undetected. Dynamic watermarking has been validated in power systems in [47]. A combination of Gaussian and Bernoulli processes to generate a watermarking signal is suggested in [190] for general detection of deception attacks on sensors and actuators. The same idea is proposed for use against covert attacks (on both A_2 and A_8) in [191] by inserting a modulation system

between A_8 and the actuation to misguide and confuse the attacker.

(iii) Baiting:

Like the watermarking case, suppose we begin with a worst-case scenario where the attacker is assumed to have complete access to the entire system dynamics, all of its sensors, and all of its actuators. The question is if one can design a method by which such an attacker cannot remain stealthy and can be revealed. These methods, termed *Baiting* [192] and *Moving Target* [193], then seek to design the system in a way such that this worst-case scenario can be detected. In [169], [192], the method consists of baiting the attacker to reveal themselves by introducing an arbitrary offset in the system dynamics which guarantees that a worst-case attack proposed in [194] can be quickly detected. By introducing virtual state variables in addition to the original system state variables, [195], [196] offer a method to prevent an eavesdropping attacker from inferring system knowledge, A , from the system output and control signals. This lack of knowledge of A prevents the attacker from achieving worst-case stealthy attacks. Moving Target Defenses (MTD), in a general cyber-security context, are defense schemes in which the defender varies system attributes in order to introduce unpredictability into the attack surface [197]. The moving target approach can also be utilized to detect the presence of attacks on both the control inputs and sensor measurements [196].

(iv) Learning-Based Anomaly Detection:

Anomaly detection employs technique that uses machine learning to detect the presence of suspicious data [198]. For a review on applications of anomaly detection in computer networks, the reader is referred to [199], [200]. Anomaly detection techniques in power systems are introduced in [201]. Applications of Neural Networks (NNs) and Bayesian learning are studied for anomaly detection in the context of security in the presence of attacks [202]–[206]. Particularly, in the latter, it is assumed that the Byzantine nodes are aware of the true hypothesis and they are compromised to degrade detection performance. The problem of distributed detection is formulated as a *Binary hypothesis test* by the sensors. A direct application of this work is in [207] to detect deception attacks on Phasor Measurement Units (PMUs) data. Also, it is used in [208] for SCADA networks, where a *whitelist* is generated by learning the network legitimate traffic for a given period of time and is used for detection of other threats. An unsupervised detection method is employed in [209] to detect anomalies.

There are several works that discuss designing anomaly detectors through other tools. In this direction, [210] uses a Round-Robin algorithm for localizing the

deception attacks on power systems. Another localizing work in power systems is [211], where a graph-theoretic technique is used to localize where the effect of an attack exists in a wide-area control architecture. A recursive distributed Kalman filter in the presence of sensor attacks (A_2) is developed in [212], [213]. Some works also combine the resiliency with detection methods and investigate the resilience of the detection tools under attacked conditions (e.g., [214]). In [215], a majority voting is utilized for detection of deception attacks in smart grid. Application of Kalman filter in detection of replay attacks (A_2) in SCADA systems has been discussed in [216].

C. Security Metric

With various defense mechanisms and underlying systems and control tools described above, one may need to ascertain the suitability of one method over another for a given application. For this purpose, a security metric that quantifies the benefit obtainable from a given method is needed. There is a rich history in the literature on defining metrics for the security of systems (e.g., [38], [103], [217]). The following metric is proposed in this paper:

$$\mathcal{S}(I) = \frac{1}{T} \frac{\sum_{k=0}^{k=T} \mathcal{D}(I^*[k] - I[k])}{\sum_{k=0}^{k=T} \mathcal{D}(I^*[k])}, \quad (4)$$

where $\mathcal{D}(z)$ is a norm of z , I^* is the value of the variable I in a nominal, healthy condition, u is an external input, and $[0, T]$ is the period of interest. Likewise, the continuous-time version of (4) can be defined. Here, $\mathcal{S}(I)$ represents how much the system is affected by the attack. I vary depending on the application and threat assessment. For example, I can be in the form of mutual information [166] or the difference of agents' values and their consensus value, if the goal is to reach the consensus amongst the agents [143]. Some other works, e.g., [37], [218], define security metric as the capability of the attacks' undetectability.

The security metric in (4) can be used for a resilient control design by incorporating an additional term to the standard cost function used in optimal control as

$$\mathcal{J} = \sum_{k=1}^{k=\infty} x^T[k]Qx[k] + u^T[k]Ru[k] + \mathcal{S}(I). \quad (5)$$

Such an addition obviously implies that a trade-off is introduced between resilient control and optimal control. It is interesting note that the appropriate trade-off between resilience an optimality is labelled as an *intelligent* solution in transportation systems (see for example, [57], [63], [66]).

In summary, in this section, we have presented attack models as well as three classes of defense mechanisms that have been proposed in the literature using systems and control methods. A threat assessment metric was proposed (in Fig. 4) in order to view these three methods in a unified manner, and quantified as in (4).

The threat assessment metric involves the identification of a suitable variable I that best denotes the most vulnerable quantity in a system under attack. It also includes the appropriate norm \mathcal{D} that provides a suitable measure of the threat. In the next section, we discuss how the system threat and the corresponding variable I can be assessed. The role of the system network topology in this regard is also analyzed.

III. THREAT ASSESSMENT AND NETWORK TOPOLOGIES

In this section, we review various threat assessment tools proposed in the literature. We also analyze the effect of network topologies on the three defense mechanisms discussed in Section II.

A. Threat Assessment

One can argue that even prior to assembling any defense mechanism and to understand which variables to be used for defining I in (4) for guarding against attacks, an overall analysis of the system vulnerability and a threat assessment needs to be carried out. In what follows we survey various methods that have been proposed in the literature towards such a threat assessment

One straightforward approach for threat assessment is to use a test bed to implement different attacks [219]. Another well-known technique is so-called *attack trees*, where the attacker's reachable points and possibilities are exhibited on an attack graph [220], [221]. A rich introduction on attack graphs can be found in [221]. Other quantitative vulnerability assessments in SCADA are discussed in [222], [223]. For survey of threat assessment, the reader is referred to [224].

The first step in threat assessment is the characterization of the worst case scenarios and the maximum damage that each attack can cause. Determining the conditions under which the maximum damage can be caused to the system is also part of the analysis. A good example of such analyses is [225] where it is shown that in a multi-agent system, attacks, on the root nodes can destabilize the entire system with the access of at least one of its eigenvalues. Attack analysis mainly is carried out with the premise that the detection cannot be achieved by usual detection filters. This might be due to possibility of *zero dynamic attacks* or *stealthy attacks*, where in the

former there are cases that the measured values are zero in the sampling times and the attack hides itself between the samples [226] and in the latter the attack affects the measurement so that it become the same as at least one non-attacked case. The stealthiness of an attack is usually translated into certain algebraic conditions [194] in the underlying system. Another example of attack analysis for introducing undetectable attack is discussed in [174]. In [227], [228], Kullback-Leibler divergence is employed to develop a stealthiness and obtain worst-case attack policies as a trade-off between system performance degradation and attack stealthiness. In [229], [230], worst case deception attacks are analyzed in stochastic systems and the number of sensors to secure the system using a Kalman filter approach is proposed. Attacks on Kalman filters have been also analyzed in [231]. Moreover, in [232] a Hidden Markov and a Neural Network model are used to classify the attacks. The detectability of the cyber-attacks on state estimation problem (3) with graph-theoretical algorithms is analyzed in [233]. In [234], stealthy scenarios of sensor deception attacks in discrete-event systems are investigated through an *insertion-deletion* structure. Another example of such investigations is [235] where *insecurity* conditions that deception attacks remain undetected is studied. In [174], *zero state inducing* attacks (on A_2) are introduced where the output of the system with such attacks would remain the same as the case when initial conditions are zero, with the assumption that the initial conditions cannot be altered by the attackers. Another type of attack arises when in sampled-data systems, the actuation hold is faster than sensing sampling times [226], [236]–[238]. In these works, a *zero-dynamic* output can be injected to the system so that while to the system operators it may appear that the output remains at zero, the actual system response is becoming unbounded. In [227], [239], the degradation of system performance under a linear attack policy on A_2 is analyzed. The timing of DoS attacks (A_1) is discussed in [240]. The paper [241] investigates the worst case attacks on state estimators (3). An attack analysis on SCADA water networks is discussed in [242]. An optimization-based analysis on a single malicious agent in a network (A_6) is analyzed in [120]. [52] is an example of threat assessment for electricity markets.

B. Effects of the Network Topology

Another important aspect that should be addressed when it comes to CPS security is the cost required to reduce I in (4). This cost is in general dependent on the underlying network topology. In this subsection, we explore

the relation between the underlying network topology in a CPS and the three defense mechanisms discussed in Section II. We discuss how prevention mechanisms may require a more dense graph, i.e. more number of edges, than what resilience mechanisms would require, and therefore relatively more expensive; resilience strategies in turn require more edges than prevention-based ones would. This also corresponds to the decreasing level of conservatism between these three defense mechanisms. Prevention mechanisms can be viewed as being most conservative, as they are designed assuming that very little is known about the system as well as the attack; in comparison, resilience mechanisms require more knowledge, and detection mechanisms require even more information. In addition, we can argue that as the information about the attack becomes less, the strength of the defense can be increased by making the corresponding graph topology denser. In the following section, we discuss the relation between network topology and the resulting properties of the three defense mechanisms. We begin with a few definitions before discussing the network topology properties.

Definition 1: (Some Graph Definitions): An undirected graph is denoted by $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$, where $\mathcal{V} = \{v_1, v_2, \dots, v_n\}$ is a set of nodes (or vertices) and $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$ is the set of edges. The neighbors of node $v_i \in \mathcal{V}$ are given by the set $\mathcal{N}_i = \{v_j \in \mathcal{V} \mid (v_i, v_j) \in \mathcal{E}\}$ and the degree of node v_i is $d_i = |\mathcal{N}_i|$. A graph is called connected if there exists a path between any couple of nodes in \mathcal{G} . The *edge-boundary* of a set of nodes $S \subset \mathcal{V}$ is given by $\partial S = \{(v_i, v_j) \in \mathcal{E} \mid v_i \in S, v_j \in \mathcal{V} \setminus S\}$. The *isoperimetric constant* of G is defined as [243]

$$i(G) \triangleq \min_{S \subset \mathcal{V}, |S| \leq \frac{n}{2}} \frac{|\partial S|}{|S|}. \quad (6)$$

By choosing S as the vertex with the smallest degree we obtain $i(G) \leq \min_i d_i \triangleq d_{\min}$.

1) *On Prevention Mechanisms:* The effect of the structure of the underlying network has been studied in the context of prevention mechanisms using the concept of the *network expansion*. Network expansion, which is characterized by the isoperimetric or Cheeger constant $i(\mathcal{G})$, introduces how many edges connects any subset of nodes to the rest of the network. Network expansion has various applications in secure network coding and information diffusion in the networks [244], [245]. This network connectivity measure, as we will see later, is the strongest compared to other well-known measures. This means that having a secure network to be preventive to attacks demands a high level of connectivity.

2) *On Resilience Mechanisms:* A network connectivity measure used in the literature for ensuring the system

resilience is called *network robustness*. In particular, network \mathcal{G} is called k -robust, if for any disjoint and nonempty subsets of nodes in the network at least one of them has a node that is connected to k nodes outside of itself [132]. Network robustness has implications for the resilience of certain dynamics: if the network is $(2k + 1)$ -robust (for some non-negative integer k), then there are certain dynamics that allow the nodes in the network to reach consensus even when there are up to k malicious nodes in the neighborhood of every correctly behaving node [135], [246], [247]. The network robustness is a weaker notion compared to network expansion, mentioned before. More particularly, if the network is k -robust, then we have $i(\mathcal{G}) \geq k$.

3) *On Detection Mechanisms*: A network is called k -vertex connected (or k -edge connected) if it is connected after removing up to any k nodes (or edges) from the graph [248]. The concept of node connectivity also has implications for the robustness of certain dynamics on networks. For instance, if the network is $(2F + 1)$ -connected (for some non-negative integer F), then there are certain information diffusion dynamics (or algorithms) that allow information to spread reliably in the network, even when there are up to F malicious nodes (in total) that deviate from the prescribed dynamics in arbitrary ways [132], [134], [173]. Some works applied such a connectivity measure to ensure the privacy of a distributed online learning task against adversarial agents which try to reconstruct the updating rule of autonomous agents [249]. Network vertex and edge connectivity are the weakest notions of network connectivity compared to other connectivity measures such as network robustness and network expansion which were discussed earlier.

An example showing the relative strength of the above network connectivity measures is shown in Fig. 7. The gap between the robustness and vertex connectivity (and minimum degree) parameters can be arbitrarily large, as illustrated by the graph \mathcal{G} in Fig. 7 (a). While the minimum degree and node connectivity of the graph \mathcal{G} are both equal to $\frac{n}{4}$, it is only 1-robust (consider subsets $S_1 \cup S_2$ and $S_3 \times S_4$). Moreover, this graph has isoperimetric constant of at most 0.5 (since the edge boundary of $S_1 \cup S_2$ has size $\frac{n}{4}$), but is 1-robust. The relationships between these different graph-theoretic measures of robustness are summarized in the Venn diagram in Fig. 7 (b).

We should note that although increasing network connectivity will result in increasing the tolerance of the control system, making extra communication links is costly in various applications. With this in mind, a few studies have looked at reaching a specific level of network connectivity with minimum number of links

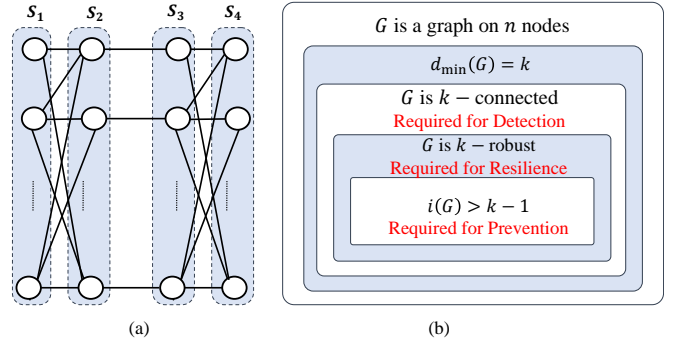


Fig. 7. (a) A graph showing the strength of different connectivity measures, (b) Venn diagram of various network connectivity indices.

[250].

IV. SUMMARY AND FUTURE WORKS

A high integration of instrumentation, communication, and control into physical systems has led to the study of CPS of late with increased attention. A key feature that is ubiquitous in CPS is a need to ensure their security in the face of cyberattacks. In this paper, we carried out a survey of systems and control methods that have been proposed for the security of CPS. We classified these methods into three categories based on the type of defense proposed against the cyberattacks, which include prevention, resilience, and detectionisolation. Prevention mechanisms are proposed to postpone and/or avoid disclosure attacks [95]. Resilience, the property by which the maximum damage inflicted by the attack is contained, has been demonstrated in many papers using methods such as [15], [100], [132]. Detection & isolation methods, as the names suggest, seek to restore the system to normalcy as quickly as possible by detecting and isolating the attack from the system [14]. A unified threat assessment metric is proposed in order to evaluate how CPS security is achieved in each of these three cases. Also surveyed are risk assessment tools and the effect of network topology on CPS security. An emphasis has been placed on energy and air-transportation applications in the overall survey.

The varied, impactful, and malicious nature of the actual cyberattacks underscores the huge importance of the study of CPS security. Given the scope of the systems and control methodology for achieving robustness, optimality, and efficiency in the presence of various perturbations, it is not surprising that the over two hundred papers cited in the survey correspond to systems and control methods by which such security in CPS can be achieved.

The papers referenced and the methods reported therein represent the first step towards achieving security

in CPS. Unlike exogenous disturbances, cyberattacks correspond to a customized, system-specific, malicious and active inputs that can continuously increase in complexity as the system evolves. As a result, it is imperative that the defense mechanisms that are proposed continue to advance the state of the art, to not just keep in pace with the complexity of the attack, at least a few steps ahead.

The above clearly indicates that a lot more remains to be done to ensure CPS-security. We mention below a few specific directions of interest, in no particular order:

- 1) CPS-Security and Machine Learning: The explosive interest in Machine Learning (ML), buoyed by its success in image and speech recognition, begs the obvious question of its role in ensuring CPS security. An important challenge here is to understand how anomaly detection can be carried out in the presence of dynamic inputs. Despite increasing role of ML in CPS applications, another important question that needs to be addressed is the inherent vulnerability that is associated with any ML tool. It is shown in [251] how non-resilient a classifier ML is against input data deception attacks. Likewise, several other researches show weakness of some reinforcement learning tools against attacks [252]. Adversarial machine learning [98], [253] must be developed considering ML's role in CPS and high impacts of CPS-security.
- 2) Real-Time Threat-Assessment: An important ingredient associated any CPS-security tool is an accurate threat assessment. Determining the key indicators for this purpose, in real-time, is one of the key challenges that should be addressed. In this regard, network-theoretic tools may be highly relevant. Associated follow-on steps for detection, prevention, and resilience are of important interest as well.
- 3) Scalability: Extending all case studies reported to realistic systems with thousands of nodes and links are essential in order to make an impact on critical infrastructures. A central question here is the development of numerically scalable algorithms be developed for rapid detection, localization, and mitigation of attacks for such gigantic networks?
- 4) Resilience Metric: How can we define better resilience metrics for control systems? The relation between such a metric and standard control tools such as stability margins, controllability Gramians, \mathcal{H}_2 or \mathcal{H}_1 norms, need to be examined. The effect of network topology in resilience, especially in the

context of cascading failures, needs to be explored.

We invite the entire systems and control community to engage in this important research topic.

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