THE CHATTY SENSOR: A PROVABLY-COVERT CHANNEL IN CYBER PHYSICAL SYSTEMS

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INTRODUCTION

- **Cyber Physical Systems (CPS)** - Smart systems that include networks of physical and computational components, all aimed to governed a physical process.
- **Examples**: Nuclear Plants, Power Generations, Water Plant, Transportations.

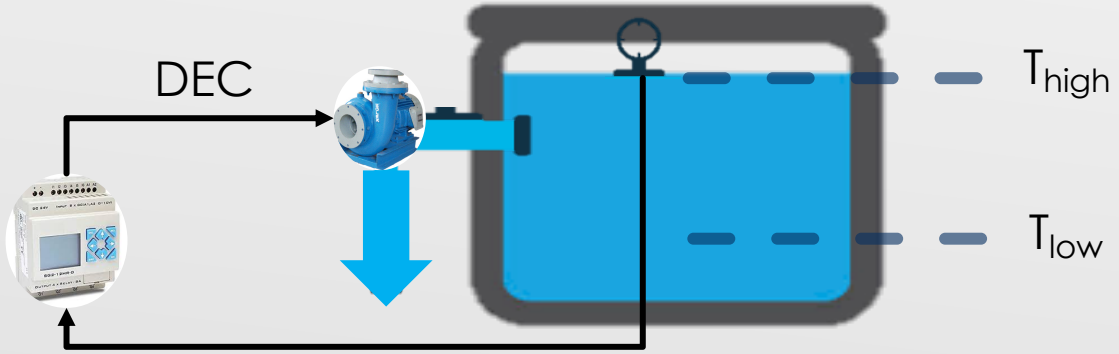
- Critical for our life
- Built from large number of devices:

  Sensors, Actuators, Controllers…

- Operating in *Feedback Control Loops*

INTRODUCTION: FEEDBACK CONTROL LOOP

- Feedback control loops are the main method used to stabilize physical values in CPS.
- Threshold-controller
  - Actuator with two possible commands to increase / decrease the physical value: *INC* / *DEC*
  - Two thresholds: T_{high},T_{low}
- When the sensor measurements reach T_{high} / T_{low} , the controller changes its output to decrease / increase the signal.



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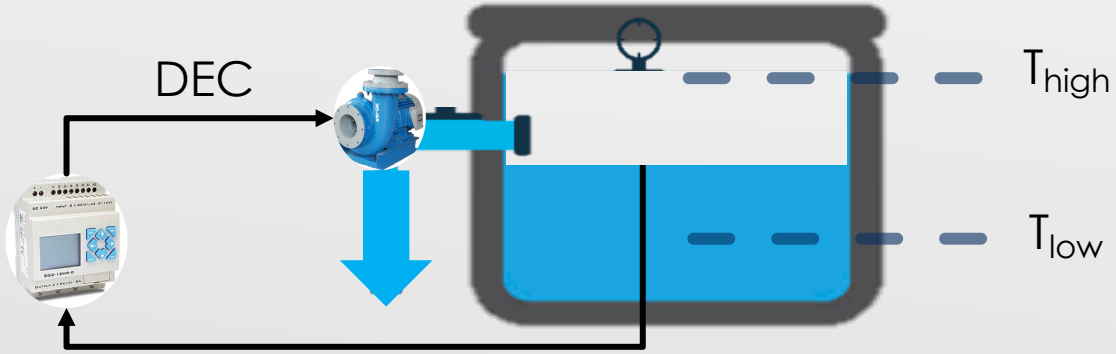

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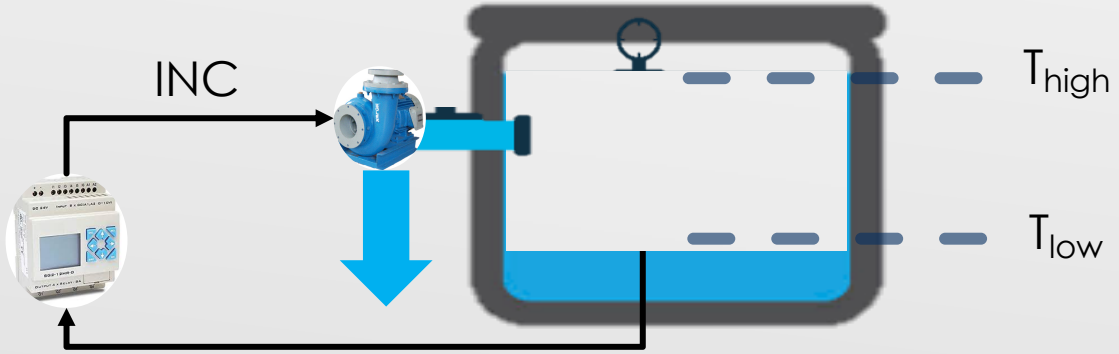

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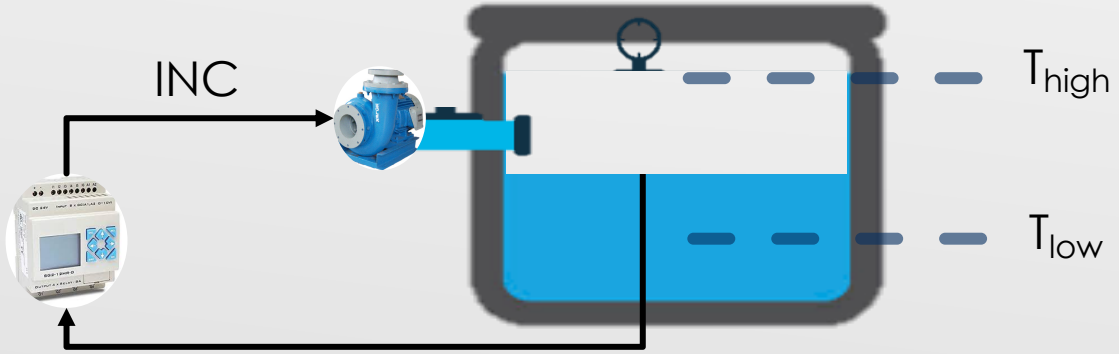
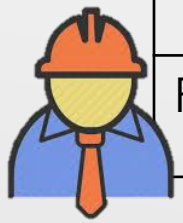


- Widely used in: phase controller, current limiter, pH controllers.

INTRODUCTION: DEVICE SELECTION

- Devices are chosen based on **sufficient specification** and **lowest cost**.



	Device A	Device B
Specification	SPEC High Quality	SPEC Sufficient Quality
Price	Expensive	Cheap

INTRODUCTION: DEVICE SELECTION

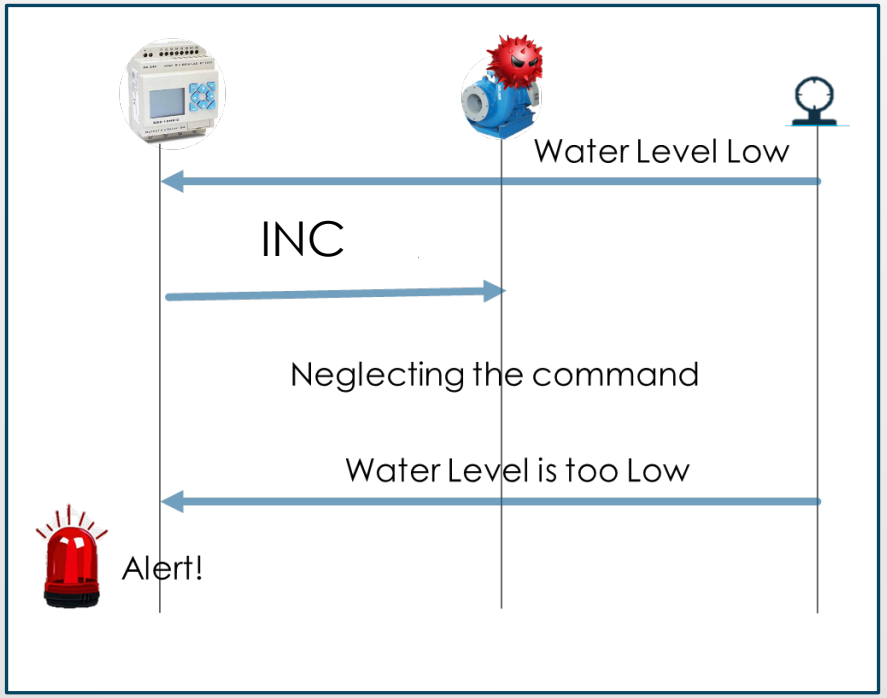
- Devices are chosen based on **sufficient specification** and **lowest cost**.

	Device A	Device B	Malicious
Specification	SPEC High Quality	SPEC Sufficient Quality	SPEC Sufficient Quality
Price	Expensive	Cheap	Cheaper

- **Supply Chain Attack:**
  - Attacker offers a cheaper device, with sufficient specification.
  - OR: Attacker replaces benign devices, with malicious one.
- **Attacker Goal:** To cause damage, by deploying its own malicious device.

ATTACKER CHALLENGE - 1

- Successful, stealthy attack requires communication
  - e.g. from corrupt sensor to corrupt actuator:



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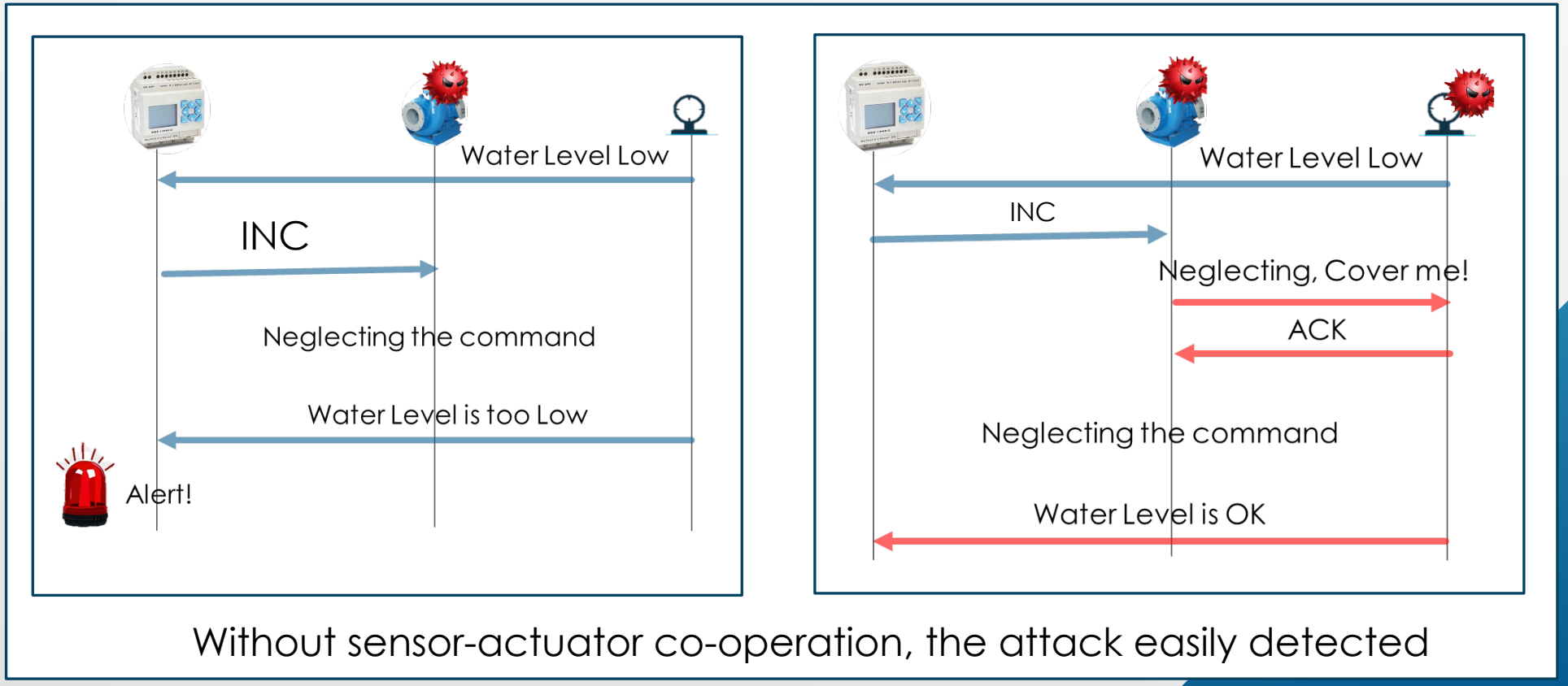
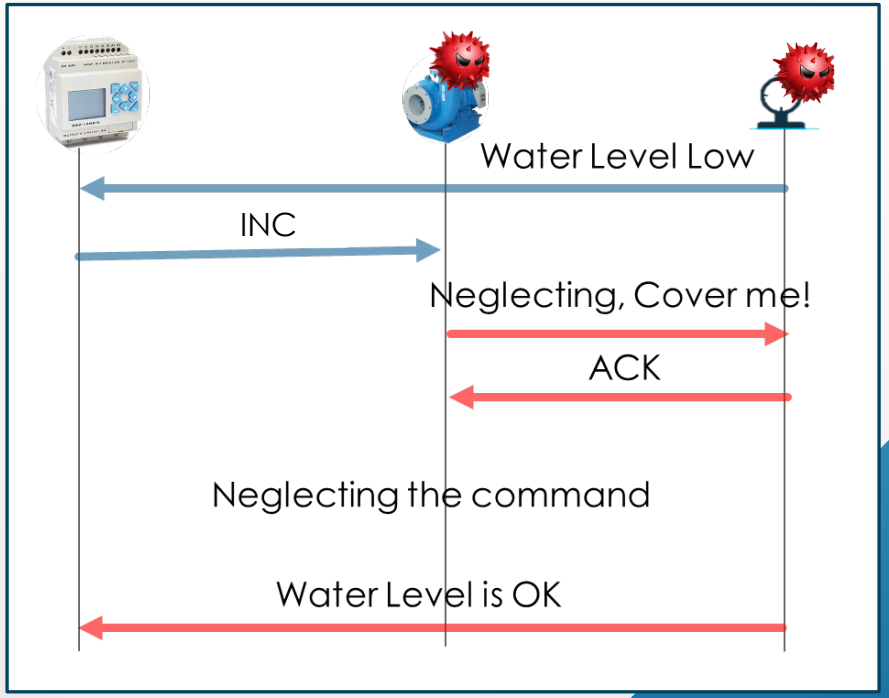


Without sensor-actuator co-operation, the attack easily detected

ATTACKER CHALLENGE - 1

- How to communicate **between** malicious devices?
  - Sensor to Actuator (S2A) – This work.
  - Actuator to Sensor (A2S) – Prev. work.



ATTACKER CHALLENGES

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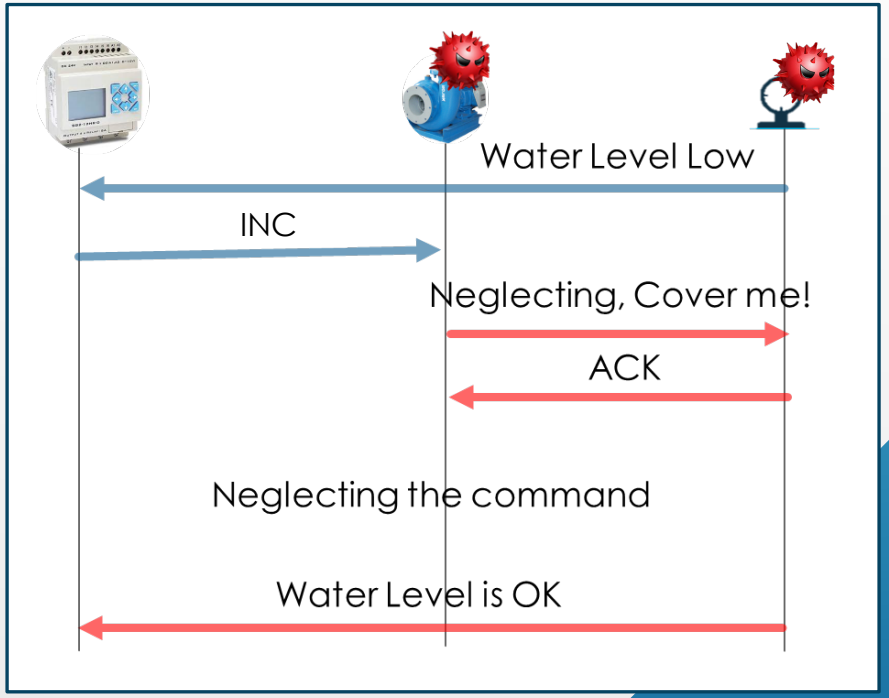
- How to avoid detection?



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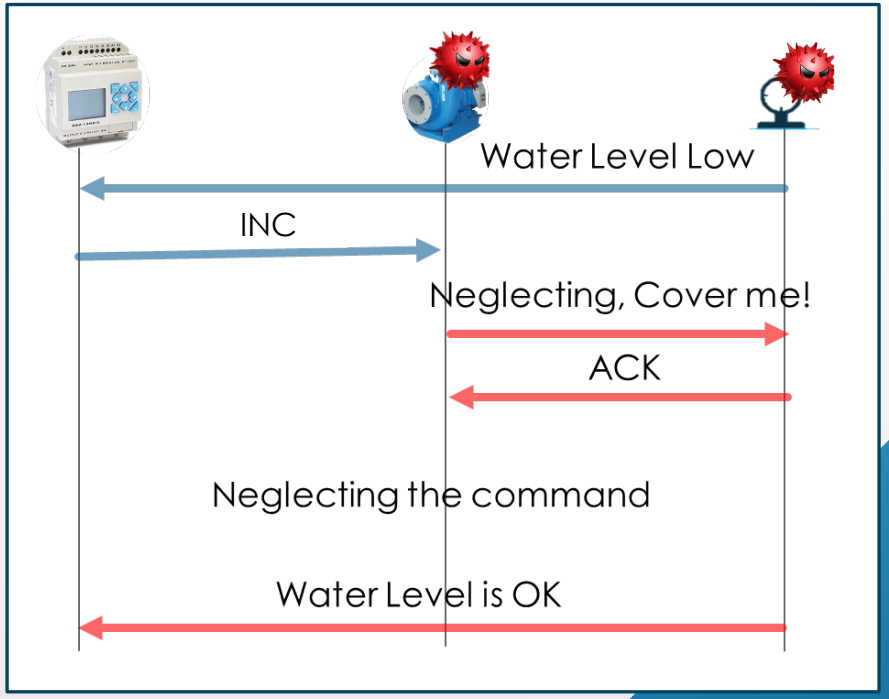
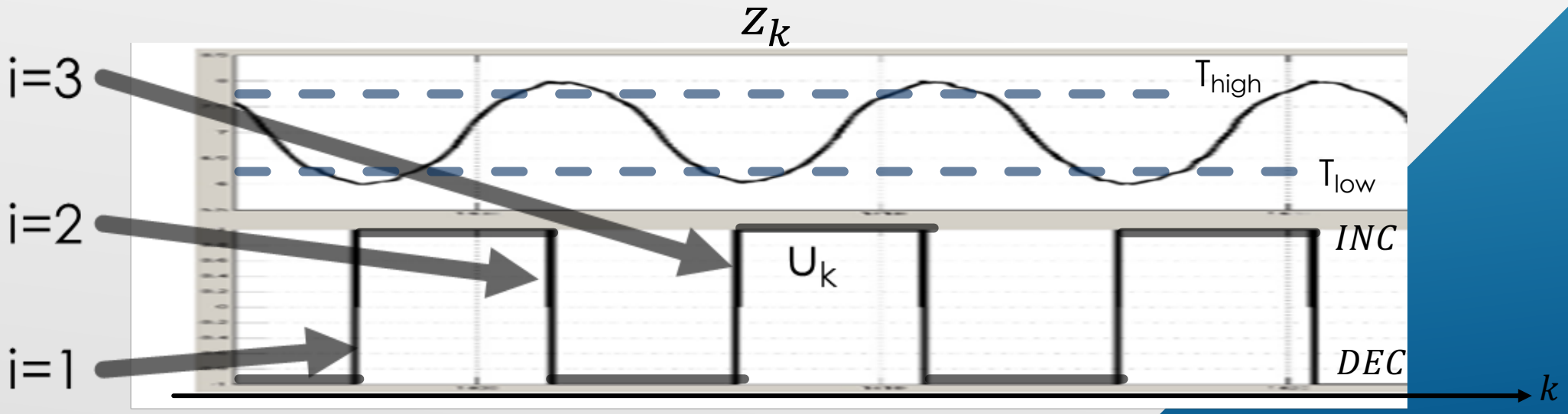


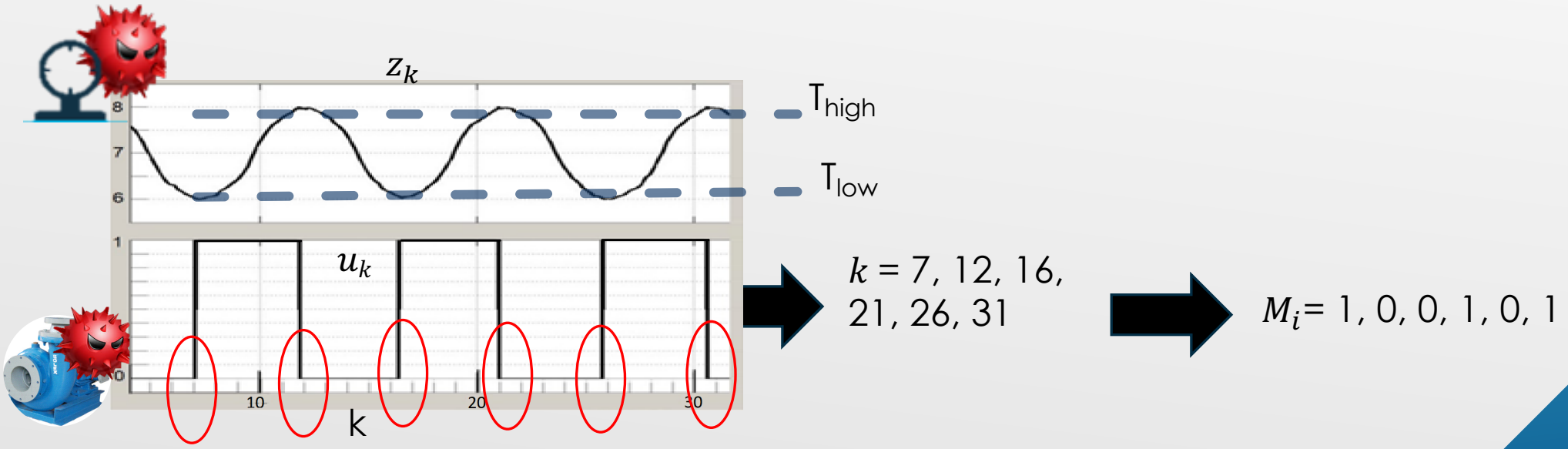
CHATTY-SENSOR COMMUNICATION METHOD

- For any time-step k, the **sensor** reports z_k.
- The process value continuously iterates and pass the thresholds: T_{high},T_{low}
- Whenever z_k passes a threshold, the controller **switches** the command $u_k \in \{INC, DEC\}$ to the **actuator**.
- We denote the i[th] *transition of the actuator's output* by *i*.



CHATTY-SENSOR COMMUNICATION METHOD

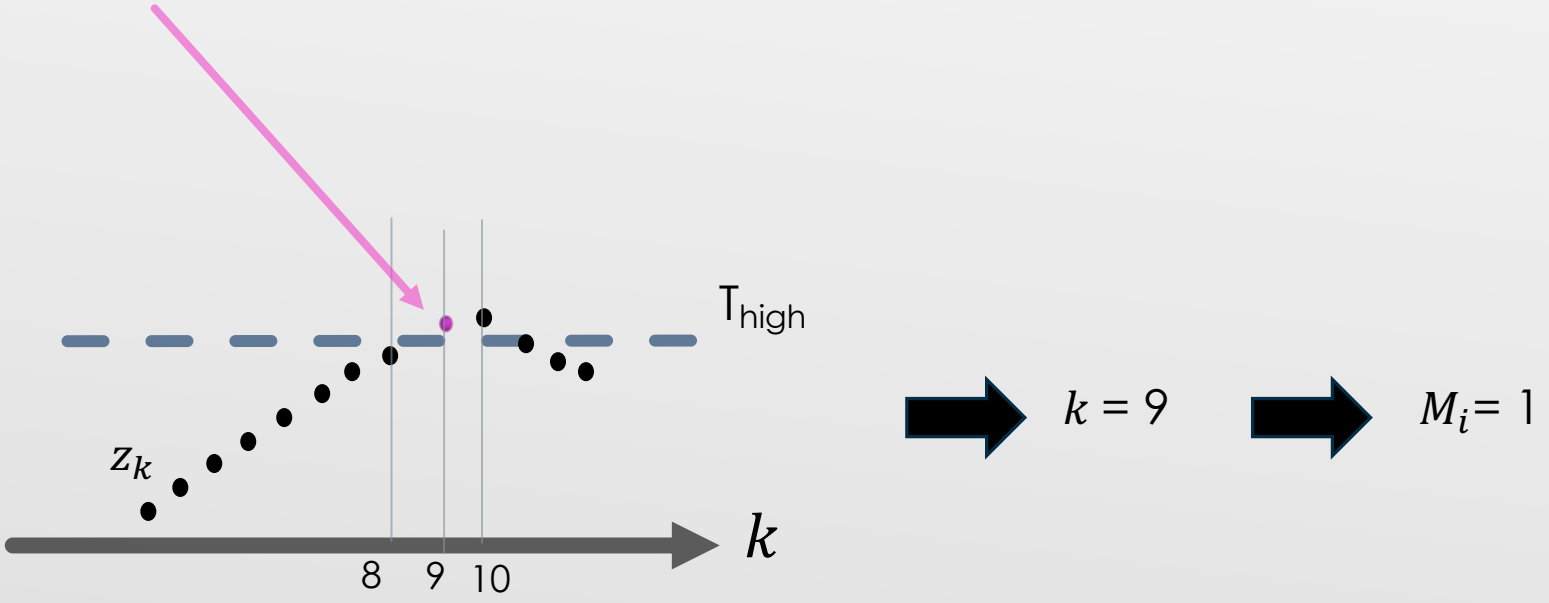
- Sensor encodes covert bits of information, on the **parity of the transition time-steps**:
  - Transition at even / odd times will signal bit 0/1.



Assumption: Sensor and Actuator have a parity-synchronized clocks.

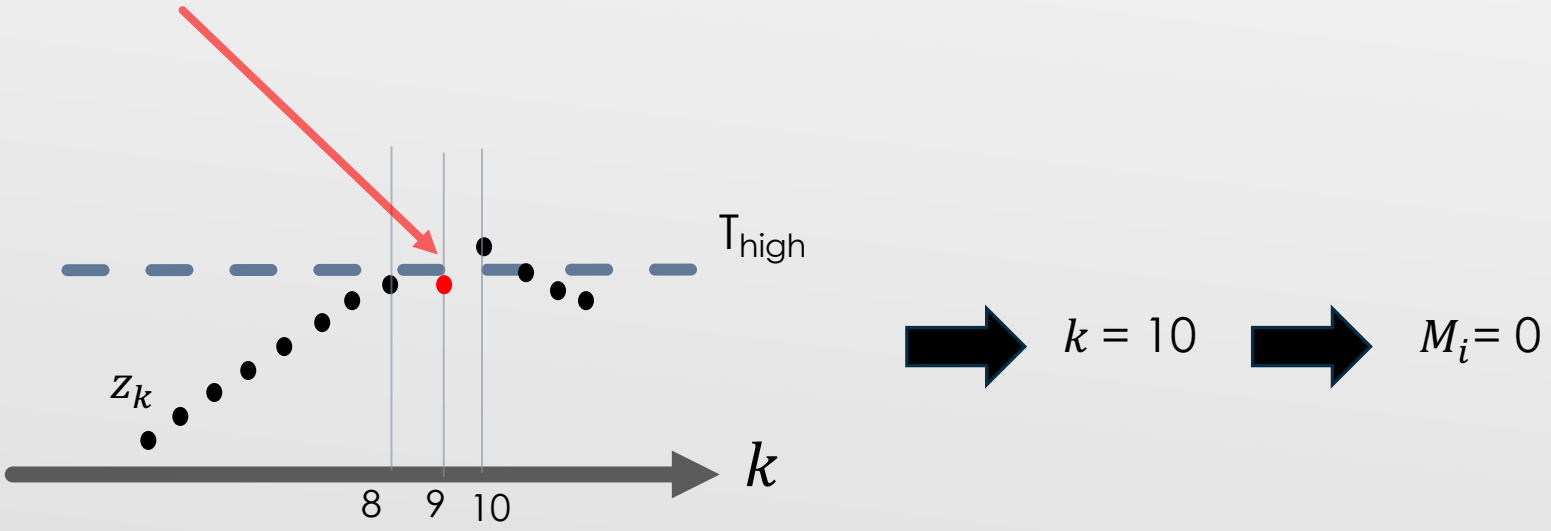
CHATTY-SENSOR COMMUNICATION METHOD

- Chatty-sensor influences the transition time-step.
  - Decreasing / increasing the reported value.
- For example:
  - Transition about to happen at k=9 -> but should be at k=10.



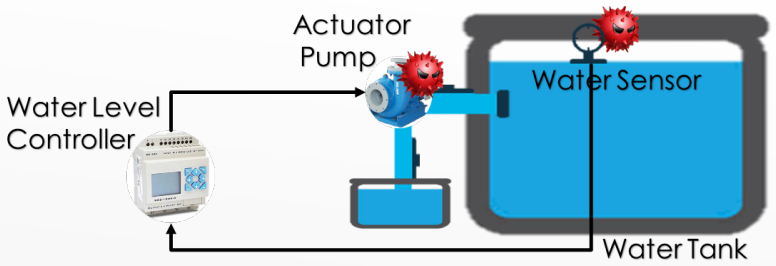
CHATTY-SENSOR COMMUNICATION METHOD

- Chatty-sensor influence the transition time-step.
  - Decreasing / increasing the reported value.
- For example:
  - Transition about to happen at k=9 -> but should be at k=10.
  - Chatty-sensor reduces the reported value at k=9 -> Transition now is at k=10.



$k = 10$ $M_i = 0$

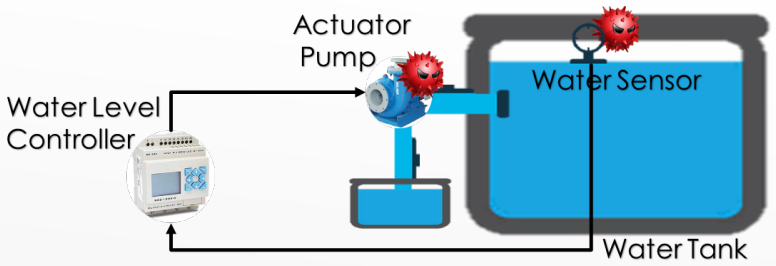
ATTACKER CHALLENGES



- How to communicate **between** malicious devices?

Transition Parity

ATTACKER CHALLENGES



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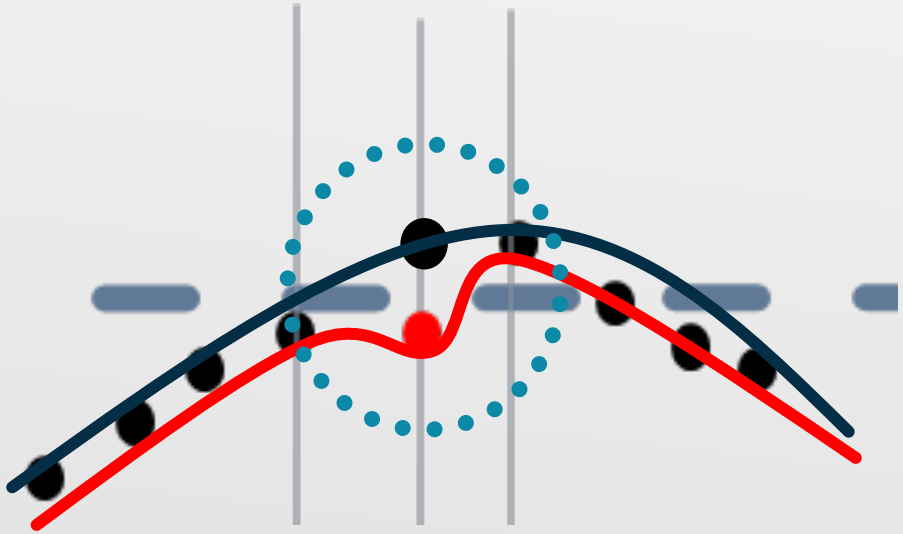


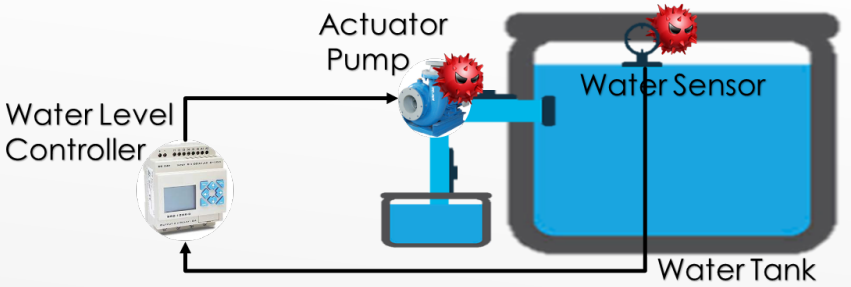
Transition Parity

Creates Anomaly in the CPS behavior…

Chatty-sensor

Benign sensor

ATTACKER CHALLENGE - 2

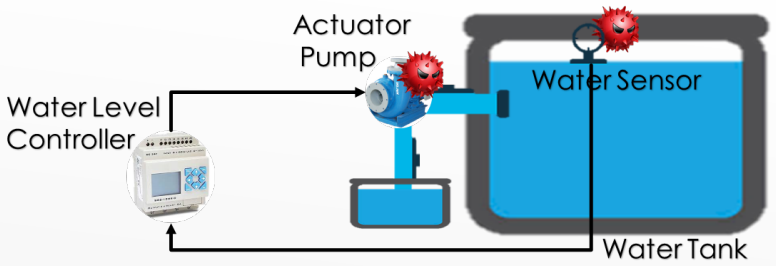


- A lot of works on anomalies detections in CPS.

- Communication Network Anomalies:
  - For example (one of many):
    - Kleinmann, Amit, and Avishai Wool. "Accurate modeling of the siemens s7 scada protocol for intrusion detection and digital forensics.“, 2014.

- Physical Anomalies – malicious sensor reporting / malfunctioning actuator
  - For example (one of many):
    - Urbina, David I., et al. "Limiting the impact of stealthy attacks on industrial control systems.", 2016.

ATTACKER CHALLENGES

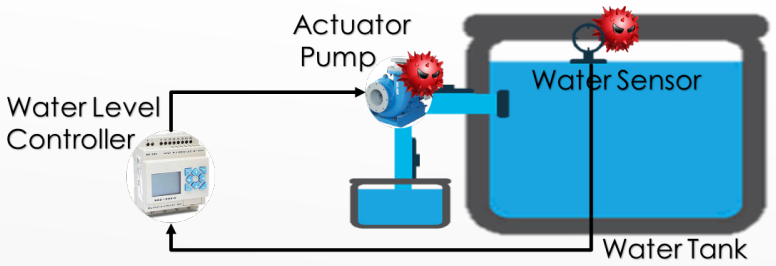


- How to communicate **between** malicious devices?
- **How to avoid detection?**

Transition Parity

Creates Anomaly in the CPS behavior…

ATTACKER CHALLENGES



- How to communicate **between** malicious devices?
- **How to avoid detection?**

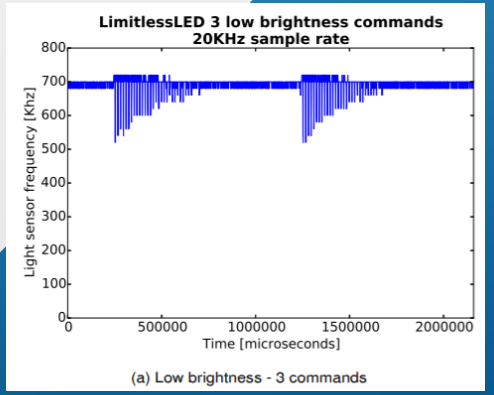
Covert Channel

Transition Parity

Creates Anomaly in the CPS behavior…

COVERT CHANNELS

- "**Covert**" - using some "**unmonitorred**" channels
  - Encoding information using light brightness ("Extended functionality attacks on IoT devices: The case of smart lights", Shamir et. al. 2016)
  - Packet headers ("Embedding Covert Channels into TCP/IP", Murdoch et. al. , 2005)
  - Acoustic emissions of a motor ("Process-aware covert channels using physical instru-mentation in cyber-physical systems", Krishnamurthy et. al. 2018)
  - And more…
- Monitoring the "**unmonitorred**" property, reveals the communication channel.



Eyal Ronen and Adi Shamir. Extended functionality attacks on IoT devices: The case of smart lights. In2016 IEEE European Symposium on Security and Privacy(EuroS&P), pages 3–12. IEEE, 2016

PROVABLE COVERT CHANNELS

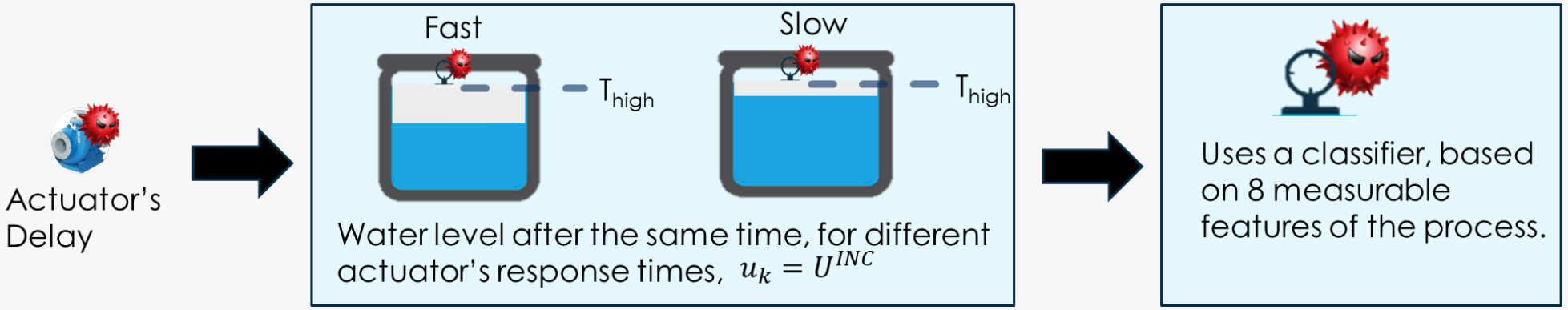
- "**Provable-Covert**" –
  - No secret property
  - Proving that it is impossible to detect the channel (under well defined assumptions)

$$\Pr(D(\text{  }) = Mal.) \approx \Pr(D(\text{  }) = Mal.)$$

PROVABLE COVERT CHANNELS

- **IT Networks**: Provable channels were presented in the past:
  - Liu, Yali, et al. "Robust and undetectable steganographic timing channels for iid traffic.", 2010.
- **CPS Provable Covert Channel:**

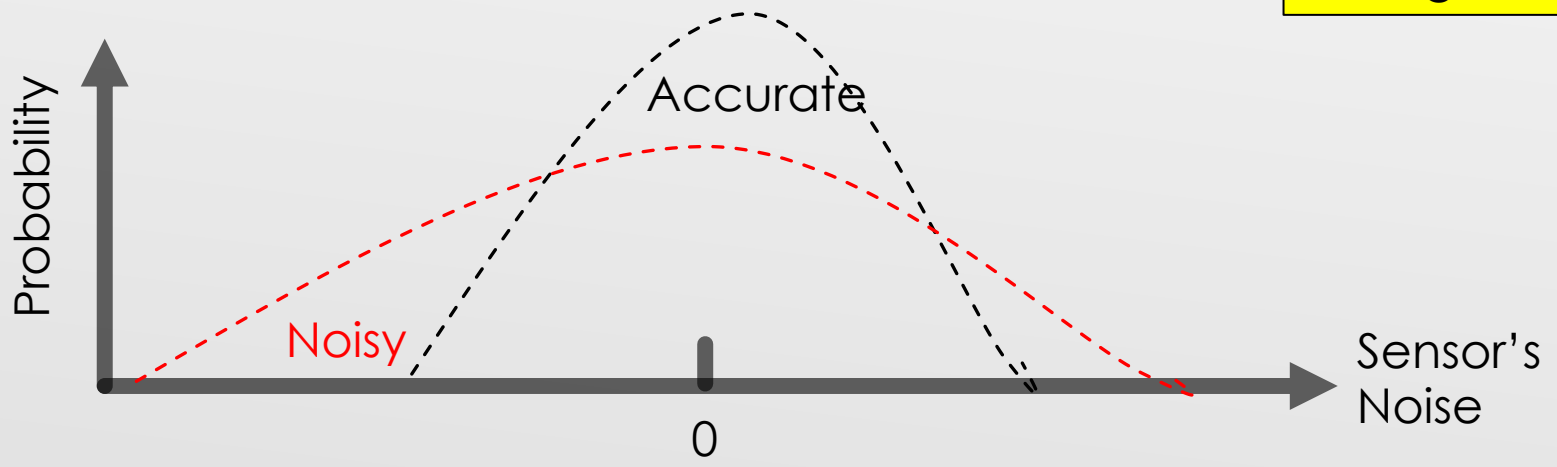
Herzberg, Amir, and Yehonatan Kfir. "The Leaky Actuator: A Provably-covert Channel in Cyber Physical Systems." *Proceedings of the ACM Workshop on Cyber-Physical Systems Security & Privacy*. ACM, 2019.



CHATTY-SENSOR COVERT CHANNEL

- **How to (provably) avoid detection?**
- The provably-covert channel is based on **two basic observations** about sensors:
  - The **reported measurements has a random** noise, derived from some (known) distribution.
  - There are different **benign** types of sensors in the market:
    - Accurate (narrow noise distribution)
    - Noisy (wide noise distribution).

- Adding Noise at all time-steps
- Make sure to add positive / negative noise at the transition time

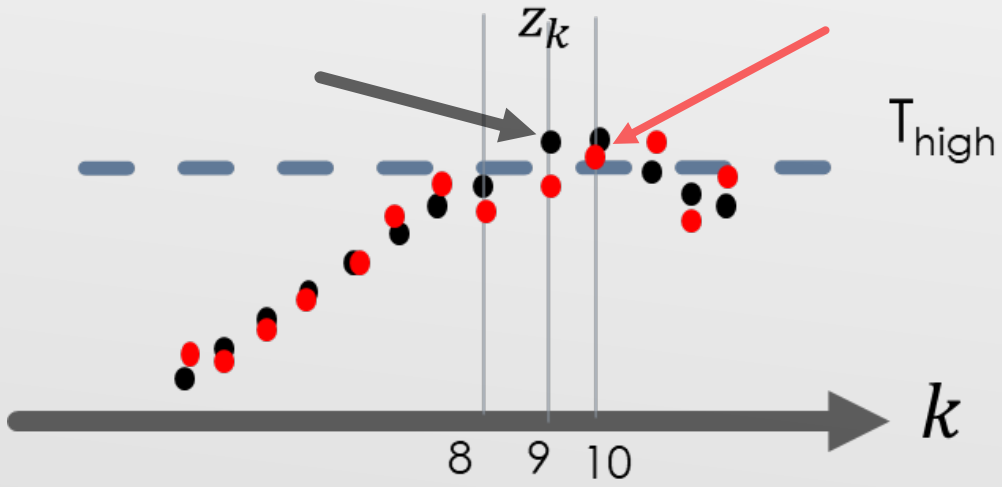


CHATTY-SENSOR COVERT CHANNEL

▸The Chatty-sensor uses an **internal accurate sensor** to measure the process.

▸At time-steps with transition: the chatty-sensor **chooses** whether to add **positive or negative noise** to the internal sensor.

▸All the other time-steps: The Chatty-sensor **randomly chooses positive or negative noise** to add.



Internal benign sensor

Chatty-sensor

CHATTY-SENSOR COVERT CHANNEL

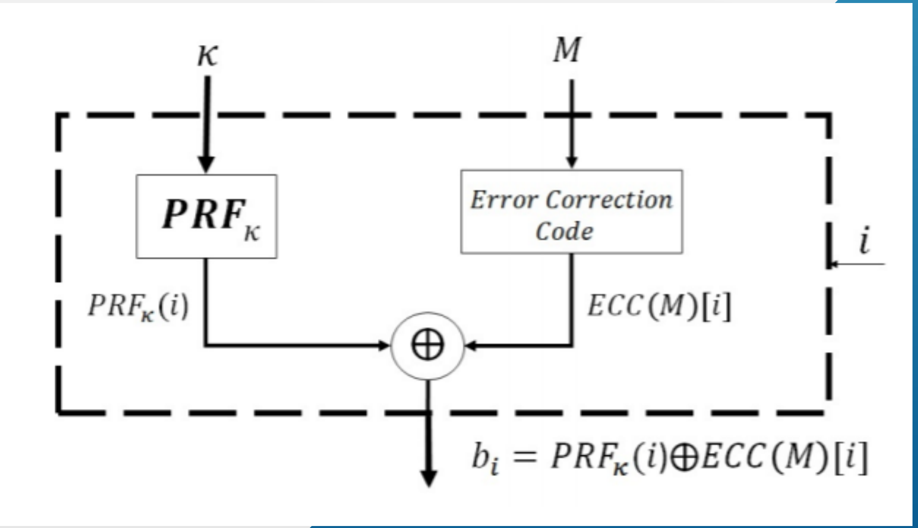
- **Problem [Encoding]:** Channel is noisy…
  - **Solution:** Error Correction Code. Sending encoded message **m**, m=ECC(M).

$$\Pr(D(\text{[image]}) = Mal.) \approx \Pr(D(\text{[image]}) = Mal.)$$

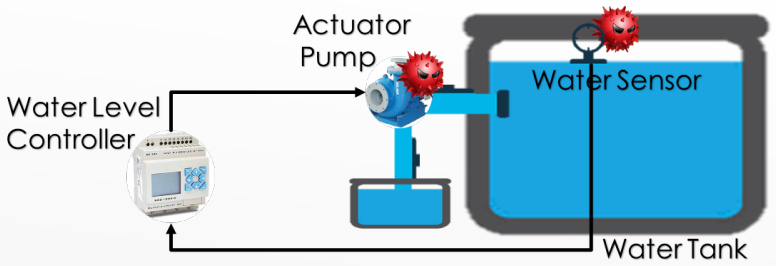
CHATTY-SENSOR COVERT CHANNEL

- **Problem [Encoding]:** Channel is noisy...
  - **Solution:** Error Correction Code. Sending encoded message **m,** m=ECC(M).
- **Problem [Indistinguishability]**: If the encoded message is m=00000000…, the noise at the transitions will always be derived from P_{down}
  - **Solution**: Sending pseudo-random bits, b_i, derived from m_i.
    - $\kappa \xleftarrow{\$} \{0,1\}^l$ is a key, deployed at the sensor and actuator.
  - **Assumption**: Sensor and actuator have a synchronized i.

$\Pr(D($  $) = Mal.) \approx \Pr(D($  $) = Mal.)$



ATTACKER CHALLENGES



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Pseudo-random	Transition Parity

Evaluation

EVALUATION

- How good is the receiver in intercepting the chatty-sensor bits?
- **Theoretical:** Channel Capacity.
- **Practical**: Bit-error-rate of our chatty-sensor design.

EVALUATION: CHANNEL CAPACITY

- **Channel Capacity** – highest information rate that can be achieved.
- Evaluated in a pH control process Simulink simulation.
- Based on real-world pH sensors noise.
  - σ_{CS}, σ_{HQ} - chatty-sensor / internal high-quality sensor noise standard deviation.
- **Results**: About 0.12 bit of information on every transition.
  - 1 transition every 5 seconds = 1.44 bits per minute.

$\frac{\sigma_{CS}}{\sigma_{HQ}}$	Avg. Bit Flip Probability	Avg. Channel Capacity
2	0.32	0.1
3	**0.3**	**0.12**
4	0.33	0.08
5	0.38	0.04

EVALUATION

- **Channel Capacity – 0.12 bit per transition**.
- **Bit-Error-Rate (BER)** – fraction of errors in the bits decoding.
  - Using repetition as error-correction-code: **~10% decoding errors**, with repetition of 13.
- We need better error-correction-codes for this channel [Future Work].

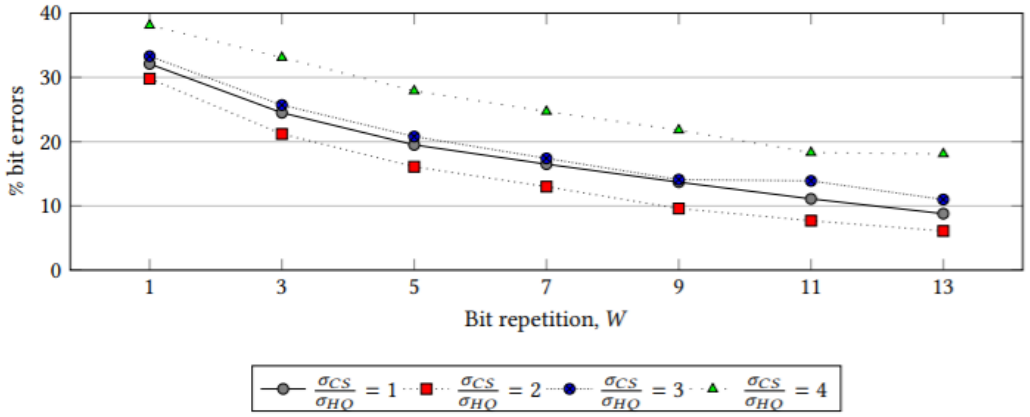

Figure 7: Bit-error-rate (BER) with test-set Size = 10,000 and for different ratios between the honest sensor accuracy σ_{HQ} and the chatty-sensor accuracy σ_{CS}.

SUMMARY AND DISCUSSION

- Choosing devices based on **specification** and **price** enables **provable** covert attacks.
- As for as we know – this is the first **provable** covert channel from **sensors to actuator**.
- Requires to improve defenses:
  - Adding randomness to the channel (e.g. in the controller logic)
  - Purchasing devices from different vendors.
- In future works:
  - Improving the BER – maybe by non-provable method.

QUESTIONS?