

Security-by-Design for Fortifying Cybersecurity of IoT/CPS

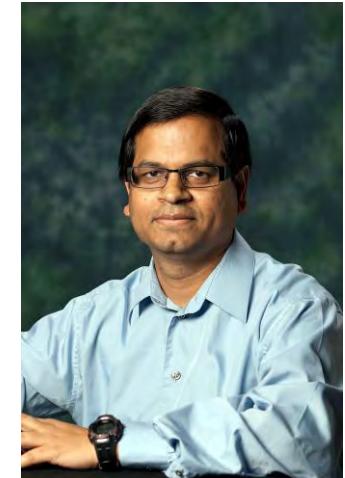
**Keynote – 2nd International Workshop on Energy Efficient
Trustworthy Sustainable Edge-Cloud Computing (ET-Edge 2024),
at 24th IEEE/ACM International Symposium on Cluster, Cloud and
Internet Computing (CCGRID) 2024.**



Homepage:
www.smohanty.org

**Philadelphia, USA
06 May 2024**

**Prof./Dr. Saraju Mohanty
University of North Texas, USA.**



Outline

- IoT/CPS – Big Picture
- Challenges in IoT/CPS Design
- Cybersecurity Solution for IoT/CPS
- Drawbacks of Existing Cybersecurity Solutions
- Security-by-Design (SbD) – The Principle
- Security-by-Design (SbD) - Specific Examples
- Is Blockchain a Solution for All Cybersecurity Problems?
- Is Physical Unclonable Function (PUF) a Solution for All Cybersecurity Problems?
- Conclusion

The Big Picture

Issues Challenging City Sustainability



Pollution



Water Crisis



Energy Crisis



Traffic

Smart City Technology - As a Solution

■ Smart Cities: For effective management of limited resource to serve largest possible population to improve:

- Livability
- Workability
- Sustainability

At Different Levels:
➤ Smart Village
➤ Smart State
➤ Smart Country

➤ Year 2050: 70% of world population will be urban



Source: S. P. Mohanty, U. Choppali, and E. Kougianos, "Everything You wanted to Know about Smart Cities", *IEEE Consumer Electronics Magazine*, Vol. 5, No. 3, July 2016, pp. 60--70.

Smart Cities Vs Smart Villages



Source: <http://edwingarcia.info/2014/04/26/principal/>

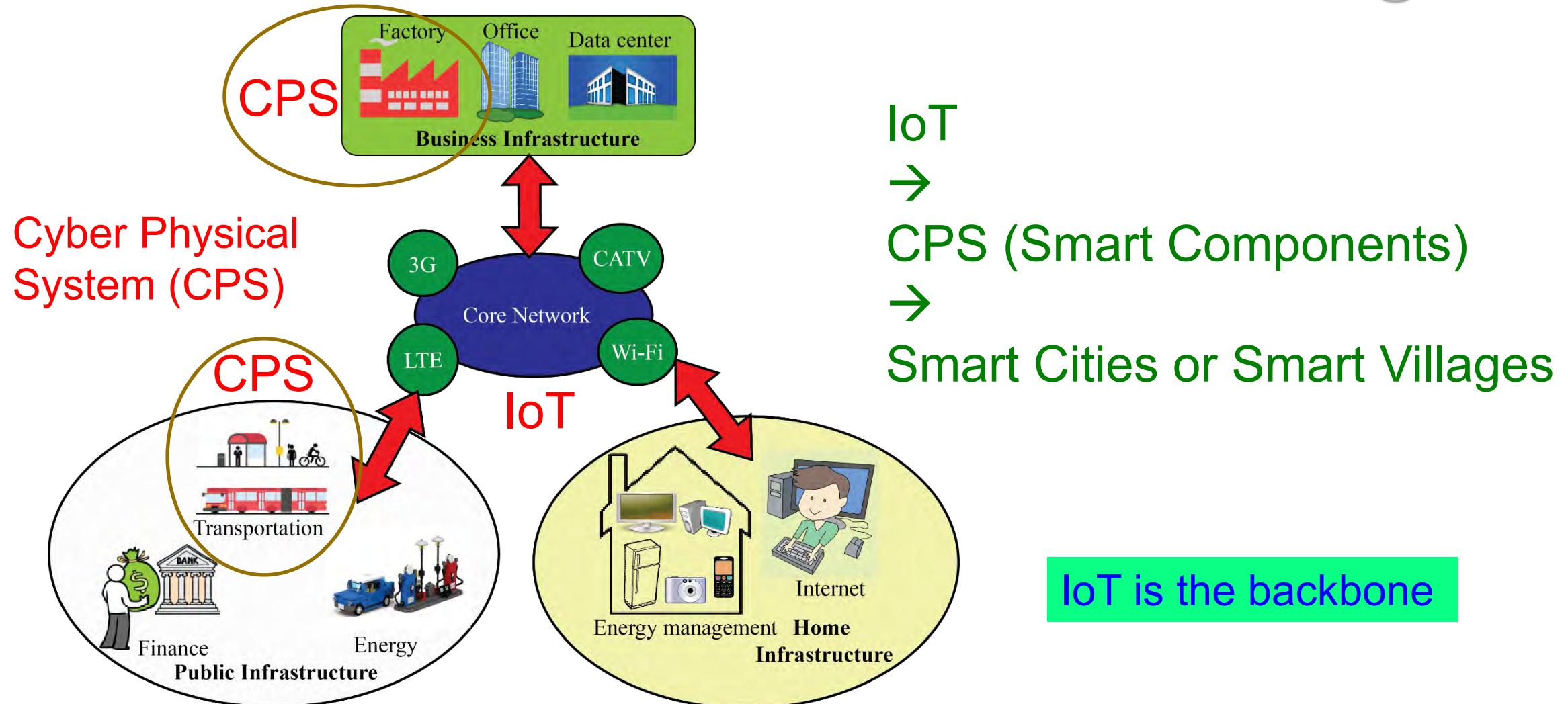
Smart Cities
CPS Types - More
Design Cost - High
Operation Cost – High
Energy Requirement - High

Smart Villages
CPS Types - Less
Design Cost - Low
Operation Cost – Low
Energy Requirement - Low



Source; P. Chanak and I. Banerjee, "Internet of Things-enabled Smart Villages: Recent Advances and Challenges," *IEEE Consumer Electronics Magazine*, DOI: 10.1109/MCE.2020.3013244.

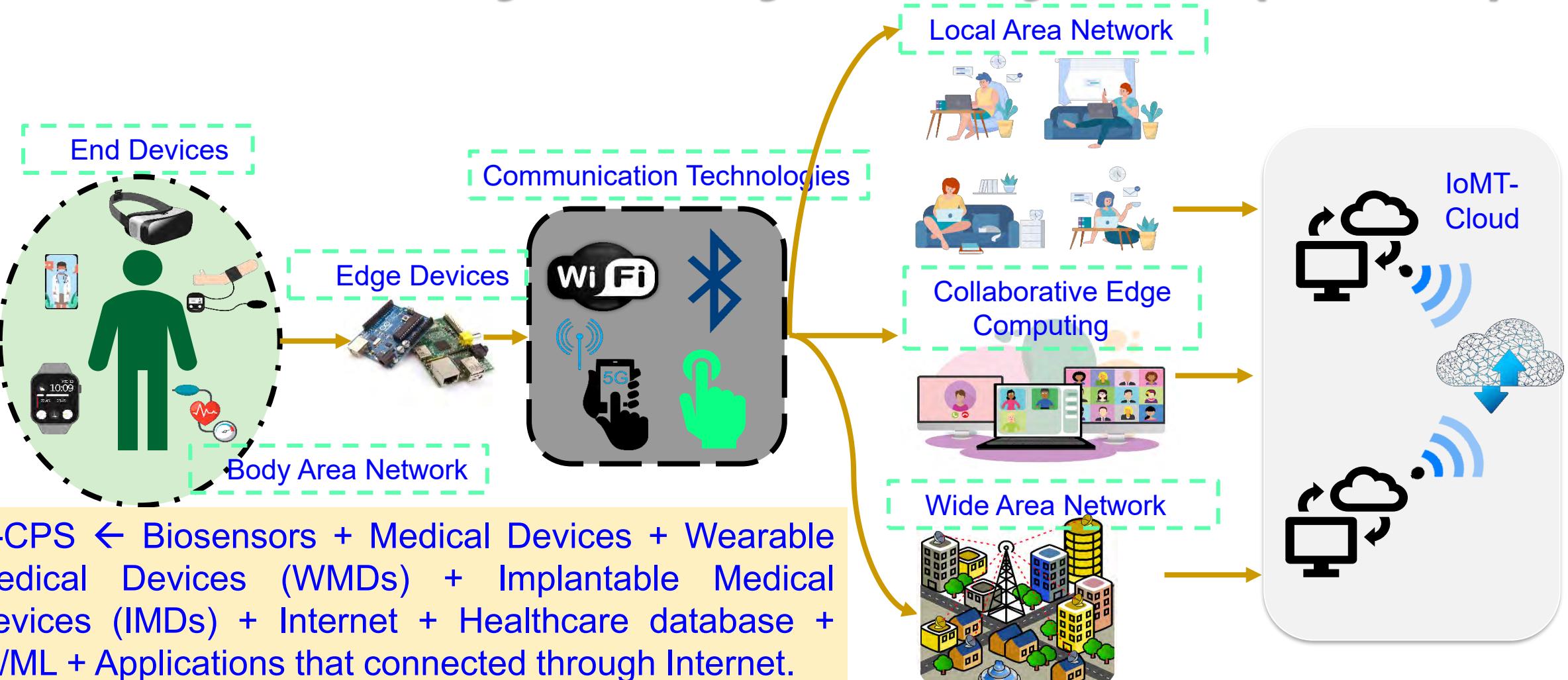
IoT → CPS → Smart Cities or Smart Villages



Source: S. P. Mohanty, U. Choppali, and E. Kougianos, "Everything You wanted to Know about Smart Cities", *IEEE Consumer Electronics Magazine*, Vol. 5, No. 3, July 2016, pp. 60--70.

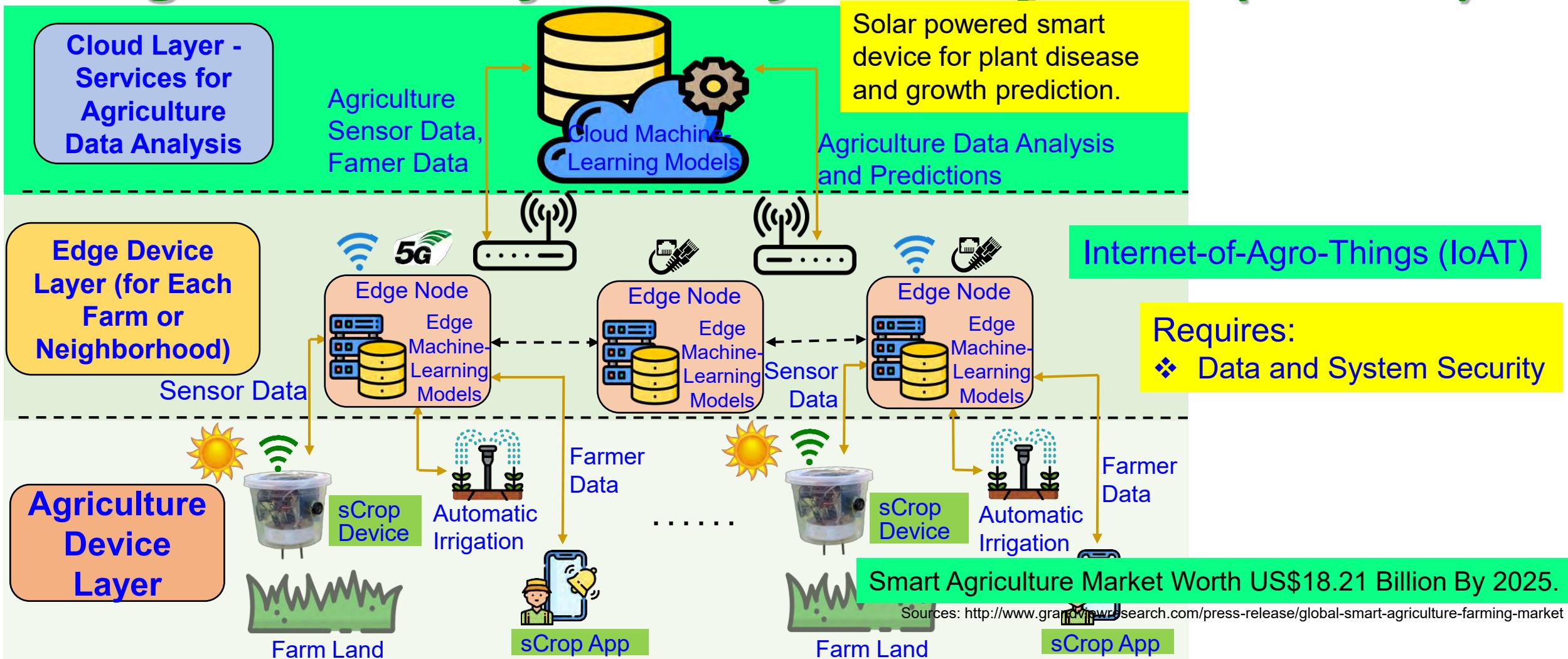
IoT is the backbone

Healthcare Cyber-Physical System (H-CPS)



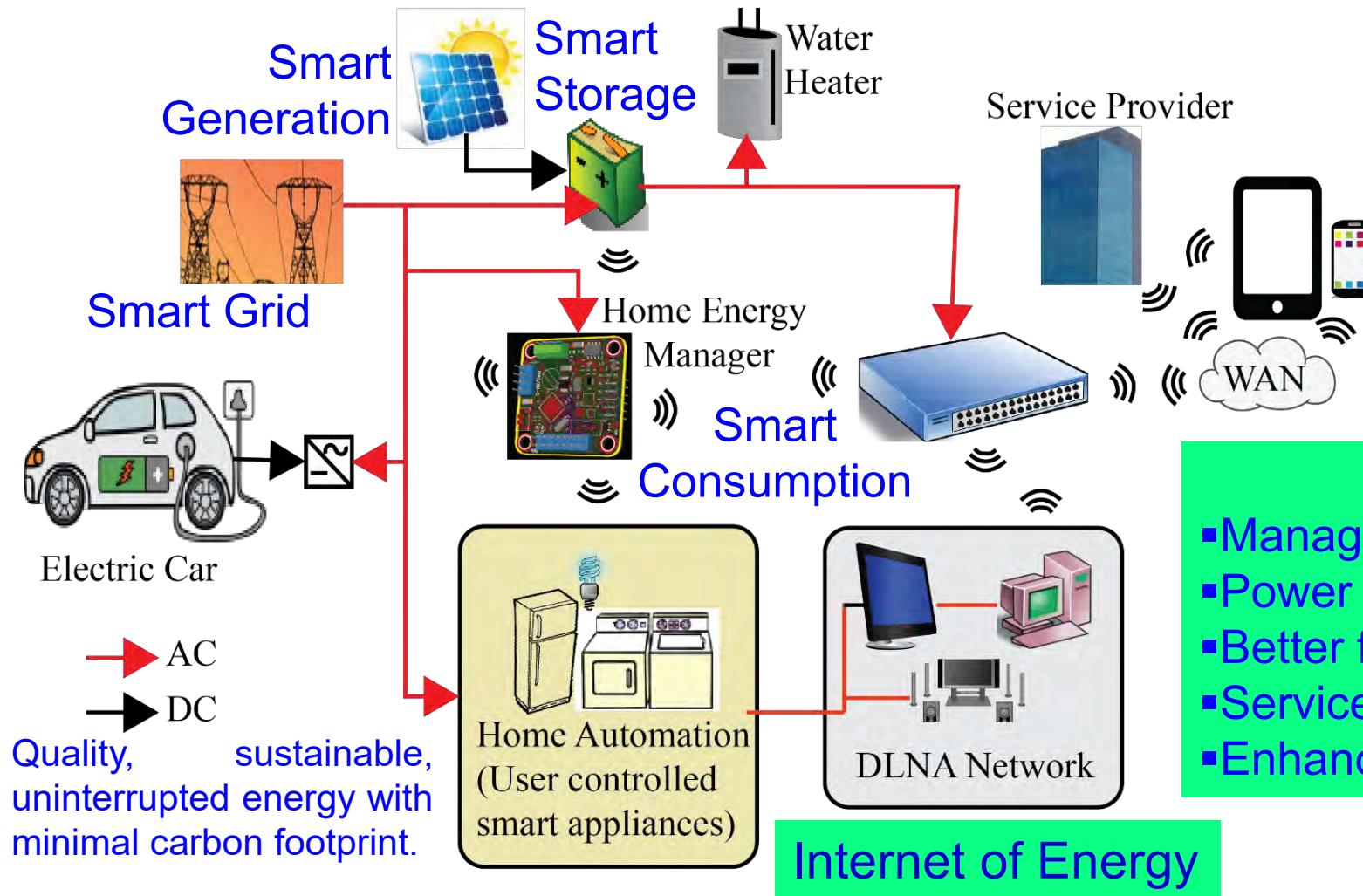
Frost and Sullivan predicts smart healthcare market value to reach US\$348.5 billion by 2025.

Agriculture Cyber-Physical System (A-CPS)



Source: V. Uddalapally, S. P. Mohanty, V. Pallagani, and V. Khandelwal, "sCrop: A Novel Device for Sustainable Automatic Disease Prediction, Crop Selection, and Irrigation in Internet-of-Agro-Things for Smart Agriculture", *IEEE Sensors Journal*, Vol. 21, No. 16, August 2021, pp. 17525--17538, DOI: 10.1109/JSEN.2020.3032438.

Energy Cyber-Physical System (E-CPS)



Requires:

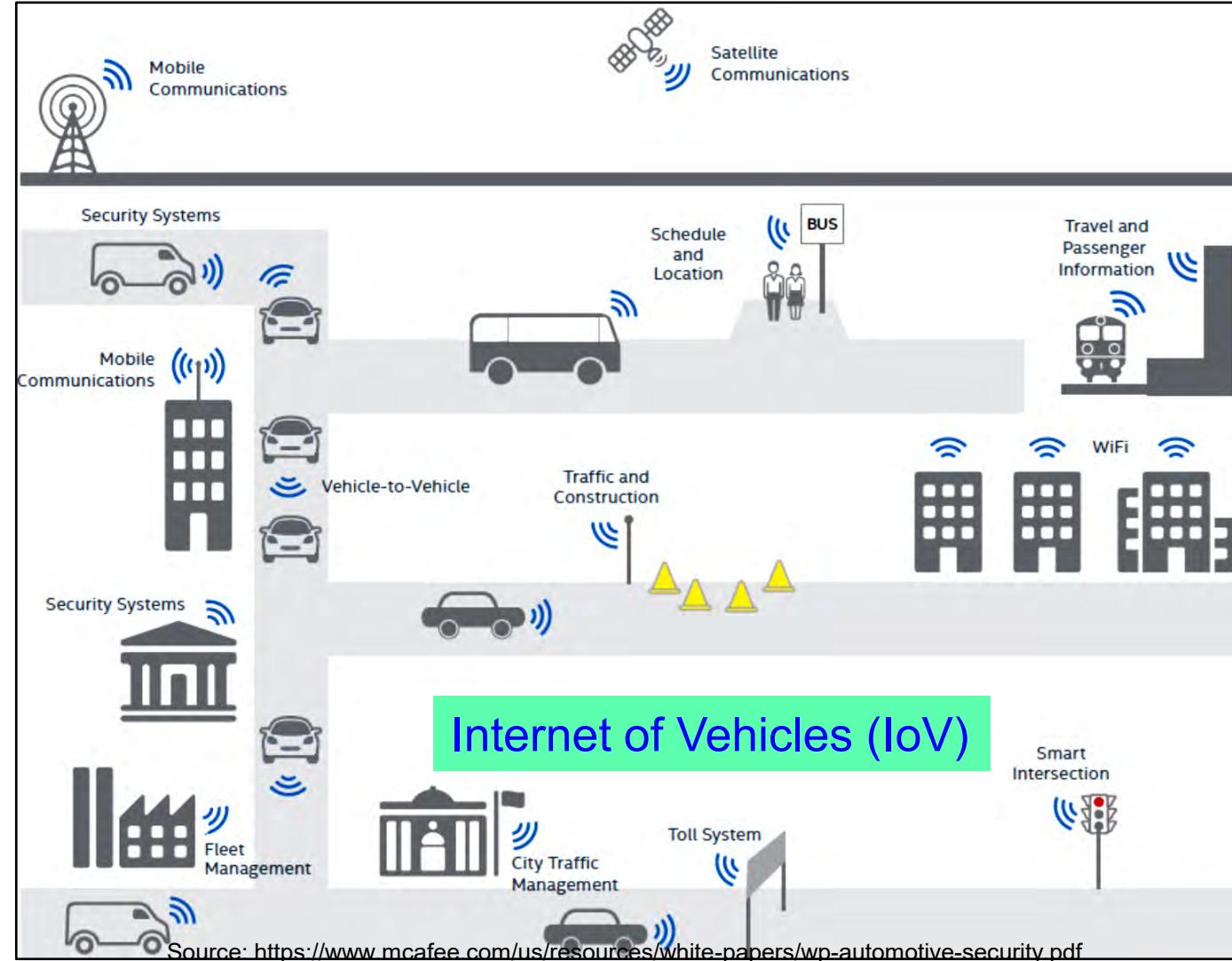
- ❖ Data, Device, and System Security

IoT Role:

- Management of energy usage
- Power generation dispatch for solar, wind, etc.
- Better fault-tolerance of the grid
- Services for plug-in electric vehicles (PEV)
- Enhancing consumer relationships

Source: S. P. Mohanty, U. Choppali, and E. Kougianos, "Everything You wanted to Know about Smart Cities", *IEEE Consumer Electronics Magazine*, Vol. 5, No. 3, July 2016, pp. 60–70.

Transportation Cyber-Physical System (T-CPS)



IoT Role Includes:

- Traffic management
- Real-time vehicle tracking
- Vehicle-to-Vehicle communication
- Scheduling of train, aircraft
- Automatic payment/ticket system
- Automatic toll collection

Requires:

- ❖ Data, Device, and System Security
- ❖ Location Privacy

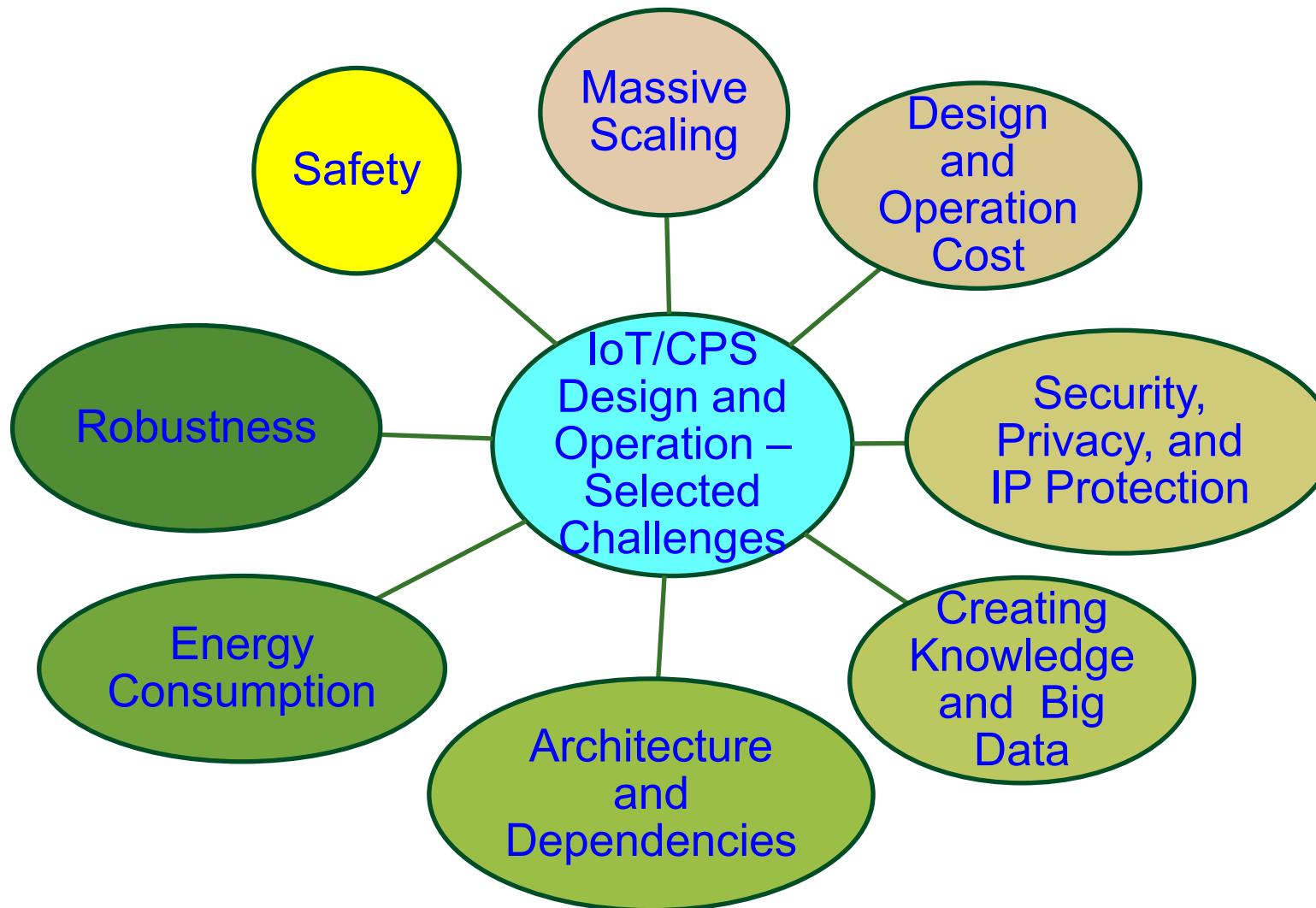
"The global market of IoT based connected cars is expected to reach \$46 Billion by 2020."

Source: Datta 2017, CE Magazine Oct 2017

Challenges in IoT/CPS Design



IoT/CPS – Selected Challenges



Source: Mohanty ICIT 2017 Keynote

Massive Growth of Sensors/Things



Source: <https://www.linkedin.com/pulse/history-iot-industrial-internet-sensors-data-lakes-0-downtime>

Security Challenges – Information



Hacked: Linkedin, Tumblr, & Myspace

Linked in
tumblr.
myspace

Who did it: A hacker going by the name Peace.
What was done: 500 million passwords were stolen.

Details: Peace had the following for sale on a Dark Web Store:

- 167 million Linkedin passwords
- 360 million Myspace passwords
- 68 million Tumblr passwords
- 100 million VK.com passwords
- 71 million Twitter passwords

Personal Information



Credit Card Theft



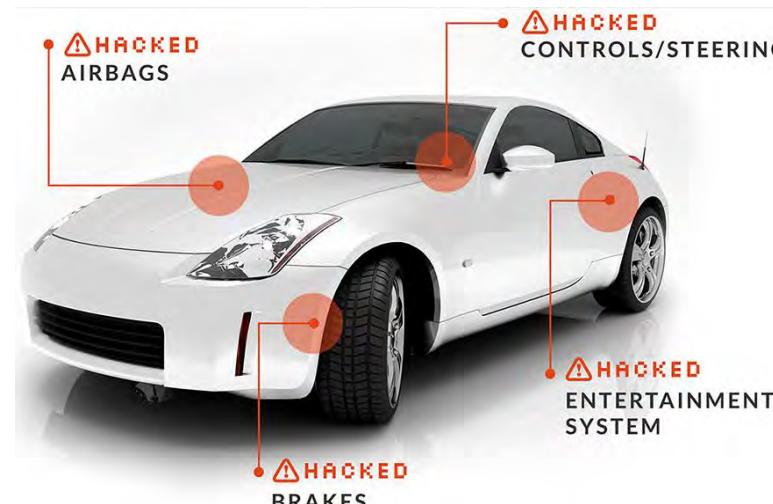
Credit Card/Unauthorized Shopping

Cybersecurity Challenges - System

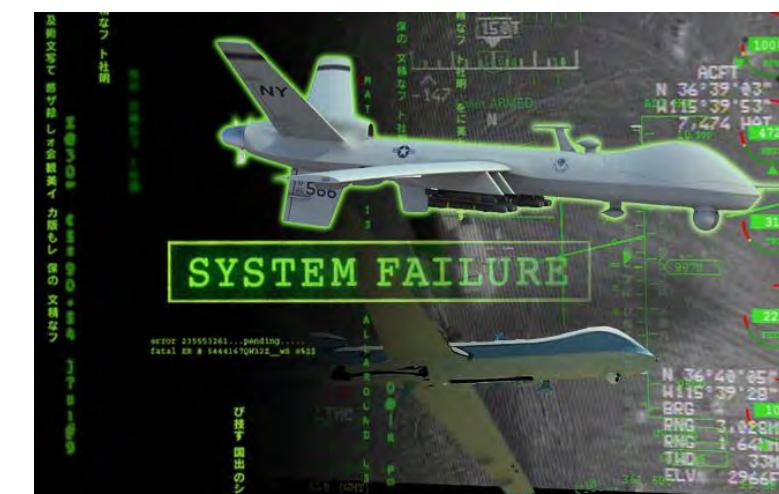
Power Grid Attack



Source: <http://www.csionline.com/article/3177209/security/why-the-ukraine-power-grid-attacks-should-raise-alarm.html>



Source: <http://money.cnn.com/2014/06/01/technology/security/car-hack/>



Source: <http://politicalblindspot.com/u-s-drone-hacked-and-hijacked-with-ease/>

Attacks on IoT Devices



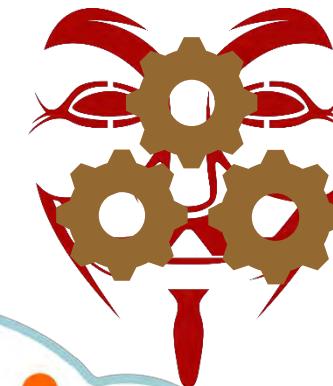
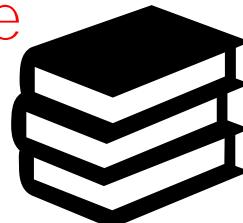
Denial of Service
Attack



Impersonation
Attack



Dictionary and
Brute Force
Attack



Reverse Engineering
Attack

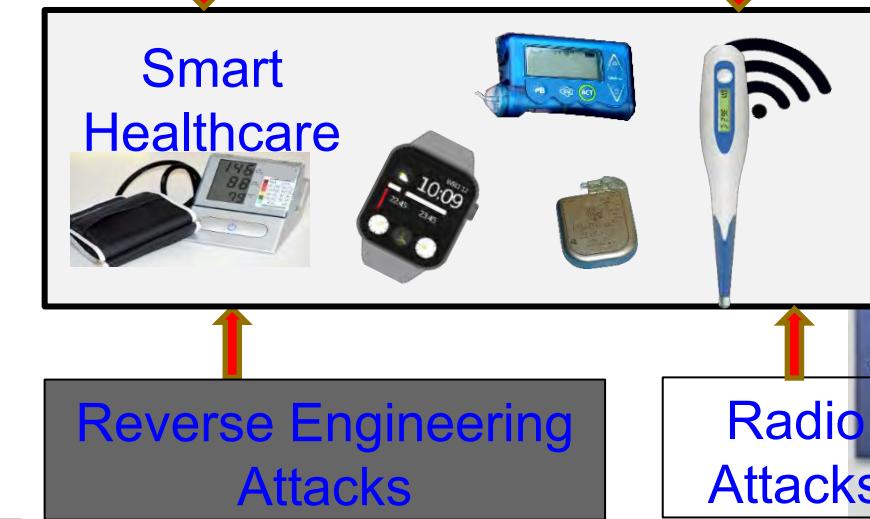
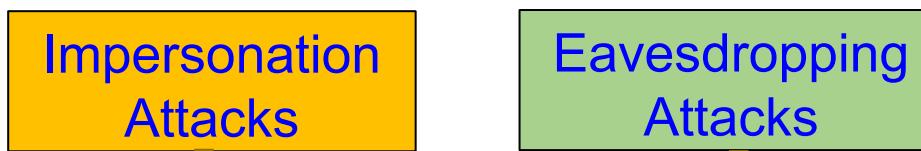


Eavesdropping
Attack

Smart Healthcare - Cybersecurity and Privacy Issue

Selected Smart Healthcare Security/Privacy Challenges

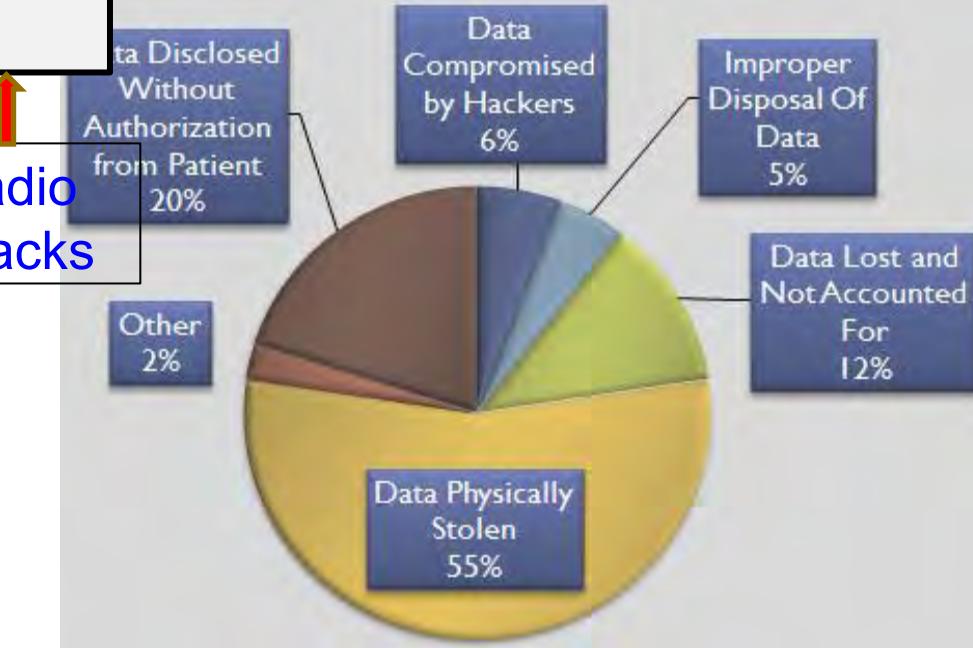
- Data Eavesdropping
- Data Confidentiality
- Data Privacy
- Location Privacy
- Identity Threats
- Access Control
- Unique Identification
- Data Integrity
- Device Security



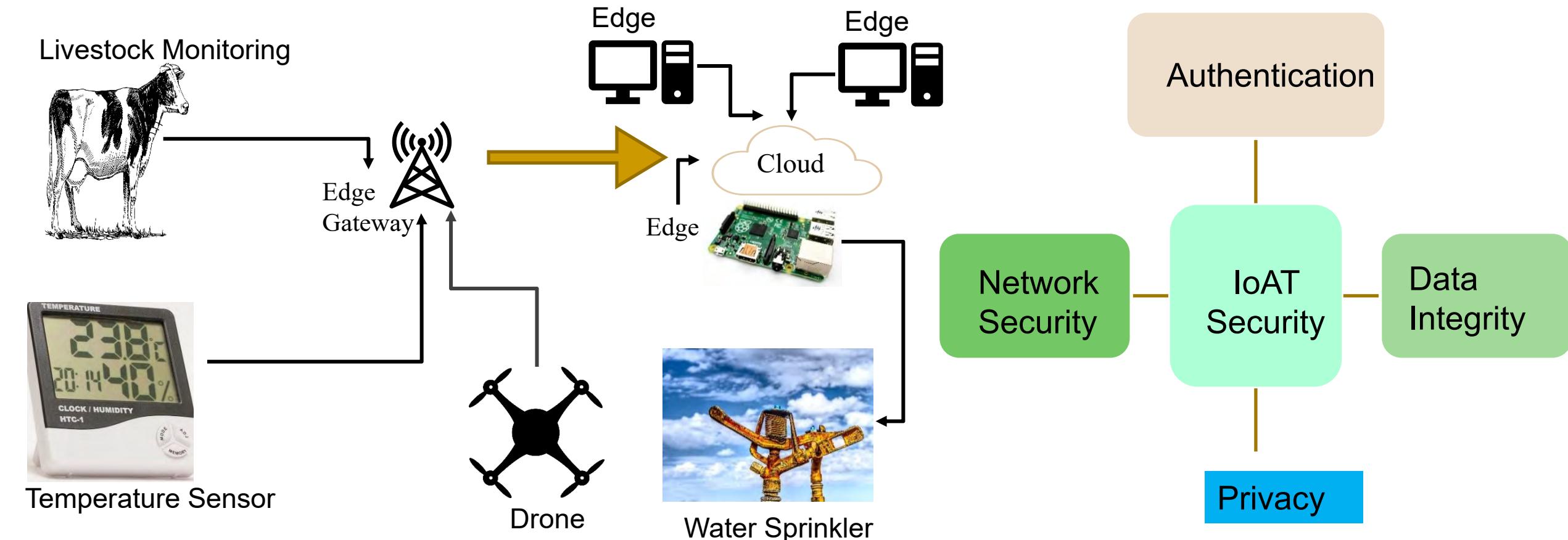
HIPAA

Health Insurance Portability
and Accountability Act

HIPPA Privacy Violation by Types

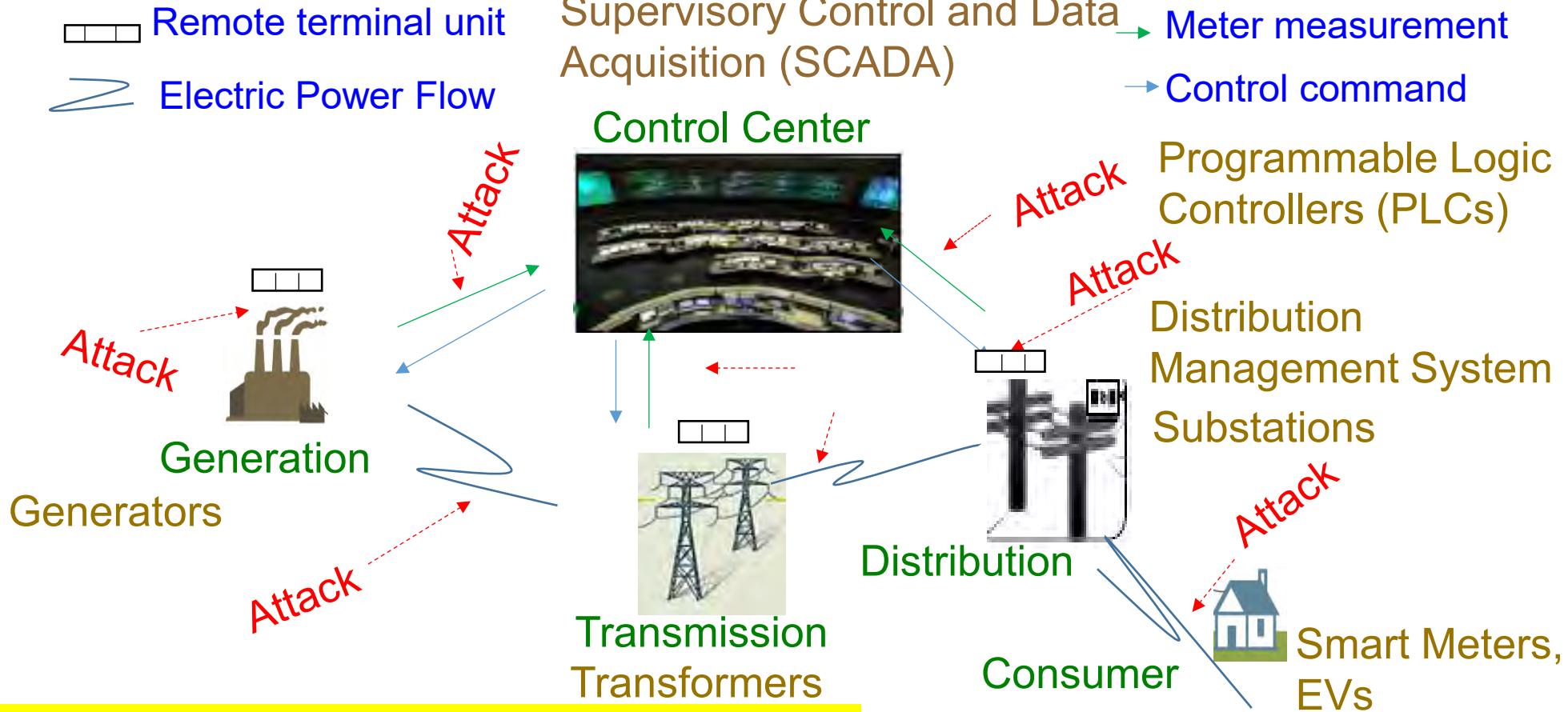


Internet of Agro-Things (IoAT) - Cybersecurity Issue



Source: V. K. V. V. Bathalapalli, S. P. Mohanty, E. Kougianos, V. P. Yanambaka, B. K. Baniya and B. Rout, "A PUF-based Approach for Sustainable Cybersecurity in Smart Agriculture," in *Proc. 19th OITS International Conference on Information Technology (OCIT)*, 2021, pp. 375-380, doi: 10.1109/OCIT53463.2021.00080.

Smart Grid - Vulnerability



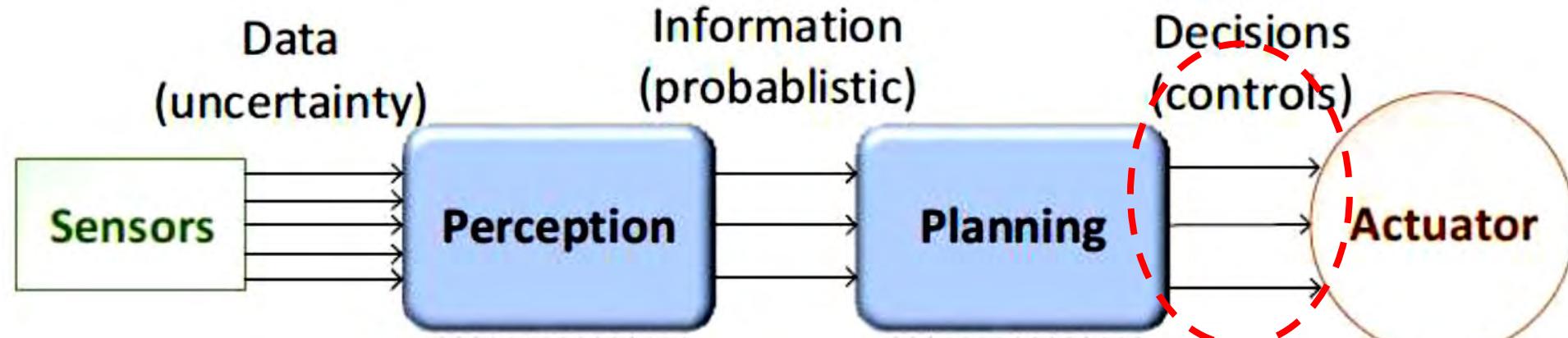
ICT components of smart grid is cyber vulnerable.

Source: (1) R. K. Kaur, L. K. Singh and B. Pandey, "Security Analysis of Smart Grids: Successes and Challenges," *IEEE Consumer Electronics Magazine*, vol. 8, no. 2, pp. 10-15, March 2019.
(2)https://www.enisa.europa.eu/topics/critical-information-infrastructures-and-services/smart-grids/smart-grids-and-smart-m Metering/ENISA_Annex%20II%20-%20Security%20Aspects%20of%20Smart%20Grid.pdf

Smart Car – Modification of Input Signal of Control Can be Dangerous



- Typically vehicles are controlled by human drivers
- Designing an Autonomous Vehicle (AV) requires decision chains.
- AV actuators controlled by algorithms.
- Decision chain involves sensor data, perception, planning and actuation.
- Perception transforms sensory data to useful information.
- Planning involves decision making.



Source: S. J. Plathottam and P. Ranganathan, "Next Generation Distributed and Networked Autonomous Vehicles: Review," in *Proc. 10th International Conference on Communication Systems and Networks (COMSNETS)*, 2018, pp. 577-582, DOI: <https://doi.org/10.1109/COMSNETS.2018.8328277>.

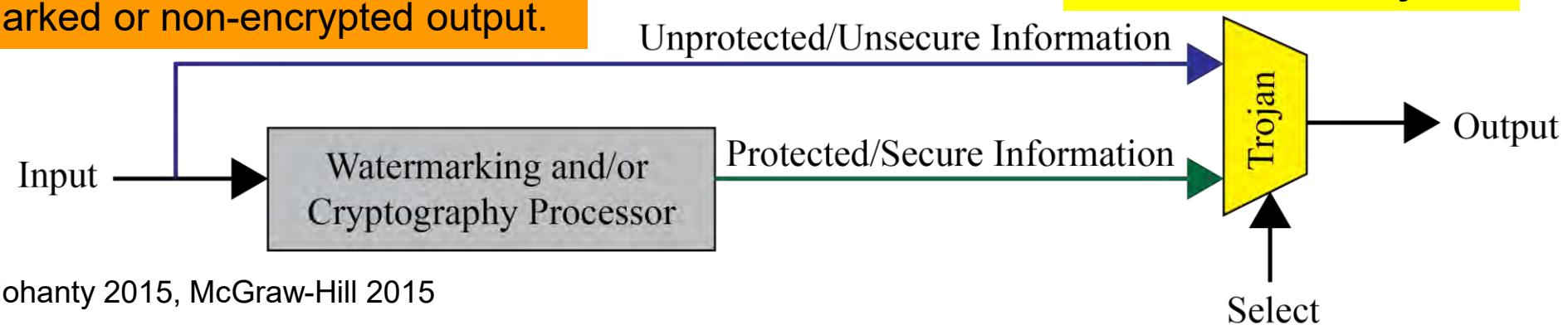
Trojans can Provide Backdoor Entry to Adversary



Provide backdoor to adversary.
Chip fails during critical needs.

Information may bypass giving a non-watermarked or non-encrypted output.

Hardware Trojans



Source: Mohanty 2015, McGraw-Hill 2015

Fake Data and Fake Hardware – Both are Equally Dangerous in CPS



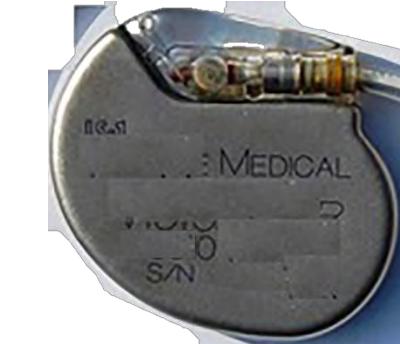
AI can be fooled by fake data



AI can create fake data (Deepfake)



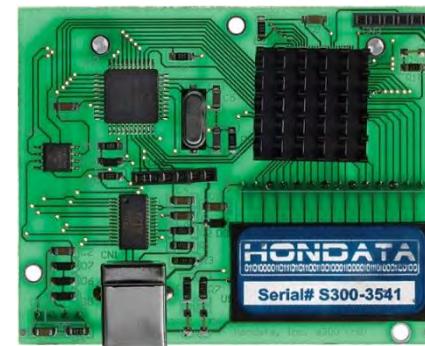
Authentic
An implantable medical device



Fake
An implantable medical device

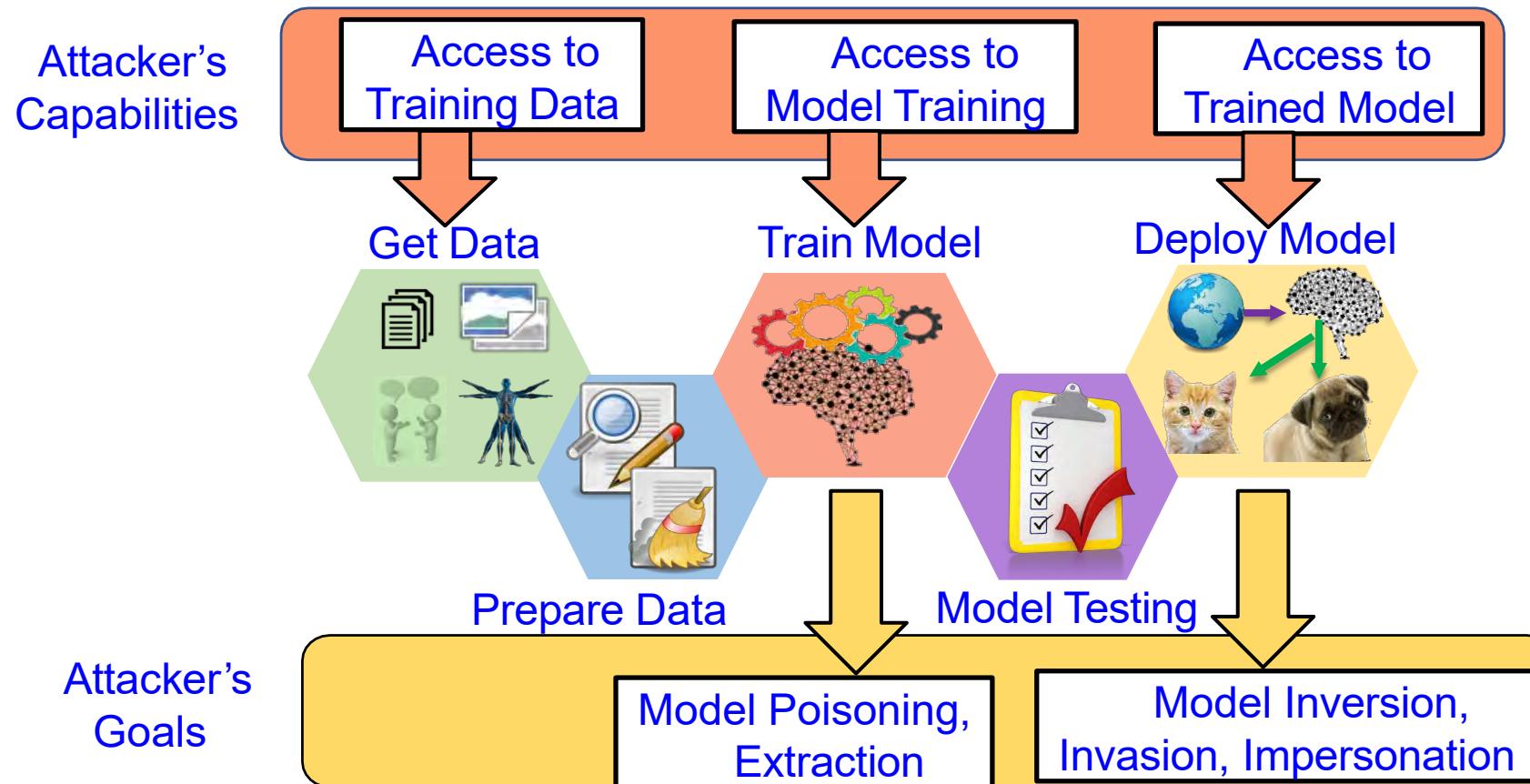


Authentic
A plug-in for car-engine computers



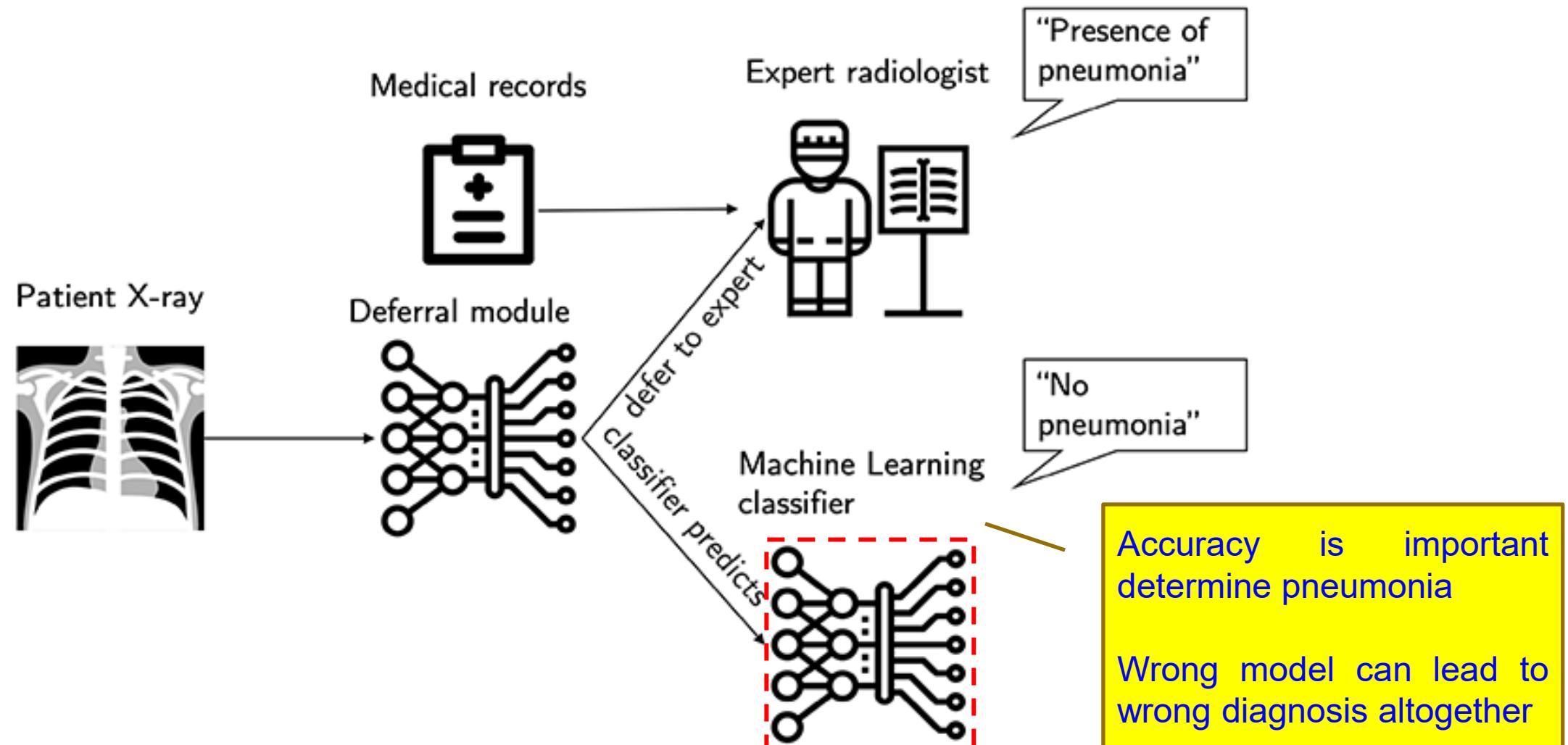
Fake
A plug-in for car-engine computers

AI Security - Attacks



Source: Sandip Kundu ISVLSI 2019 Keynote.

Wrong ML Model → Wrong Diagnosis



Source: <https://www.healthcareitnews.com/news/new-ai-diagnostic-tool-knows-when-defer-human-mit-researchers-say>

AI Security - Trojans in Artificial Intelligence (TroiAI)



Label:
Stop sign



Label:
Speed limit sign



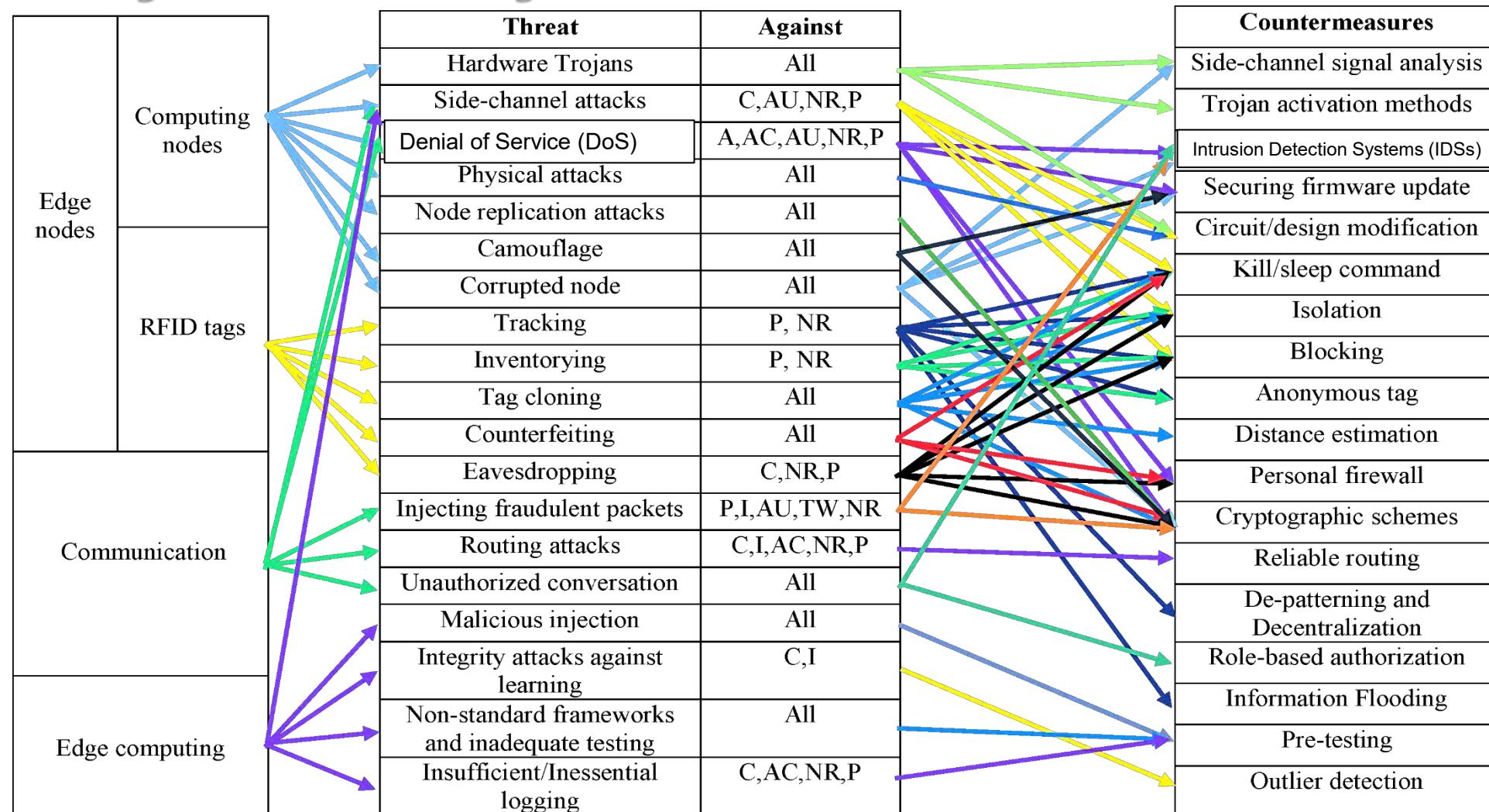
Adversaries can insert **Trojans** into AIs, leaving a trigger for bad behavior that they can activate during the AI's operations

Source: https://www.iarpa.gov/index.php?option=com_content&view=article&id=1150&Itemid=448

Cybersecurity Solution for IoT/CPS



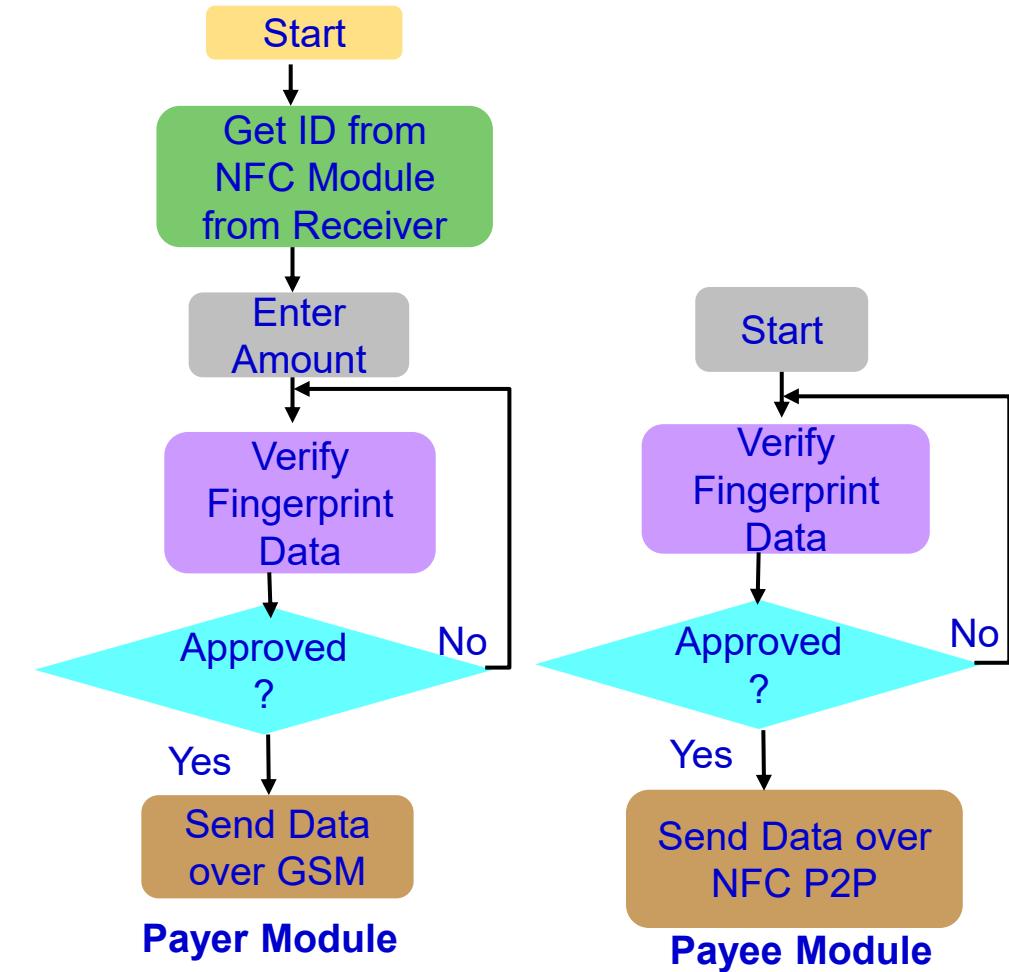
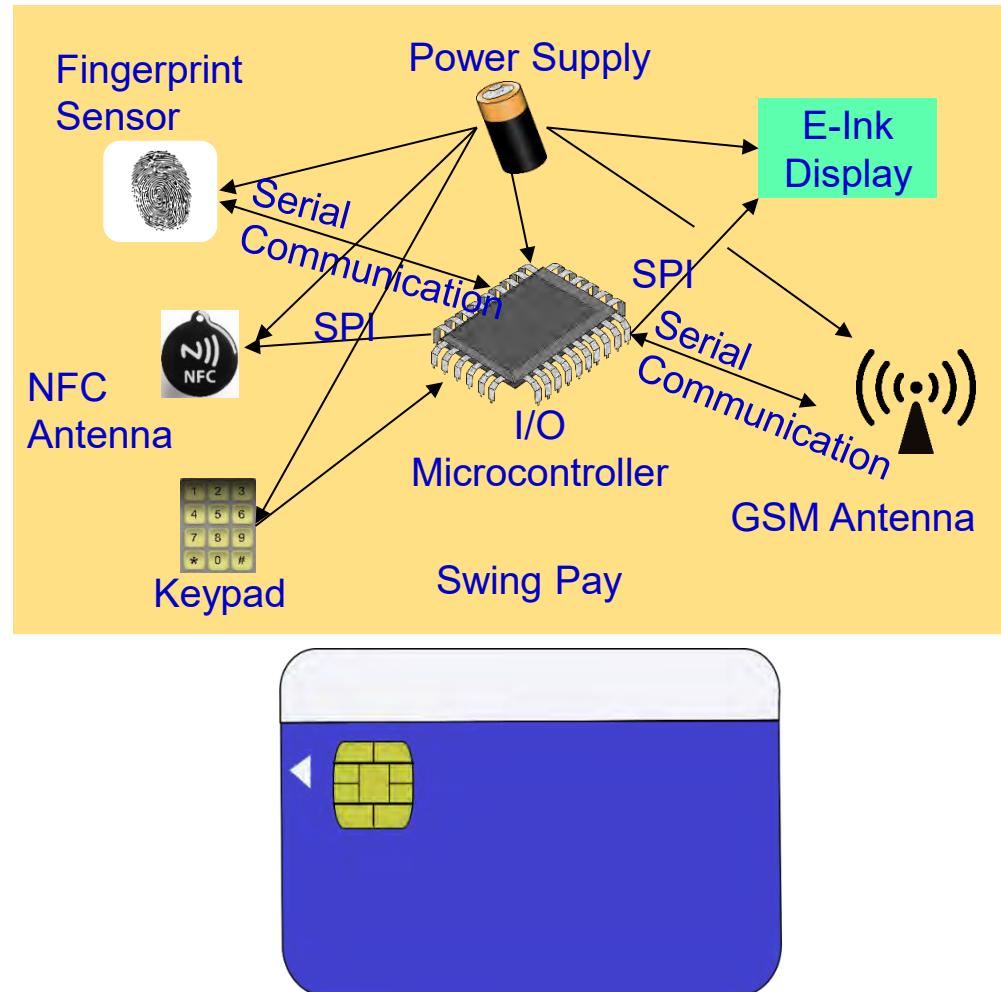
IoT Cybersecurity - Attacks and Countermeasures



C - Confidentiality, I – Integrity, A - Availability, AC – Accountability, AU – Auditability, TW – Trustworthiness, NR - Non-repudiation, P - Privacy

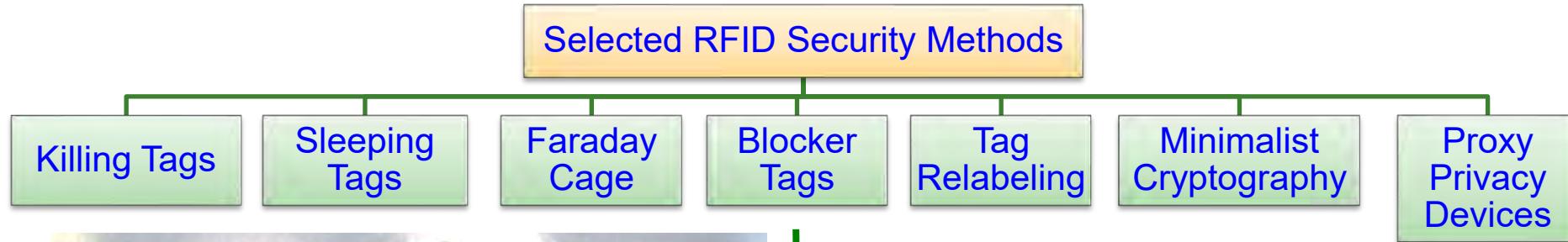
Source: A. Mosenia, and Niraj K. Jha. "A Comprehensive Study of Security of Internet-of-Things", IEEE Transactions on Emerging Topics in Computing, 5(4), 2016, pp. 586-602.

Our Swing-Pay: NFC Cybersecurity Solution

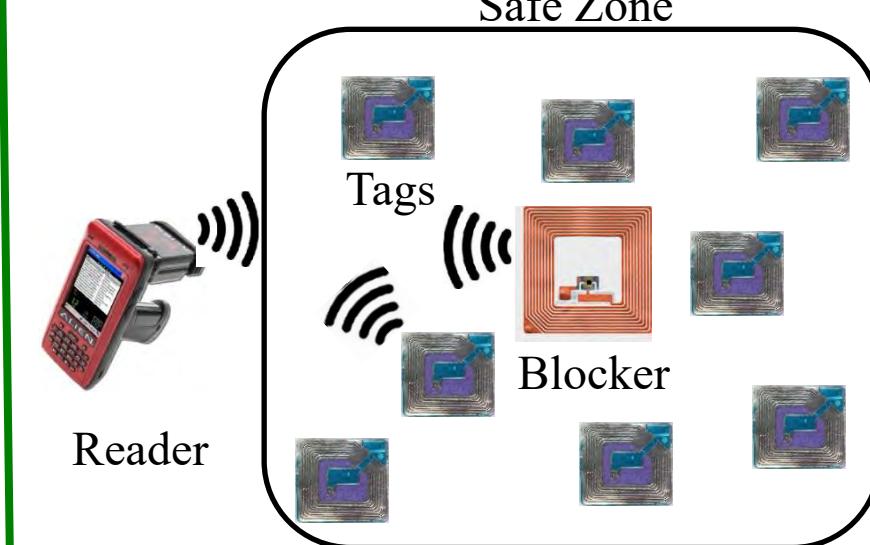
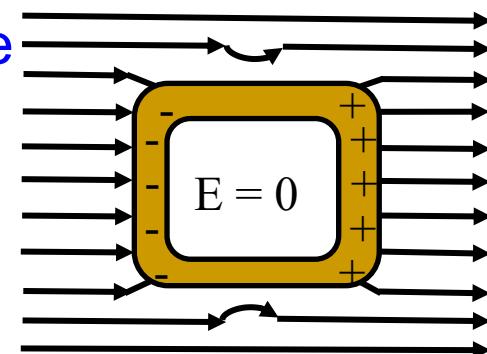


Source: S. Ghosh, J. Goswami, A. Majumder, A. Kumar, **S. P. Mohanty**, and B. K. Bhattacharyya, "Swing-Pay: One Card Meets All User Payment and Identity Needs", *IEEE Consumer Electronics Magazine (MCE)*, Volume 6, Issue 1, January 2017, pp. 82--93.

RFID Cybersecurity - Solutions



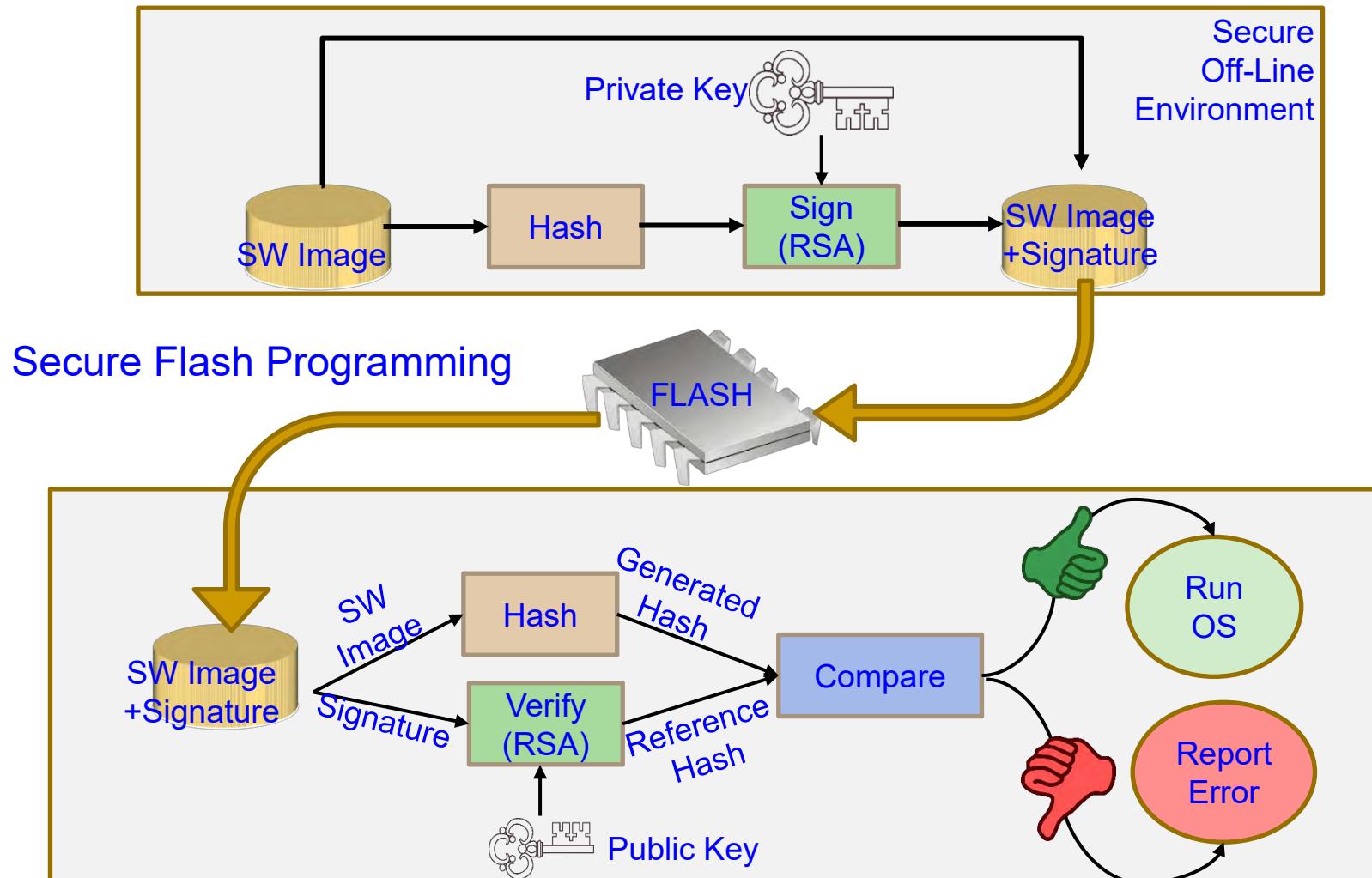
Faraday Cage



Blocker Tags

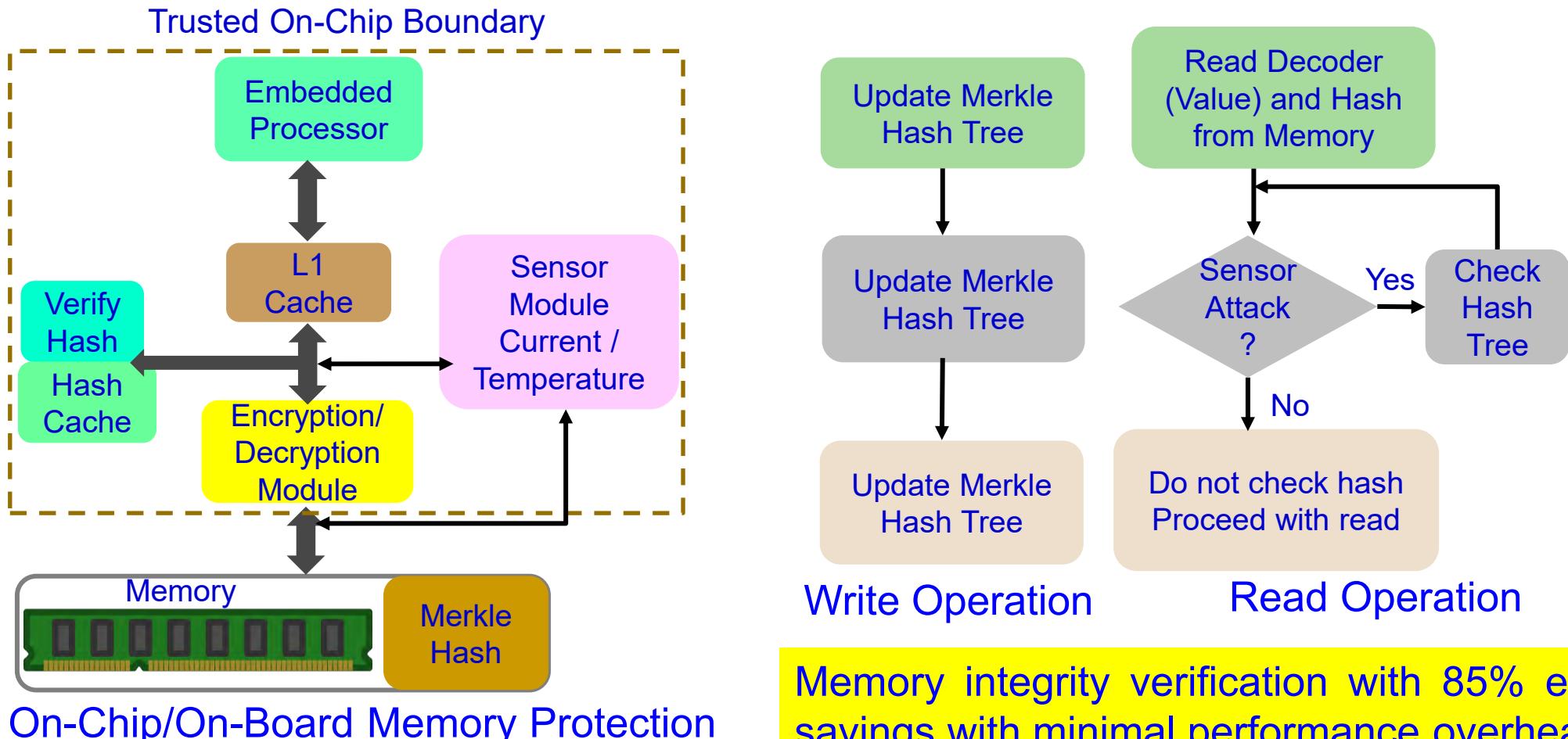
Source: Khattab 2017, Springer 2017 RFID Security

Firmware Cybersecurity - Solution



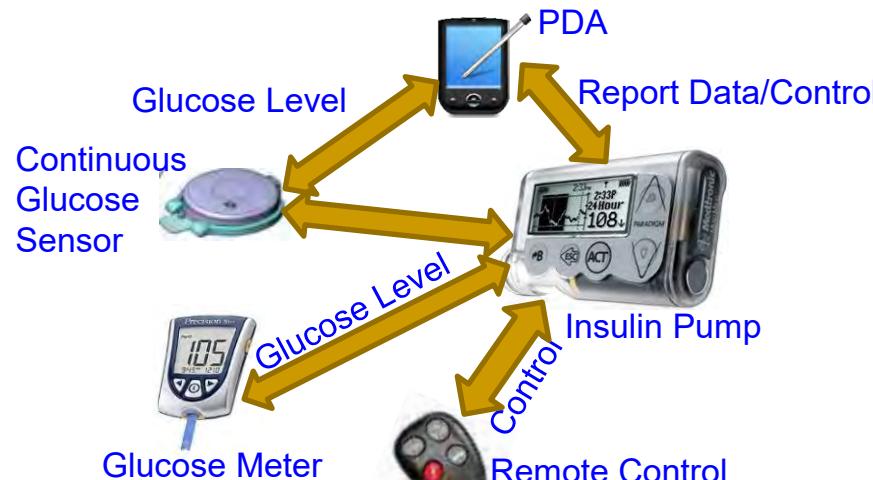
Source: <https://www.nxp.com/docs/en/white-paper/AUTOSECURITYWP.pdf>

Embedded Memory Security

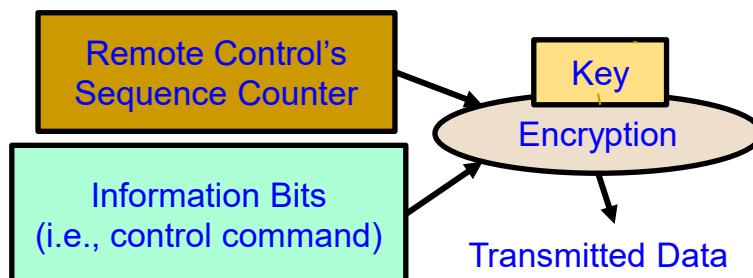


Source: S. Nimgaonkar, M. Gomathisankaran, and S. P. Mohanty, "MEM-DnP: A Novel Energy Efficient Approach for Memory Integrity Detection and Protection in Embedded Systems", *Springer Circuits, Systems, and Signal Processing Journal (CSSP)*, Volume 32, Issue 6, December 2013, pp. 2581--2604.

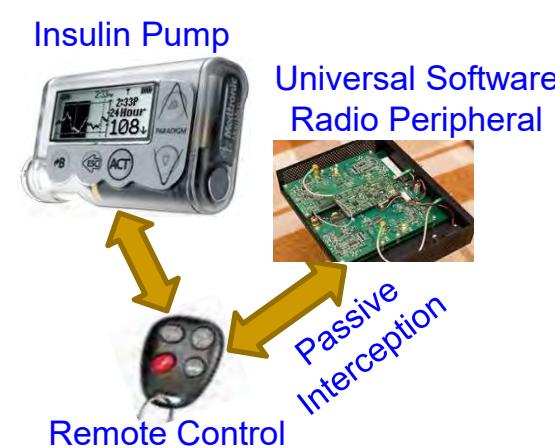
Smart Healthcare Cybersecurity



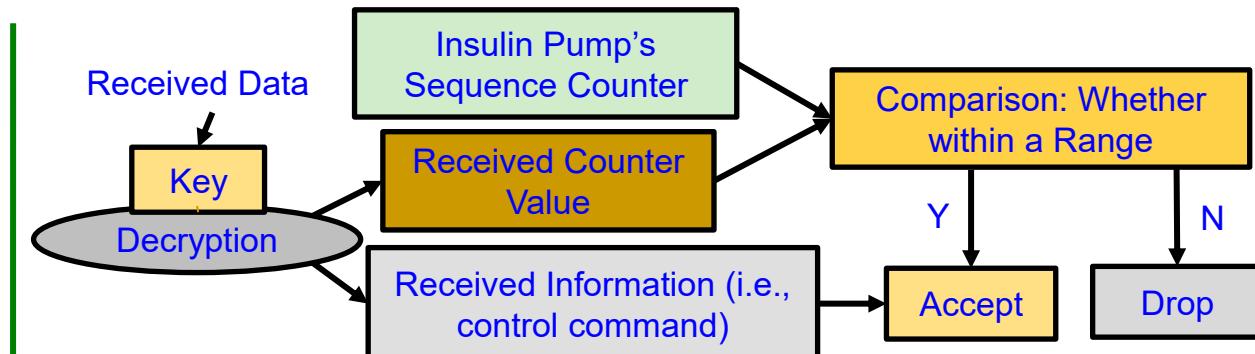
Insulin Delivery System



Rolling Code Encoder in Remote Control



Security Attacks



Rolling Code Decoder in Insulin Pump

Source: Li and Jha 2011; HEALTH 2011

Drawbacks of Existing Cybersecurity Solutions



IT Cybersecurity Solutions Can't be Directly Extended to IoT/CPS Cybersecurity

IT Cybersecurity

- IT infrastructure may be well protected rooms
- Limited variety of IT network devices
- Millions of IT devices
- Significant computational power to run heavy-duty security solutions
- IT security breach can be costly

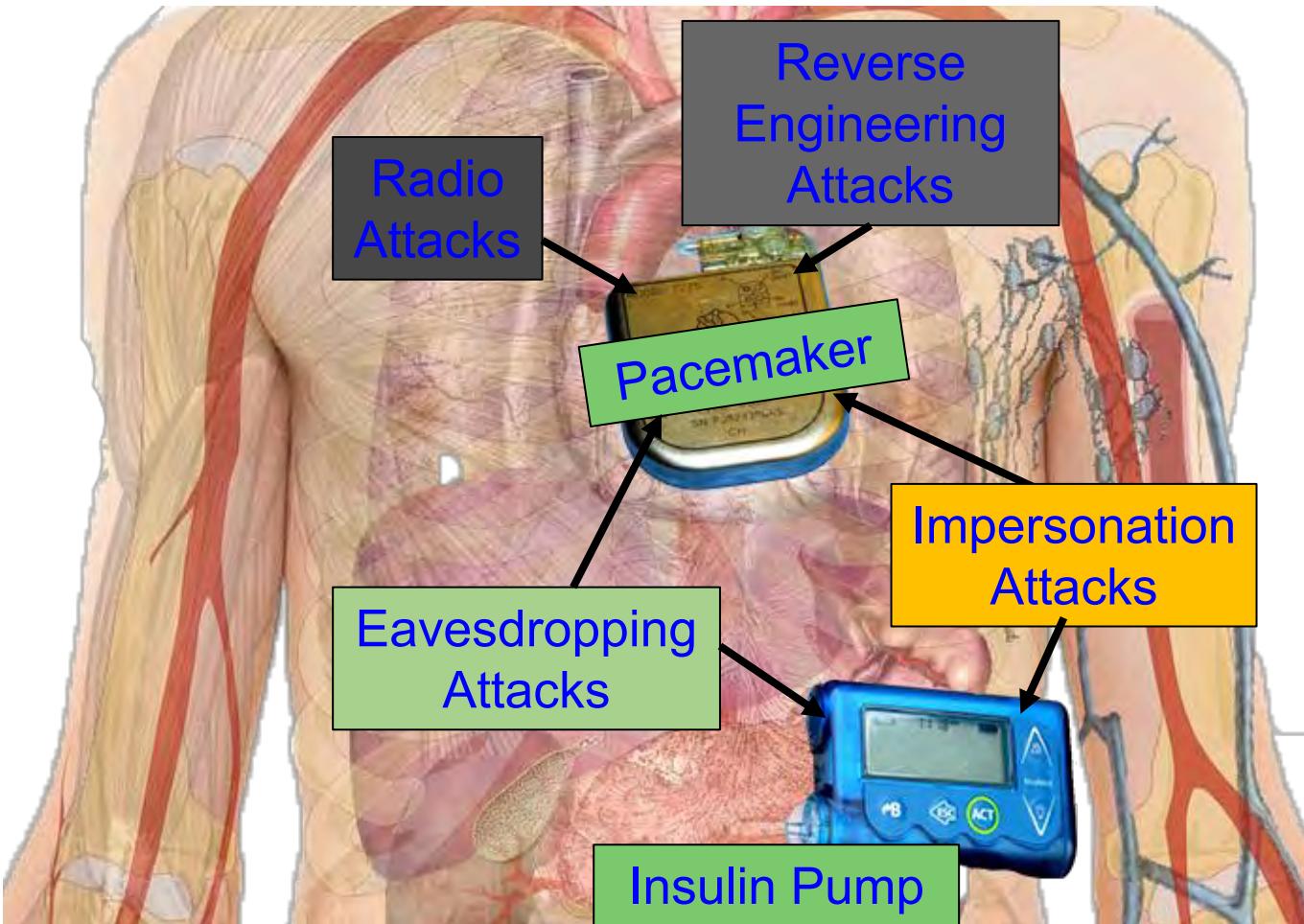
IoT Cybersecurity

- IoT may be deployed in open hostile environments
- Significantly large variety of IoT devices
- Billions of IoT devices
- May not have computational power to run security solutions
- IoT security breach (e.g. in a IoMT device like pacemaker, insulin pump) can be life threatening

Maintaining of Cybersecurity of Electronic Systems, IoT, CPS, needs **Energy**, and affects performance.

Cybersecurity Measures in Healthcare

Cyber-Physical Systems is Hard

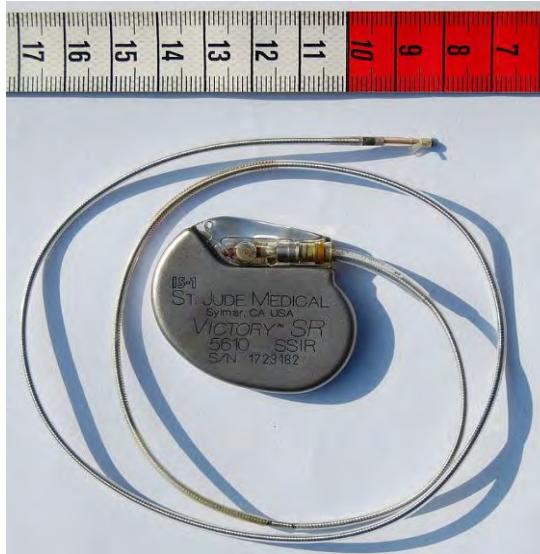


Collectively (WMD+IMD):
Implantable and Wearable
Medical Devices (IWMDs)

Implantable and Wearable Medical
Devices (IWMDs):
→ Longer Battery life
→ Safer device
→ Smaller size
→ Smaller weight
→ Not much computational capability

H-CPS Cybersecurity Measures is Hard

- Energy Constrained



Pacemaker
Battery Life
- 10 years



Neurostimulator
Battery Life
- 8 years

- Implantable Medical Devices (IMDs) have integrated battery to provide energy to all their functions → Limited Battery Life depending on functions
- Higher battery/energy usage → Lower IMD lifetime
- Battery/IMD replacement → Needs surgical risky procedures

Source: C. Camara, P. Peris-Lopez, and J. E.Tapiadura, "Security and privacy issues in implantable medical devices: A comprehensive survey", *Elsevier Journal of Biomedical Informatics*, Volume 55, June 2015, Pages 272-289.

Smart Car Cybersecurity - Latency Constrained

Protecting Communications

Particularly any Modems for In-vehicle Infotainment (IVI) or in On-board Diagnostics (OBD-II)

Over The Air (OTA) Management

From the Cloud to Each Car

Cars can have 100 Electronic Control Units (ECUs) and 100 million lines of code, each from different vendors
– Massive cybersecurity issues.

Protecting Each Module

Sensors, Actuators, and Anything with a Microcontroller Unit (MCU)

Mitigating Advanced Threats

Analytics in the Car and in the Cloud

Source: http://www.symantec.com/content/en/us/enterprise/white_papers/public-building-security-into-cars-20150805.pdf

- Connected cars require latency of ms to communicate and avoid impending crash:
 - Faster connection
 - Low latency
 - Energy efficiency

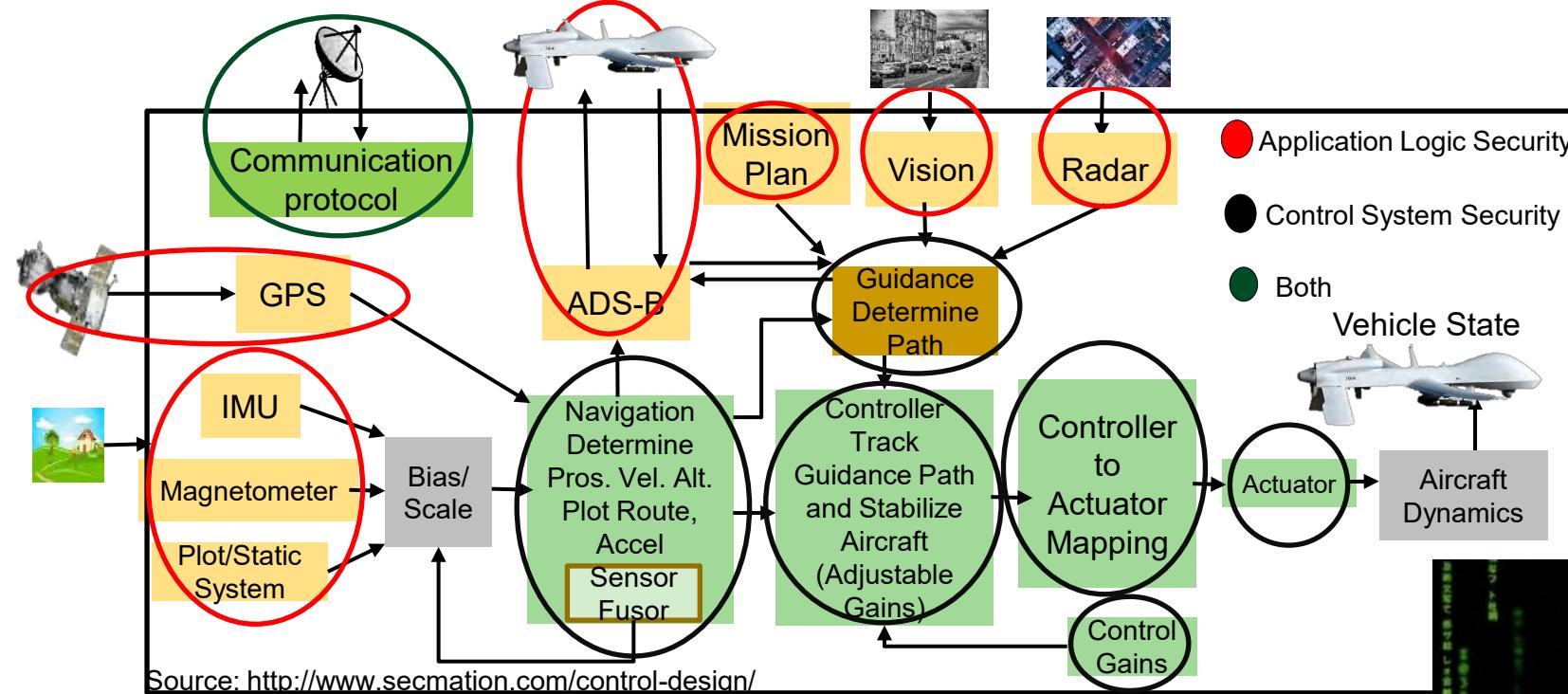
Security Mechanism Affects:

- Latency
- Mileage
- Battery Life



Car Cybersecurity –
Latency Constrained

UAV Cybersecurity - Energy & Latency Constrained



Cybersecurity Mechanisms Affect:
Battery Life Latency Weight Aerodynamics

UAV Security – Energy and Latency Constraints



Source: <http://politicalblindspot.com/u-s-drone-hacked-and-hijacked-with-ease/>

Smart Grid Security Constraints



Smart Grid – Security Objectives

Availability

Integrity

Confidentiality



Smart Grid – Security Requirements

Identification

Authentication

Authorization

Trust

Access Control

Privacy

Smart Grid – Security Solution Constraints

Transactions Latency

Communication Latency

Transactions Computational Overhead

Energy Overhead on Embedded Devices

Security Budget

Source: R. K. Pandey and M. Misra, "Cyber security threats - Smart grid infrastructure," in Proc. National Power Systems Conference (NPSC), 2016, pp. 1-6.

Cybersecurity Attacks – Software Vs Hardware Based

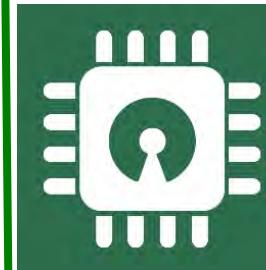
Software Based

- Software attacks via communication channels
- Typically from remote
- More frequent
- Selected Software based:
 - Denial-of-Service (DoS)
 - Routing Attacks
 - Malicious Injection
 - Injection of fraudulent packets
 - Snooping attack of memory
 - Spoofing attack of memory and IP address
 - Password-based attacks



Hardware Based

- Hardware or physical attacks
- Maybe local
- More difficult to prevent
- Selected Hardware based:
 - Hardware backdoors (e.g. Trojan)
 - Inducing faults
 - Electronic system tampering/ jailbreaking
 - Eavesdropping for protected memory
 - Side channel attack
 - Hardware counterfeiting



Source: Mohanty ICCE Panel 2018

Cybersecurity Solutions – Software Vs Hardware Based

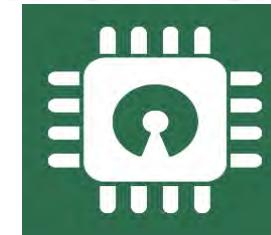
Software Based



- Introduces latency in operation
- Flexible - Easy to use, upgrade and update
- Wider-Use - Use for all devices in an organization
- Higher recurring operational cost
- Tasks of encryption easy compared to hardware – substitution tables
- Needs general purpose processor
- Can't stop hardware reverse engineering

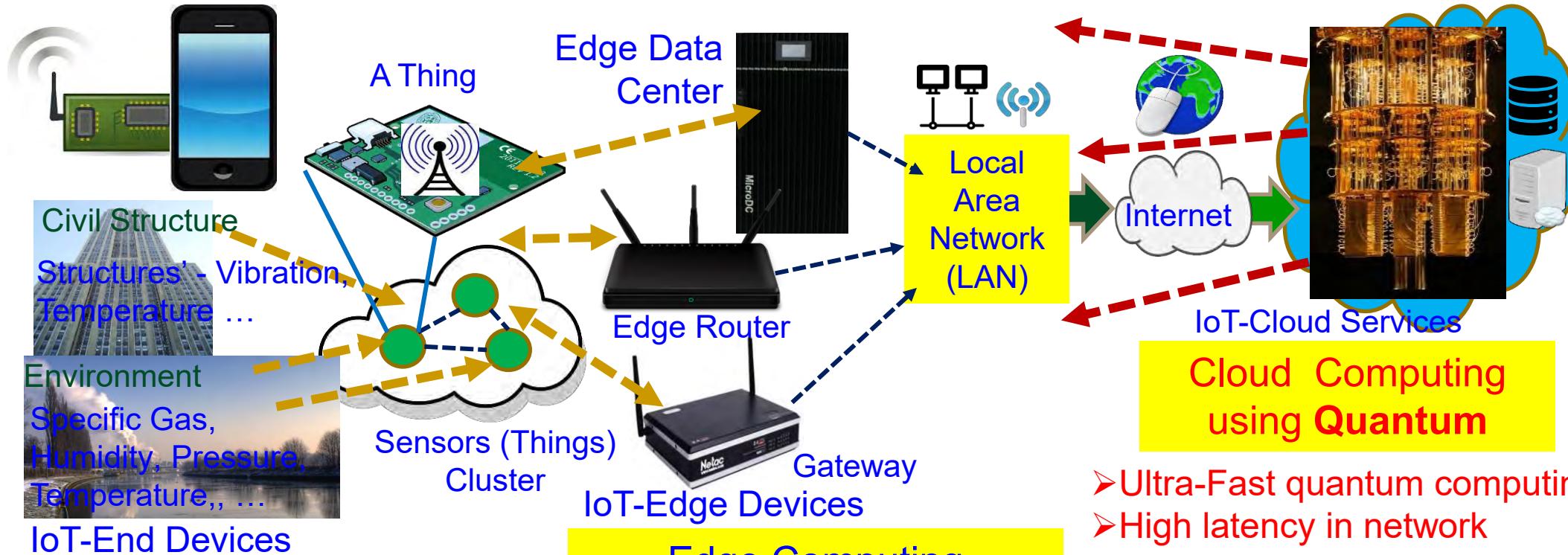
Source: Mohanty ICCE Panel 2018

Hardware Based



- High-Speed operation
- Energy-Efficient operation
- Low-cost using ASIC and FPGA
- Tasks of encryption easy compared to software – bit permutation
- Easy integration in CE systems
- Possible security at source-end like sensors, better suitable for IoT
- Susceptible to side-channel attacks
- Can't stop software reverse engineering

Cybersecurity Nightmare ← Quantum Computing



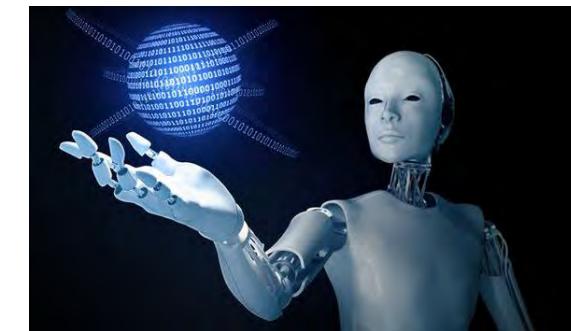
- Minimal computational resource
- Negligible latency in network
- Very lightweight security

- Less computational resource
- Minimal latency in network
- Lightweight security

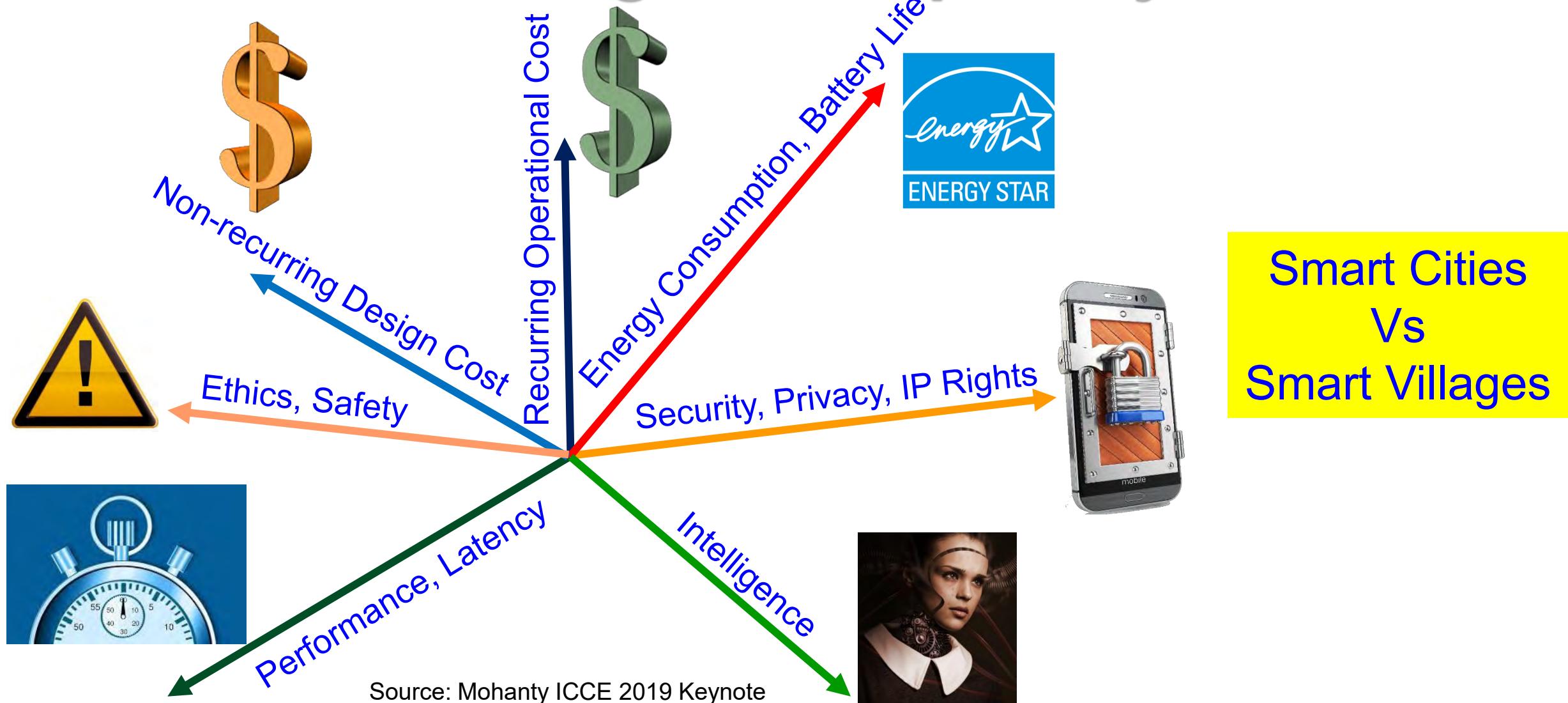
A quantum computer could break a 2048-bit RSA encryption in 8 hours.

- Ultra-Fast quantum computing resources
- High latency in network
- Breaks every encryption in no time

Security-by-Design (SbD) – The Principle



IoT/CPS Design – Multiple Objectives



Smart Cities
Vs
Smart Villages

Privacy by Design (PbD) → General Data Protection Regulation (GDPR)

1995

Privacy by Design (PbD)

- ❖ Treat privacy concerns as design requirements when developing technology, rather than trying to retrofit privacy controls after it is built



2018

General Data Protection Regulation (GDPR)

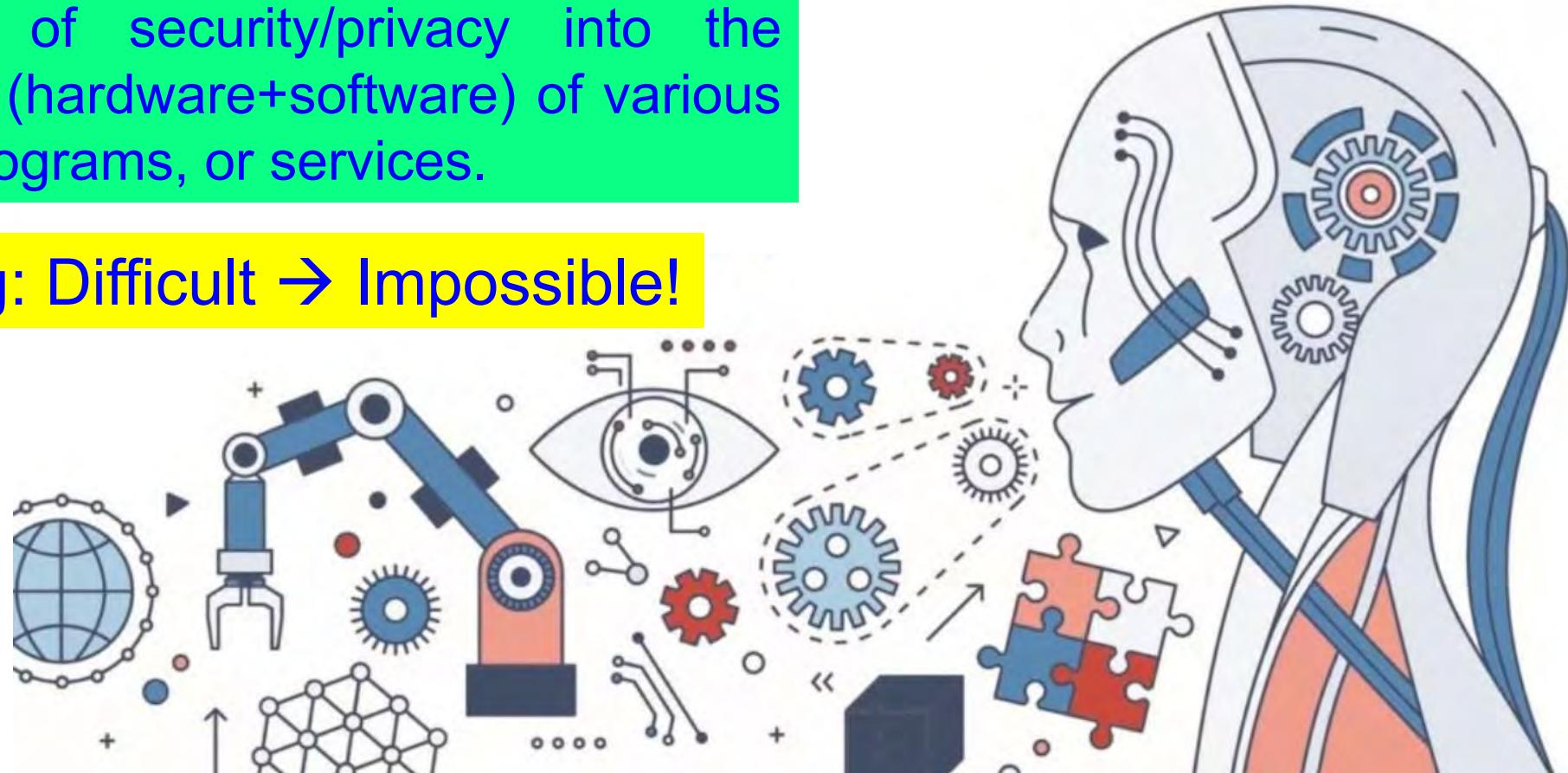
- ❖ GDPR makes Privacy by Design (PbD) a legal requirement

Security by Design
aka
Secure by Design (SbD)

Security by Design (SbD) and/or Privacy by Design (PbD)

Embedding of security/privacy into the architecture (hardware+software) of various products, programs, or services.

Retrofitting: Difficult → Impossible!



Security by Design (SbD)



7 Fundamental Principles

- Proactive not Reactive
- Security/Privacy as the Default
- Security/Privacy Embedded into Design
- Full Functionality - Positive-Sum, not Zero-Sum
- End-to-End Security/Privacy - Lifecycle Protection
- Visibility and Transparency
- Respect for Users

Source: https://iapp.org/media/pdf/resource_center/Privacy%20by%20Design%20-%207%20Foundational%20Principles.pdf

Security-by-Design (SbD) – Principles ...

- Security features should be Proactive not Reactive: Cybersecurity solutions for SbD approach should be done in a proactive fashion in anticipation that cybersecurity issues will arise, instead of exploring solutions after cybersecurity crisis takes place.
- Security should be Default: Cybersecurity features of the smart electronics should be default option in the context of hardware, software, and system specifications.

Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, V. Iyer, and B. Rout, "iTPM: Exploring PUF-based Keyless TPM for Security-by-Design of Smart Electronics", in *Proceedings of the IEEE Computer Society Annual Symposium on VLSI (ISVLSI)*, 2023, pp. 1-6, DOI: <https://doi.org/10.1109/ISVLSI59464.2023.10238586>.

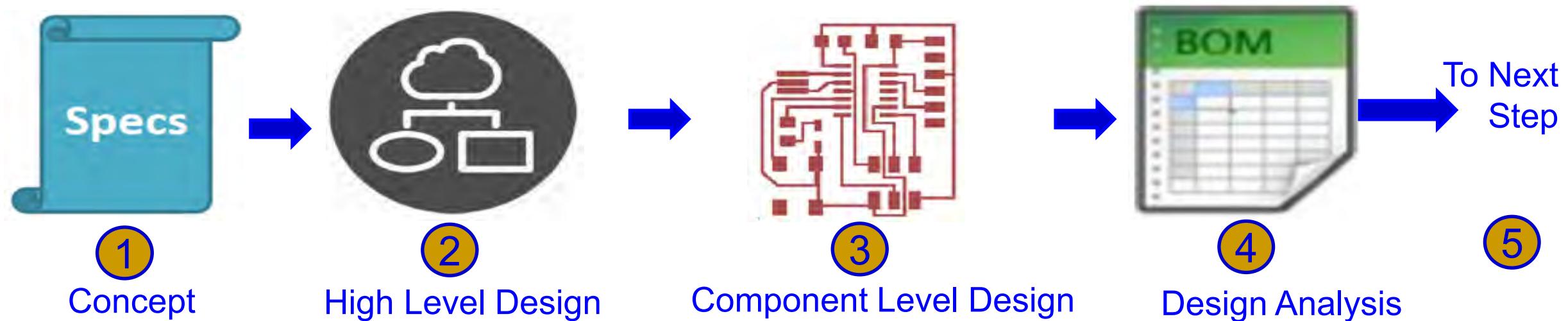
Security-by-Design (SbD) – Principles ...

- Security should be Embedded into Design: Cybsecurity solutions of a system should be integrated in the design and should be builtin as if the solutions can't be separated from the system.
- Security should be incorporated as a Full Functionality - PositiveSum, not Zero-Sum without trade-offs: To facilitate effective integration with smart electronics, the SbD approach should have not tradeoffs and shouldn't have energy, battery, and performance overheads.

Security-by-Design (SbD)

- Security-Solutions should be End-to-End Security for Lifecycle Protection: The cybersecurity solutions should provide security in the entire life-cycle of the smart electronics, from design to deployment.
- Security-Solutions should have Visibility and Transparency: The SbD approach in an Electronic system should be easily understandable and information should be visible and clear.
- Security-Solutions should have Respect for Users: The cybersecurity solutions should respect the users in terms of their safety, privacy, and convenience.

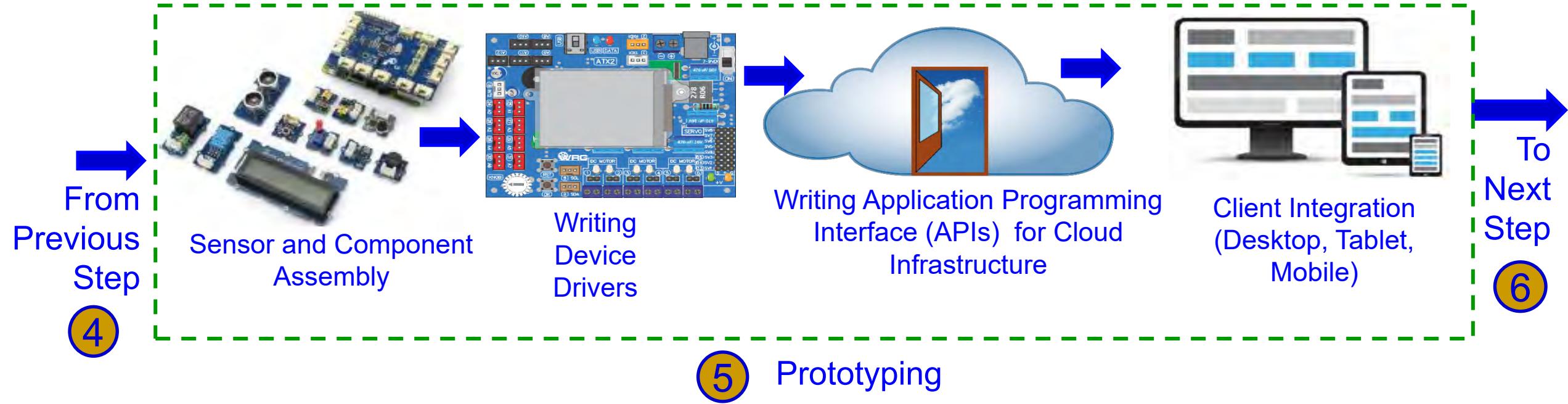
SbD Principle – IoT/CPS Design Flow ...



How to integrate cybersecurity and privacy at every stage of design flow?

Source: <http://events.linuxfoundation.org/sites/events/files/slides/Design%20-%20End-to-End%20%20IoT%20Solution%20-%20Shivakumar%20Mathapathi.pdf>

SbD Principle – IoT/CPS Design Flow ...



How to integrate cybersecurity and privacy at every stage of design flow?

Source: <http://events.linuxfoundation.org/sites/events/files/slides/Design%20-%20End-to-End%20%20IoT%20Solution%20-%20Shivakumar%20Mathapathi.pdf>

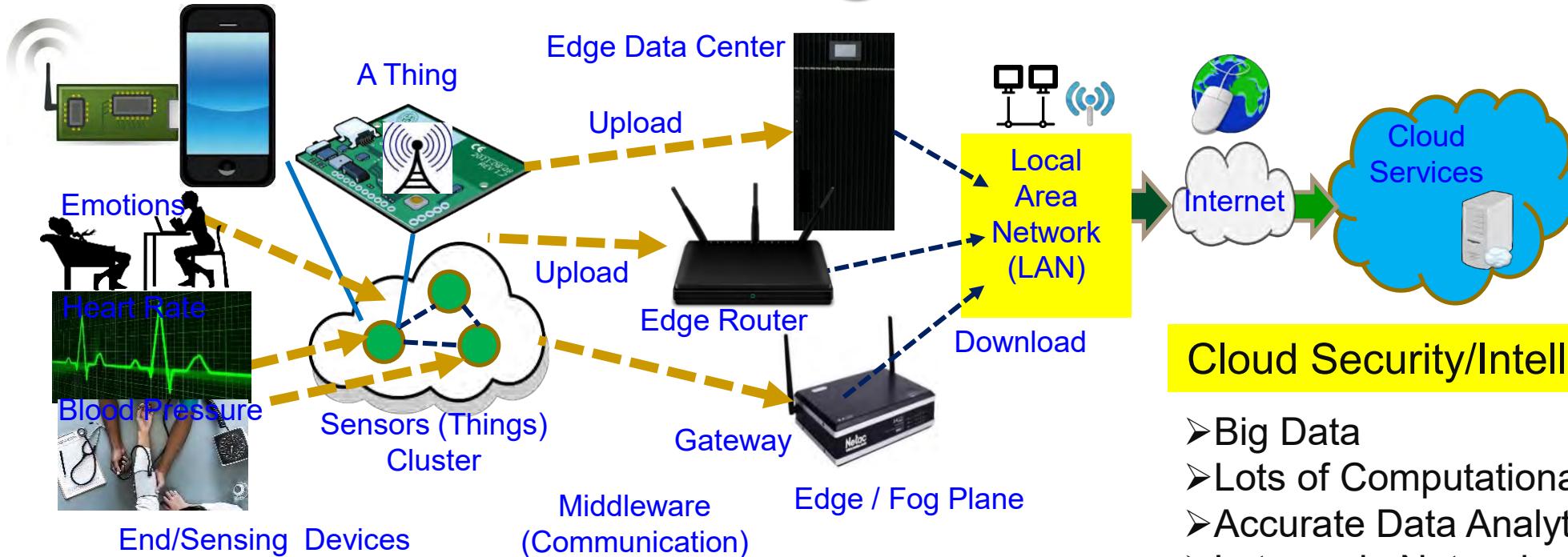
SbD Principle – IoT/CPS Design Flow



How to validate and document cybersecurity and privacy features at every stage of production?

Source: <http://events.linuxfoundation.org/sites/events/files/slides/Design%20-%20End-to-End%20IoT%20Solution%20-%20Shivakumar%20Mathapathi.pdf>

CPS – IoT-Edge Vs IoT-Cloud



End Security/Intelligence

- Minimal Data
- Minimal Computational Resource
- Least Accurate Data Analytics
- Very Rapid Response

Edge Security/Intelligence

- Less Data
- Less Computational Resource
- Less Accurate Data Analytics
- Rapid Response

Cloud Security/Intelligence

- Big Data
- Lots of Computational Resource
- Accurate Data Analytics
- Latency in Network
- Energy Overhead in Communications

Heavy-Duty ML is more suitable for smart cities

TinyML at End and/or Edge is key for smart villages.

Secure SoC - Alternatives



Development of hardware amenable algorithms.



Building efficient VLSI architectures.



Hardware-software co-design for security, power, and performance tradeoffs.



SoC design for cybersecurity, power, and performance tradeoffs.

Trustworthy Electronic System

- A selective attributes of electronic system to be trustworthy:
 - It must maintain integrity of information it is processing.
 - It must conceal any information about the computation performed through any side channels such as power analysis or timing analysis.
 - It must perform only the functionality it is designed for, nothing more and nothing less.
 - It must not malfunction during operations in critical applications.
 - It must be transparent only to its owner in terms of design details and states.
 - It must be designed using components from trusted vendors.
 - It must be built/fabricated using trusted fabs.

Hardware-Assisted Security (HAS)

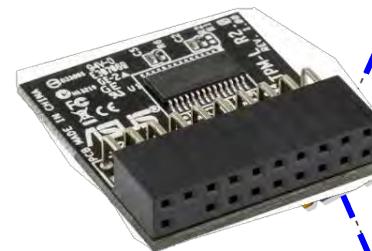
- Software based Security:
 - A general purposed processor is a deterministic machine that computes the next instruction based on the program counter.
 - Software based security approaches that rely on some form of encryption can't be full proof as breaking them is just matter of time.
 - It is projected that quantum computers that use different paradigms than the existing computers will make things worse.
- Hardware-Assisted Security (HAS): Security/Protection provided by the hardware: for information being processed by an electronic system, for hardware itself, and/or for the system.

Hardware Cybersecurity Primitives

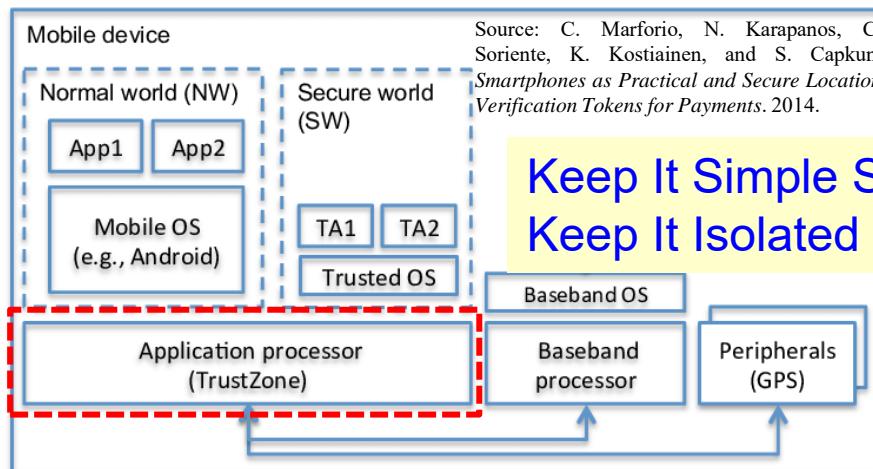
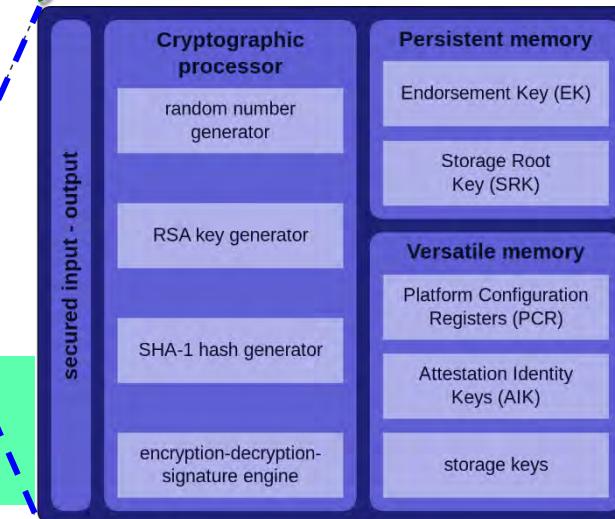
– TPM, HSM, TrustZone, and PUF



Hardware Security Module (HSM)



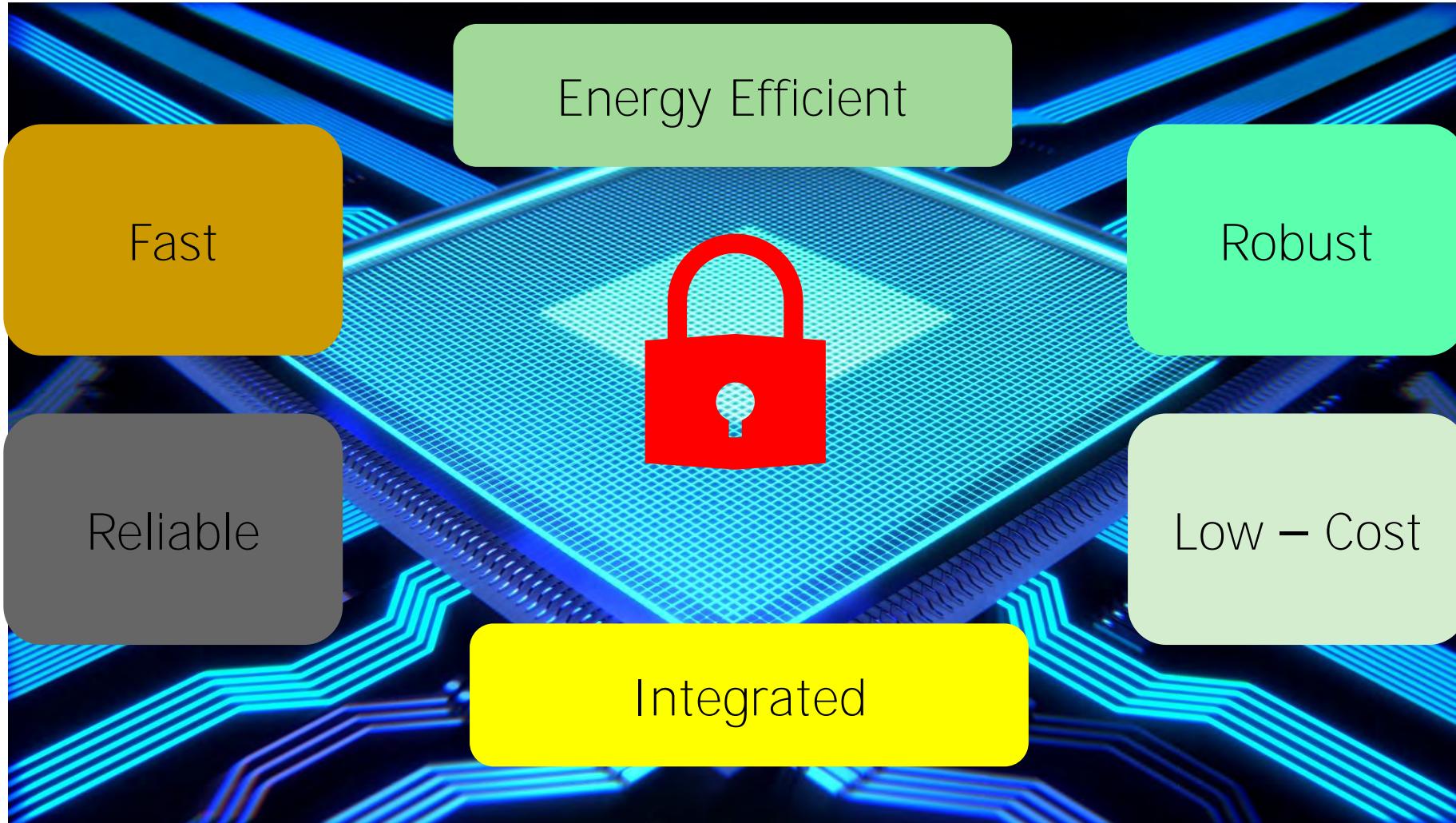
Trusted Platform Module (TPM)



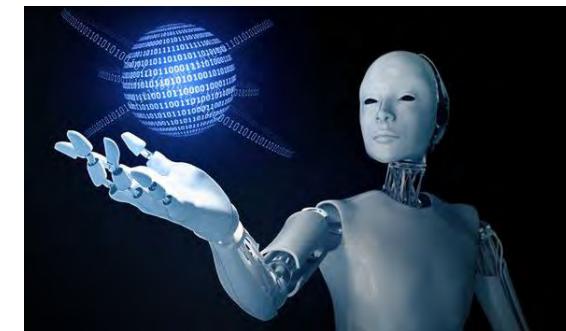
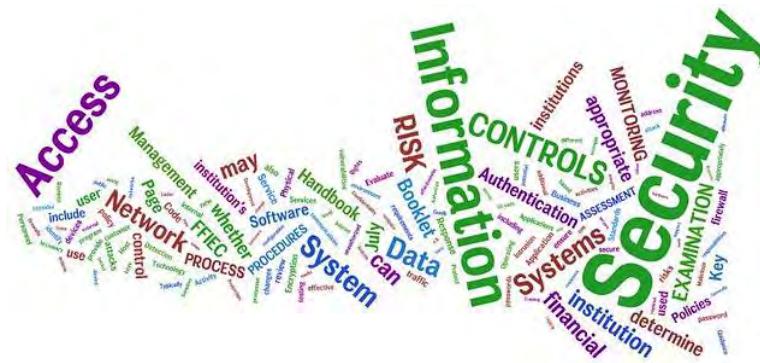
Physical Unclonable Functions (PUF)

Source: Electric Power Research Institute (EPRI)

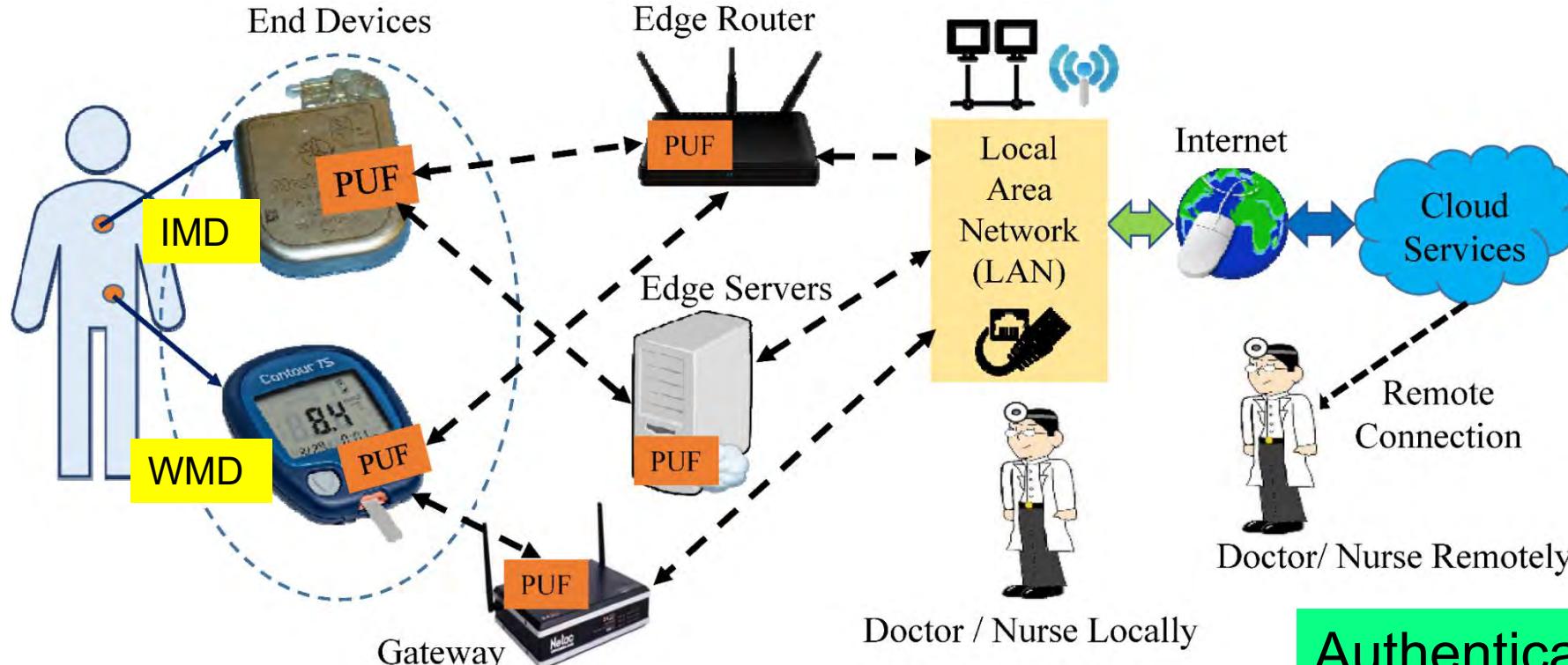
SbD/HAS - Advantages



Security-by-Design (SbD) – Specific Examples



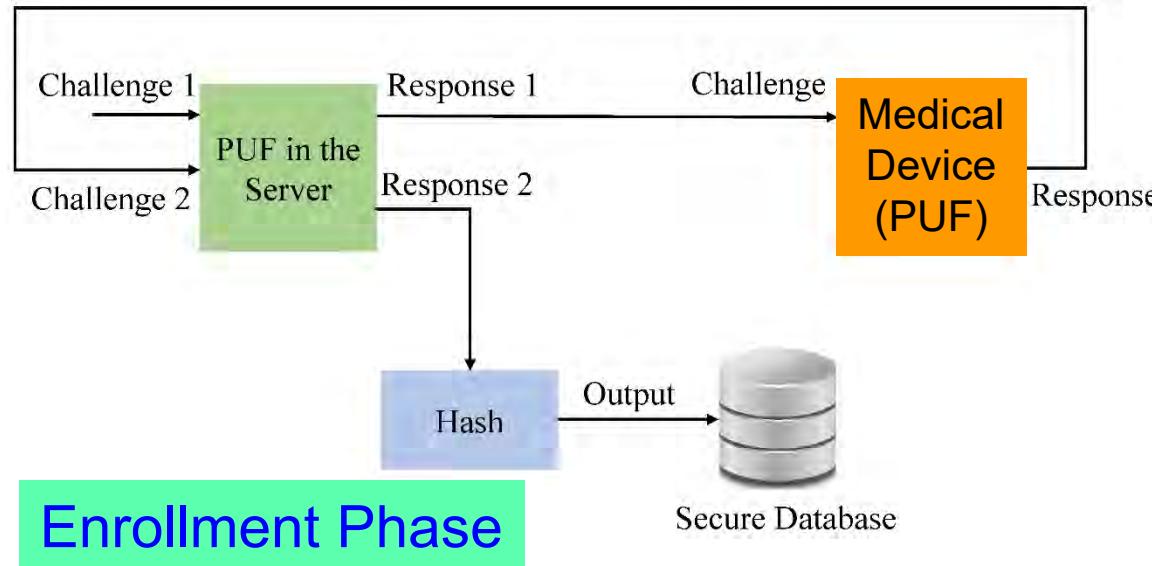
PMsec: Our Secure by Design Approach for Robust Security in Healthcare CPS



Authenticates Time - 1 sec
Power Consumption - 200 μ W

Source: V. P. Yanambaka, S. P. Mohanty, E. Kougianos, and D. Puthal, "PMsec: Physical Unclonable Function-Based Robust and Lightweight Authentication in the Internet of Medical Things", *IEEE Transactions on Consumer Electronics (TCE)*, Volume 65, Issue 3, August 2019, pp. 388–397.

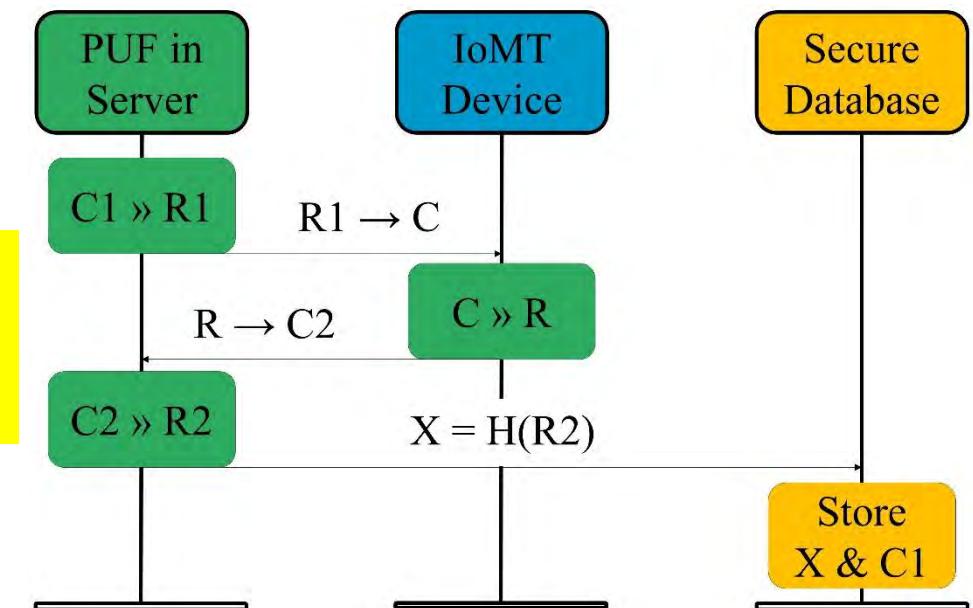
IoMT Security – Our Proposed PMsec



At the Doctor

- When a new IoMT-Device comes for an User

Device Registration Procedure

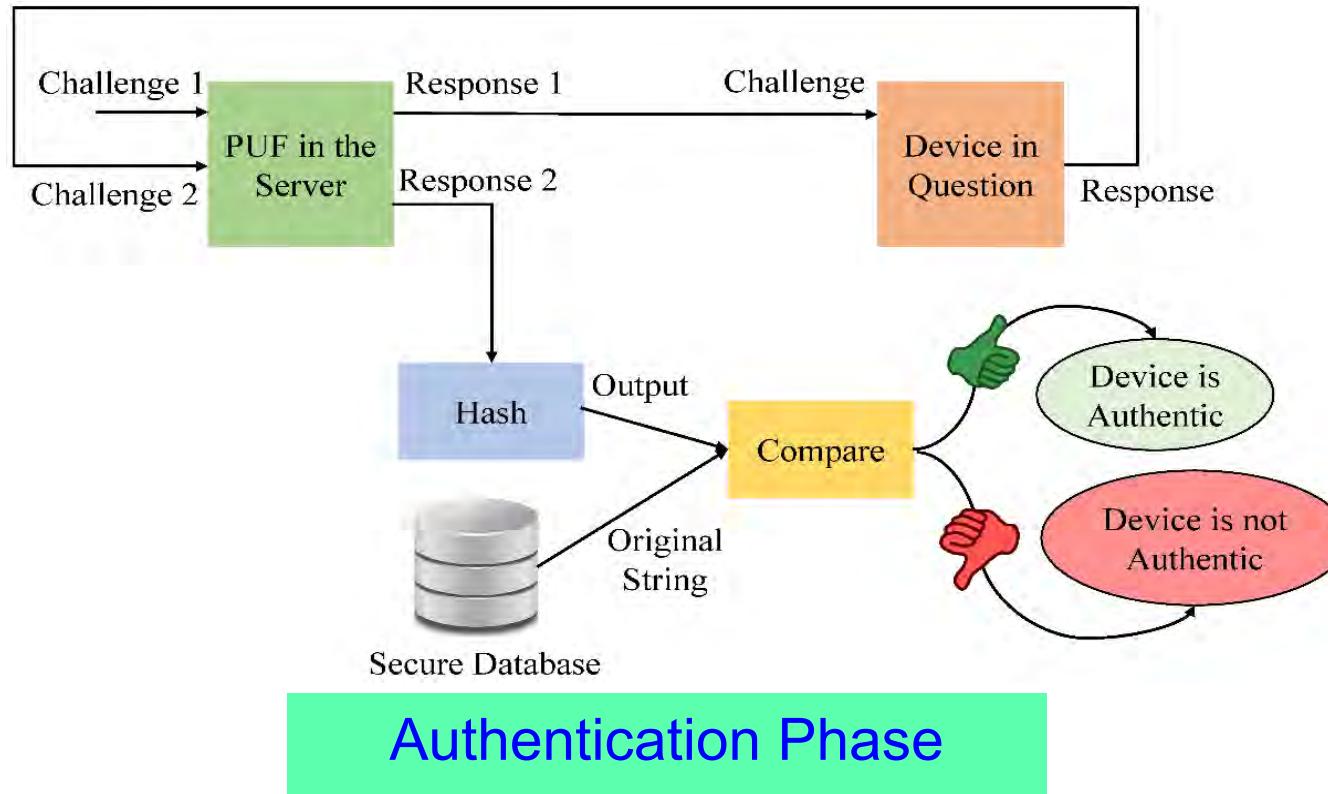


PUF Security Full Proof:

- Only server PUF Challenges are stored, not Responses
- Impossible to generate Responses without PUF

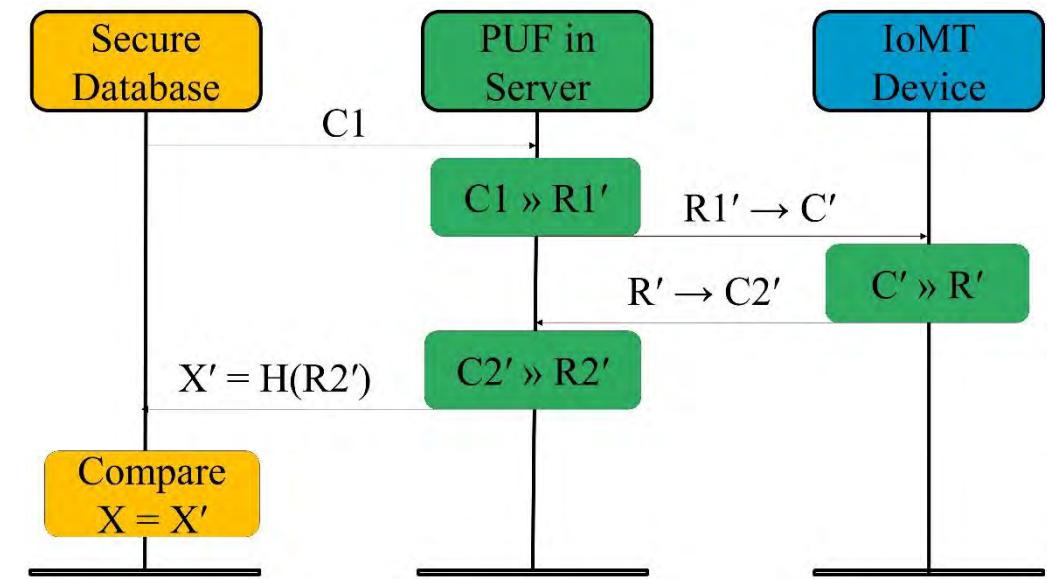
Source: V. P. Yanambaka, S. P. Mohanty, E. Kougianos, and D. Puthal, "PMsec: Physical Unclonable Function-Based Robust and Lightweight Authentication in the Internet of Medical Things", *IEEE Transactions on Consumer Electronics (TCE)*, Volume 65, Issue 3, August 2019, pp. 388--397.

IoMT Security – Our Proposed PMsec



At the Doctor
➤ When doctor needs to access an existing IoMT-device

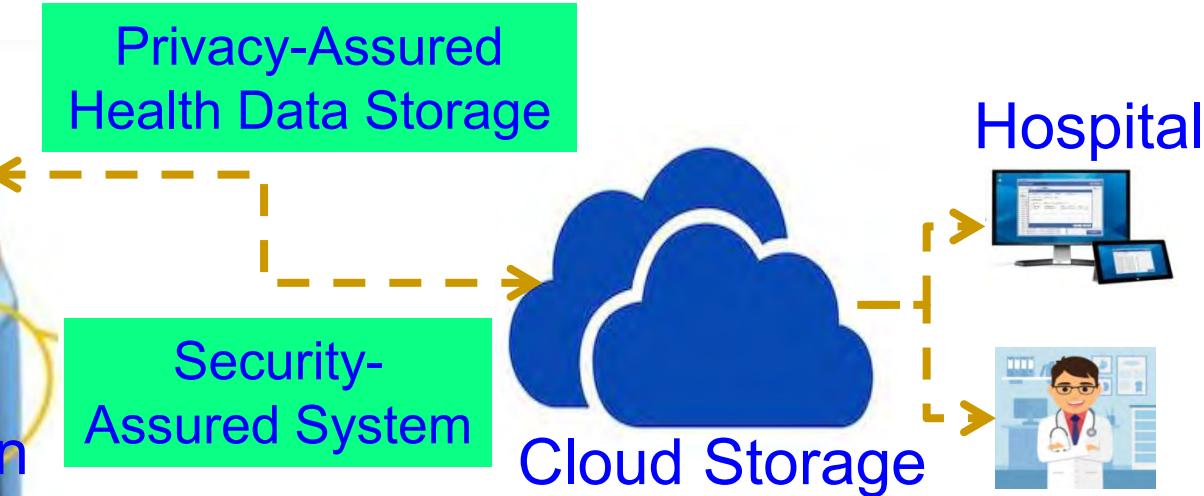
Device Authentication Procedure



Source: V. P. Yanambaka, S. P. Mohanty, E. Koulianou, and D. Puthal, "PMsec: Physical Unclonable Function-Based Robust and Lightweight Authentication in the Internet of Medical Things", *IEEE Transactions on Consumer Electronics (TCE)*, Volume 65, Issue 3, August 2019, pp. 388–397.

iGLU: Accurate Glucose Level Monitoring and Secure Insulin Delivery

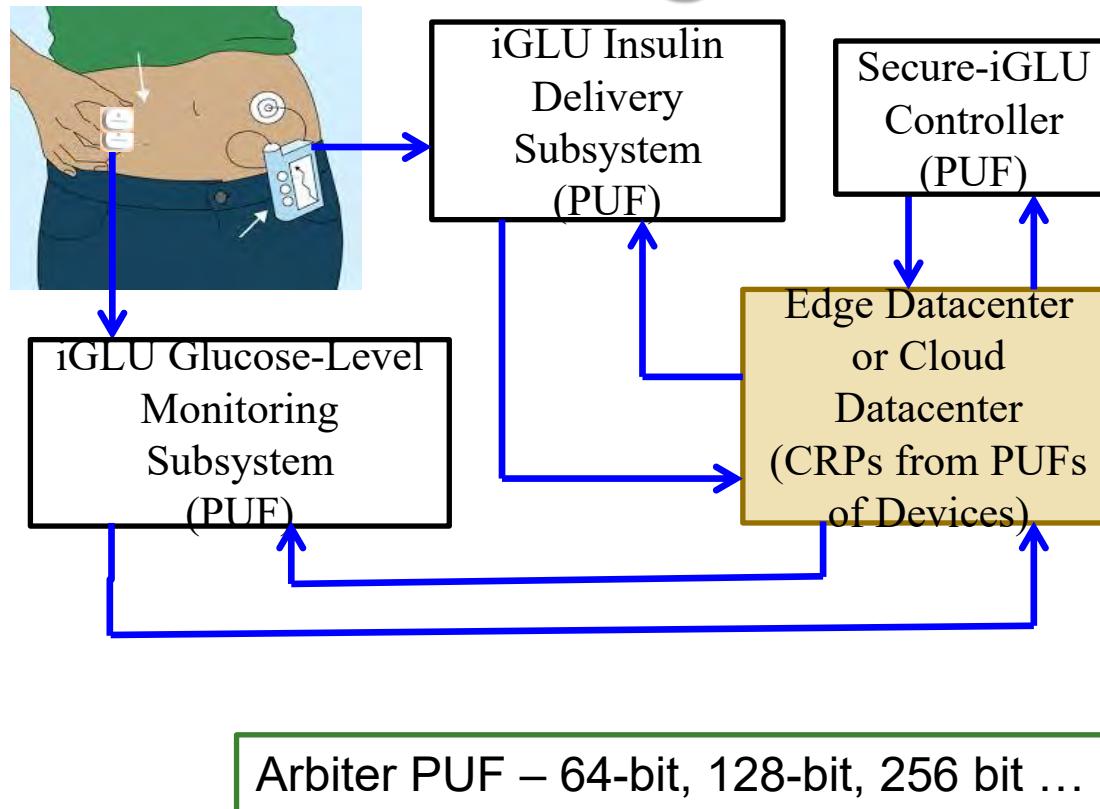
Continuous Glucose Monitoring
Display of Artificial Pancreases Parameters System (APS)
Insulin Secretion



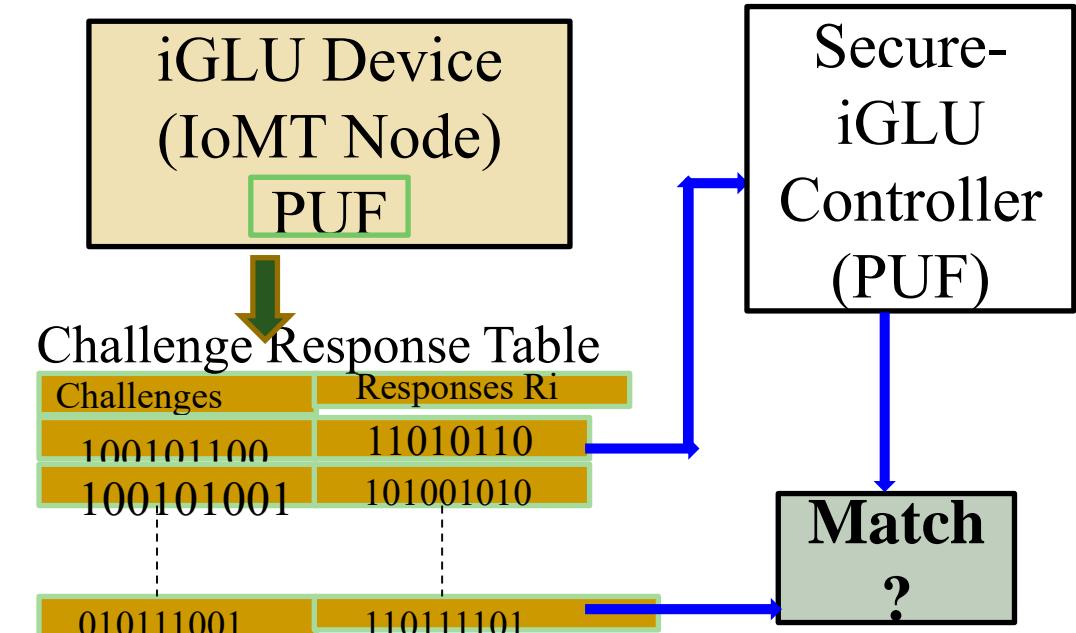
Near Infrared (NIR) based Noninvasive, Accurate, Continuous Glucose Monitoring

P. Jain, A. M. Joshi, and S. P. Mohanty, "iGLU: An Intelligent Device for Accurate Non-Invasive Blood Glucose-Level Monitoring in Smart Healthcare", *IEEE Consumer Electronics Magazine (MCE)*, Vol. 9, No. 1, January 2020, pp. 35–42.

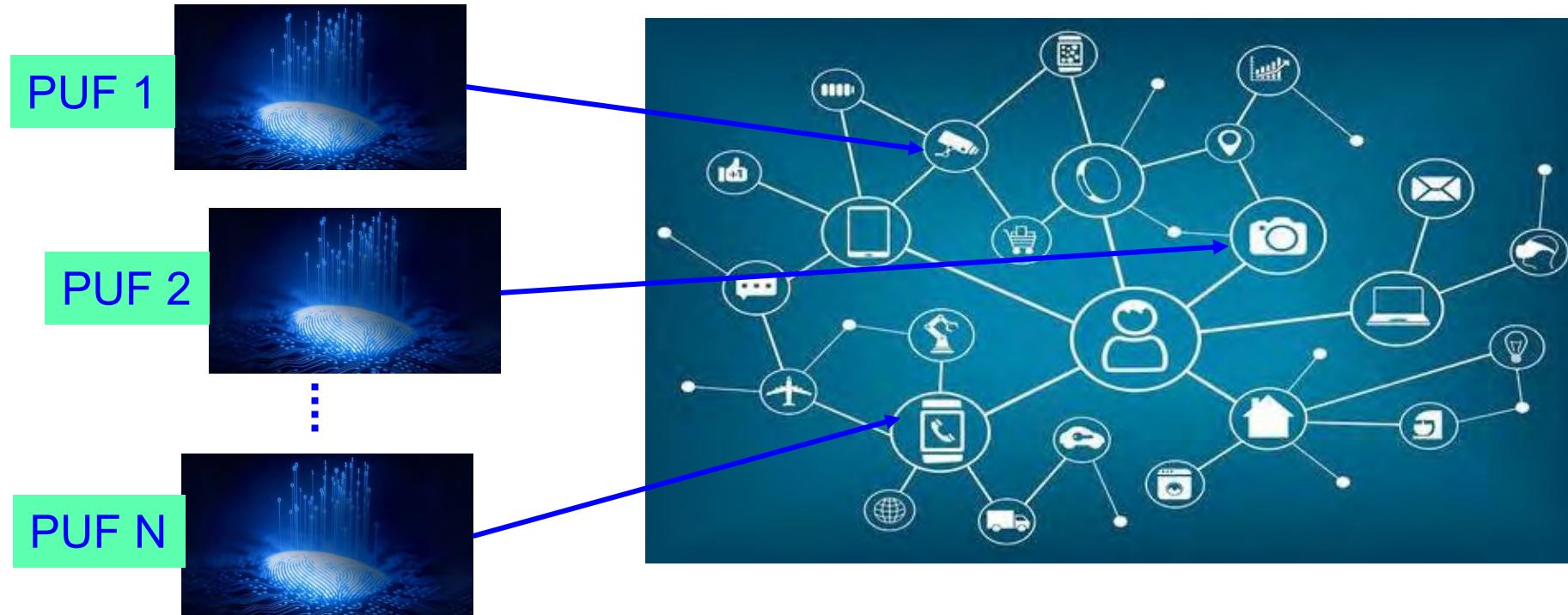
Secure-iGLU: Accurate Glucose Level Monitoring and Secure Insulin Delivery



Source: A. M. Joshi, P. Jain, and S. P. Mohanty, "Secure-iGLU: A Secure Device for Noninvasive Glucose Measurement and Automatic Insulin Delivery in IoMT Framework", *Proceedings of the 19th IEEE Computer Society Annual Symposium on VLSI (ISVLSI)*, 2020, pp. 440-445.

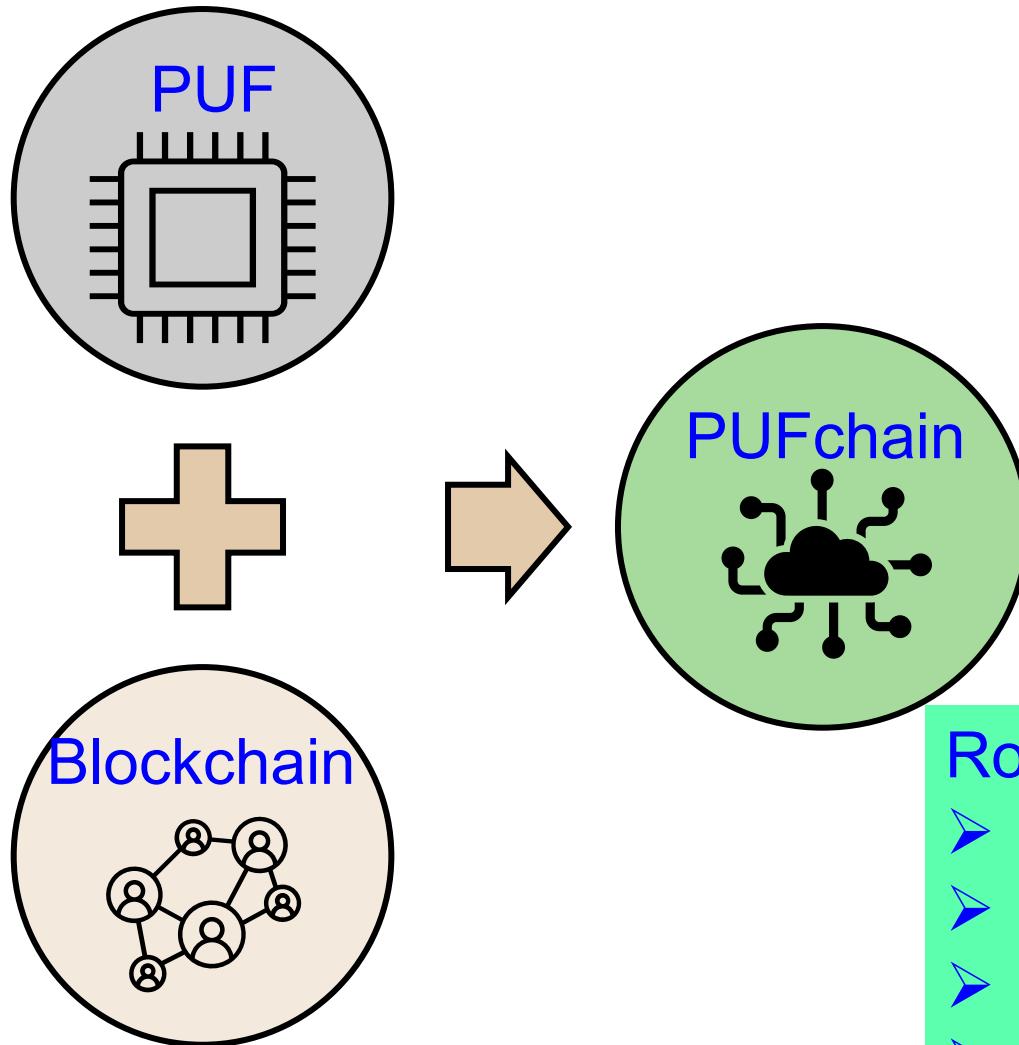


We Proposed World's First Hardware-Integrated Blockchain (PUFchain) that is Scalable, Energy-Efficient, and Fast



Source: S. P. Mohanty, V. P. Yanambaka, E. Kougianos, and D. Puthal, "PUFchain: Hardware-Assisted Blockchain for Sustainable Simultaneous Device and Data Security in Internet of Everything (IoE)", *IEEE Consumer Electronics Magazine (MCE)*, Vol. 9, No. 2, March 2020, pp. 8-16.

PUFchain – The Big Idea

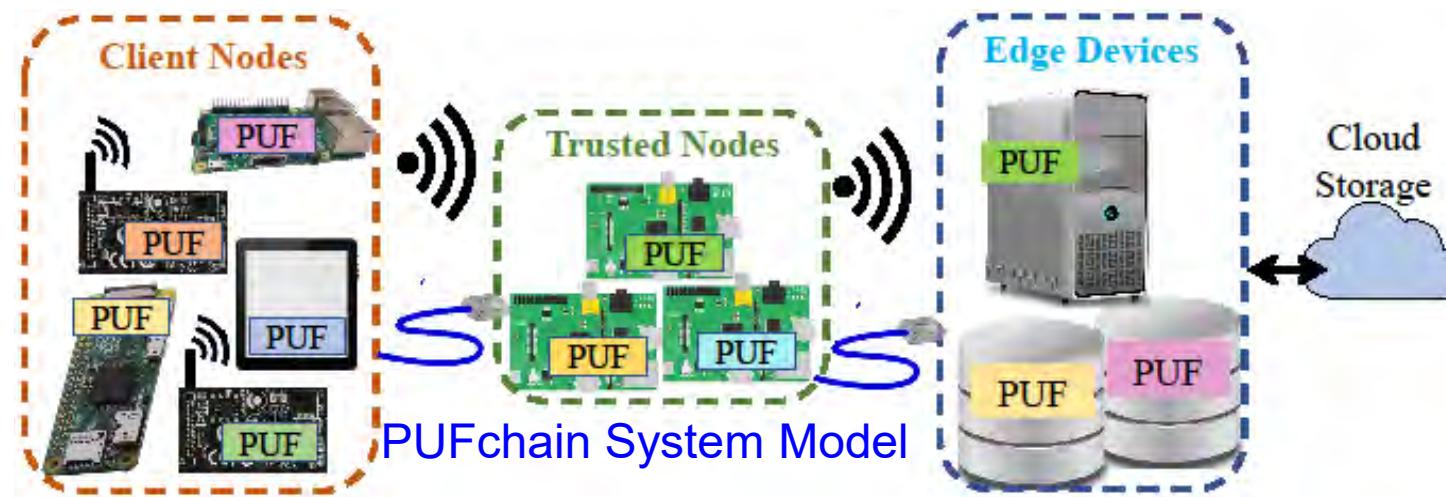


Blockchain Technology is integrated with Physically Unclonable Functions as PUFchain by storing the PUF Key into immutable Blockchain

Roles of PUF:

- Hardware Accelerator for Blockchain
- Independent Authentication
- Double-Layer Protection
- 3 modes: PUF, Blockchain, PUF+Blockchain

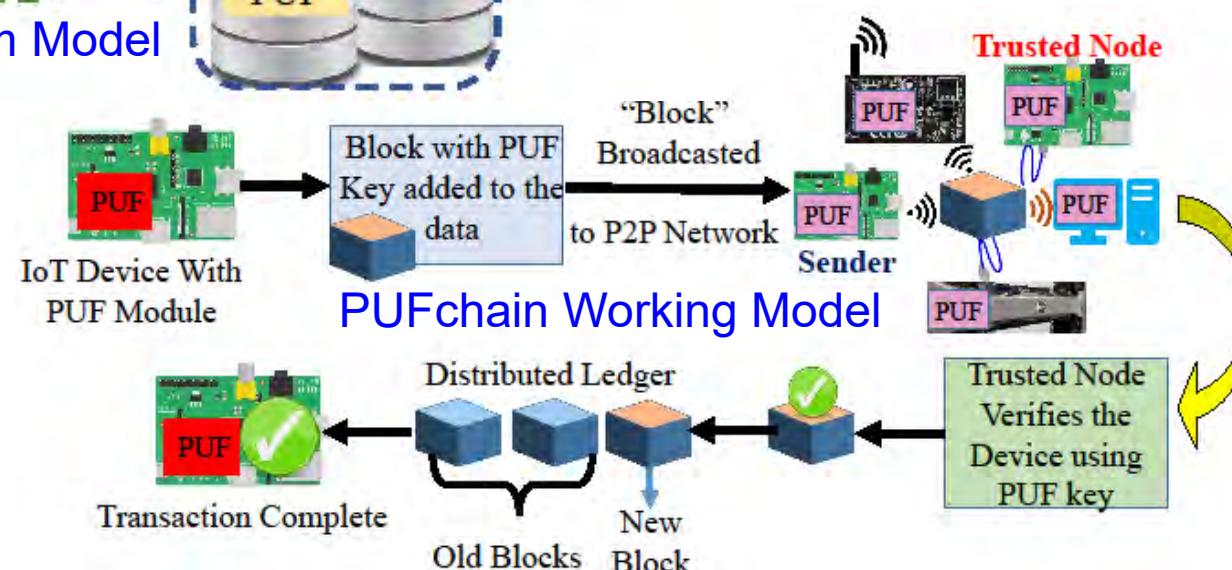
PUFchain: Our Hardware-Assisted Scalable Blockchain



Can provide:
Device, System, and
Data Security

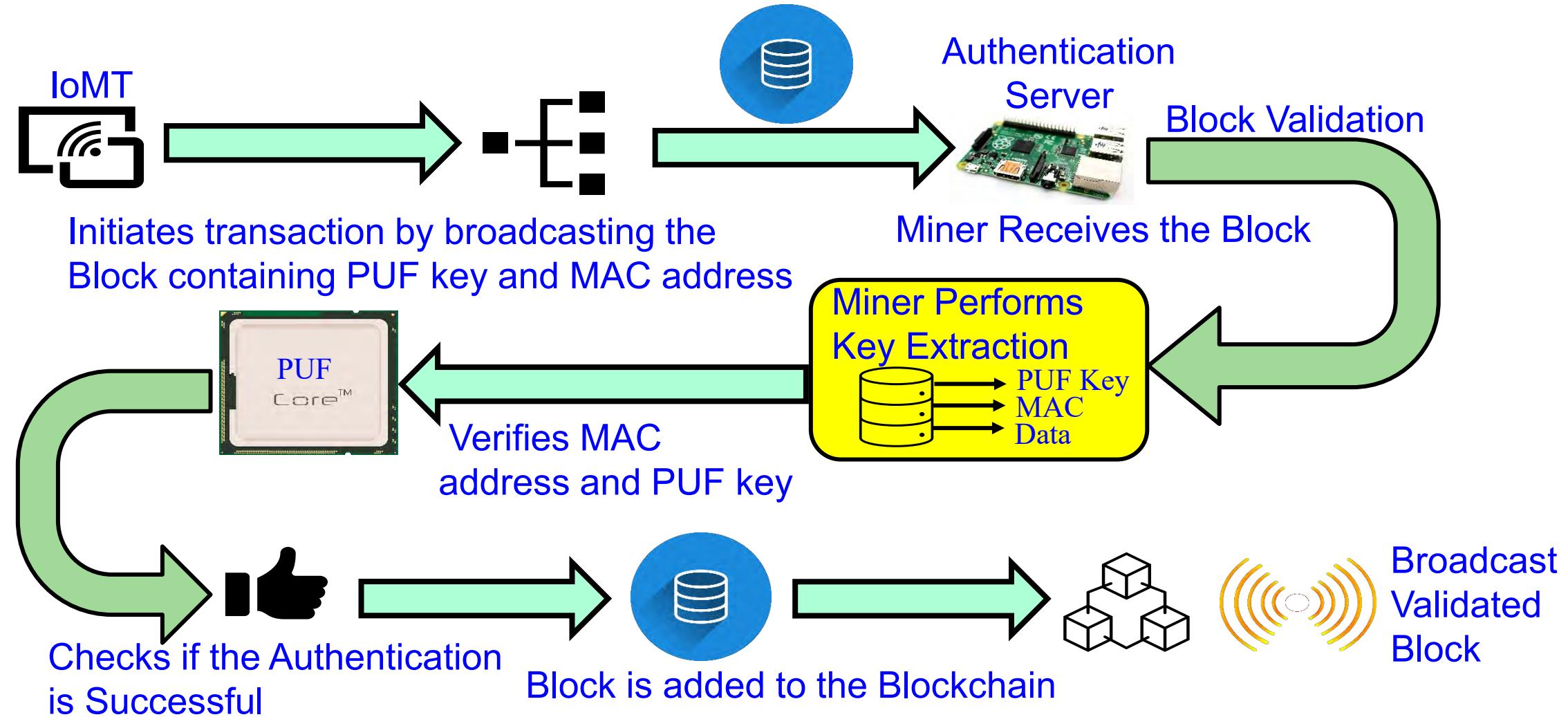
PUFChain 2 Modes:
(1) PUF Mode and
(2) PUFChain Mode

- ✓ PoP is 1,000X faster than PoW
- ✓ PoP is 5X faster than PoAh



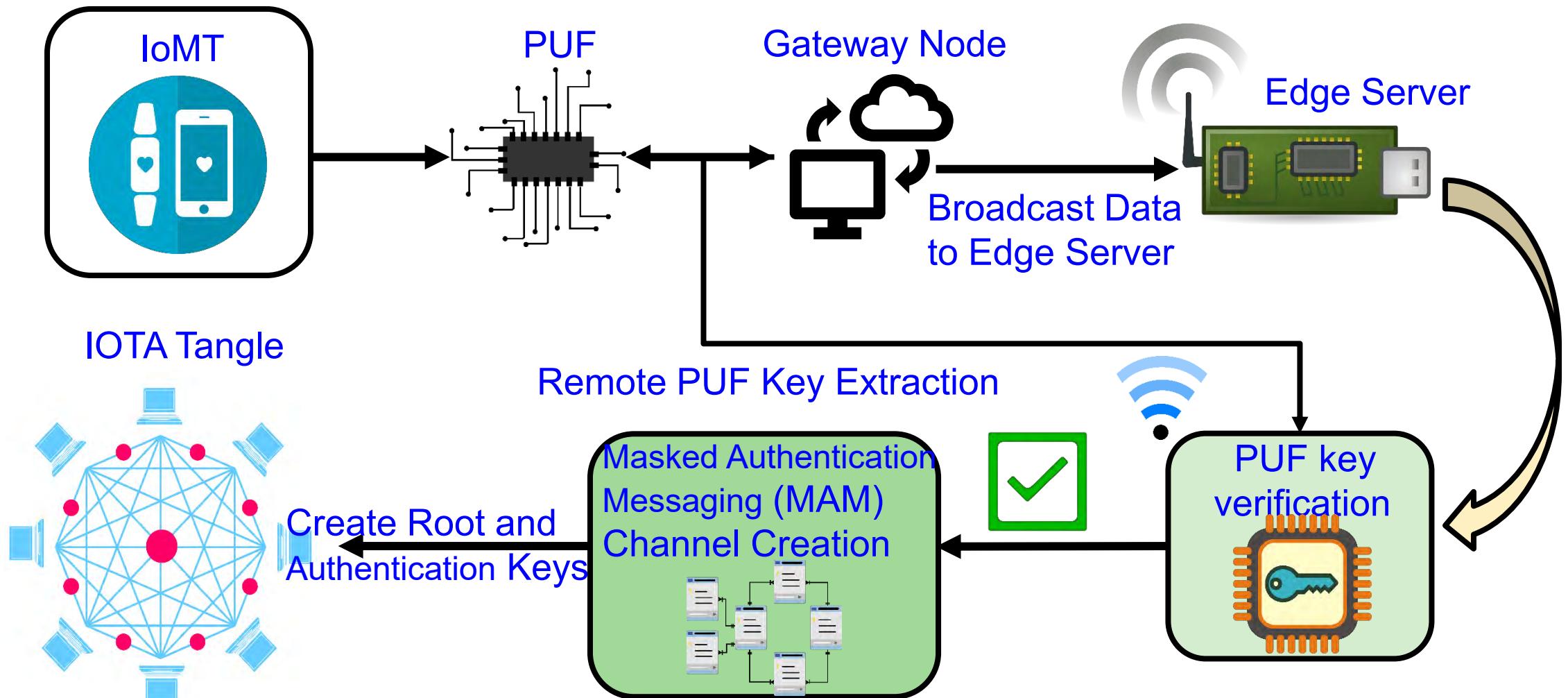
Source: S. P. Mohanty, V. P. Yanambaka, E. Kougianos, and D. Puthal, "PUFchain: Hardware-Assisted Blockchain for Sustainable Simultaneous Device and Data Security in Internet of Everything (IoE)", *IEEE Consumer Electronics Magazine (MCE)*, Vol. 9, No. 2, March 2020, pp. 8-16.

PUFchain 2.0: Our Hardware-Assisted Scalable Blockchain



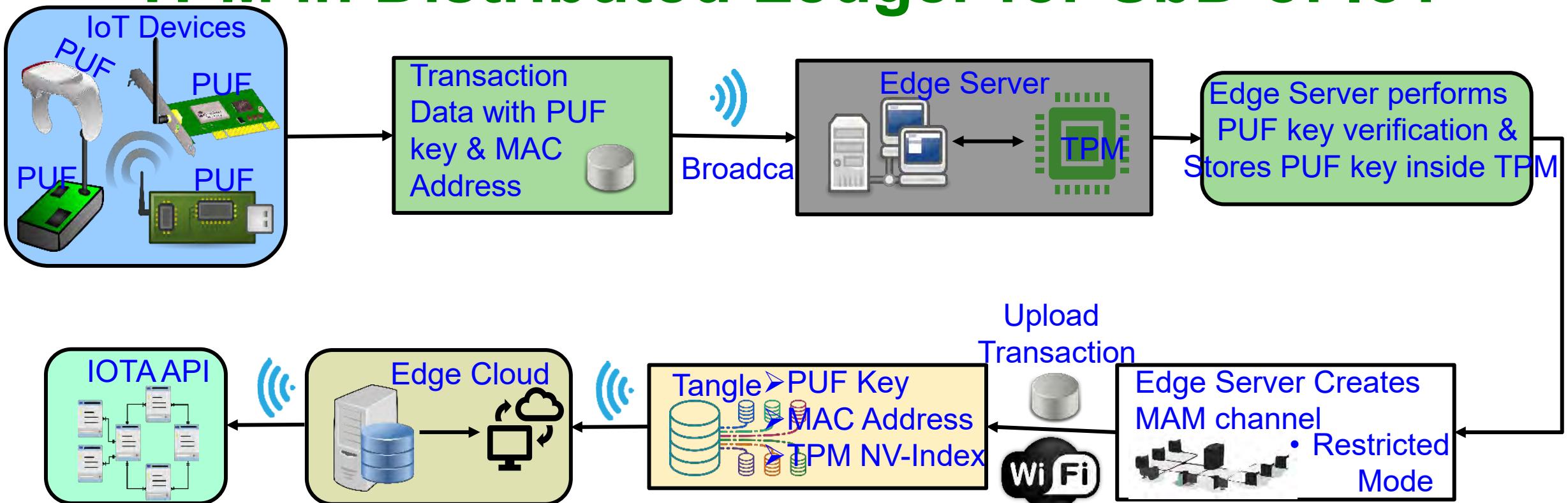
Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, B. K. Baniya, and B. Rout, “[PUFchain 2.0: Hardware-Assisted Robust Blockchain for Sustainable Simultaneous Device and Data Security in Smart Healthcare](#)”, *Springer Nature Computer Science (SN-CS)*, Vol. 3, No. 5, Sep 2022, Article: 344, 19-pages, DOI: <https://doi.org/10.1007/s42979-022-01238-2>.

PUFchain 3.0 - Architecture



Source: V. K. V. V. Bathalapalli, S. P. Mohanty, E. Koulianou, B. K. Baniya, and B. Rout, “[PUFchain 3.0: Hardware-Assisted Distributed Ledger for Robust Authentication in the Internet of Medical Things](#)”, in *Proceedings of IFIP International Internet of Things Conference (IFIP-IoT)*, 2022, pp. 23–40, DOI: https://doi.org/10.1007/978-3-031-18872-5_2.

Our PUFchain 4.0: Integrating PUF-based TPM in Distributed Ledger for SbD of IoT



- Tangle is a simple fee-less, miner less Distributed Ledger Technology
- In Tangle, Incoming transactions must validate tips (Unverified Transactions) to become part of the Network.

Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, V. Iyer, and B. Rout, “[PUFchain 4.0: Integrating PUF-based TPM in Distributed Ledger for Security-by-Design of IoT](#)”, in *Proceedings of the ACM Great Lakes Symposium on VLSI (GLSVLSI)*, 2023, pp. 231–236, DOI: <https://doi.org/10.1145/3583781.3590206>.

Our PUFchain 4.0: Integrating PUF-based TPM in Distributed Ledger for SbD of IoT

Research Works	Application	DLT or Blockchain	Authentication Mechanism	Performance Metrics
Mohanty et al. 2020 - PUFchain	IoT (Device and Data)	Blockchain	Proof-of-PUF-Enabled Authentication	PUF Design Uniqueness - 47.02%, Reliability-1.25%
Chaudhary et al. 2021 - Auto-PUFchain	Hardware Supply Chain	Blockchain	Smart Contracts	Gas Cost for Ethereum transaction 21.56 USD (5-Stage)
AI-Joboury et al. 2021 - PoQDB	IoT (Data)	Blockchain & Cobweb	IoT M2M Messaging (MQTT)	Transaction Time - 15 ms
Wang et al. 2022 - PUF-Based Authentication	IoMT (Device)	Blockchain	Smart Contracts	NA
Hellani et al. 2021-Tangle the Blockchain	IoT (Data)	Blockchain & Tangle	Smart Contracts	NA
Bathalapalli et al. 2022-PUFchain 2.0	IoMT (Device)	Blockchain	Media Access Control (MAC) & PUF based Authentication	Total On-Chip Power - 0.081 W, PUF Hamming Distance - 48.02 %
PUFchain 3.0 in 2022	IoMT (Device)	Tangle	Masked Authentication Messaging	Authentication 2.72 sec, Reliability - 100% (Approx), MAM Mode-Restricted
PUFchain 4.0 (This Paper)	IoT(Device & Data)	Tangle	PUF Based TPM (SbD)	PUF Key Generation Time-87 ms, PUF Reliability-99% Power Consumption-2.7-3.3 Watt

Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, V. Iyer, and B. Rout, “[PUFchain 4.0: Integrating PUF-based TPM in Distributed Ledger for Security-by-Design of IoT](#)”, in *Proceedings of the ACM Great Lakes Symposium on VLSI (GLSVLSI)*, 2023, pp. 231–236, DOI: <https://doi.org/10.1145/3583781.3590206>.

Smart Grid Cybersecurity - Solutions

Smart Grid – Security Solutions

Network
Security

Data
Security

Key
Management

Network Security
Protocol



Smart Meter



Phasor Measurement Unit (PMU)

Smart Grid
Cybersecurity
- Strategies

- Make Smart Grids Survivable
- Use Scalable Security Measures
- Integrate Security and Privacy by Design
- Deploy a Defense-in-Depth Approach
- Enhance Traditional Security Measures

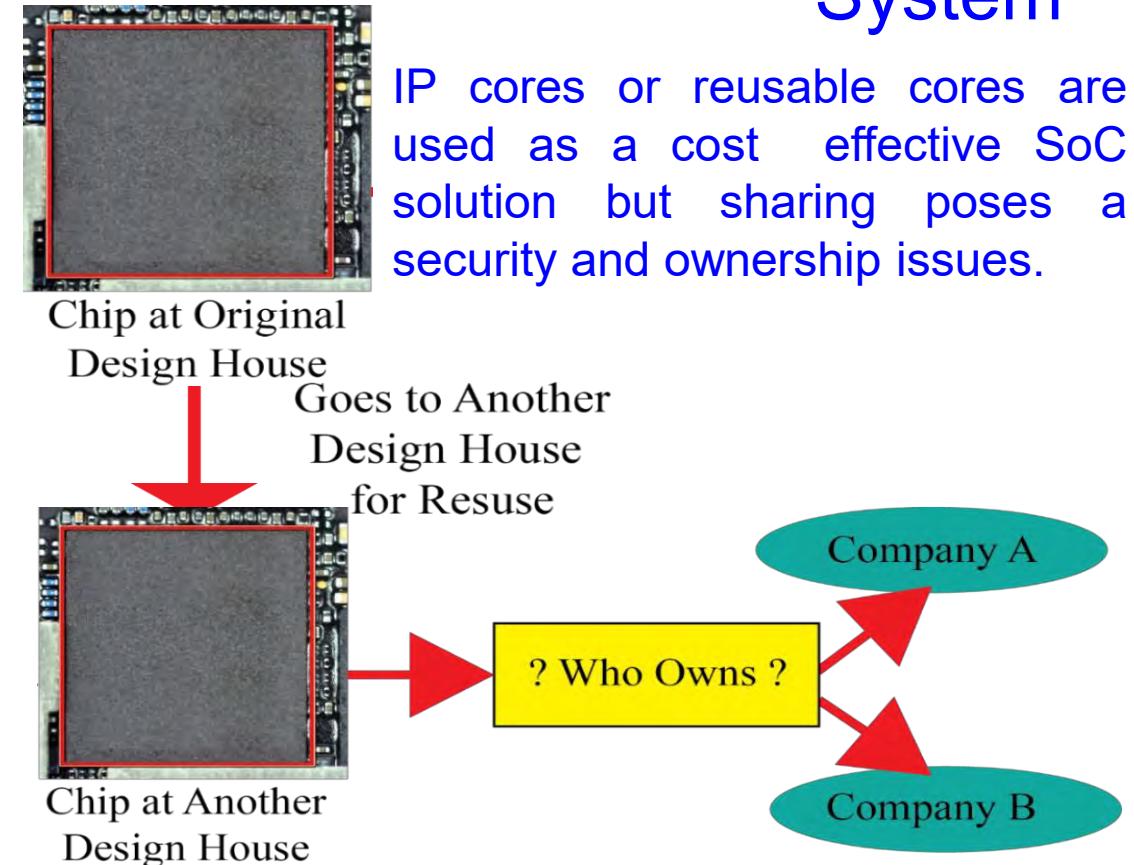
Source: S. Conovalu and J. S. Park. "Cybersecurity strategies for smart grids", *Journal of Computers*, Vol. 11, no. 4, (2016): 300-310.

Data and System Authentication and Ownership Protection – My 20 Years of Experiences

Data System

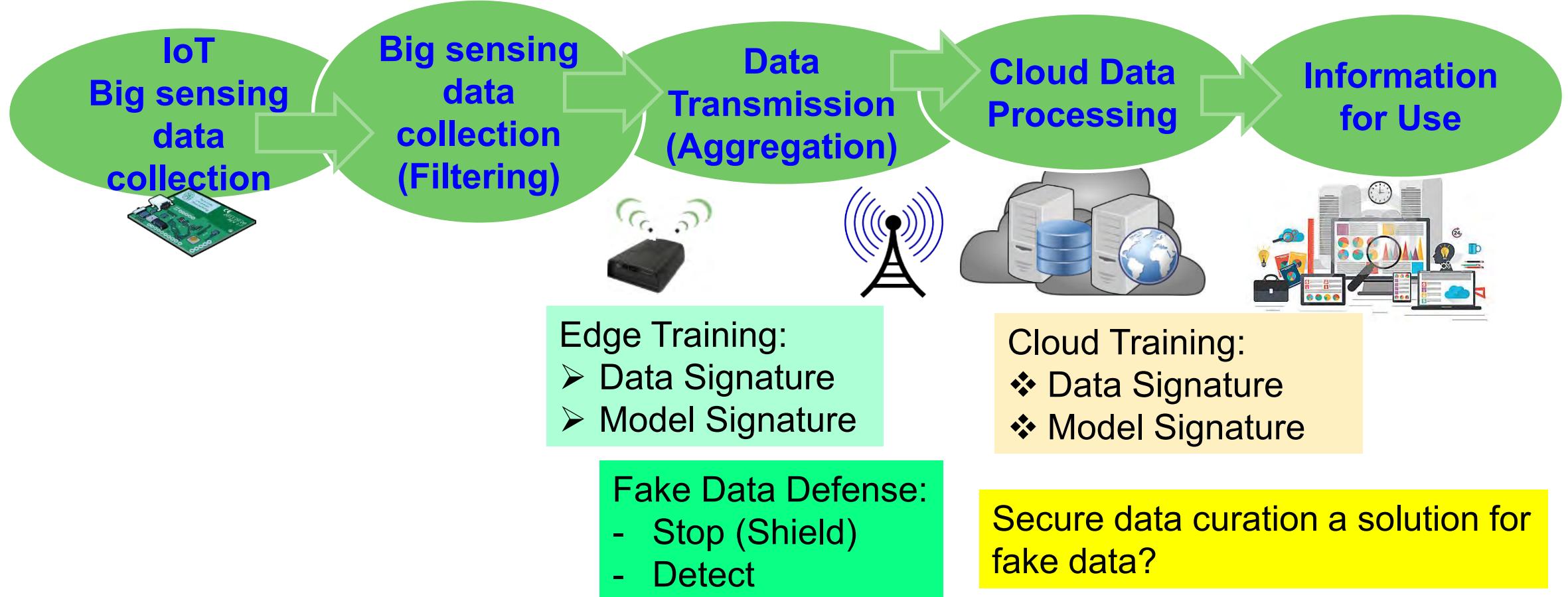


- Whose is it?
- Is it tampered with?
- Where was it created?
- Who had created it?
- ... and more.



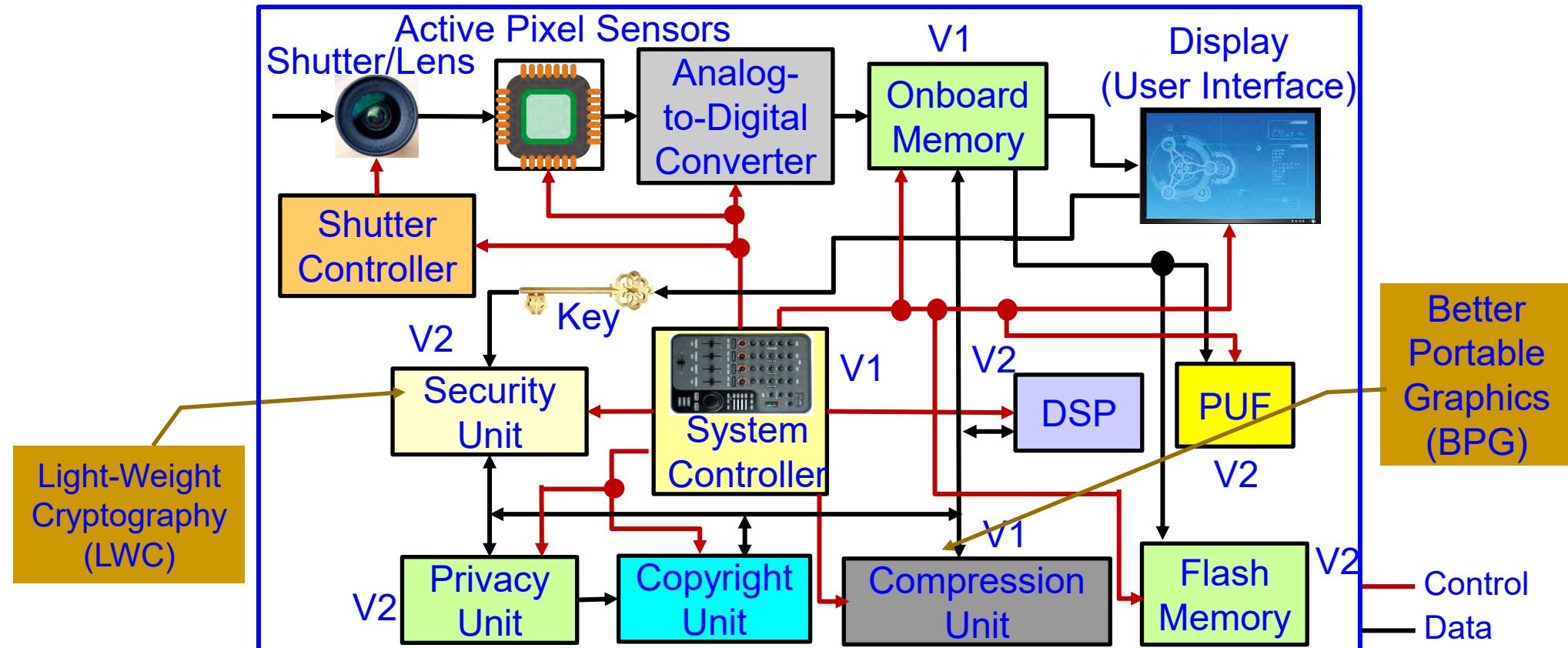
Source: S. P. Mohanty, A. Sengupta, P. Guturu, and E. Koulianou, "Everything You Want to Know About Watermarking", *IEEE Consumer Electronics Magazine (CEM)*, Volume 6, Issue 3, July 2017, pp. 83–91.

Data Quality Assurance in IoT/CPS



Source: C. Yang, D. Puthal, S. P. Mohanty, and E. Kougianos, "Big-Sensing-Data Curation for the Cloud is Coming", *IEEE Consumer Electronics Magazine (CEM)*, Volume 6, Issue 4, October 2017, pp. 48--56.

Secure Digital Camera (SDC) – My Invention

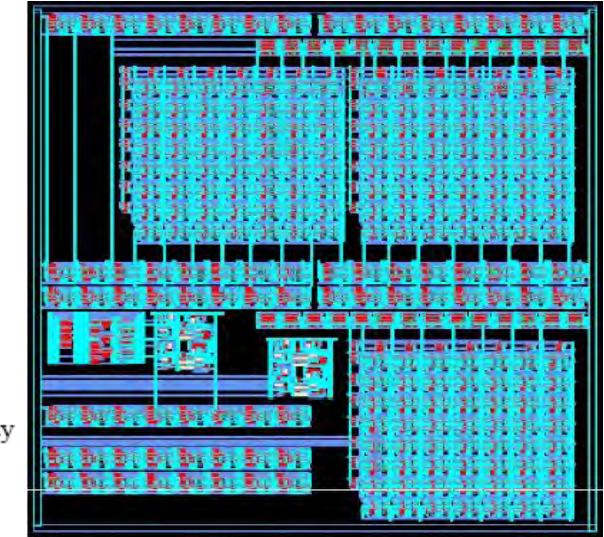
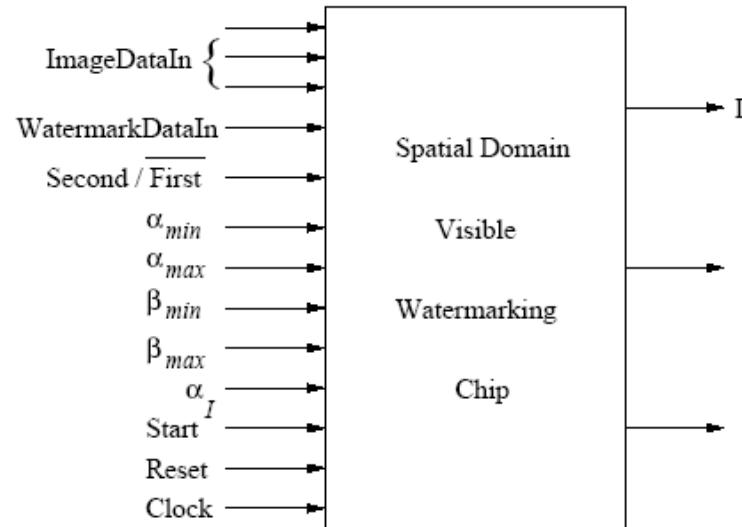
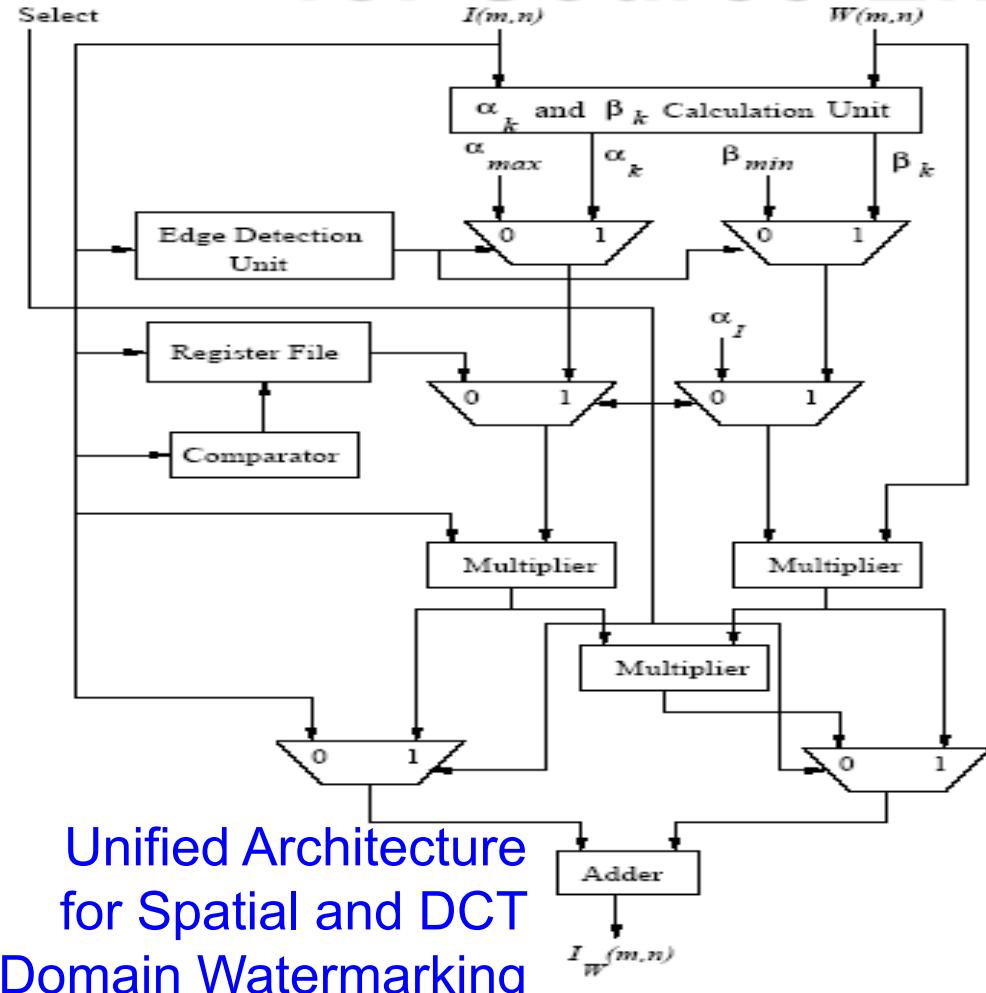


Include additional/alternative hardware/software components and uses DVFS like technology for energy and performance optimization.

Security and/or Privacy by Design (SbD and/or PbD)

Source: S. P. Mohanty, "A Secure Digital Camera Architecture for Integrated Real-Time Digital Rights Management", *Elsevier Journal of Systems Architecture (JSA)*, Volume 55, Issues 10-12, October-December 2009, pp. 468-480.

Our Design: First Ever Watermarking Chip for Source-End Visual Data Protection



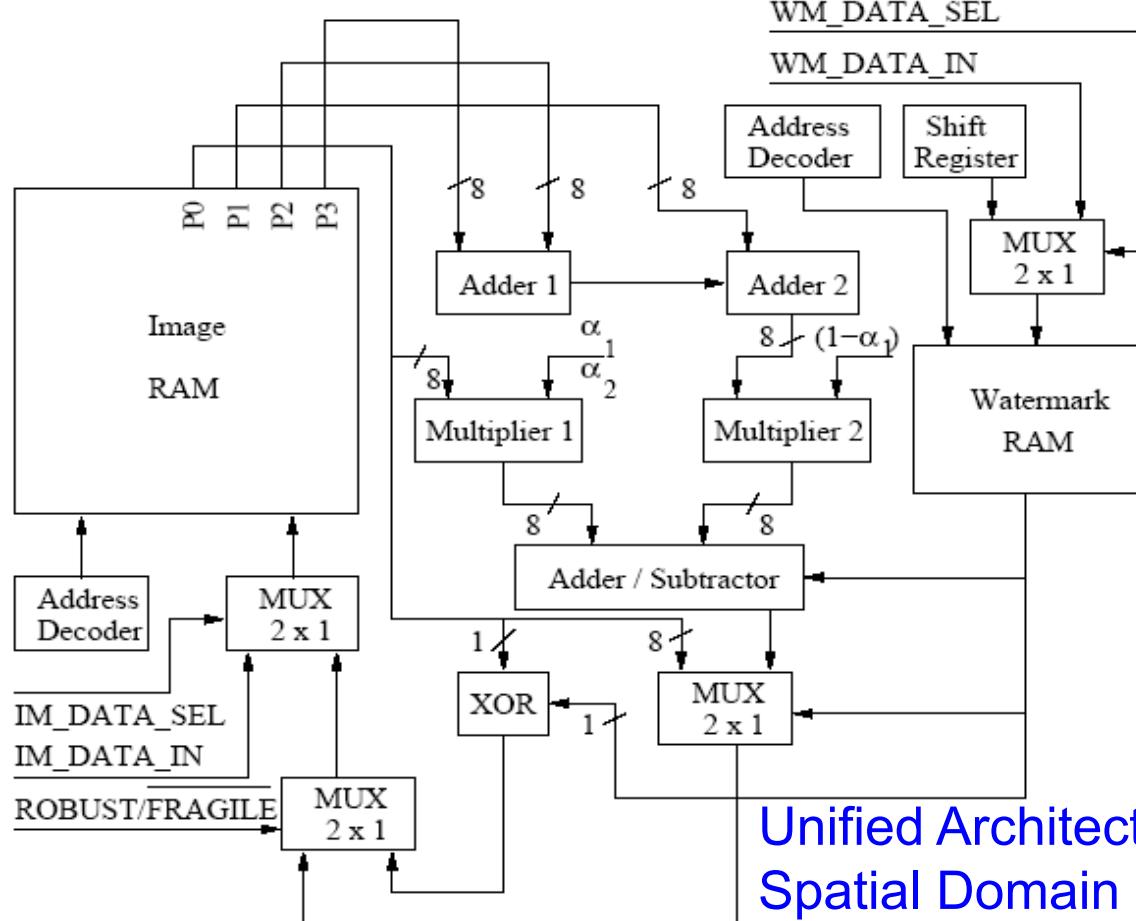
Chip Design Data

Total Area : 9.6 sq mm, No. of Gates: 28,469

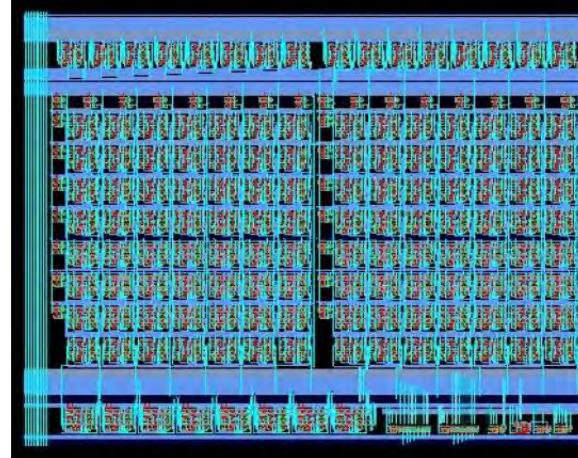
Power Consumption: 6.9 mW, Operating Frequency: 292 MHz

Source: S. P. Mohanty, N. Ranganathan, and R. K. Namballa, "A VLSI Architecture for Visible Watermarking in a Secure Still Digital Camera (S²DC) Design", *IEEE Transactions on Very Large Scale Integration Systems (TVLSI)*, Vol. 13, No. 8, August 2005, pp. 1002-1012.

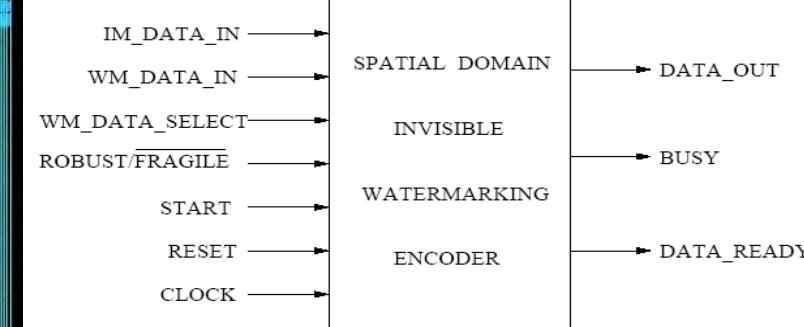
Our Design: First Ever Watermarking Chip for Source-End Visual Data Integrity



Unified Architecture for
Spatial Domain Robust
and Fragile Watermarking



Chip Layout

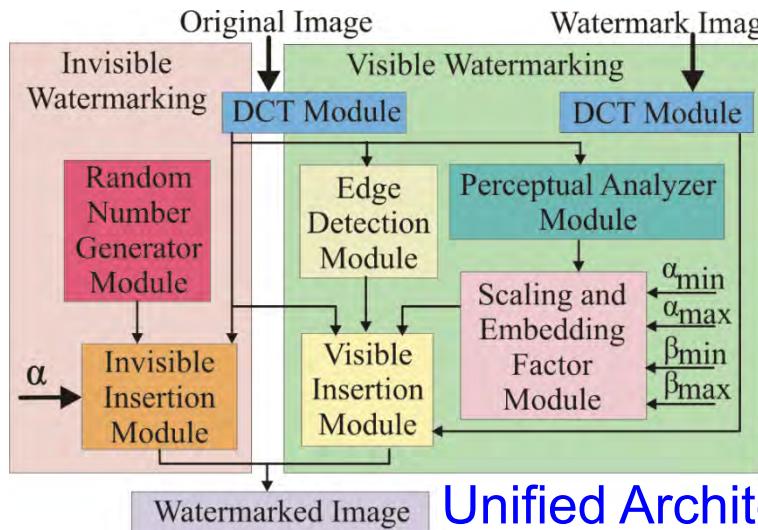


Pin Diagram

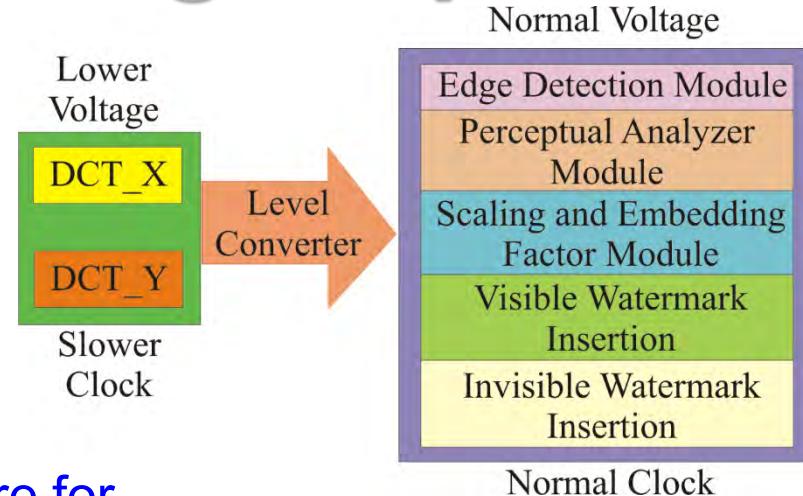
Chip Design Data
Total Area : 0.87 sq mm, No. of Gates: 4,820
Power Consumption: 2.0 mW, Frequency: 500 MHz

Source: S. P. Mohanty, E. Koulianou, and N. Ranganathan, "VLSI Architecture and Chip for Combined Invisible Robust and Fragile Watermarking", *IET Computers & Digital Techniques (CDT)*, Sep 2007, Vol. 1, Issue 5, pp. 600-611.

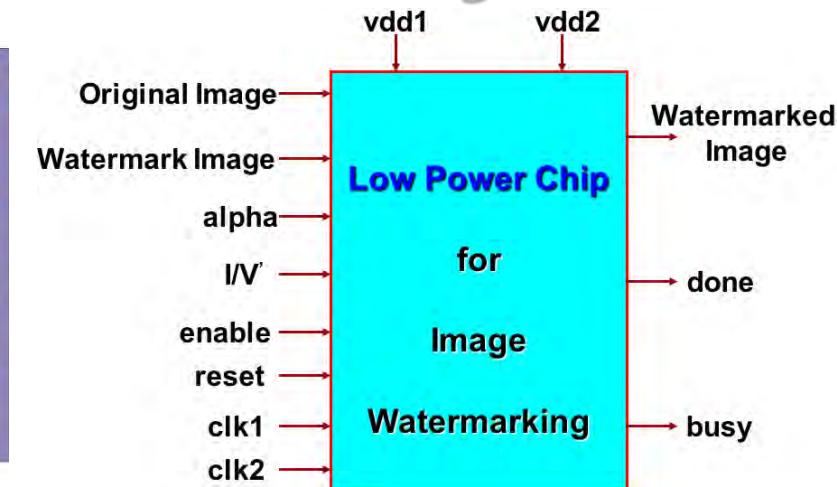
Our Design: First Ever Low-Power Watermarking Chip for Data Quality



Unified Architecture for
DCT Domain Watermarking



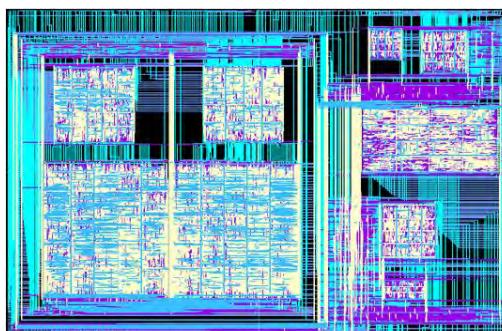
DVDF Low-Power Design



Pin Diagram

Chip Design Data

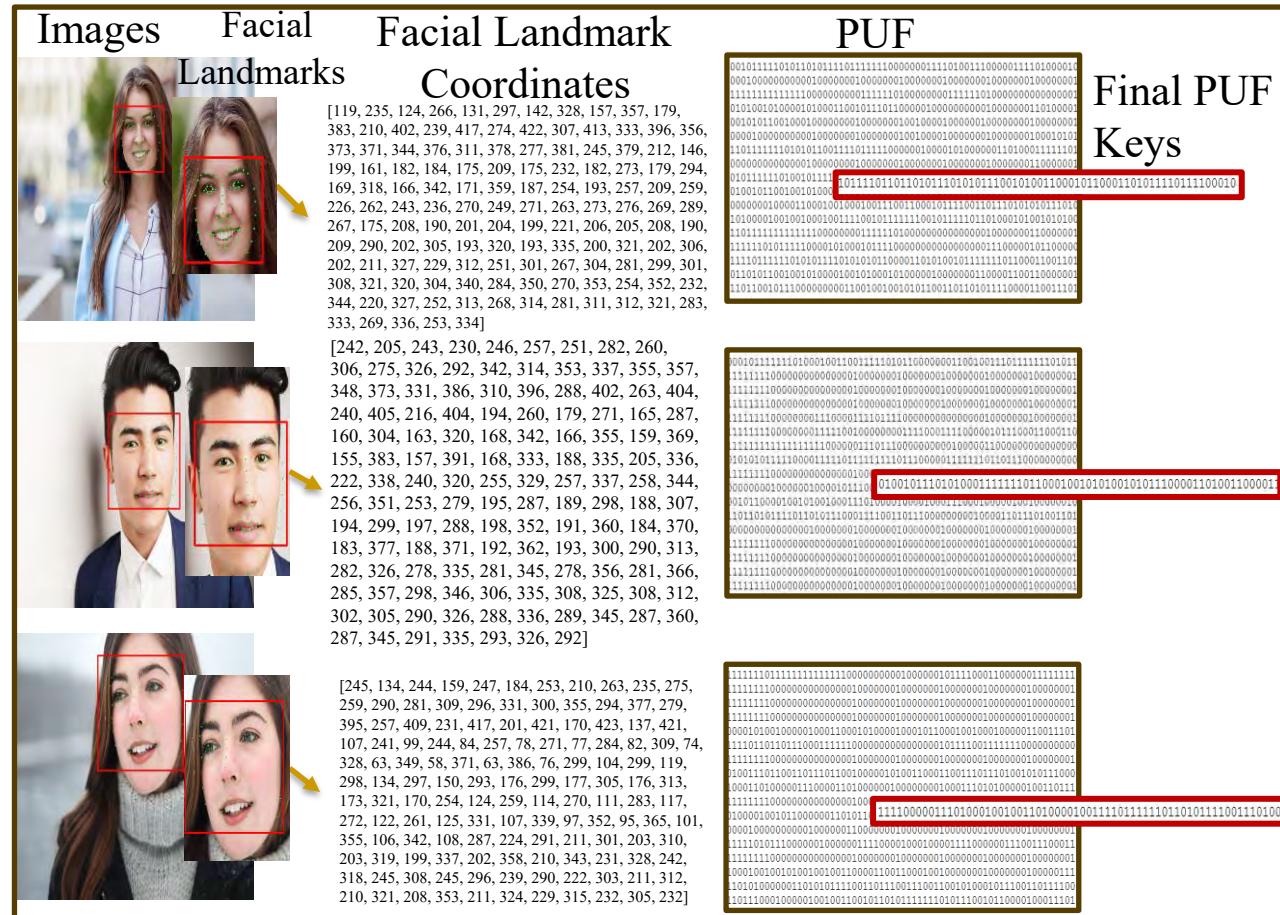
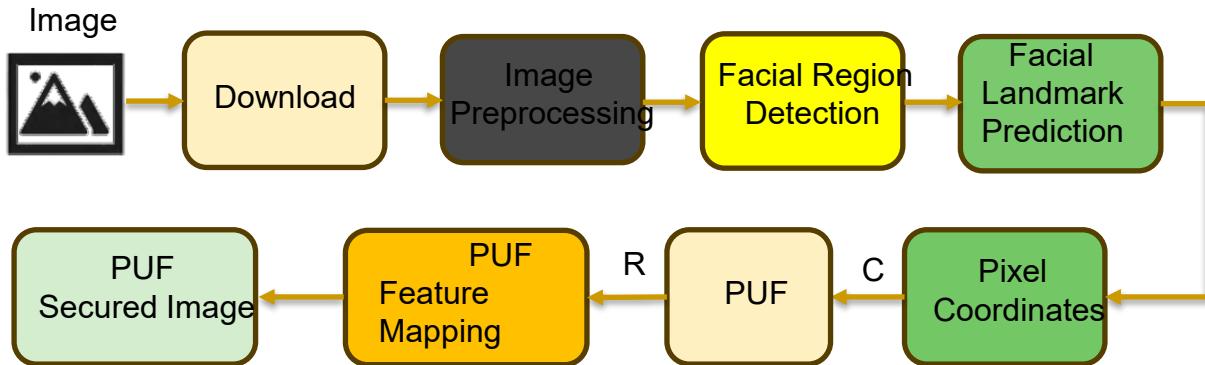
Total Area : 16.2 sq mm, No. of Transistors: 1.4 million
 Power Consumption: 0.3 mW, Operating Frequency:
 70 MHz and 250 MHz at 1.5 V and 2.5 V



Chip Layout

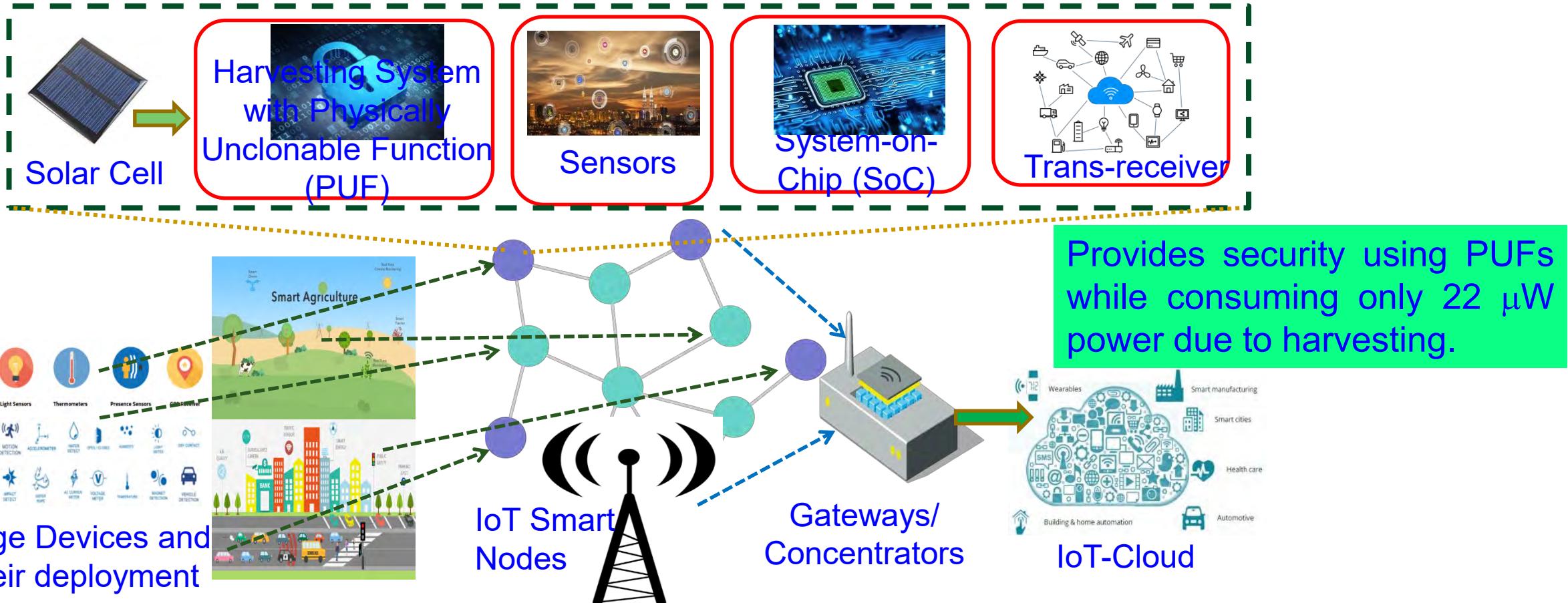
Source: S. P. Mohanty, N. Ranganathan, and K. Balakrishnan, "A Dual Voltage-Frequency VLSI Chip for Image Watermarking in DCT Domain", *IEEE Transactions on Circuits and Systems II (TCAS-II)*, Vol. 53, No. 5, May 2006, pp. 394-398.

Our PUFshield: for Deepfake Mitigation Through PUF-Based Facial Feature Attestation ...



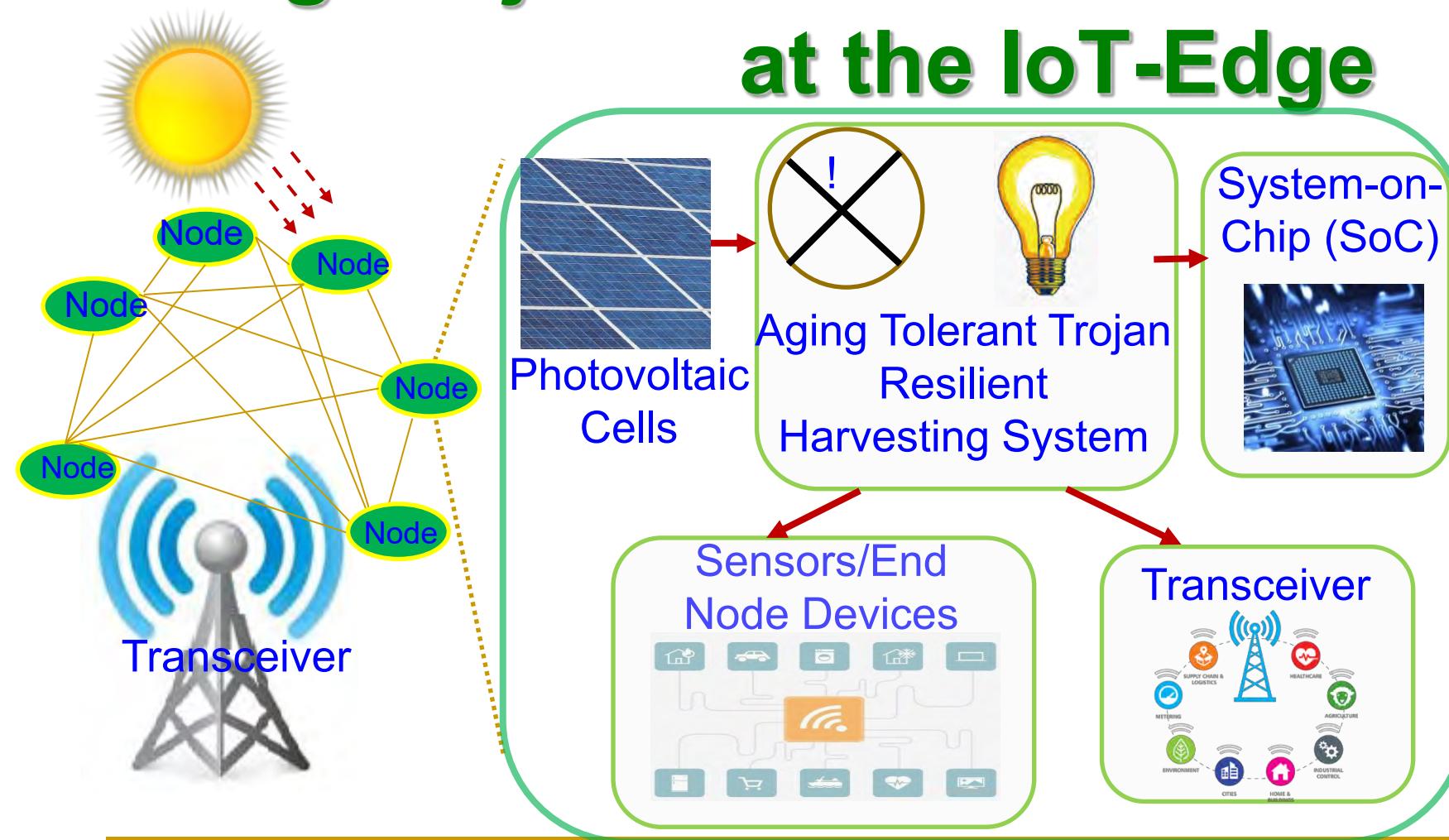
Source: V. K. V. V. Bathalapalli, V. P. Yanambaka, **S. P. Mohanty**, and E. Kougianos, "PUFshield: A Hardware-Assisted Approach for Deepfake Mitigation Through PUF-Based Facial Feature Attestation", in *Proceedings of the ACM Great Lakes Symposium on VLSI (GLSVLSI)*, 2024, pp. XXX--YYY, DOI: <https://doi.org/10.1145/3649476.3660394>.

Our SbD: Eternal-Thing: Combines Security and Energy Harvesting at the IoT-Edge



Source: S. K. Ram, S. R. Sahoo, Banee, B.Das, K. K. Mahapatra, and S. P. Mohanty, "Eternal-Thing: A Secure Aging-Aware Solar-Energy Harvester Thing for Sustainable IoT", *IEEE Transactions on Sustainable Computing*, Vol. 6, No. 2, April 2021, pp. 320—333, DOI: <https://doi.org/10.1109/TSUSC.2020.2987616>.

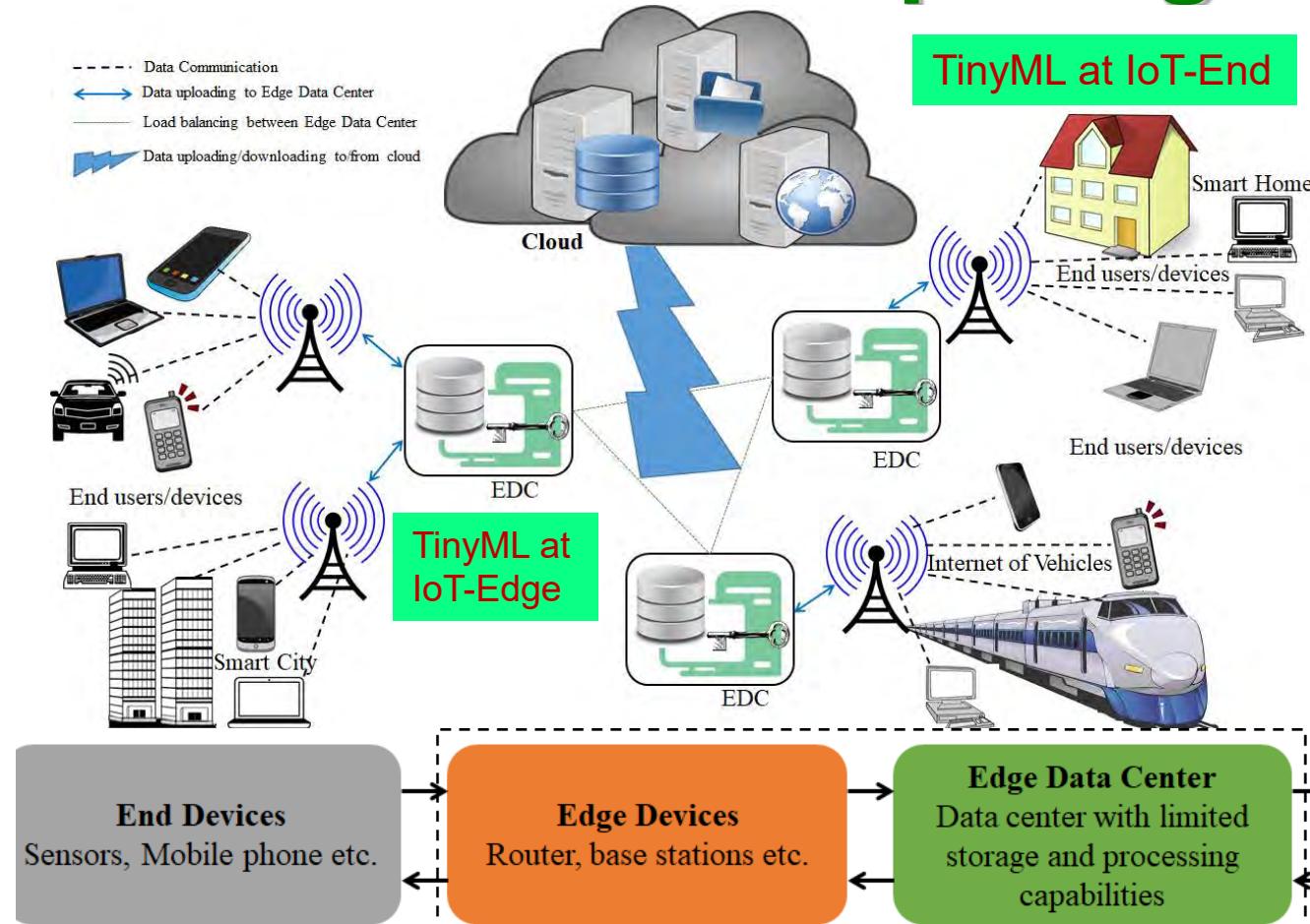
Our SbD based Eternal-Thing 2.0: Combines Analog-Trojan Resilience and Energy Harvesting at the IoT-Edge



Provides security against analog-Trojan while consuming only 22 μW power due to harvesting.

Source: S. K. Ram, S. R. Sahoo, B. B. Das, K. K. Mahapatra, and S. P. Mohanty, "[Eternal-Thing 2.0: Analog-Trojan Resilient Ripple-Less Solar Harvesting System for Sustainable IoT](#)", ACM Journal on Emerging Technologies in Computing Systems (JETC), Vol. 19, No. 2, March 2023, pp. 12:1–12:25, DOI: <https://doi.org/10.1145/3575800>.

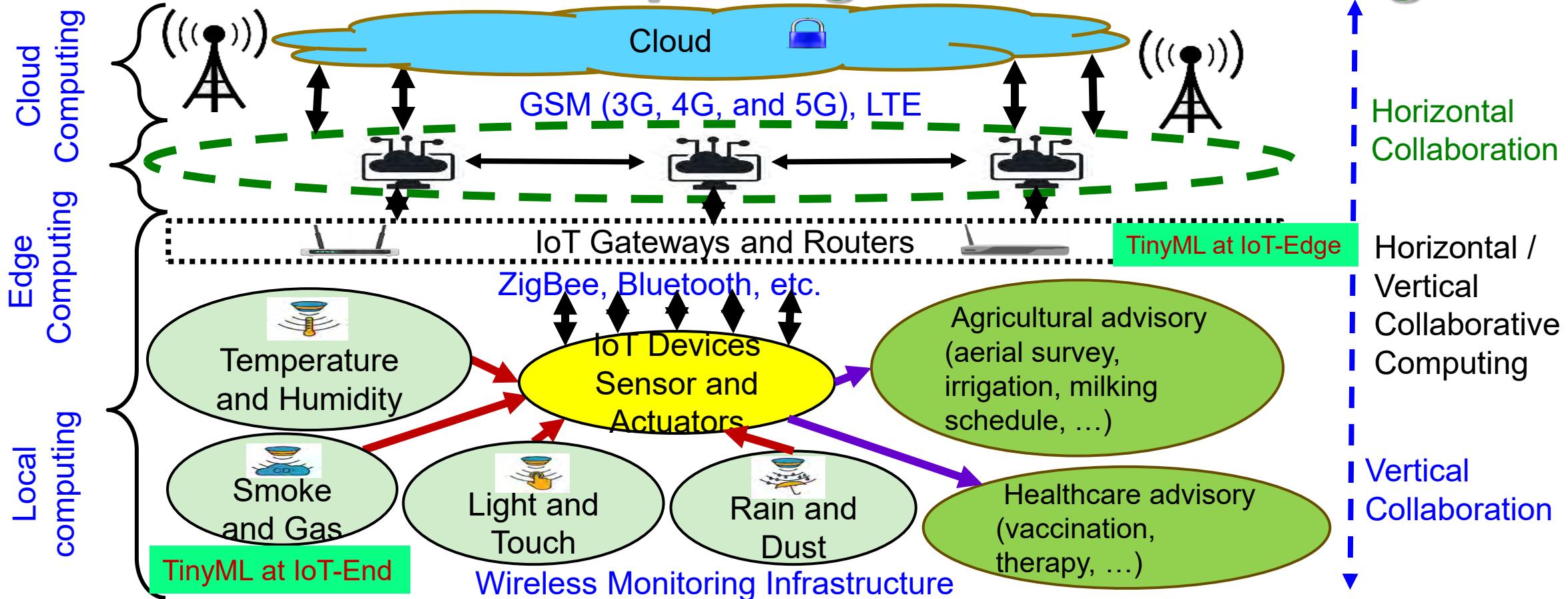
Collaborative Edge Computing is Cost Effective Sustainable Computing for Smart Villages



Collaborative edge computing connects the IoT-edges of multiple organizations that can be near or far from each other
→ Providing bigger computational capability at the edge with lower design and operation cost.

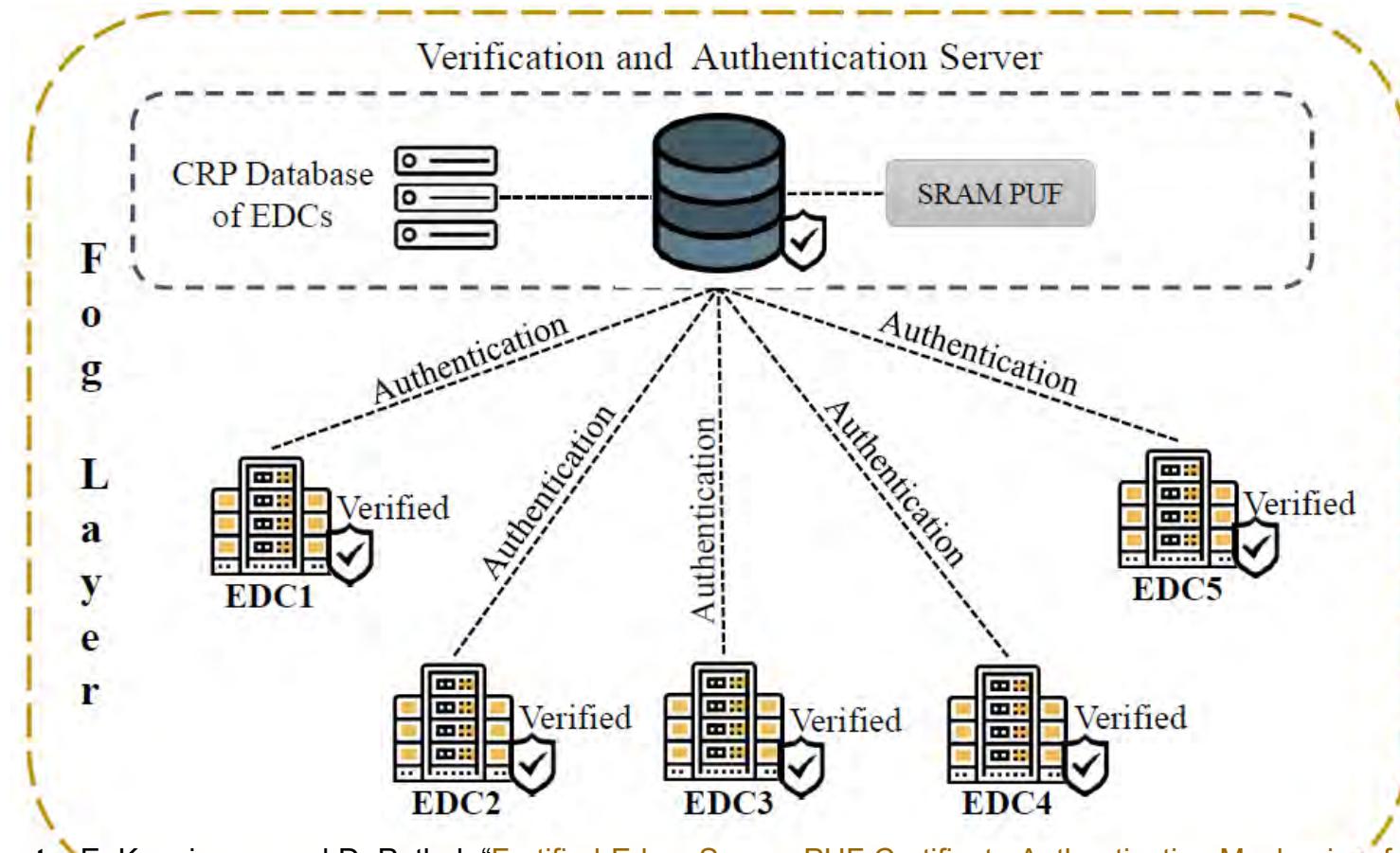
Source: D. Puthal, M. S. Obaidat, P. Nanda, M. Prasad, S. P. Mohanty, and A. Y. Zomaya, "Secure and Sustainable Load Balancing of Edge Data Centers in Fog Computing", *IEEE Communications Mag*, Vol. 56, No 5, May 2018, pp. 60–65, DOI: <https://doi.org/10.1109/MCOM.2018.1700795>.

Collaborative Edge Computing is Cost Effective Sustainable Computing for Smart Villages



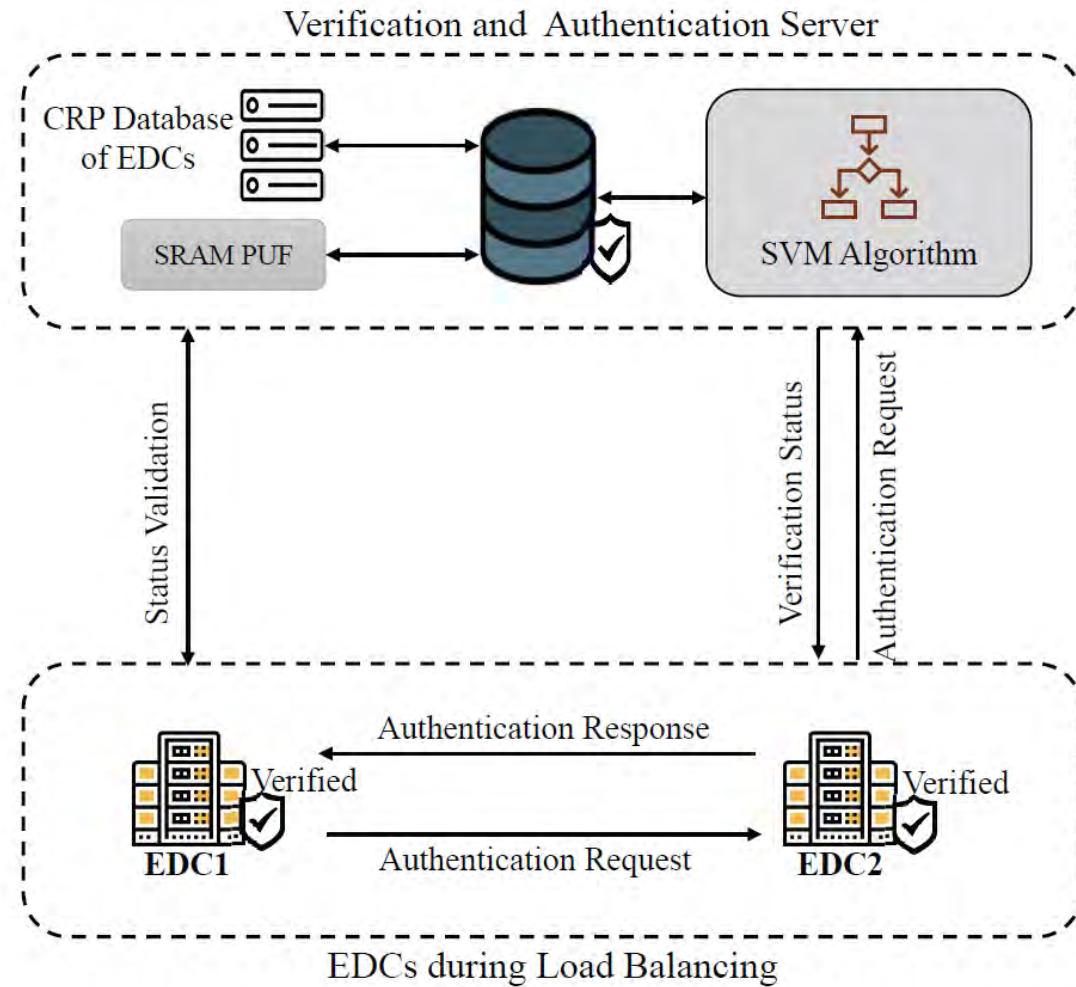
Source: D. Puthal, S. P. Mohanty, S. Wilson and U. Choppali, "Collaborative Edge Computing for Smart Villages", *IEEE Consumer Electronics Magazine (MCE)*, Vol. 10, No. 03, May 2021, pp. 68-71, DOI: <https://doi.org/10.1109/MCE.2021.3051813>.

Our Fortified-Edge: PUF based Authentication in Collaborative Edge Computing



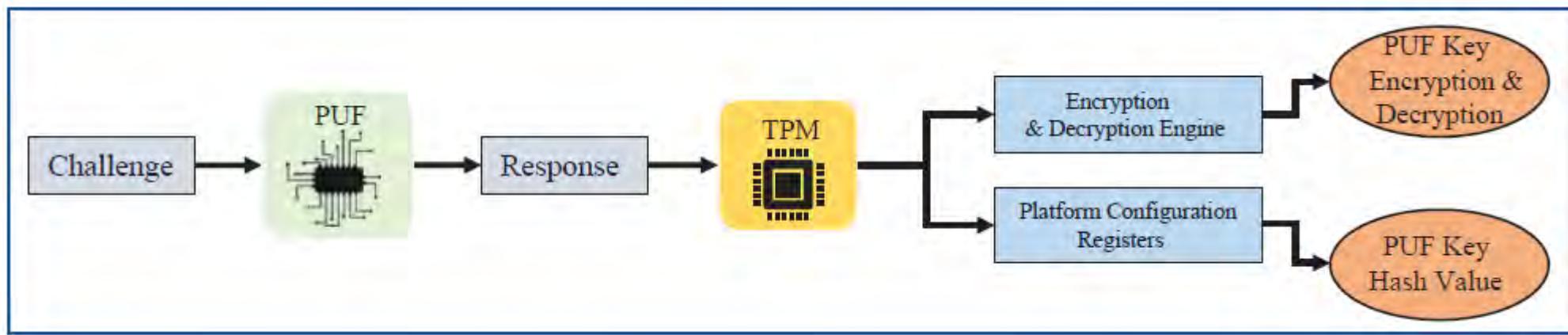
Source: S. G. Aarella, **S. P. Mohanty**, E. Kougianos, and D. Puthal, "[Fortified-Edge: Secure PUF Certificate Authentication Mechanism for Edge Data Centers in Collaborative Edge Computing](#)", in *Proceedings of the ACM Great Lakes Symposium on VLSI (GLSVLSI)*, 2023, pp. 249–254, DOI: <https://doi.org/10.1145/3583781.3590249>.

Our Fortified-Edge 2.0: ML based Monitoring and Authentication of PUF-Integrated Secure EDC



Source: S. G. Aarella, **S. P. Mohanty**, E. Kougianos, and D. Puthal, "Fortified-Edge 2.0: Machine Learning based Monitoring and Authentication of PUF-Integrated Secure Edge Data Center", in *Proceedings of the IEEE-CS Symposium on VLSI (ISVLSI)*, 2023, pp. 1-6, DOI: <https://doi.org/10.1109/ISVLSI59464.2023.10238517>.

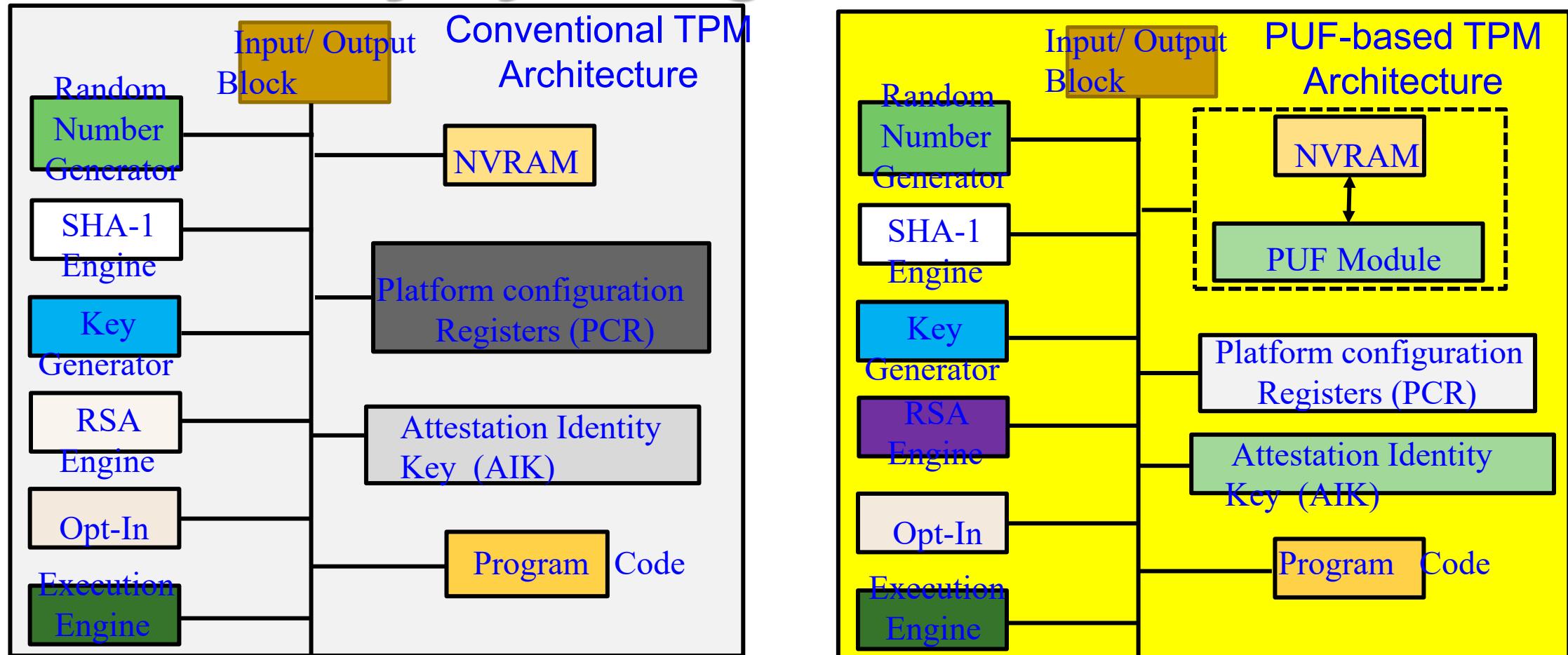
Our iTPM: Exploring PUF-based Keyless TPM for Security-by-Design of Smart Electronics



- The proposed SbD primitive works by performing secure verification of the PUF key using TPM's Encryption and Decryption engine. The securely verified PUF Key is then bound to TPM using Platform Configuration Registers (PCR).
- By binding PUF with PCR in TPM, a novel PUF-based access control. The policy can be defined, as bringing in a new security ecosystem for the emerging Internet-of-Everything era.

Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, V. Iyer, and B. Rout, "iTPM: Exploring PUF-based Keyless TPM for Security-by-Design of Smart Electronics", in *Proceedings of the IEEE-CS Symposium on VLSI (ISVLSI)*, 2023, pp. XXX, DOI: [XXX](#).

Our iTPM: Exploring PUF-based Keyless TPM for Security-by-Design of Smart Electronics



Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, V. Iyer, and B. Rout, "iTPM: Exploring PUF-based Keyless TPM for Security-by-Design of Smart Electronics", in *Proceedings of the IEEE-CS Symposium on VLSI (ISVLSI)*, 2023, pp. XXX, DOI: [XXX](#).

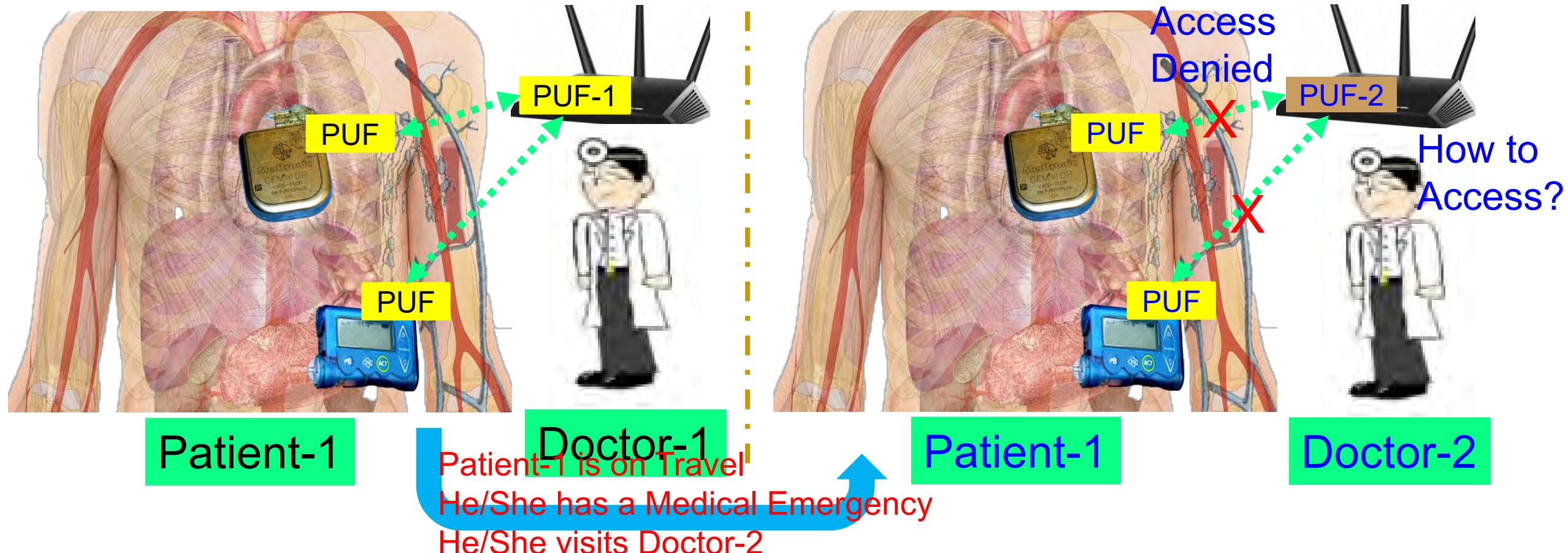
Is Physical Unclonable Function (PUF) the Solution for Every Cybersecurity Problem?

If PUF is So Great, Why Isn't Everyone Using It?

- PUF technology is difficult to implement well.
- In addition to security system expertise, one needs analog circuit expertise to harness the minute variances in silicon and do it reliably.
- Some PUF implementations plan for a certain amount of marginality in the analog designs, so they create a PUF field of 256 bits (for example), knowing that only 50 percent of those PUF features might produce reliable bits, then mark which features are used on each production part.
- PUF technology relies on such minor variances, long-term quality can be a concern: will a PUF bit flip given the stresses of time, temperature, and other environmental factors?
- Overall the unique mix of security, analog expertise, and quality control is a formidable challenge to implementing a good PUF technology.

Source: <https://embeddedcomputing.com/technology/processing/semiconductor-ip/demystifying-the-physically-unclonable-function-puf>

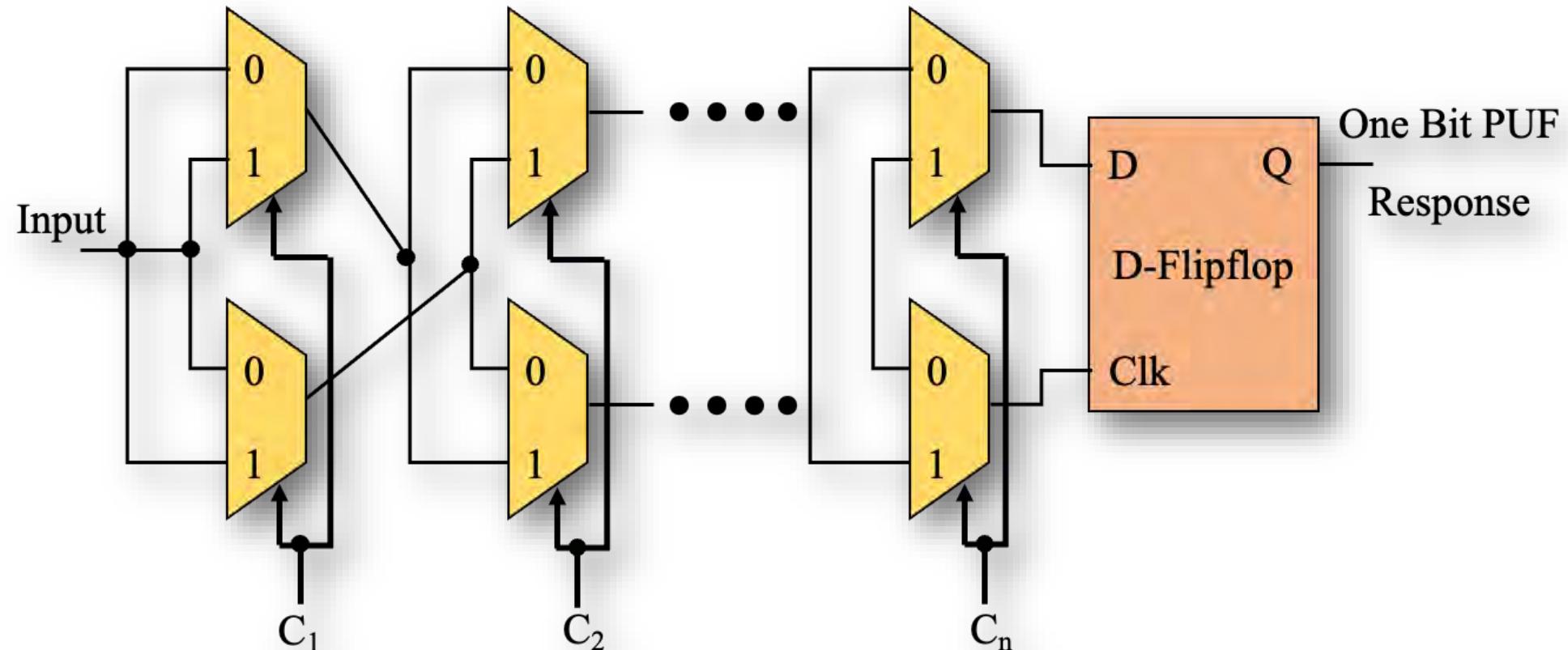
PUF based Cybersecurity in Smart Healthcare - Doctor's Dilemma



Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, V. Iyer, and B. Rout, “PMsec 2.0: A Security-By-Design Solution for Doctor’s Dilemma Problem in Smart Healthcare”, in *Proceedings of the OITS International Conference on Information Technology (OCIT)*, 2023, pp. 456–461, DOI: <https://doi.org/10.1109/OCIT59427.2023.10430808>.

PUF Limitations – Larger Key Needs Large ICs

- Larger key requires larger chip circuit.

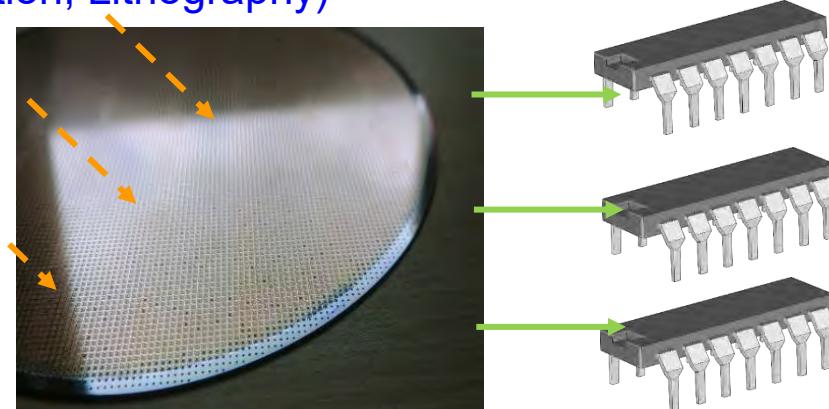


1 – Bit Arbiter PUF Architecture

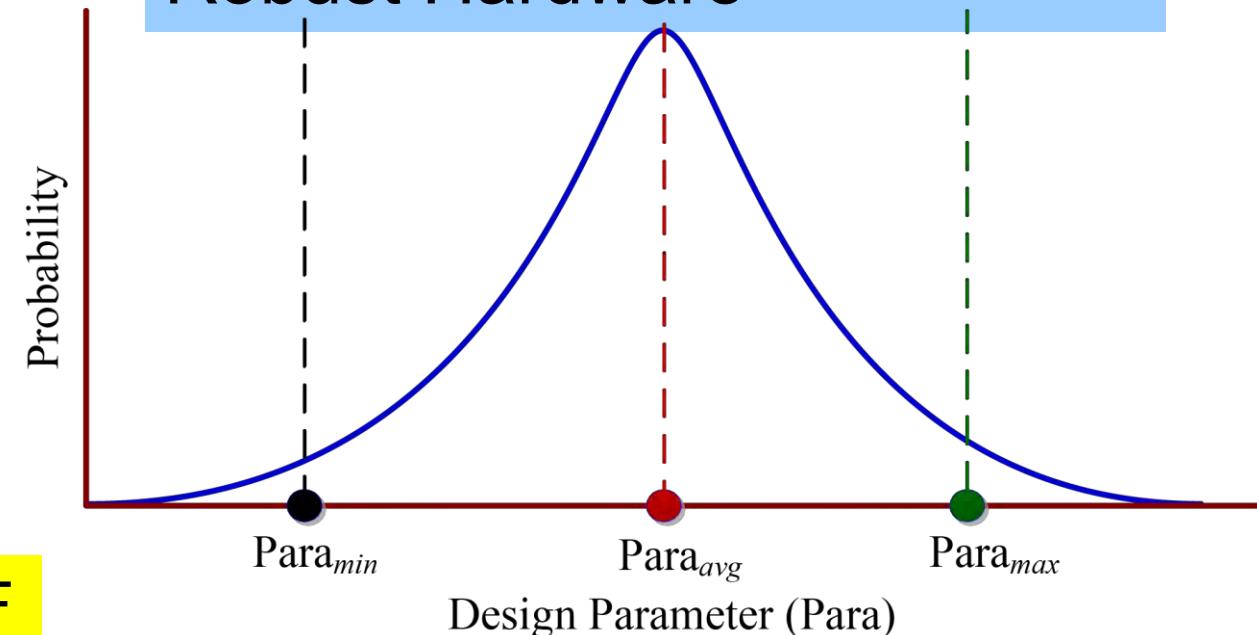
IC for PUF – Variability versus Variability-Aware Design

Variability → Randomness for PUF

Manufacturing Variations
(e.g. Oxide Growth, Ion Implantation, Lithography)



Variability-Aware Design → Robust Hardware

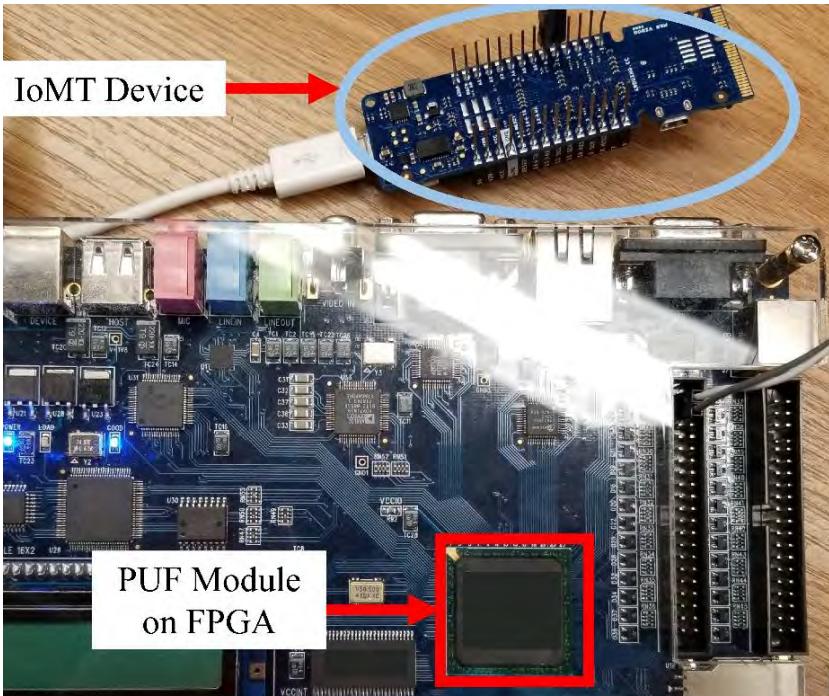


Variability Features → Randomness → PUF

Is it not case of Conflicting Objectives?
How to have a Robust-IC design that functions as a PUF?

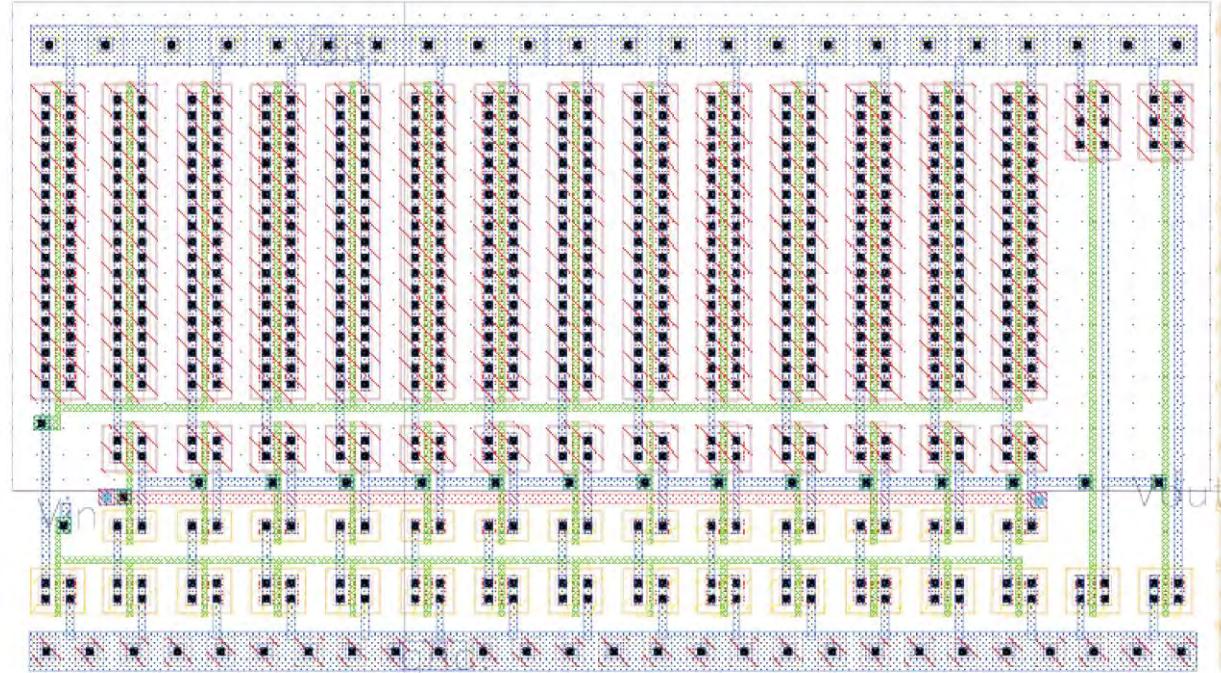
Optimize $(\mu+n\sigma)$ to reduce variability for Robust Design

PUF – FPGA versus IC



Source: V. P. Yanambaka, S. P. Mohanty, E. Kougianos, and D. Puthal, “PMsec: Physical Unclonable Function-Based Robust and Lightweight Authentication in the Internet of Medical Things”, *IEEE Transactions on Consumer Electronics (TCE)*, Volume 65, Issue 3, August 2019, pp. 388–397.

- Faster prototyping
- Lesser design effort
- Minimal skills
- Cheap
- Rely on already existing post fabrication variability

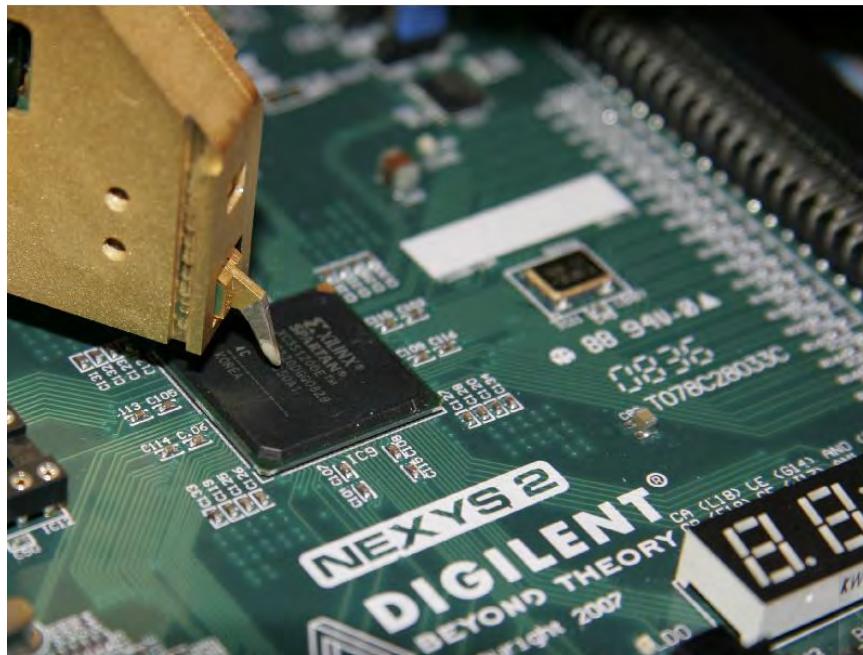


Source: S. P. Mohanty and E. Kougianos, “Incorporating Manufacturing Process Variation Awareness in Fast Design Optimization of Nanoscale CMOS VCOs”, *IEEE Transactions on Semiconductor Manufacturing (TSM)*, Volume 27, Issue 1, February 2014, pp. 22–31.

- Takes time to get it from fab
- More design effort
- Needs analog design skills
- Can be expensive
- Choice to send to fab as per the need

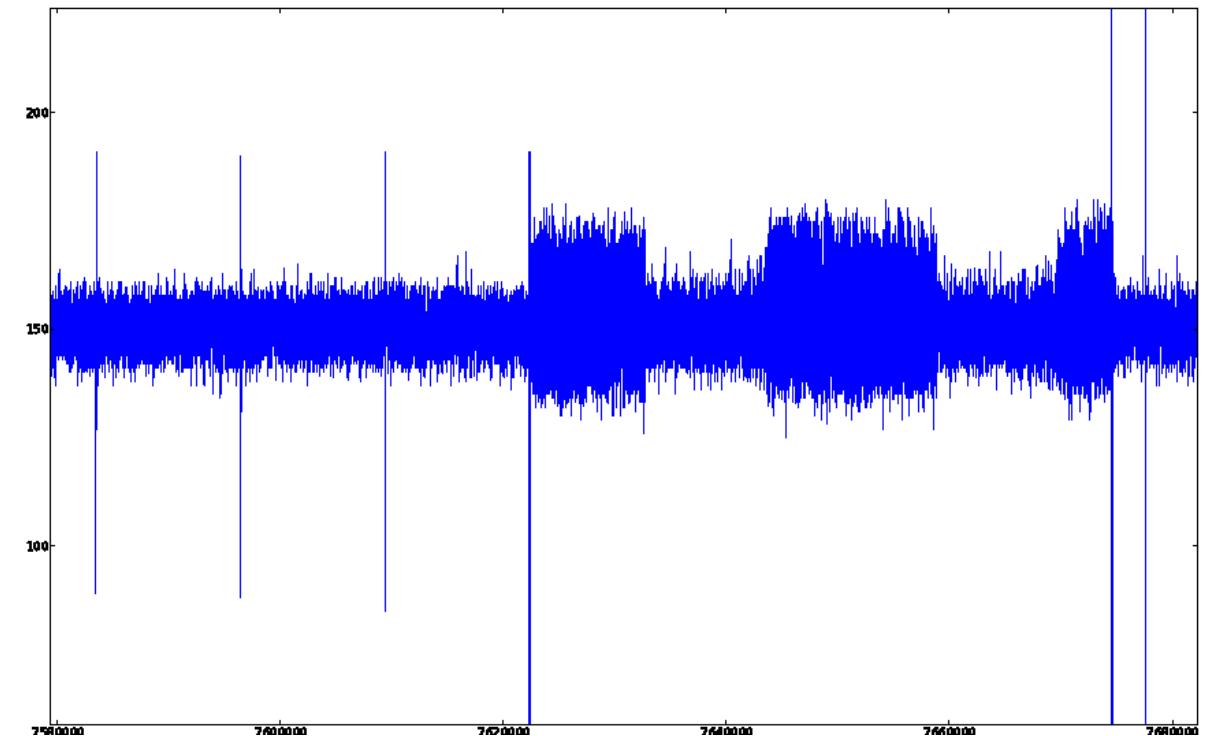
PUF - Side Channel Leakage

- Delay-based PUF implementations are vulnerable to side-channel attacks.



Langer ICR HH 150 probe over Xilinx Spartan3E-1200 FPGA

Source: Merli, D., Schuster, D., Stumpf, F., Sigl, G. (2011). Side-Channel Analysis of PUFs and Fuzzy Extractors. In: McCune, J.M., Balacheff, B., Perrig, A., Sadeghi, AR., Sasse, A., Beres, Y. (eds) Trust and Trustworthy Computing. Trust 2011. Lecture Notes in Computer Science, vol 6740. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-21599-5_3



Magnification of the last part of the complete trace. Three trigger signals can be identified: (1) between oscillator phase and error correction phase, (2) between error correction and hashing, and (3) at the end of hashing.

PUF – Trojan Issue

- Improper implementation of PUF could introduce "backdoors" to an otherwise secure system.
- PUF introduces more entry points for hacking into a cryptographic system.



Provide backdoor to adversary.
Chip fails during critical needs.

Source: Rührmair, Ulrich; van Dijk, Marten (2013). *PUFs in Security Protocols: Attack Models and Security Evaluations* (PDF), in Proc. IEEE Symposium on Security and Privacy, May 19–22, 2013

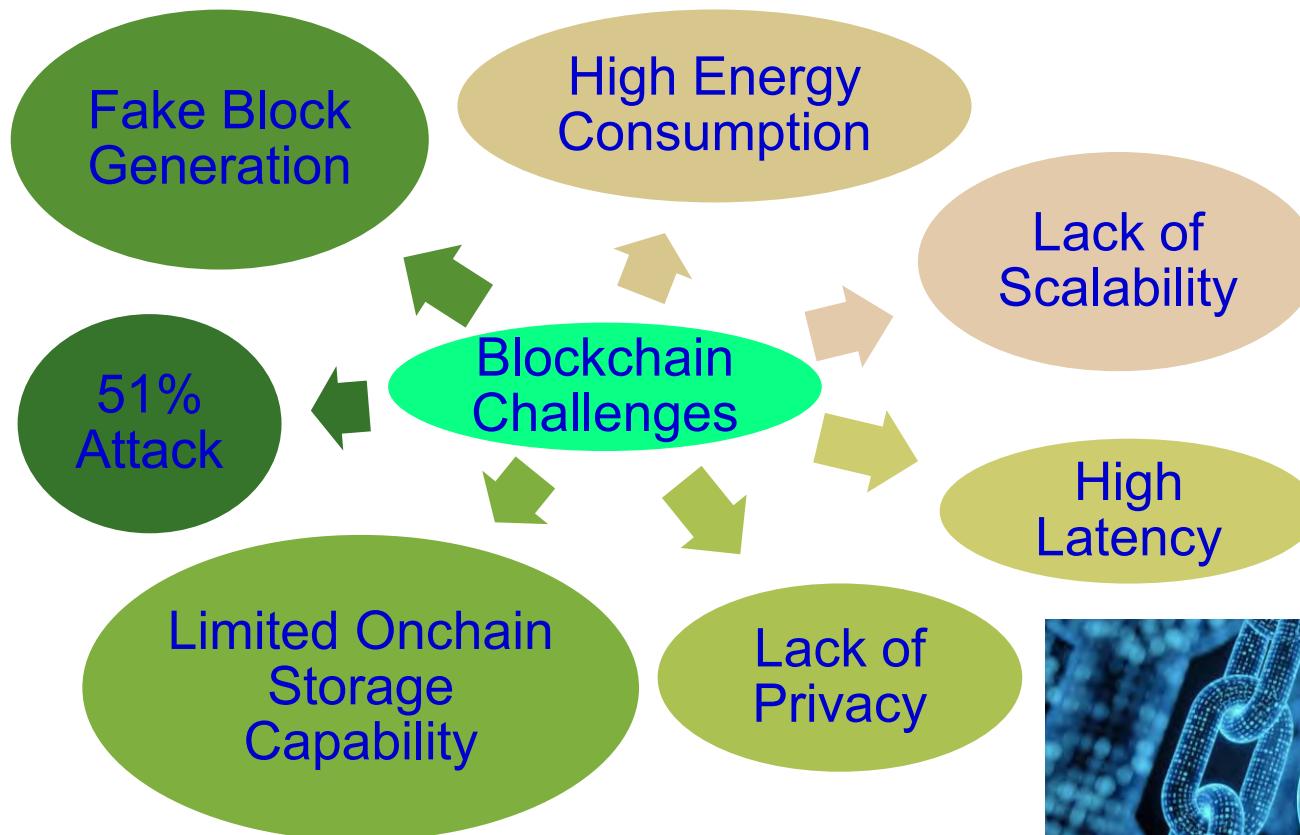
PUF – Machine Learning Attack

- One types of non-invasive attacks is machine learning (ML) attacks.
- ML attacks are possible for PUFs as the pre- and post-processing methods ignore the effect of correlations between PUF outputs.
- Many ML algorithms are available against known families of PUFs.

Source: Ganji, Fatemeh (2018), "On the learnability of physically unclonable functions", Springer. ISBN 978-3-319-76716-1.

Is Blockchain the Solution for Every Cybersecurity Problem?

Blockchain has Many Challenges



Source: <https://www.otorox.com>



Source: <https://www.monash.edu/blockchain/news/how-do-we-know-blockchain-can-t-be-hacked-or-manipulated-or-can-it>

Source: D. Puthal, N. Malik, S. P. Mohanty, E. Kougianos, and G. Das, "Everything you Wanted to Know about the Blockchain", *IEEE Consumer Electronics Magazine*, Volume 7, Issue 4, July 2018, pp. 06--14.

Blockchain Energy Need is Huge



Energy for mining of 1 bitcoin



Energy consumption 2 years
of a US household



Energy
consumption
for each bitcoin
transaction



80,000 X



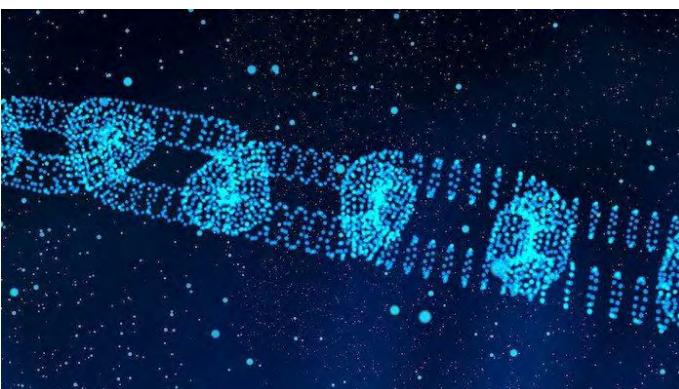
Energy consumption of
a credit card processing

Blockchain has Cybersecurity Challenges

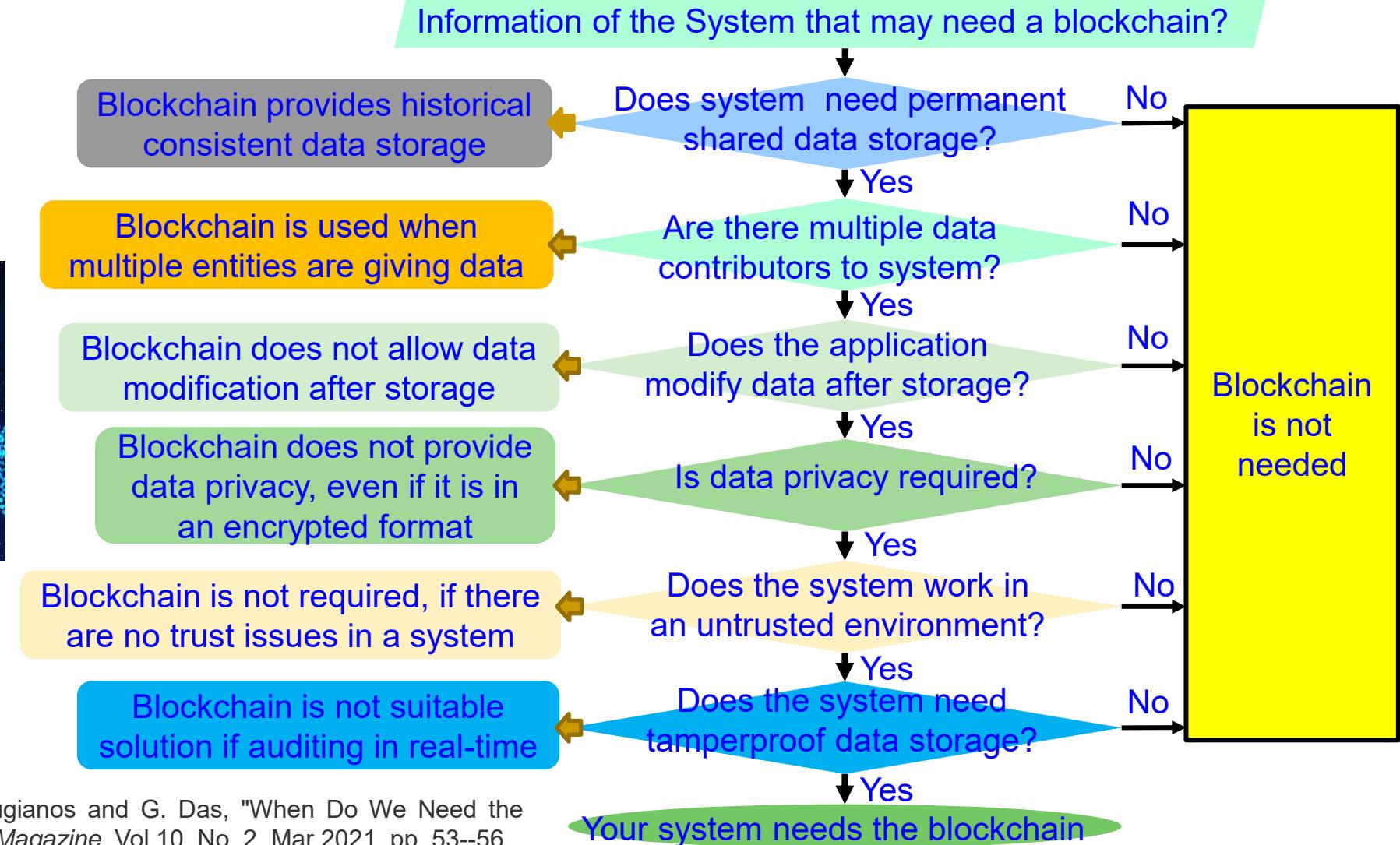
Selected attacks on the blockchain and defences		
Attacks	Descriptions	Defence
Double spending	Many payments are made with a body of funds	Complexity of mining process
Record hacking	Blocks are modified, and fraudulent transactions are inserted	Distributed consensus
51% attack	A miner with more than half of the network's computational power dominates the verification process	Detection methods and design of incentives
Identity theft	An entity's private key is stolen	Reputation of the blockchain on identities
System hacking	The software systems that implement a blockchain are compromised	Advanced intrusion detection systems

Source: N. Kolokotronis, K. Limniotis, S. Shieales, and R. Griffiths, "Secured by Blockchain: Safeguarding Internet of Things Devices," *IEEE Consumer Electronics Magazine*, vol. 8, no. 3, pp. 28–34, May 2019.

When do You Need the Blockchain?



Information of the System that may need a blockchain?



Source: D. Puthal, S. P. Mohanty, E. Kougianos and G. Das, "When Do We Need the Blockchain?", *IEEE Consumer Electronics Magazine*, Vol 10, No. 2, Mar 2021, pp. 53--56.

Conclusion



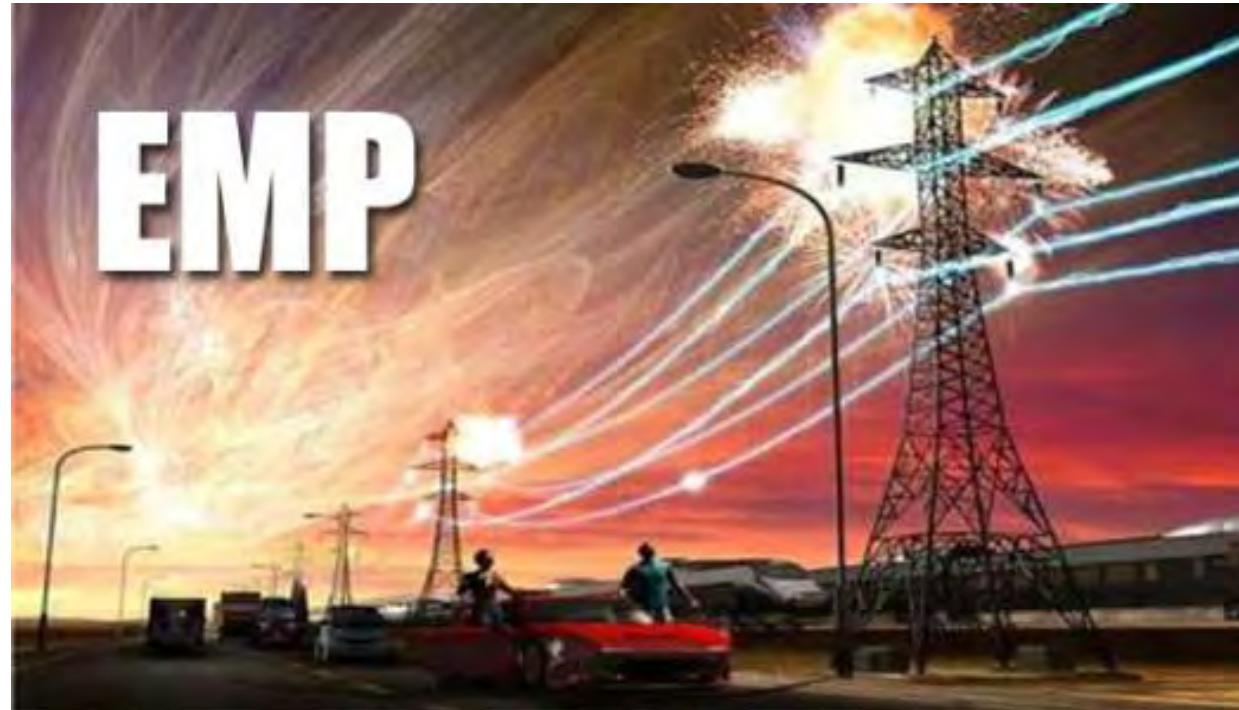
Conclusion

- Cybersecurity and Privacy are important problems in IoT-driven Cyber-Physical Systems (CPS).
- Various elements and components of IoT/CPS including Data, Devices, System Components, AI need security.
- Both software and hardware-based attacks and solutions are possible for cybersecurity in IoT/CPS.
- Cybersecurity in IoT-based H-CPS, A-CPS, E-CPS, and T-CPS, etc. can have serious consequences.
- Existing cybersecurity solutions have serious overheads and may not even run in the end-devices (e.g. a medical device) of CPS/IoT.
- Security-by-Design (SbD) advocate features at early design phases, no-retrofitting.
- Hardware-Assisted Security (HAS): Security provided by hardware for: (1) information being processed, (2) hardware itself, (3) overall system.
- Research on topologies and protocols for PUF based cybersecurity is ongoing.

Future Directions

- Privacy and/or Security by Design (PbD or SbD) needs research.
- Cybersecurity, Privacy, IP Protection of Information and System (in Cyber-Physical Systems or CPS) need more research.
- Cybersecurity of IoT-based systems (e.g. Smart Healthcare device/data, Smart Agriculture, Smart Grid, UAV, Smart Cars) needs research.
- Sustainable Smart City and Smart Villages: need sustainable IoT/CPS.
- More research is needed for low-overhead PUF design and protocols that can be integrated in any IoT-enabled systems.

Electromagnetic Pulse (EMP) Attack



Source: <http://bwcentral.org/2016/06/an-electromagnetic-pulse-emp-nuclear-attack-may-end-modern-life-in-america-overnight/>

- An electromagnetic pulse (EMP) is the electric wave produced by nuclear blasts which can knocking out electronics and the electrical grid as far as 1,000 miles away.
- The disruption could cause catastrophic damage and loss of life if power is not restored or backed up quickly.