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FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Resilient Monitoring, Diagnosis, Control, and System/Security Codesign for CPS

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Overview

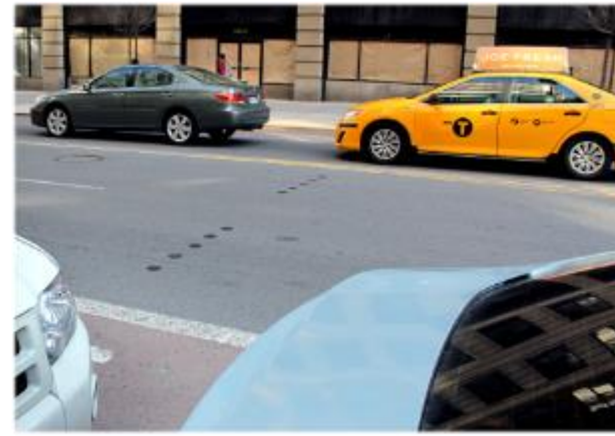
* Resilient Monitoring
  * Attack-resilient observation selection
  * Mobile guards
  * Placement and scheduling of intrusion detection in CPS
  * Optimal monitoring to mitigate attacks
* Diagnosis
  * Sensor placement for fault detection and localization
  * Network monitoring: DDS detection and mitigation
* Control
  * Resilient supervisory control for autonomous traffic intersections
  * Attack-resilient traffic control
* System/security codesign
  * Information Flow Policies in Cyber-Physical Systems
  * Platform-supported Resilience for CPS

Resilient Monitoring for CPS

Attacks against CPS Monitoring

A. Laszka

* To dynamically control any system, we must have accurate information about its evolving state
* An attacker may compromise sensors in order to maliciously alter control decisions
* For example, recent studies have found vulnerabilities in many traffic sensors
  * an attacker may cause disastrous traffic congestions by compromising these sensors



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Resilient Sensor Placement

A. Laszka

- We assume a denial-of-service type attacker, who impairs some of our sensors after they have been deployed
- **Resilient placement problem**: placing sensors so that even if some of them are impaired, we can still perform state estimation and prediction with minimal uncertainty
- Results:
  - computational complexity (NP-hardness)
  - approximation algorithms
  - optimal algorithms for special cases
- Traffic simulation results on the Vanderbilt campus area show that resilient placement can reduce uncertainty by 67%

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Guarding Networks through Mobile Heterogeneous Guards

W. Abbas

* Mobile guards (such as UAVs) are being increasingly used for the surveillance and monitoring of critical infrastructure networks such as gas and oil pipelines.

* Advantages include increased efficiency, deployment in remote areas, cost-effectiveness, immediate response etc.

* Challenges: Using the capabilities of mobile guards and considering the network structure
    * How many guards should be deployed?
    * At what critical points within the networks?
    * What could be the movement strategies of guards?

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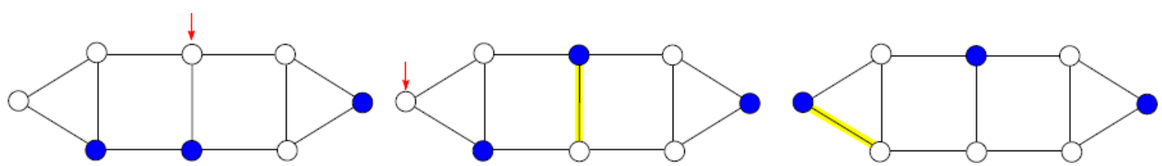
Guarding Networks through Mobile Heterogeneous Guards

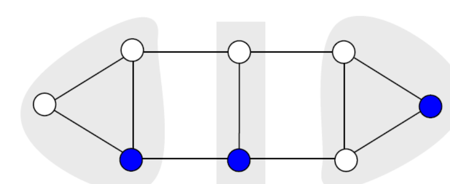
W. Abbas

- Mobile guards' deployment within a network for the detection and response against intruders can be related to the ***eternal security*** type problems in graphs.
- **Eternal security:** At all times, all nodes are being guarded by at least one guard even after a guard moves from one node to the other in response to an intrusion activity.



- **Major issues**: How many guards? Where to deploy? Which guard should respond?
- Finding optimal number of guards to achieve eternal security is *NP-hard*.
- We propose a an efficient algorithm to achieve eternal security through mobile guards having different detection and response ranges.
- **Basic idea:**

Partition a graph into appropriate clusters → Assign appropriate guard to each cluster → Nodes in each cluster are eternally secured by its guard



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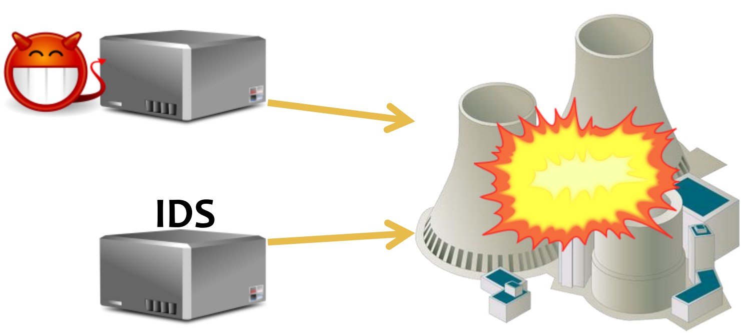
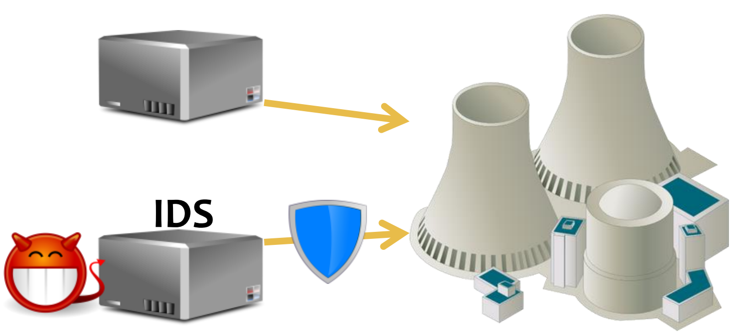
Intrusion Detection Systems (IDS) for CPS

W. Abbas, A. Laszka

* IDS alarms about the attack before it can cause major damage
* Deploying IDS can increase the resilience of CPS
* Challenges:
  * CPS may have resource bounded (e.g., limited energy supply, computational capabilities) devices
  * IDS may not be deployed at every node, or may not be active at all times
* Thus, **placement and scheduling** problems need to be solved





Example: IDS for Water Distribution Networks

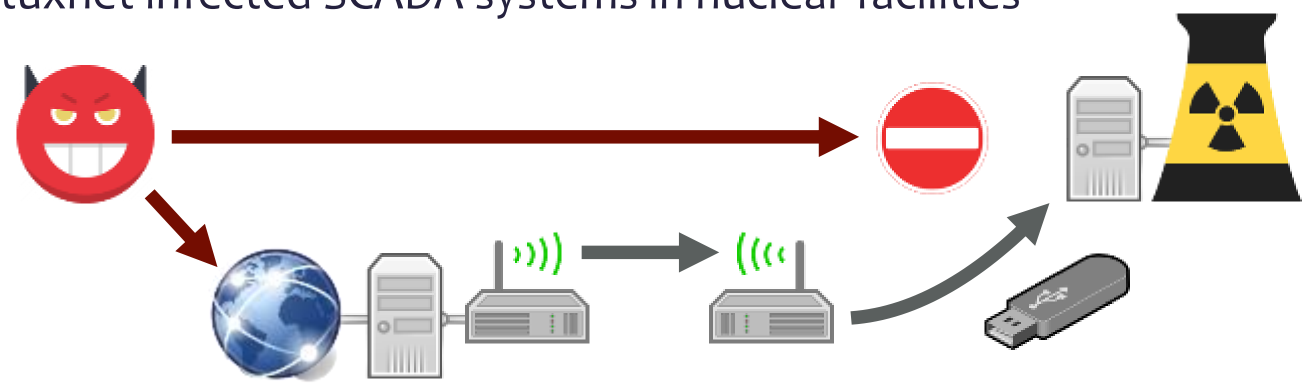
W. Abbas, A. Laszka

- Leaks may occur in the pipes, which can be detected by sensors deployed at various points
- An attacker might compromise sensors to generate false alarms or to suppress valid alarms
- We assume resource-bounded sensing devices, and formulate the scheduling problem for optimal detection of attacks with respect to the minimization of losses
- Results:
  - Computational complexity (NP hard)
  - Heuristics
  - Special cases

Computer Worms and CPS

A. Laszka

* Highly sensitive cyber-physical systems (e.g., control systems for nuclear facilities) are usually supposed to be secured by the "air gap"
* However, computer worms that propagate over removable drives and local networks may infect even these systems
  * e.g., Stuxnet infected SCADA systems in nuclear facilities



* In order to stop a worm before it can cause substantial damage to our system, we have to be able to detect it in time

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Optimal Monitoring to Mitigate Attacks

A. Laszka

* Worm propagation is modeled as a non-deterministic diffusion process
* Defender can monitor a limited number of nodes for the presence of a worm (e.g., auditing log files to detect suspicious activity)
* Attacker can select some starting points for the worm
* Defender wins if the worm is detected some time before it reaches the target system (or if it never reaches the target system)
* Results:
  * non-strategic attacker: optimal deployment is NP-hard, but approximable
  * strategic attacker: optimal deployment is inapproximable, but we have good heuristics

Resilient Diagnosis for CPS

Sensor placement for fault detection and localization in water distribution systems

W. Abbas

Objective

For a given flow network (water distribution network), the goal is to distribute the minimum number of sensors that can

1) Detect a link failure AND
2) Identify a link failure (uniquely identify a link failure)

Approach:
Sensor network design for the detection and identification of faults

Evaluation:
Simulation of real networks

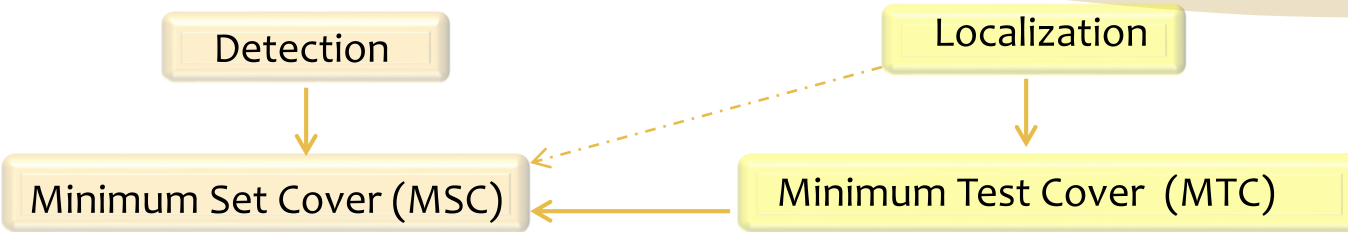
Methods:

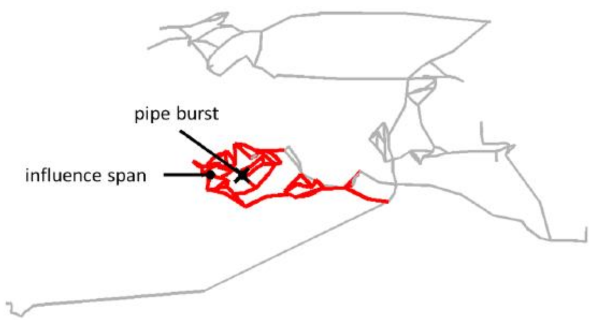
- System models (network flow model, fault model, sensor model, and influence model).
- Formulation of detection & localization as coverage problems.
- Submodular function optimization

Resilient monitoring:
Resilience to sensors failures, Performance evaluations

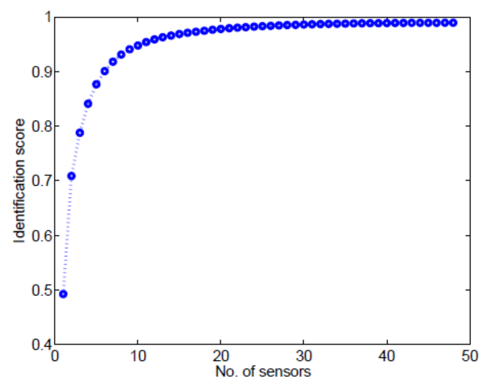
Sensor placement for fault detection and localization in water distribution systems

W. Abbas

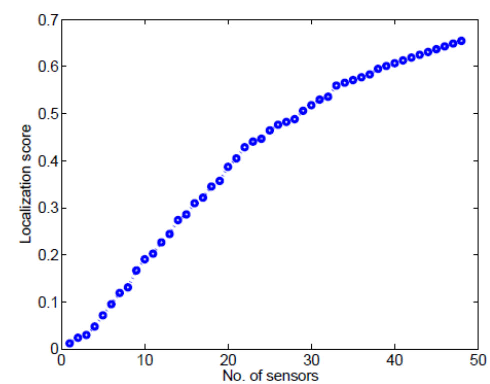




A water distribution network with 168 pipes and 129 nodes.



Identification score: Percentage of pair-wise link failures detected.



Localization score: Percentage of localization sets that can uniquely identify fault events.

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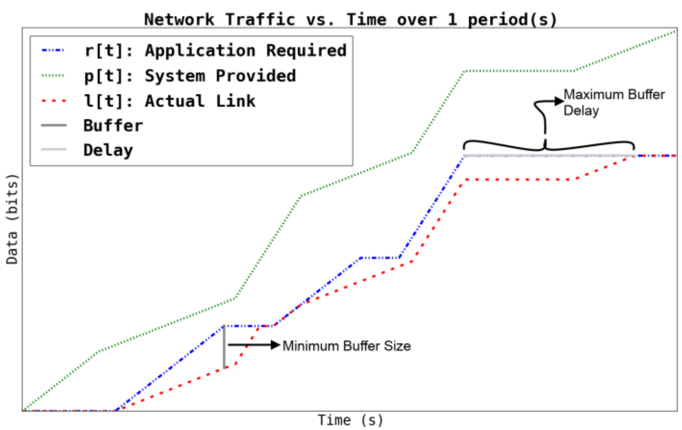
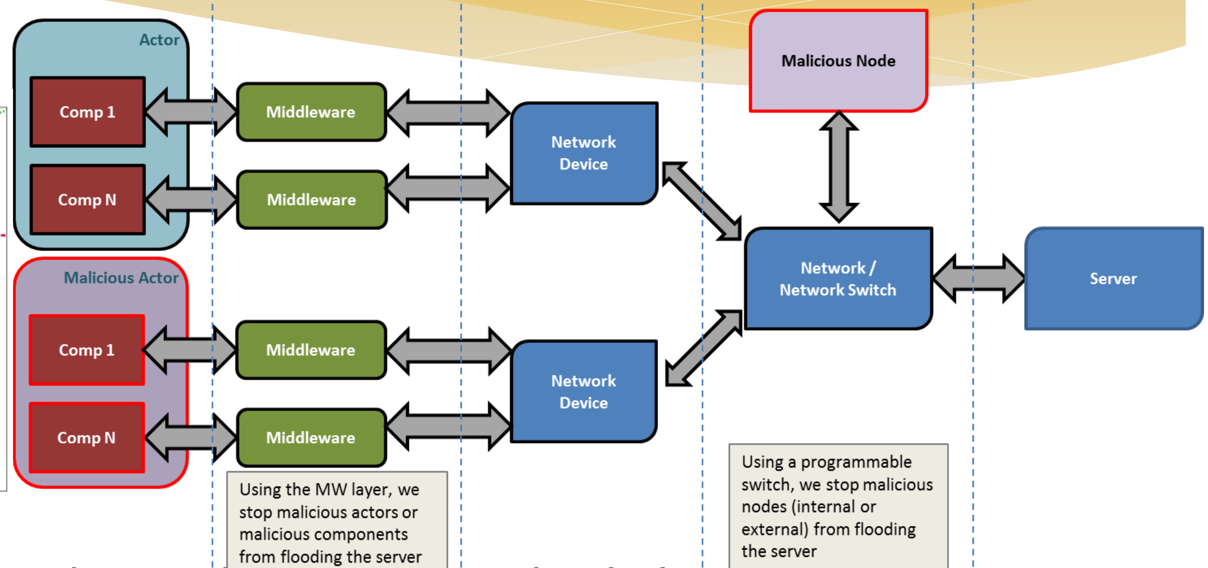
DDoS Detection & Prevention

W. Emfinger





* Using network modeling/analysis techniques based on Network Calculus
  * Precisely model application network behavior, with some bounds on deviation
* Assume infrastructure is controlled and verified; only applications may be compromised
* Middleware detects that application traffic production deviates from model
* Use out-of-band communication between server and clients
  * Server sees multiple clients simultaneously producing more data than normal
  * Informs client-side middleware to throttle clients and prevent denial of service

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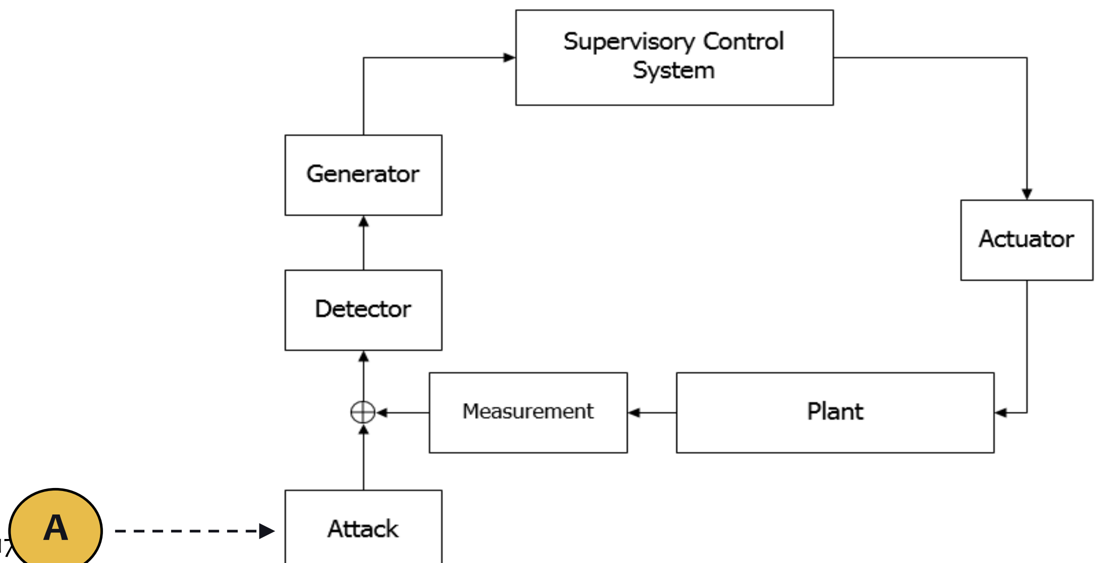
Attack-Resilient Control

Resilient Supervisory Control for Autonomous Intersection

A. Ghafouri

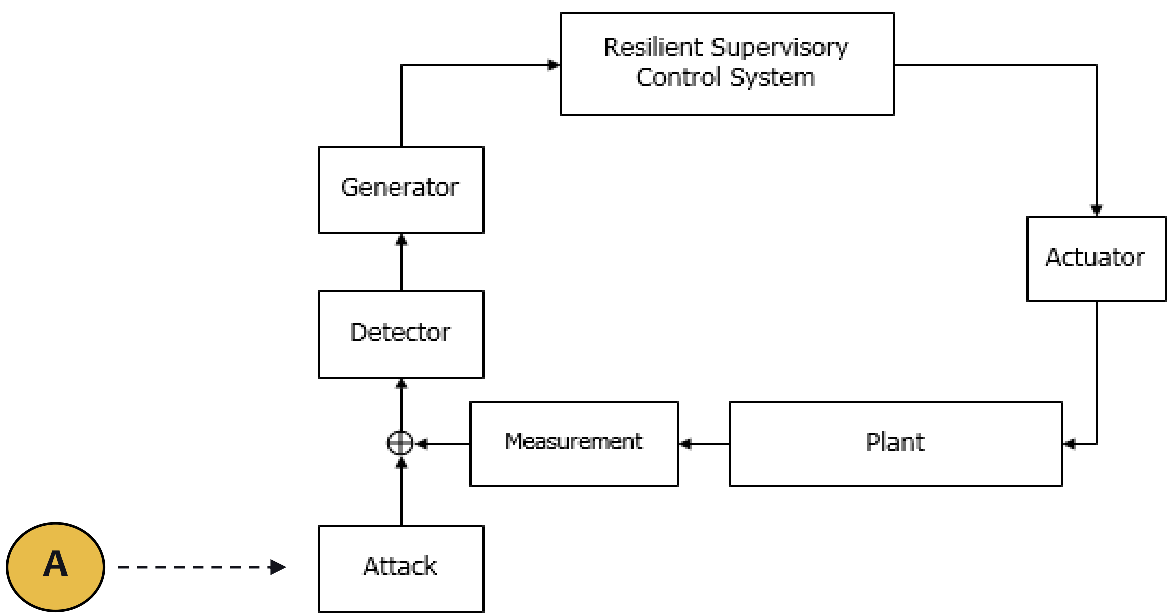
- Modeling sensor attacks for an autonomous intersection that is governed by the supervisory control system
- Characterization of *stealthy attacks* that compromise the safety of the system
- Developing an algorithm for finding all the successful attacks (i.e., stealthy attacks that lead to collision)
- Proving the vulnerability of the supervisory control system to stealthy attacks



Resilient Supervisory Control for Autonomous Intersection

A. Ghafouri

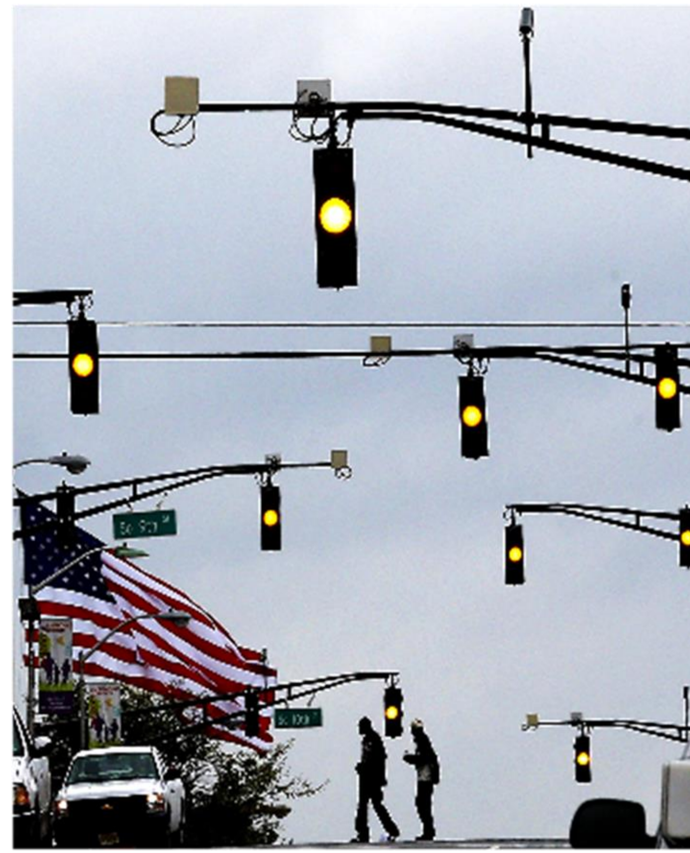
* Design of the **Resilient Supervisory Control System** (RSCS) ***(in progress)***
  * The RSCS is robust to stealthy deception attacks, i.e., safety will not be compromised even in the presence of stealthy attacks.
* Simulation and performance analysis of the RSCS using SUMO ***(in progress)***
  * Trade-off between resiliency and performance of the system is expected.



Attack-Resilient Traffic Control

A. Laszka

* Recent studies have shown that many traffic control devices (e.g., traffic lights) are vulnerable to cyber-attacks
* Attackers cannot cause accidents due to hardware-based failsafes , but they may cause disastrous traffic congestions
* **Resilient traffic control**: configuring traffic lights so that even if some of them are maliciously reconfigured, the level of traffic congestion remains minimal
* We study a game between a defender, who configures traffic lights, and an attacker, who compromises and reconfigures some of them



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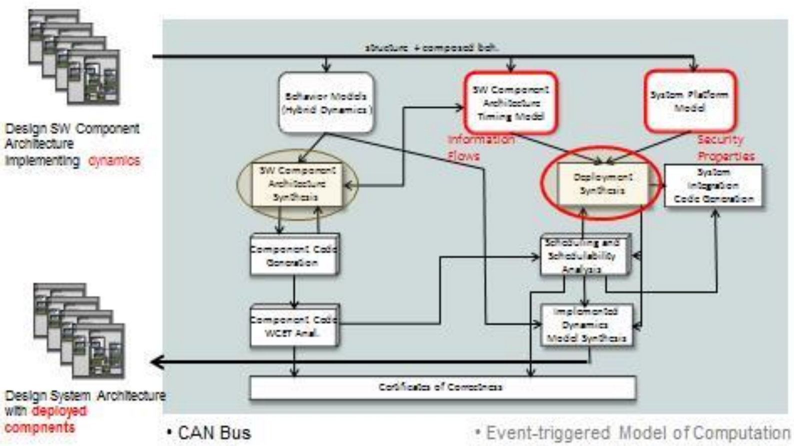
System-security Co-design

System-Level Co-design for CPS Security

D. Lindecker, I. Madari, J. Sztipanovits

System-level Synthesis Steps Information Architecture



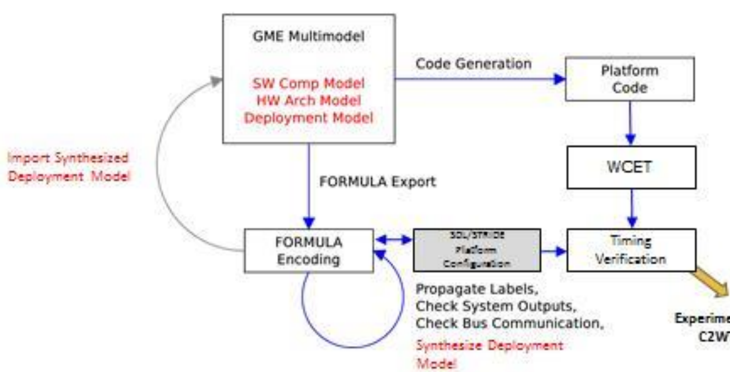
- CAN Bus
- TT bus

- Event-triggered Model of Computation
- Time-triggered Model of Computation

Challenges

- Modeling language suite
  (behavior, information flows, SW components, architecture, timing, platform, deployment) - reuse previous work
- Security Requirement Modeling
  (need to be composable with other modeling aspects)
- Common Semantic Domain and Formal Framework
  (functional, performance and security models need to be anchored to a semantic domain suitable for synthesis)
- Synthesis Framework and Co-design flow
  (mapping system-level synthesis problem on the formal framework and tools)
- Integrated Tool Suite and Validation
  (target domain rich enough for testing the co-design tool suite)

Workflow for Designing Secure Distributed Embedded Systems



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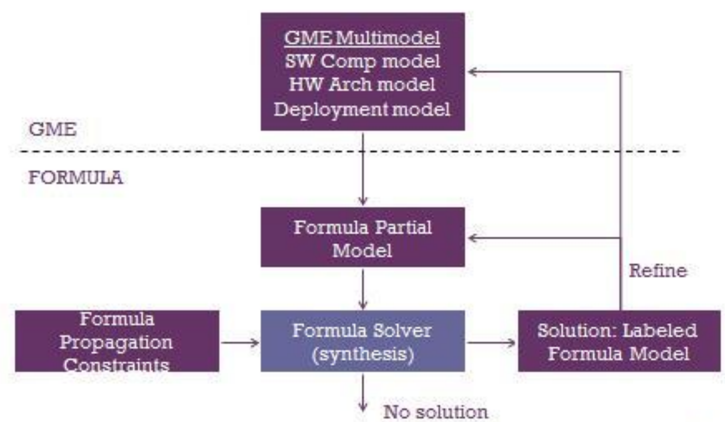
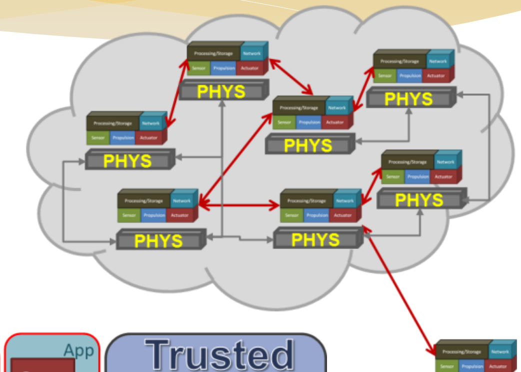
Label Propagation and Synthesis

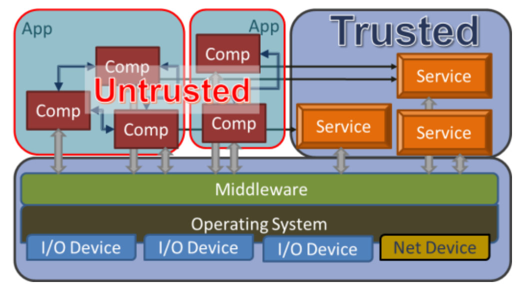


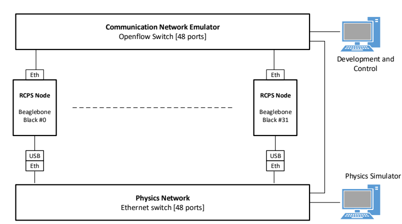
Platform-supported Resilience for CPS

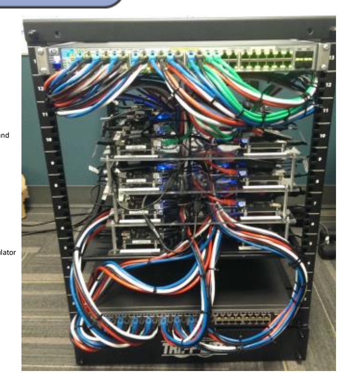
W. Emfinger. G. Karsai, P. Kumar

- Resilience is a system-level property, permeating the entire CPS architecture
- Model: Trusted (and protected) platform + Untrusted apps
- Challenges:
  - How to model the resilient architecture? What makes it resilient?
  - How to build a resilient software application platform for CPS?
  - How to analyze in a scalable manner to obtain assurances for resilience?
- Resilient CPS Platform
  - Component-based application model: component model with interaction semantics
  - Application deployment model: trusted and managed deployment
  - Resource monitoring and constrained information flows on the platform level
  - Hardened platform interfaces and services
- CPS Experimentation:
  - Embedded controllers + Emulated network + Physics sim









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