Sustainable Healthcare Cyber-Physical Systems

Expert Lecture – AICTE Training and Learning Academy Faculty Development Program (ATAL-FDP)

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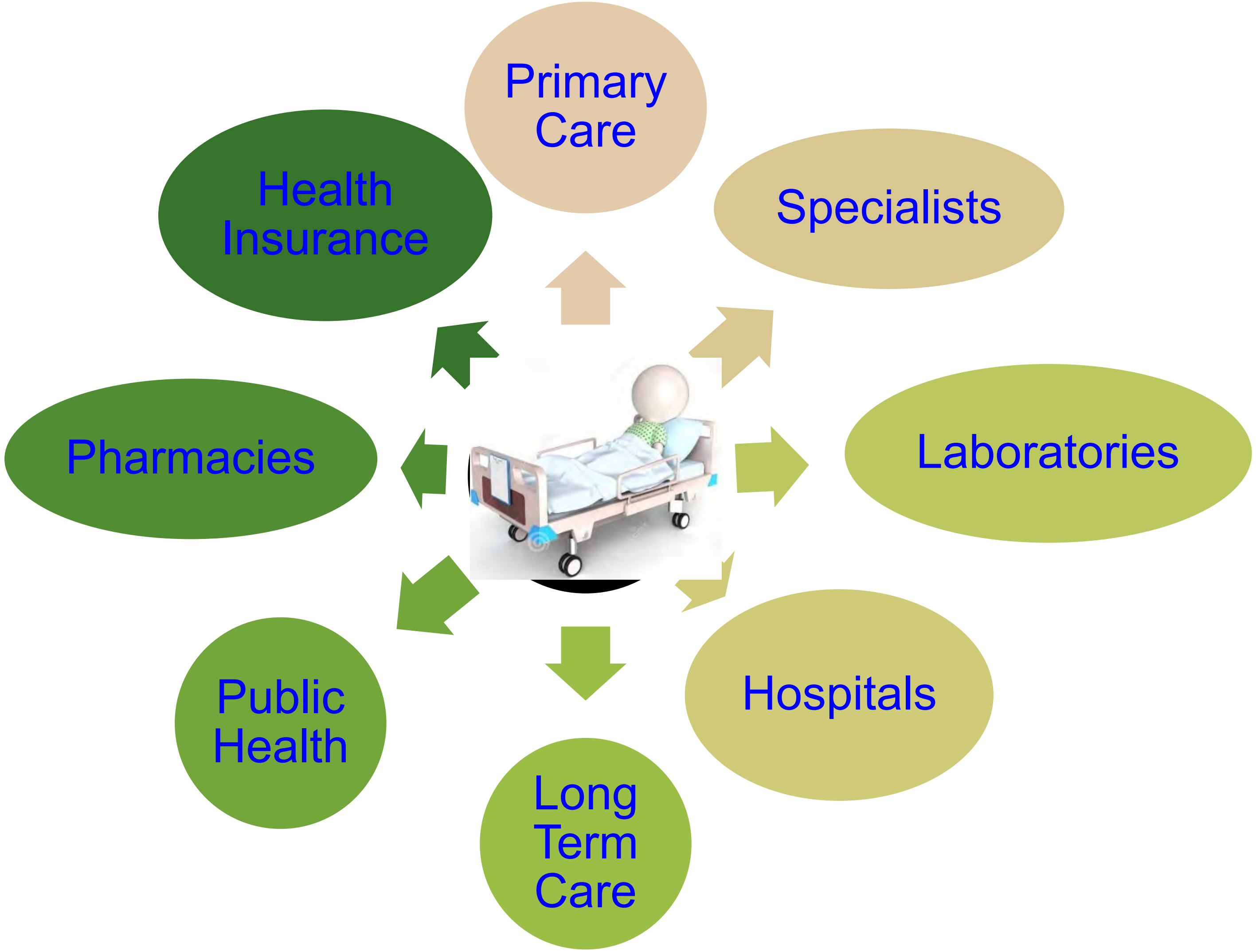
Outline

- Smart Healthcare – Broad Introduction
- Smart Healthcare – Challenges Against Sustainability
- Selected Cybersecurity Solutions for IoT/CPS
- Drawbacks of Existing Cybersecurity Solutions of IoMT/H-CPS
- Security by Design (SbD) Principle
- Security by Design (SbD) Example Solutions
- Trustworthy Pharmaceutical Supply Chain
- Trustworthy Medical Prescription
- Conclusion

Smart Healthcare – Broad Introduction

Traditional Healthcare



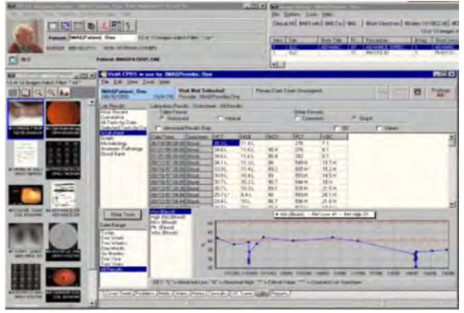
- Physical presence needed
- Deals with many stakeholders
- Stakeholders may not interact
- May not be personalized
- Not much active feedback
- Less effective follow-up from physicians

Healthcare → Smart Healthcare

Healthcare

eHealth → Telemedicine → mHealth → cHealth → sHealth

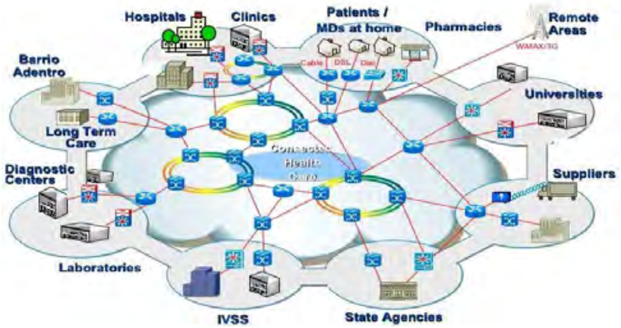
eHealth: The use of information and communication technologies (ICT) to improve healthcare services.



Telemedicine: Telemedicine is the use of telecommunication and information technology to provide clinical healthcare from a distance.

mHealth: Healthcare supported by *mobile devices* that uses mobile telecommunications and multimedia technologies for the delivery of healthcare services and health information.

cHealth



sHealth

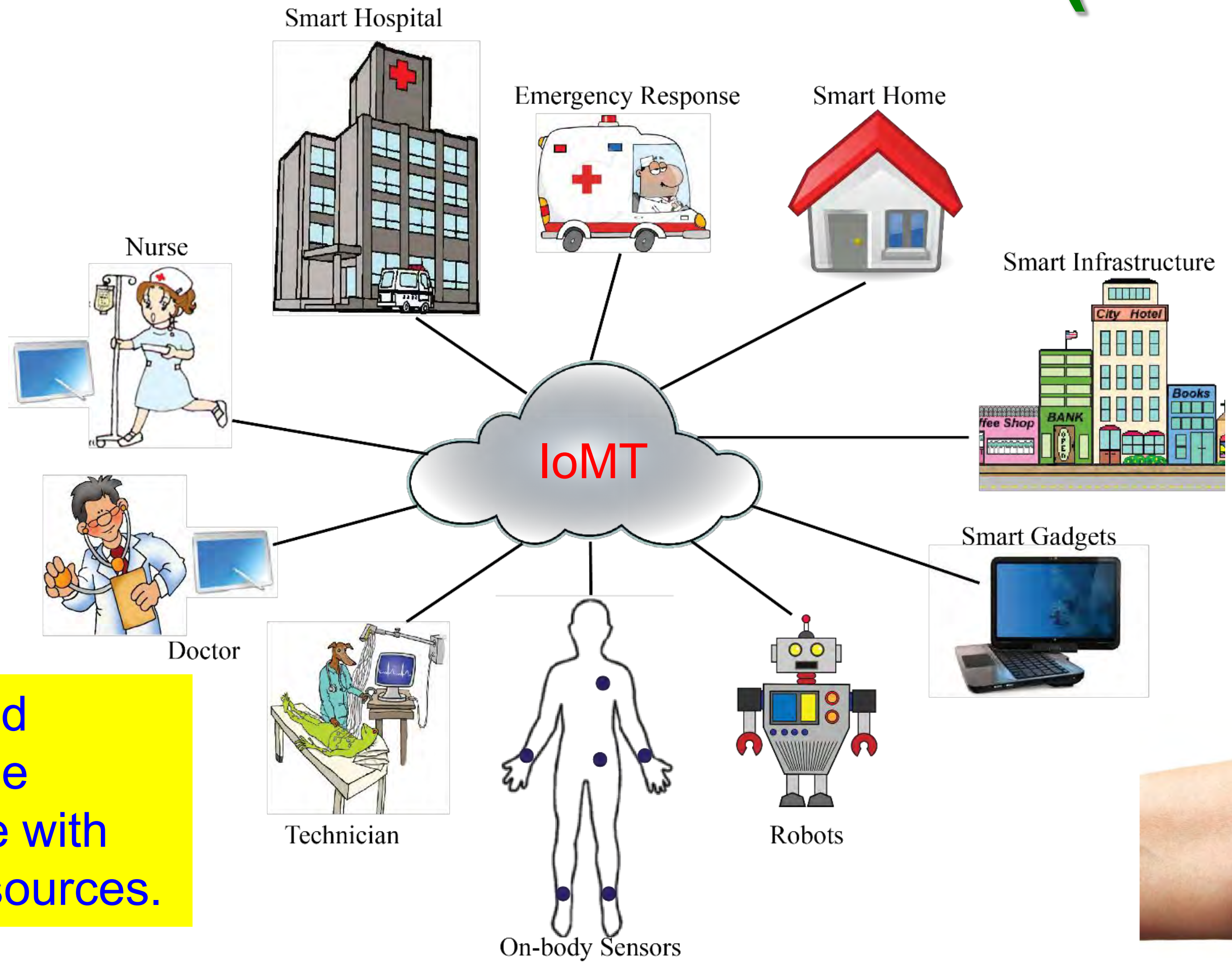
Embedded Skin Patches

Thync's - UltrasoVibeund

Muse - EEG

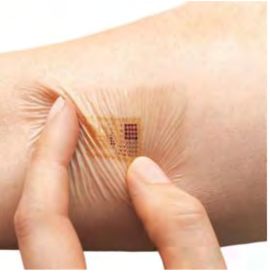
Source: **S. P. Mohanty**, “Smart Healthcare: From Healthcare to Smart Healthcare”, ICCE 2020 Panel, Jan 2020.

Smart Healthcare (sHealth)



Fitness Trackers

Headband with Embedded Neurosensors

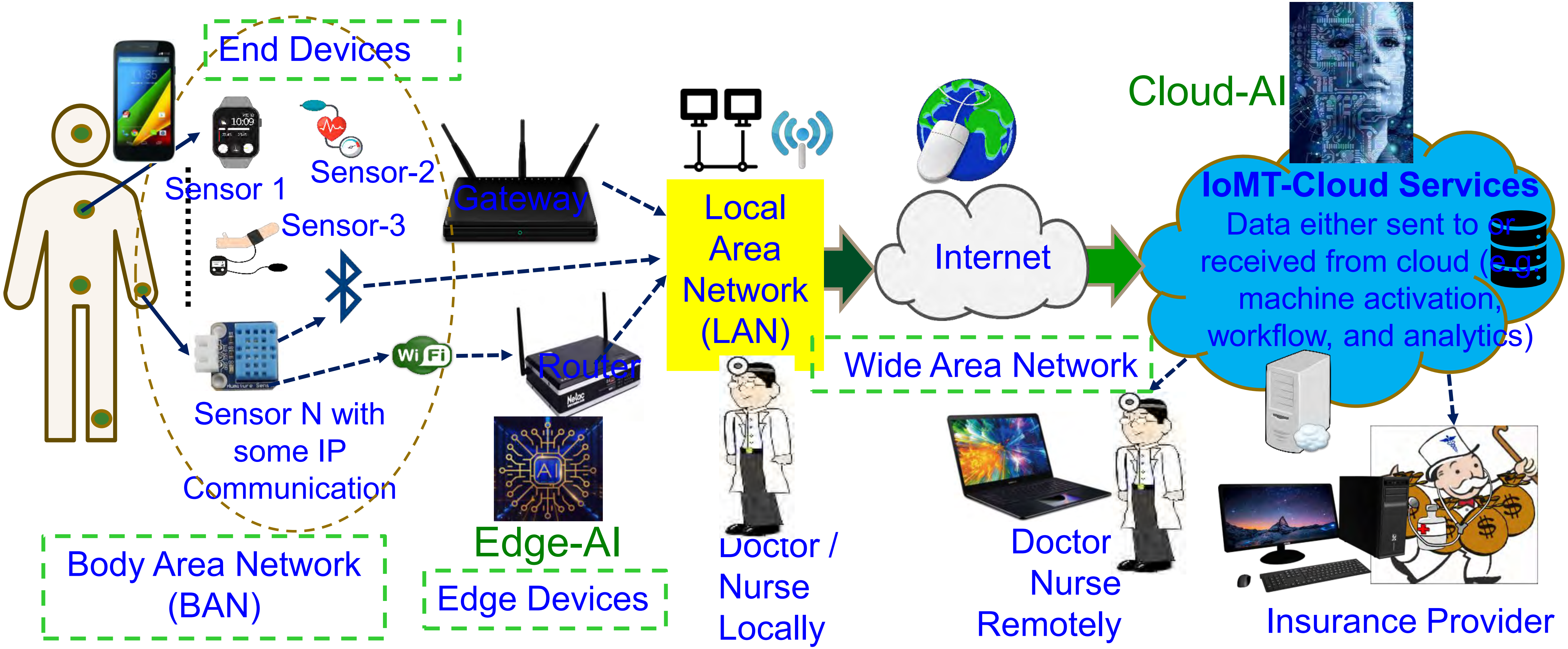


Embedded Skin Patches

Quality and sustainable healthcare with limited resources.

Source: P. Sundaravadivel, E. Kougianos, S. P. Mohanty, and M. Ganapathiraju, “Everything You Wanted to Know about Smart Health Care”, *IEEE Consumer Electronics Magazine (MCE)*, Vol. 7, Issue 1, January 2018, pp. 18-28.

Smart Healthcare – Healthcare CPS

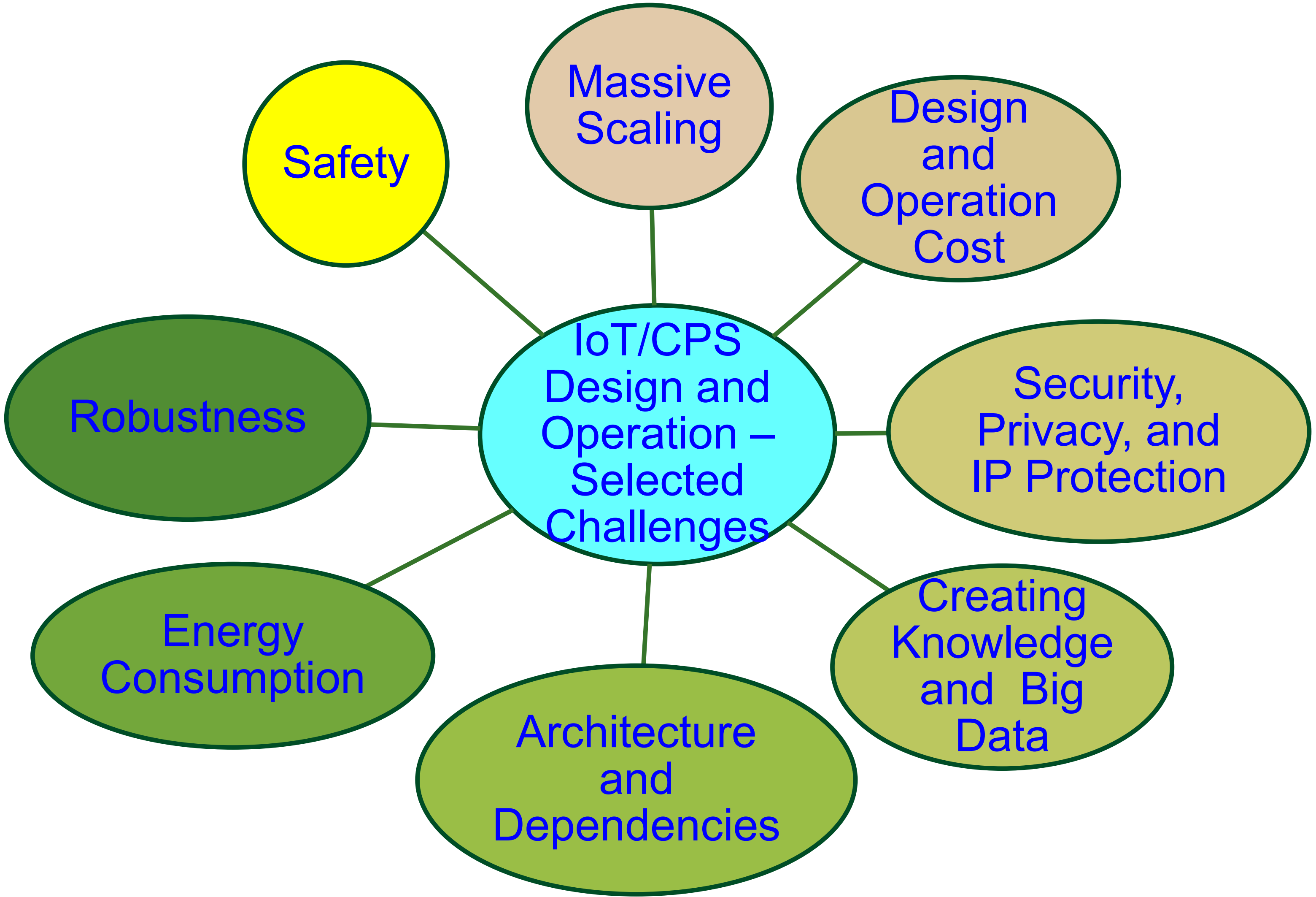


Frost and Sullivan predicts smart healthcare market value to reach US$348.5 billion by 2025.

Source: S. P. Mohanty, Secure IoT by Design, Keynote, 4th IFIP International Internet of Things Conference (IFIP-IoT), 2021, Amsterdam, Netherlands, 5th November 2021.

Smart Healthcare –
Challenges Against Sustainability

CPS – Sustainability Challenges

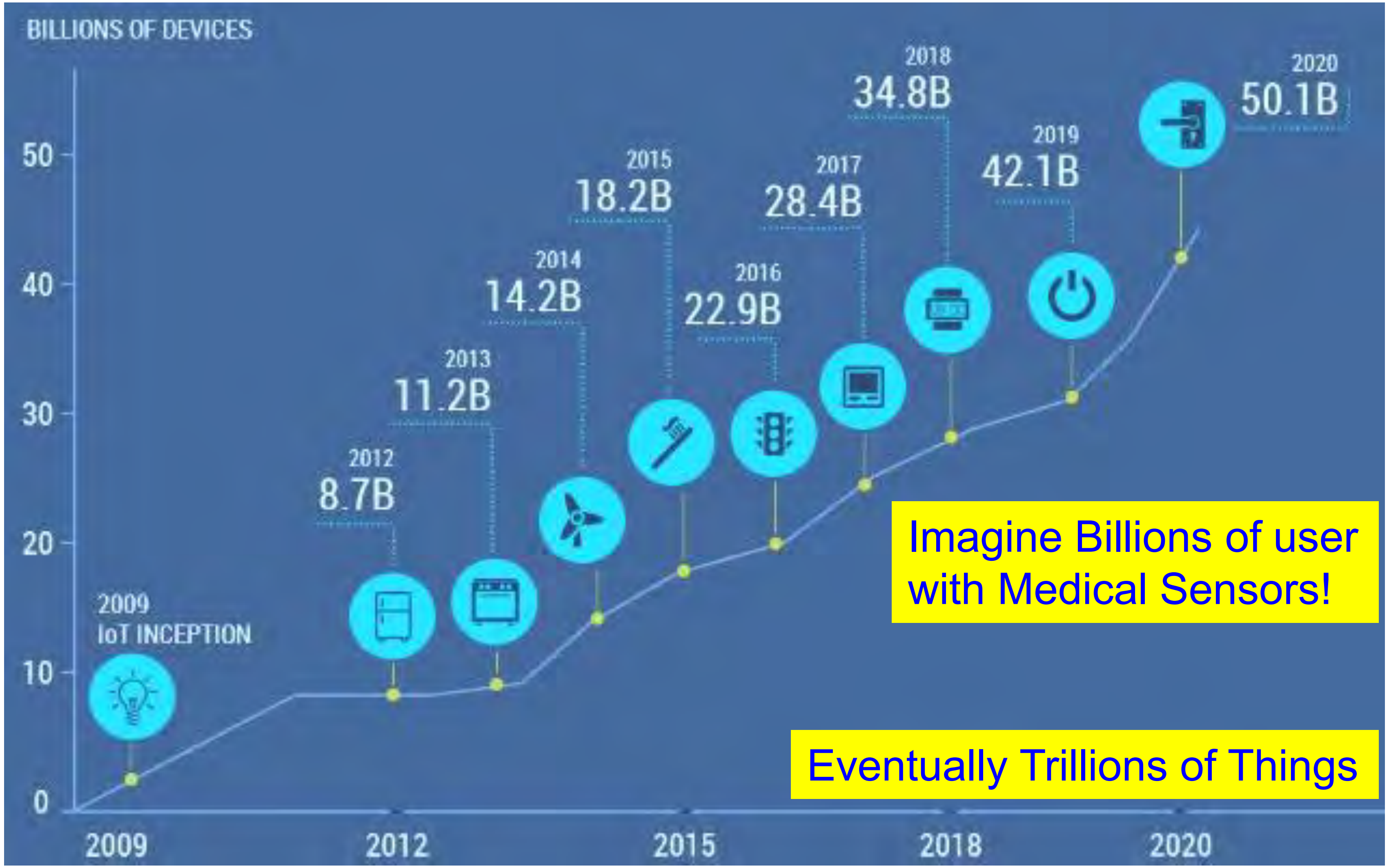


IoT/CPS Design and Operation – Selected Challenges

- Safety
- Massive Scaling
- Design and Operation Cost
- Security, Privacy, and IP Protection
- Creating Knowledge and Big Data
- Architecture and Dependencies
- Energy Consumption
- Robustness

Source: Mohanty ICIT 2017 Keynote

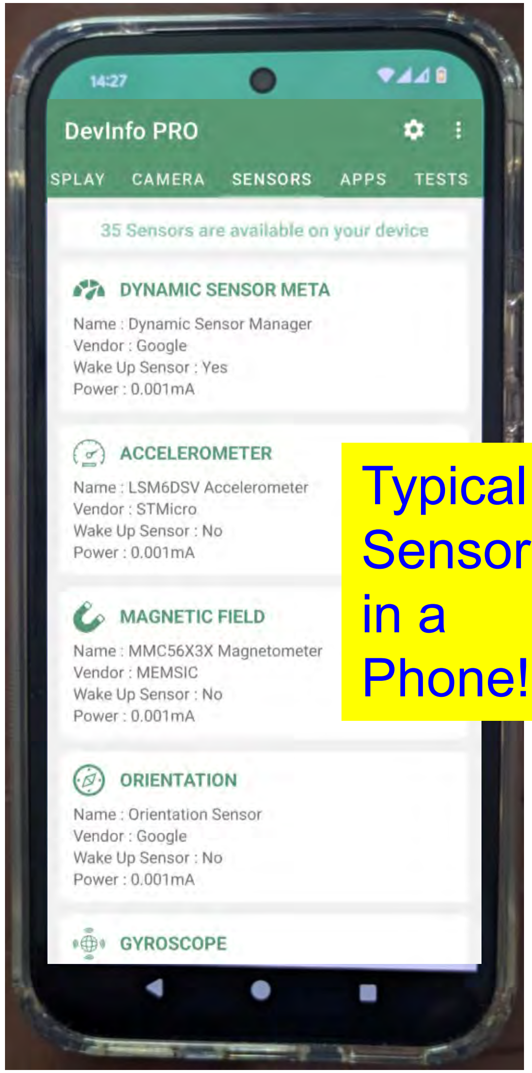
Massive Growth of Sensors/Things



Imagine Billions of user with Medical Sensors!

Eventually Trillions of Things

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



35 Sensors are available on your device

DYNAMIC SENSOR META
Name : Dynamic Sensor Manager
Vendor : Google
Wake Up Sensor : Yes
Power : 0.001mA

ACCELEROMETER
Name : LSM6DSV Accelerometer
Vendor : STMicro
Wake Up Sensor : No
Power : 0.001mA

MAGNETIC FIELD
Name : MMC56X3X Magnetometer
Vendor : MEMSIC
Wake Up Sensor : No
Power : 0.001mA

ORIENTATION
Name : Orientation Sensor
Vendor : Google
Wake Up Sensor : No
Power : 0.001mA

GYROSCOPE

Typical Sensors in a Phone!

Challenges of Data in IoT/CPS are Multifold

Data Curation

Data Cost

Lots of Data

Data Storage

Data Ownership

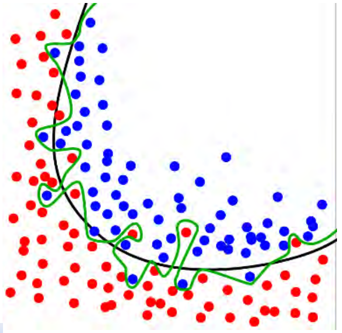
Data Modeling

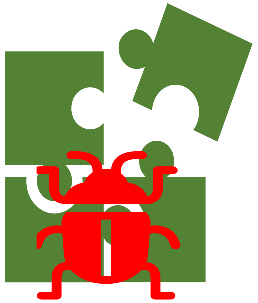
Data Quality

AI/ML Modeling Challenges

Machine Learning Issues

- High Energy Requirements
- High Computational Resource Requirements
- Large Amount of Data Requirements
- Underfitting and Overfitting Issue
- Class Imbalance Issue
- Fake Data Issue
- Attack on Training Process

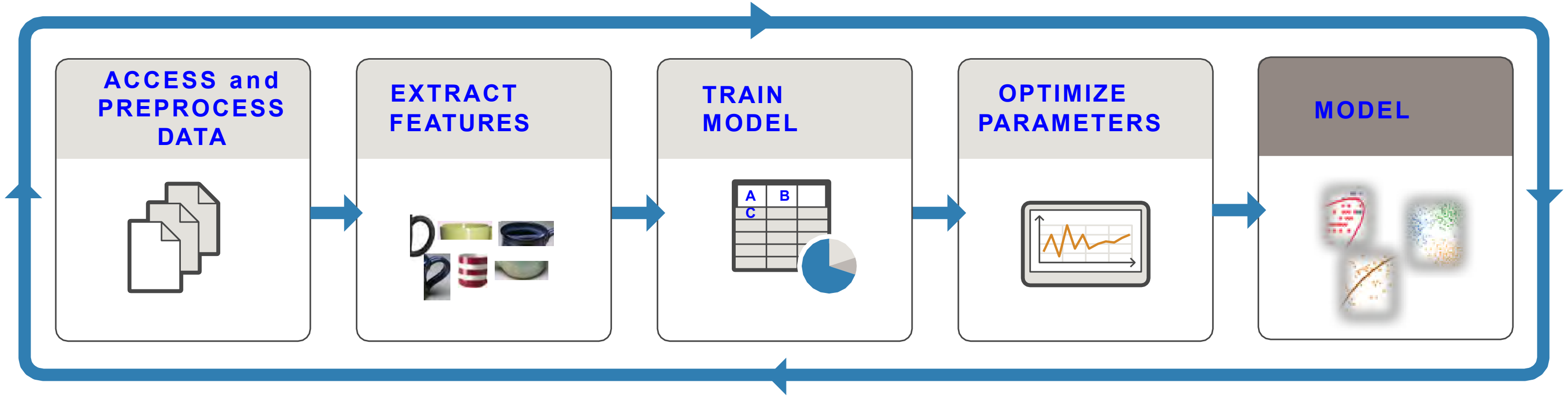




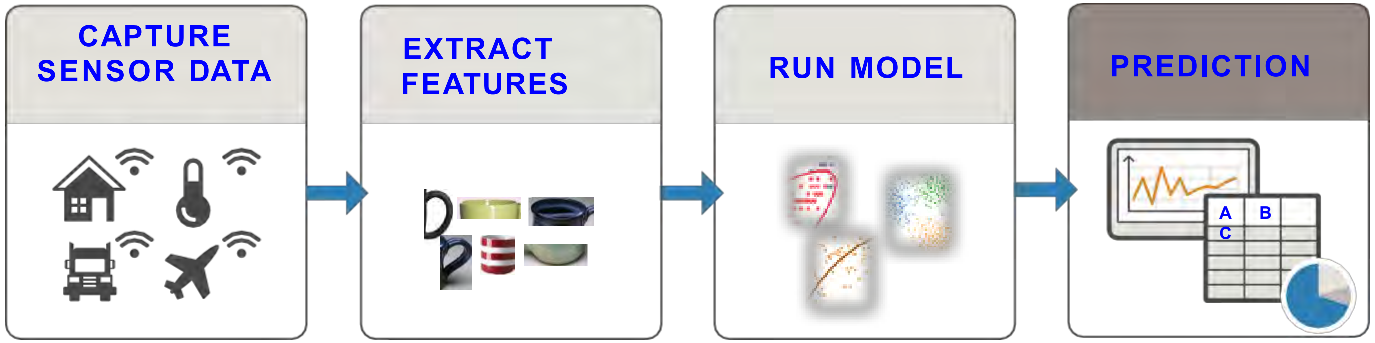
Source: Mohanty ISCT Keynote 2019

Deep Neural Network (DNN) - Resource and Energy Costs

TRAIN: Iterate until you achieve satisfactory performance.



PREDICT: Integrate trained models into applications.



Source: https://www.mathworks.com/campaigns/offers/mastering-machine-learning-with-matlab.html

Needs Significant:

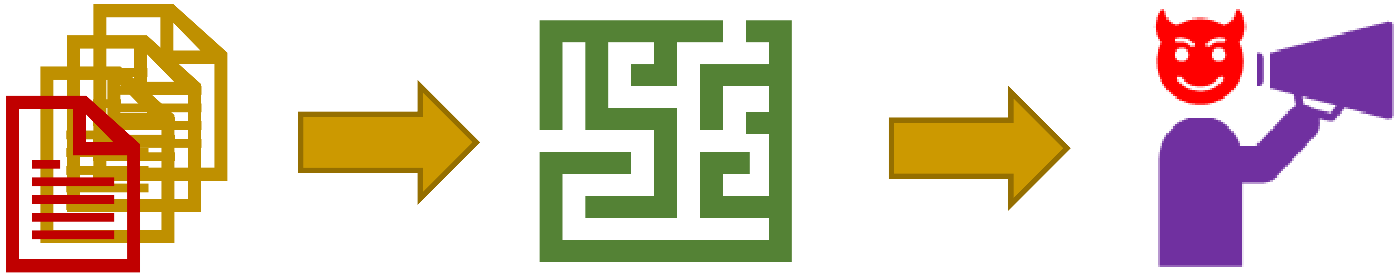
- ➢ Computational Resource
- ➢ Computation Energy

Limited Computational Capability
Limited Battery Life

Needs:

- ➢ Computational Resource
- ➢ Computation Energy

AI/ML – Cybersecurity Issue

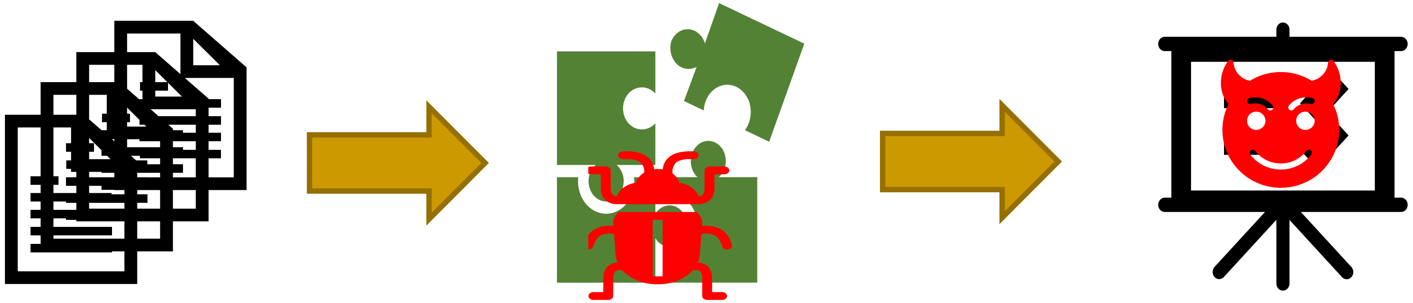


Corrupted Input Dataset

Predictive modelling

Corrupted Decision/ Prediction

Input attack in machine learning



Input Dataset

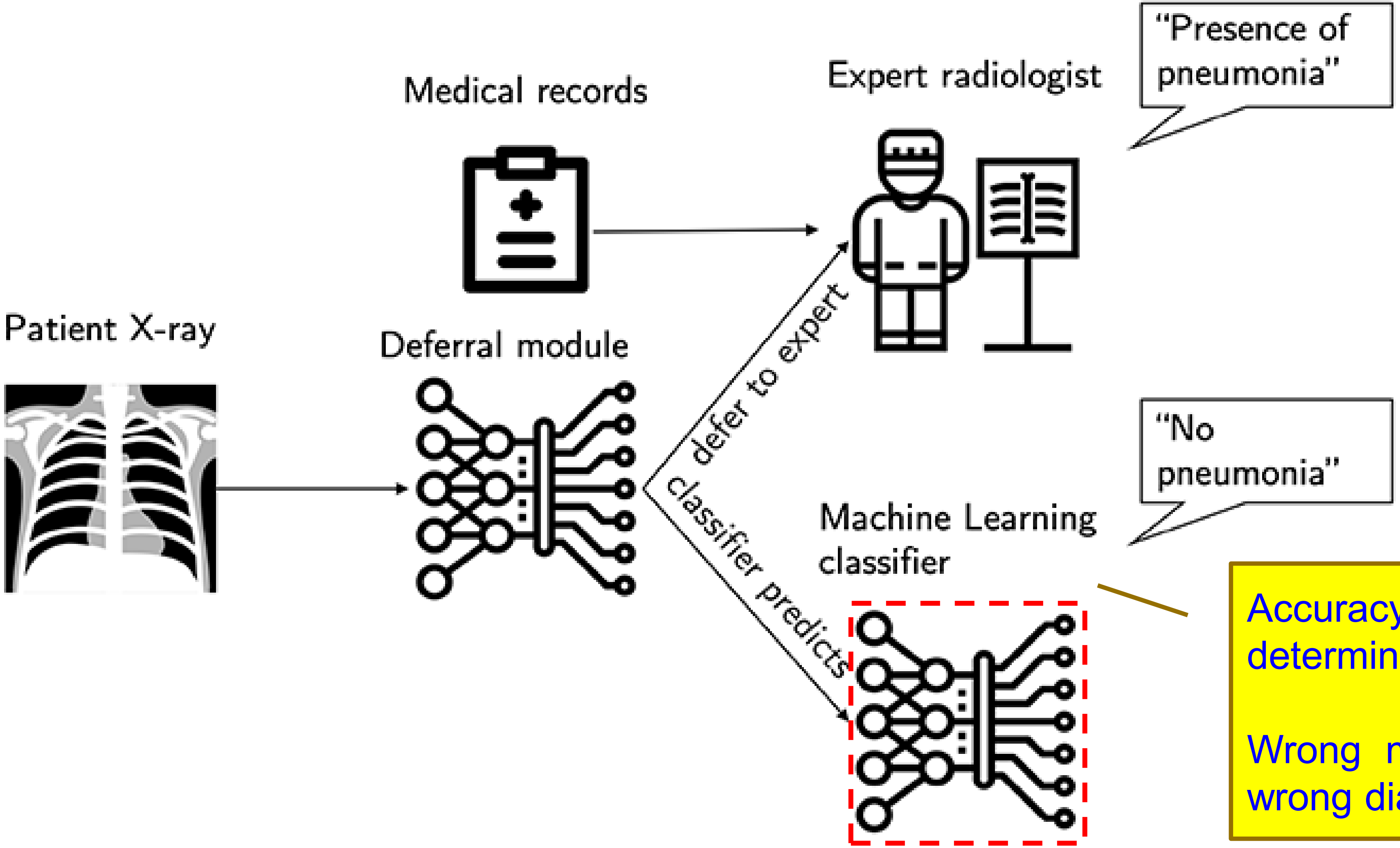
Attacked training Process

Corrupt Classifications

Poisoning attack in training process

Source: D. Puthal, and **S. P. Mohanty**, "Cybersecurity Issues in AI", *IEEE Consumer Electronics Magazine (MCE)*, Vol. 10, No. 4, July 2021, pp. 33--35.

Wrong ML Model → Wrong Diagnosis

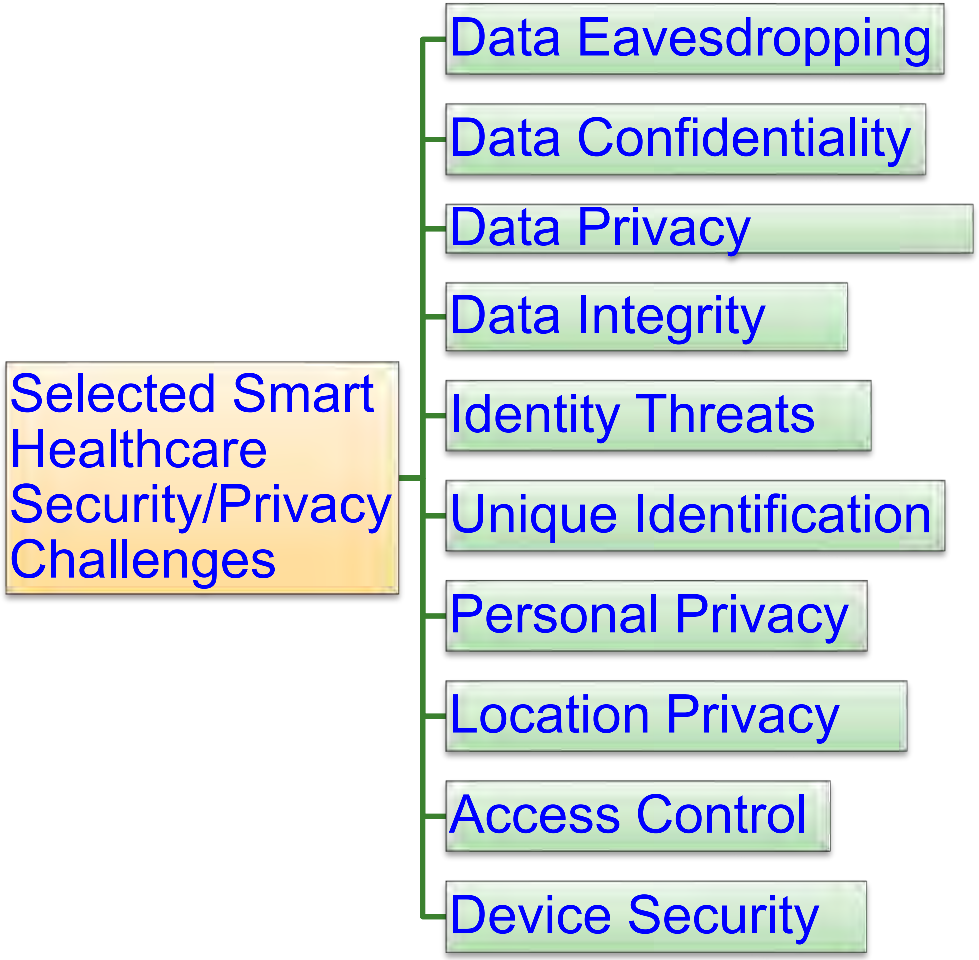


Accuracy is important determine pneumonia

Wrong model can lead to wrong diagnosis altogether

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

Smart Healthcare - Security Challenges

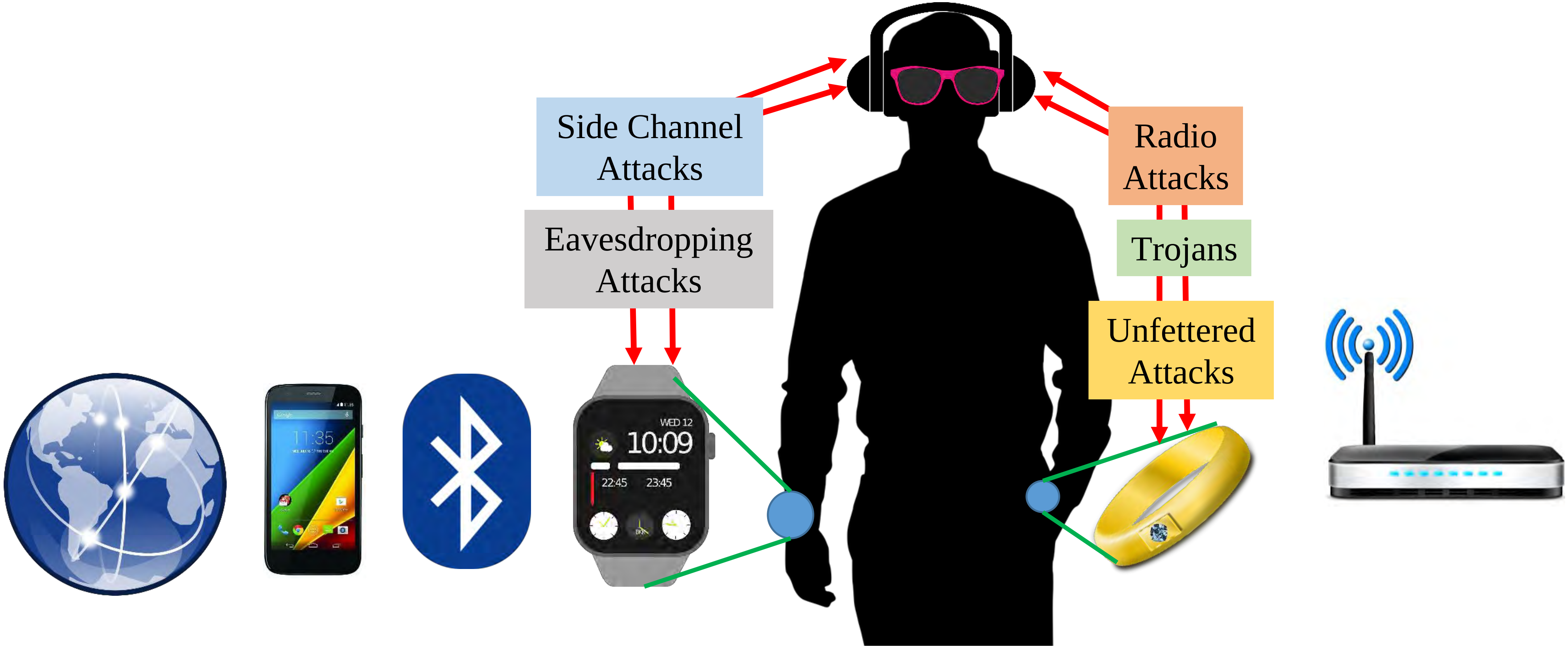


Selected Smart Healthcare Security/Privacy Challenges

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

Source: P. Sundaravadivel, E. Kougianos, S. P. Mohanty, and M. Ganapathiraju, “Everything You Wanted to Know about Smart Health Care”, *IEEE Consumer Electronics Magazine (CEM)*, Volume 7, Issue 1, January 2018, pp. 18-28.

Attacks on Wearable Devices



Side Channel Attacks

Eavesdropping Attacks

Radio Attacks

Trojans

Unfettered Attacks

Implantable Medical Devices - Attacks

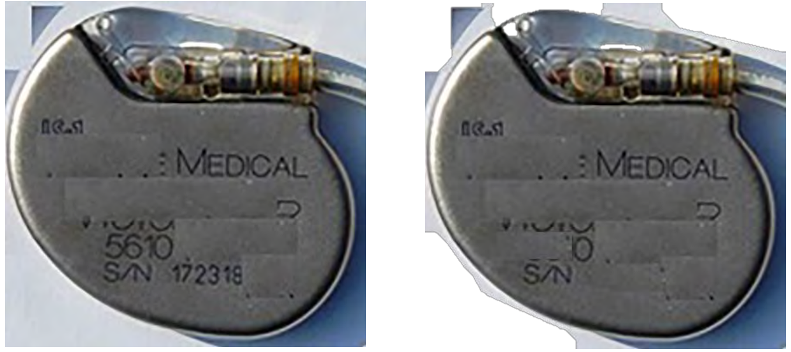
- The vulnerabilities affect implantable cardiac devices and the external equipment used to communicate with them.
- The devices emit RF signals that can be detected up to several meters from the body.
- A malicious individual nearby could conceivably hack into the signal to jam it, alter it, or snoop on it.

Source: Emily Waltz, Can "Internet-of-Body" Thwart Cyber Attacks on Implanted Medical Devices?, *IEEE Spectrum*, 28 Mar 2019, https://spectrum.ieee.org/the-human-os/biomedical/devices/thwart-cyber-attacks-on-implanted-medical-devices.amp.html.

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

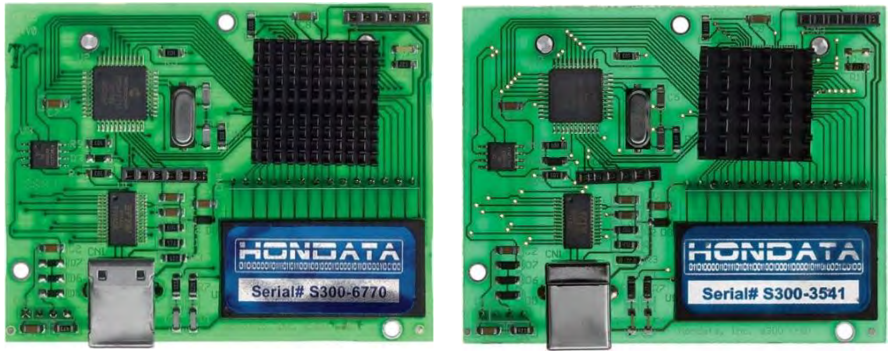
AI can be fooled by fake data

AI can create fake data (Deepfake)



Authentic Fake

An implantable medical device



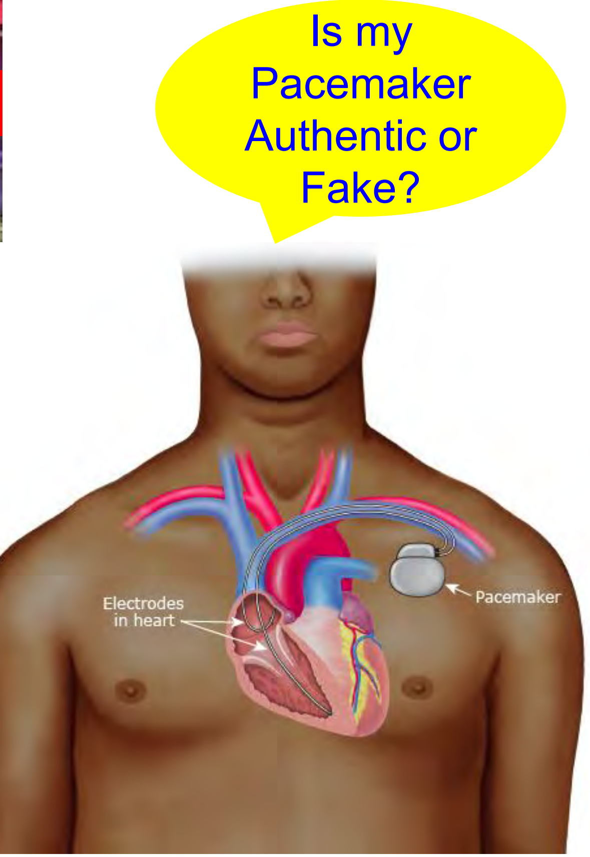
Authentic Fake

A plug-in for car-engine computers

Fake is Cheap – Why not Buy?

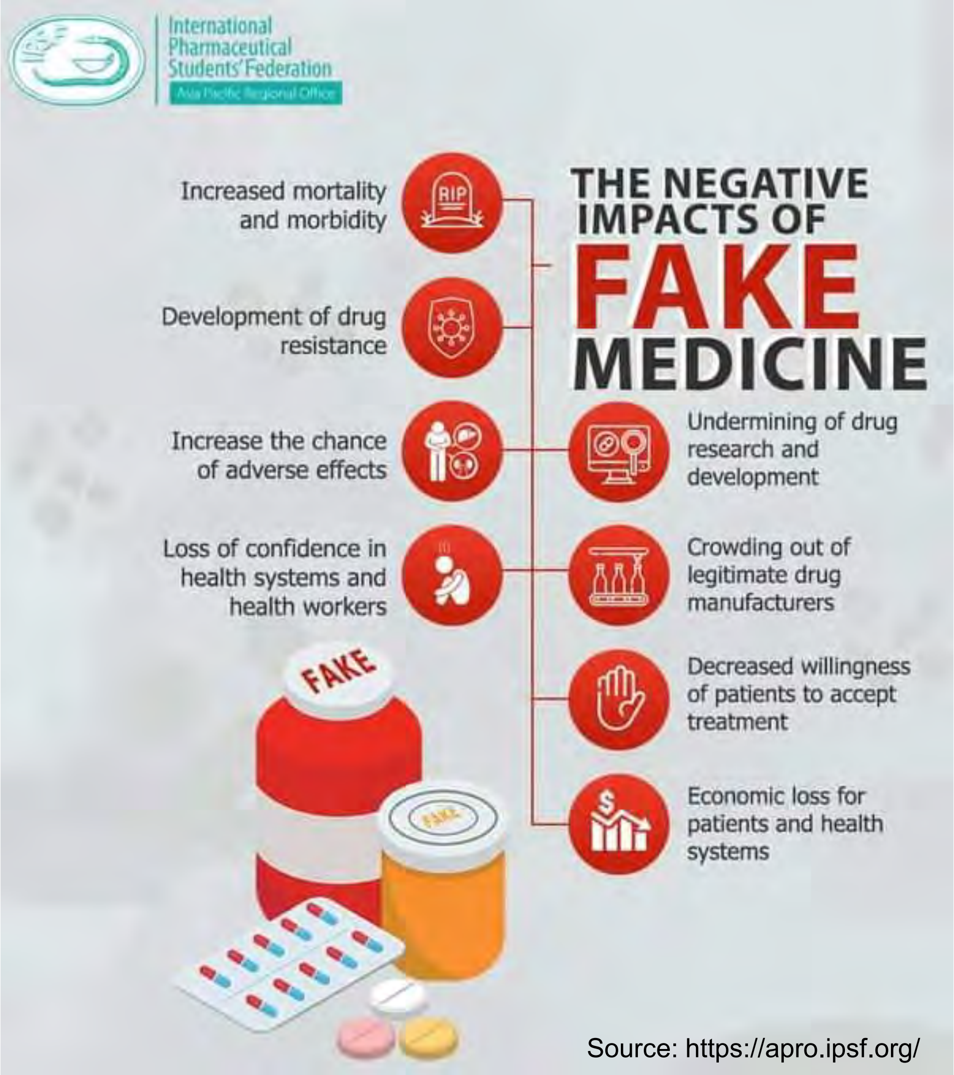
Fake ECU Inside

Source: https://www.quora.com



Fake battery inside

Source: https://nypost.com/



International Pharmaceutical Students' Federation
Asia Pacific Regional Office

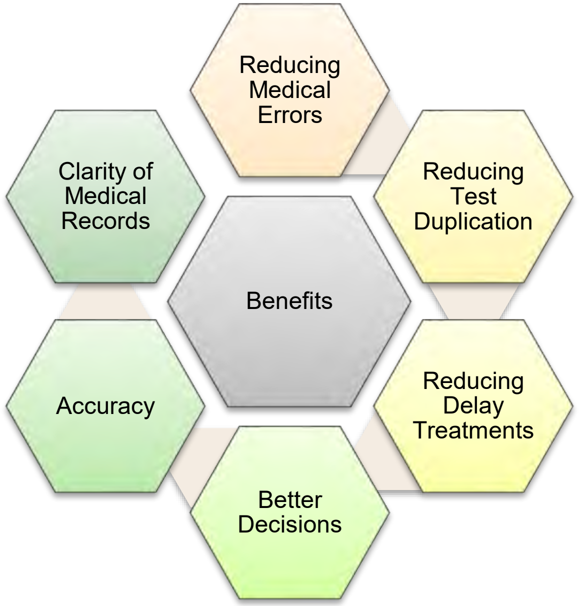
THE NEGATIVE IMPACTS OF FAKE MEDICINE

- Increased mortality and morbidity
- Development of drug resistance
- Increase the chance of adverse effects
- Loss of confidence in health systems and health workers
- Undermining of drug research and development
- Crowding out of legitimate drug manufacturers
- Decreased willingness of patients to accept treatment
- Economic loss for patients and health systems

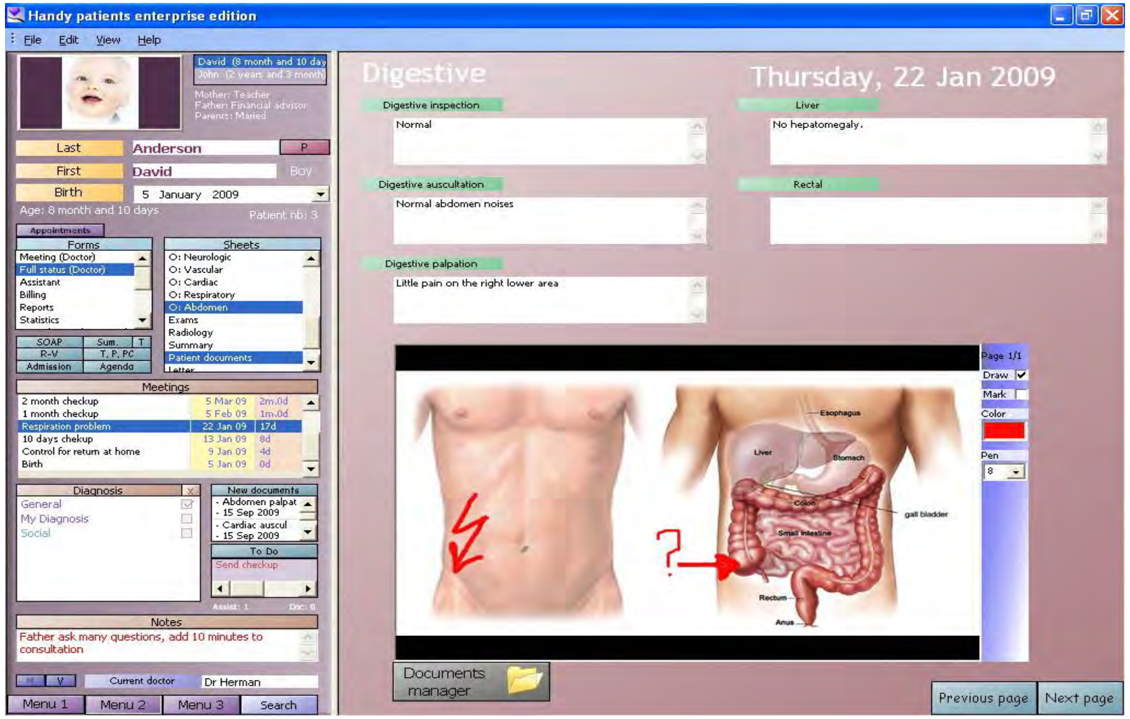
Source: https://apro.ipsf.org/

Electronic Health Records (EHR's)

- Electronic Health Record (EHR) is an electronic version of patient medical history maintained by the provider
- Contains demographics, progress notes, problems, medications, and other administrative information



Reducing Medical Errors
Reducing Test Duplication
Reducing Delay Treatments
Better Decisions
Accuracy
Clarity of Medical Records
Benefits



David (8 month and 10 day
John (2 years and 3 month)

Mother: Teacher
Father: Financial advisor
Parents: Maried

Last: Anderson P
First: David Boy
Birth: 5 January 2009
Age: 8 month and 10 days
Patient nb: 3

Forms: Meeting (Doctor), Full status (Doctor), Assistant, Billing, Reports, Statistics

Sheets: O: Neurologic, O: Vascular, O: Cardiac, O: Respiratory, O: Abdomen, Exams, Radiology, Summary, Patient documents, Letter

Meetings

2 month checkup	5 Mar 09	2m.0d
1 month checkup	5 Feb 09	1m.0d
Respiration problem	22 Jan 09	17d
10 days chekup	13 Jan 09	8d
Control for return at home	9 Jan 09	4d
Birth	5 Jan 09	0d

Diagnosis
General ☑
My Diagnosis □
Social □

New documents
- Abdomen palpat
- 15 Sep 2009
- Cardiac auscul
- 15 Sep 2009

To Do
Send checkup

Assist: 1 Doc: 0

Notes
Father ask many questions, add 10 minutes to consultation

Current doctor: Dr Herman

Digestive

Thursday, 22 Jan 2009

Digestive inspection: Normal

Liver: No hepatomegaly.

Digestive auscultation: Normal abdomen noises

Rectal:

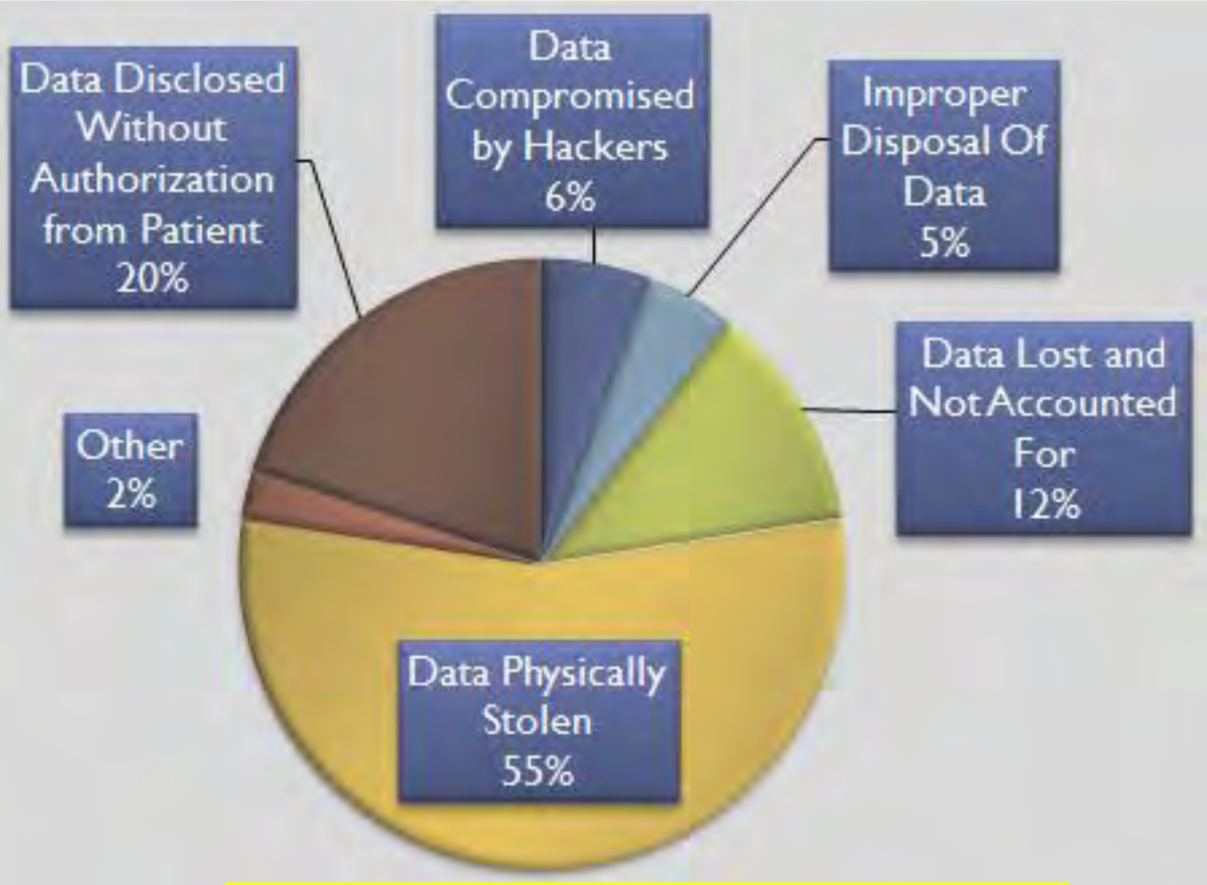
Digestive palpation: Little pain on the right lower area

Image Source: DaCarpenther, An electronic medical record example, Handy patients electronic medical record (free open-source version)

Health Insurance Portability and Accountability Act (HIPPA)

HIPAA

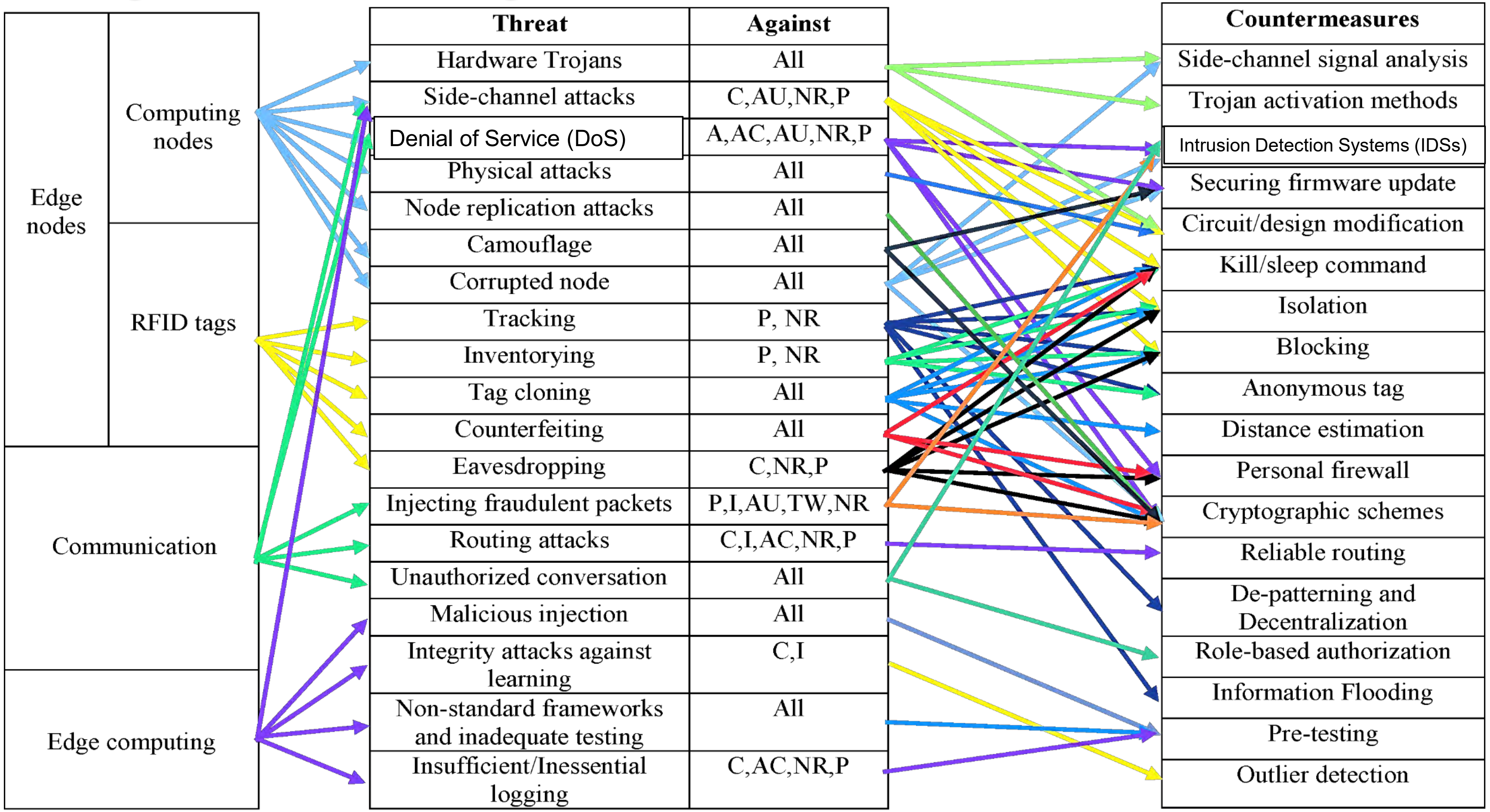
Health Insurance Portability and Accountability Act



HIPPA Privacy Violation by Types

Cybrsecurity Solution for IoT/CPS

IoT Cybersecurity - Attacks and Countermeasures



Edge nodes	Computing nodes
	RFID tags
Communication	
Edge computing	

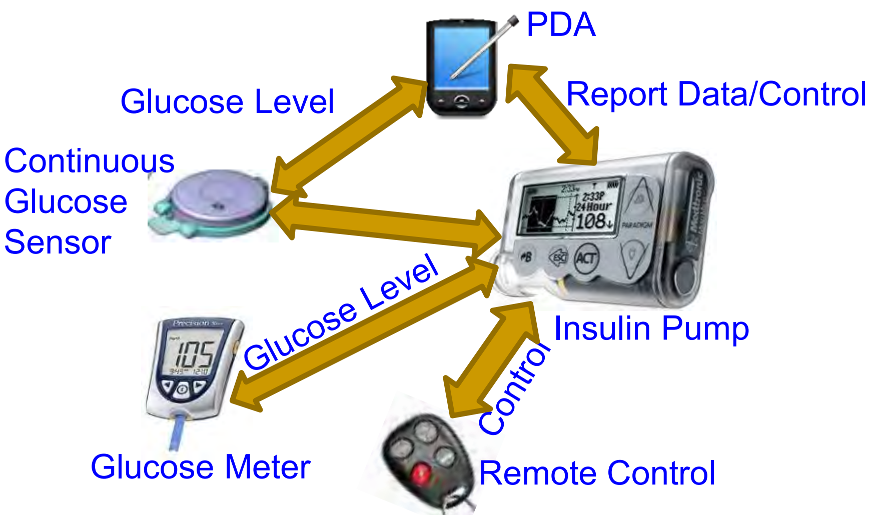
Threat	Against
Hardware Trojans	All
Side-channel attacks	C,AU,NR,P
Denial of Service (DoS)	A,AC,AU,NR,P
Physical attacks	All
Node replication attacks	All
Camouflage	All
Corrupted node	All
Tracking	P, NR
Inventorying	P, NR
Tag cloning	All
Counterfeiting	All
Eavesdropping	C,NR,P
Injecting fraudulent packets	P,I,AU,TW,NR
Routing attacks	C,I,AC,NR,P
Unauthorized conversation	All
Malicious injection	All
Integrity attacks against learning	C,I
Non-standard frameworks and inadequate testing	All
Insufficient/Inessential logging	C,AC,NR,P

Countermeasures
Side-channel signal analysis
Trojan activation methods
Intrusion Detection Systems (IDSs)
Securing firmware update
Circuit/design modification
Kill/sleep command
Isolation
Blocking
Anonymous tag
Distance estimation
Personal firewall
Cryptographic schemes
Reliable routing
De-patterning and Decentralization
Role-based authorization
Information Flooding
Pre-testing
Outlier detection

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.

Smart Healthcare Cybersecurity



PDA

Glucose Level

Report Data/Control

Continuous Glucose Sensor

Glucose Level

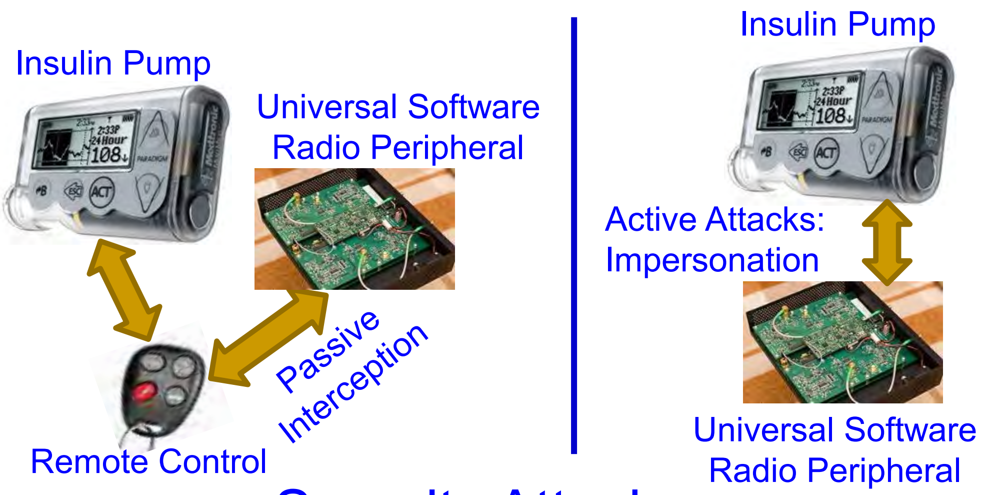
Insulin Pump

Control

Glucose Meter

Remote Control

Insulin Delivery System



Insulin Pump

Universal Software Radio Peripheral

Passive Interception

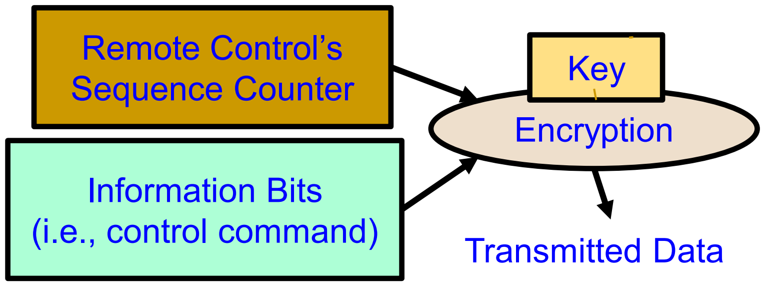
Remote Control

Insulin Pump

Active Attacks: Impersonation

Universal Software Radio Peripheral

Security Attacks



Remote Control's Sequence Counter

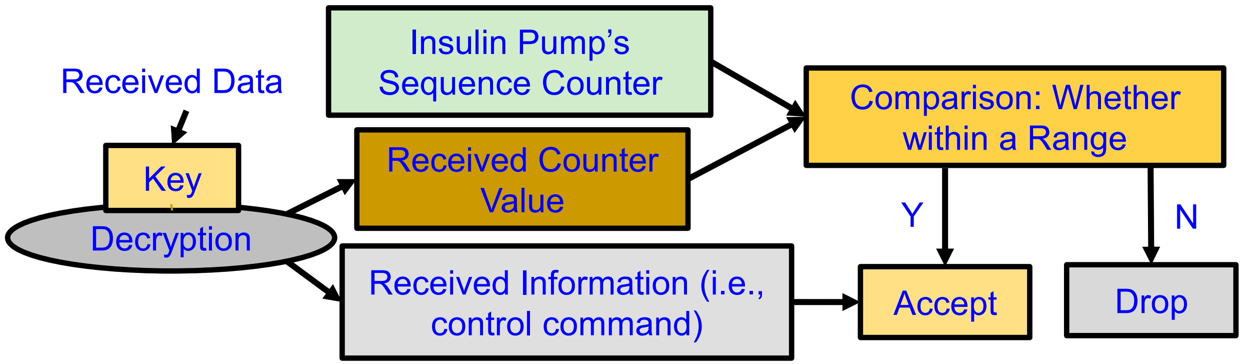
Key

Encryption

Information Bits (i.e., control command)

Transmitted Data

Rolling Code Encoder in Remote Control



Received Data

Insulin Pump's Sequence Counter

Key

Decryption

Received Counter Value

Comparison: Whether within a Range

Y

N

Received Information (i.e., control command)

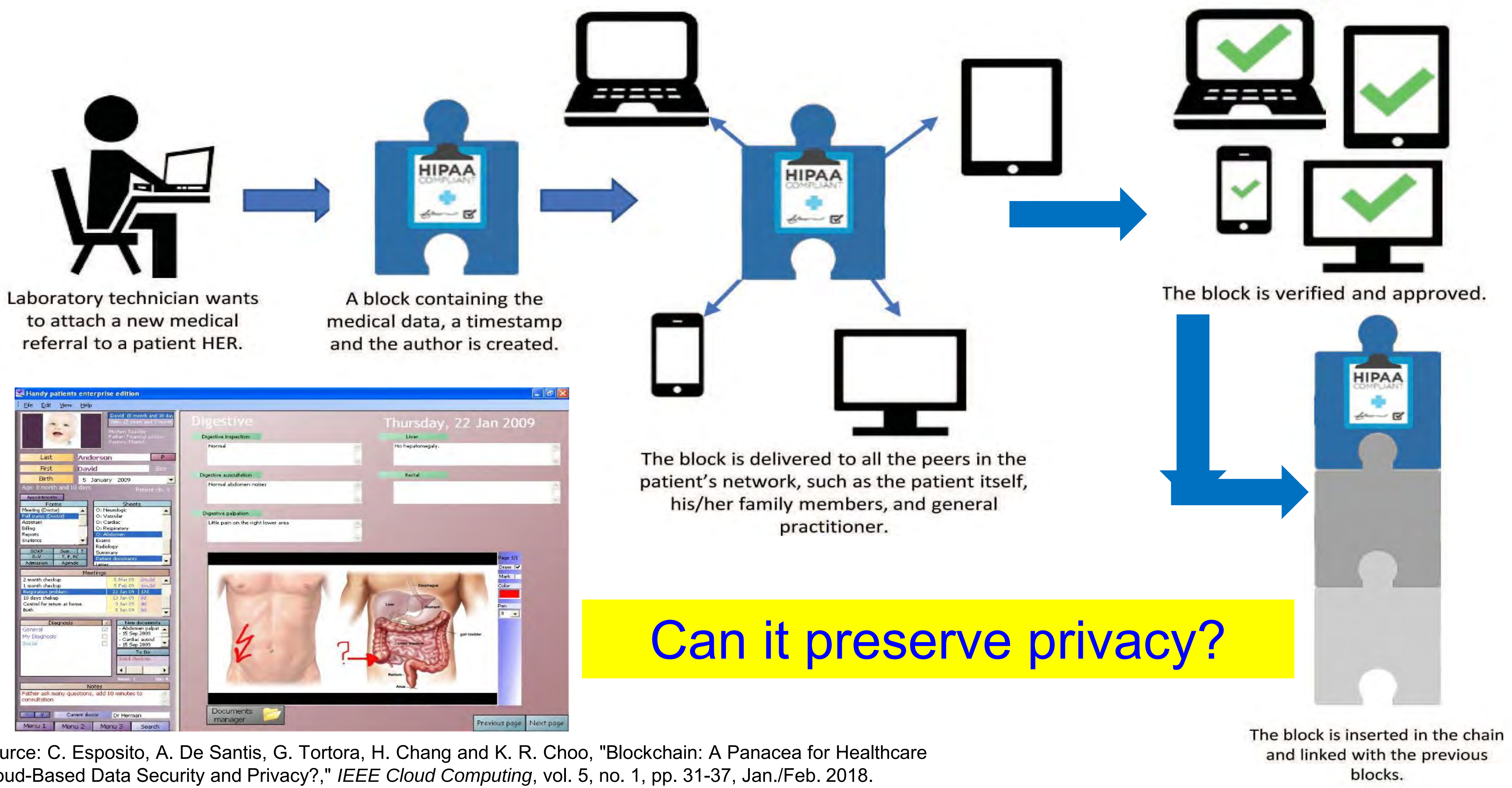
Accept

Drop

Rolling Code Decoder in Insulin Pump

Source: Li and Jha 2011: HEALTH 2011

Blockchain in Smart Healthcare



Laboratory technician wants to attach a new medical referral to a patient HER.

A block containing the medical data, a timestamp and the author is created.

The block is delivered to all the peers in the patient's network, such as the patient itself, his/her family members, and general practitioner.

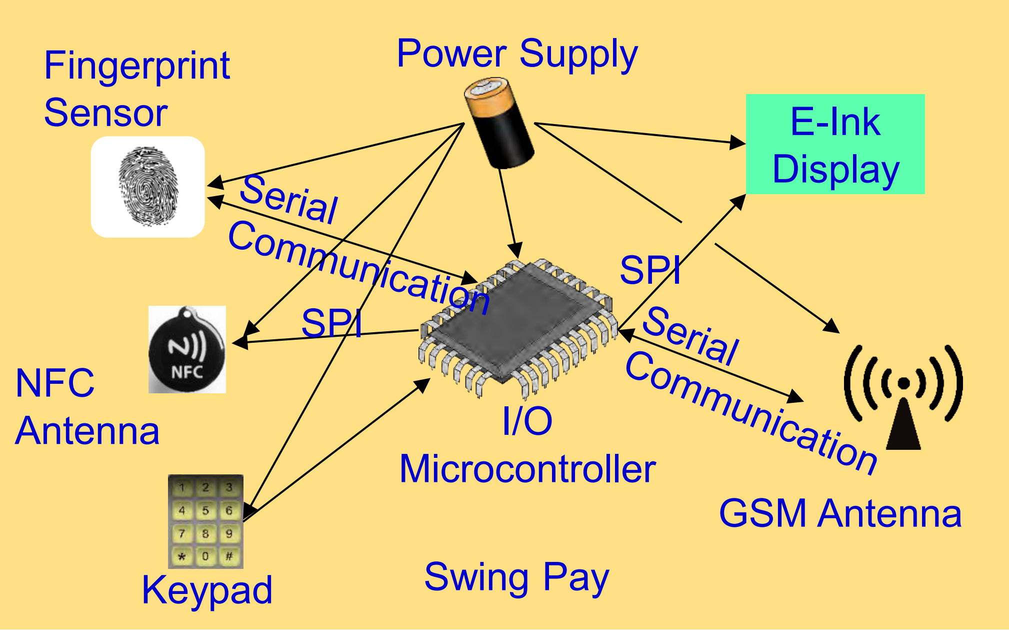
The block is verified and approved.

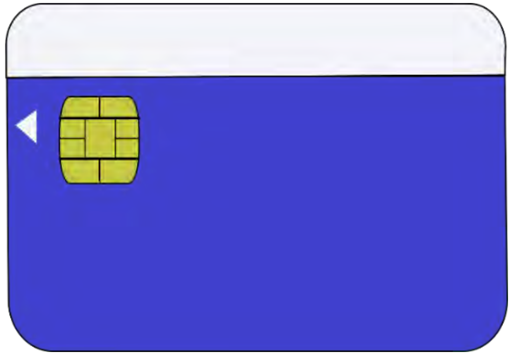
The block is inserted in the chain and linked with the previous blocks.

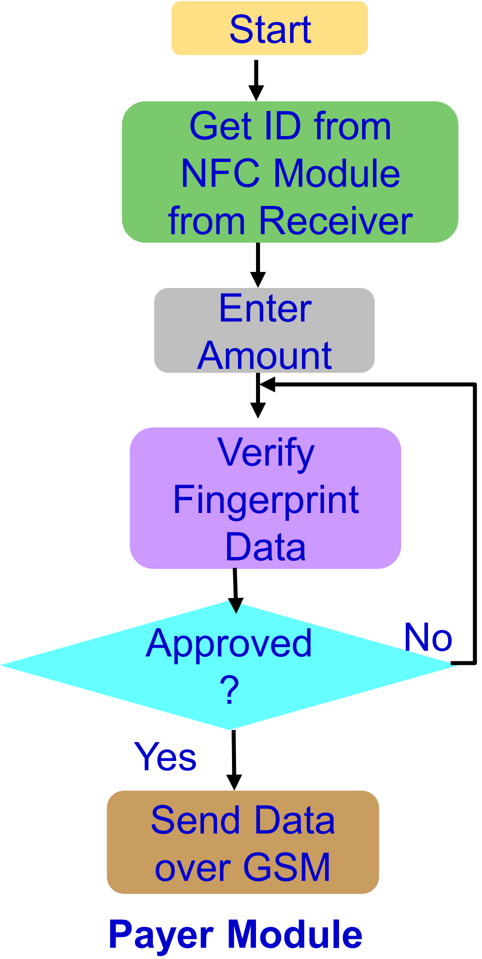
Can it preserve privacy?

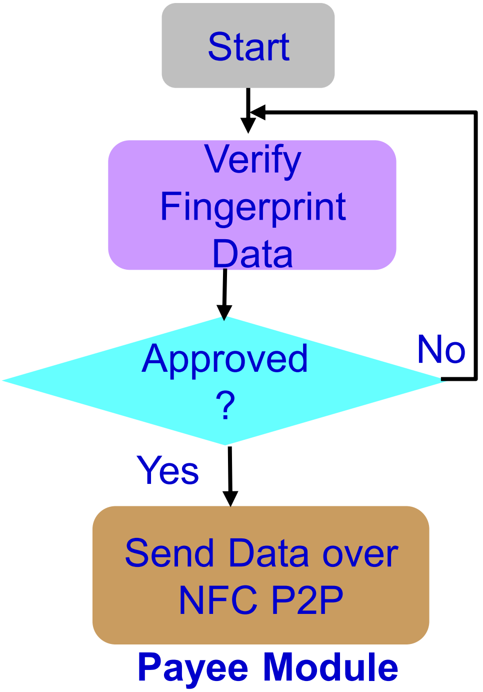
Source: C. Esposito, A. De Santis, G. Tortora, H. Chang and K. R. Choo, "Blockchain: A Panacea for Healthcare Cloud-Based Data Security and Privacy?," *IEEE Cloud Computing*, vol. 5, no. 1, pp. 31-37, Jan./Feb. 2018.

Our Swing-Pay - NFC Cybersecurity Solution



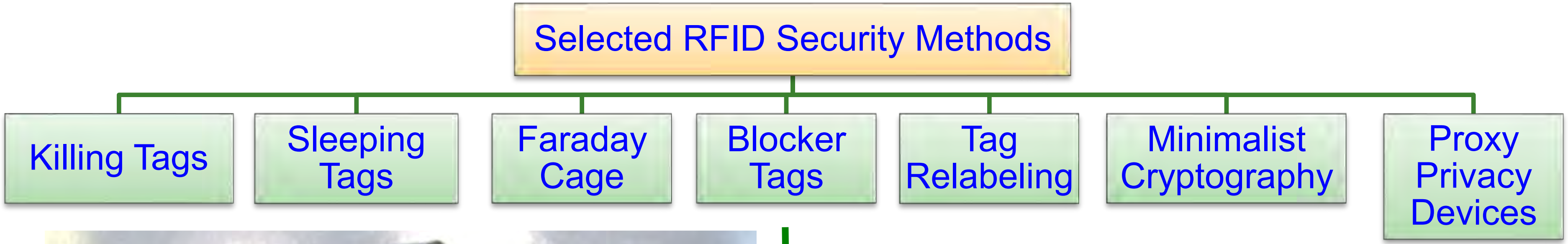






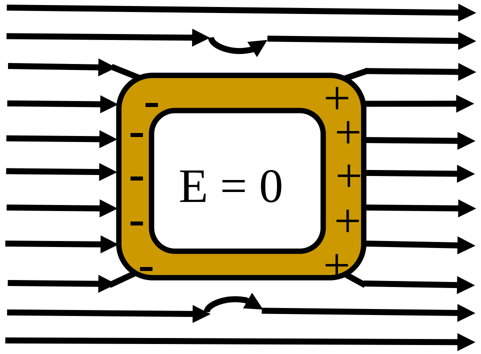
Source: S. Ghosh, J. Goswami, A. Majumder, A. Kumar, **S. P. Mohanty**, and B. K. Bhattacharyya, "Swing-Pay: One Card Meets All User Payment and Identity Needs", *IEEE Consumer Electronics Magazine (MCE)*, Volume 6, Issue 1, January 2017, pp. 82--93.

RFID Cybersecurity - Solutions

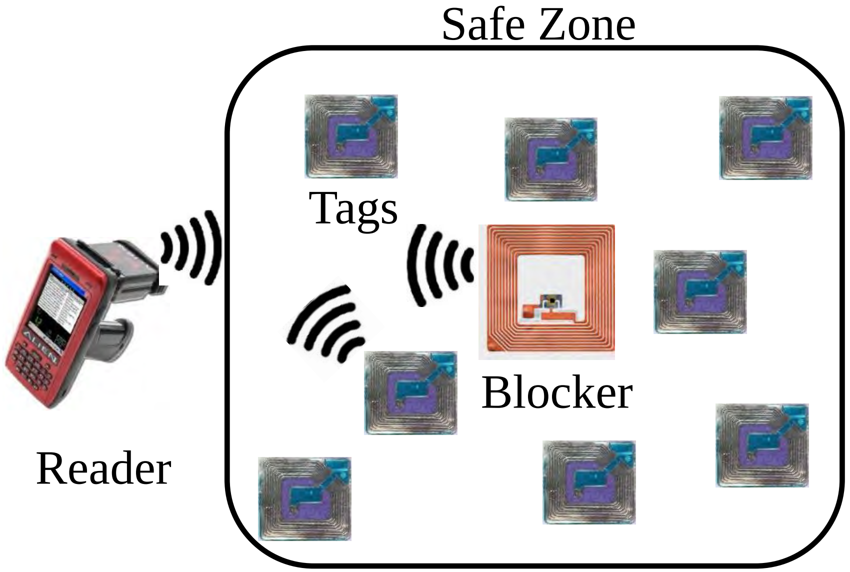


Selected RFID Security Methods

- Killing Tags
- Sleeping Tags
- Faraday Cage
- Blocker Tags
- Tag Relabeling
- Minimalist Cryptography
- Proxy Privacy Devices



Faraday Cage



Blocker Tags

Source: Khattab 2017, Springer 2017 RFID Security

Drawbacks of Existing Cybersecurity Solutions

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

IT Cybersecurity

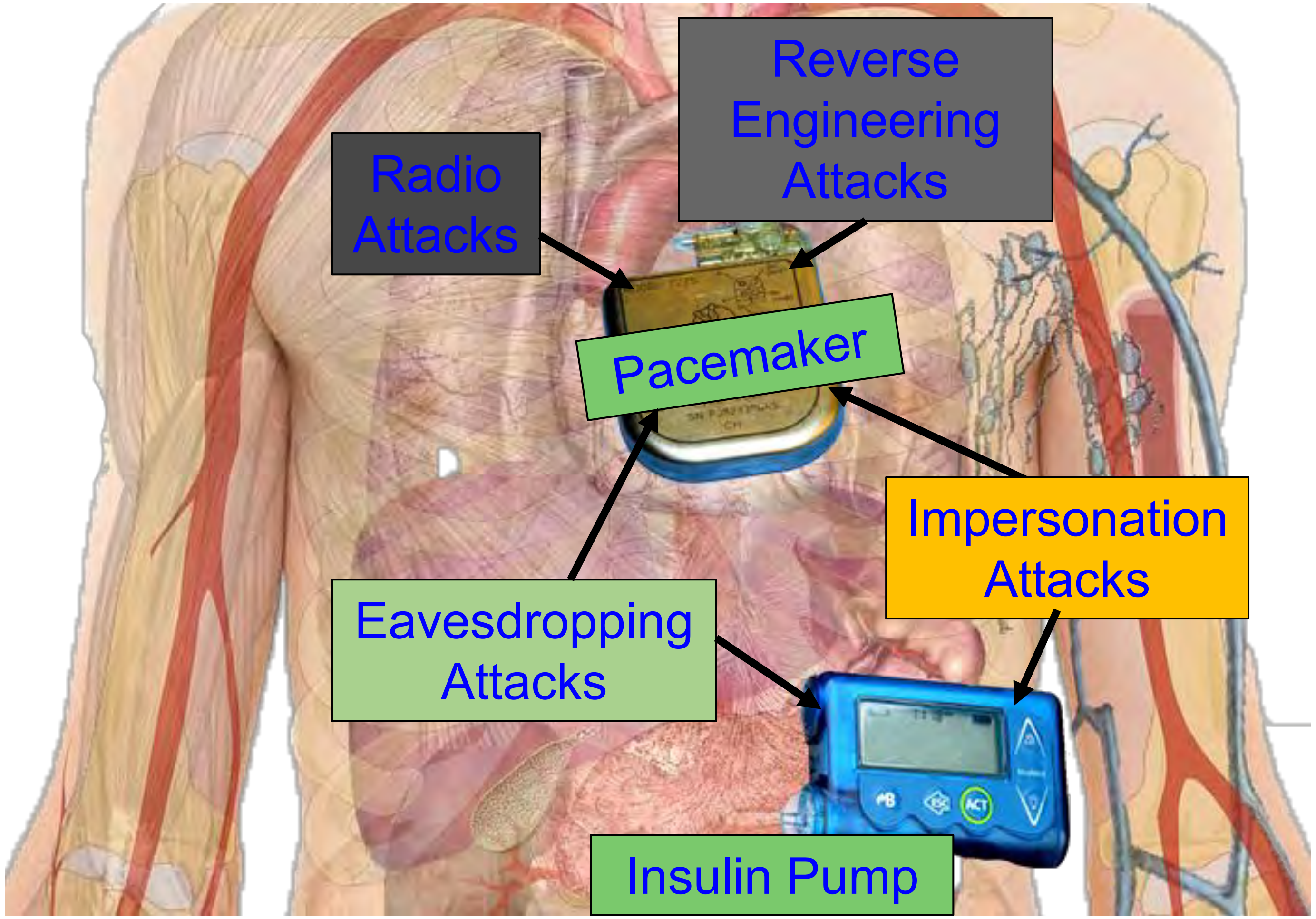
- IT infrastructure may be well protected rooms
- Limited variety of IT network devices
- Millions of IT devices
- Significant computational power to run heavy-duty security solutions
- IT security breach can be costly

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.

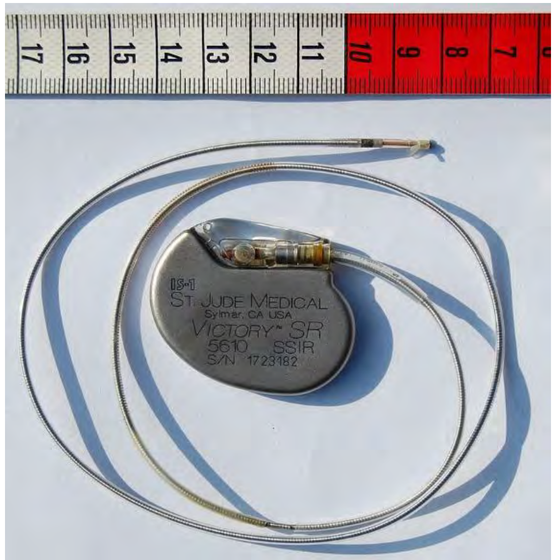
Cybersecurity Measures in Healthcare Cyber-Physical Systems is Hard



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

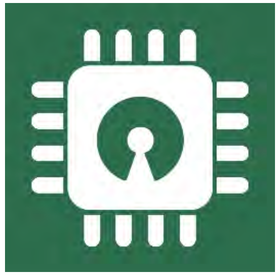
- Implantable Medical Devices (IMDs) have integrated battery to provide energy to all their functions → Limited Battery Life depending on functions
- Higher battery/energy usage → Lower IMD lifetime
- Battery/IMD replacement → Needs surgical risky procedures

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

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

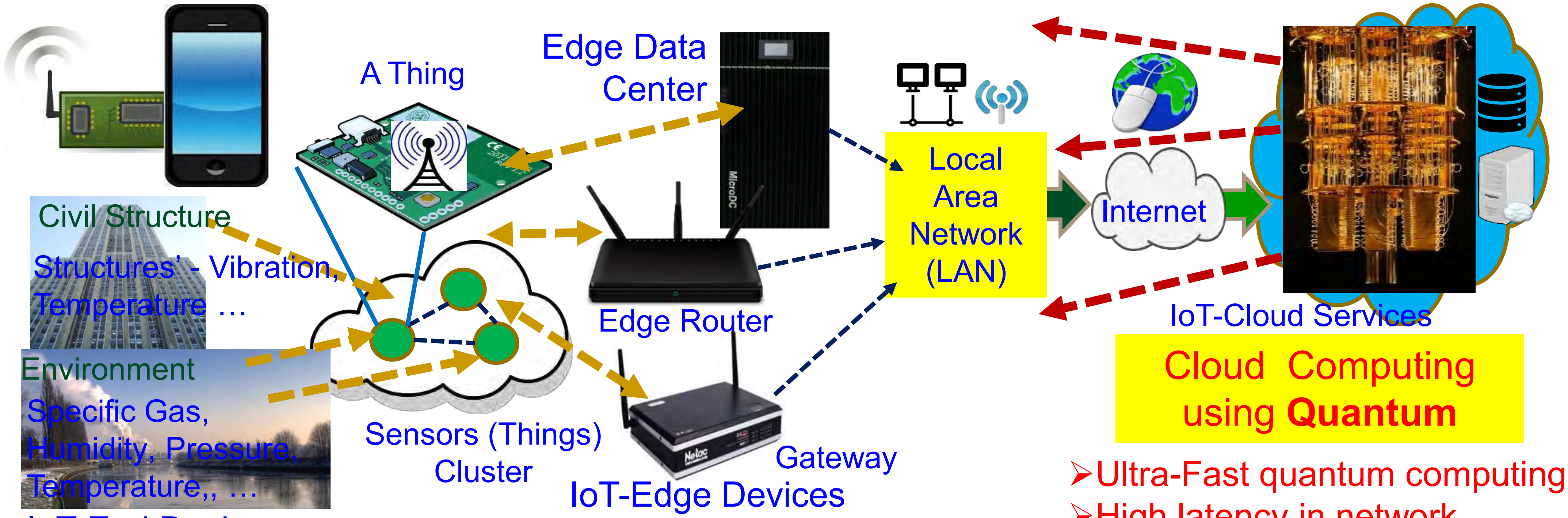
- Introduces latency in operation
- Flexible - Easy to use, upgrade and update
- Wider-Use - Use for all devices in an organization
- Higher recurring operational cost
- Tasks of encryption easy compared to hardware – substitution tables
- Needs general purpose processor
- Can’t stop hardware reverse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



A Thing

Edge Data Center

Local Area Network (LAN)

Internet

IoT-Cloud Services

Civil Structure

Structures' - Vibration, Temperature …

Environment

Specific Gas, Humidity, Pressure, Temperature,, …

Sensors (Things) Cluster

Edge Router

Gateway

IoT-Edge Devices

IoT-End Devices

In-Sensor/End-Device Computing

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

Edge Computing

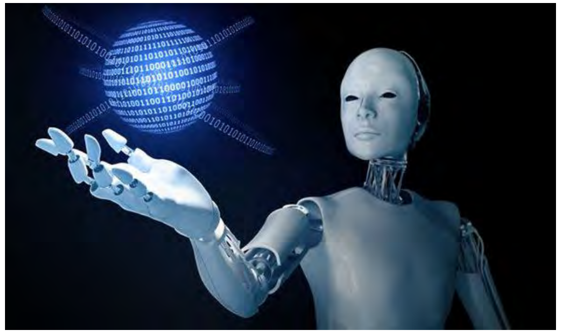
- Less computational resource
- Minimal latency in network
- Lightweight security

Cloud Computing using **Quantum**

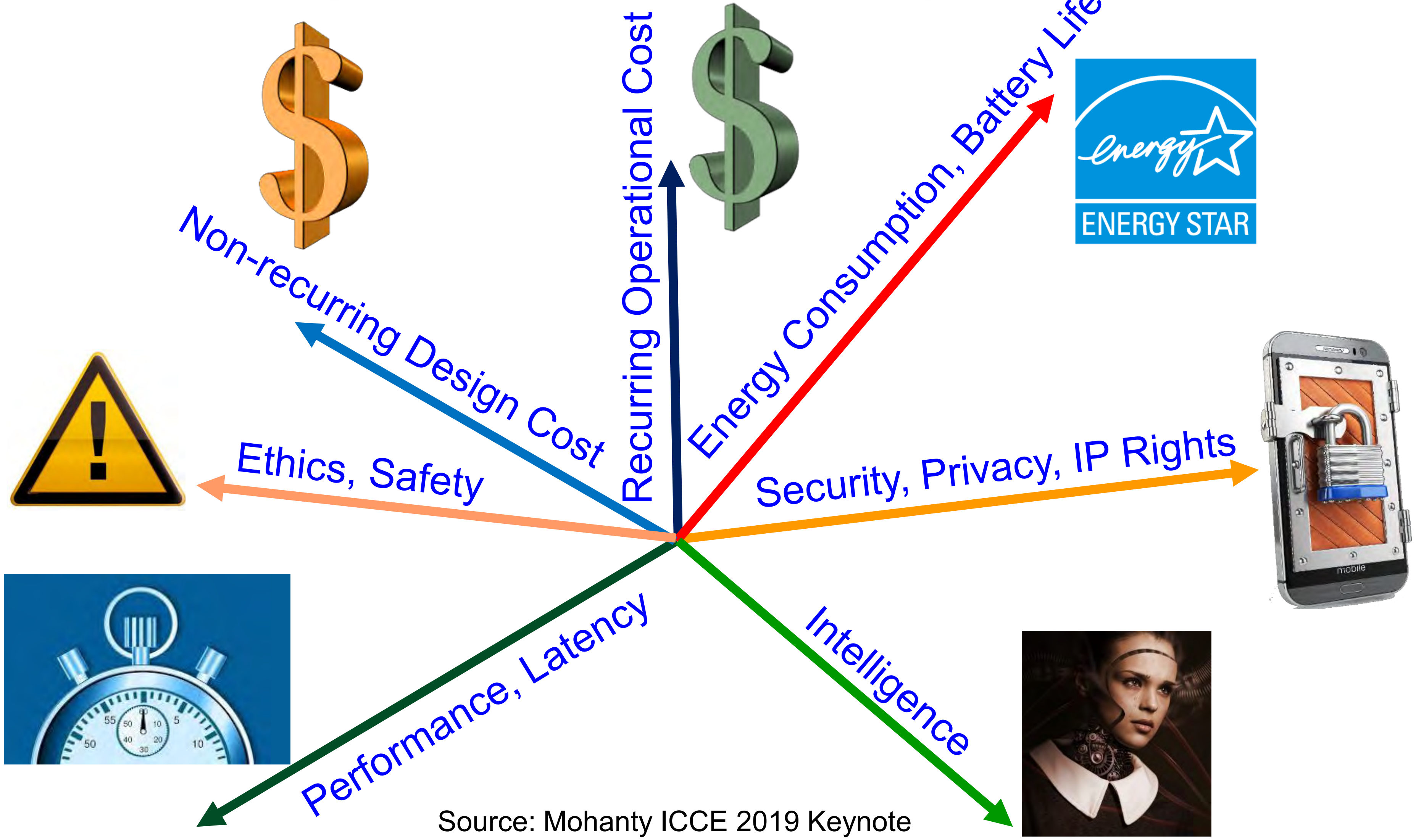
- Ultra-Fast quantum computing resources
- High latency in network
- Breaks every encryption in no time

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

Security-by-Design (SbD) – The Principle



CPS Design - Multiple Objectives for Sustainability



Recurring Operational Cost

Energy Consumption, Battery Life

Non-recurring Design Cost

Ethics, Safety

Security, Privacy, IP Rights

Performance, Latency

Intelligence

Source: Mohanty ICCE 2019 Keynote

Smart Cities
Vs
Smart Villages

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

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

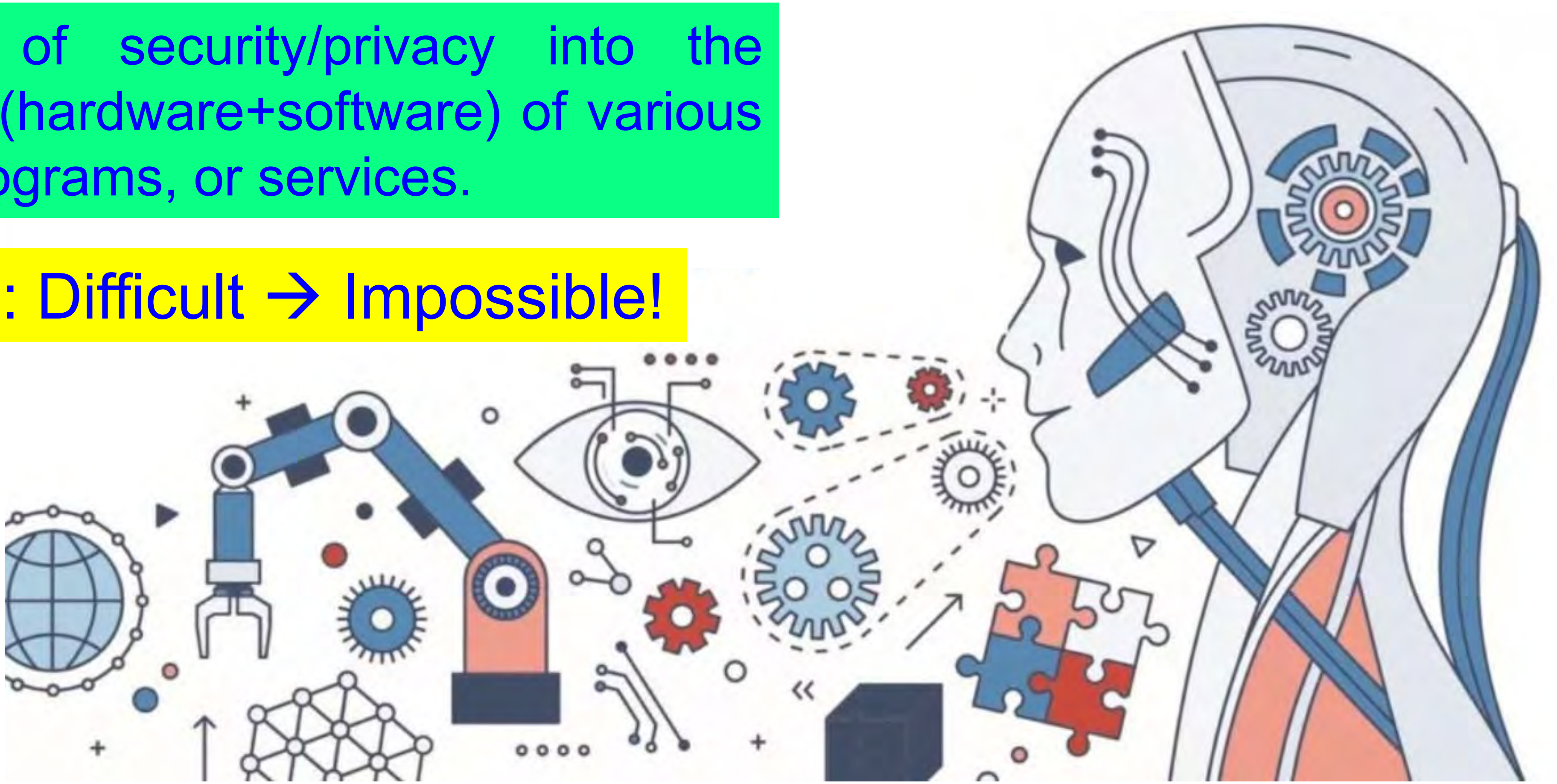
aka

Secure by Design (SbD)

Security by Design (SbD)

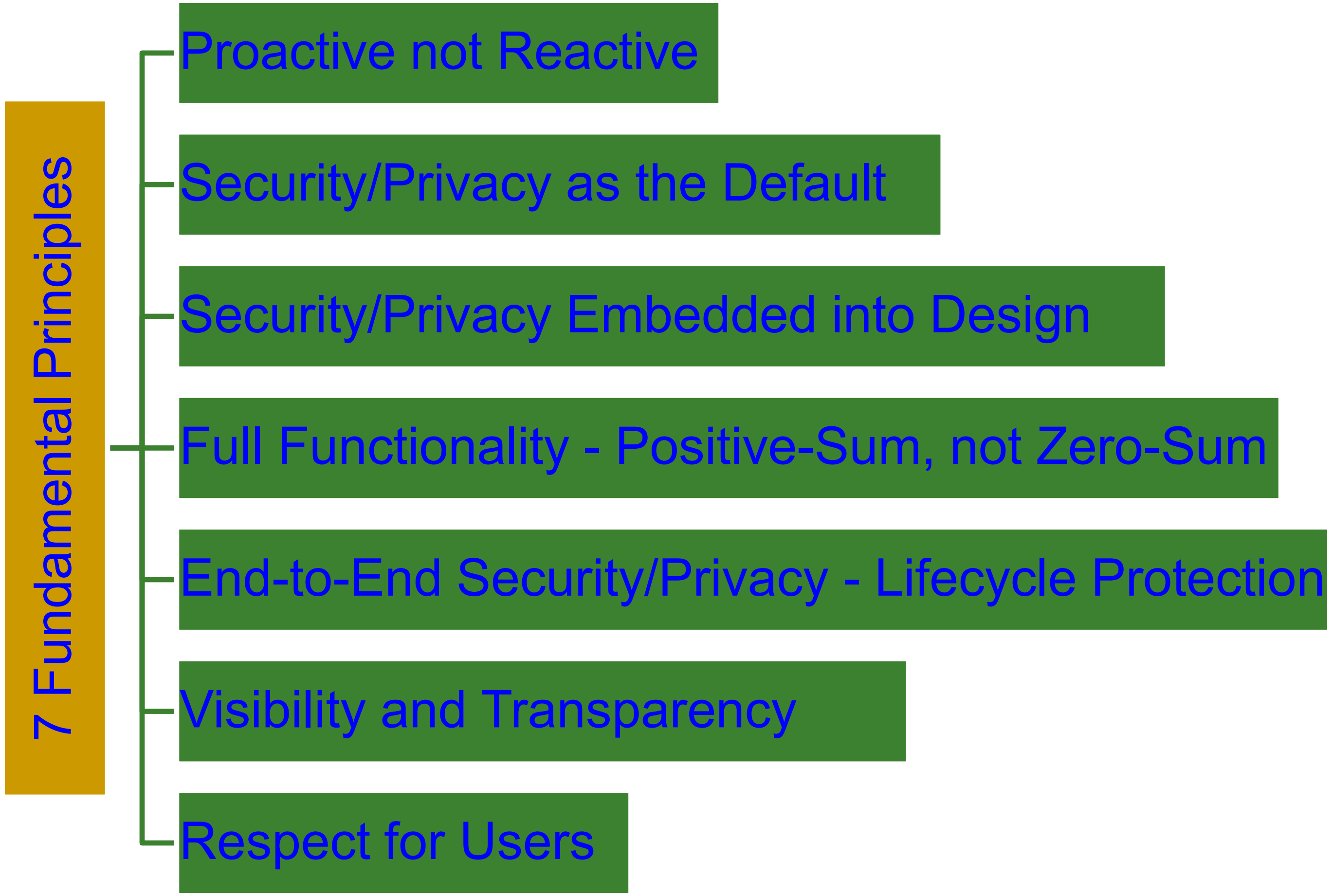
Embedding of security/privacy into the architecture (hardware+software) of various products, programs, or services.

Retrofitting: Difficult → Impossible!



Source: https://teachprivacy.com/tag/privacy-by-design/

Security by Design (SbD)

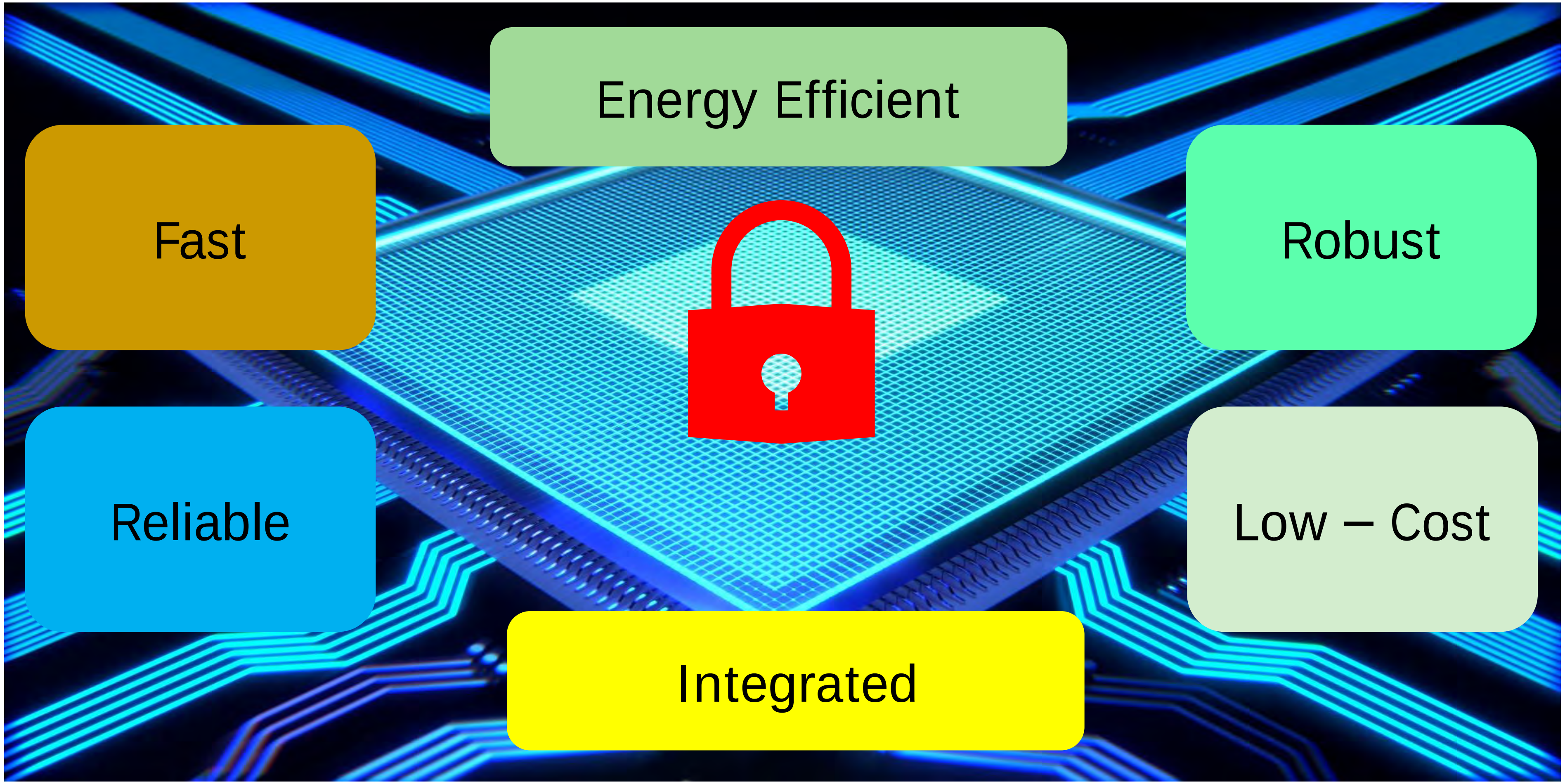


7 Fundamental Principles

- 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) or Hardware Assisted Security (HAS) - Advantages



Energy Efficient

Fast

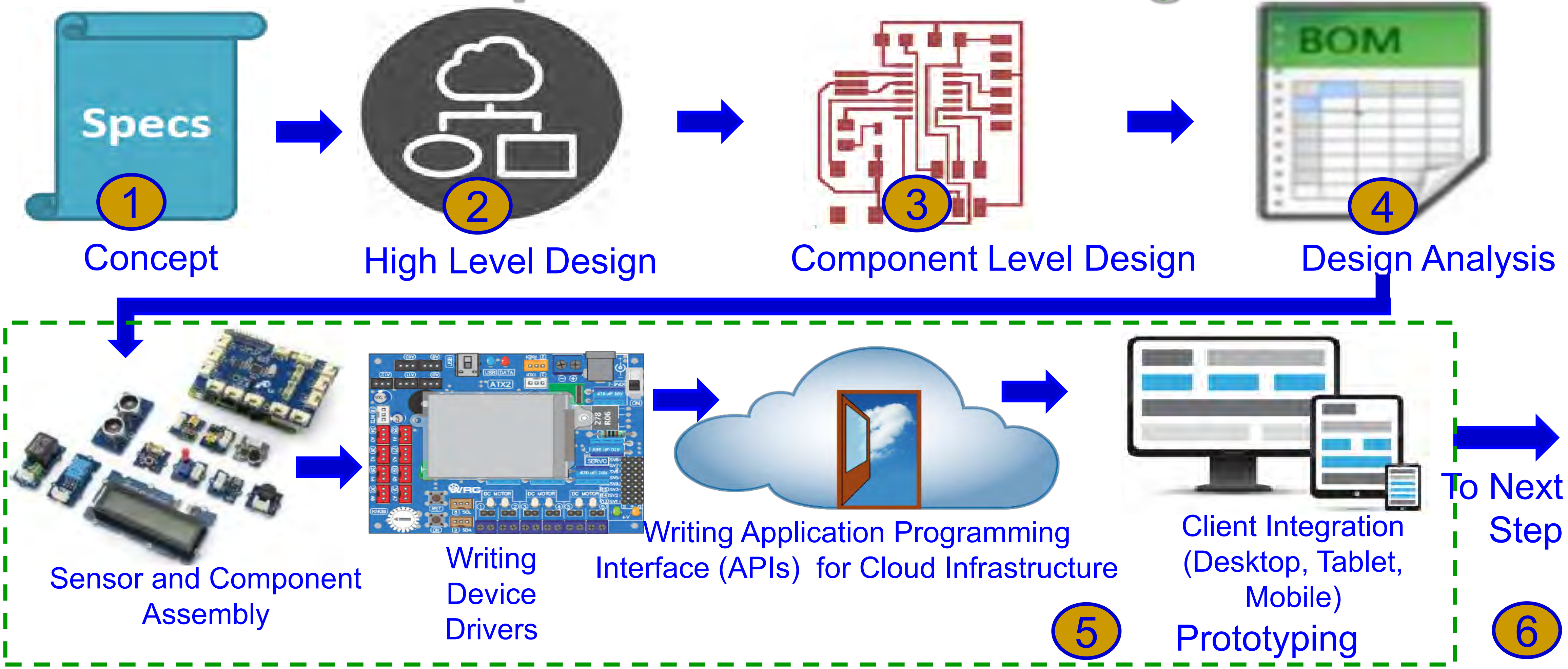
Robust

Reliable

Low – Cost

Integrated

SbD Principle – IoT/CPS Design Flow



1 Concept

2 High Level Design

3 Component Level Design

4 Design Analysis

Sensor and Component Assembly

Writing Device Drivers

Writing Application Programming Interface (APIs) for Cloud Infrastructure

Client Integration (Desktop, Tablet, Mobile)

5 Prototyping

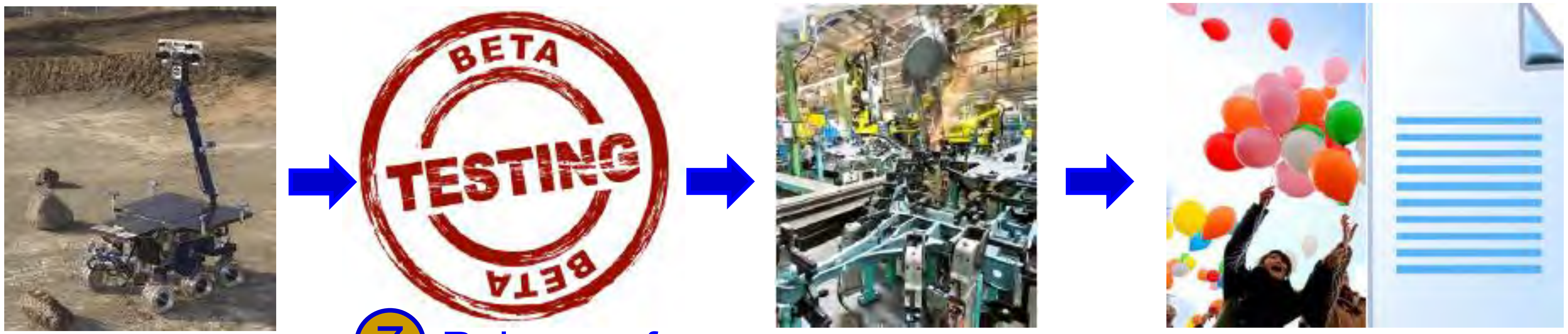
To Next Step

6

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%20IoT%20Solution%20-%20Shivakumar%20Mathapathi.pdf

SbD Principle – IoT/CPS Design Flow

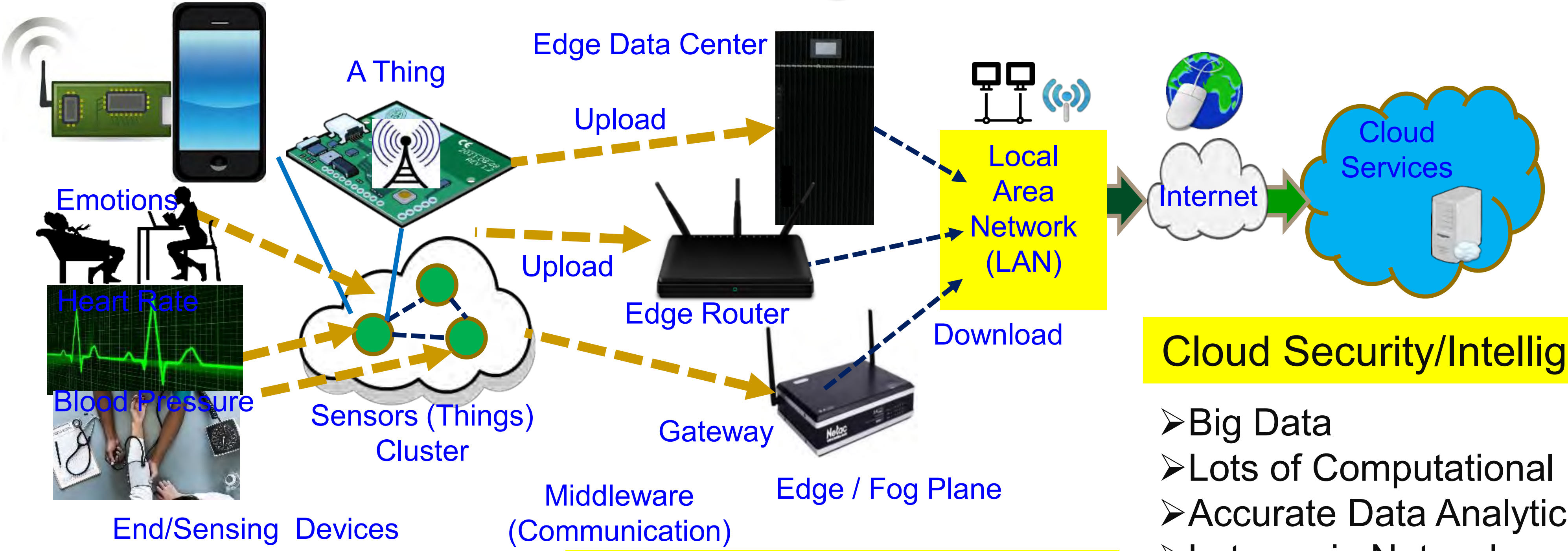


6 Field Testing → 7 Release of Beta Version → 8 Production → 9 Release and Documentation

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%20%20IoT%20Solution%20-%20Shivakumar%20Mathapathi.pdf

CPS – IoT-Edge Vs IoT-Cloud



Cloud Security/Intelligence

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

End Security/Intelligence

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

Edge Security/Intelligence

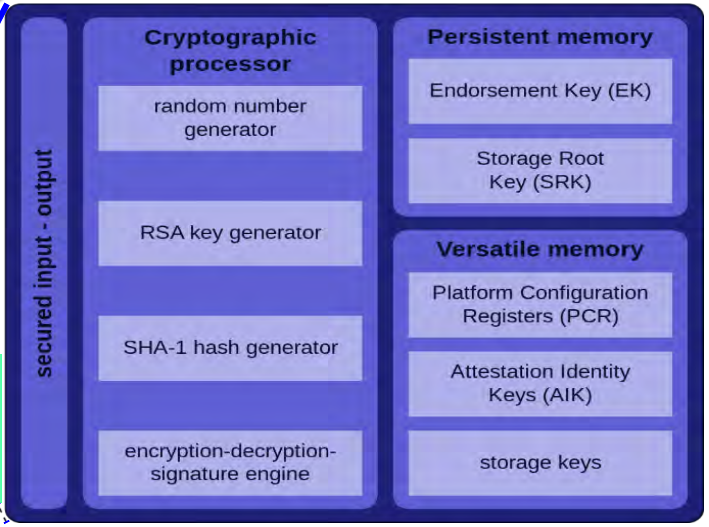
- Less Data
- Less Computational Resource
- Less Accurate Data Analytics
- Rapid Response

Heavy-Duty ML is more suitable for smart cities

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

Hardware Cybersecurity Primitives – HSM, TrustZone, TPM, and PUF

Hardware Security Module (HSM)



secured input - output

Cryptographic processor

- random number generator
- RSA key generator
- SHA-1 hash generator
- encryption-decryption-signature engine

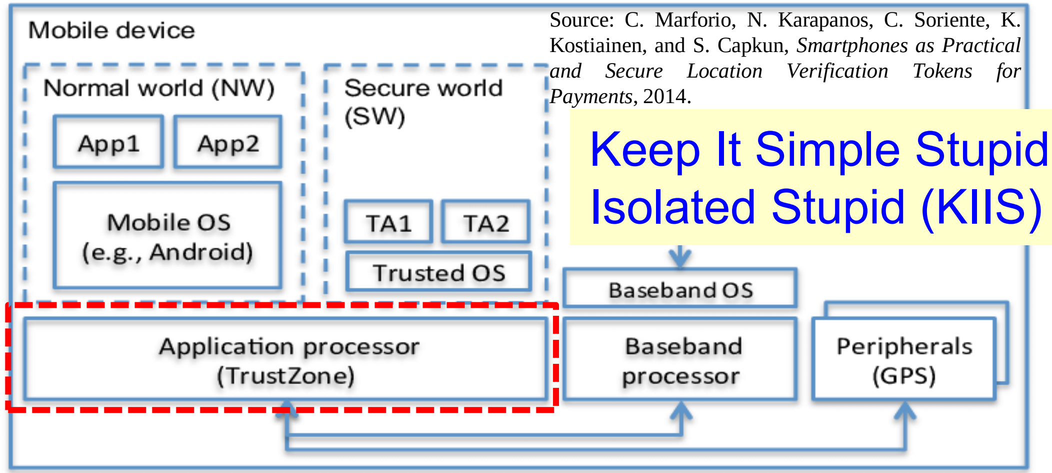
Persistent memory

- Endorsement Key (EK)
- Storage Root Key (SRK)

Versatile memory

- Platform Configuration Registers (PCR)
- Attestation Identity Keys (AIK)
- storage keys

Trusted Platform Module (TPM)



Mobile device

Normal world (NW): App1, App2, Mobile OS (e.g., Android)

Secure world (SW): TA1, TA2, Trusted OS

Baseband OS

Application processor (TrustZone)

Baseband processor

Peripherals (GPS)

Source: C. Marforio, N. Karapanos, C. Soriente, K. Kostiainen, and S. Capkun, *Smartphones as Practical and Secure Location Verification Tokens for Payments*, 2014.

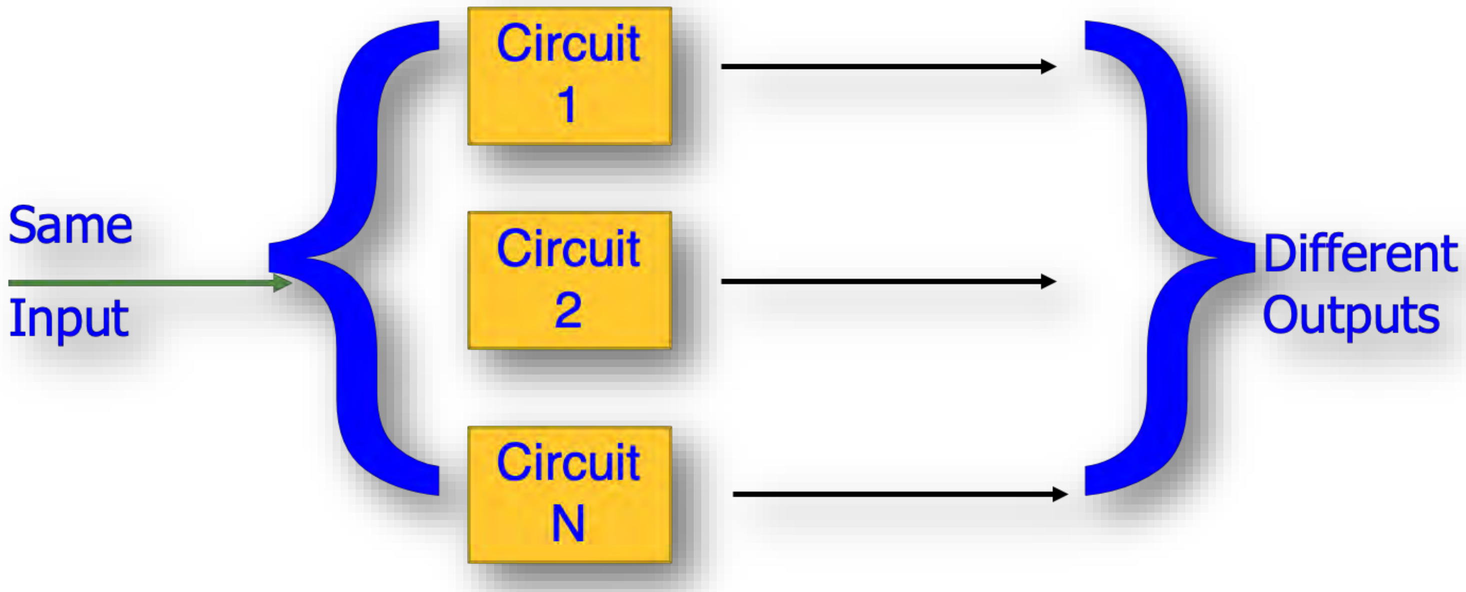
Keep It Simple Stupid (KISS) → Keep It Isolated Stupid (KIIS)

Physical Unclonable Functions (PUF)

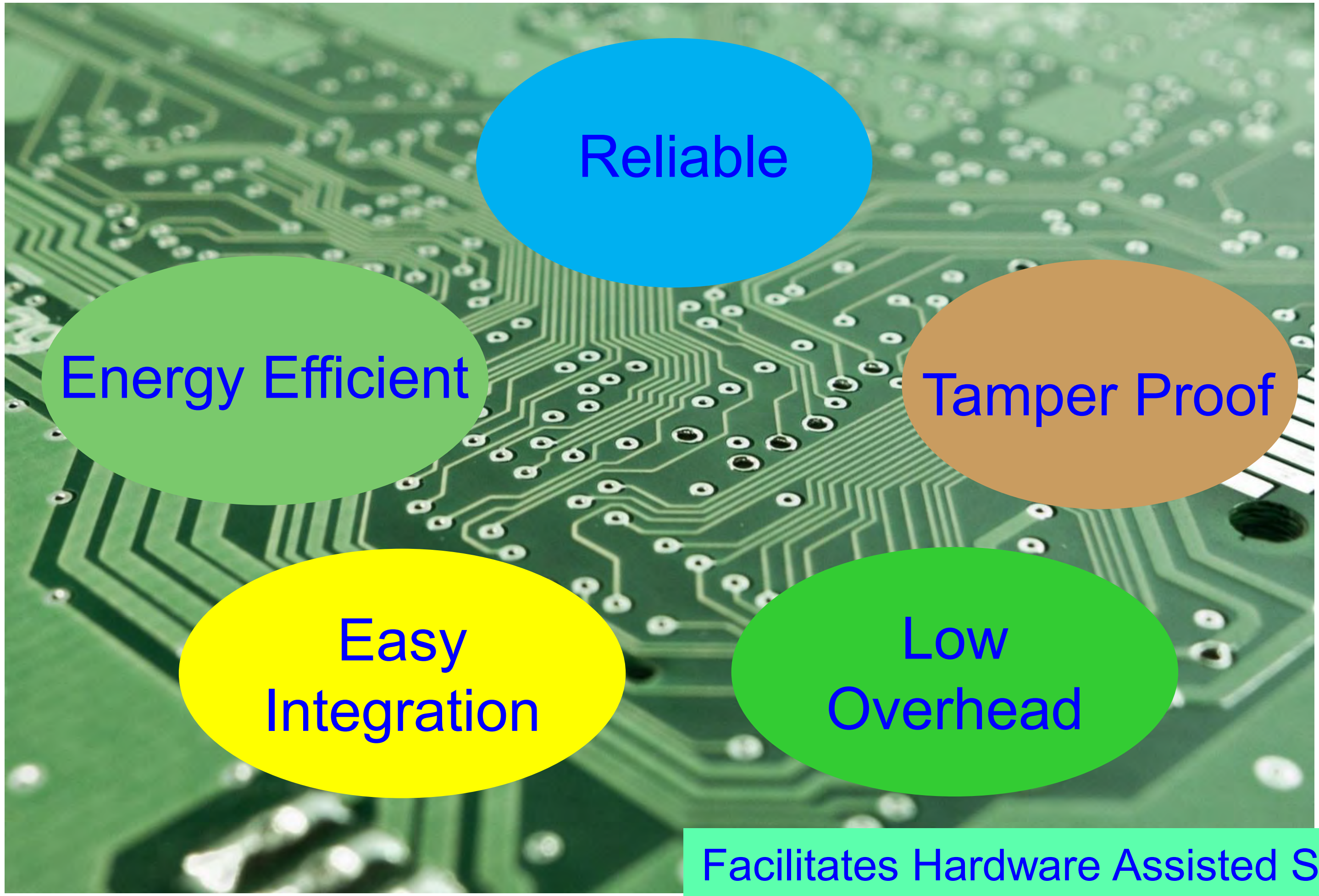
Source: Electric Power Research Institute (EPRI)

Physical Unclonable Functions (PUF)

- Uses manufacturing variations for generating unique set of keys for cryptographic applications.
- Input of PUF is a challenge and output from PUF is response.



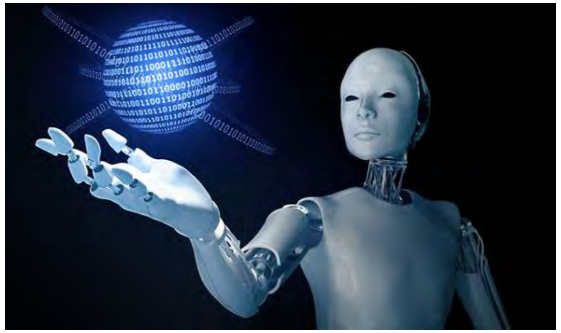
Physical Unclonable Function (PUF): Advantages



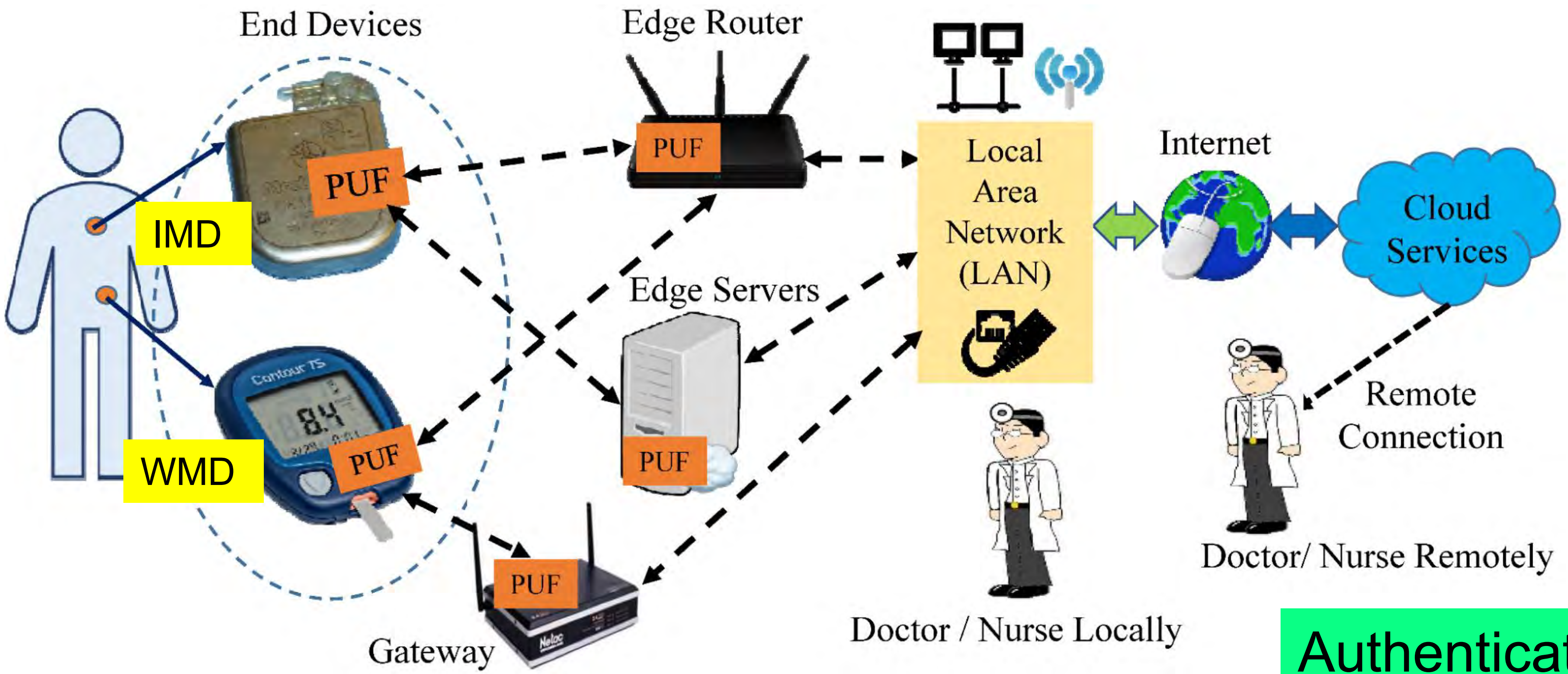
- A secure fingerprint generation scheme based on process variations in an Integrated Circuit
- PUFs don't store keys in digital memory, rather derive a key based on the physical characteristics of the hardware; thus secure.
- A simple design that generates cryptographically secure keys for the device authentication

Facilitates Hardware Assisted Security (HAS) or Security-by-Design (SbD).

Security-by-Design (SbD) – Specific Examples



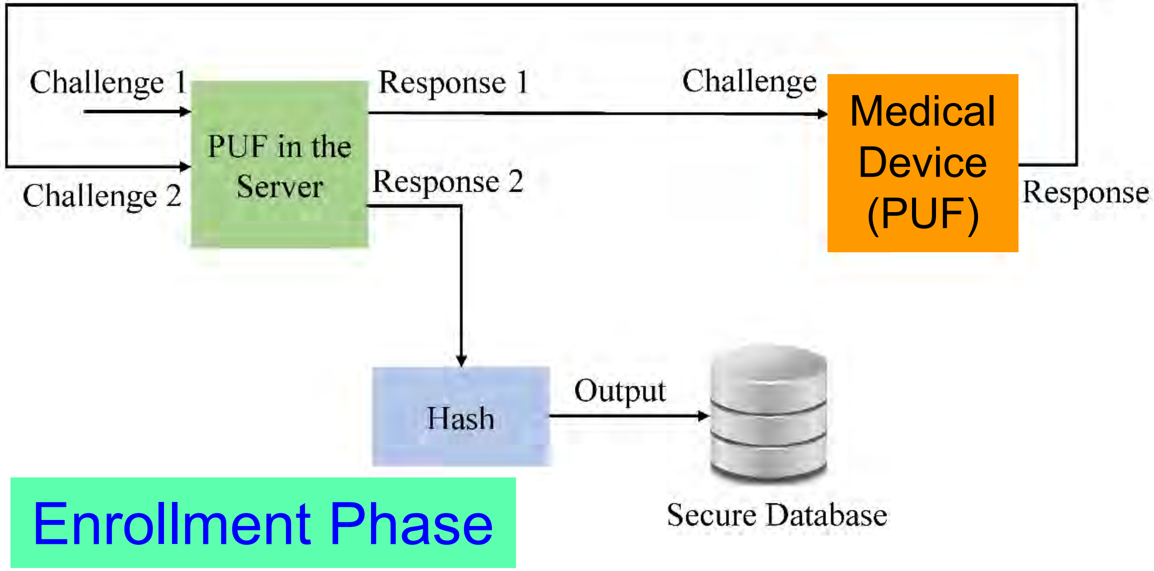
PMsec: Our Secure by Design Approach for Robust Security in Healthcare CPS



Authenticates Time - 1 sec
Power Consumption - 200 μW

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

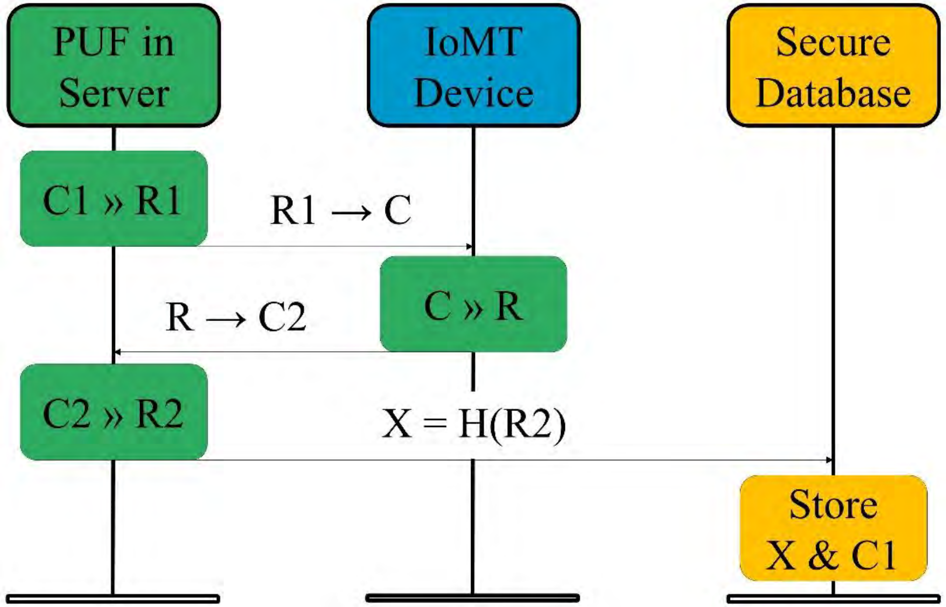


Enrollment Phase

At the Doctor

- When a new IoMT-Device comes for an User

Device Registration Procedure

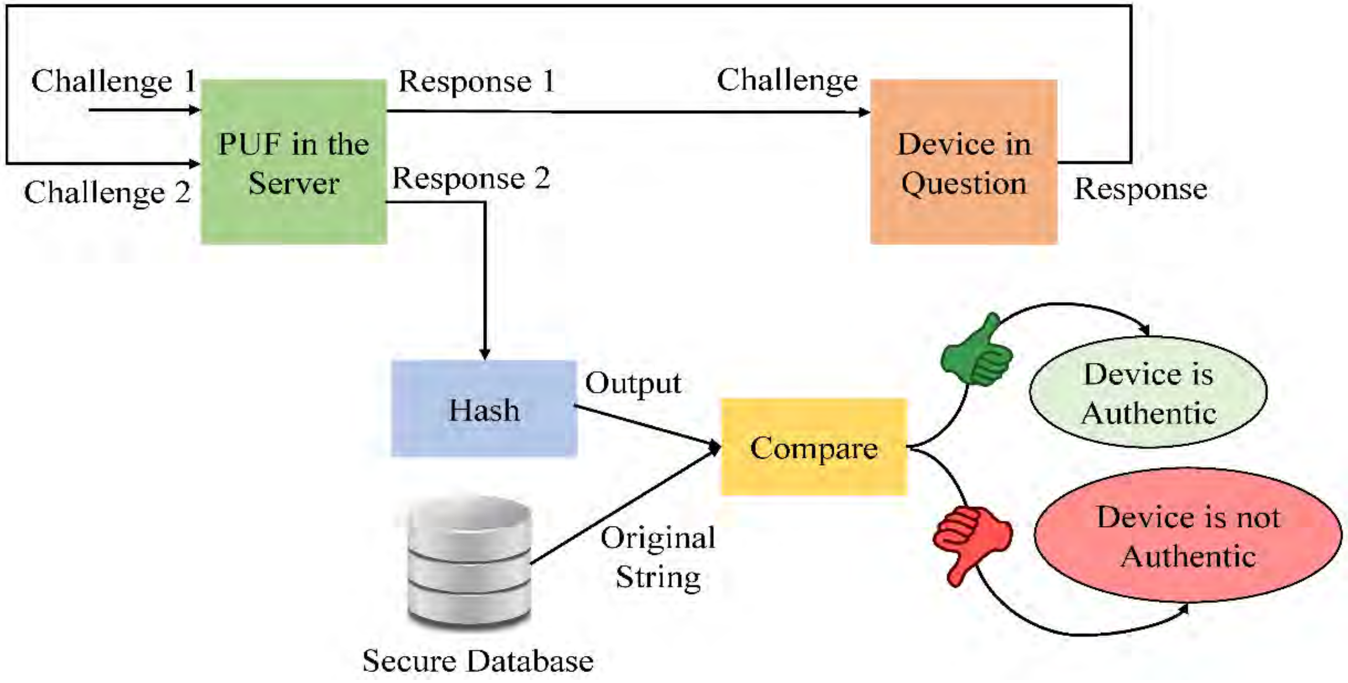


PUF Security Full Proof:

- 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

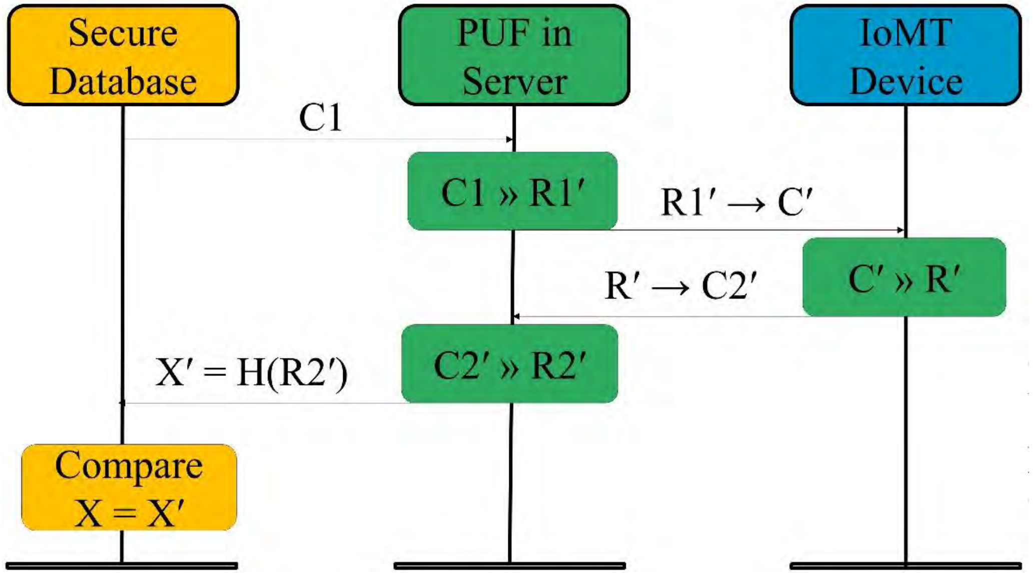


Authentication Phase

At the Doctor

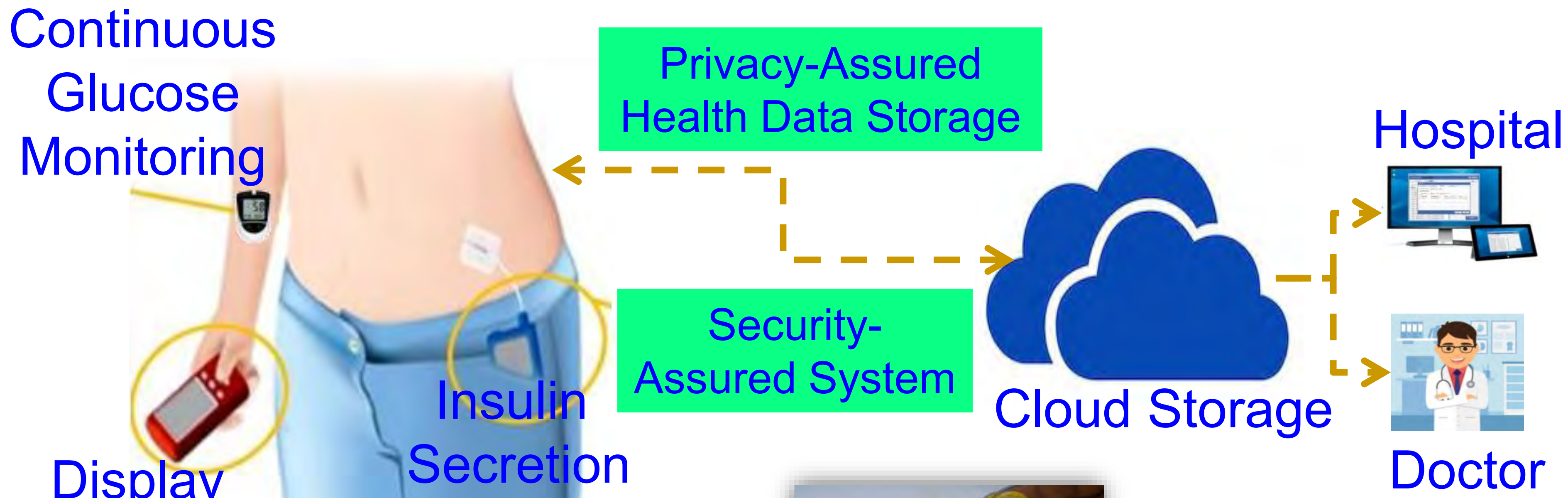
- ➢ When doctor needs to access an existing IoMT-device

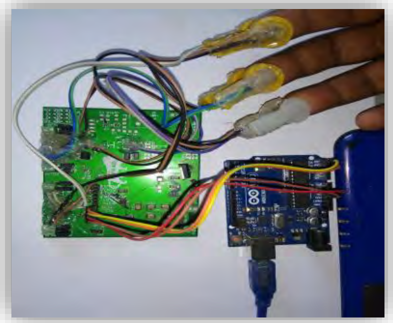
Device Authentication Procedure



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.

Secure-iGLU - Our Intelligent Non-Invasive Glucose Monitoring with Insulin Control Device


Continuous Glucose Monitoring
Privacy-Assured Health Data Storage
Hospital
Security-Assured System
Cloud Storage
Insulin Secretion
Doctor
Display of Parameters
Artificial Pancreases System (APS)

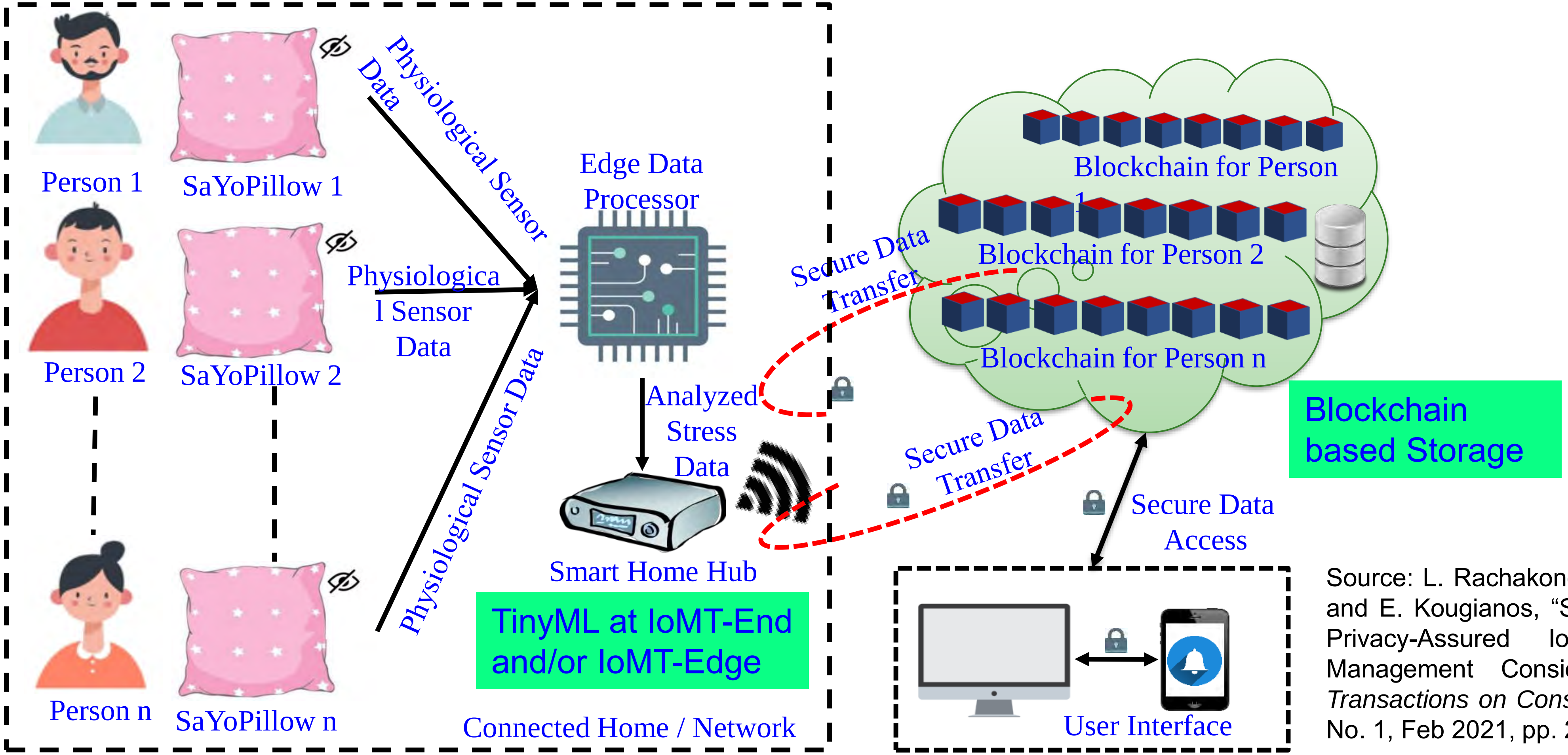


Near Infrared (NIR) based Noninvasive, Accurate, Continuous Glucose Monitoring

Smart Healthcare (H-CPS) → Security, Privacy, …

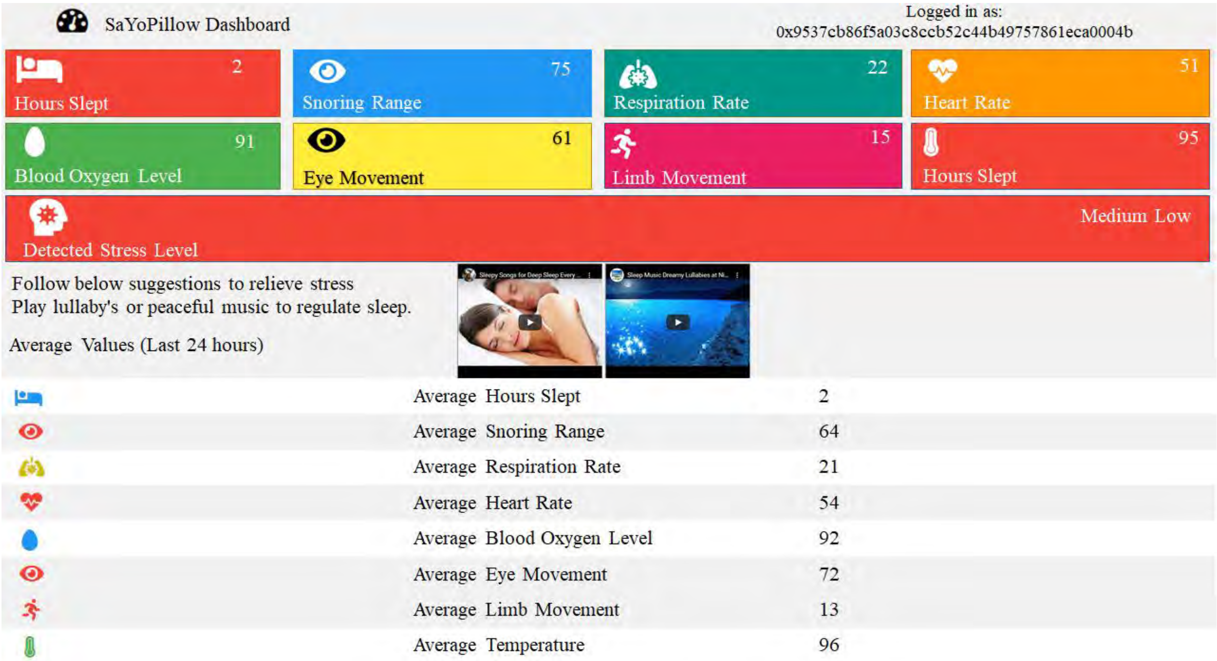
P. Jain, A. M. Joshi, and S. P. Mohanty, “iGLU: An Intelligent Device for Accurate Non-Invasive Blood Glucose-Level Monitoring in Smart Healthcare”, *IEEE Consumer Electronics Magazine (MCE),* Vol. 9, No. 1, January 2020, pp. 35–42.

Our Smart-Yoga Pillow (SaYoPillow) with TinyML and Blockchain based Security



Source: L. Rachakonda, A. K. Bapatla, S. P. Mohanty, and E. Kougianos, “SaYoPillow: Blockchain-Integrated Privacy-Assured IoMT Framework for Stress Management Considering Sleeping Habit”, *IEEE Transactions on Consumer Electronics (TCE)*, Vol. 67, No. 1, Feb 2021, pp. 20-29.

SaYoPillow: Blockchain Results



SaYoPillow Dashboard

Logged in as:
0x9537cb86f5a03c8ccb52c44b49757861eca0004b

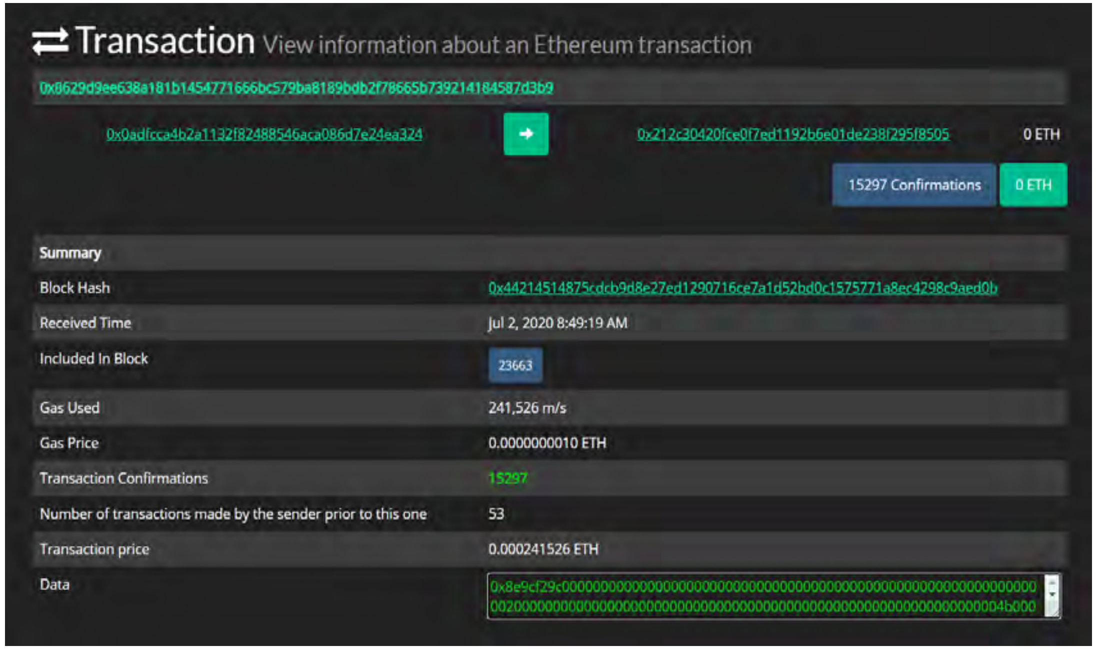
Hours Slept	2
Snoring Range	75
Respiration Rate	22
Heart Rate	51
Blood Oxygen Level	91
Eye Movement	61
Limb Movement	15
Hours Slept	95

Detected Stress Level — Medium Low

Follow below suggestions to relieve stress
Play lullaby's or peaceful music to regulate sleep.

Average Values (Last 24 hours)

Average Hours Slept	2
Average Snoring Range	64
Average Respiration Rate	21
Average Heart Rate	54
Average Blood Oxygen Level	92
Average Eye Movement	72
Average Limb Movement	13
Average Temperature	96



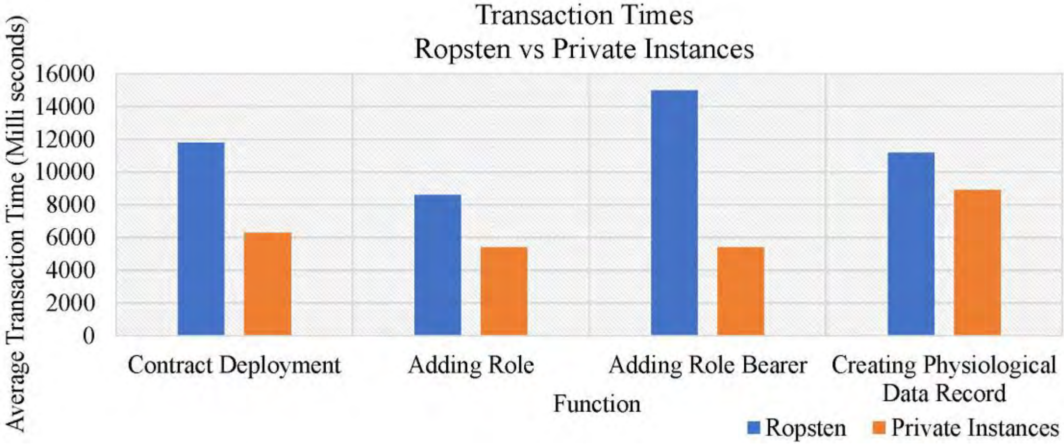
⇄ Transaction View information about an Ethereum transaction

0x8629d9ee638a181b1454771666bc579ba8189bdb2f78665b739214184587d3b9

0x0adfcca4b2a1132f82488546aca086d7e24ea324 → 0x212c30420fce0f7ed1192b6e01de238f295f8505 0 ETH

15297 Confirmations 0 ETH

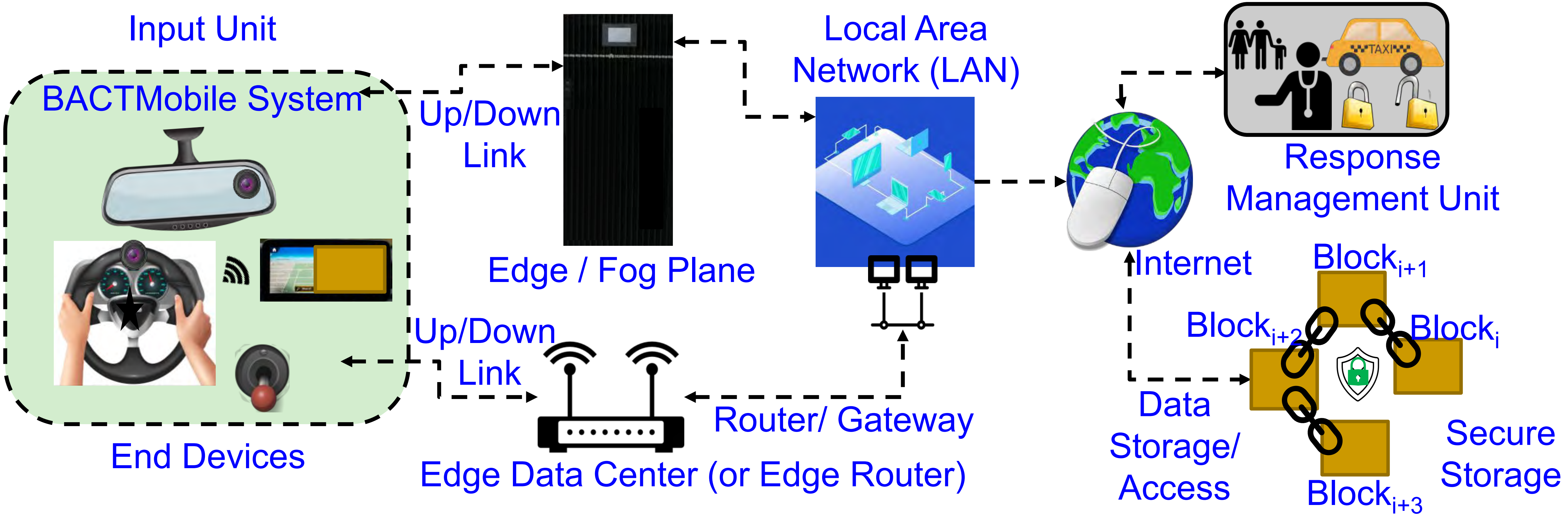
Summary	
Block Hash	0x44214514875cdcb9d8e27ed1290716ce7a1d52bd0c1575771a8ec4298c9aed0b
Received Time	Jul 2, 2020 8:49:19 AM
Included In Block	23663
Gas Used	241,526 m/s
Gas Price	0.0000000010 ETH
Transaction Confirmations	15297
Number of transactions made by the sender prior to this one	53
Transaction price	0.000241526 ETH
Data	0x8e9cf29c0000000000000000000000000000000000000000000000000000000000000 00200000000000000000000000000000000000000000000000000000000000004b000



Transaction times of Private Ethereum in SaYoPillow is 2X faster in operations as compared to public ethereum test network Ropsten, as it is impacted by network congestion.

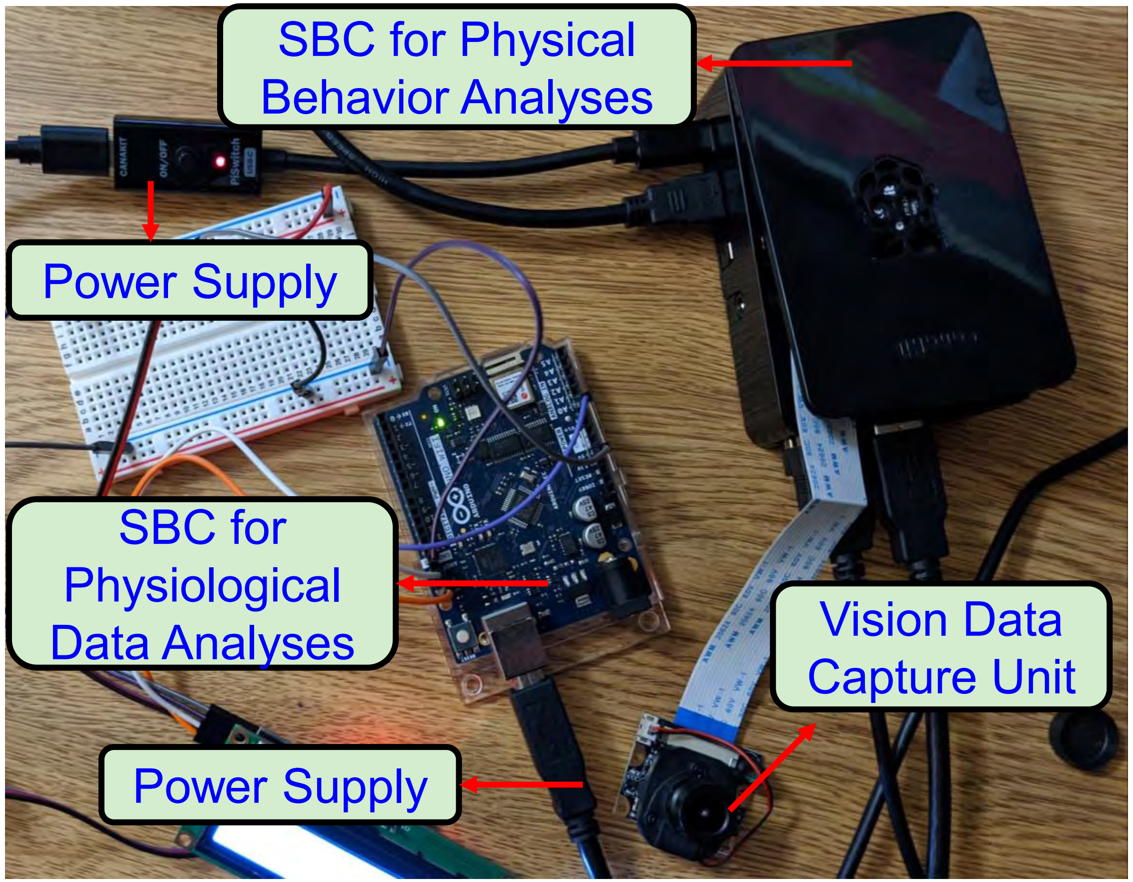
Source: L. Rachakonda, A. K. Bapatla, S. P. Mohanty, and E. Kougianos, "SaYoPillow: Blockchain-Integrated Privacy-Assured IoMT Framework for Stress Management Considering Sleeping Habits", *IEEE Transactions on Consumer Electronics (TCE)*, Vol. 67, No. 1, Feb 2021, pp. 20-29.

Our Smart Blood Alcohol Concentration Tracking Mechanism in Healthcare CPS - BACTmobile



Source: L. Rachakonda, A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "BACTmobile: A Smart Blood Alcohol Concentration Tracking Mechanism for Smart Vehicles in Healthcare CPS Framework", *Springer Nature Computer Science (SN-CS)*, Vol. 3, No. 3, May 2022, Article: 236, 24-pages, DOI: https://doi.org/10.1007/s42979-022-01142-9.

Our Smart Blood Alcohol Concentration Tracking Mechanism in Healthcare CPS - BACTmobile



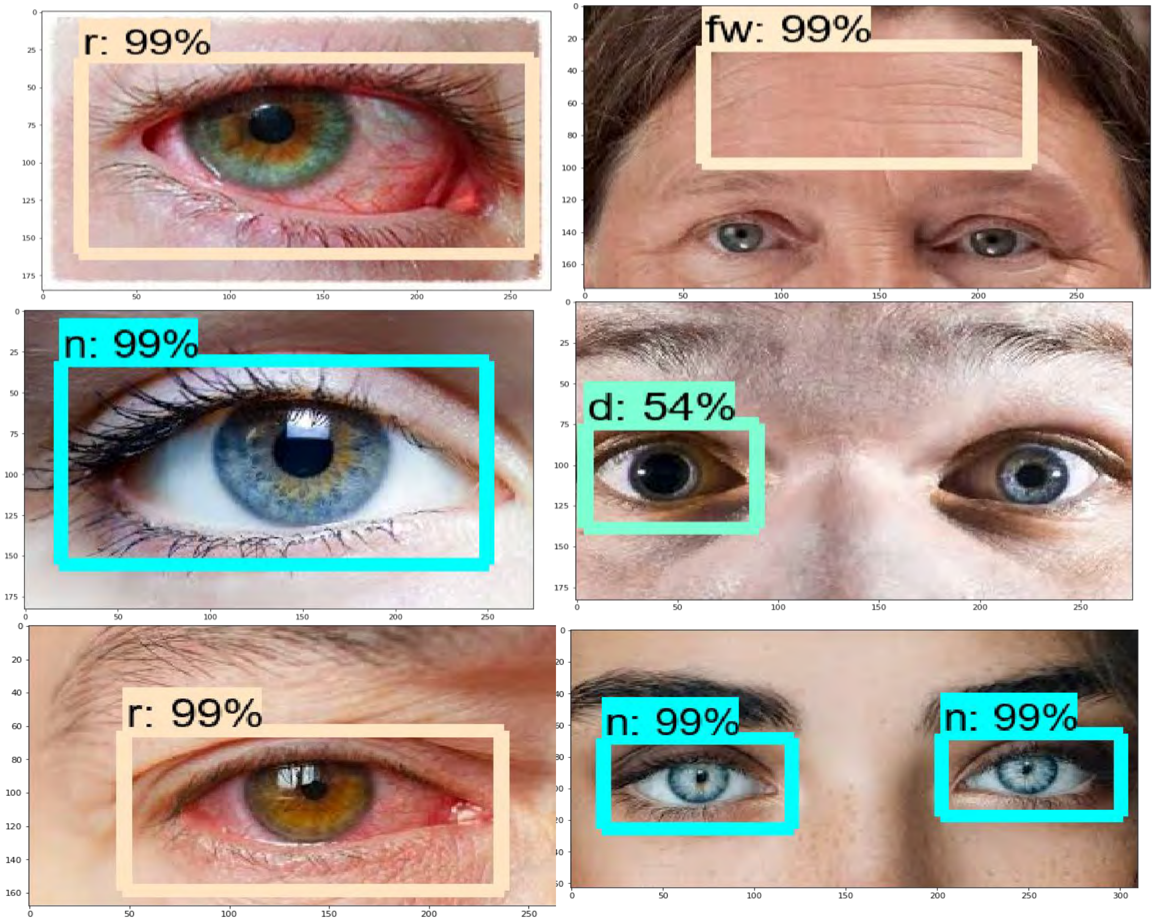
SBC for Physical Behavior Analyses

Power Supply

SBC for Physiological Data Analyses

Vision Data Capture Unit

Power Supply

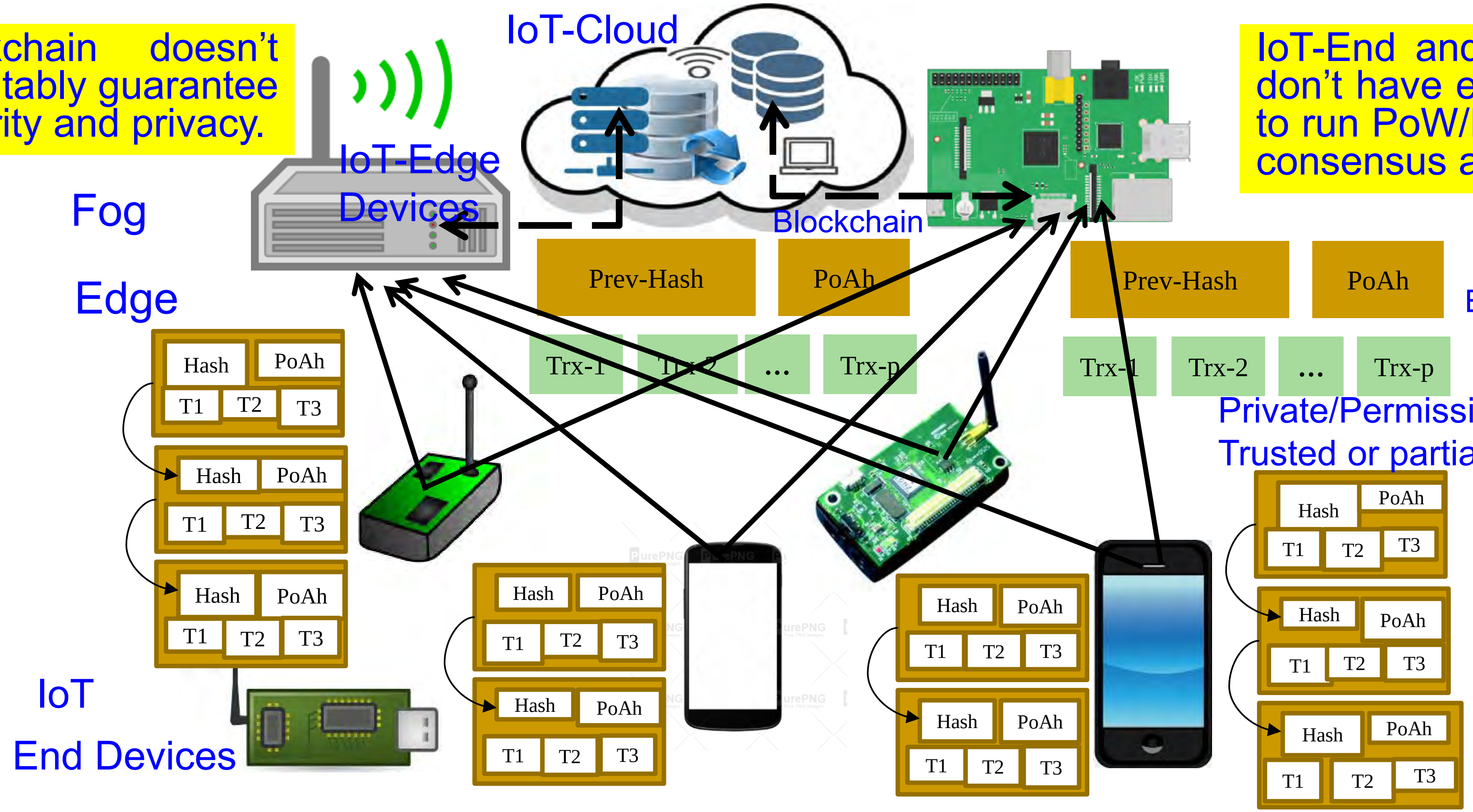


Source: L. Rachakonda, A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "BACTmobile: A Smart Blood Alcohol Concentration Tracking Mechanism for Smart Vehicles in Healthcare CPS Framework", *Springer Nature Computer Science (SN-CS)*, Vol. 3, No. 3, May 2022, Article: 236, 24-pages, DOI: https://doi.org/10.1007/s42979-022-01142-9.

IoT-Friendly Blockchain – Our EasyChain

Blockchain doesn't inheritably guarantee security and privacy.

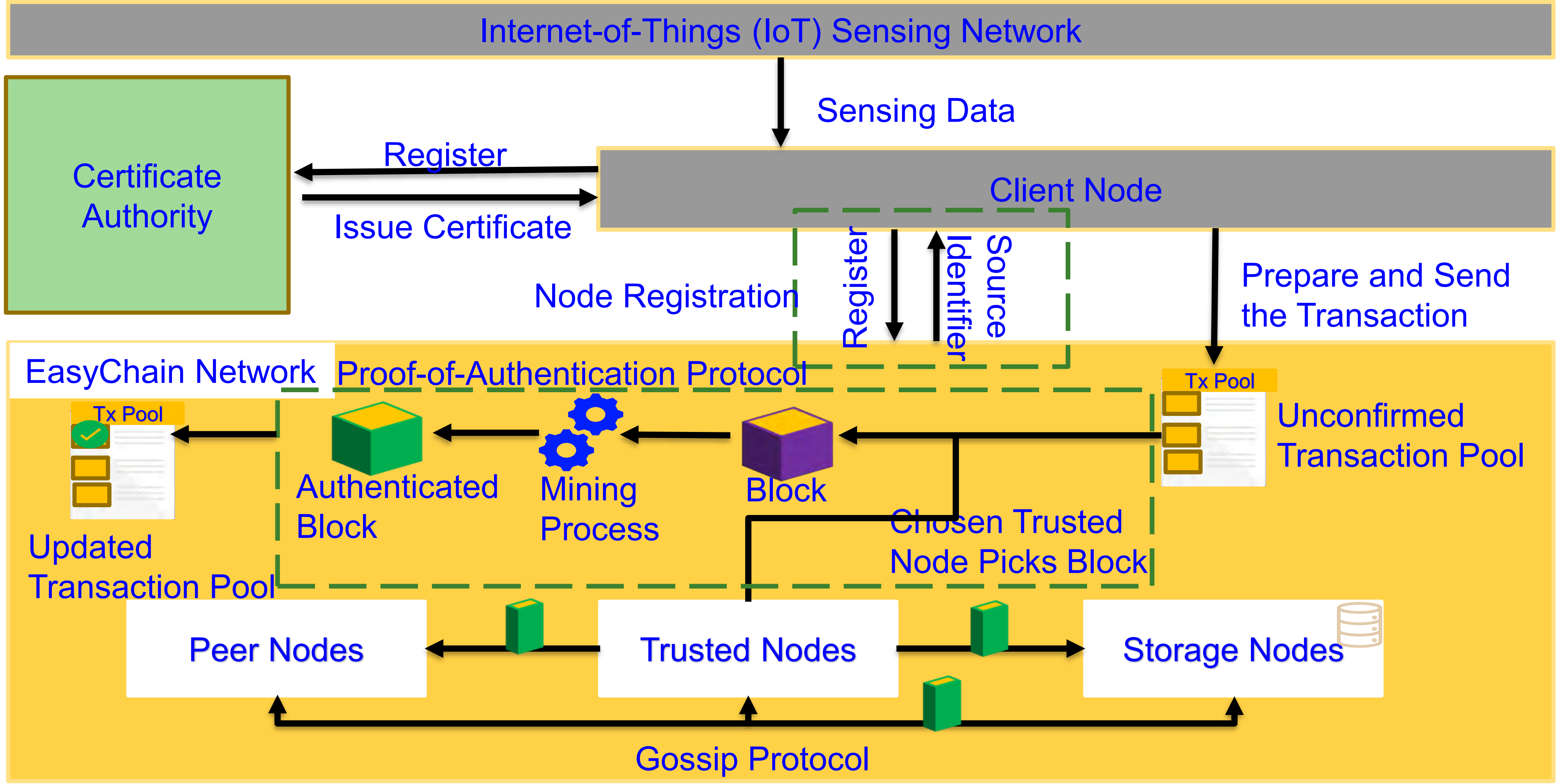
IoT-End and IoT-Edge Devices don't have enough horse power to run PoW/PoS like heavy duty consensus algorithms.



Private/Permissioned Blockchain with Trusted or partially-trusted nodes

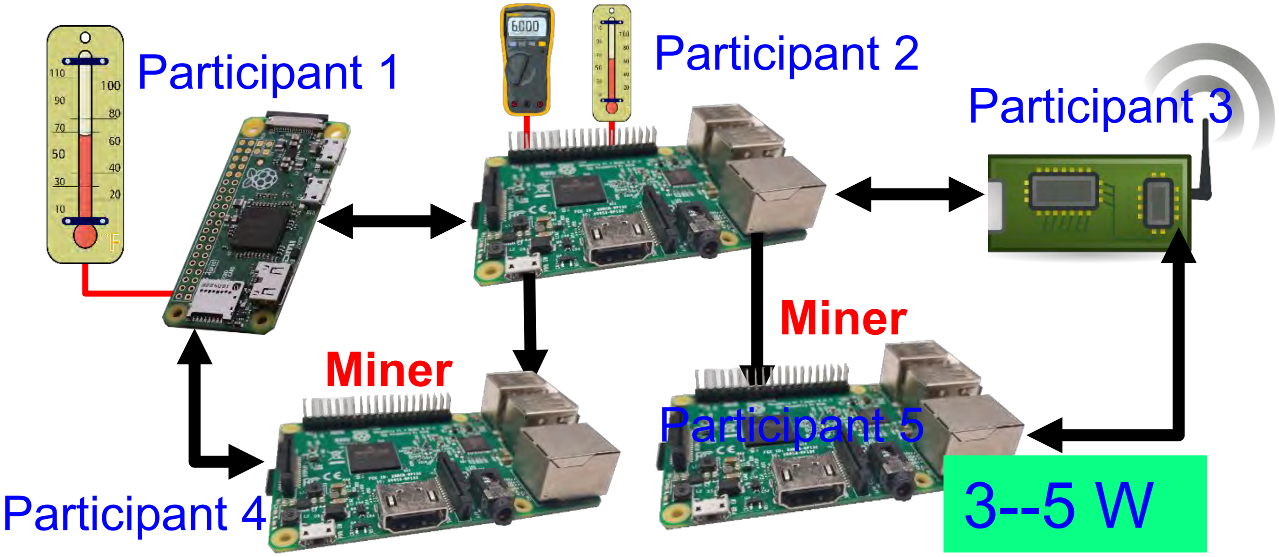
Source: D. Puthal and S. P. Mohanty, "Proof of Authentication: IoT-Friendly Blockchains", *IEEE Potentials Magazine*, Vol. 38, No. 1, January 2019, pp. 26--29.

Our EasyChain: Architectural Overview



Source: A. K. Bapatla, D. Puthal, **S. P. Mohanty**, V. P. Yanambaka, and E. Kougianos, "EasyChain: An IoT-Friendly Blockchain for Robust and Energy-Efficient Authentication", *Frontiers in Blockchain*, Vol. 6, No. 1194883, Aug 2023, pp. 1--19, DOI: https://doi.org/10.3389/fbloc.2023.1194883.

Our EasyChain with PoAh Runs in Resource Constrained Environment

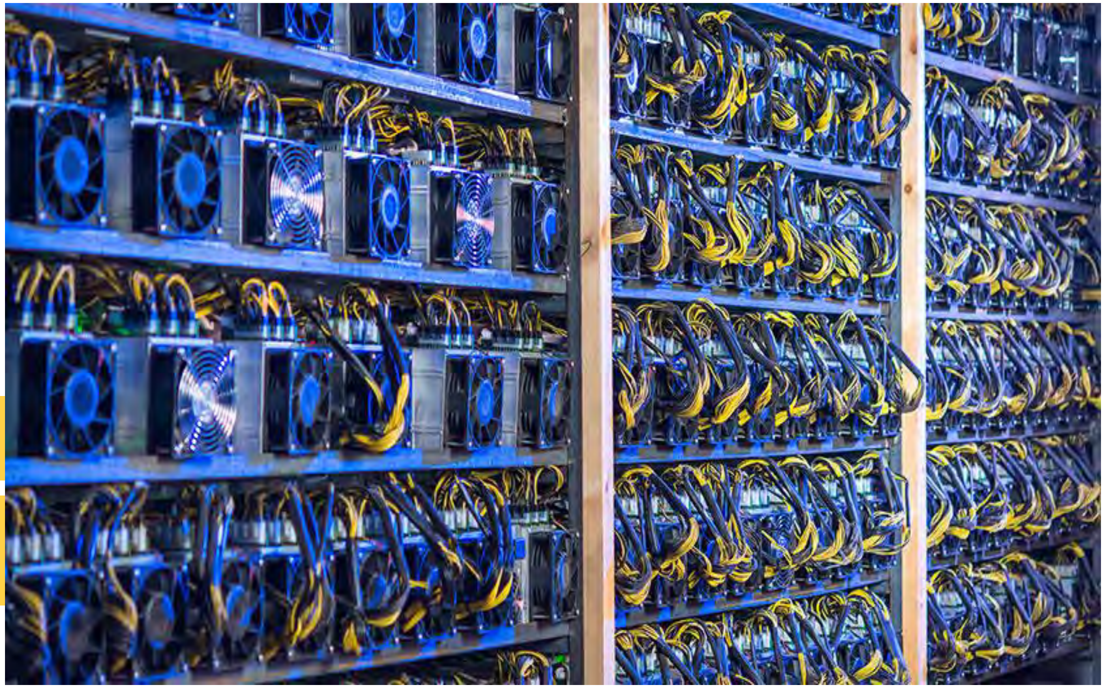


3--5 W

Our PoAh-Chain Runs even in IoT-end devices.

Blockchain using PoW Needs Significant Resource

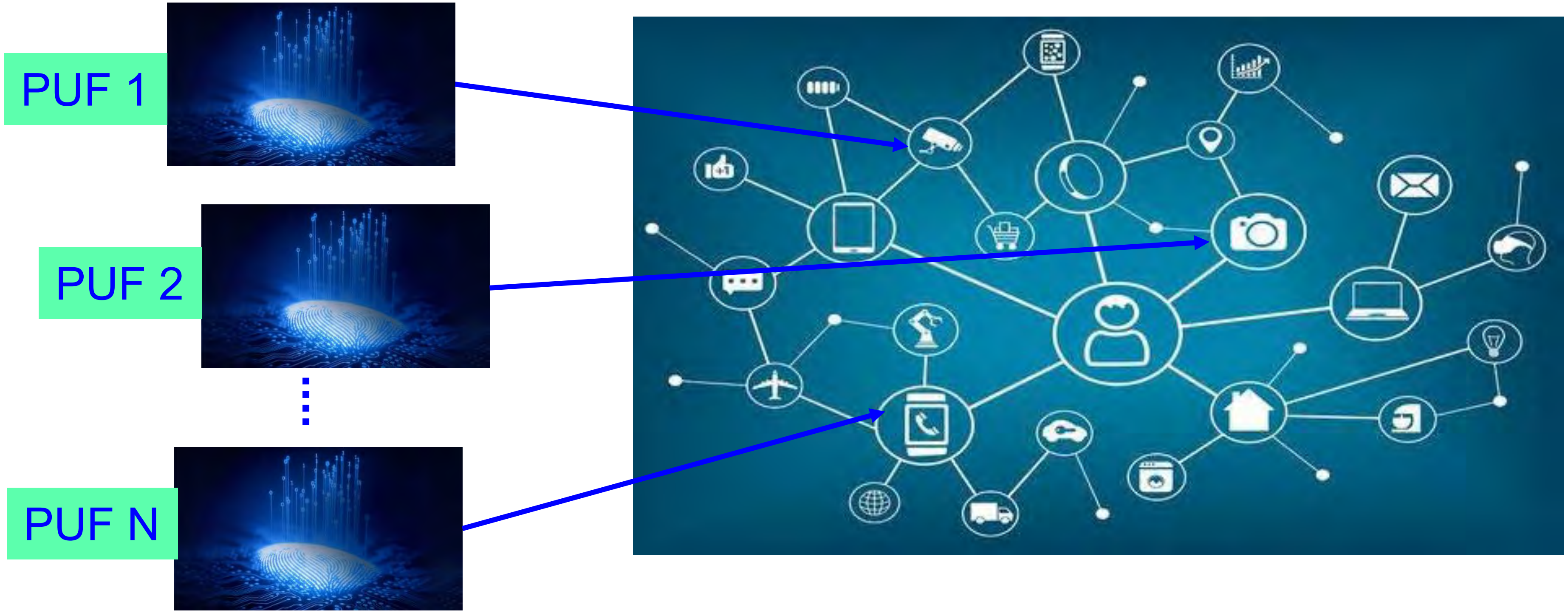
500,0000 W



Source: D. Puthal, S. P. Mohanty, V. P. Yanambaka, and E. Kougianos, "PoAh: A Novel Consensus Algorithm for Fast Scalable Private Blockchain for Large-scale IoT Frameworks", *arXiv Computer Science*, arXiv:2001.07297, January 2020, 26-pages.

Source: https://www.iea.org/newsroom/news/2019/july/bitcoin-energy-use-mined-the-gap.html

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



PUF 1

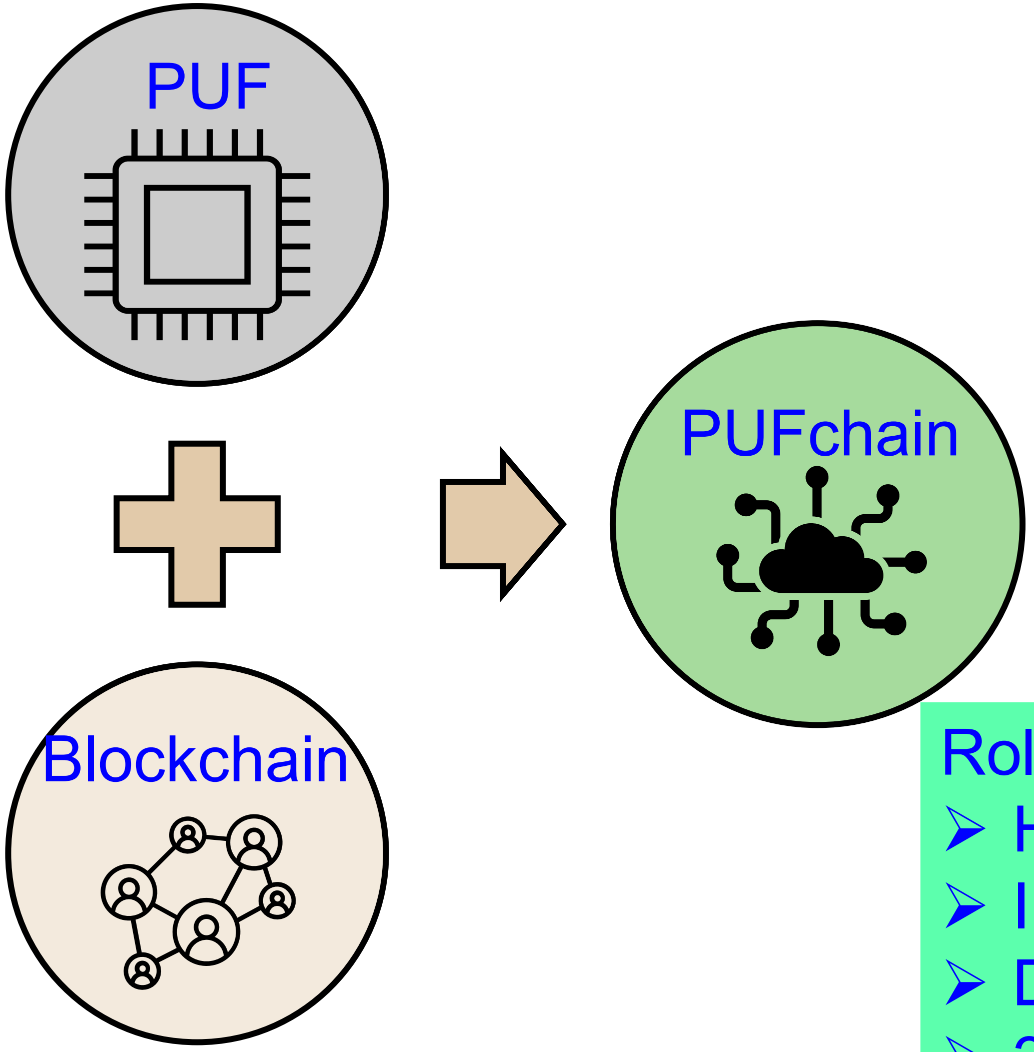
PUF 2

⋮

PUF N

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

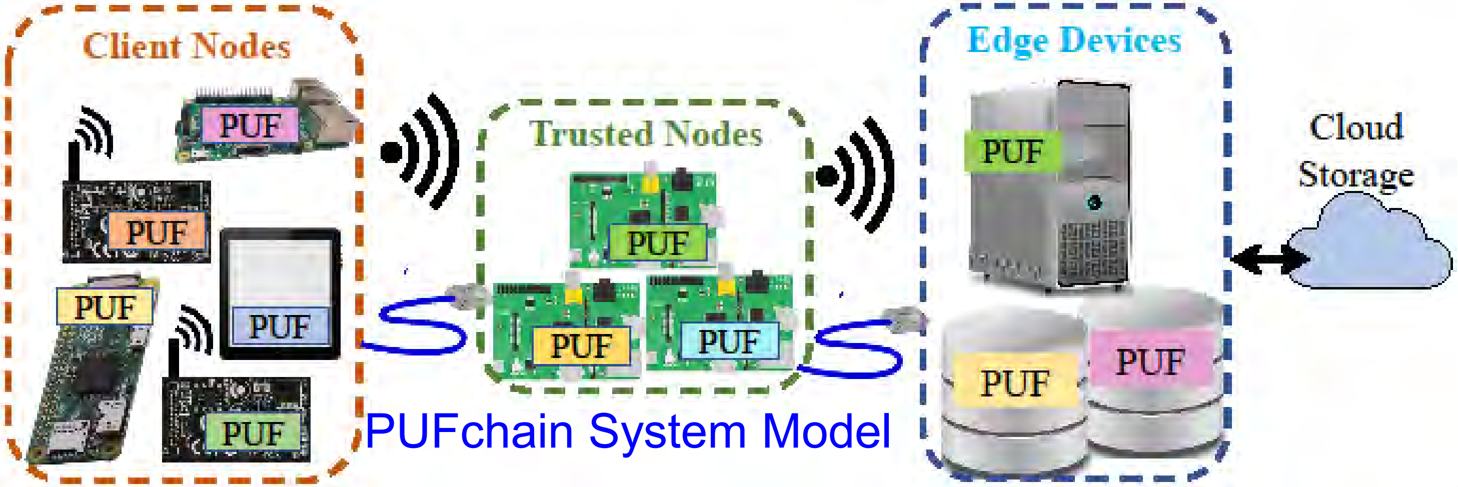


Blockchain Technology is integrated with Physically Unclonable Functions as PUFchain by storing the PUF Key into immutable Blockchain

Roles of PUF:

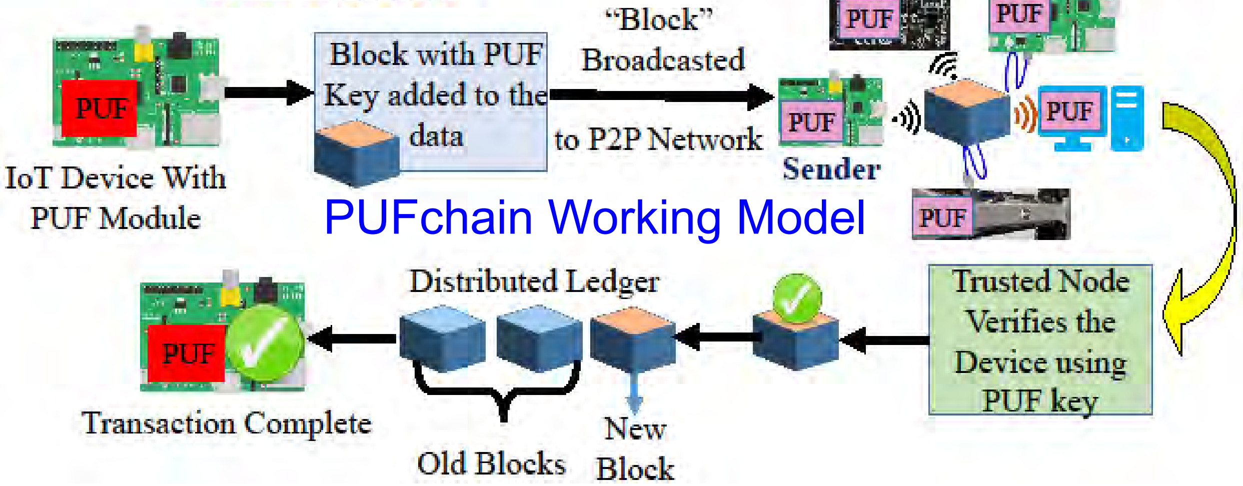
- Hardware Accelerator for Blockchain
- Independent Authentication
- Double-Layer Protection
- 3 modes: PUF, Blockchain, PUF+Blockchain

PUFchain: Our Hardware-Assisted Scalable Blockchain



PUFchain System Model

Can provide:
Device, System, and Data Security



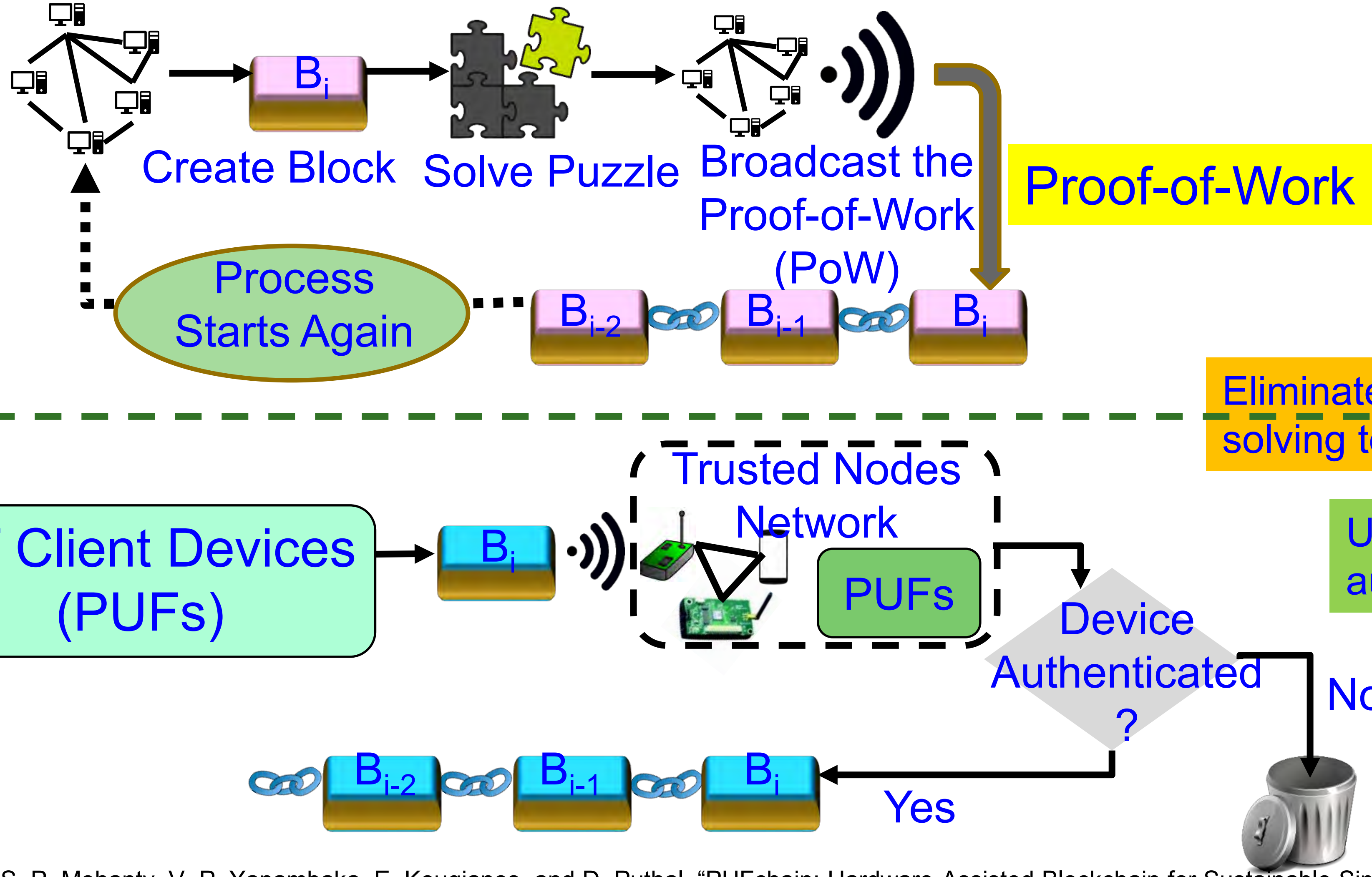
PUFchain Working Model

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.

Our Proof-of-PUF-Enabled-Authentication (PoP)



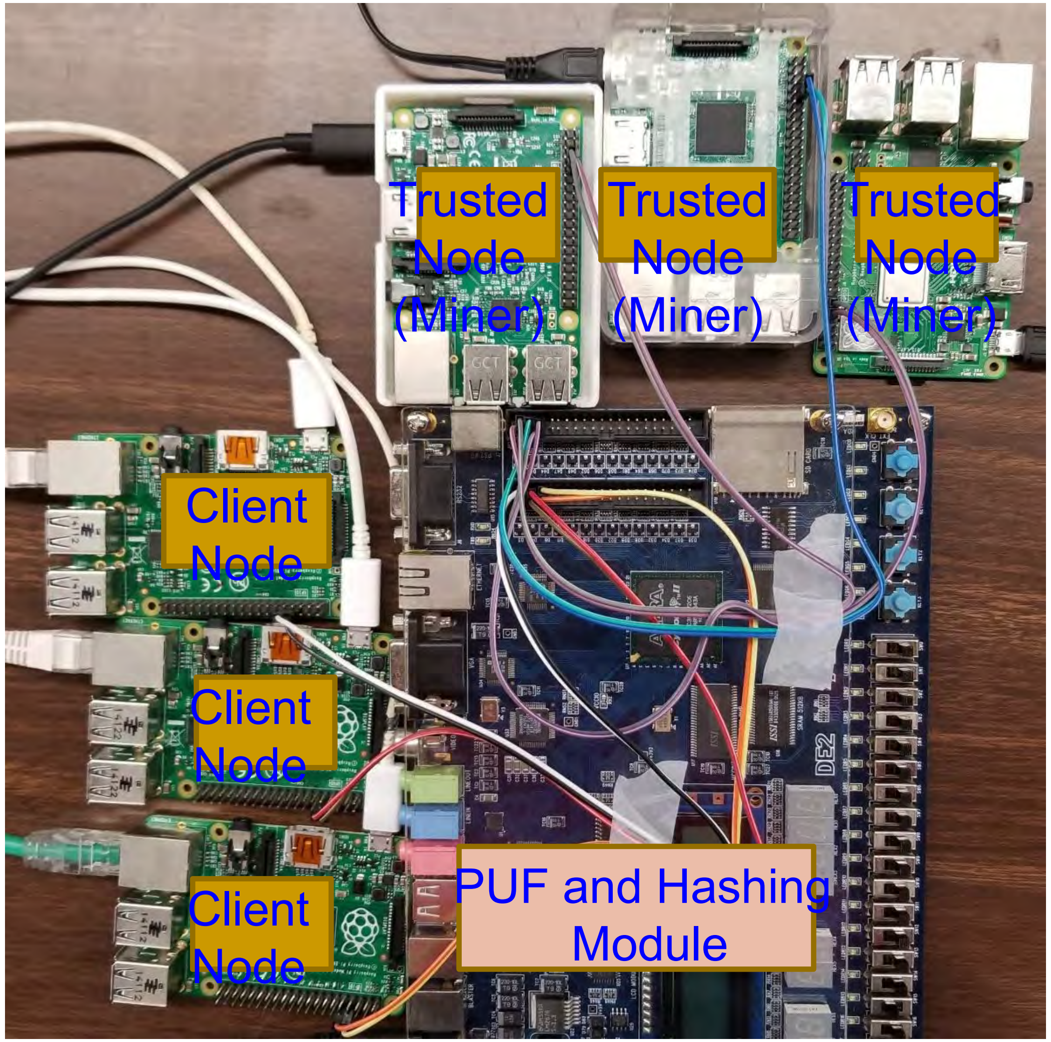
Proof-of-Work (PoW)

Eliminates cryptographic "puzzle" solving to validate blocks.

Uses a PUF-based authentication mechanism.

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: Our PoP is 1000X Faster than PoW

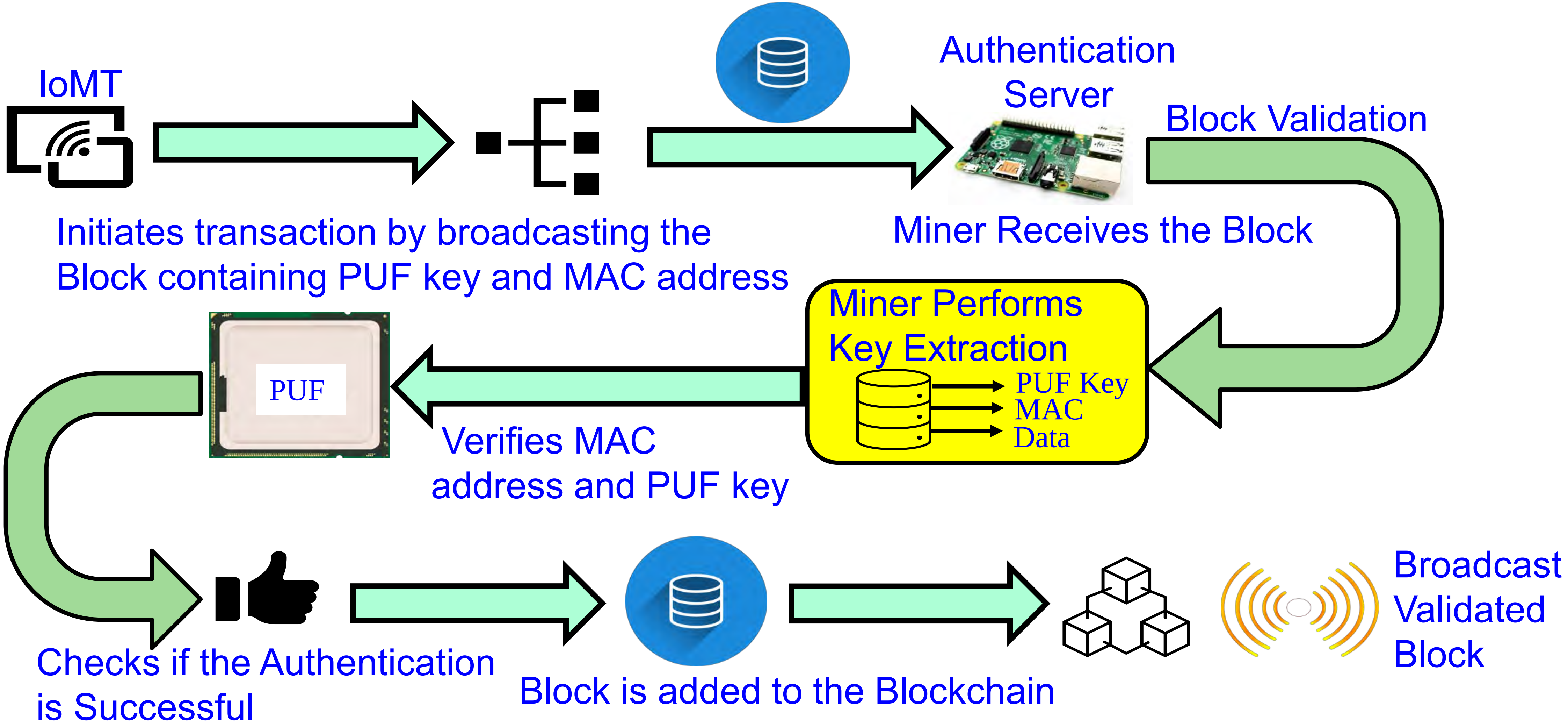


PoW - 10 min in cloud	PoAh – 950ms in Raspberry Pi	PoP - 192ms in Raspberry Pi
High Power	3 W Power	5 W Power

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

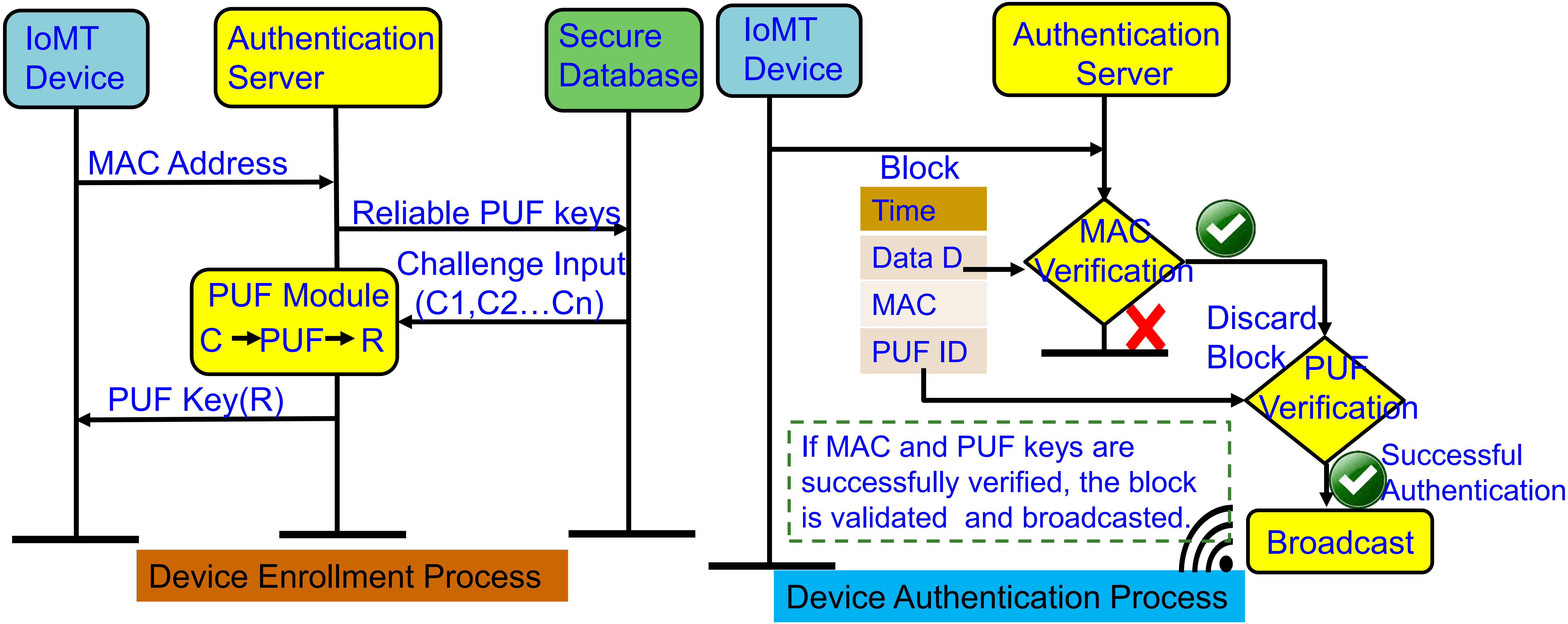
Source: S. P. Mohanty, V. P. Yanambaka, E. Kougianos, and D. Puthal, "PUFchain: Hardware-Assisted Blockchain for Sustainable Simultaneous Device and Data Security in Internet of Everything (IoE)", *IEEE Consumer Electronics Magazine (MCE)*, Vol. 9, No. 2, March 2020, pp. 8-16.

PUFchain 2.0: Our Hardware-Assisted Scalable Blockchain


IoMT
Authentication Server
Block Validation
Initiates transaction by broadcasting the Block containing PUF key and MAC address
Miner Receives the Block
Miner Performs Key Extraction
PUF Key
MAC
Data
PUF
Verifies MAC address and PUF key
Broadcast Validated Block
Checks if the Authentication is Successful
Block is added to the Blockchain

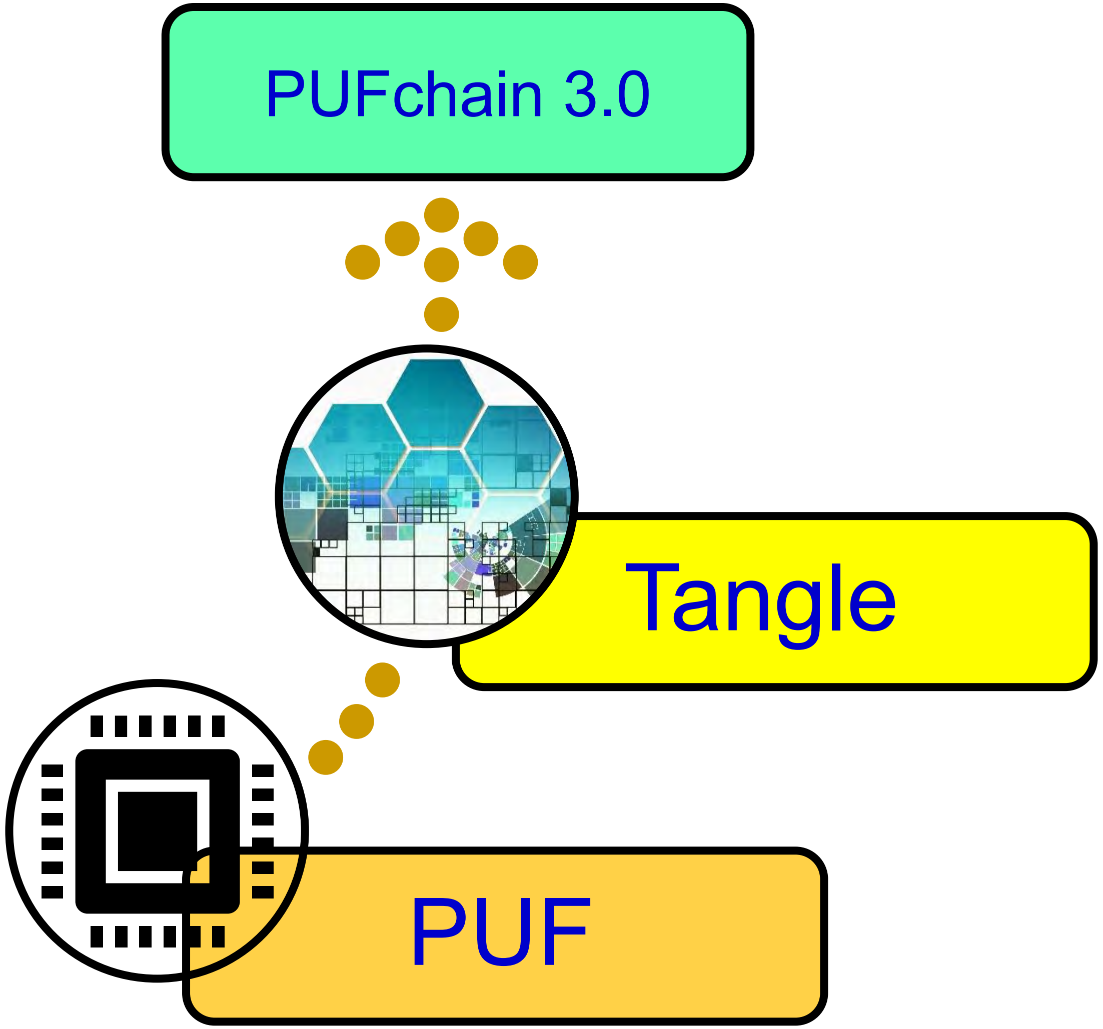
Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, B. K. Baniya, and B. Rout, "PUFchain 2.0: Hardware-Assisted Robust Blockchain for Sustainable Simultaneous Device and Data Security in Smart Healthcare", *Springer Nature Computer Science (SN-CS)*, Vol. 3, No. 5, Sep 2022, Article: 344,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

PUFchain 2.0: PUF Integrated 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.

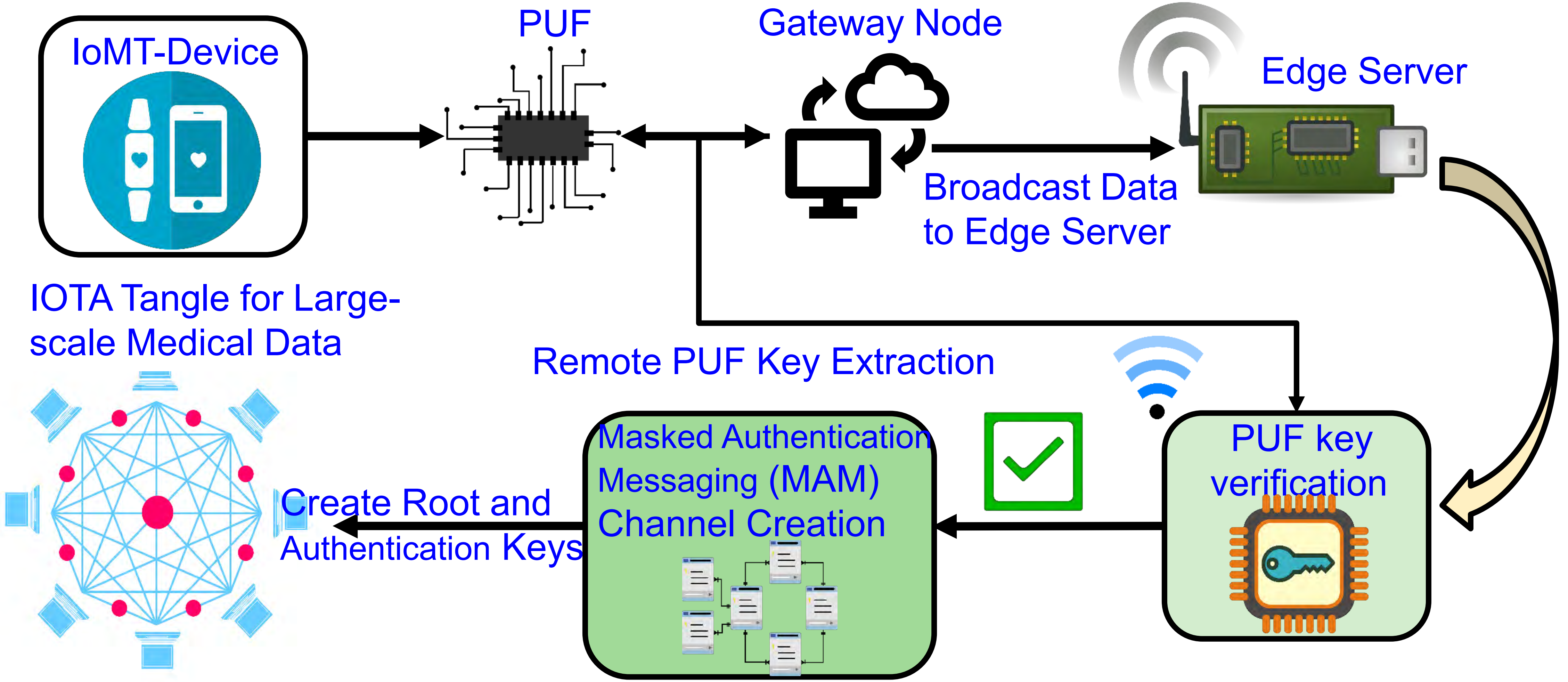
PUFchain 3.0 - Conceptual Idea



- PUFchain 3.0 is the idea of integrating PUF with scalable Tangle DLT using MAM communication protocol by creating a MAM communication channel in Tangle using PUF key

Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, 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.

PUFchain 3.0 - Architecture


IoMT-Device
PUF
Gateway Node
Edge Server
Broadcast Data to Edge Server
IOTA Tangle for Large-scale Medical Data
Remote PUF Key Extraction
Masked Authentication Messaging (MAM) Channel Creation
PUF key verification
Create Root and Authentication Keys

Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, 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.

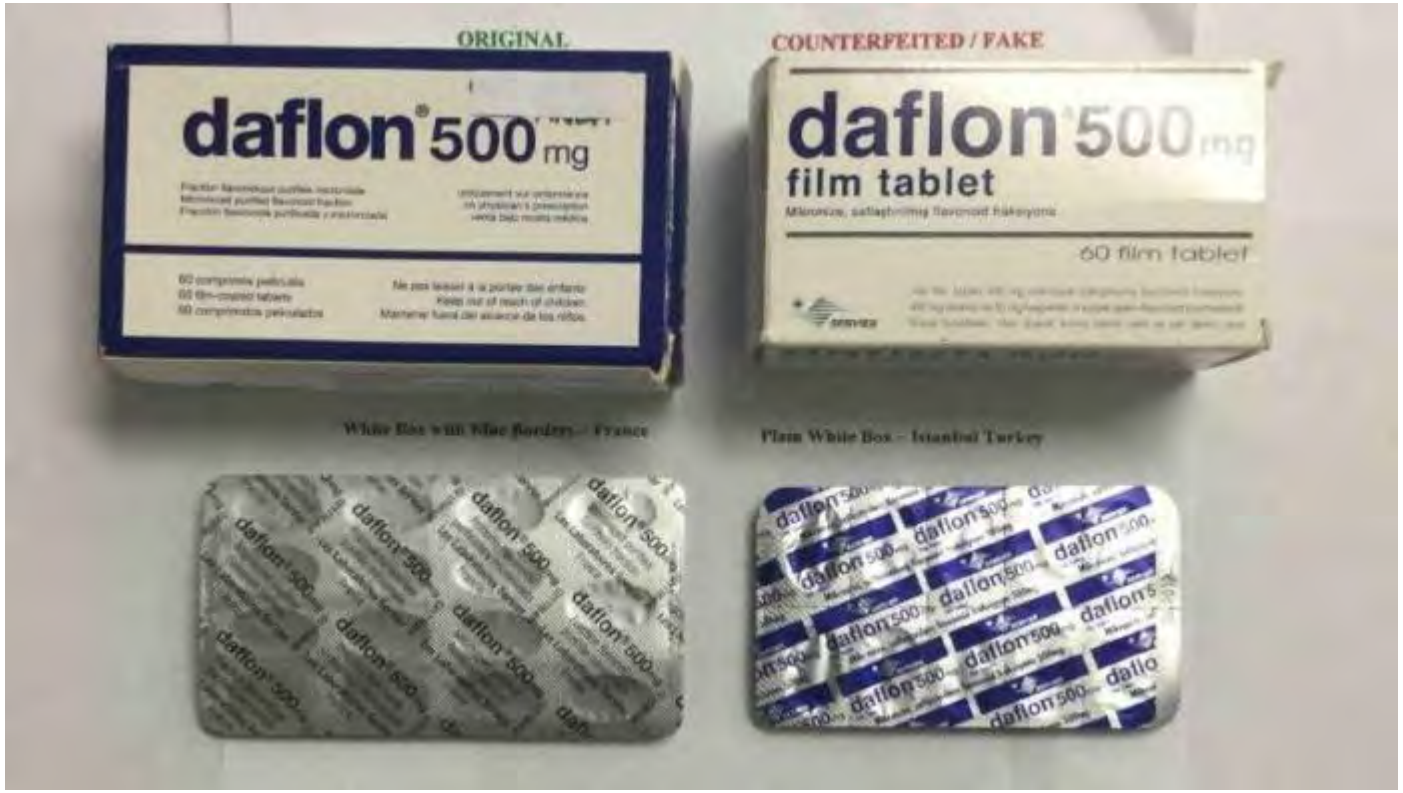
PUFchain 3.0: Comparative Analysis

Research Works	Application	DLT or Blockchain	Authentication Mechanism	Performance Metrics
Mohanty et al. 2020 - PUFchain	IoMT (Device and Data)	Blockchain	Proof-of-PUF-Enabled Authentication	PUF Design Uniqueness - 47.02%, Reliability-1.25%
Chaudhary et al. 2021 - Auto-PUFchain	Hawrdware Supply Chain	Blockchain	Smart Contracts	Gas Cost for Ethereum transaction 21.56 USD (5-Stage)
Al-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 %
Our PUFchain 3.0 in 2022	**IoMT (Device)**	**Tangle**	**Masked Authentication Messaging**	**Authentication 2.72 sec, Reliability - 100% (Approx), MAM Mode-Restricted**

Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, 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.

Smart Healthcare – Trustworthy Pharmaceutical Supply Chain

Counterfeits in Healthcare



Source: GA-FDD (Government Analyst –Food and Drug Department) issues warning over “fake” drug on local market, https://www.inewsguyana.com/ga-fdd-issues-warning-over-fake-drug-on-local-market/

The original product:

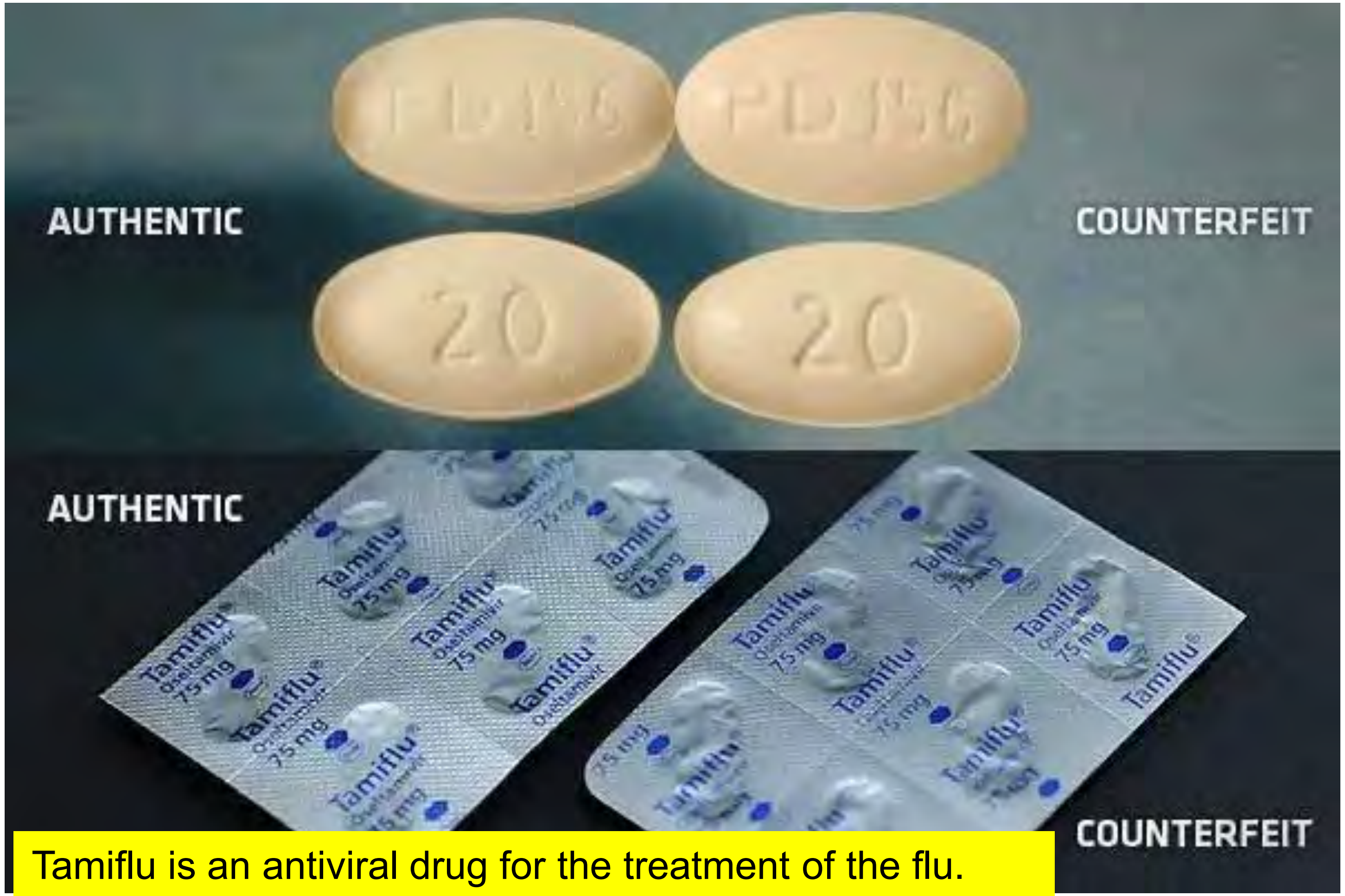
- sold in a white box with blue borders
- contains sixty (60) 500mg tablets
- divided on four (4) silver blister packs, each containing fifteen (15) tablets

The fake product:

- sold in a white box with no border
- contains sixty (60) 500mg tablets
- divided on six (6) silver with blue blister packs, each containing ten (10) tablets

Daflon 500 is used to treat gravitational (stasis) dermatitis and dermatofibrosclerosis

Counterfeits in Healthcare



Tamiflu is an antiviral drug for the treatment of the flu.

- Drug Components: Active Pharmaceutical Ingredient (API) + Excipients or inactive ingredients
- Counterfeit Drugs: Less API or no API or wrong API drugs produced in sub-standard conditions

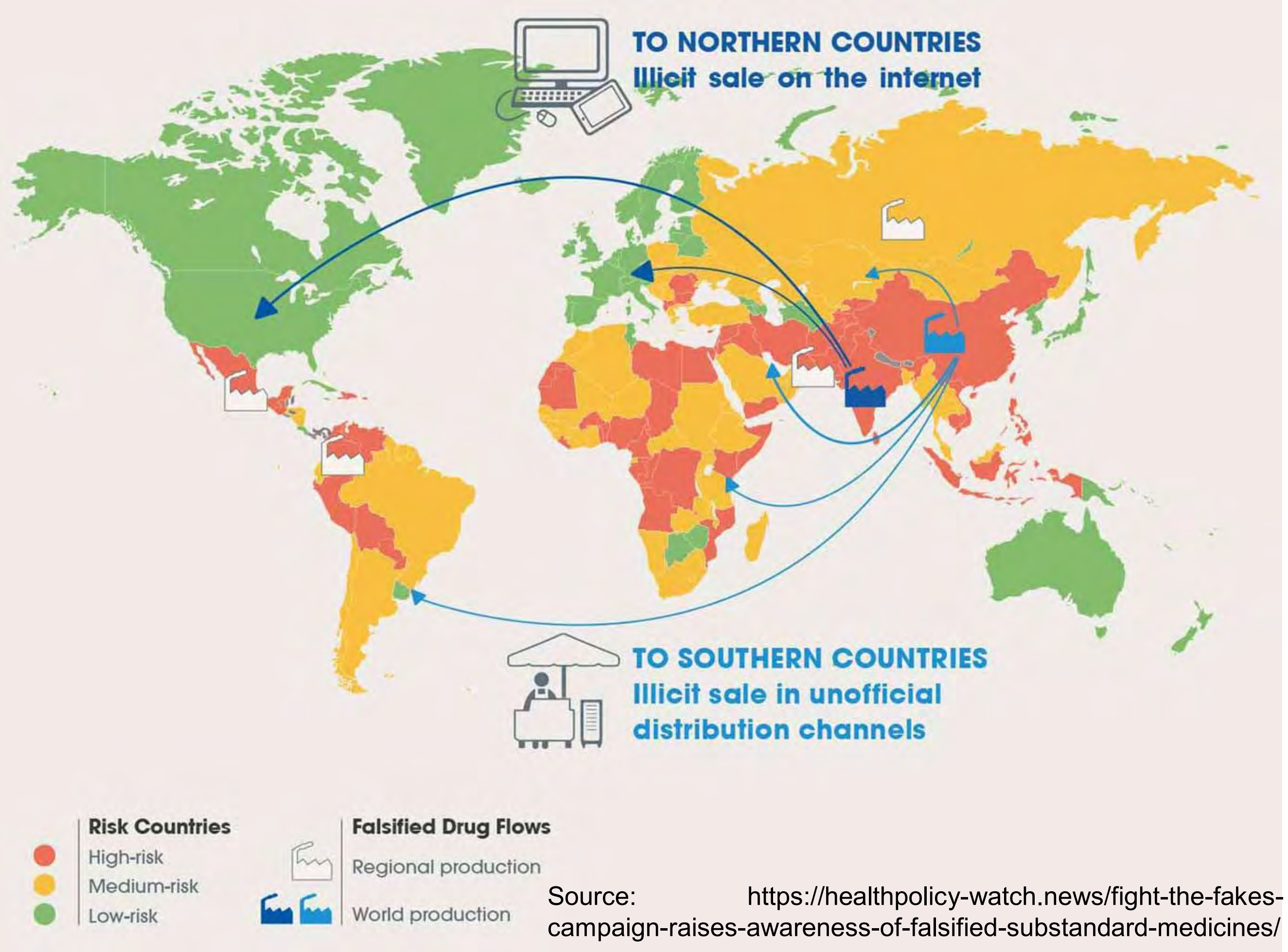
Source: GA-FDD’s (Government Analyst –Food and Drug Department’s) occasional fake drugs disclosures may be tip of the iceberg, https://www.stabroeknews.com/2019/09/06/business/ga-fdds-occasional-fake-drugs-disclosures-may-be-tip-of-the-iceberg/

Fake Medicine - Serious Global Issue

- It is estimated that close to $83 billion worth of counterfeit drugs are sold annually.
- One in 10 medical products circulating in developing countries are substandard or fake.
- In Africa: Counterfeit antimalarial drugs results in more than 120,000 deaths each year.
- USA has a closed drug distribution system intended to prevent counterfeits from entering U.S. markets, but it isn't foolproof due to many reason including illegal online pharmacy.

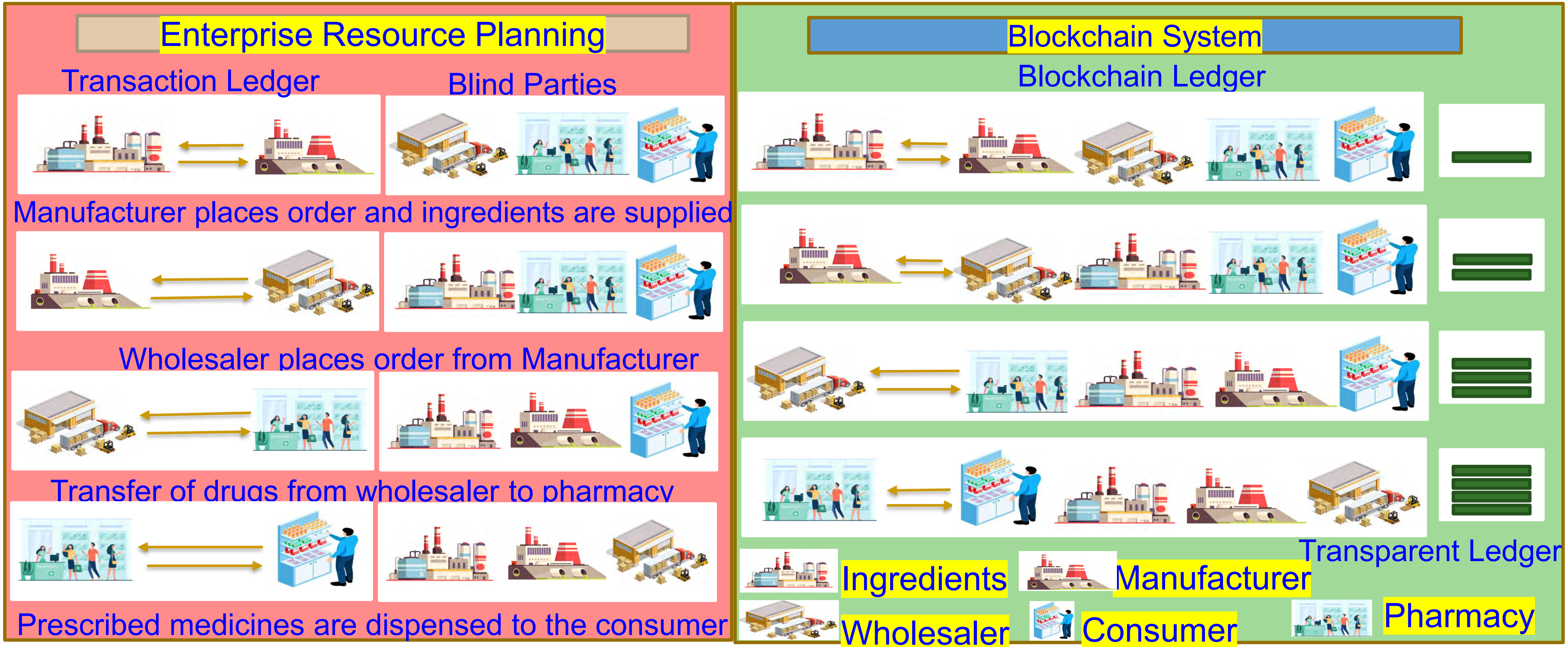
Source: https://fraud.org/fakerx/fake-drugs-and-their-risks/counterfeit-drugs-are-a-global-problem/

Source: https://allaboutpharmacovigilance.org/be-aware-of-counterfeit-medicine/



Source: https://healthpolicy-watch.news/fight-the-fakes-campaign-raises-awareness-of-falsified-substandard-medicines/

PharmaChain - Counterfeit Free Pharmaceutical



Enterprise Resource Planning

Transaction Ledger

Blind Parties

Manufacturer places order and ingredients are supplied

Wholesaler places order from Manufacturer

Transfer of drugs from wholesaler to pharmacy

Prescribed medicines are dispensed to the consumer

Blockchain System

Blockchain Ledger

Transparent Ledger

Ingredients

Manufacturer

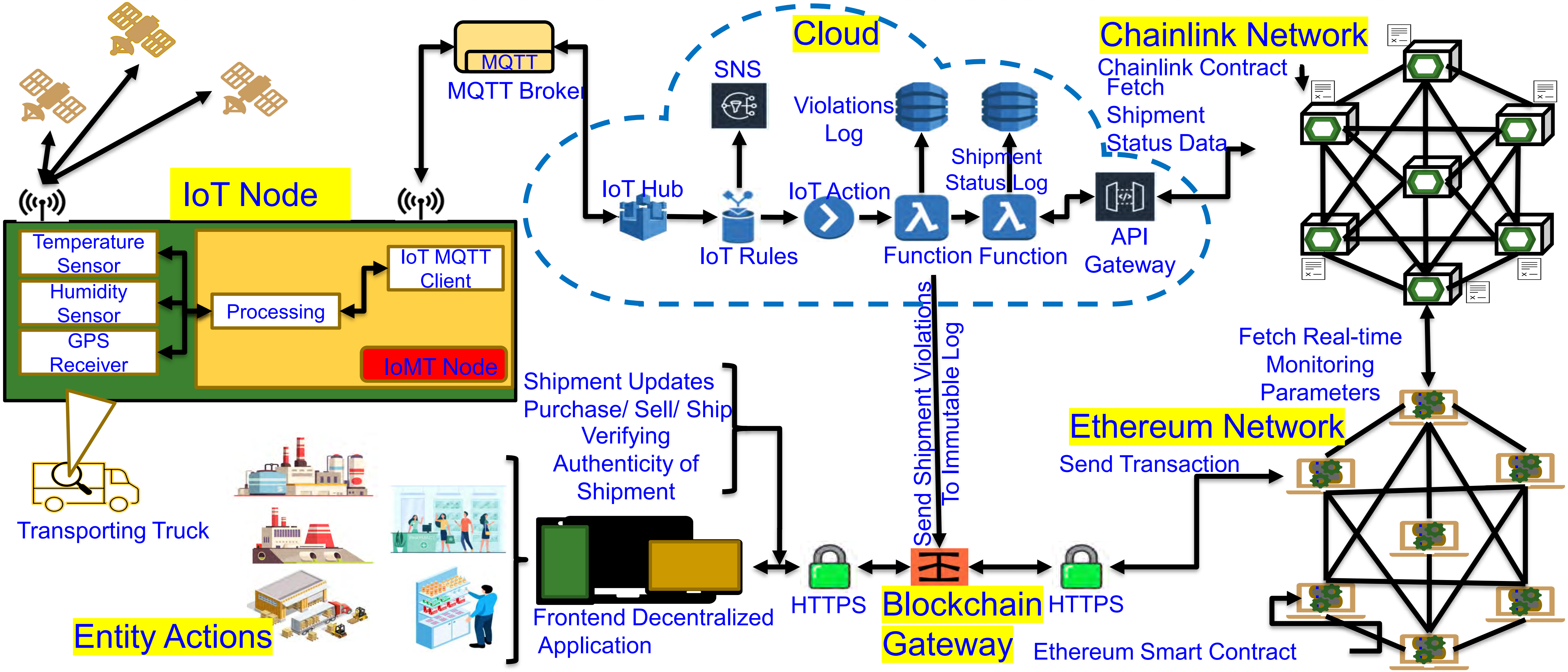
Wholesaler

Consumer

Pharmacy

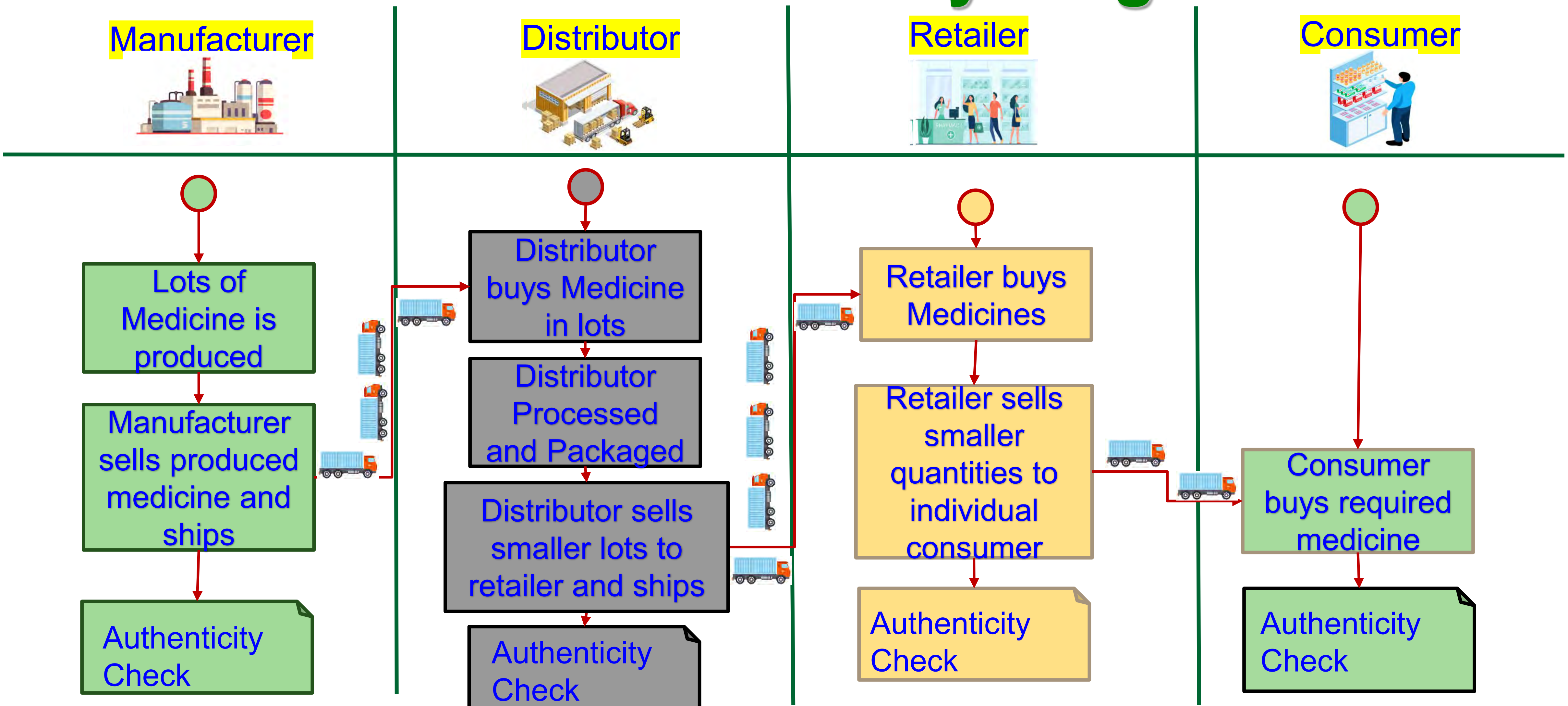
Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, D. Puthal, and A. Bapatla, "PharmaChain: A Blockchain to Ensure Counterfeit-Free Pharmaceutical Supply Chain", *IET Networks*, Vol. XX, No. YY, ZZ 2022, pp. Accepted on 24 June 2022, DOI: https://doi.org/10.1049/ntw2.12041. (Dataset for Research: GitHub)

Our PharmaChain: Architectural Overview



Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, D. Puthal, and A. Bapatla, “PharmaChain: A Blockchain to Ensure Counterfeit-Free Pharmaceutical Supply Chain”, *IET Networks*, Vol. 12, No. 2, March 2023, pp. 53--76, DOI: https://doi.org/10.1049/ntw2.12041. (Dataset for Research: GitHub)

PharmaChain Entity Diagram



Manufacturer

Lots of Medicine is produced

Manufacturer sells produced medicine and ships

Authenticity Check

Distributor

Distributor buys Medicine in lots

Distributor Processed and Packaged

Distributor sells smaller lots to retailer and ships

Authenticity Check

Retailer

Retailer buys Medicines

Retailer sells smaller quantities to individual consumer

Authenticity Check

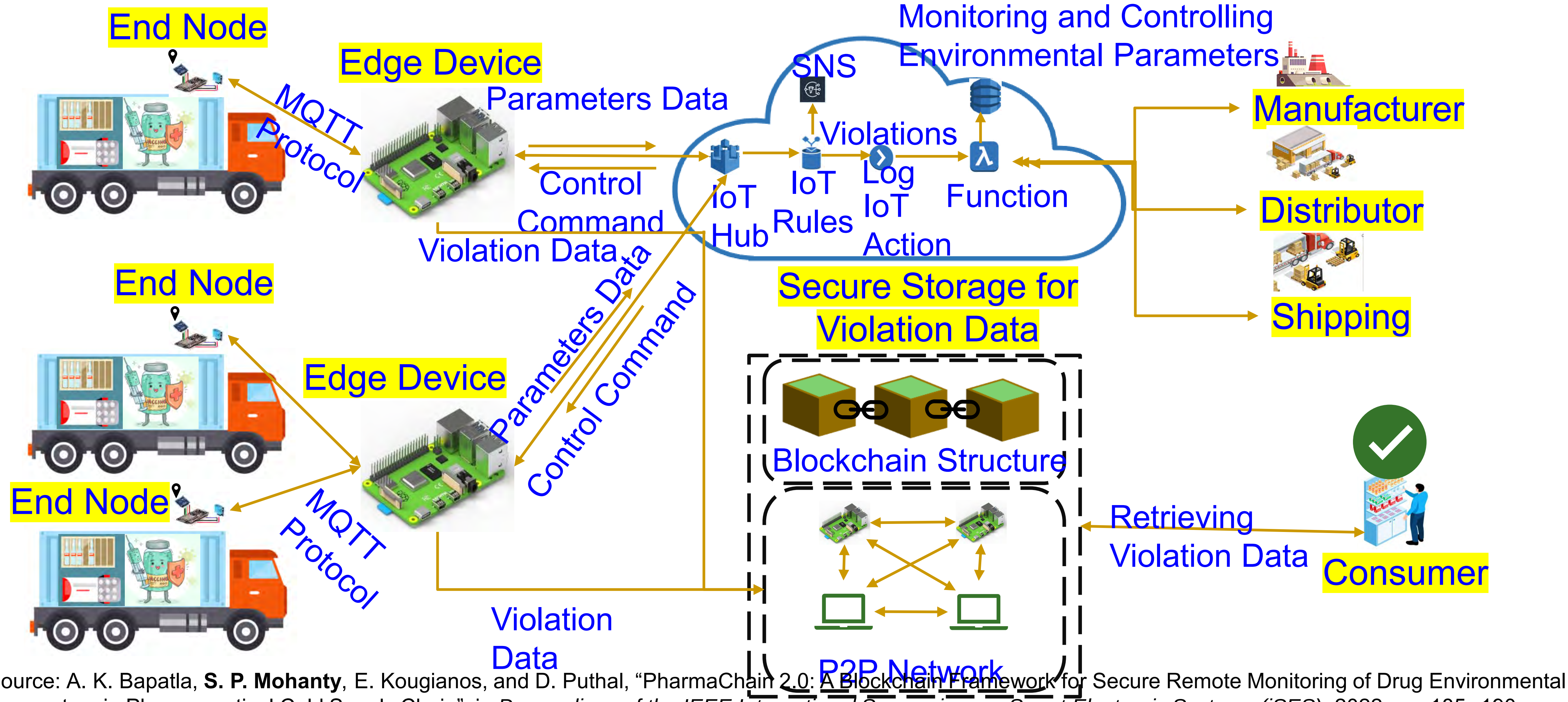
Consumer

Consumer buys required medicine

Authenticity Check

Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, D. Puthal, and A. Bapatla, "PharmaChain: A Blockchain to Ensure Counterfeit-Free Pharmaceutical Supply Chain", *IET Networks*, Vol. 12, No. 2, March 2023, pp. 53--76, DOI: https://doi.org/10.1049/ntw2.12041. (Dataset for Research: GitHub)

PharmaChain 2.0 - Architecture Overview



Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, and D. Puthal, “PharmaChain 2.0: A Blockchain Framework for Secure Remote Monitoring of Drug Environmental Parameters in Pharmaceutical Cold Supply Chain”, in *Proceedings of the IEEE International Symposium on Smart Electronic Systems (iSES)*, 2022, pp. 185--190, DOI: https://doi.org/10.1109/iSES54909.2022.00046.

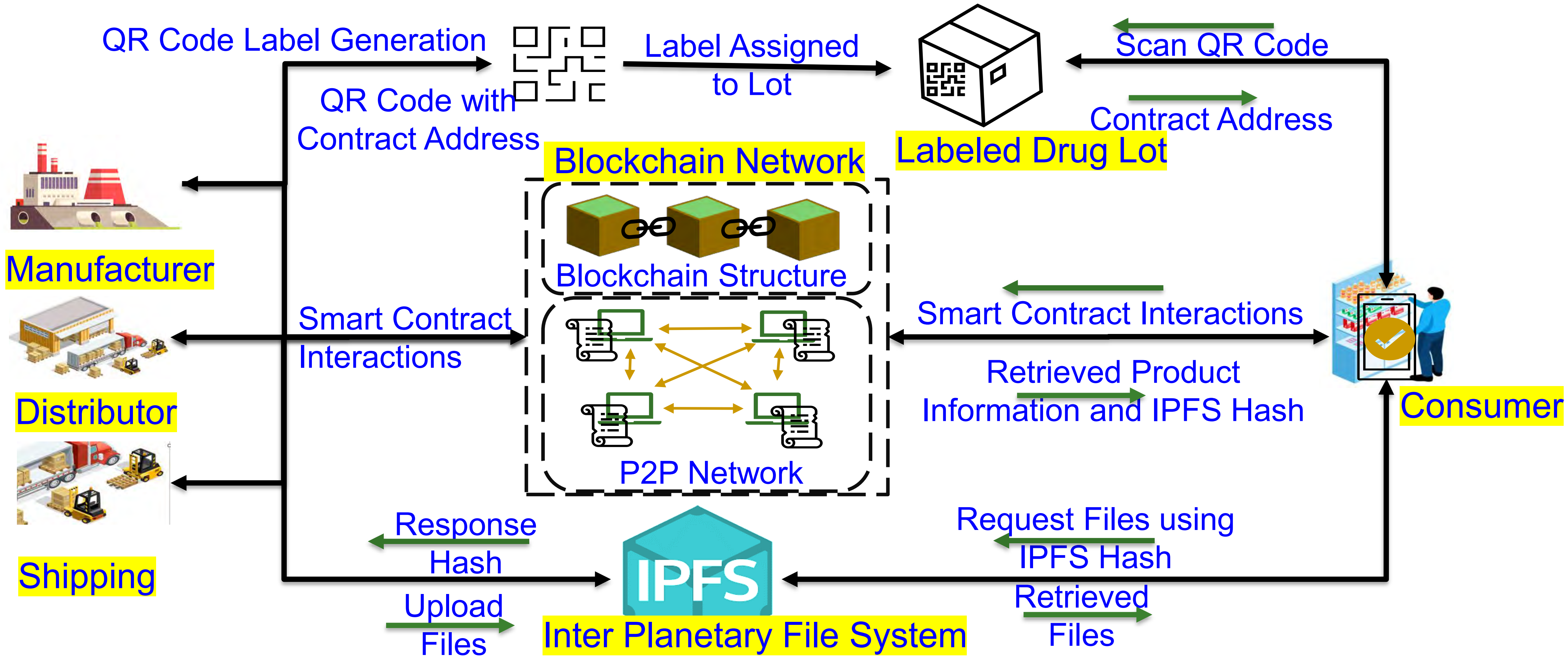
PharmaChain 2.0 - Comparative Analysis

Comparison of Proposed PharmaChain 2.0 solution with Existing Solutions

Features	**Blockchain**	**Consensus Protocol**	**Openness**	**IoT Friendly Consensus**	**Average Time**
CryptoCargo [15]	Ethereum	Proof-of-Work (PoW)	Public	No	43.36 sec
PharmaChain [9]	Ethereum	Proof-of-Authority (PoA)	Private	No	5.6 sec
Current Paper (PharmaChain 2.0)	PoAh Consensus Based Blockchain	Proof-of-Authentication (PoAh)	Private	Yes	322.28ms

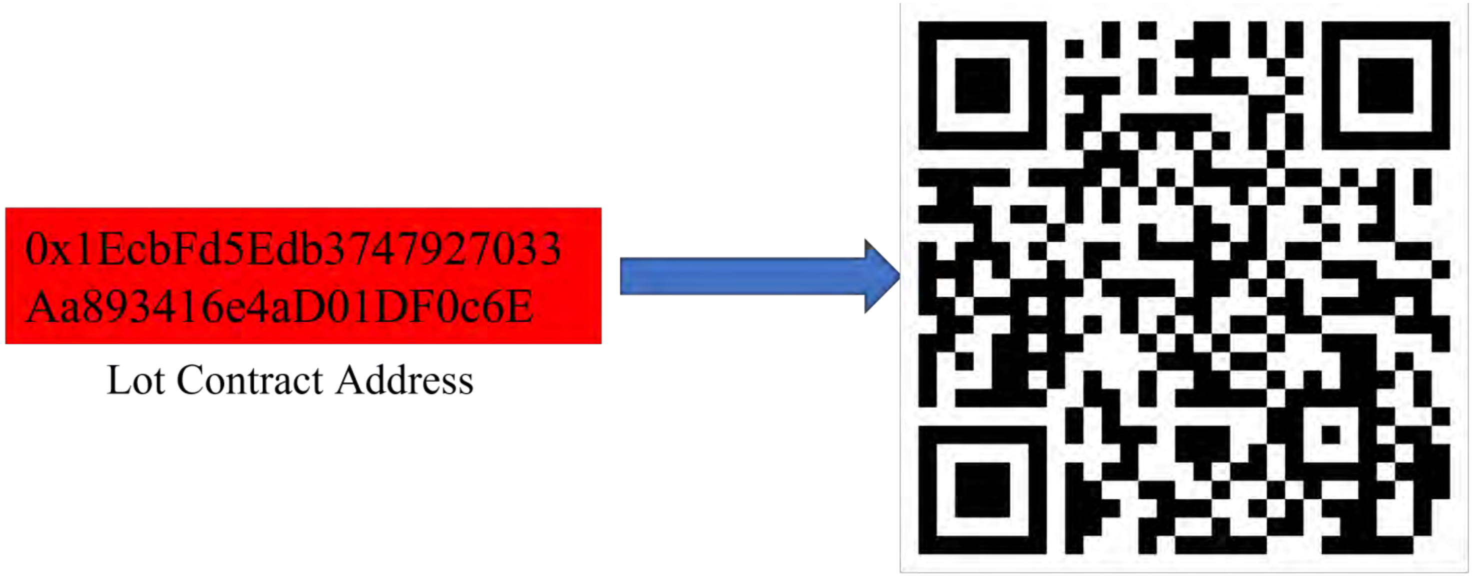
Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, and D. Puthal, “PharmaChain 2.0: A Blockchain Framework for Secure Remote Monitoring of Drug Environmental Parameters in Pharmaceutical Cold Supply Chain”, in *Proceedings of the IEEE International Symposium on Smart Electronic Systems (iSES)*, 2022, pp. Accepted.

PharmaChain 3.0 - Architectural Overview



Source: A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "PharmaChain 3.0: Efficient Tracking and Tracing of Drugs in Pharmaceutical Supply Chain using Blockchain Integrated Product Serialization Mechanism", *Springer Nature Computer Science (SN-CS)*, Vol. 5, No. 1, Jan 2024, Article: 149, 22-pages, DOI: https://doi.org/10.1007/s42979-023-02510-9.

PharmaChain 3.0 – The Key Idea



0x1EcbFd5Edb3747927033
Aa893416e4aD01DF0c6E

Lot Contract Address

QR Code Generated for Lot Labelling

New Lot Contract Address Converted to QR Code for Labeling

Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, and D. Puthal, “PharmaChain 3.0: Blockchain Integrated Efficient QR Code Mechanism for Pharmaceutical Supply Chain”, in *Proceedings of the OITS International Conference on Information Technology (OCIT)*, 2022, pp. Accepted.

PharmaChain 3.0 - Comparative Analysis

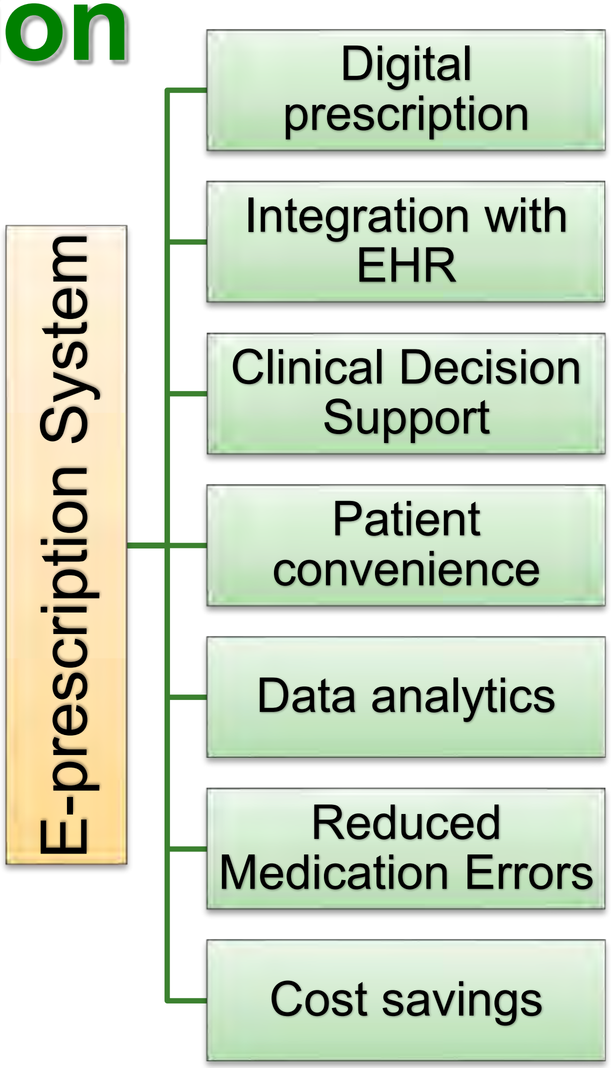
Works	Blockchain	Consensus Mechanism	Computational Needs	Openness	QR Code Integrated	Storage	Handling Large data
Crypto Cargo [11]	Ethereum	Proof-of-Work (PoW)	High	Public	No	On-Chain and Cloud	No
Kumar et.al. [9]	NA	NA	NA	NA	Yes	On-chain	No
PharmaChain [12]	Ethereum	Proof-of-Authority (PoA)	Low	Private	No	On-Chain and Cloud	No
PharmaChain 2.0	Our EasyChain	Proof-of-Authentication (PoAh)	Low	Private	No	On-Chain and Cloud	No
Current Solution (PharmaChain 3.0)	Ethereum	Proof-of-Stake (PoS)	Low	Private	Yes	On-Chain and off-Chain	Yes

Smart Healthcare –
Trustworthy Medical Prescription

Electronic Prescription

- Revolutionized the way medications are prescribed, processed, and dispensed
- Digital version of prescriptions increase legibility and reduces medication errors
- Clinical Decision Support Tools – Warn potential drug interactions, suggest alternate medication, offer dosage recommendations

- More than 100,000 reports of medication errors (FDA)
- 40% of Americans report being involved in medical errors (Institute for Healthcare Improvement/NORC at the University of Chicago)
- 1 in 5 doses of medication provided during patient visits is administered incorrectly

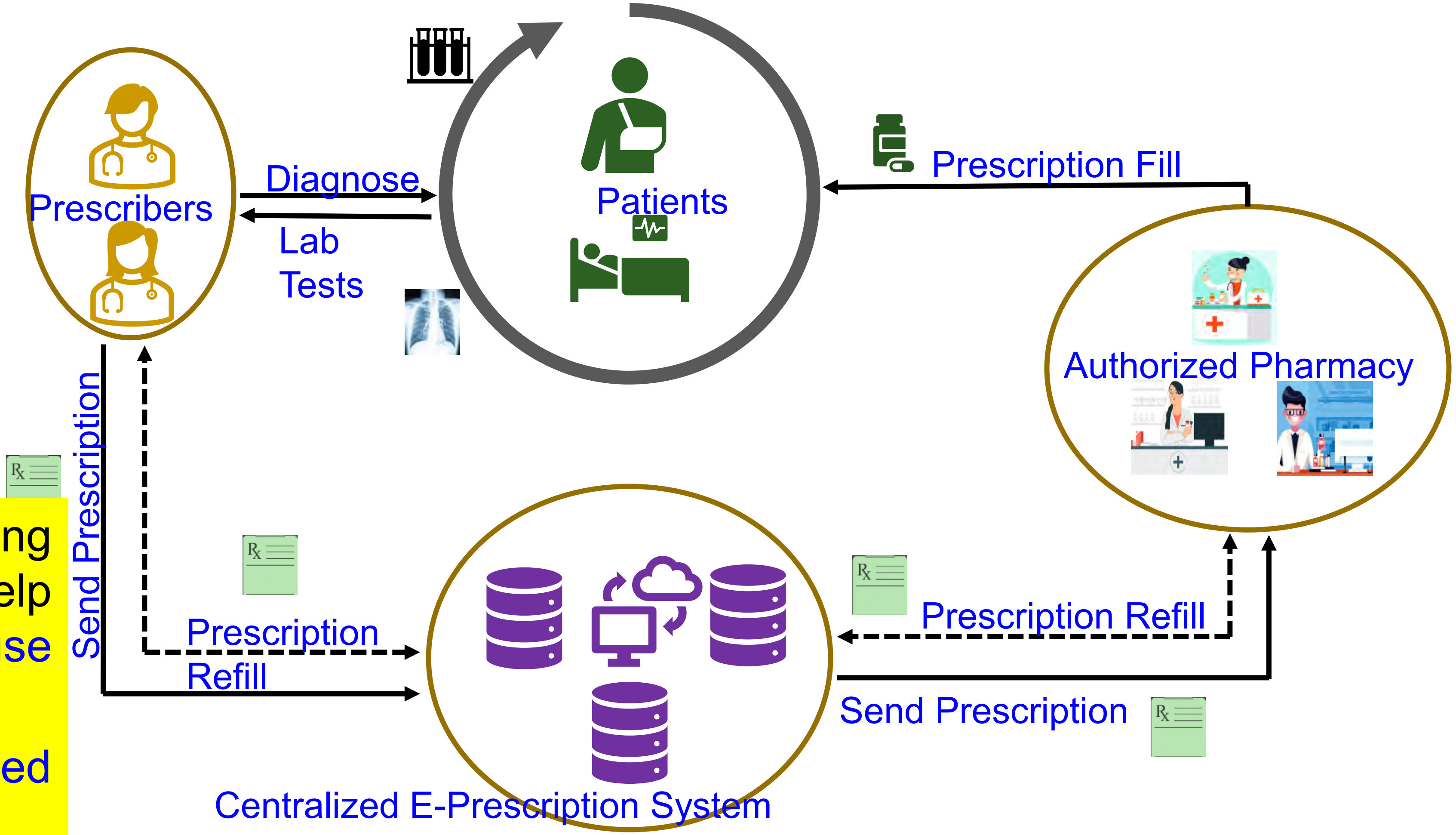


Source: A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "FortiRx: Distributed Ledger Based Verifiable and Trustworthy Electronic Prescription Sharing", in *Proceedings of the IFIP International Internet of Things Conference (IFIP-IoT)*, 2023, pp. 283--301, DOI: https://doi.org/10.1007/978-3-031-45882-8_19.

E-Prescription System and Issues

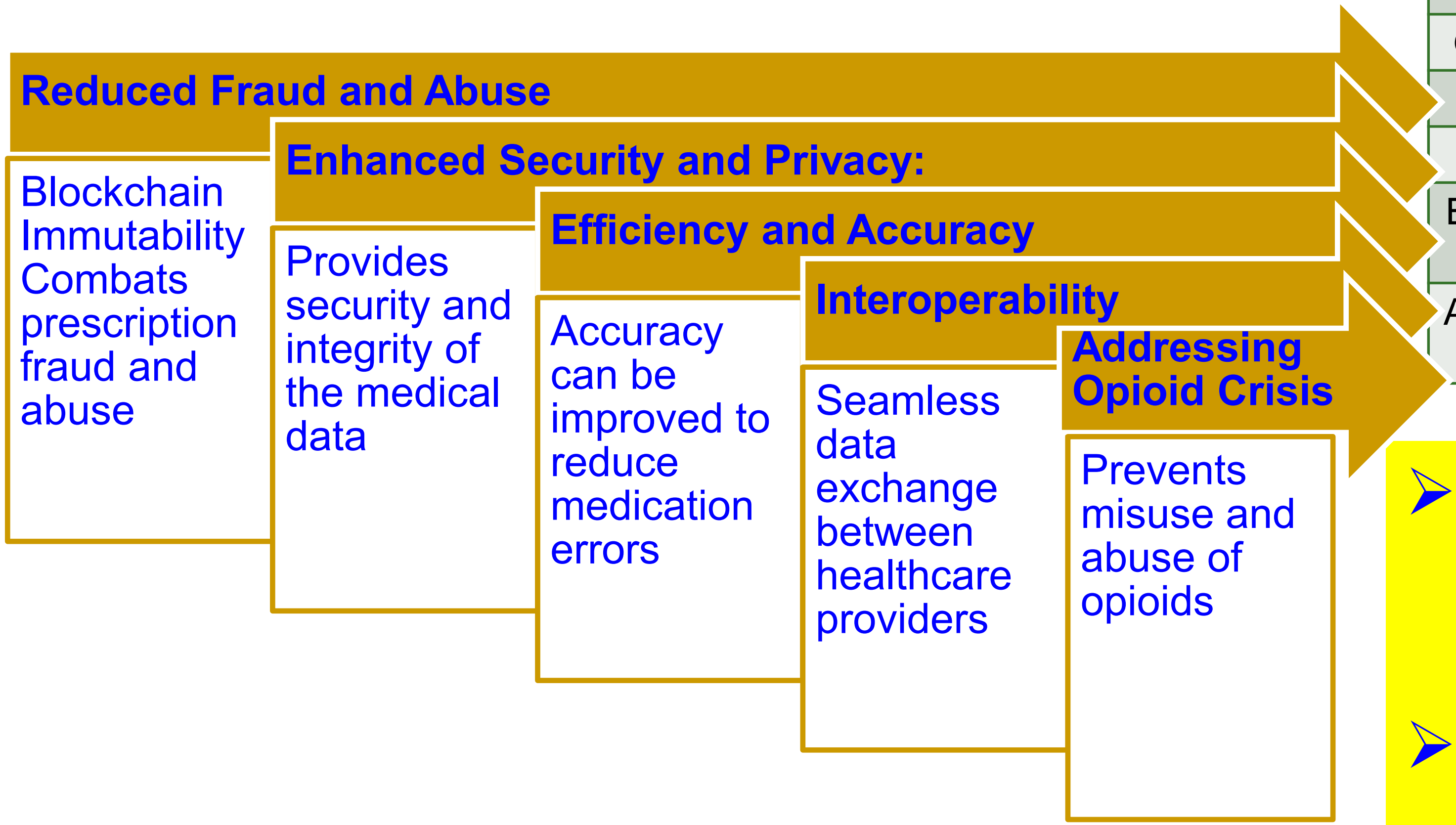
- Single Point of Failure (SPOF)
- Data Security
- Privacy Concerns
- Interoperability Concerns (PDMP)
- System availability Issues

- Prescription Drug Monitoring Programs(PDMP) help mitigate prescription misuse and diversion
- Oversight of controlled substance prescriptions



Source: A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "FortiRx: Distributed Ledger Based Verifiable and Trustworthy Electronic Prescription Sharing", in *Proceedings of the IFIP International Internet of Things Conference (IFIP-IoT)*, 2023, pp. 283--301, DOI: https://doi.org/10.1007/978-3-031-45882-8_19.

E-Prescription is the Need of the Hour



Reduced Fraud and Abuse

Blockchain Immutability Combats prescription fraud and abuse

Enhanced Security and Privacy:

Provides security and integrity of the medical data

Efficiency and Accuracy

Accuracy can be improved to reduce medication errors

Interoperability

Seamless data exchange between healthcare providers

Addressing Opioid Crisis

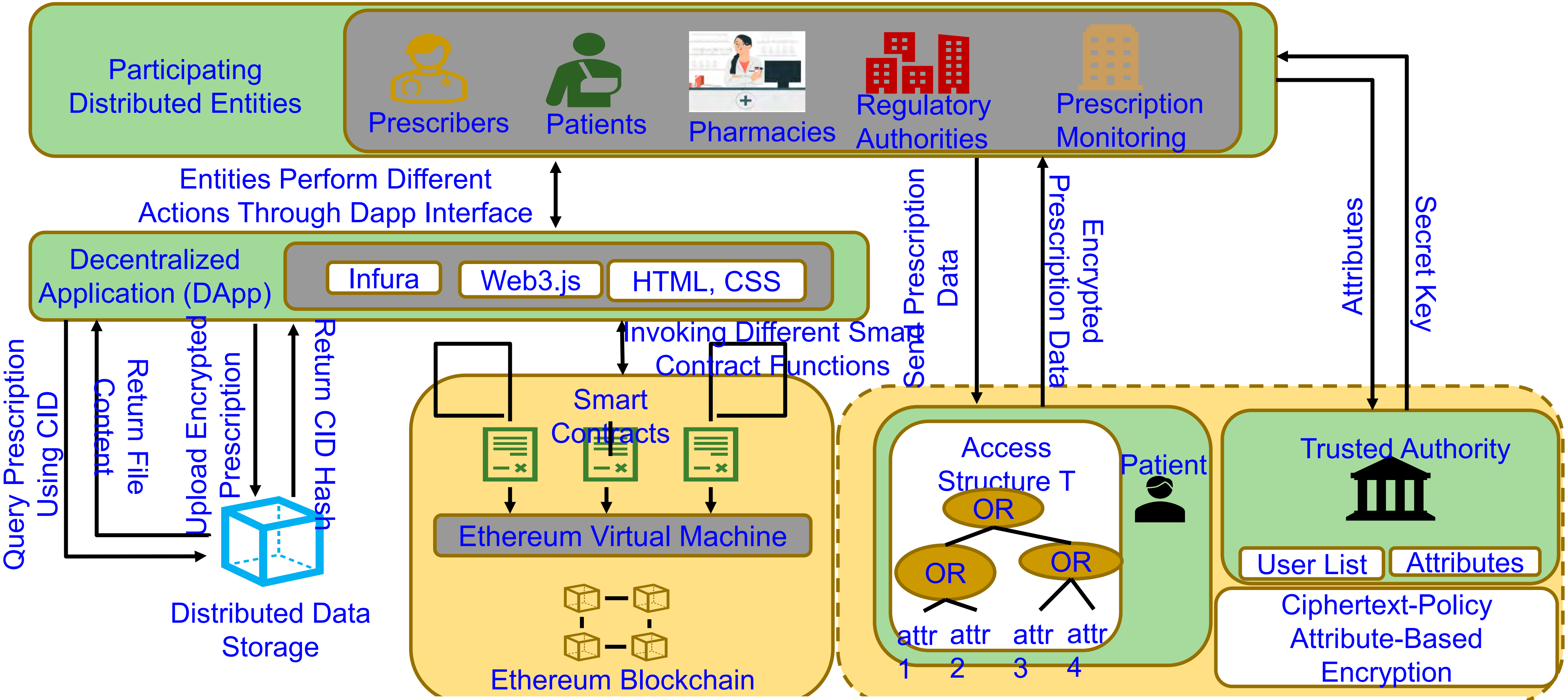
Prevents misuse and abuse of opioids

Prescription Drug Type	Annual Abusers	% Among Rx Abusers	% Among Americans
Painkillers	9.7 million	59.5%	3.43%
Opioids Alone	9.3 million	57.1%	3.29%
Sedatives	5.9 million	36.2%	2.08%
Stimulants	4.9 million	30.1%	1.73%
Benzodiazepine Alone	4.8 million	29.4%	1.70%
All Prescription Drugs	16.3 million	100%	5.76%

- 16M – 6% of Americans over the age of 12 abuse prescriptions in a year.
- 2M – 12% of prescription drug abusers are addicted.

Statistics Source: https://drugabusestatistics.org/prescription-drug-abuse-statistics/

Our FortiRx: Architecture Overview



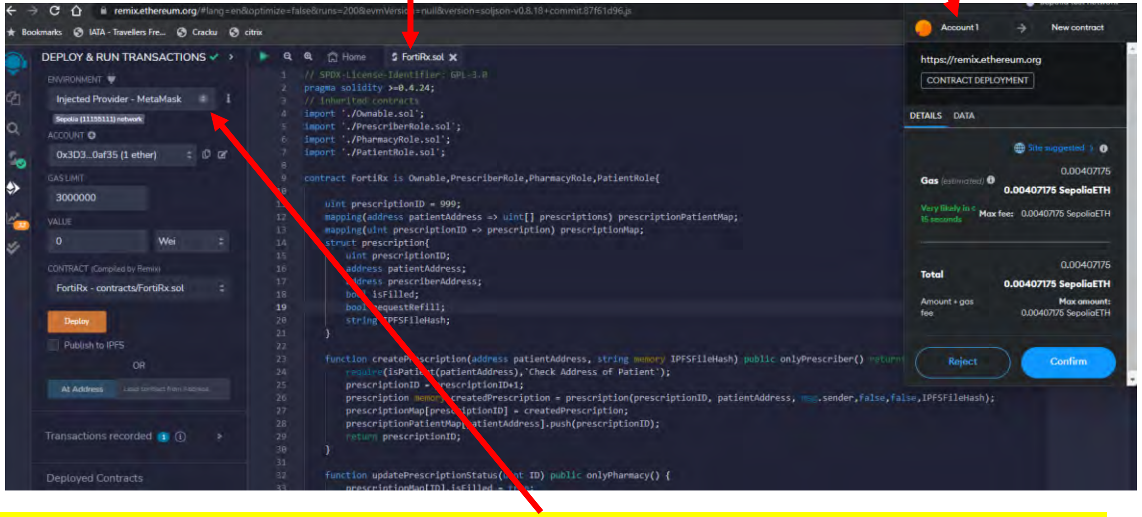
Source: A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "FortiRx: Distributed Ledger Based Verifiable and Trustworthy Electronic Prescription Sharing", in *Proceedings of the IFIP International Internet of Things Conference (IFIP-IoT)*, 2023, pp. 283--301, DOI: https://doi.org/10.1007/978-3-031-45882-8_19.

FortiRx: Smart Contract Deployment

Deployment in Sepolia

Smart Contract

Wallet Transaction


remix.ethereum.org/#lang=en&optimize=false&runs=200&evmVersion=null&version=soljson-v0.8.18+commit.87f61d96.js
Bookmarks
IATA - Travellers Fre...
Cracku
citrix
DEPLOY & RUN TRANSACTIONS
Home
FortiRx.sol
Account 1
New contract
https://remix.ethereum.org
CONTRACT DEPLOYMENT
DETAILS
DATA
Site suggested
Deploy
OR
At Address
Load contract from Address
Reject
Confirm

ENVIRONMENT: Injected Provider - MetaMask

Sepolia (11155111) network

ACCOUNT: 0x3D3...0af35 (1 ether)

GAS LIMIT: 3000000

VALUE: 0 Wei

CONTRACT (Compiled by Remix): FortiRx - contracts/FortiRx.sol

☐ Publish to IPFS

Transactions recorded 1

Deployed Contracts

```
// SPDX-License-Identifier: GPL-3.0
pragma solidity >=0.4.24;
// inherited contracts
import './Ownable.sol';
import './PrescriberRole.sol';
import './PharmacyRole.sol';
import './PatientRole.sol';

contract FortiRx is Ownable,PrescriberRole,PharmacyRole,PatientRole{

    uint prescriptionID = 999;
    mapping(address patientAddress => uint[] prescriptions) prescriptionPatientMap;
    mapping(uint prescriptionID -> prescription) prescriptionMap;
    struct prescription{
        uint prescriptionID;
        address patientAddress;
        address prescriberAddress;
        bool isFilled;
        bool requestRefill;
        string IPFSFileHash;
    }

    function createPrescription(address patientAddress, string memory IPFSFileHash) public onlyPrescriber() returns
        require(isPatient(patientAddress),'Check Address of Patient');
        prescriptionID = prescriptionID+1;
        prescription memory createdPrescription = prescription(prescriptionID, patientAddress, msg.sender,false,false,IPFSFileHash);
        prescriptionMap[prescriptionID] = createdPrescription;
        prescriptionPatientMap[patientAddress].push(prescriptionID);
        return prescriptionID;
    }

    function updatePrescriptionStatus(uint ID) public onlyPharmacy() {
        prescriptionMap[ID].isFilled = true;
```

Gas (estimated) 0.00407175 **0.00407175 SepoliaETH**

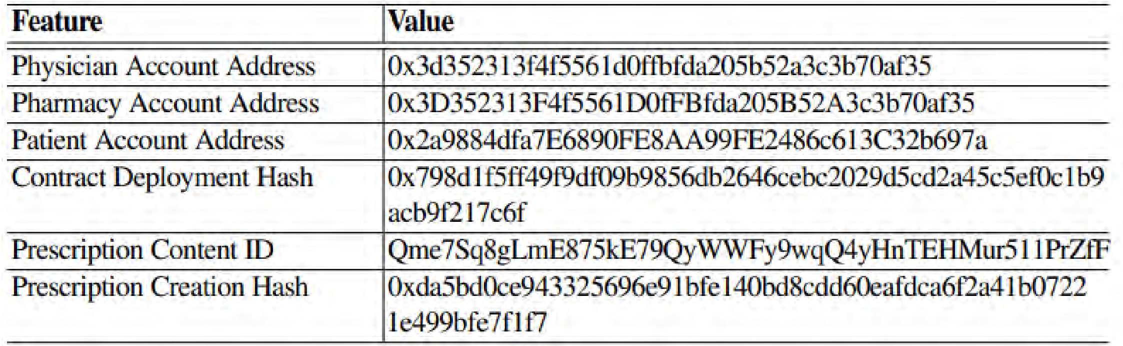
Very likely in < 15 seconds — Max fee: 0.00407175 SepoliaETH

Total 0.00407175 **0.00407175 SepoliaETH**

Amount + gas fee — Max amount: 0.00407175 SepoliaETH

Remix Environment Network Configuration

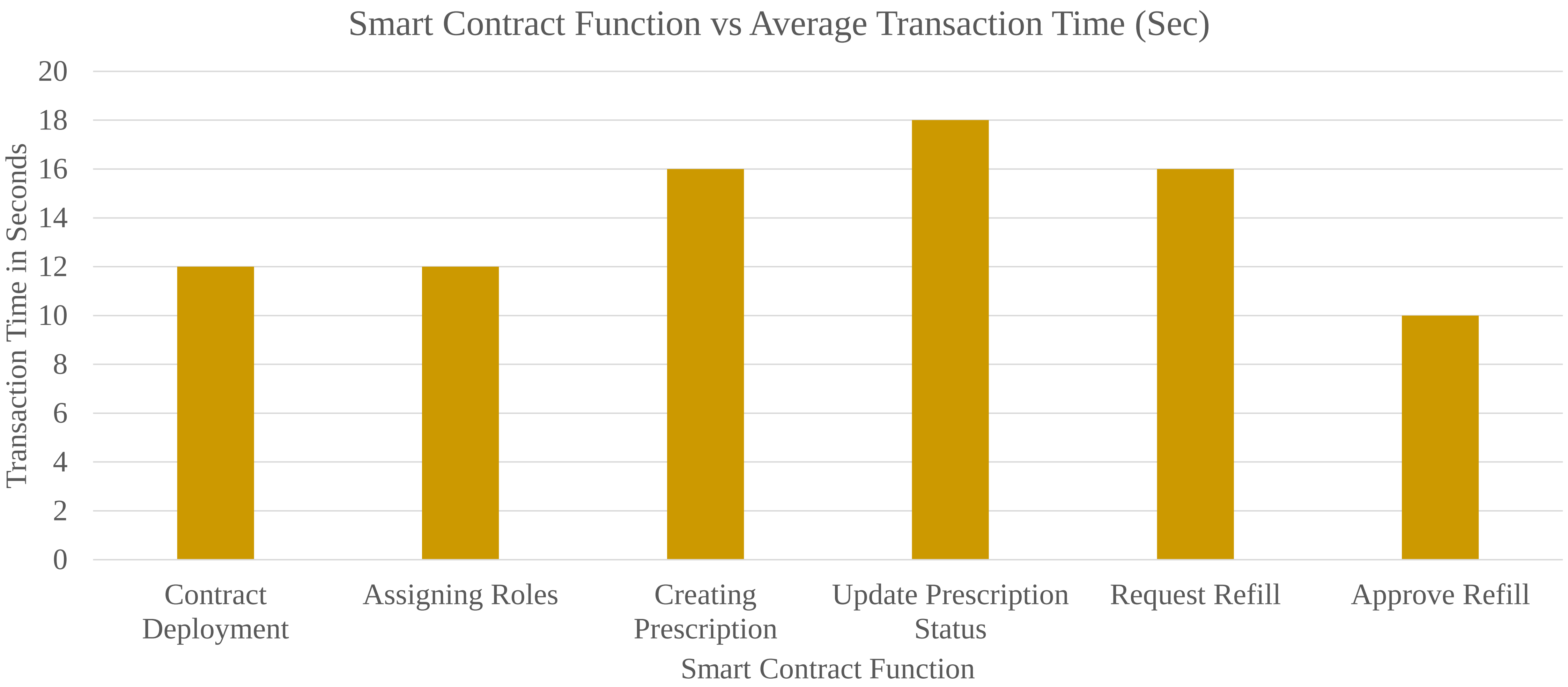
Ethereum Addresses with Roles



Feature	Value
Physician Account Address	0x3d352313f4f5561d0ffbfda205b52a3c3b70af35
Pharmacy Account Address	0x3D352313F4f5561D0fFBfda205B52A3c3b70af35
Patient Account Address	0x2a9884dfa7E6890FE8AA99FE2486c613C32b697a
Contract Deployment Hash	0x798d1f5ff49f9df09b9856db2646cebc2029d5cd2a45c5ef0c1b9 acb9f217c6f
Prescription Content ID	Qme7Sq8gLmE875kE79QyWWFy9wqQ4yHnTEHMur511PrZfF
Prescription Creation Hash	0xda5bd0ce943325696e91bfe140bd8cdd60eafdca6f2a41b0722 1e499bfe7f1f7

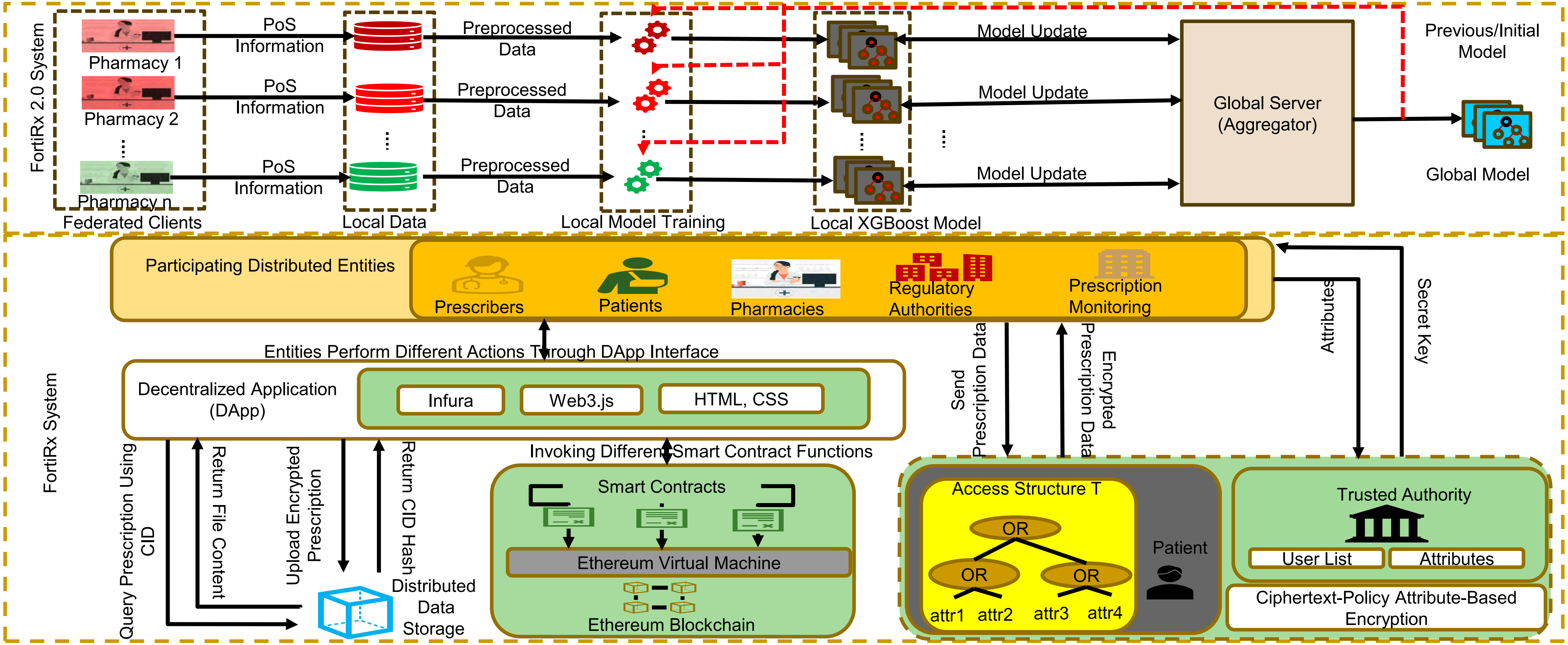
Source: A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "FortiRx: Distributed Ledger Based Verifiable and Trustworthy Electronic Prescription Sharing", in *Proceedings of the IFIP International Internet of Things Conference (IFIP-IoT)*, 2023, pp. 283--301, DOI: https://doi.org/10.1007/978-3-031-45882-8_19.

FortiRx: Transaction Confirmation Times



Source: A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "FortiRx: Distributed Ledger Based Verifiable and Trustworthy Electronic Prescription Sharing", in *Proceedings of the IFIP International Internet of Things Conference (IFIP-IoT)*, 2023, pp. 283--301, DOI: https://doi.org/10.1007/978-3-031-45882-8_19.

Our FortiRx 2.0: Architecture



Source: A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "FortiRx 2.0: Smart Privacy-Preserved Demand Forecasting of Prescription Drugs in Healthcare-CPS", in *Proceedings of the OITS International Conference on Information Technology (OCIT)*, 2023, pp. 438--443, DOI: https://doi.org/10.1109/OCIT59427.2023.10430944.

FortiRx – A Comparative Perspective

Works	Blockchain Platform	Prescription Privacy	Data Management	Drug Demand Forecasting
Ionescu et al, SmartBlock4Health, 2022	Ethereum	Asymmetric Encryption	On-chain	✗
VigilRx, 2022	Ethereum	Role-Based Access Control	On-Chain	✗
FortiRx, 2023	Ethereum	Role-Based Access Control and CP-ABE	On-chain and off-chain	✗
FortiRx 2.0	Ethereum	Role-Based Access Control and CP-ABE	On-chain and off-chain	✓

Source: A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "FortiRx 2.0: Smart Privacy-Preserved Demand Forecasting of Prescription Drugs in Healthcare-CPS", in *Proceedings of the OITS International Conference on Information Technology (OCIT)*, 2023, pp. 438--443, DOI: https://doi.org/10.1109/OCIT59427.2023.10430944.

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

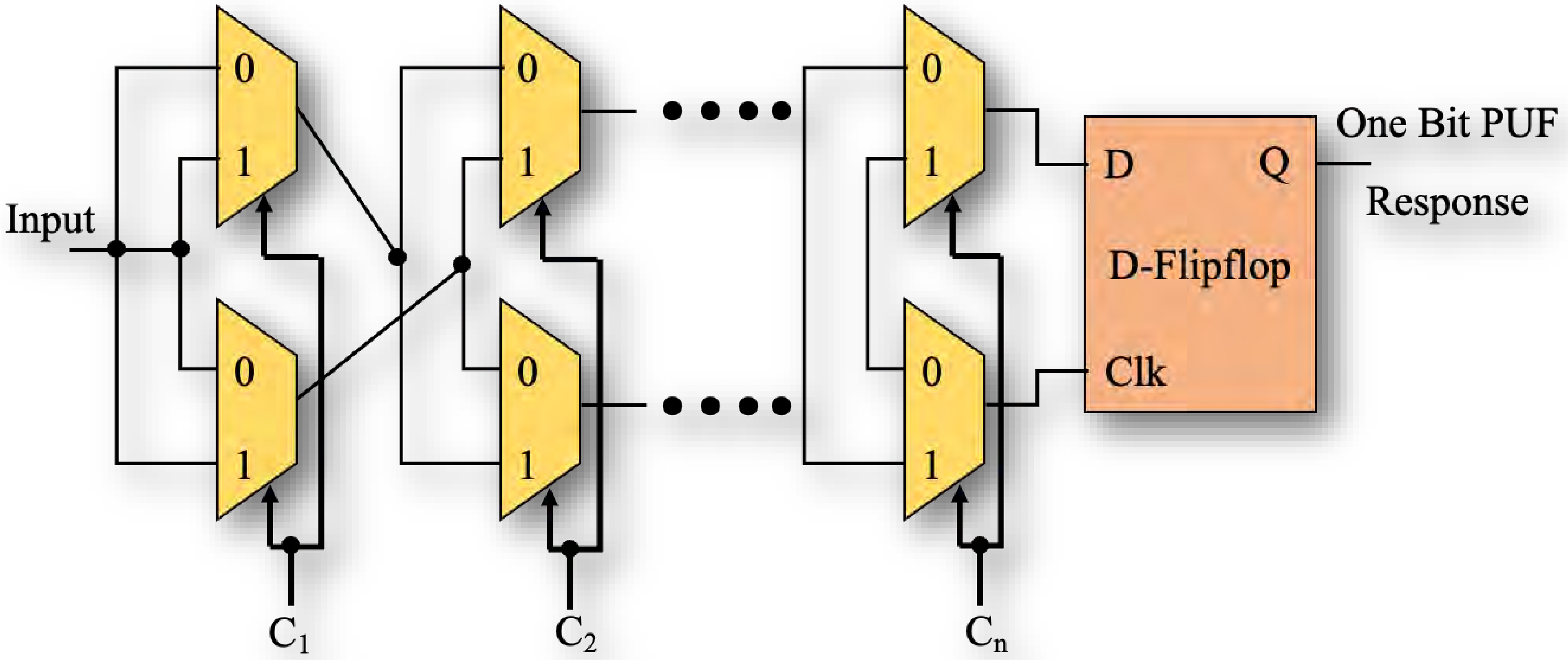
If PUF is So Great, Why Isn't Everyone Using It?

- 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

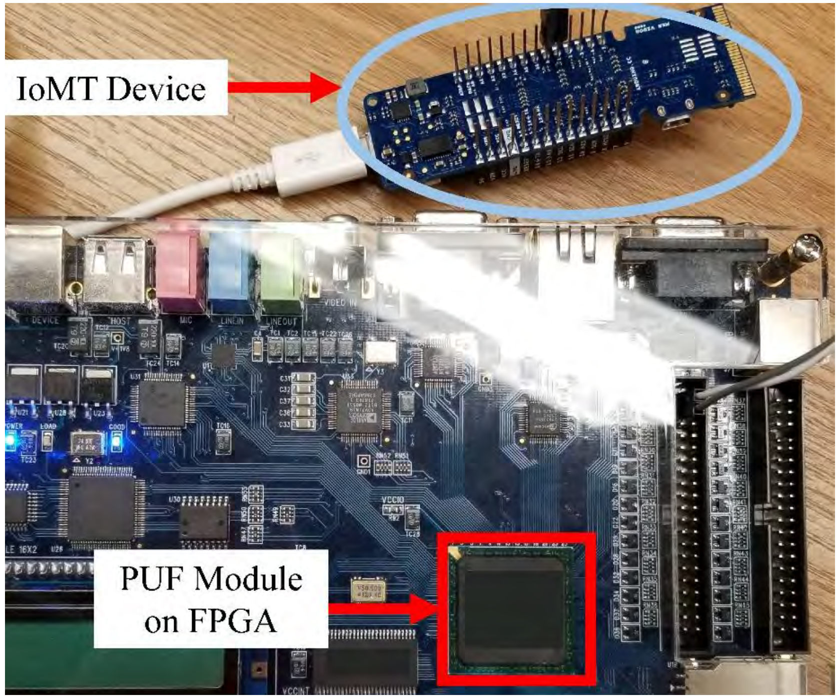
PUF Limitations – Larger Key Needs Large ICs

- Larger key requires larger chip circuit.



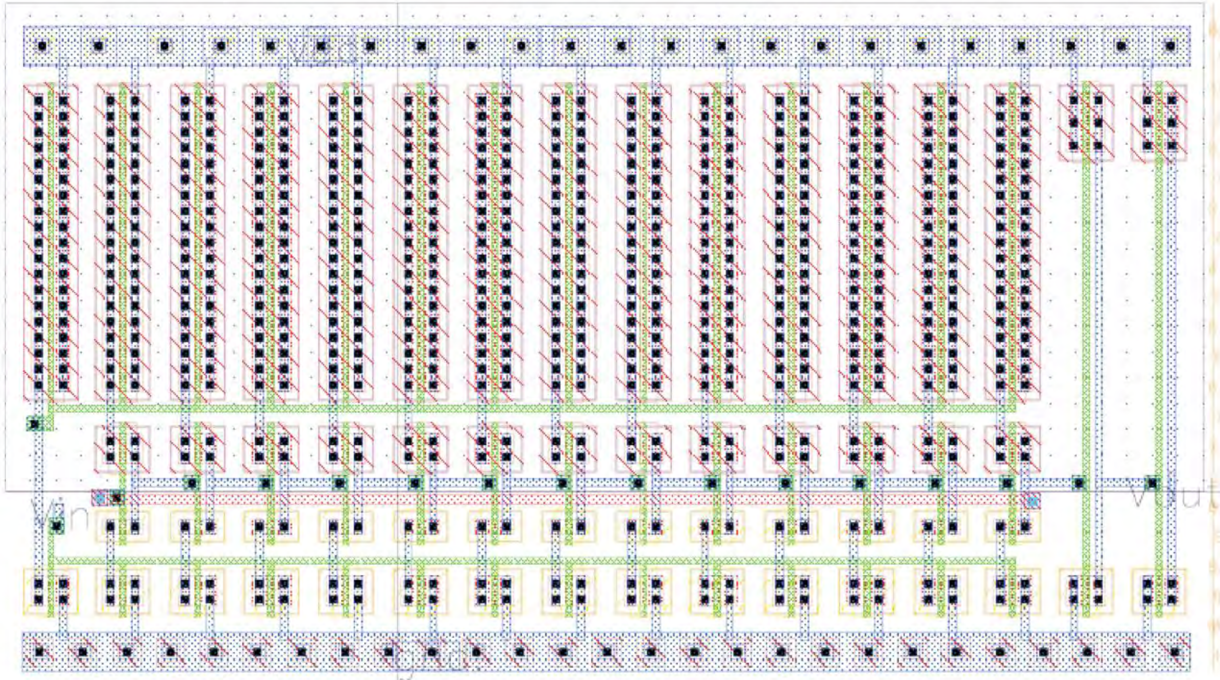
1 – Bit Arbiter PUF Architecture

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.

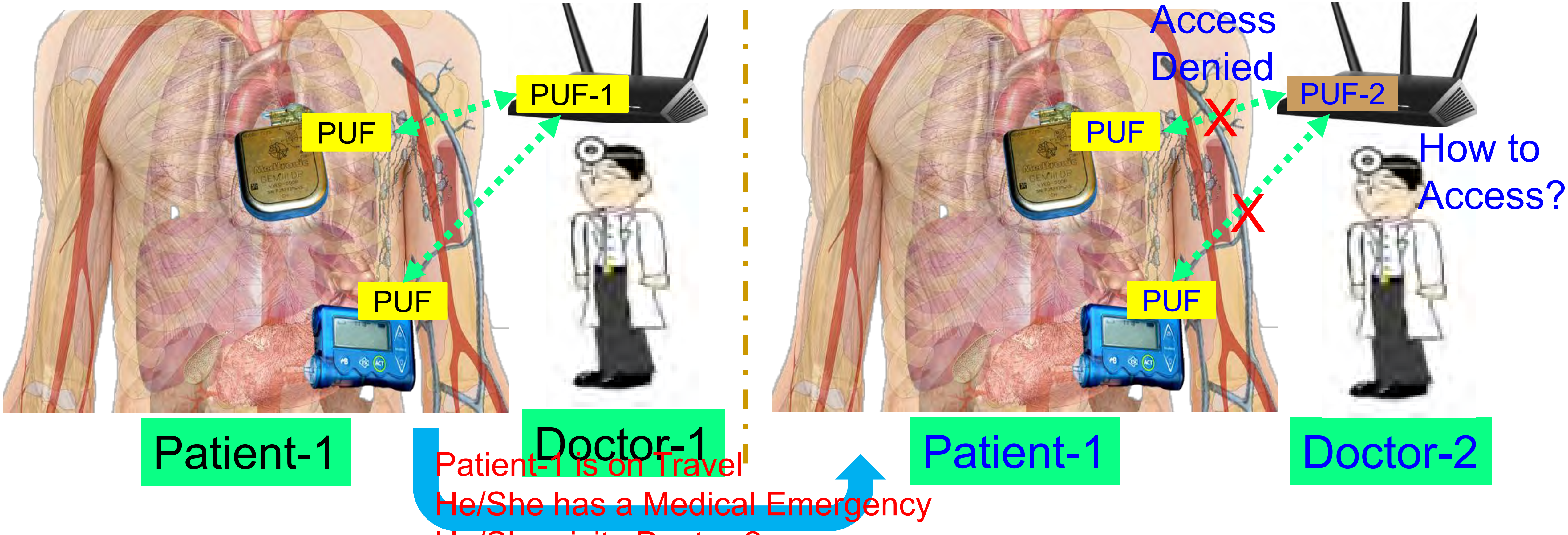
- ➢ Faster prototyping
- ➢ Lesser design effort
- ➢ Minimal skills
- ➢ Cheap
- ➢ Rely on already existing post fabrication variability



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 based Cybersecurity in Smart Healthcare - Doctor’s Dilemma



Patient-1 is on Travel

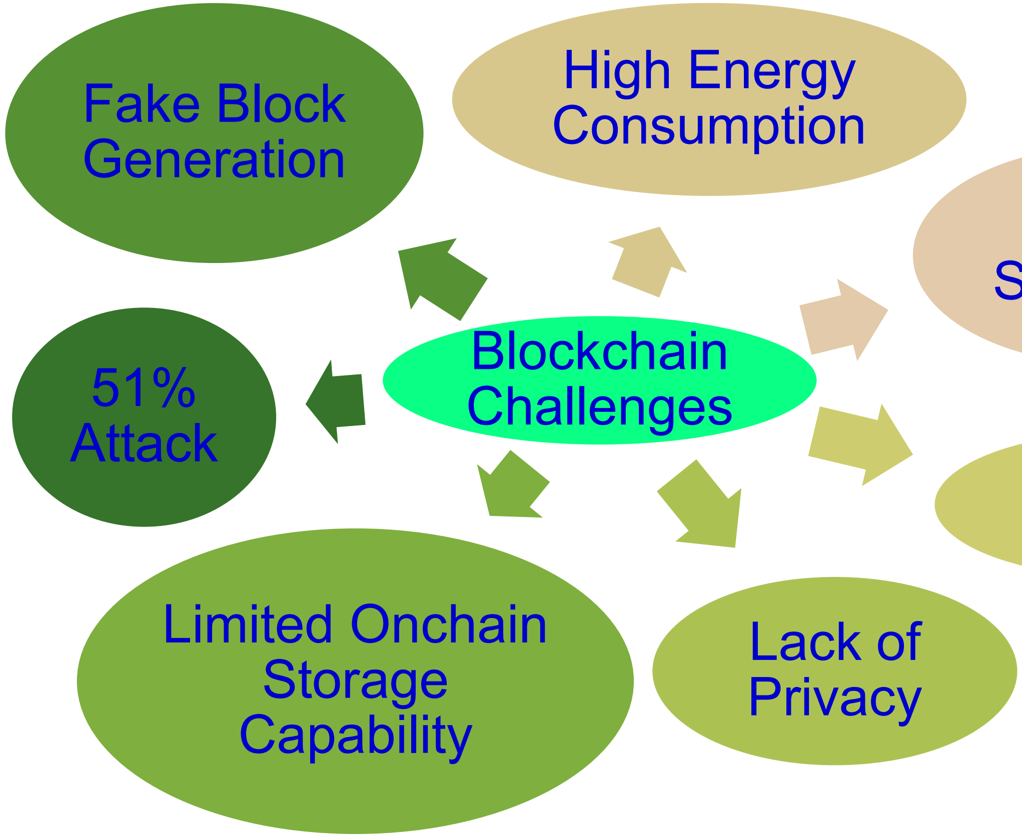
He/She has a Medical Emergency

He/She visits Doctor-2

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.

Is Blockchain the Solution for Every Cybersecurity Problem?

Blockchain has Many Challenges



Blockchain Challenges

Fake Block Generation

High Energy Consumption

Lack of Scalability

High Latency

Lack of Privacy

Limited Onchain Storage Capability

51% Attack

Source: https://www.etorox.com

Source: https://www.monash.edu/blockchain/news/how-do-we-know-blockchain-cant-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

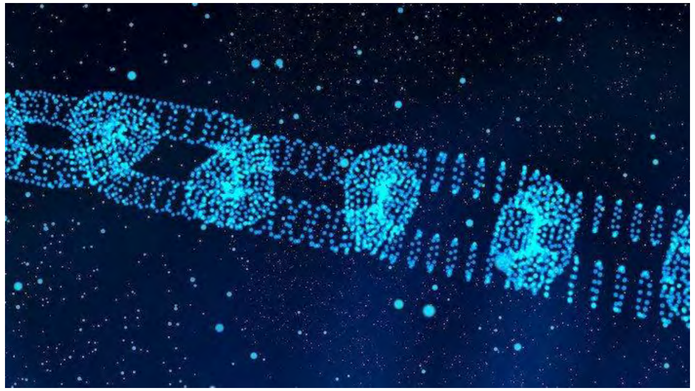
Energy consumption for each bitcoin transaction

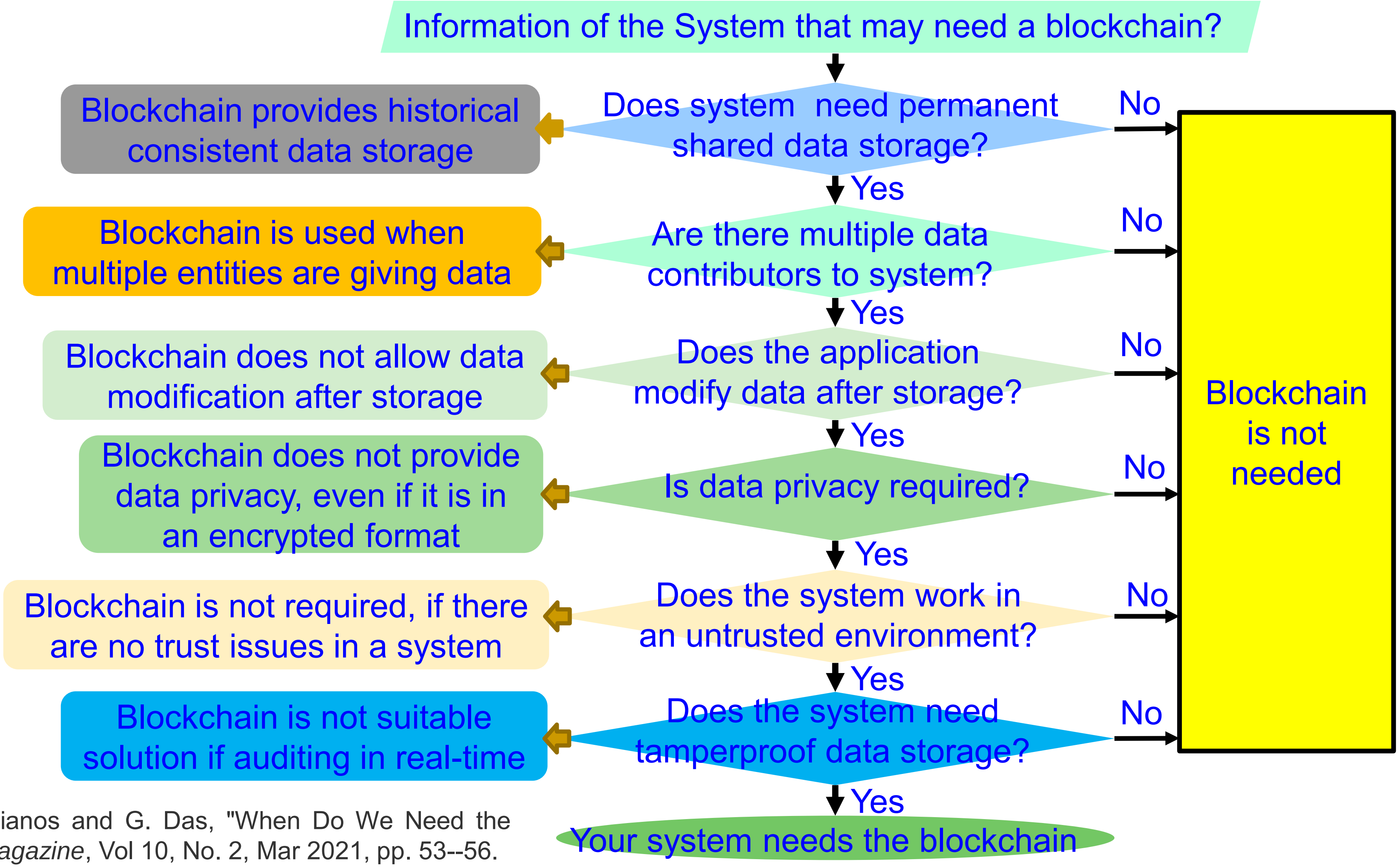
=

80,000 X

Energy consumption of a credit card processing

When do You Need the Blockchain?





Information of the System that may need a blockchain?

Does system need permanent shared data storage?

Blockchain provides historical consistent data storage

Yes

Are there multiple data contributors to system?

Blockchain is used when multiple entities are giving data

Yes

Does the application modify data after storage?

Blockchain does not allow data modification after storage

Yes

Is data privacy required?

Blockchain does not provide data privacy, even if it is in an encrypted format

Yes

Does the system work in an untrusted environment?

Blockchain is not required, if there are no trust issues in a system

Yes

Does the system need tamperproof data storage?

Blockchain is not suitable solution if auditing in real-time

Yes

Your system needs the blockchain

No

No

No

No

No

No

Blockchain is not needed

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 and Future Research

Conclusion

- Healthcare has been evolving to Healthcare-CPS (H-CPS).
- Internet of Medical Things (IoMT) is key for smart healthcare.
- Smart healthcare can reduce cost of healthcare and give more personalized experience to the individual.
- IoMT has advantages but also has limitations in terms of cybersecurity; thus challenging to build sustainable healthcare.
- Cybersecurity in smart healthcare is a serious challenge as device as well as data security and privacy are important.
- Medical device security is a difficult problem due to resource and battery constraints; thus challenge for sustainable H-CPS.
- Security-by-Design is critical for IoMT/H-CPS.

Future Research

- TinyML for smart healthcare that can run at user-end (edge/sensor) needs research.
- H-CPS requires robust data, devices, along with cybersecurity and privacy assurance to be sustainable and hence needs research.
- Security of IWMDs needs to have extremely minimal energy overhead to be useful and hence needs research.
- Integration of blockchain for smart healthcare need research due to energy and computational overheads associated with it.
- SbD research for IoMT/H-CPS is needed.
- Trustworthy Pharmaceutical Supply Chain needs research.