Sustainable Healthcare Cyber-Physical Systems (H-CPS)

Keynote – 5th International Conference on Data Science and Applications (ICDSA 2024)
https://scrs.in/conference/icdsa2024

Jaipur, India, 17--19 July 2024

Homepage:
www.smohanty.org

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University of North Texas, USA.

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 and Future Directions

Smart Healthcare – Broad Introduction

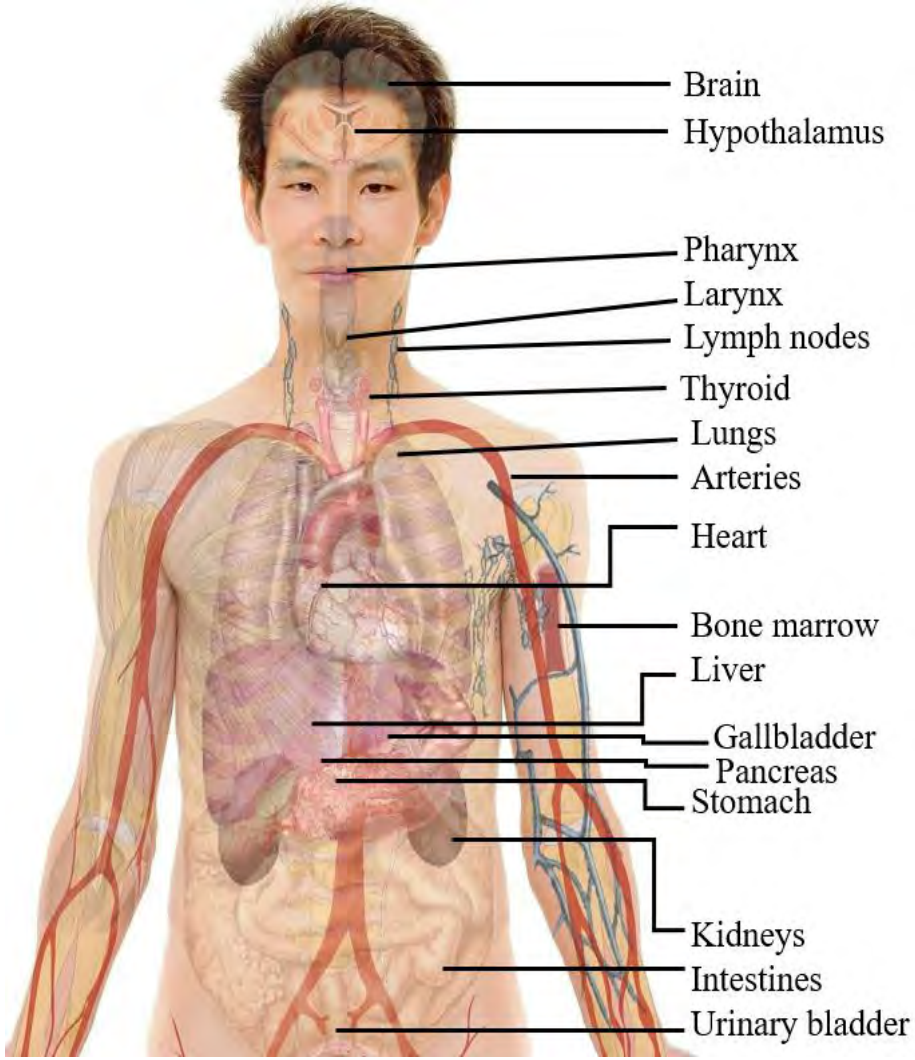
Human Body and Health

Human Body

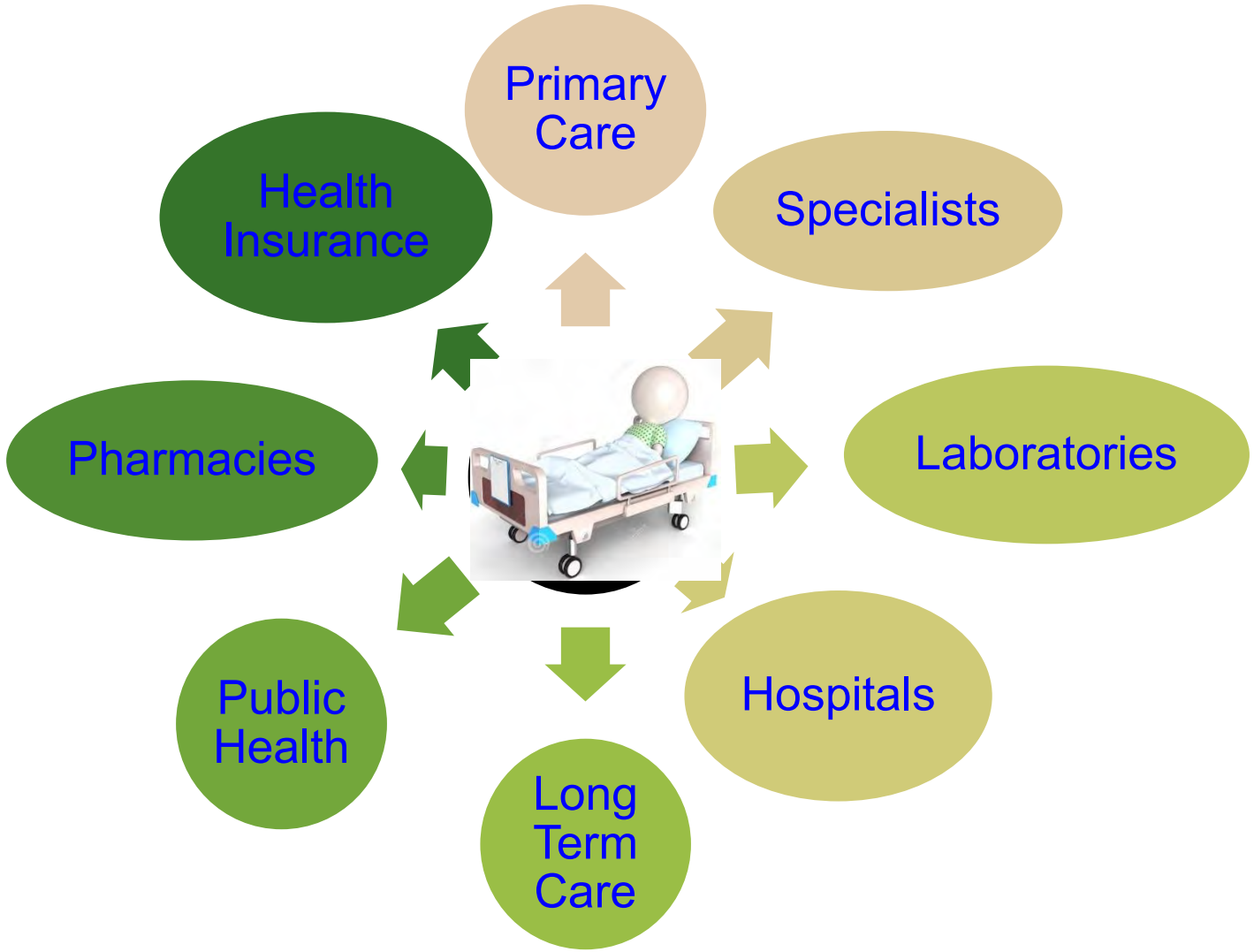
- From an engineering perspective - Human body can be defined as a combination of multi-disciplinary subsystems (electrical, mechanical, chemical …).

Health

- Human health is a state of complete physical, mental and social well-being.



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

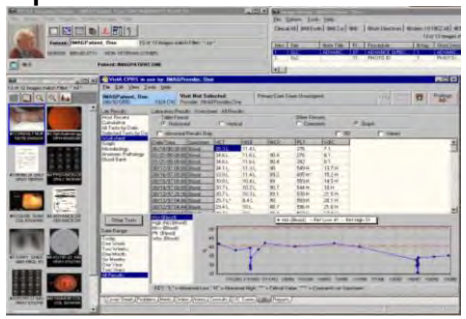
Healthcare

eHealth

Telemedicine

mHealth

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



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

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

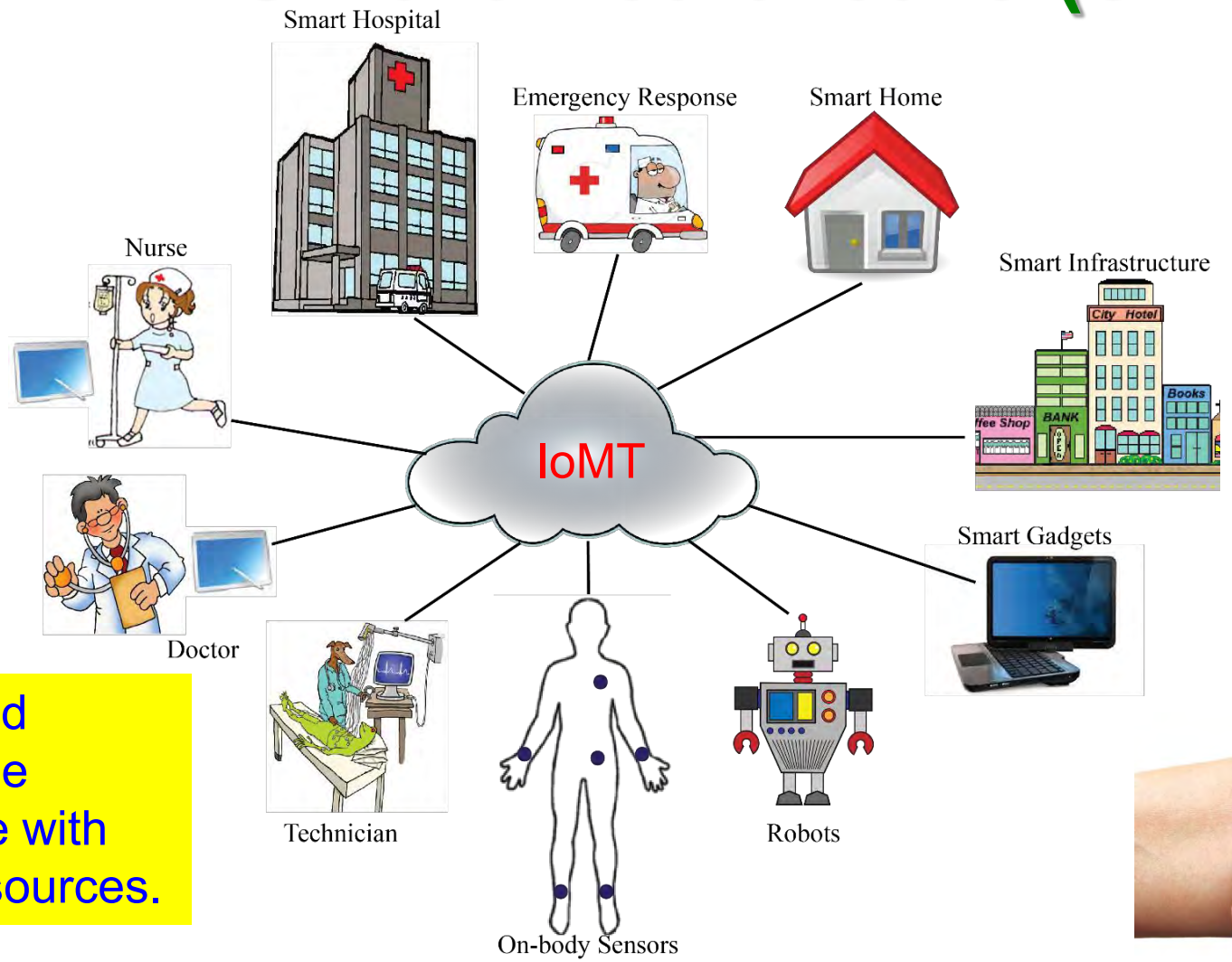
Thync's - UltrasoVibeund

Spire Stone - Breath

Muse - EEG

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

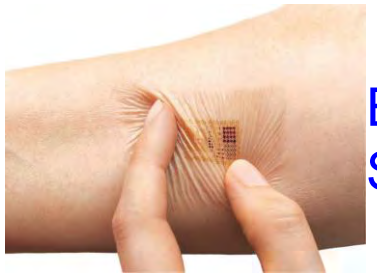
Smart Healthcare (sHealth)



Fitness Trackers

Headband with Embedded Neurosensors

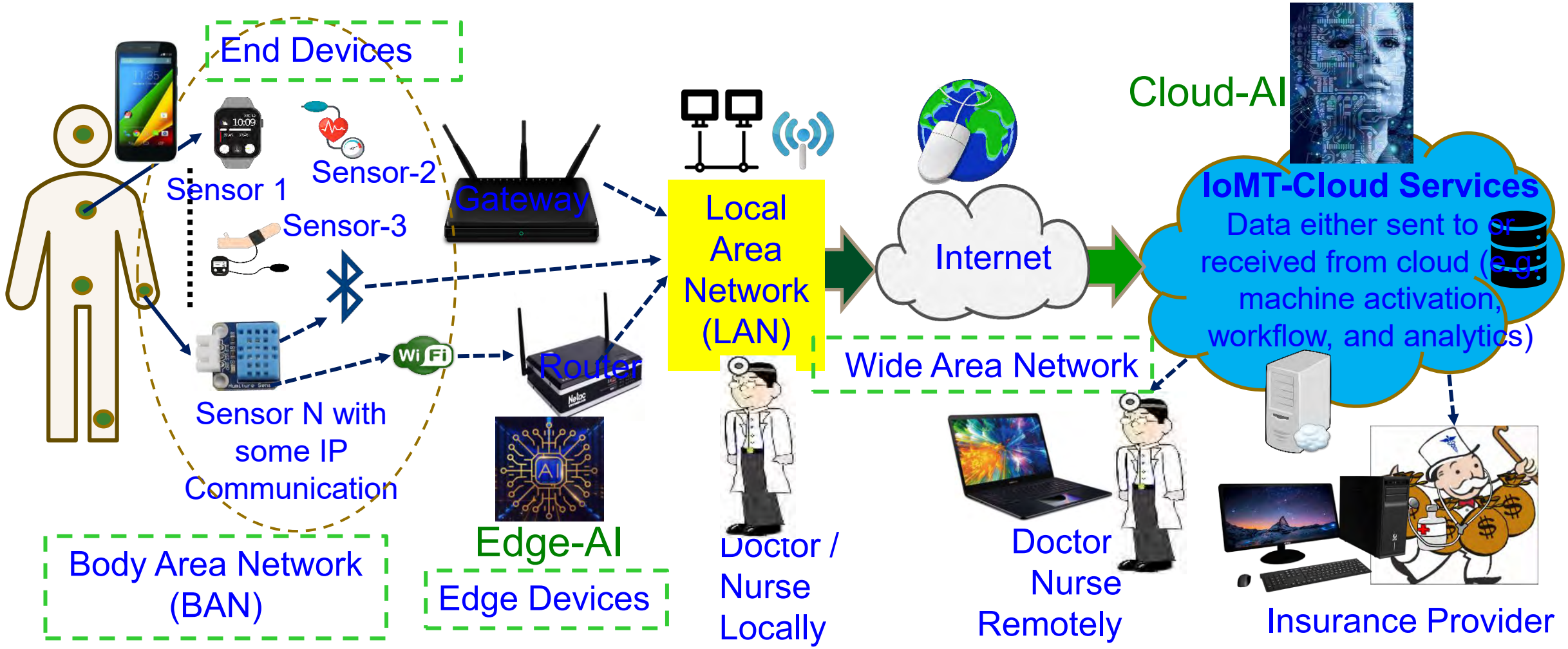
Quality and sustainable healthcare with limited resources.



Embedded Skin Patches

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

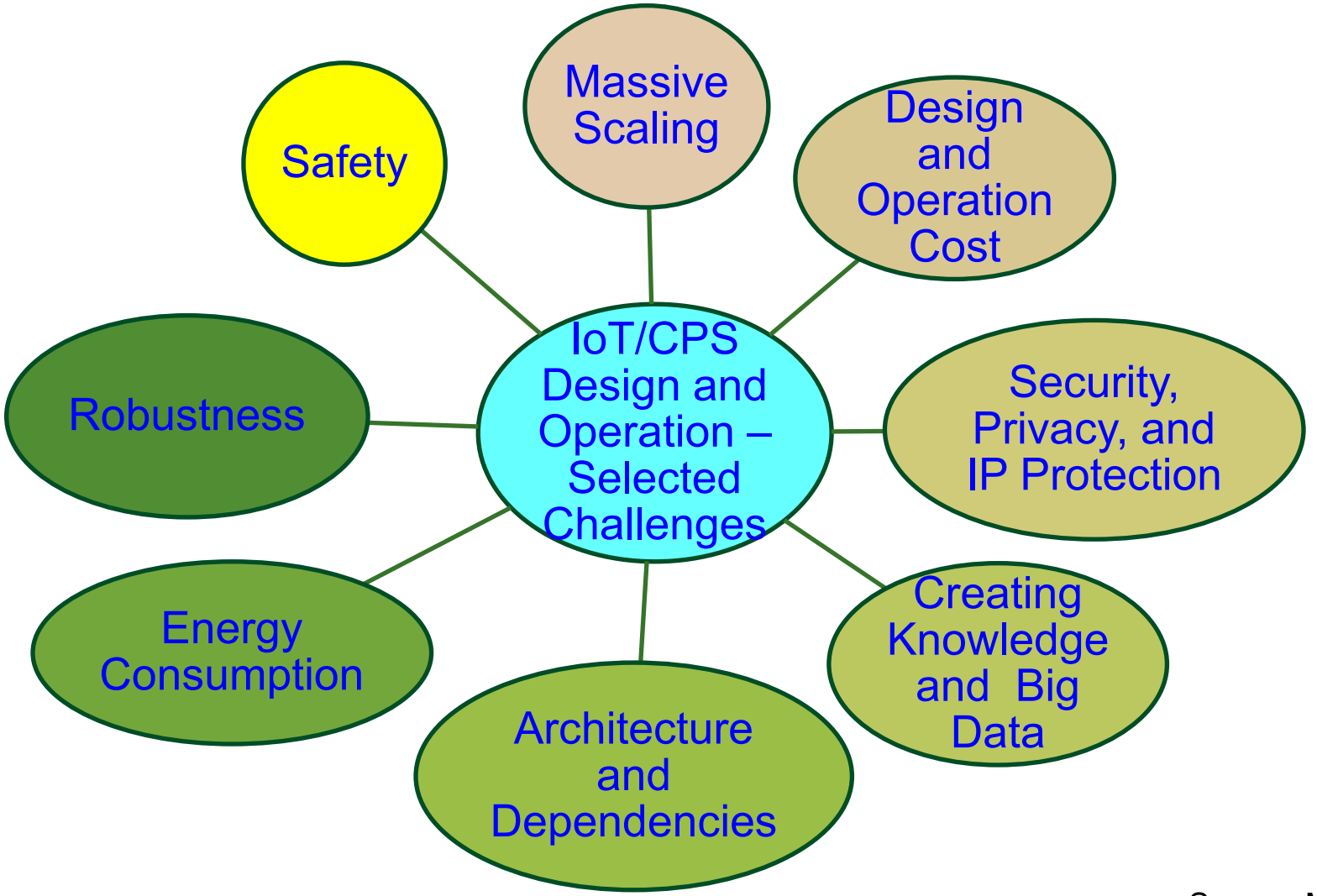


Frost and Sullivan predicts smart healthcare market value to reach US$348.5 billion by 2025.

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

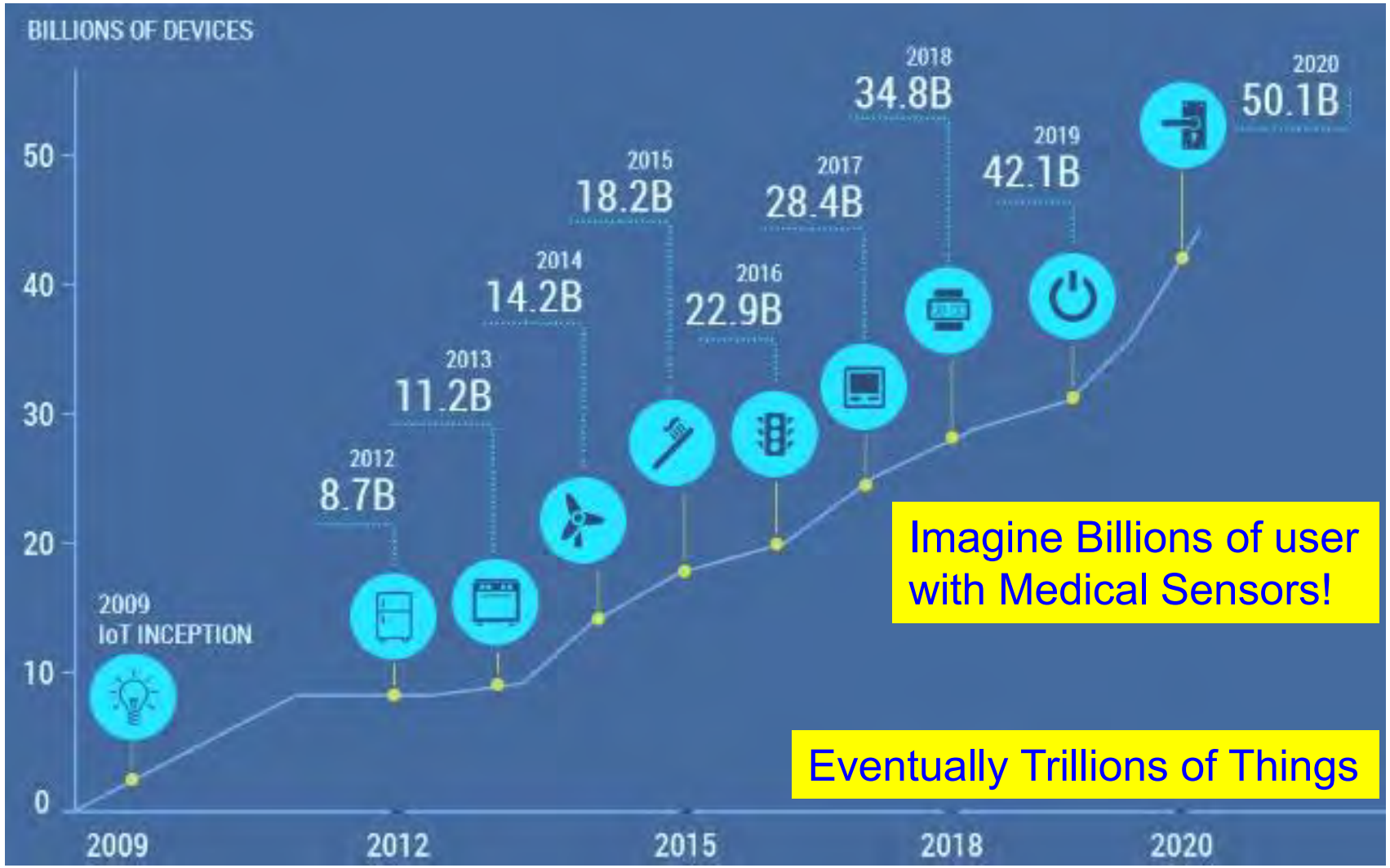
Smart Healthcare – Challenges Against Sustainability

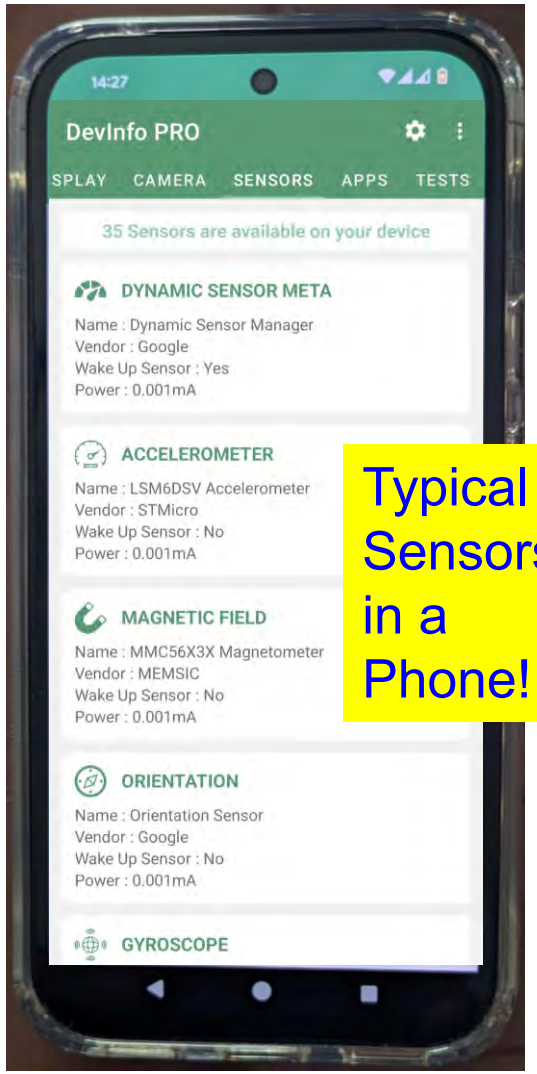
CPS – Sustainability Challenges



Source: Mohanty ICIT 2017 Keynote

Massive Growth of Sensors/Things





Typical Sensors in a Phone!

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

Challenges of Data in IoT/CPS are Multifold

Data Curation

Data Cost

Data Storage

Lots of Data

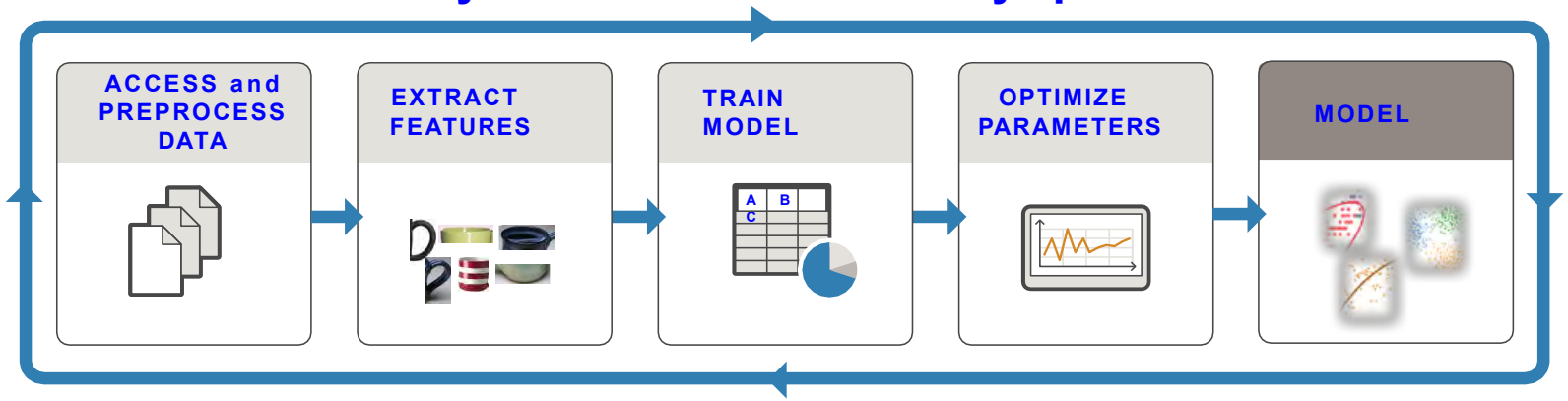
Data Ownership

Data Modeling

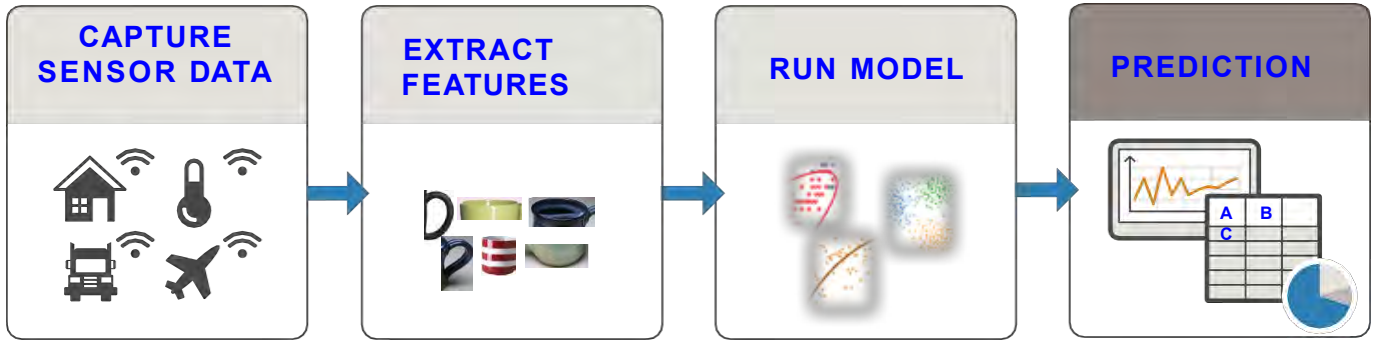
Data Quality

Deep Neural Network (DNN) - Resource and Energy Costs

TRAIN: Iterate until you achieve satisfactory performance.



PREDICT: Integrate trained models into applications.



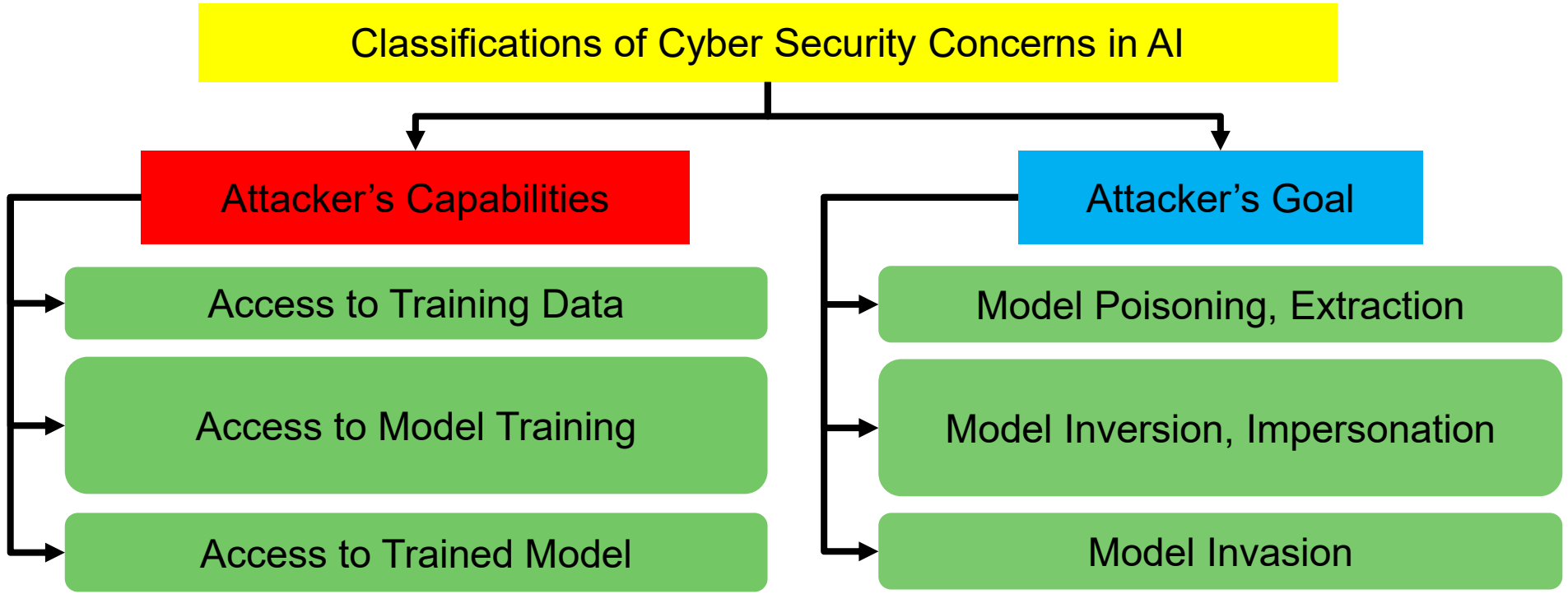
Source: https://www.mathworks.com/campaigns/offers/mastering-machine-learning-with-matlab.html

Needs Significant:
- Computational Resource
- Computation Energy

Limited Computational Capability
Limited Battery Life

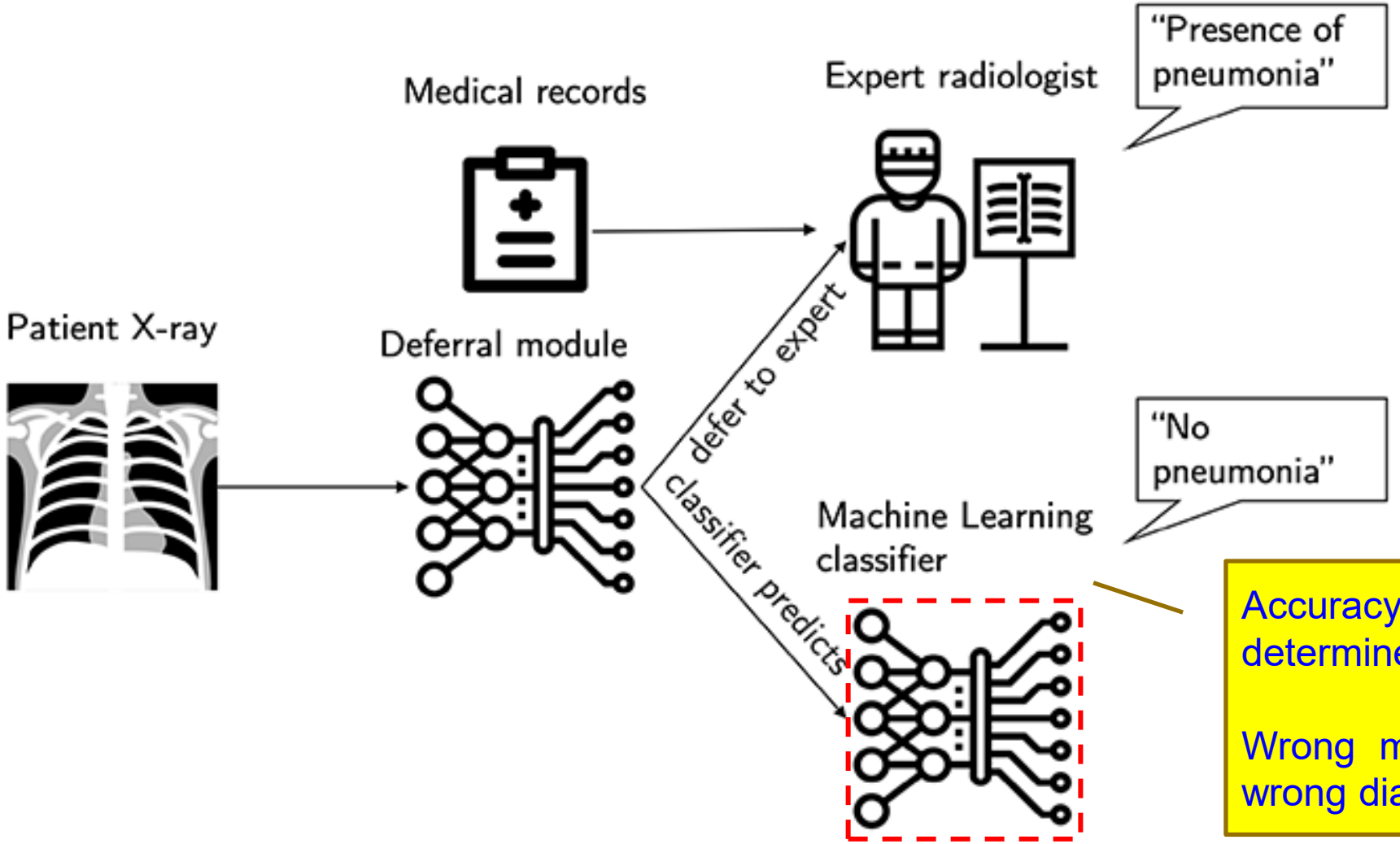
Needs:
- Computational Resource
- Computation Energy

AI/ML – Cybersecurity Issue



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

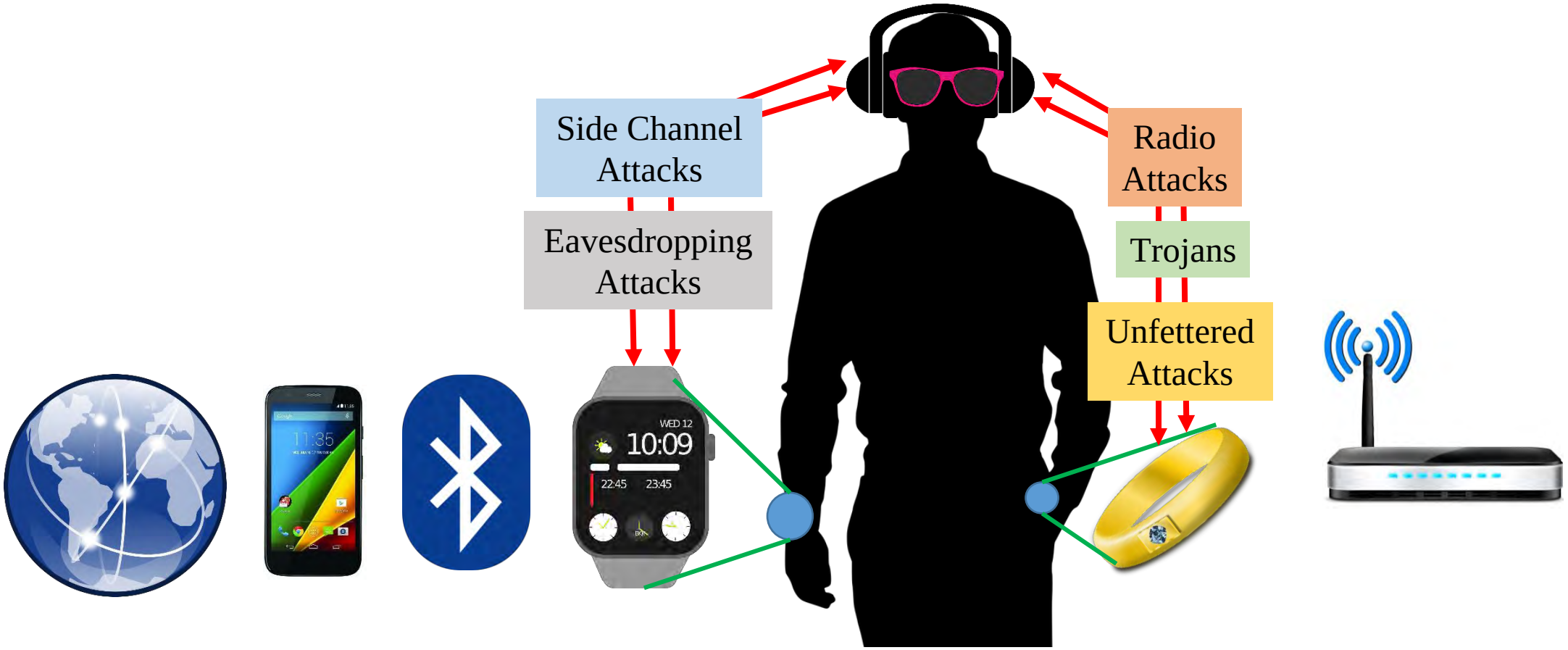
Source: https://www.healthcareitnews.com/news/new-ai-diagnostic-tool-knows-when-defer-human-mit-researchers-say

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



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.

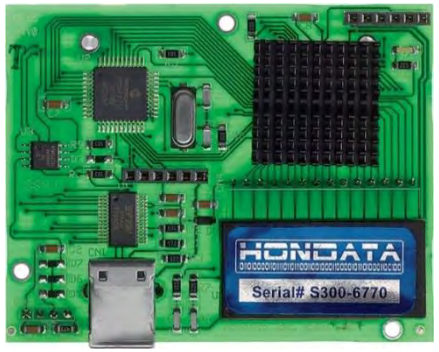
Fake Data and Fake Hardware – Both are Equally Dangerous in CPS

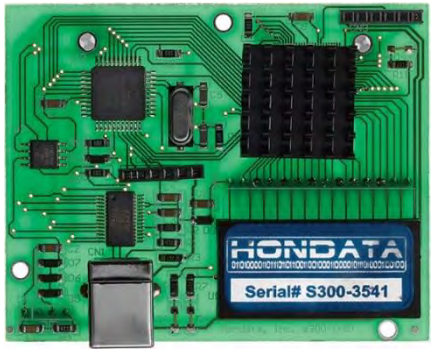
AI can be fooled by fake data

AI can create fake data (Deepfake)

Authentic Fake

An implantable medical device





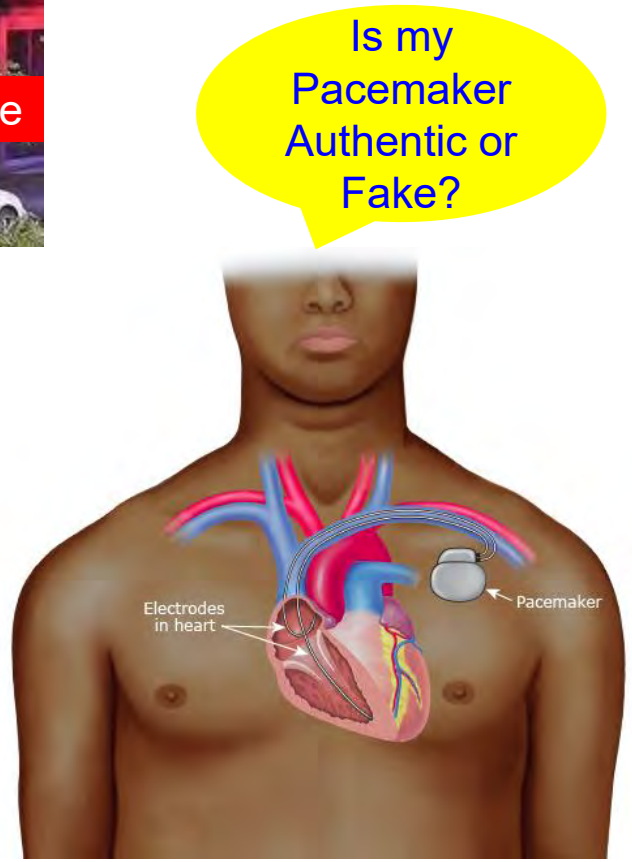
Authentic Fake

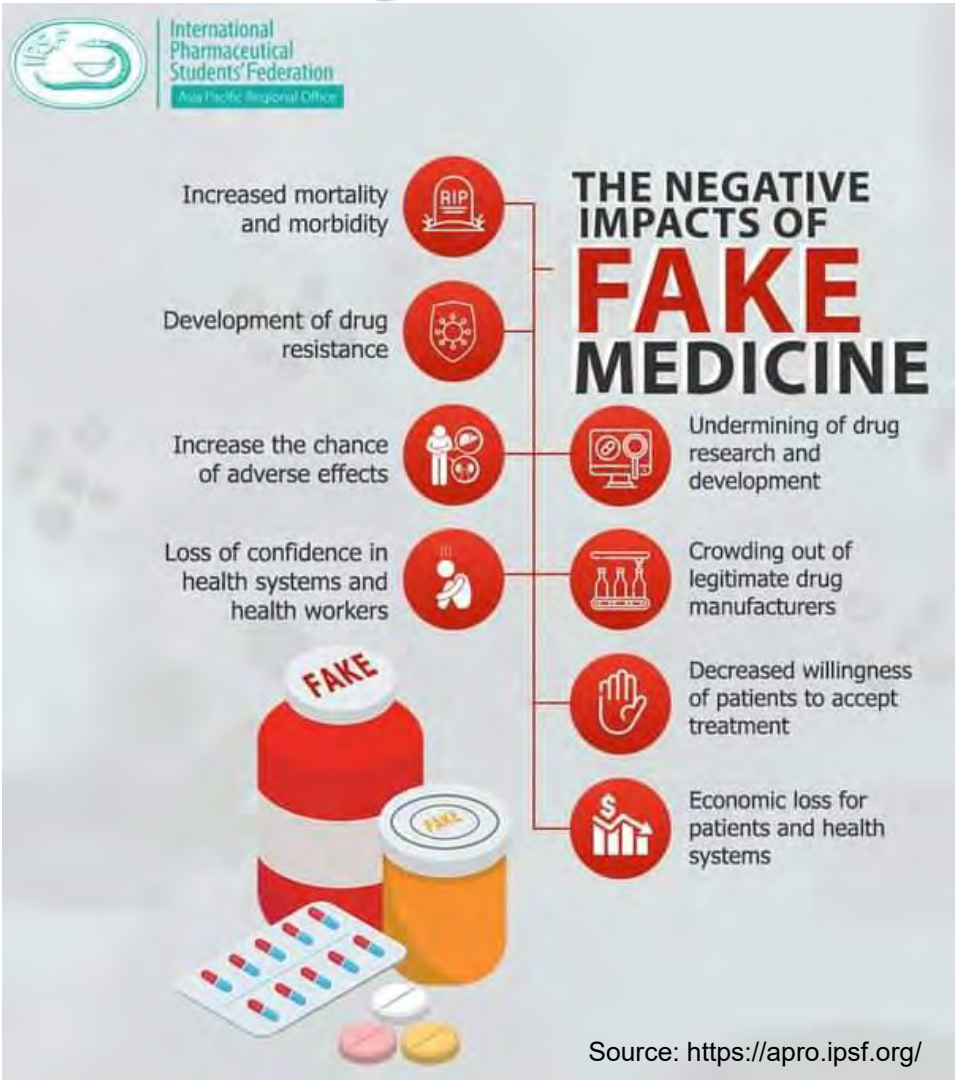
A plug-in for car-engine computers

Fake is Cheap – Why not Buy?

Source: https://www.quora.com

Source: https://nypost.com/

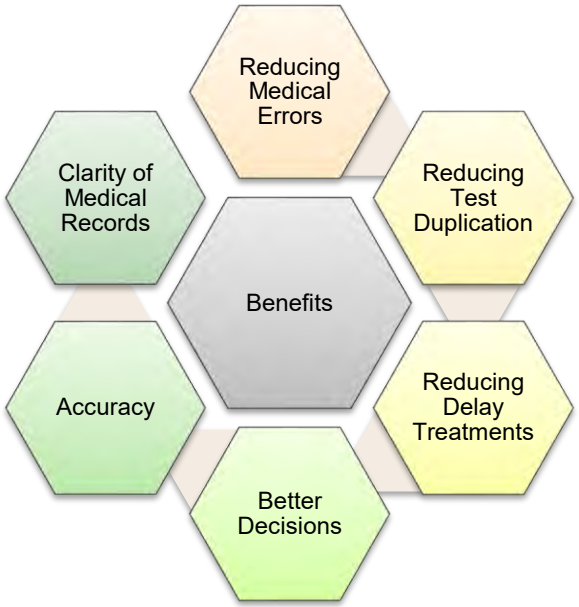




Source: https://apro.ipsf.org/

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



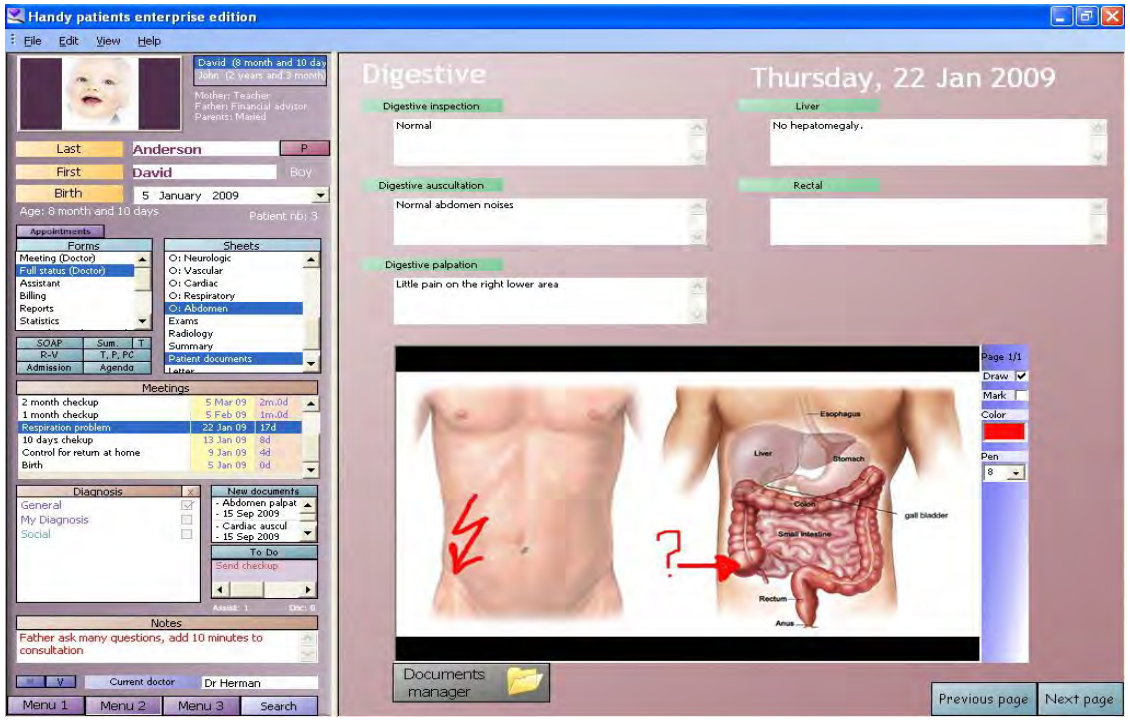
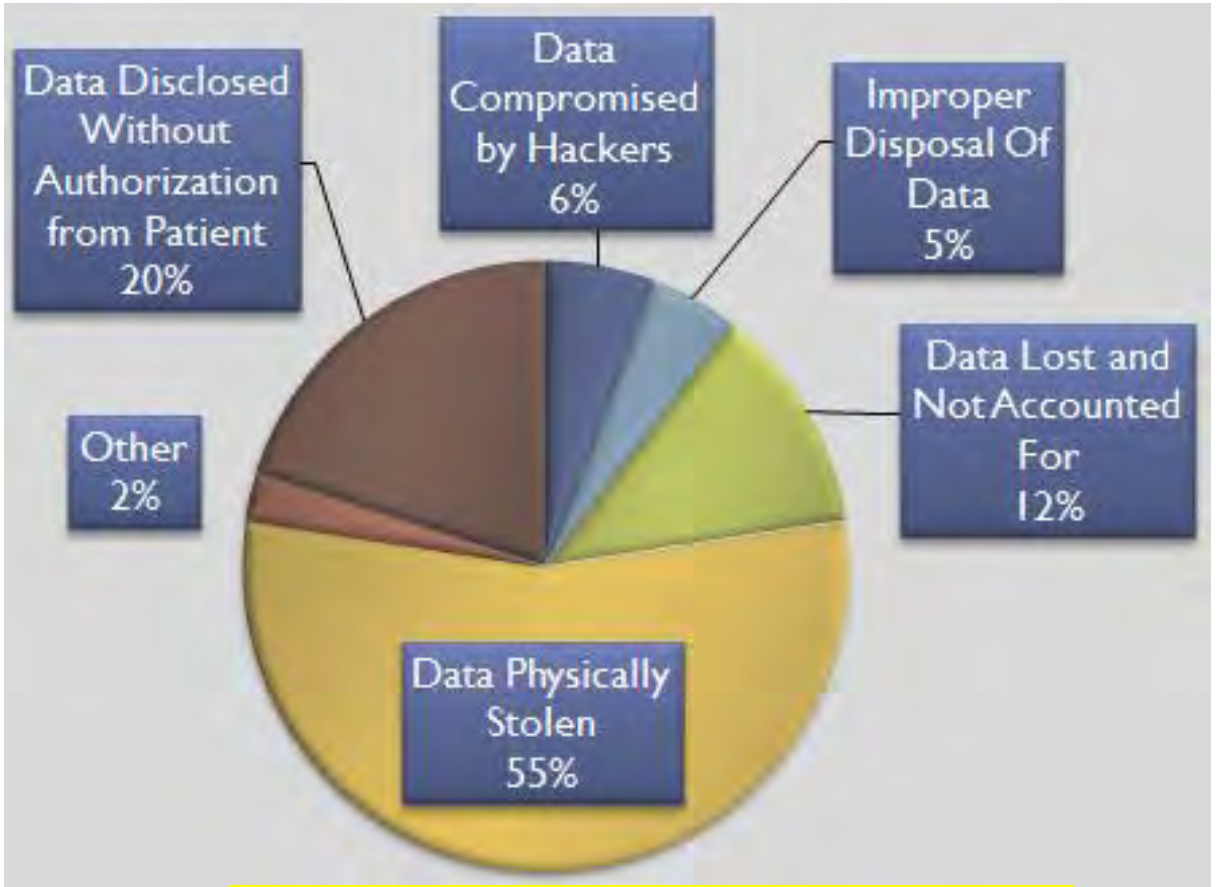


Image Source: DaCarpenther, An electronic medical record example, Handy patients electronic medical record (free open-source version)

Health Insurance Portability and Accountability Act (HIPPA)

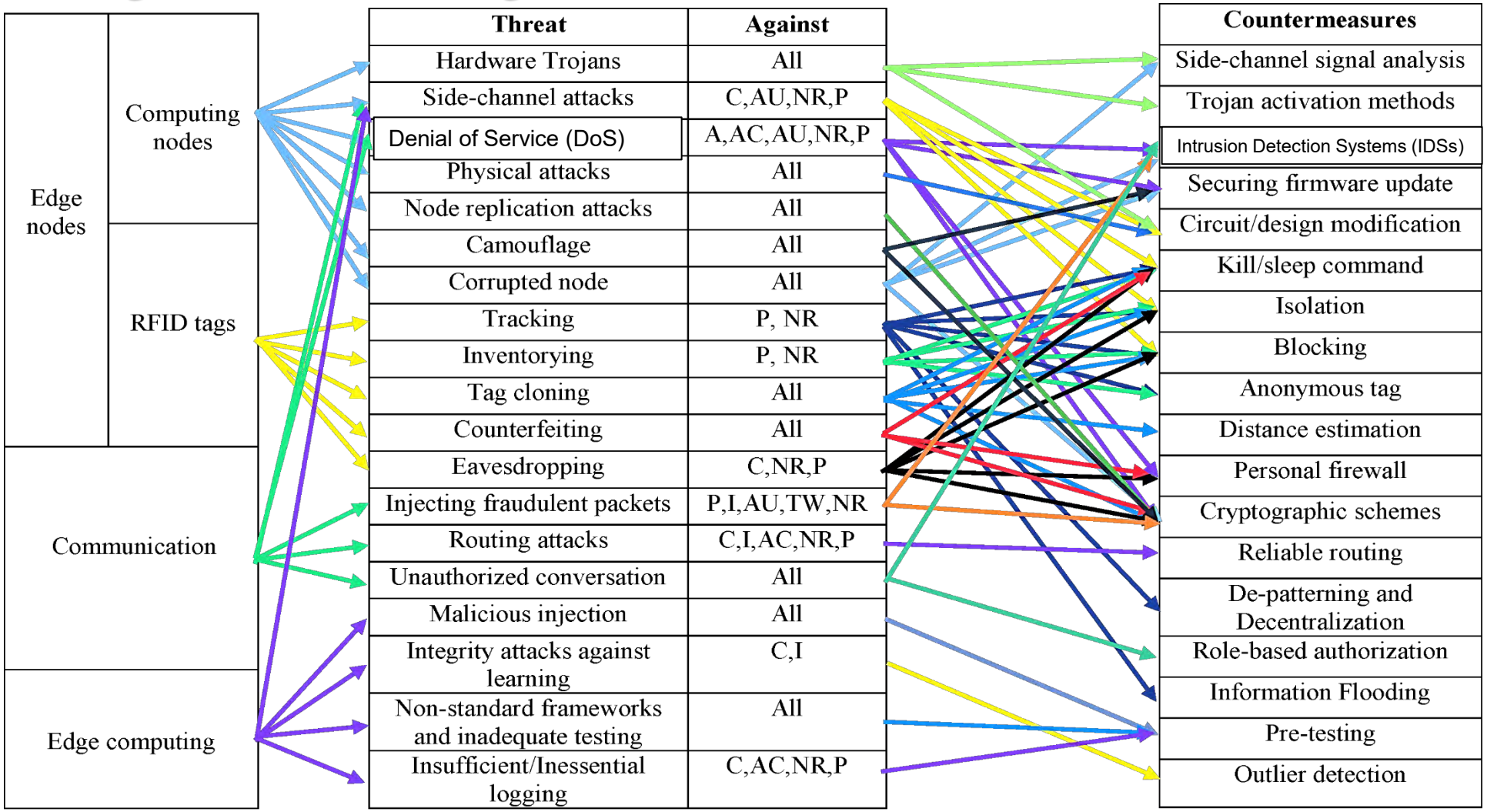
HIPAA
Health Insurance Portability and Accountability Act



HIPPA Privacy Violation by Types

Cybrsecurity Solution for IoT/CPS

IoT Cybersecurity - Attacks and Countermeasures



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

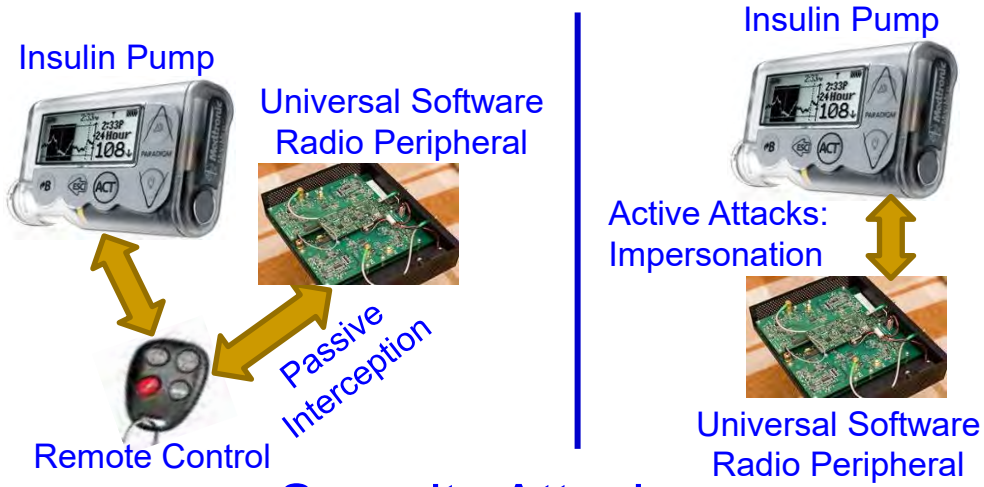
Countermeasures
Side-channel signal analysis
Trojan activation methods
Intrusion Detection Systems (IDSs)
Securing firmware update
Circuit/design modification
Kill/sleep command
Isolation
Blocking
Anonymous tag
Distance estimation
Personal firewall
Cryptographic schemes
Reliable routing
De-patterning 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

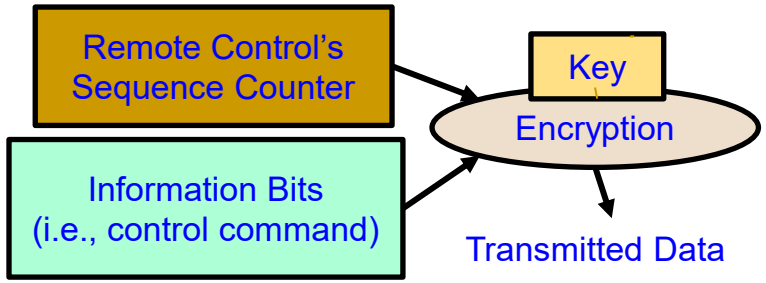
Source: A. Mosenia, and Niraj K. Jha. "A Comprehensive Study of Security of Internet-of-Things", *IEEE Transactions on Emerging Topics in Computing*, 5(4), 2016, pp. 586-602.

Smart Healthcare Cybersecurity

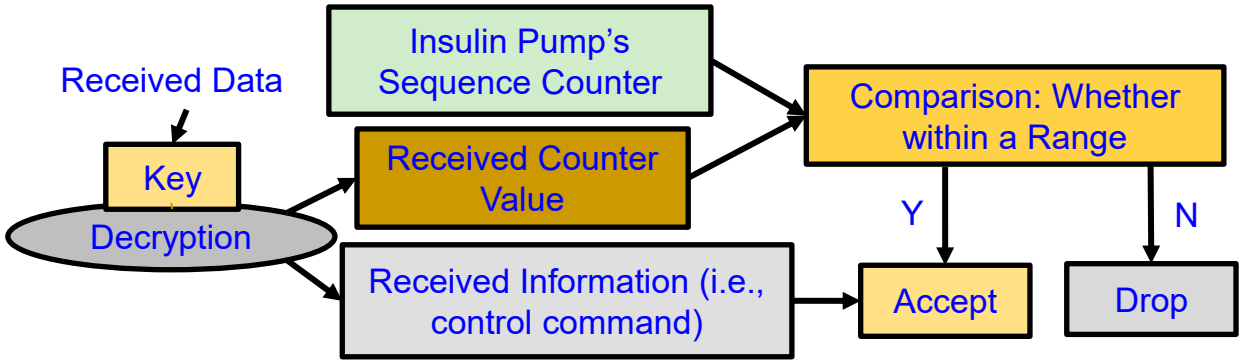
Insulin Delivery System



Security Attacks



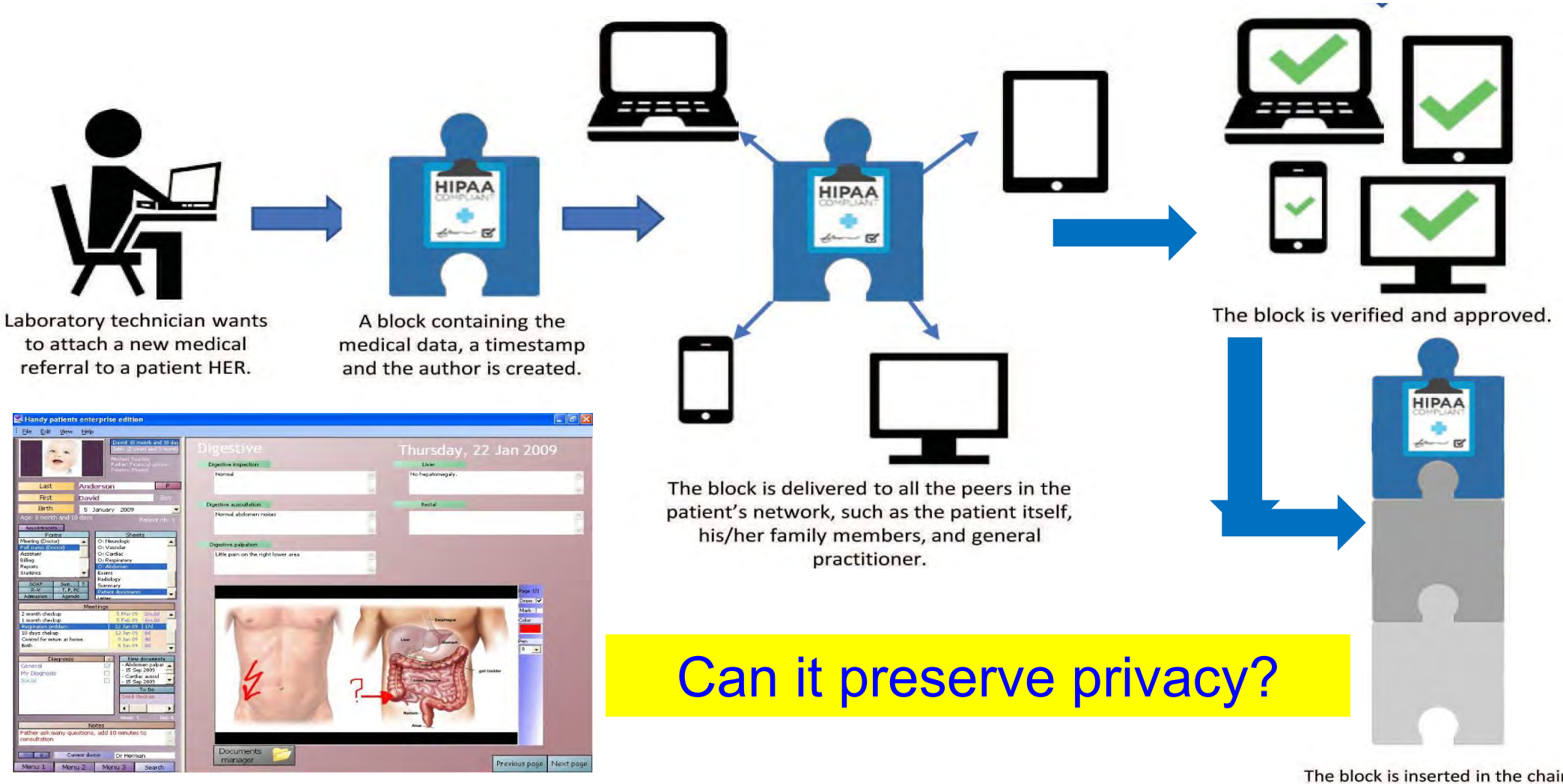
Rolling Code Encoder in Remote Control



Rolling Code Decoder in Insulin Pump

Source: Li and Jha 2011: HEALTH 2011

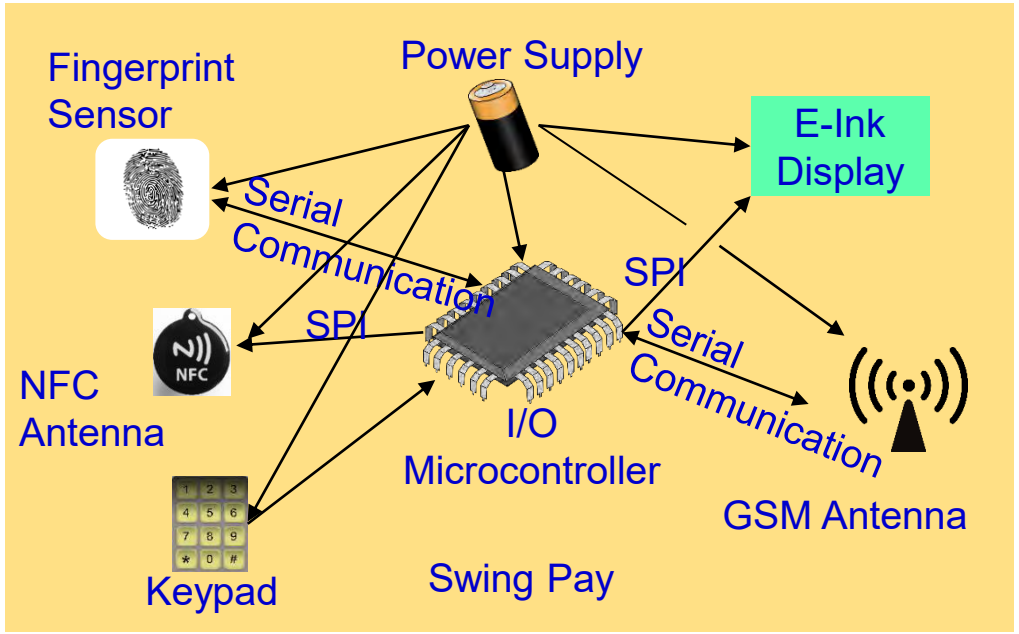
Blockchain in Smart Healthcare

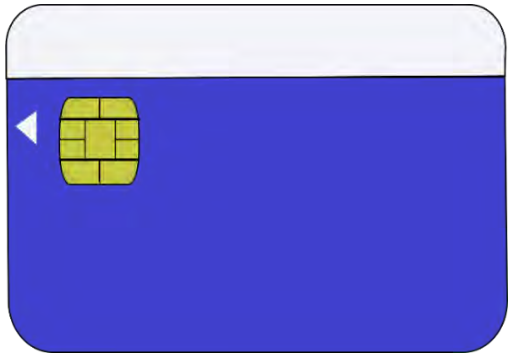


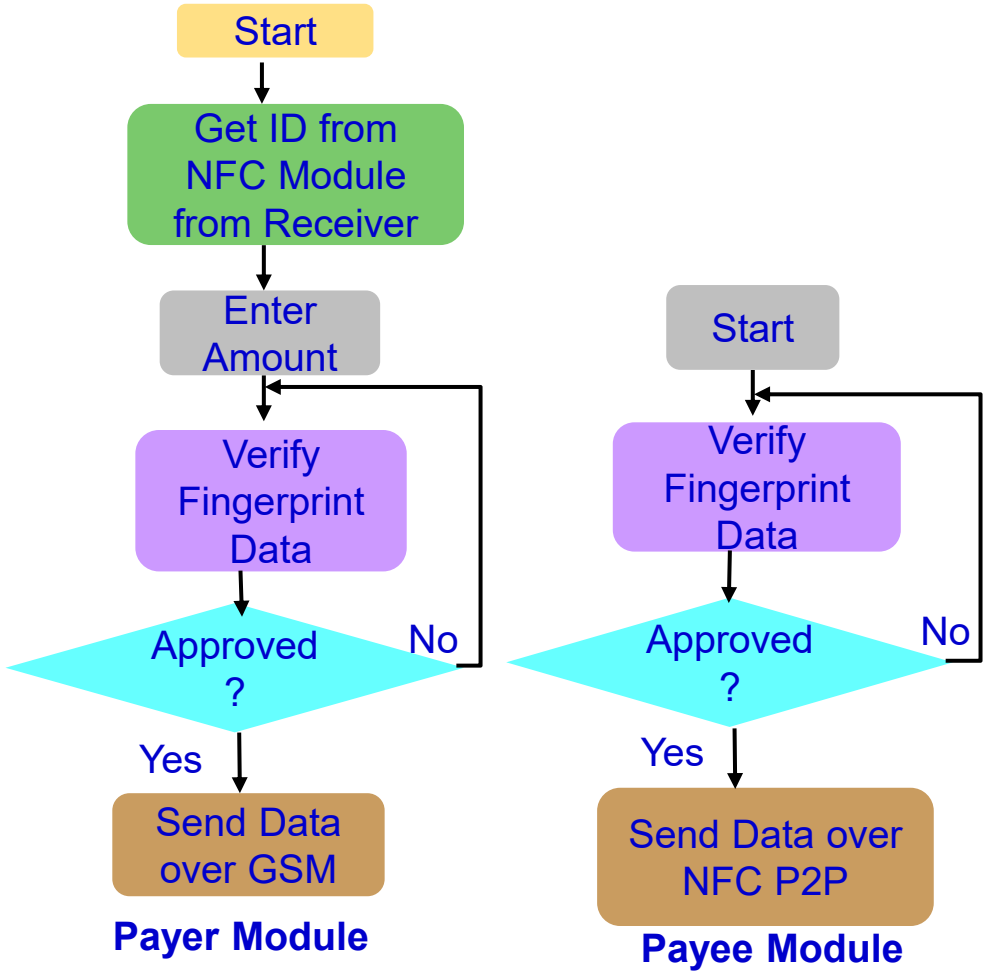
Can it preserve privacy?

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

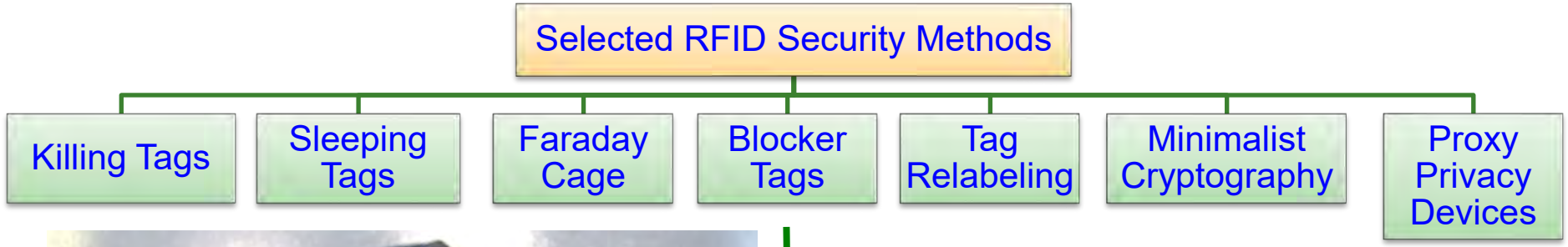




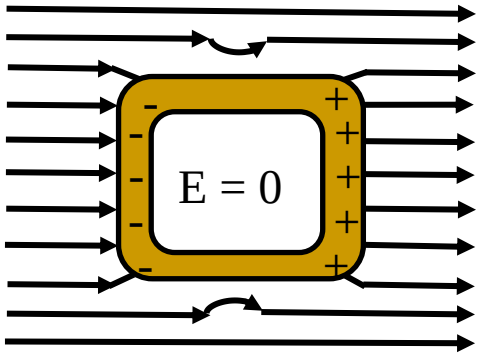


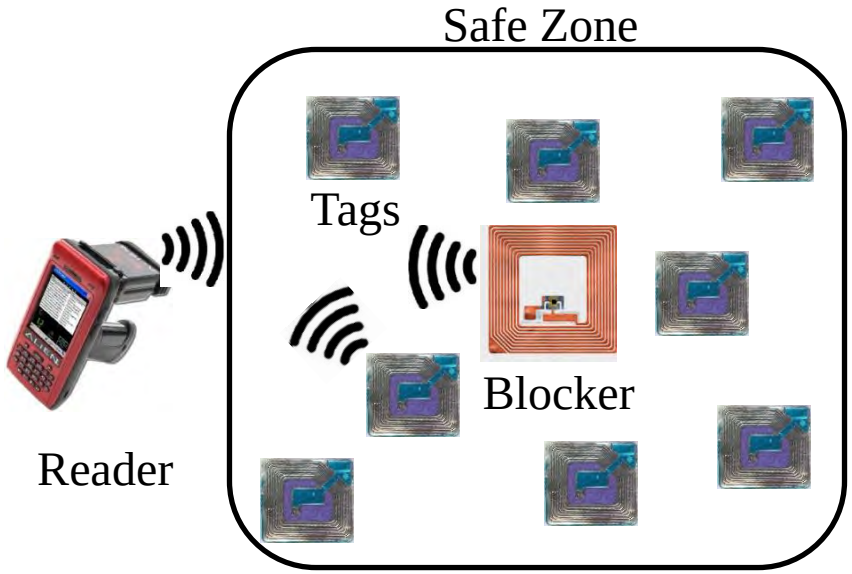
Source: S. Ghosh, J. Goswami, A. Majumder, A. Kumar, **S. P. Mohanty**, and B. K. Bhattacharyya, "Swing-Pay: One Card Meets All User Payment and Identity Needs", *IEEE Consumer Electronics Magazine (MCE)*, Volume 6, Issue 1, January 2017, pp. 82--93.

RFID Cybersecurity - Solutions



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

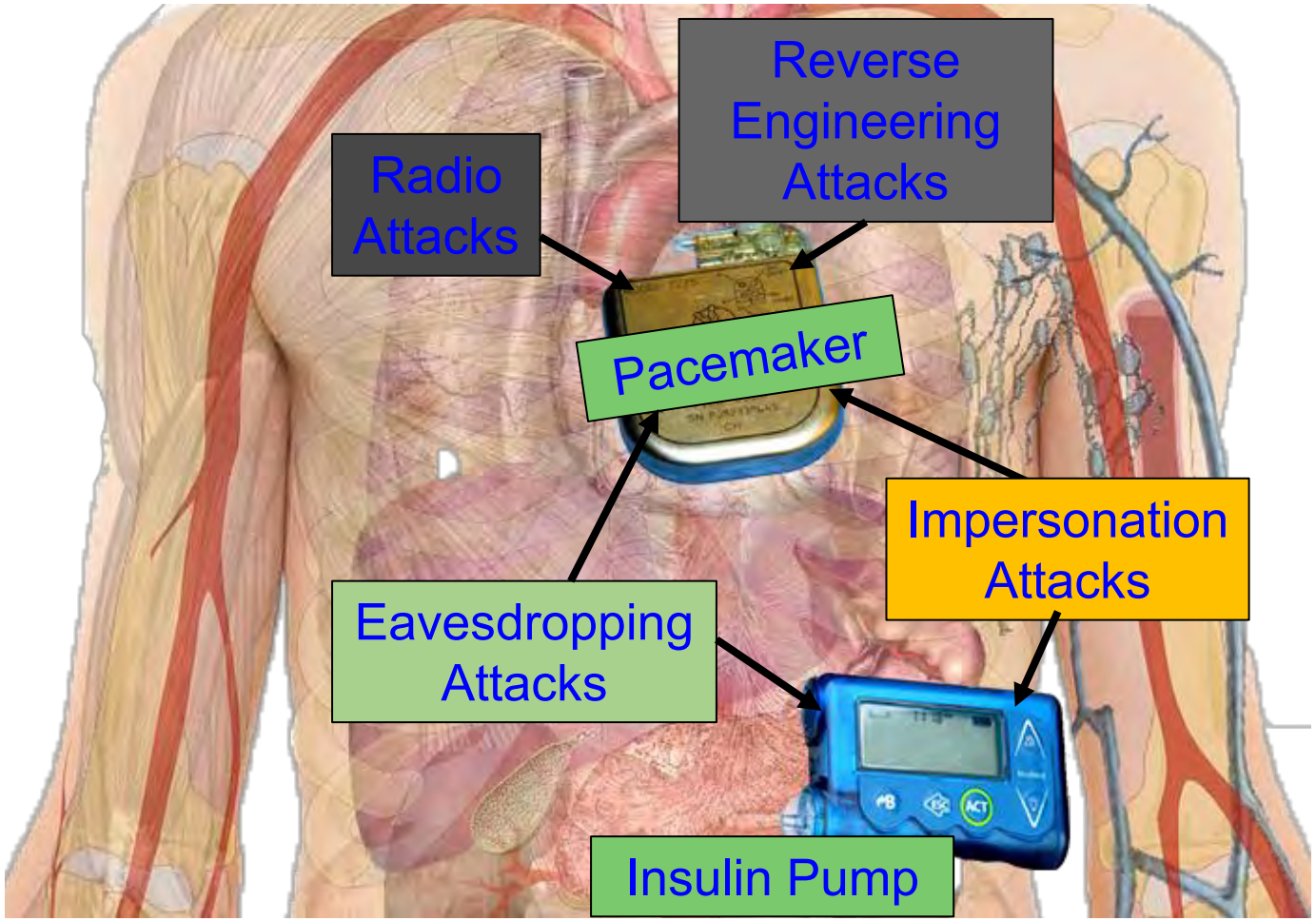
- IT infrastructure may be well protected rooms
- Limited variety of IT network devices
- Millions of IT devices
- Significant computational power to run heavy-duty security solutions
- IT security breach can be costly

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.

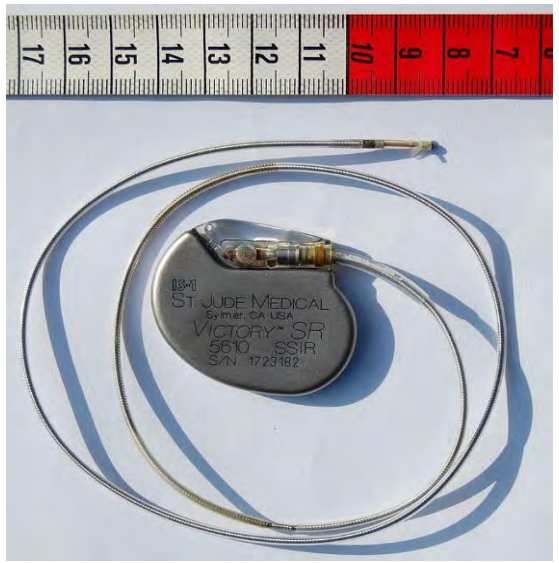
Cybersecurity Measures in Healthcare Cyber-Physical Systems is Hard



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

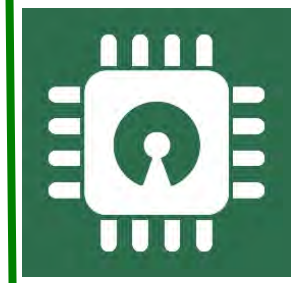
- Implantable Medical Devices (IMDs) have integrated battery to provide energy to all their functions → Limited Battery Life depending on functions
- Higher battery/energy usage → Lower IMD lifetime
- Battery/IMD replacement → Needs surgical risky procedures

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

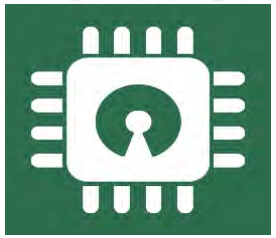
Source: Mohanty ICCE Panel 2018

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

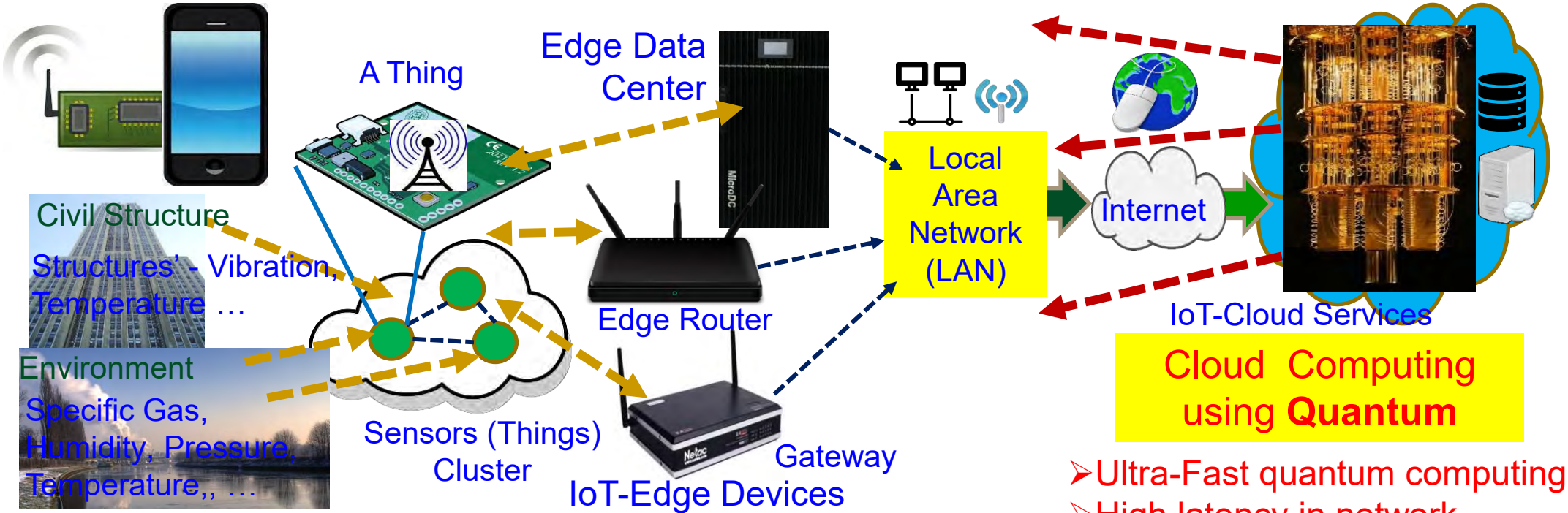
Source: Mohanty ICCE Panel 2018



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



In-Sensor/End-Device Computing

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

Edge Computing

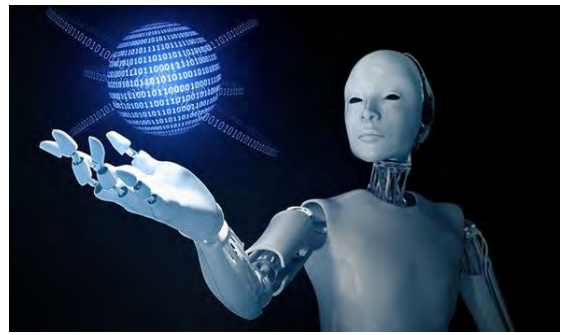
- Less computational resource
- Minimal latency in network
- Lightweight security

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

Non-recurring Design Cost

Energy Consumption, Battery Life

ENERGY STAR

Ethics, Safety

Security, Privacy, IP Rights

Smart Cities
Vs
Smart Villages

Performance, Latency

Intelligence

Source: Mohanty ICCE 2019 Keynote

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)

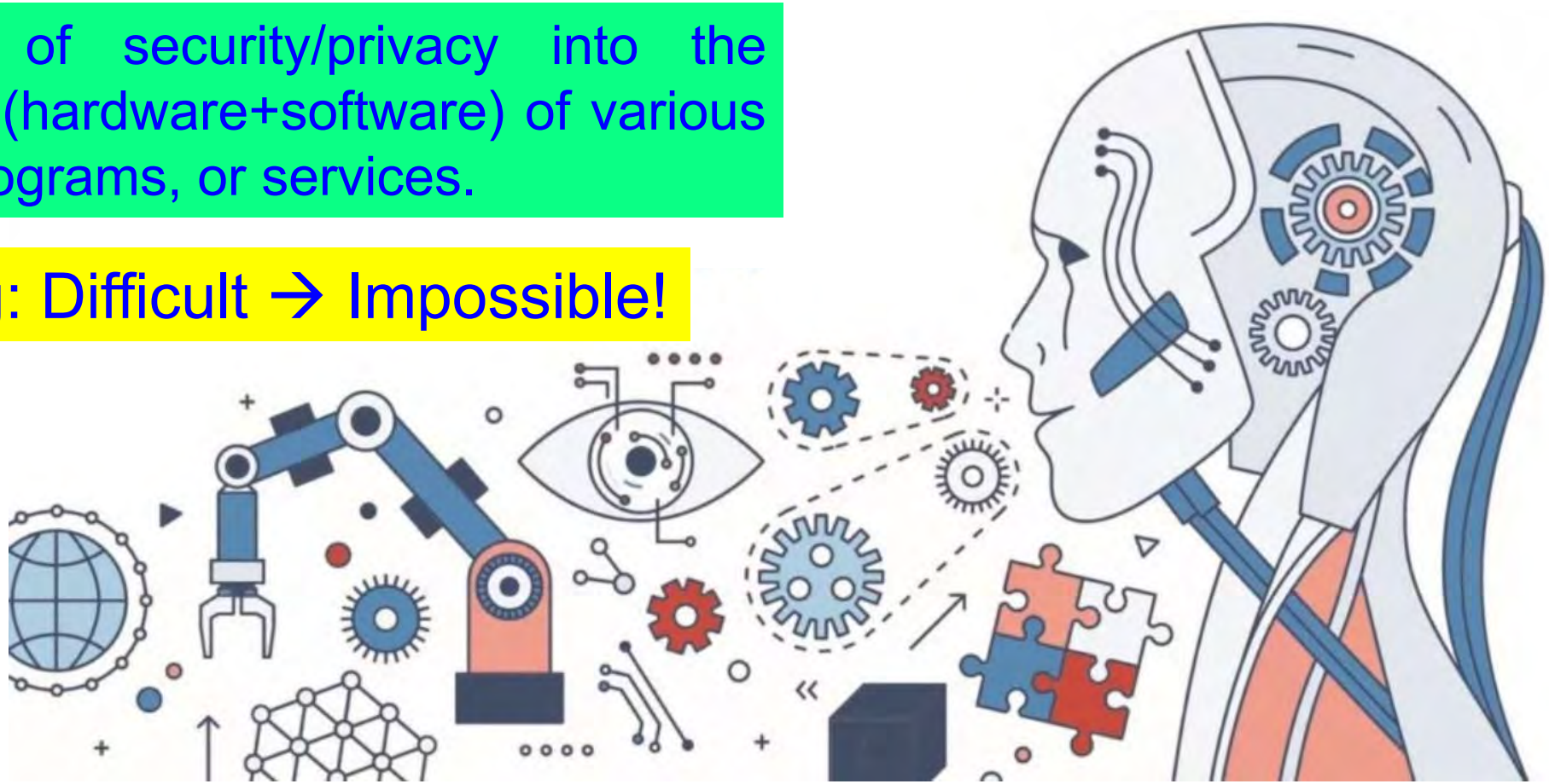
- GDPR makes Privacy by Design (PbD) a legal requirement

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/

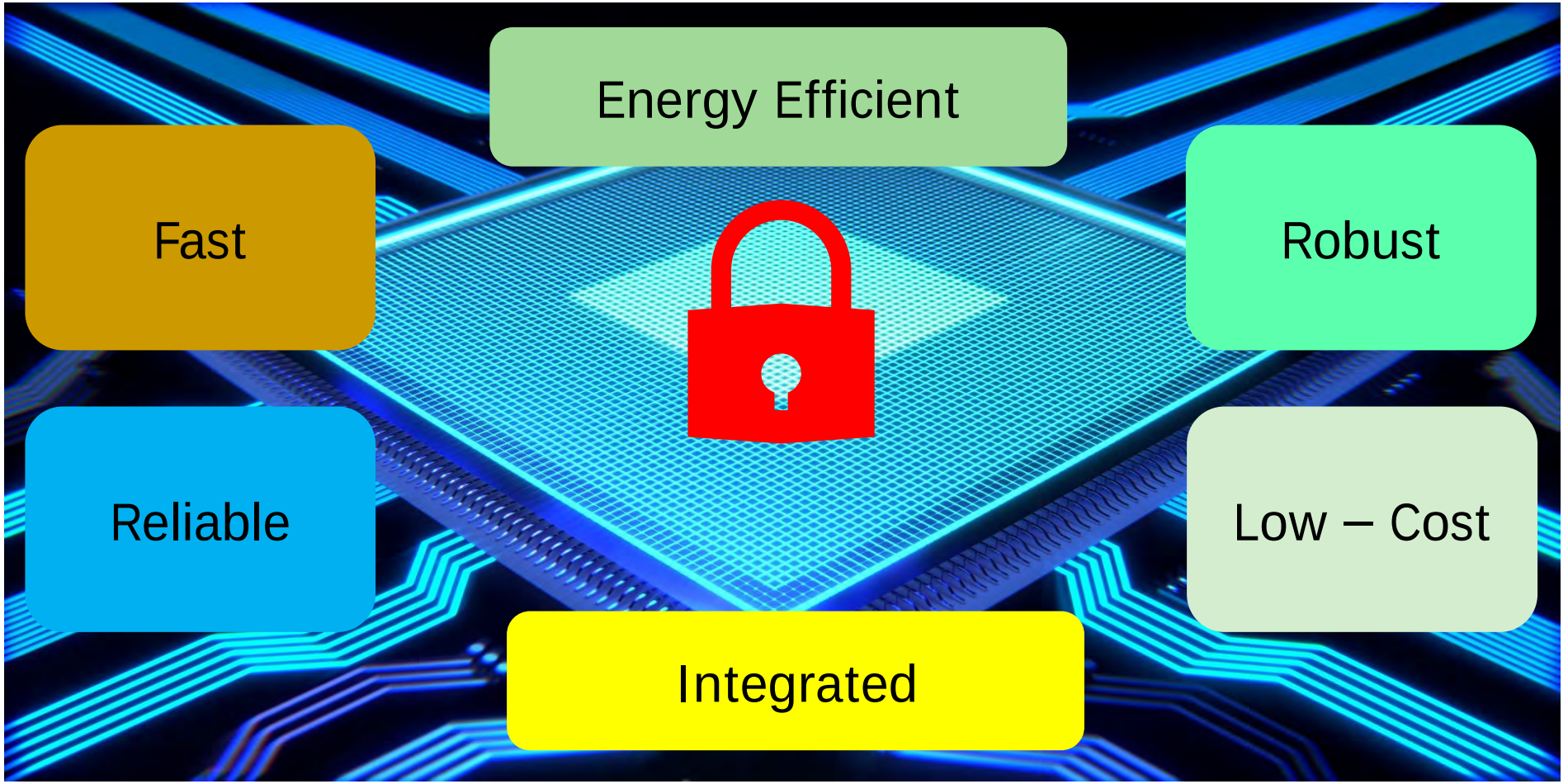
Security by Design (SbD)

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

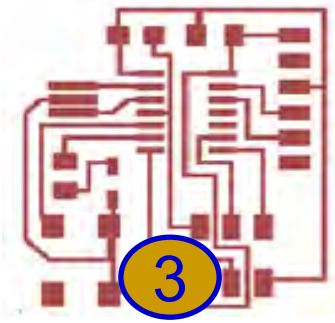
Security-by-Design (SbD) or Hardware Assisted Security (HAS) - Advantages



SbD Principle – IoT/CPS Design Flow

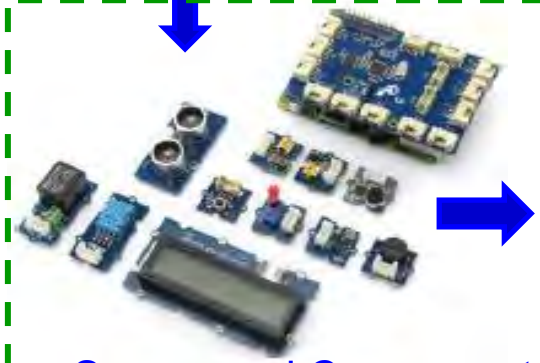
1 Concept

2 High Level Design

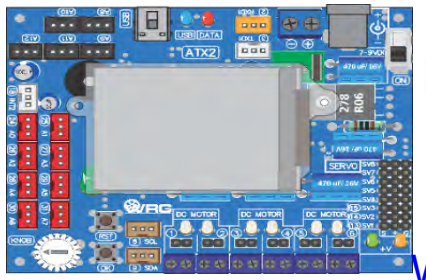


3 Component Level Design

4 Design Analysis



Sensor and Component Assembly



Writing Device Drivers

Writing Application Programming Interface (APIs) for Cloud Infrastructure

Client Integration (Desktop, Tablet, Mobile) Prototyping

5

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

SbD Principle – IoT/CPS Design Flow

6 Field Testing

7 Release of Beta Version

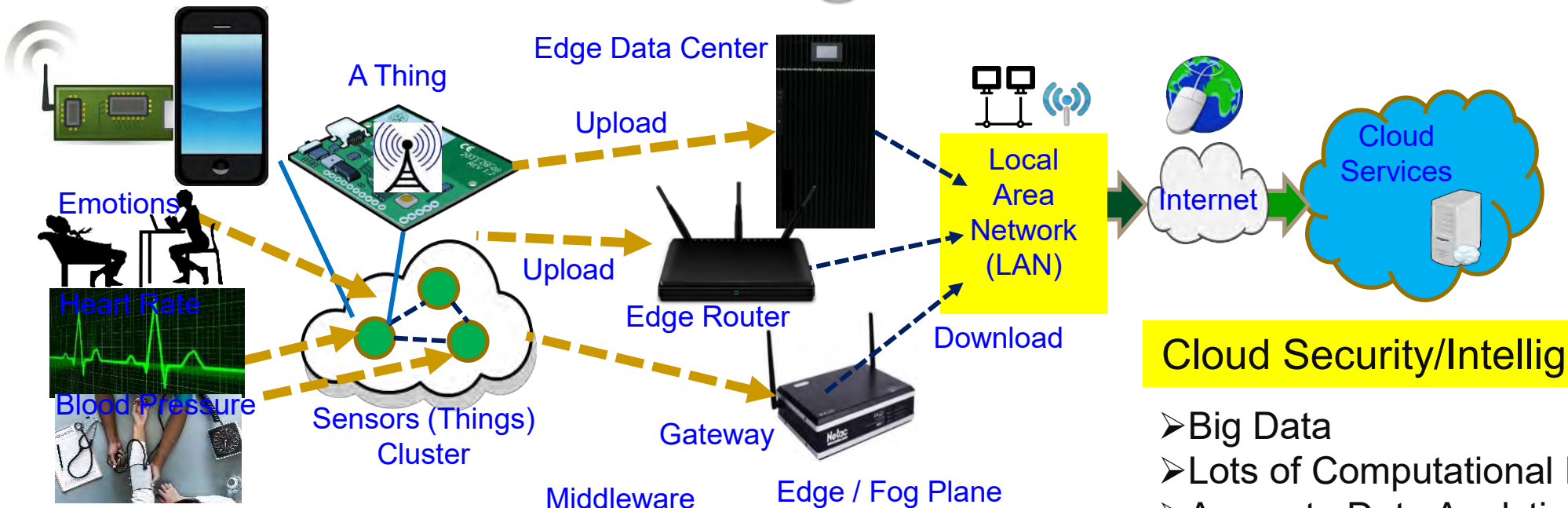
8 Production

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



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

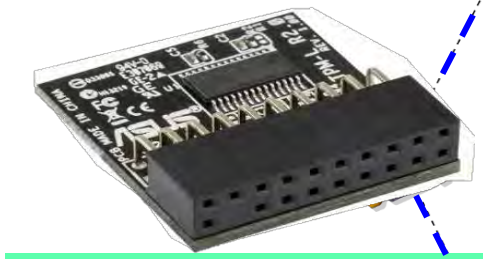
- Big Data
- Lots of Computational Resource
- Accurate Data Analytics
- Latency in Network
- Energy Overhead in Communications

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

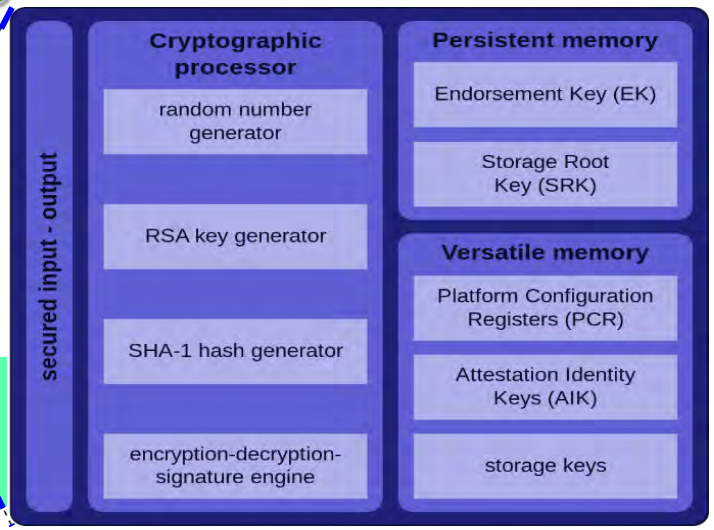
Heavy-Duty ML is more suitable for smart cities

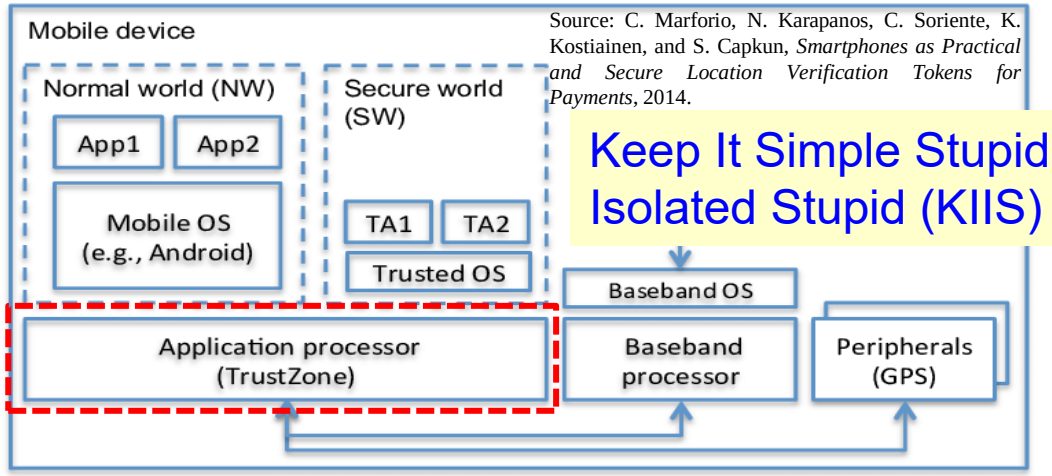
Hardware Cybersecurity Primitives – HSM, TrustZone, TPM, and PUF

Hardware Security Module (HSM)



Trusted Platform Module (TPM)





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

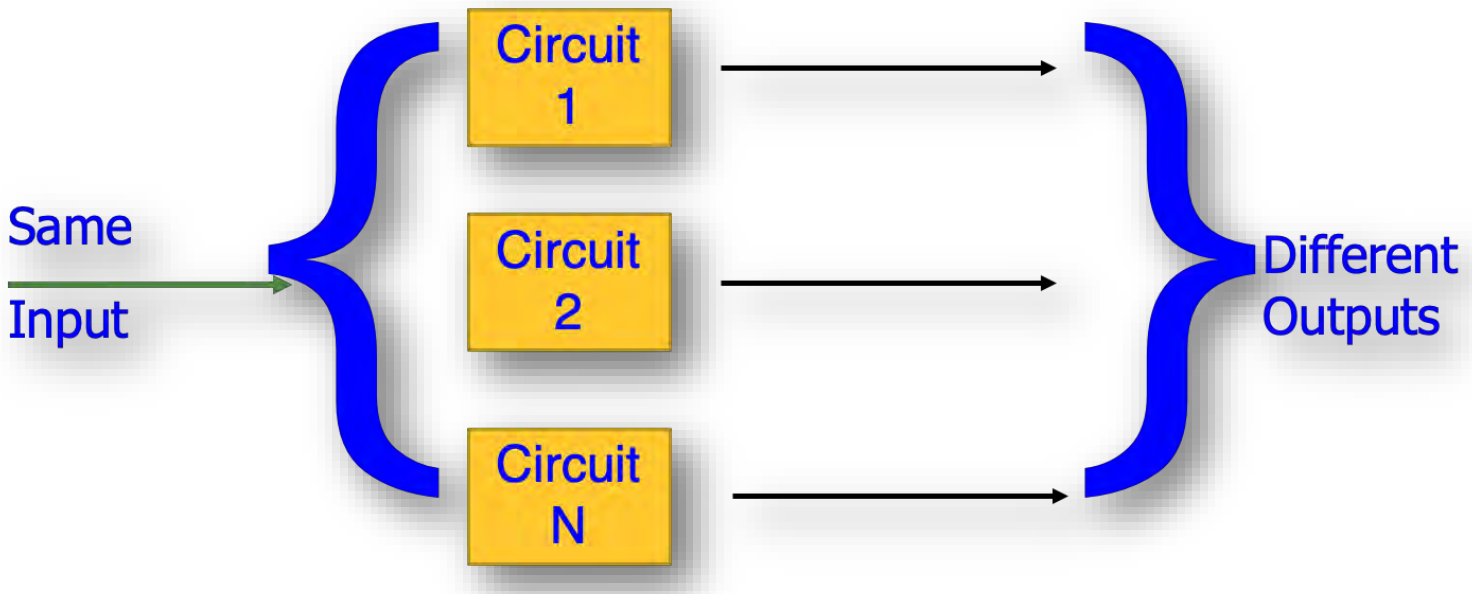
Keep It Simple Stupid (KISS) → Keep It Isolated Stupid (KIIS)

Physical Unclonable Functions (PUF)

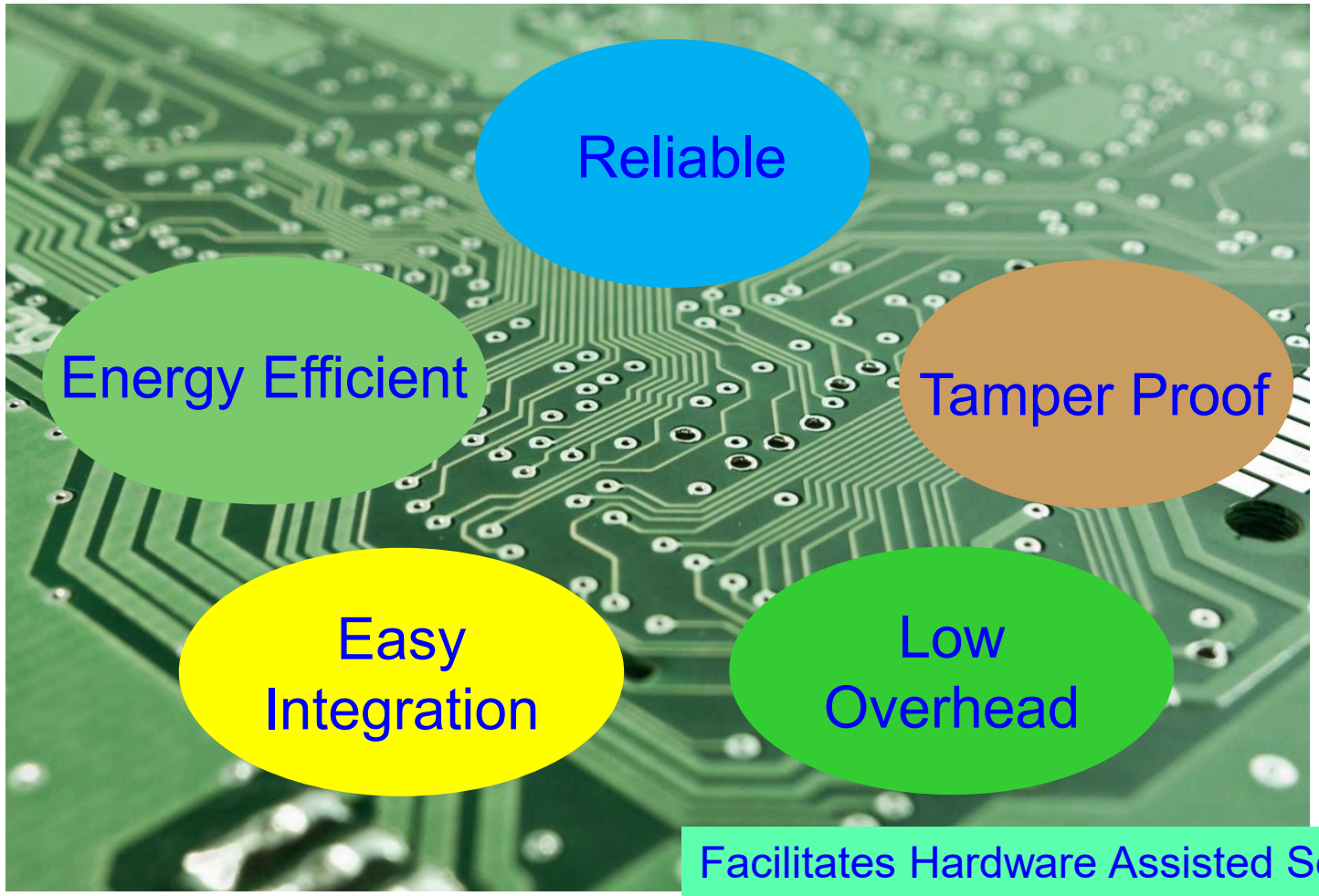
Source: Electric Power Research Institute (EPRI)

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.



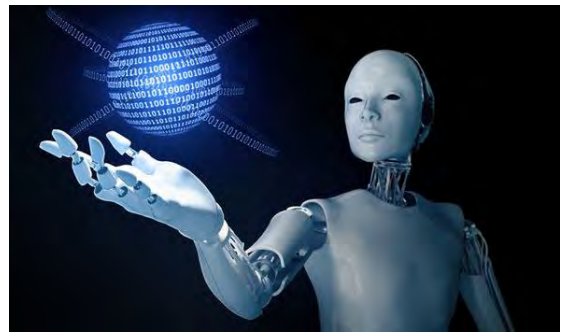
Physical Unclonable Function (PUF): Advantages



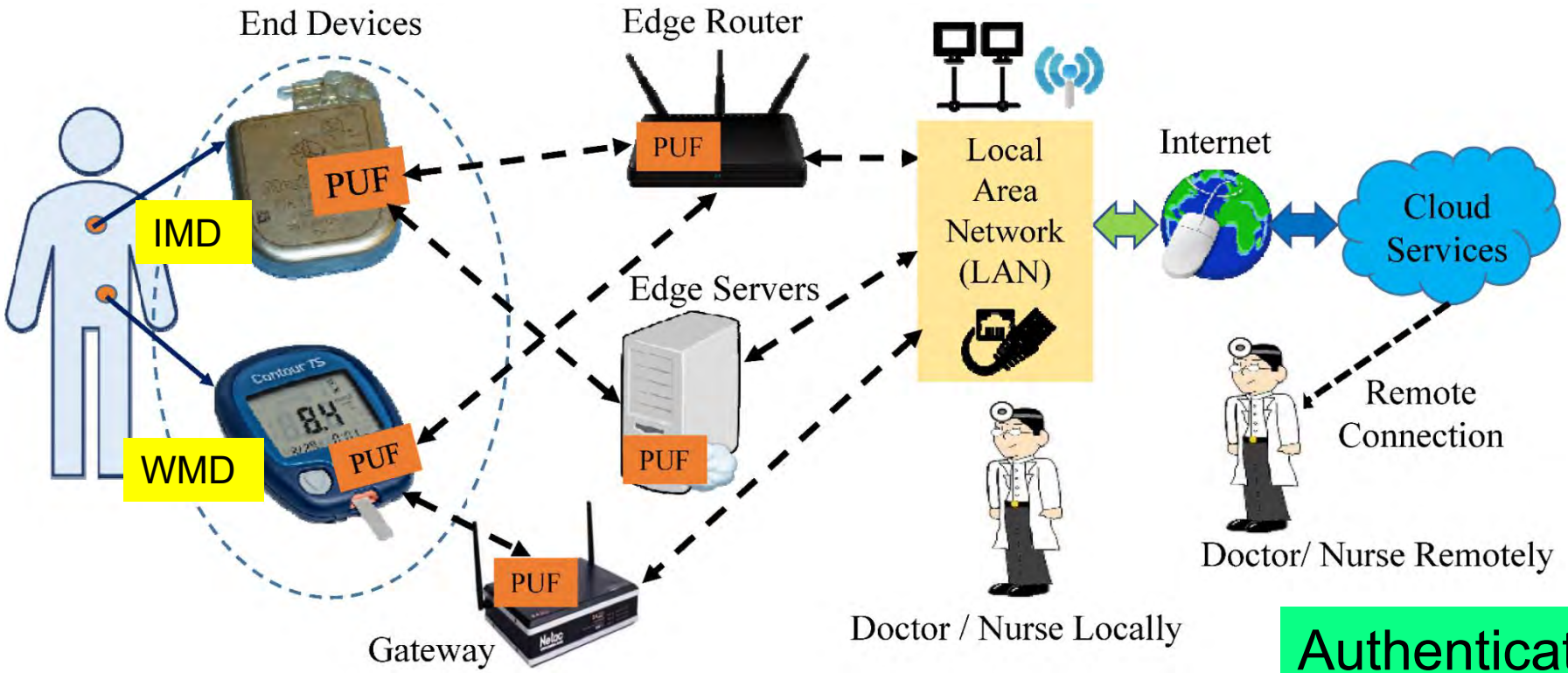
- A secure fingerprint generation scheme based on process variations in an Integrated Circuit
- PUFs don't store keys in digital memory, rather derive a key based on the physical characteristics of the hardware; thus secure.
- A simple design that generates cryptographically secure keys for the device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

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

Security-by-Design (SbD) – Specific Examples



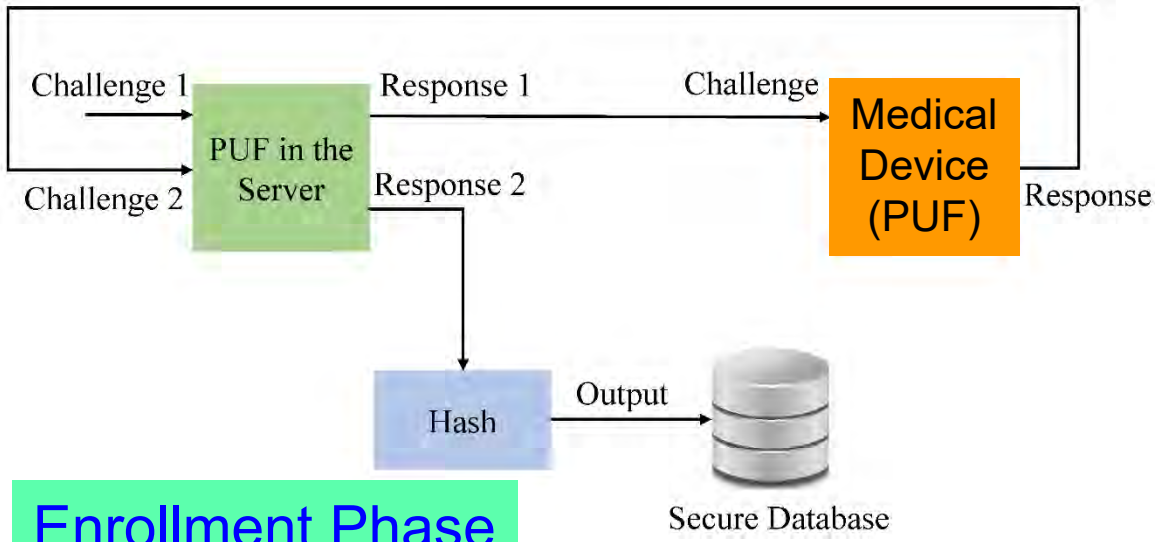
PMsec: Our Secure by Design Approach for Robust Security in Healthcare CPS



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

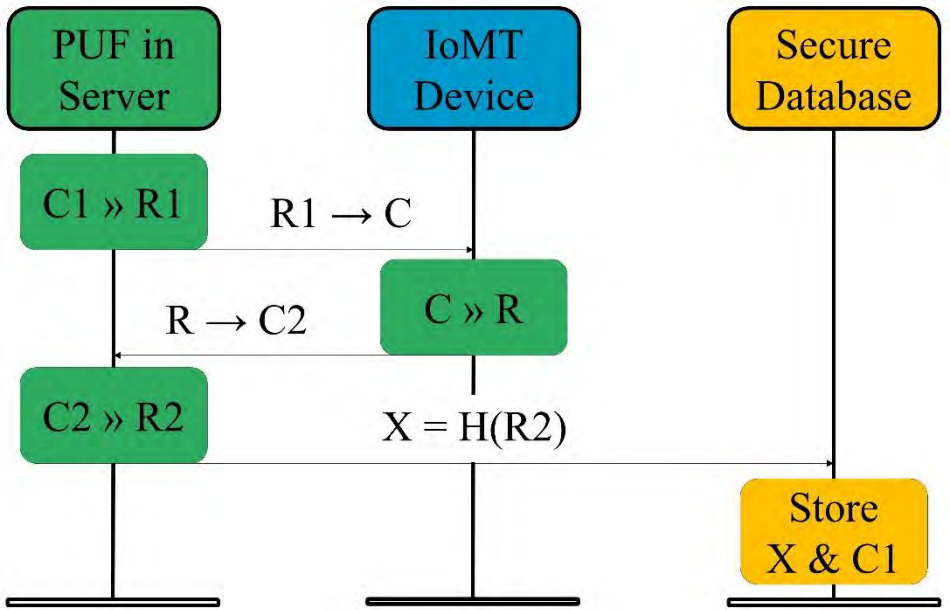


Enrollment Phase

At the Doctor

- When a new IoMT-Device comes for an User

Device Registration Procedure

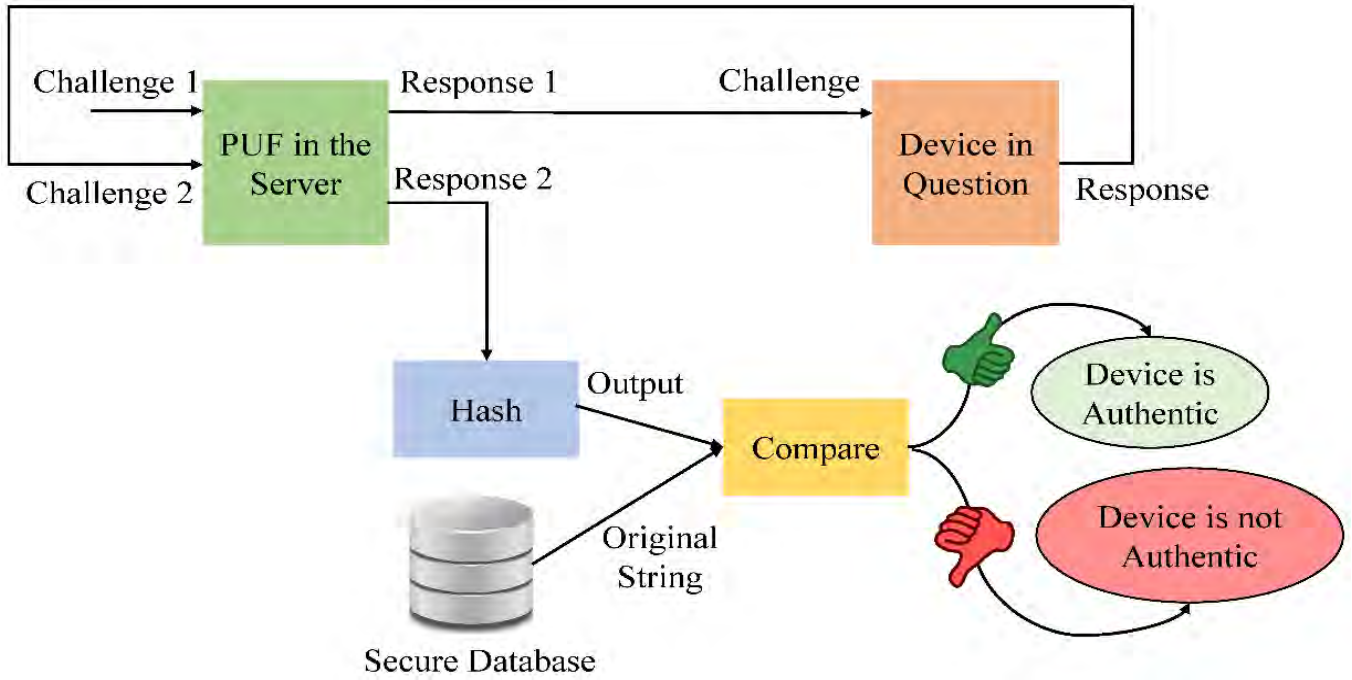


PUF Security Full Proof:

- 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

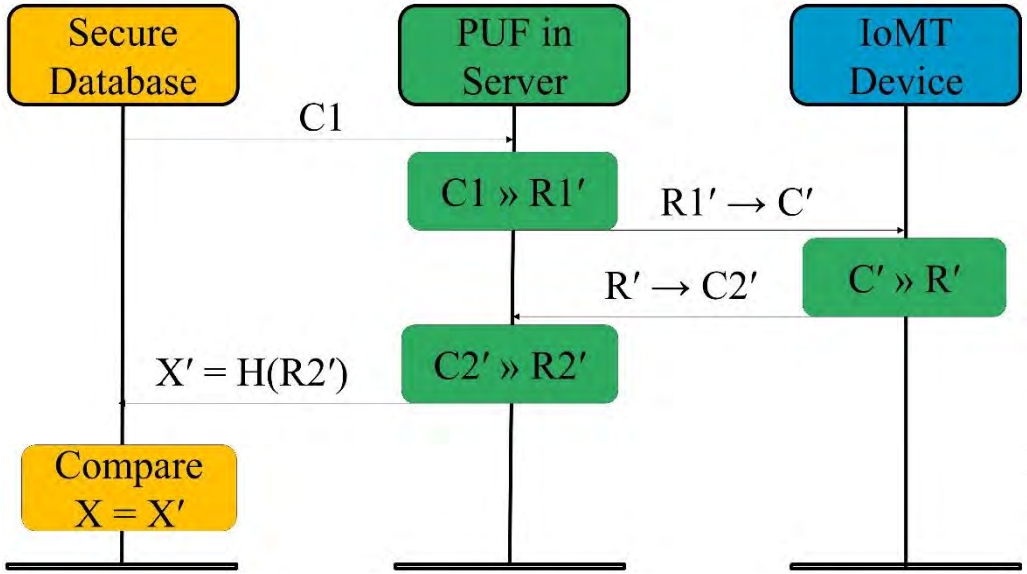


Authentication Phase

At the Doctor

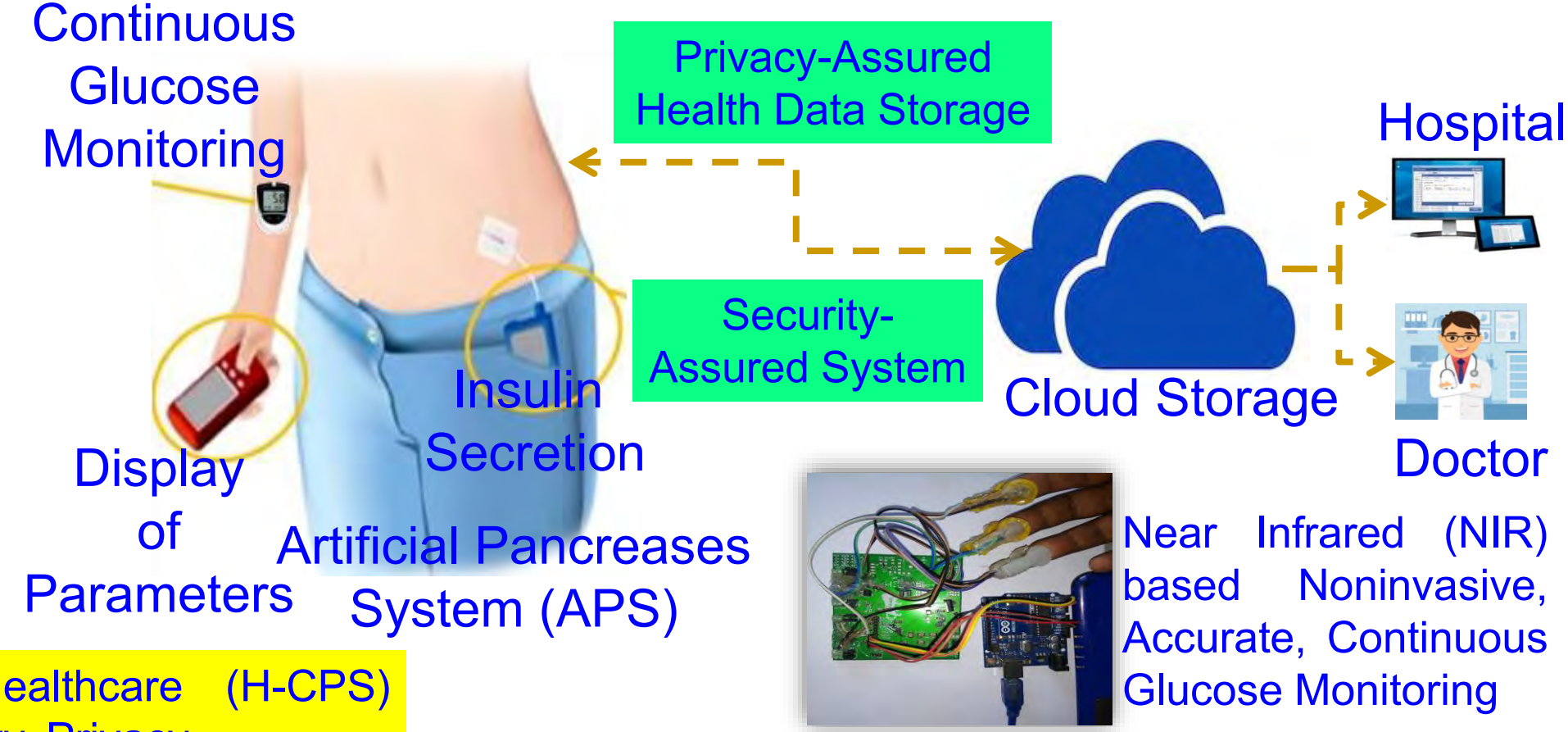
- When doctor needs to access an existing IoMT-device

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

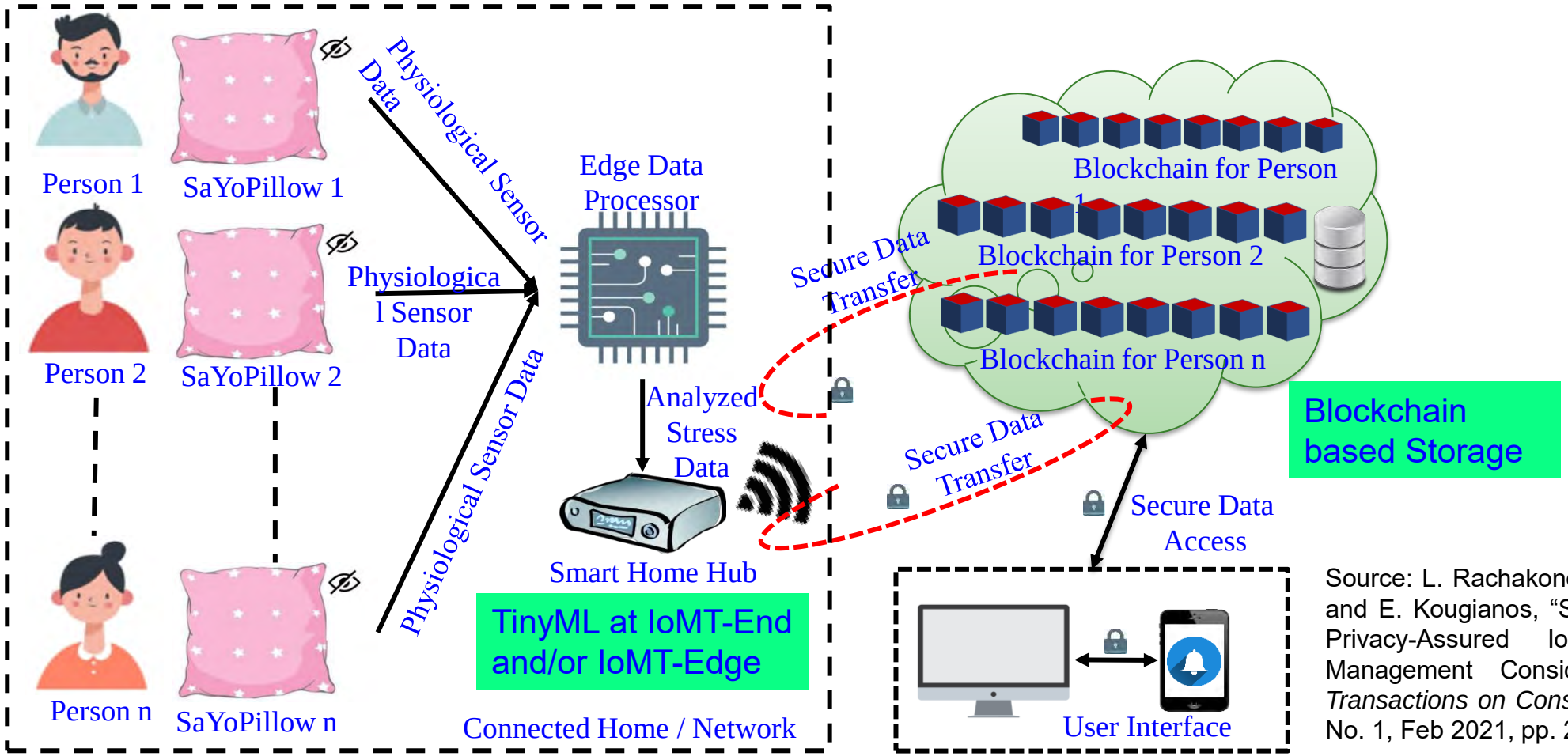


Near Infrared (NIR) based Noninvasive, Accurate, Continuous Glucose Monitoring

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

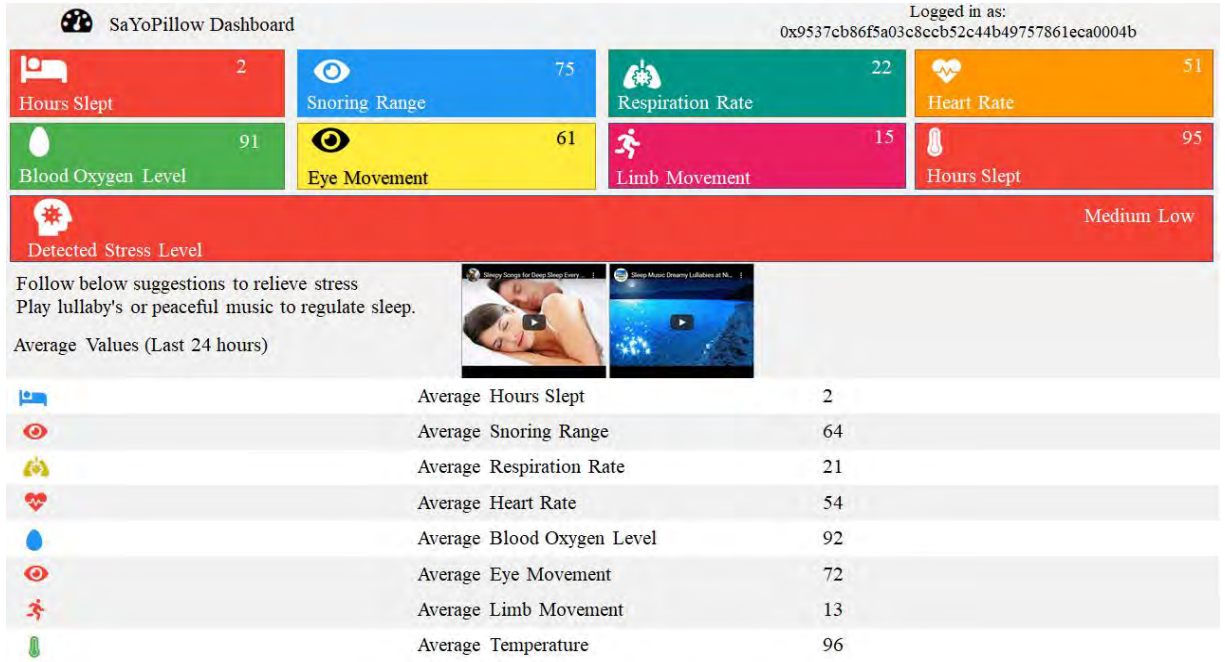
P. Jain, A. M. Joshi, and S. P. Mohanty, "iGLU: An Intelligent Device for Accurate Non-Invasive Blood Glucose-Level Monitoring in Smart Healthcare", *IEEE Consumer Electronics Magazine (MCE),* Vol. 9, No. 1, January 2020, pp. 35–42.

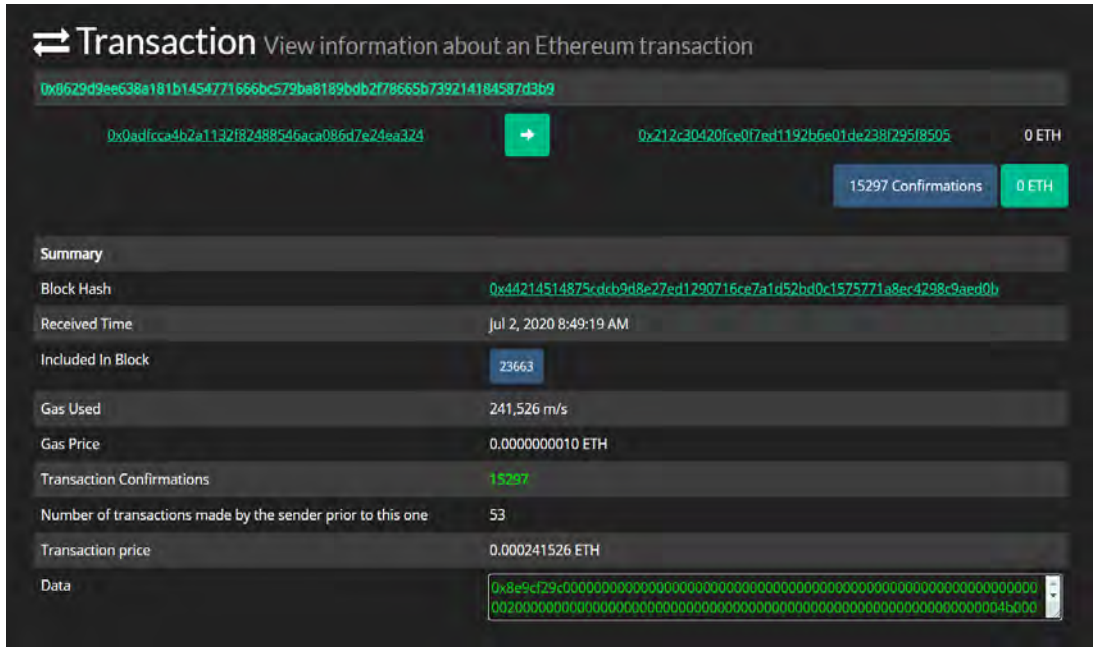
Our Smart-Yoga Pillow (SaYoPillow) with TinyML and Blockchain based Security

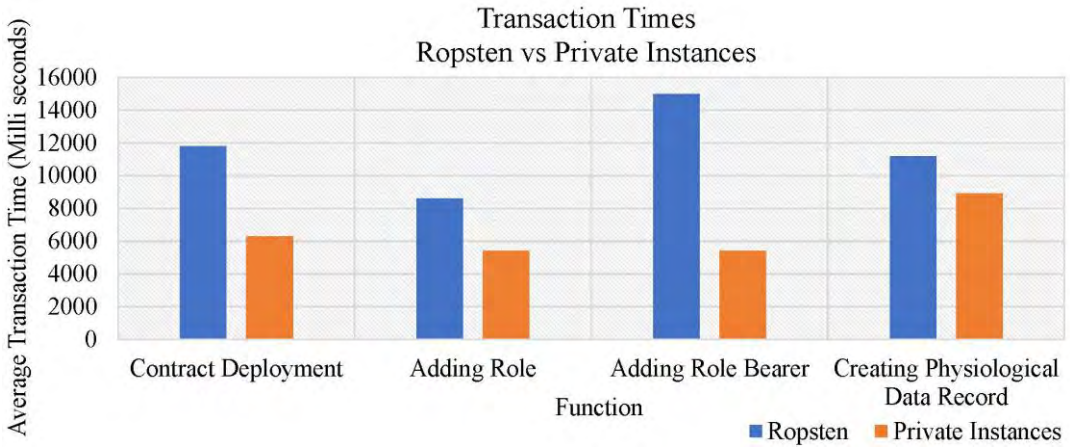


Source: L. Rachakonda, A. K. Bapatla, S. P. Mohanty, and E. Kougianos, "SaYoPillow: Blockchain-Integrated Privacy-Assured IoMT Framework for Stress Management Considering Sleeping Habit", *IEEE Transactions on Consumer Electronics (TCE)*, Vol. 67, No. 1, Feb 2021, pp. 20-29.

SaYoPillow: Blockchain Results



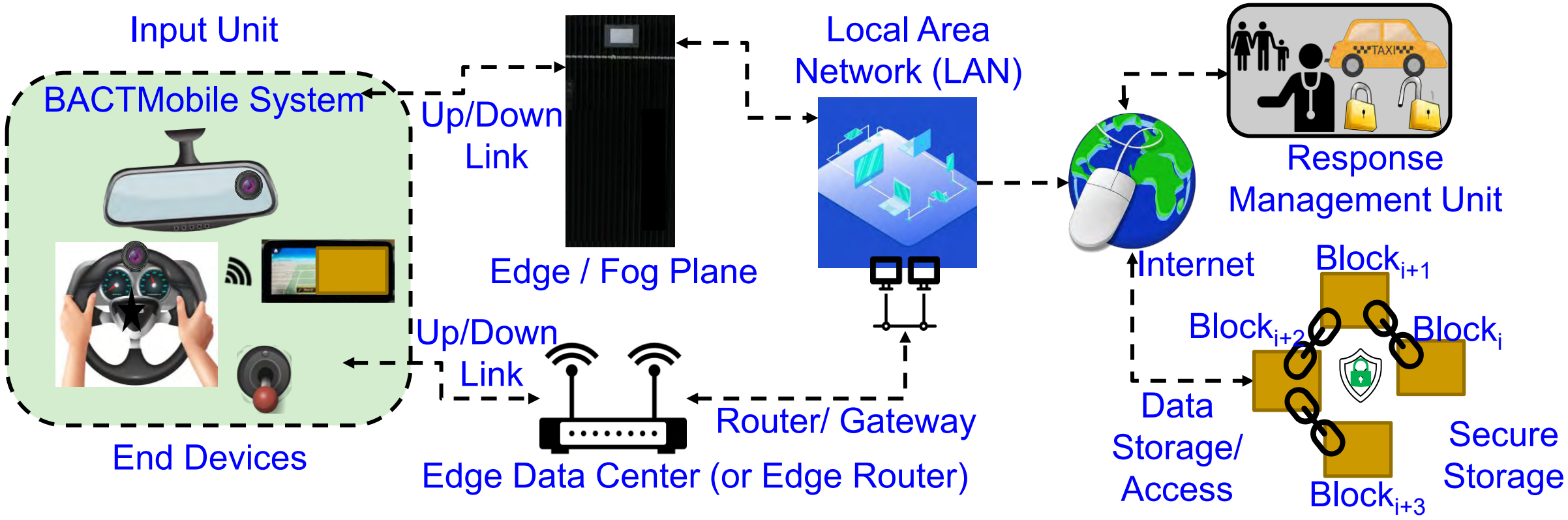




Transaction times of Private Ethereum in SaYoPillow is 2X faster in operations as compared to public ethereum test network Ropsten, as it is impacted by network congestion.

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.

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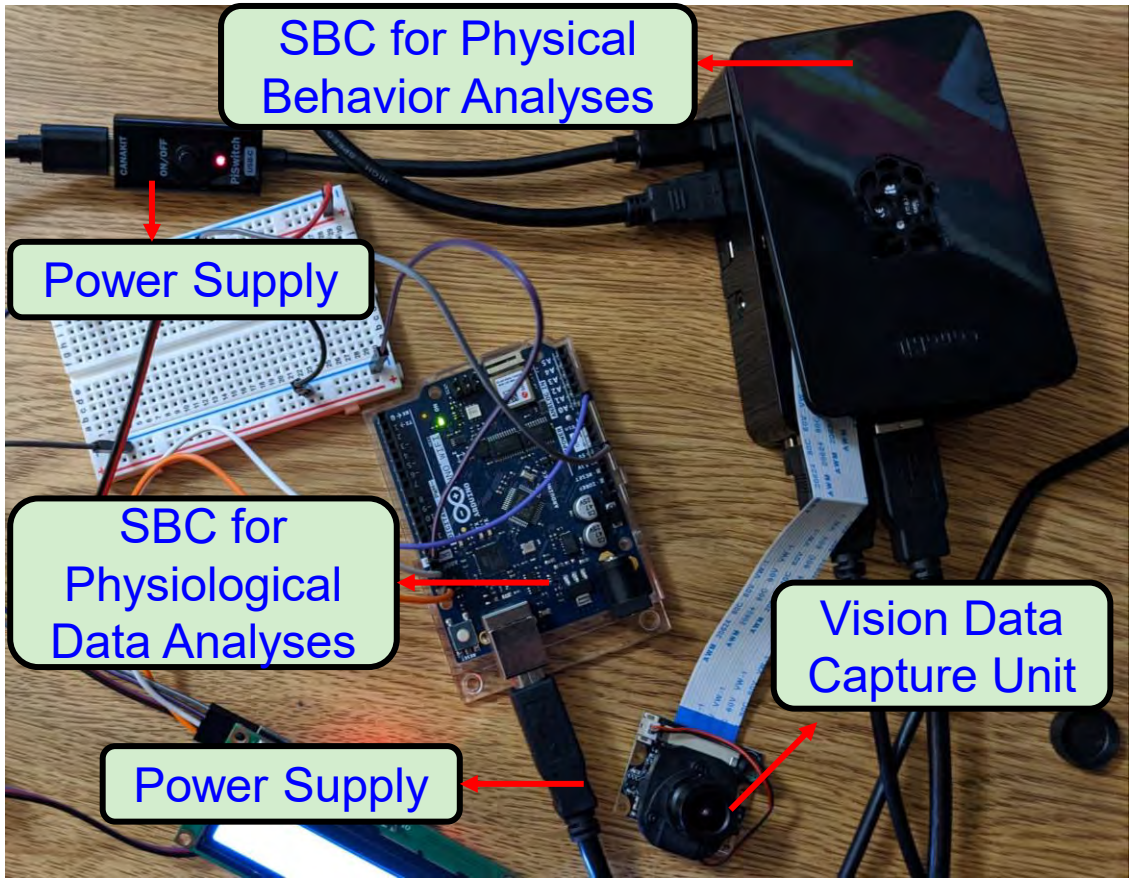
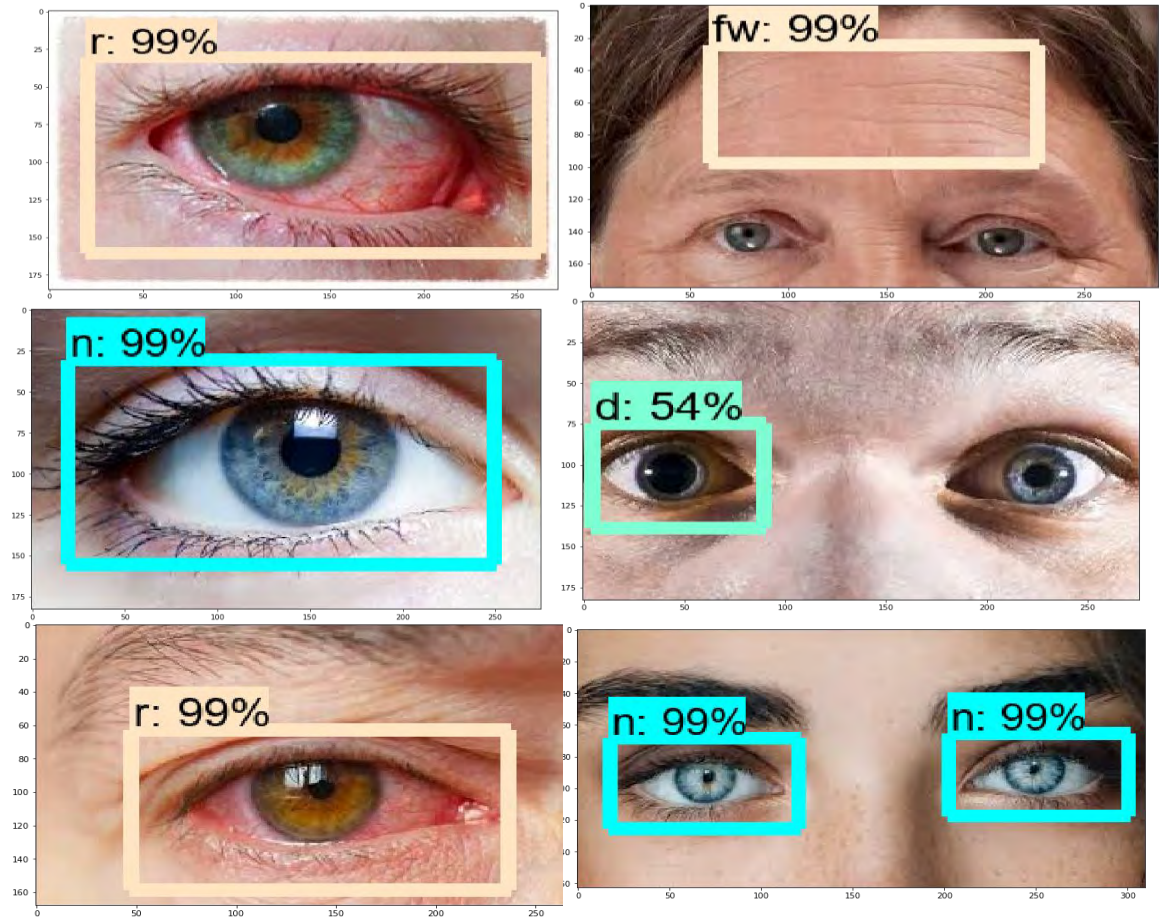


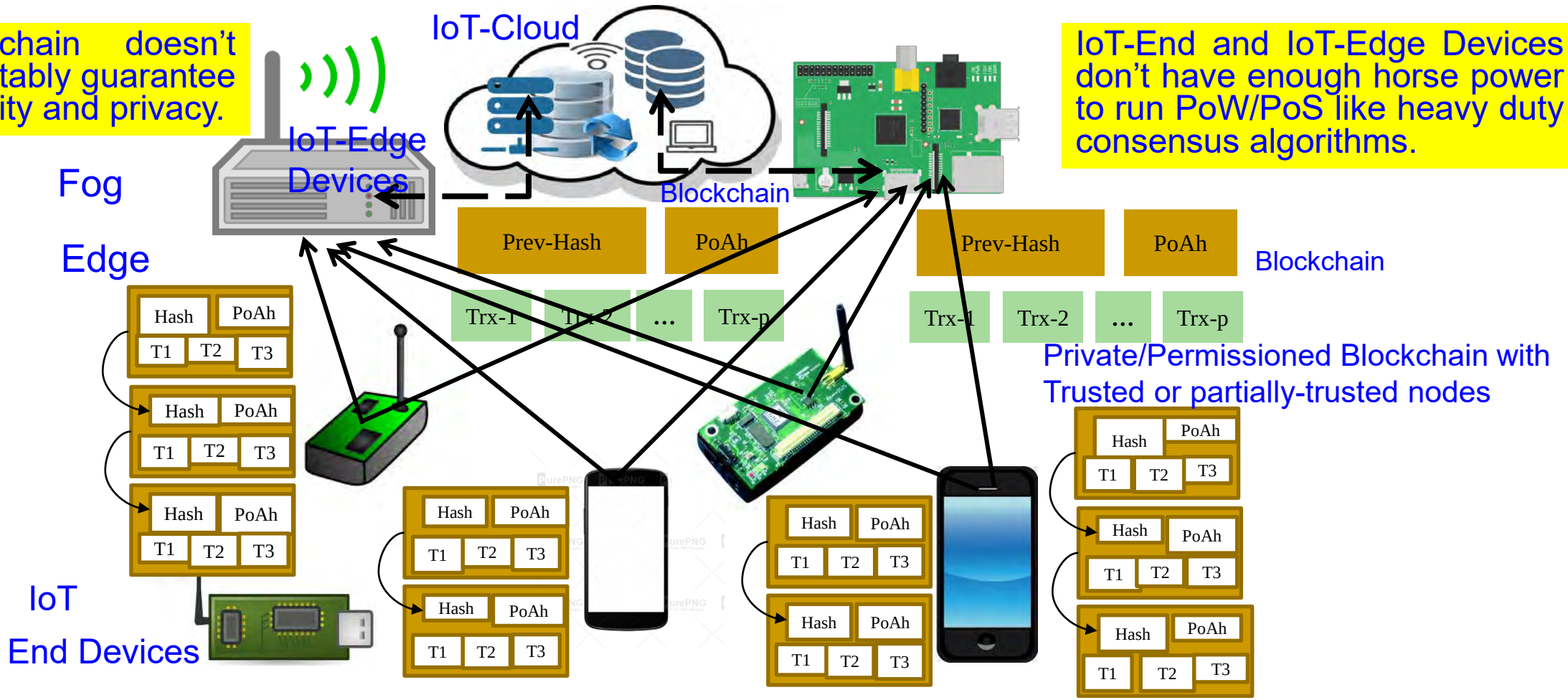


Source: L. Rachakonda, A. K. Bapatla, **S. P. Mohanty**, and E. Kougianos, "BACTmobile: A Smart Blood Alcohol Concentration Tracking Mechanism for Smart Vehicles in Healthcare CPS Framework", *Springer Nature Computer Science (SN-CS)*, Vol. 3, No. 3, May 2022, Article: 236, 24-pages, DOI: https://doi.org/10.1007/s42979-022-01142-9.

IoT-Friendly Blockchain – Our EasyChain

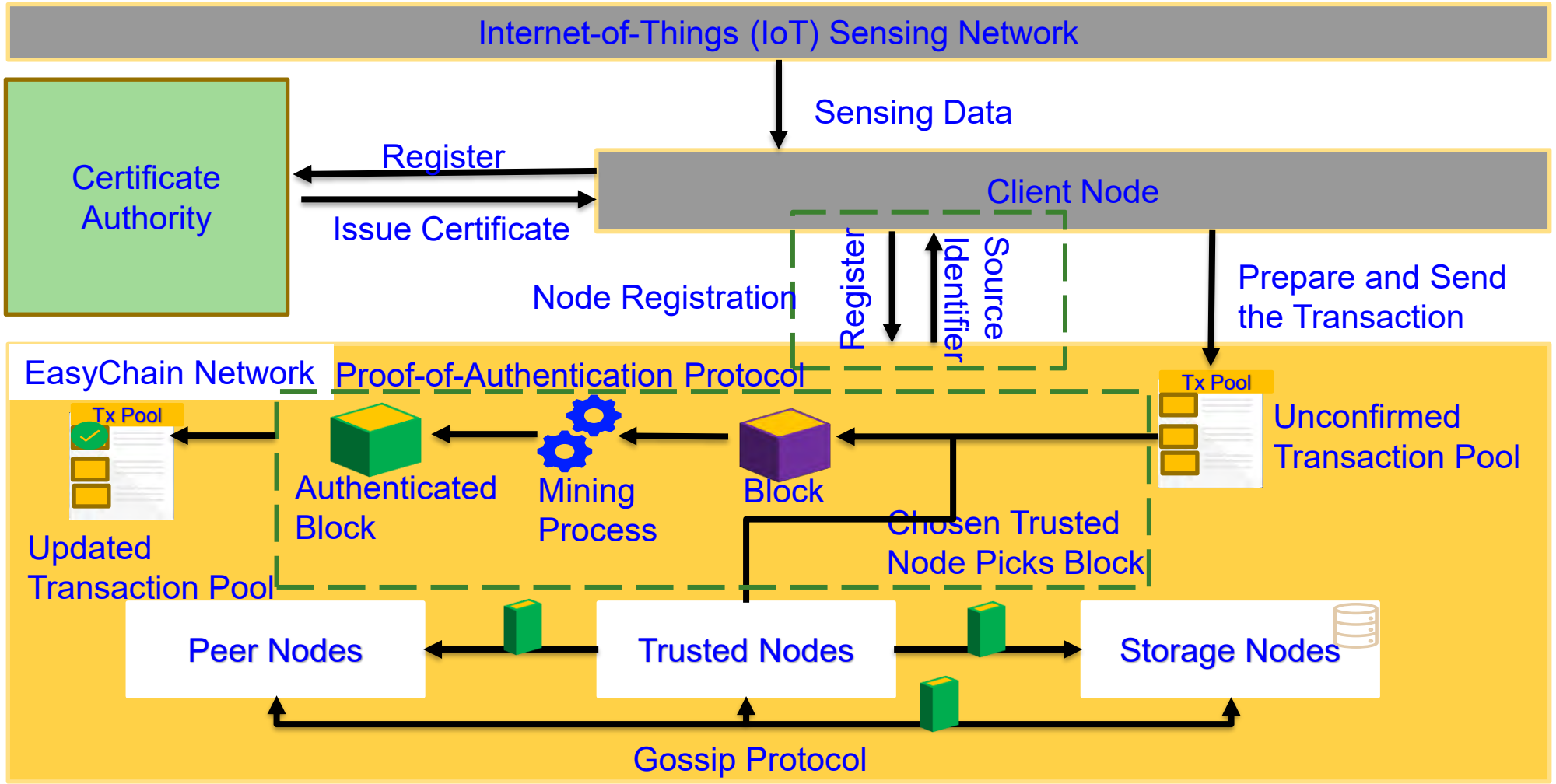
Blockchain doesn't inheritably guarantee security and privacy.

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



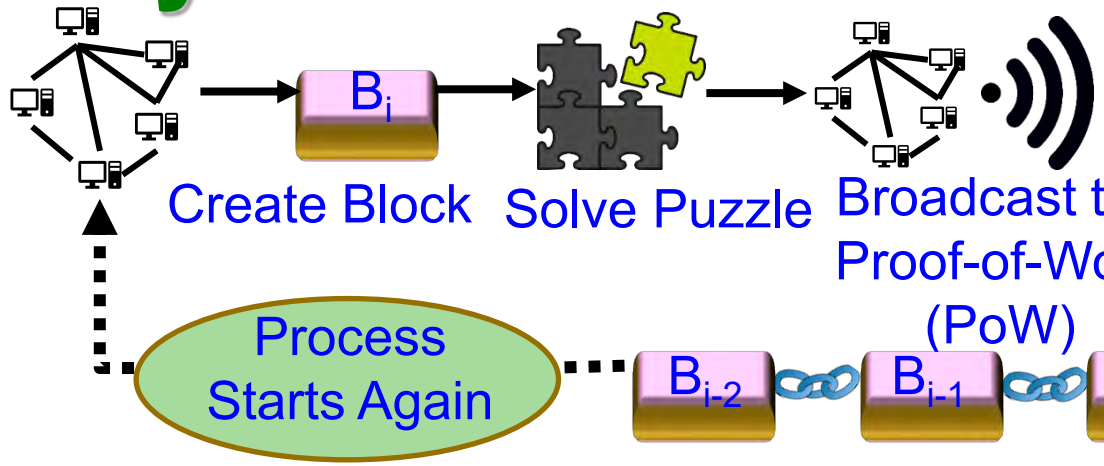
Source: D. Puthal and S. P. Mohanty, "Proof of Authentication: IoT-Friendly Blockchains", *IEEE Potentials Magazine*, Vol. 38, No. 1, January 2019, pp. 26--29.

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.

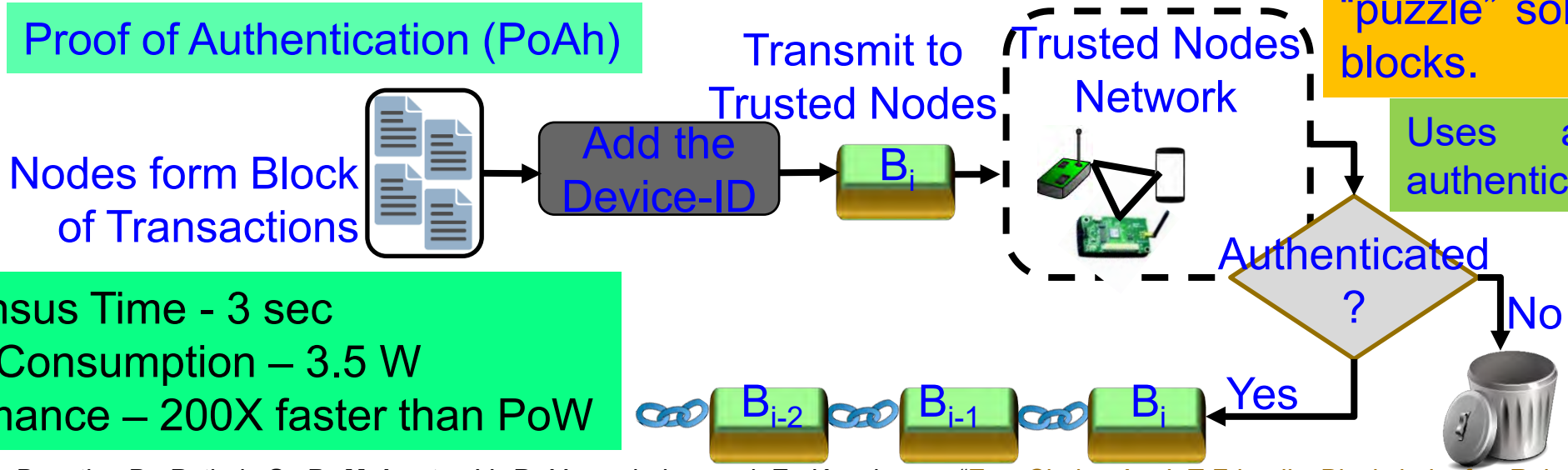
Our EasyChain: Proof-of-Authentication (PoAh)



Proof-of-Work (PoW)

Eliminates cryptographic "puzzle" solving to validate blocks.

Proof of Authentication (PoAh)

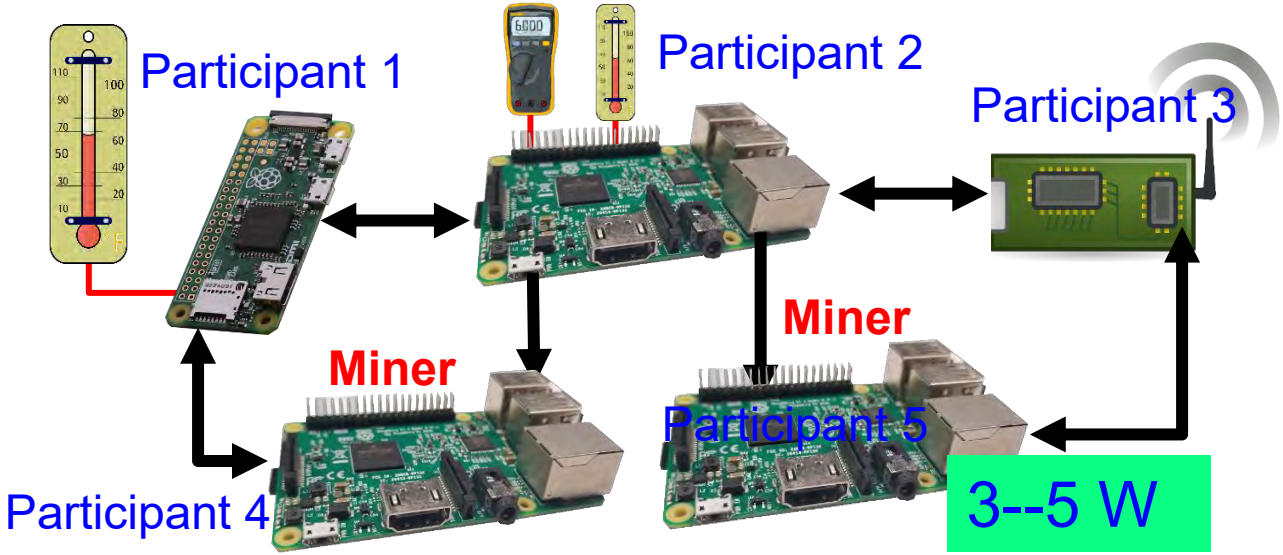


Uses a cryptographic authentication mechanism.

Consensus Time - 3 sec
Power Consumption – 3.5 W
Performance – 200X faster than PoW

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.

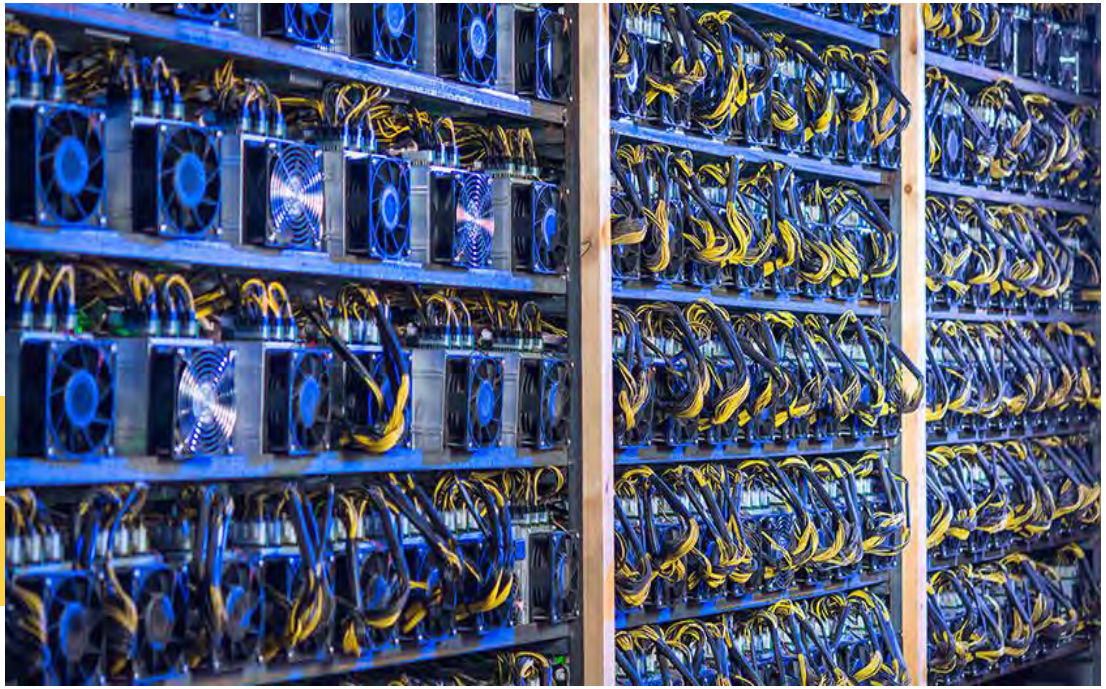
Our EasyChain with PoAh Runs in Resource Constrained Environment



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

Blockchain using PoW Needs Significant Resource

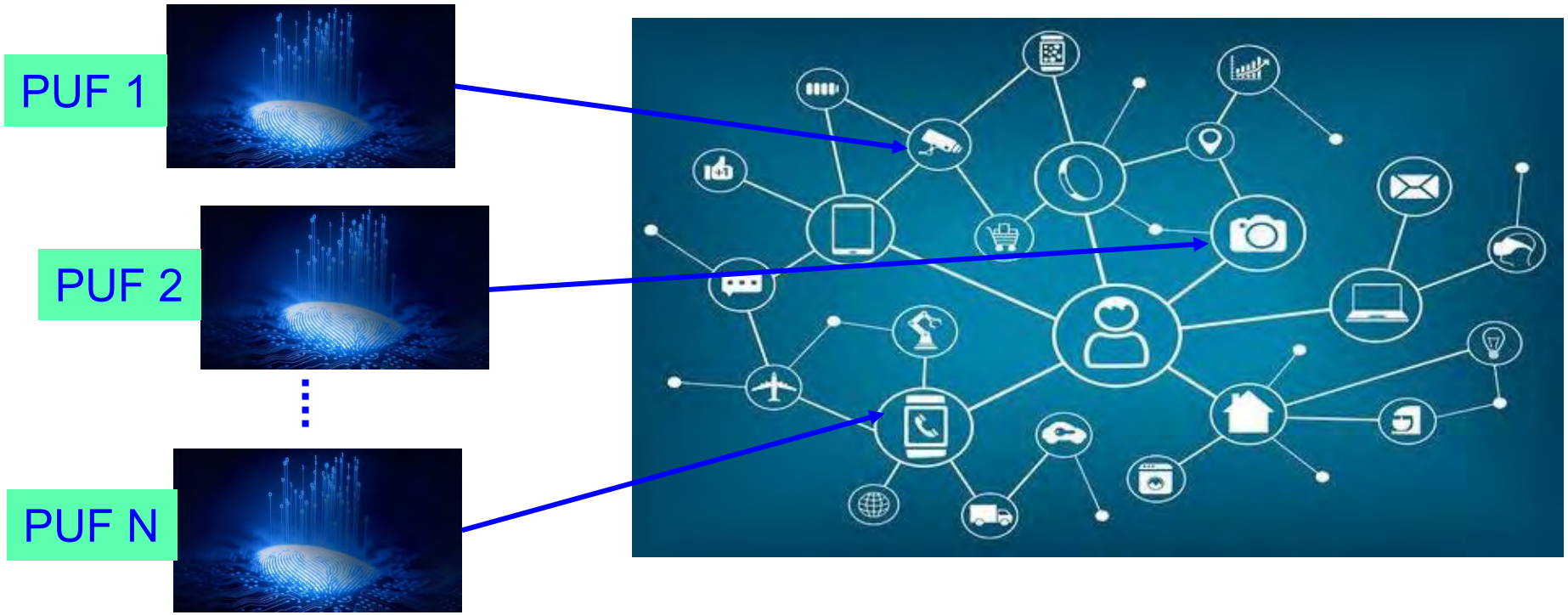
500,0000 W



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

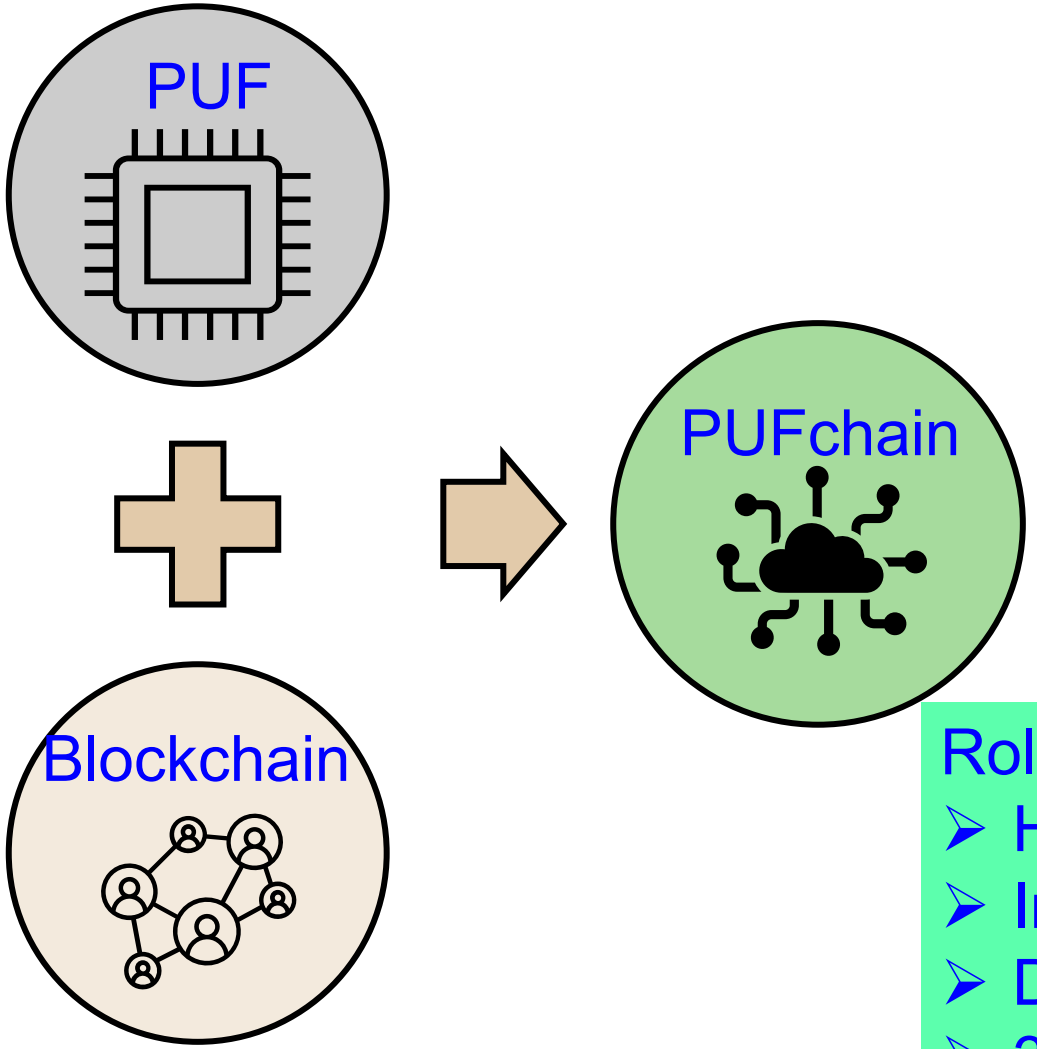
Source: D. Puthal, S. P. Mohanty, V. P. Yanambaka, and E. Kougianos, "PoAh: A Novel Consensus Algorithm for Fast Scalable Private Blockchain for Large-scale IoT Frameworks", *arXiv Computer Science*, arXiv:2001.07297, January 2020, 26-pages.

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

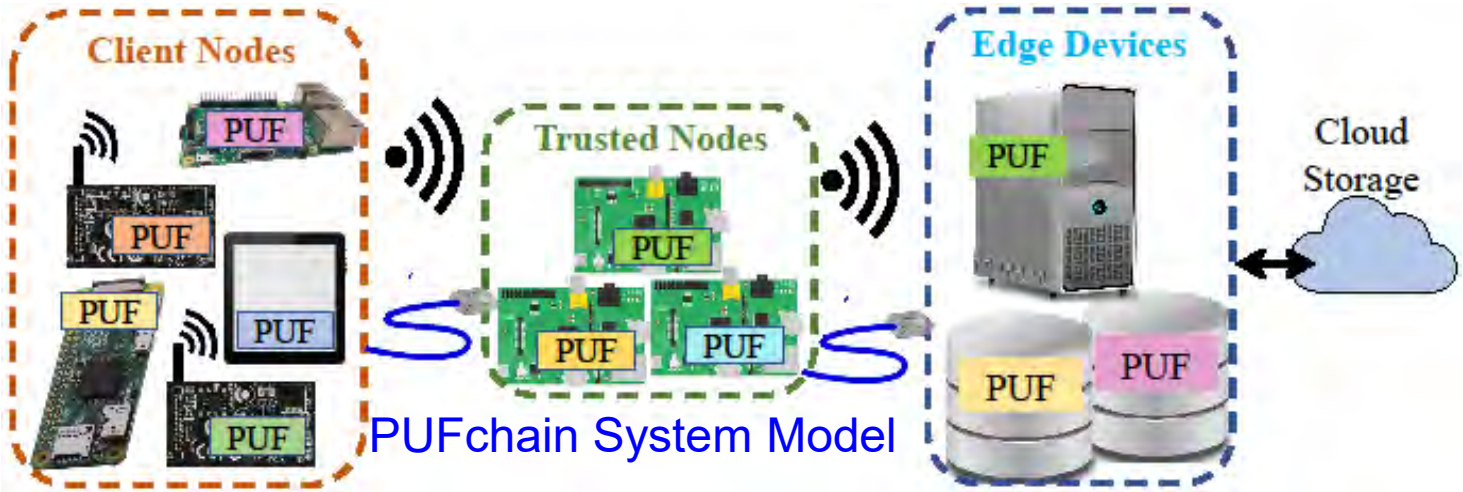


Blockchain Technology is integrated with Physically Unclonable Functions as PUFchain by storing the PUF Key into immutable Blockchain

Roles of PUF:

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

PUFchain: Our Hardware-Assisted Scalable Blockchain

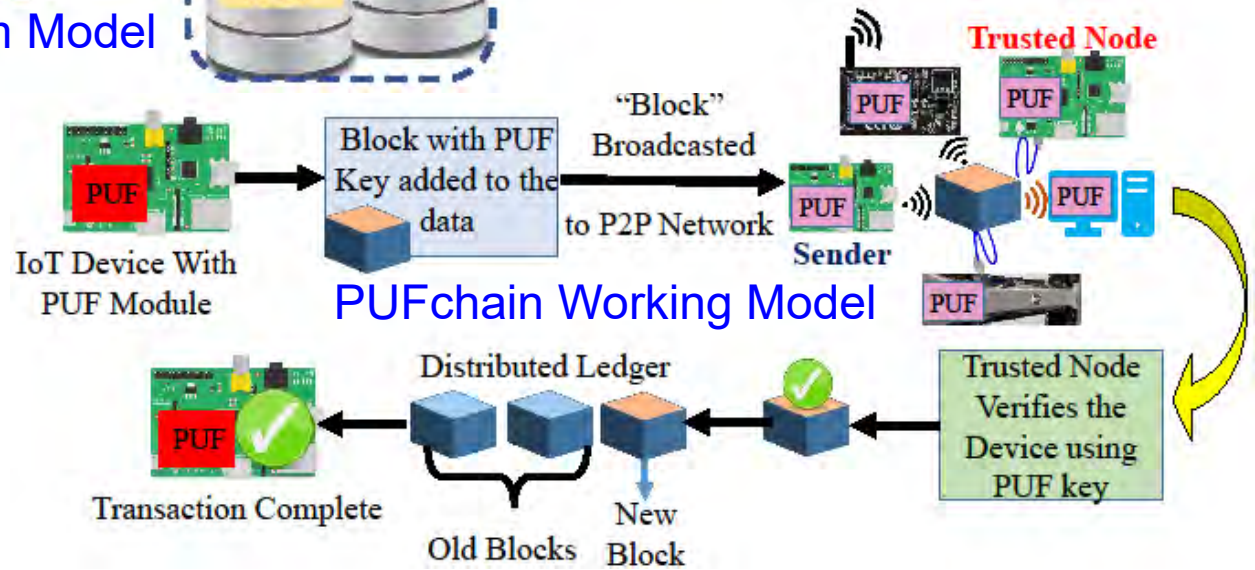


PUFchain System Model

Can provide:
Device, System, and Data Security

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

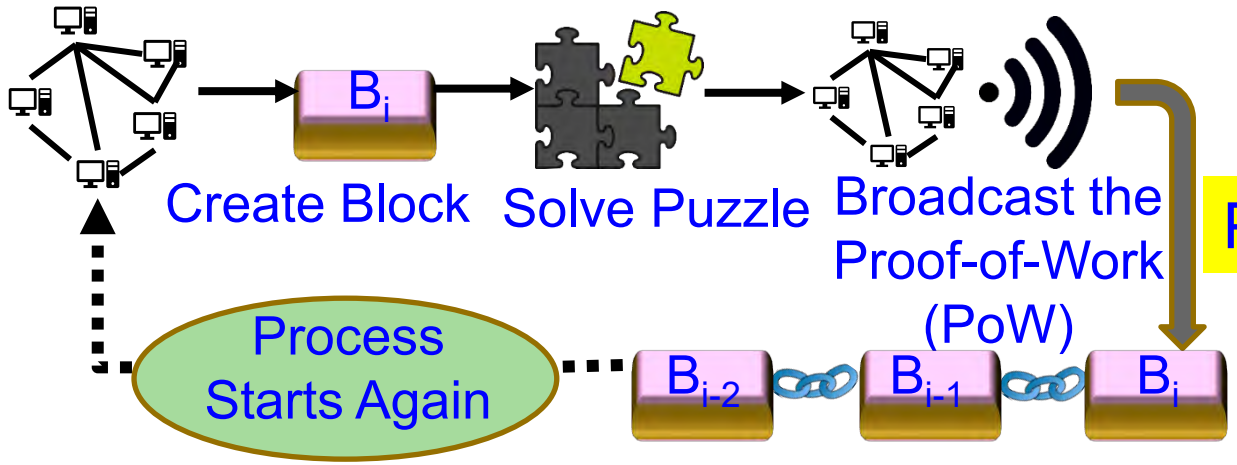
- ✓ PoP is 1,000X faster than PoW
- ✓ PoP is 5X faster than PoAh



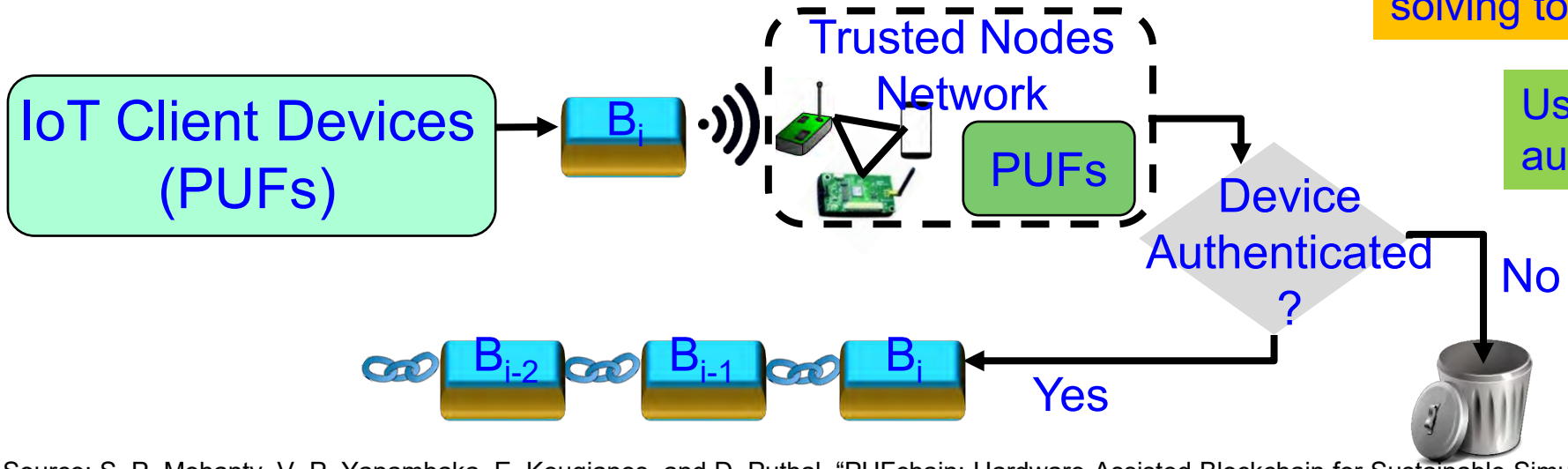
PUFchain Working Model

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)



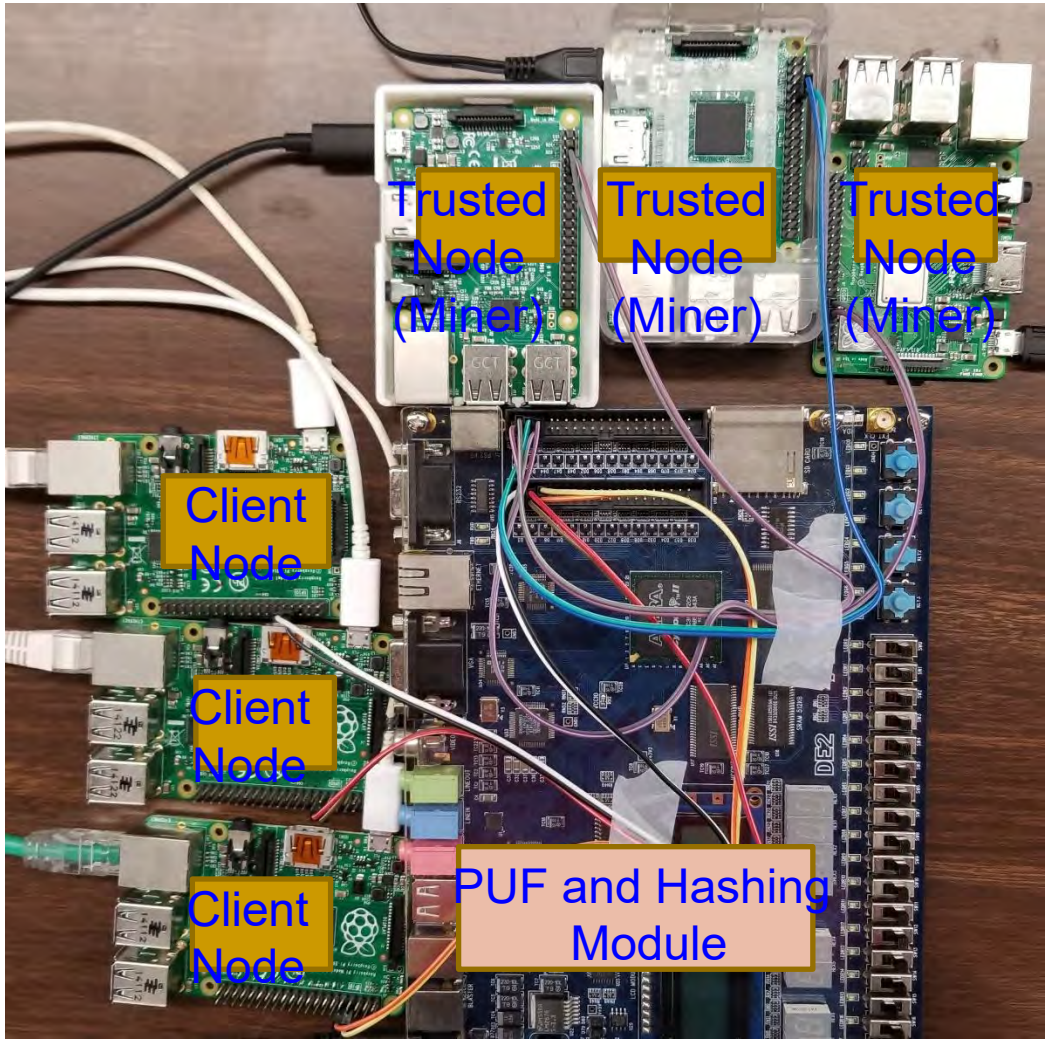
Eliminates cryptographic "puzzle" solving to validate blocks.



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

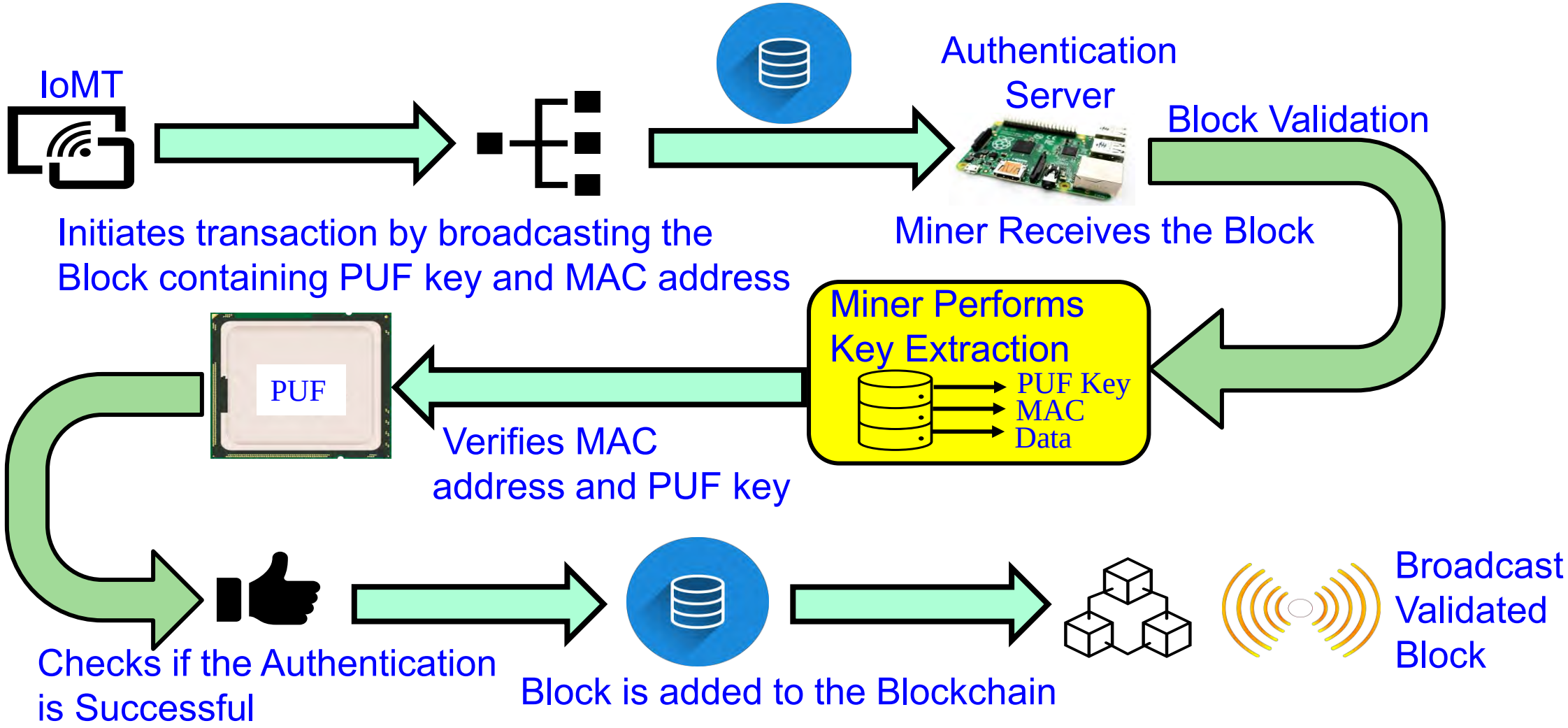


PoW - 10 min in cloud	PoAh – 950ms in Raspberry Pi	PoP - 192ms in Raspberry Pi
High Power	3 W Power	5 W Power

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

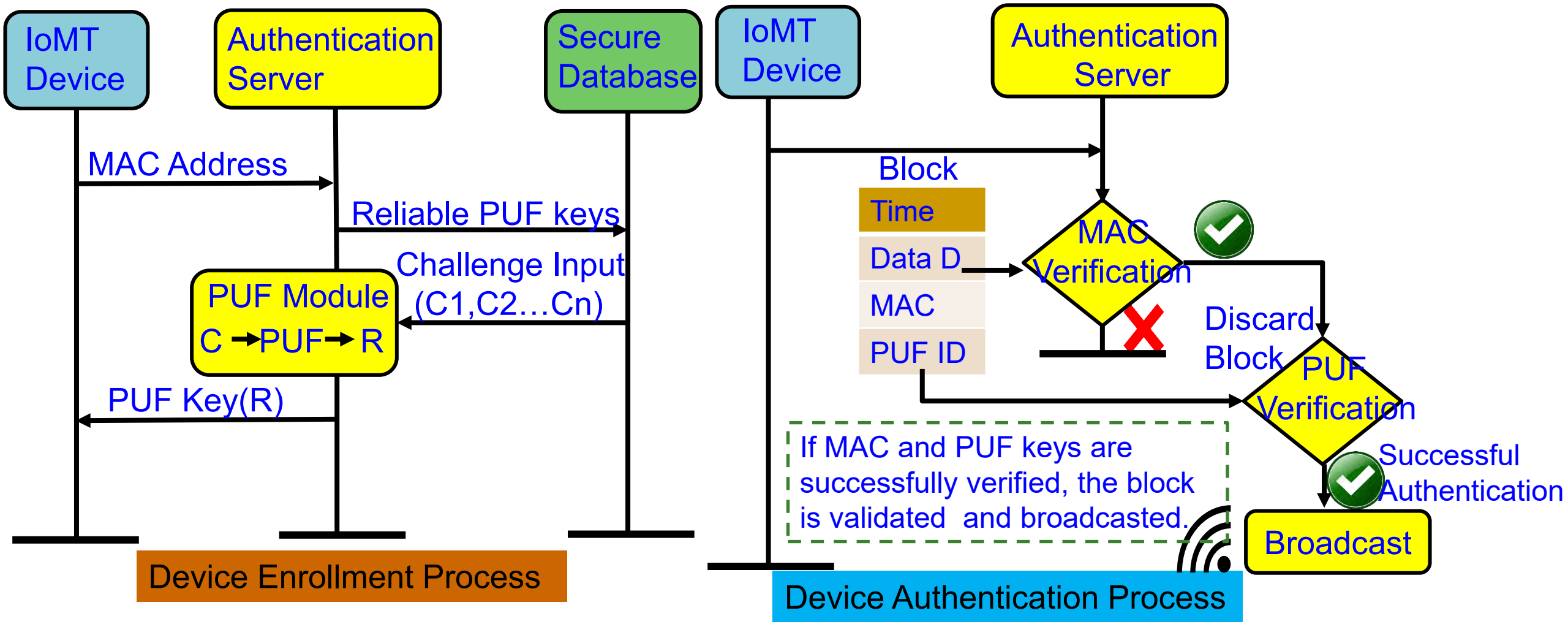
Source: S. P. Mohanty, V. P. Yanambaka, E. Kougianos, and D. Puthal, "PUFchain: Hardware-Assisted Blockchain for Sustainable Simultaneous Device and Data Security in Internet of Everything (IoE)", *IEEE Consumer Electronics Magazine (MCE)*, Vol. 9, No. 2, March 2020, pp. 8-16.

PUFchain 2.0: Our Hardware-Assisted Scalable Blockchain



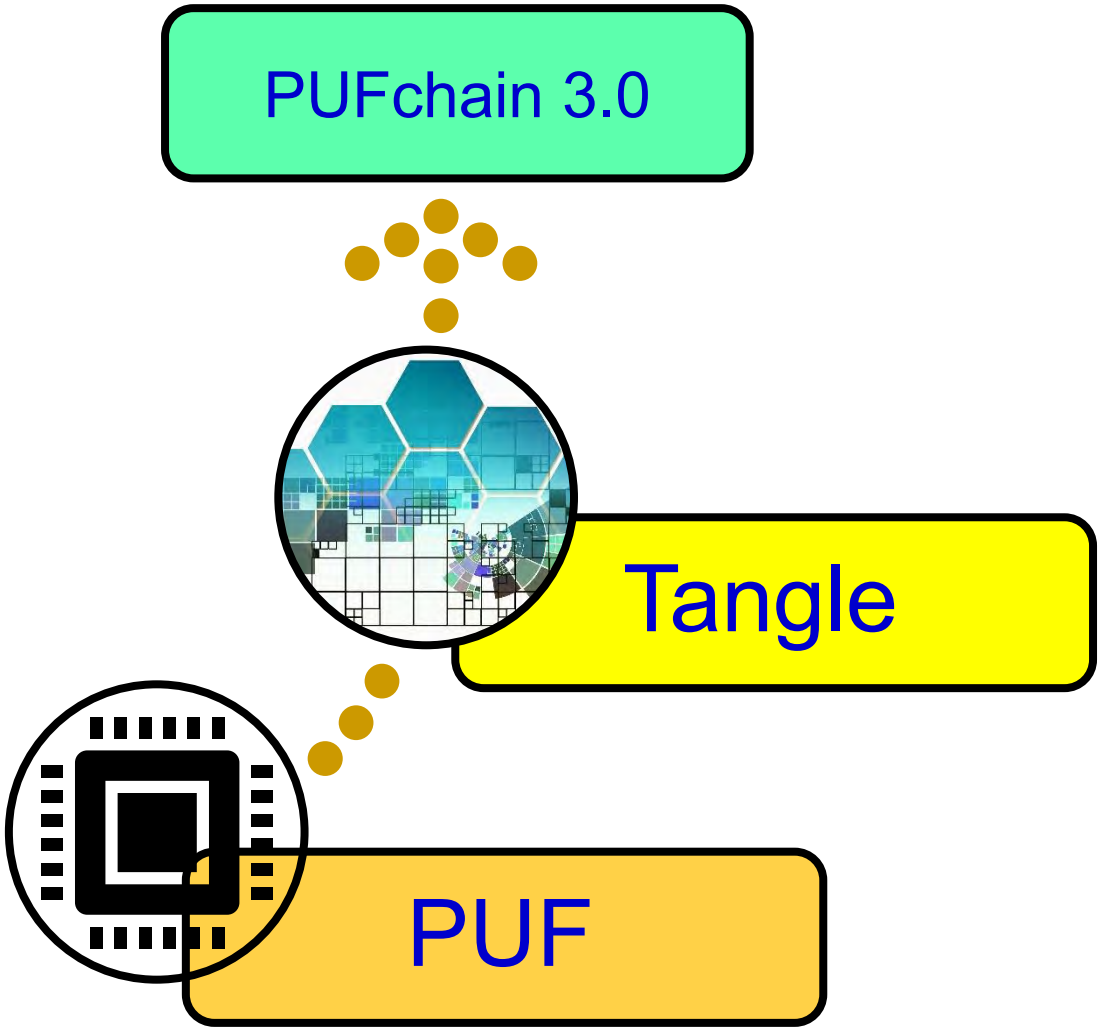
Source: V. K. V. V. Bathalapalli, **S. P. Mohanty**, E. Kougianos, B. K. Baniya, and B. Rout, "PUFchain 2.0: Hardware-Assisted Robust Blockchain for Sustainable Simultaneous Device and Data Security in Smart Healthcare", *Springer Nature Computer Science (SN-CS)*, Vol. 3, No. 5, Sep 2022, Article: 344,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

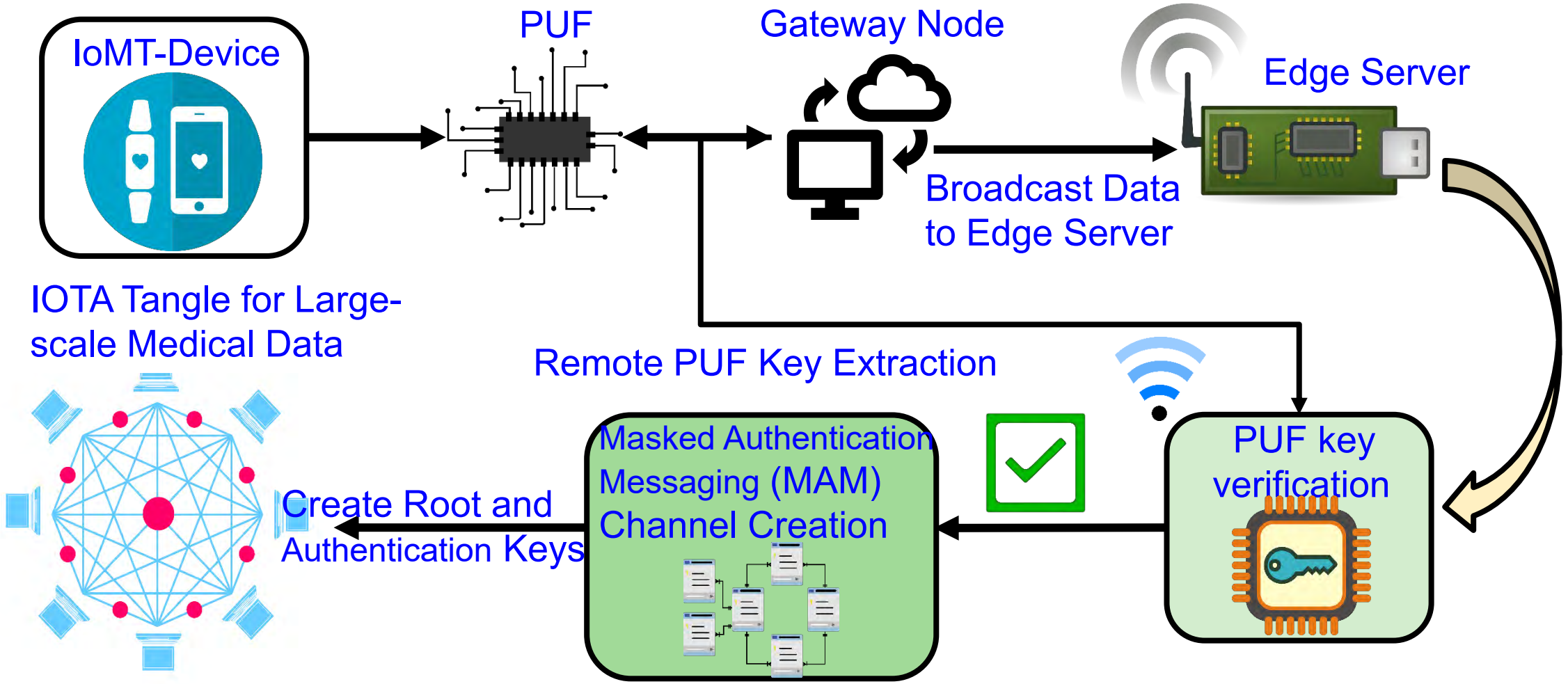
PUFchain 3.0 - Conceptual Idea



- 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



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

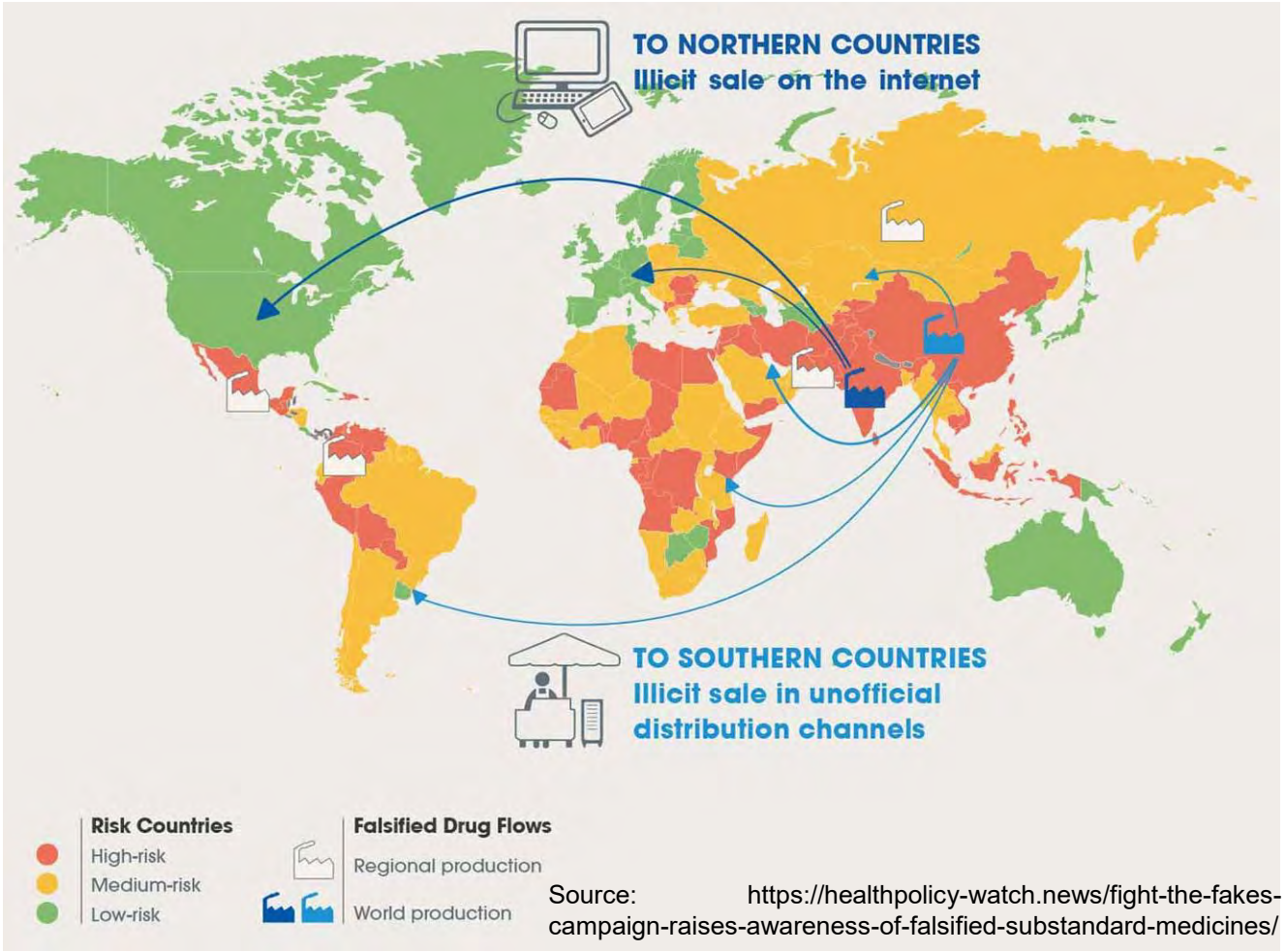
Source: GA-FDD's (Government Analyst –Food and Drug Department's) occasional fake drugs disclosures may be tip of the iceberg, https://www.stabroeknews.com/2019/09/06/business/ga-fdds-occasional-fake-drugs-disclosures-may-be-tip-of-the-iceberg/

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.

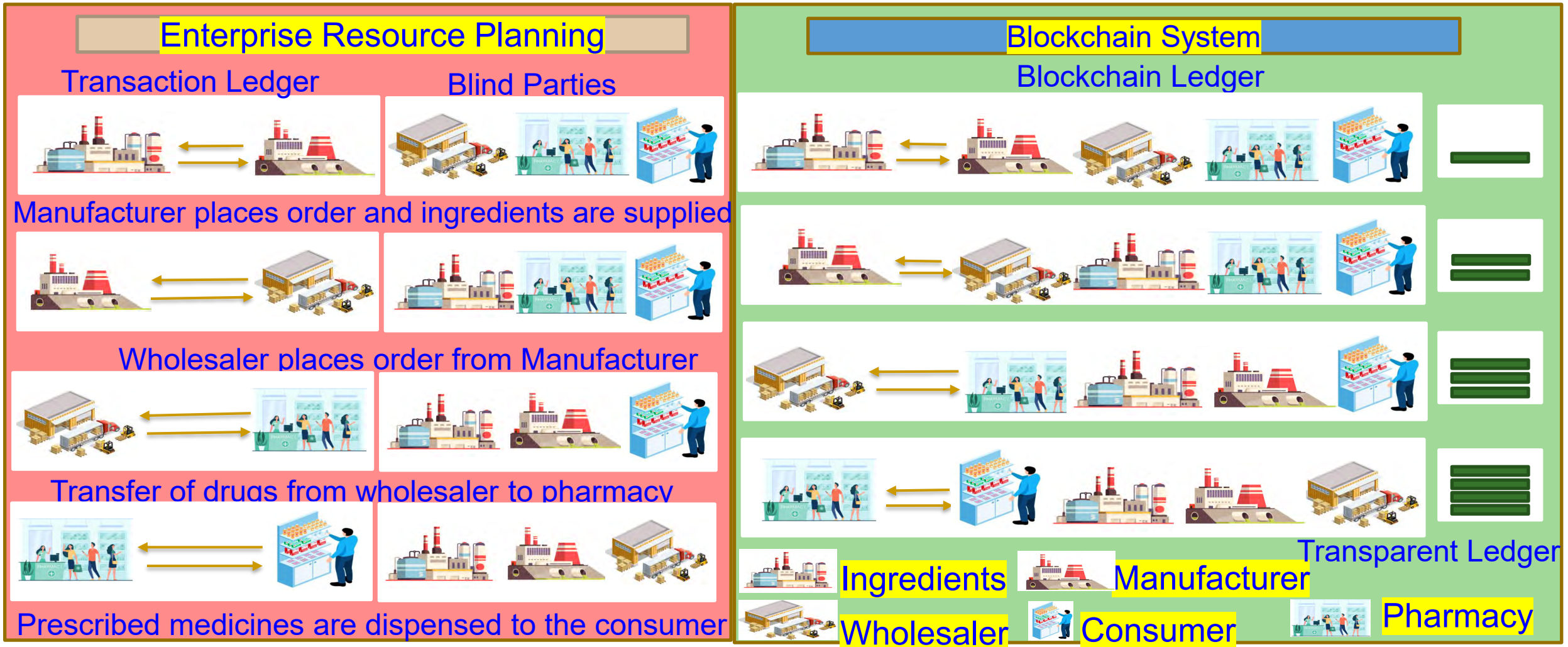
Source: https://fraud.org/fakerx/fake-drugs-and-their-risks/counterfeit-drugs-are-a-global-problem/

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



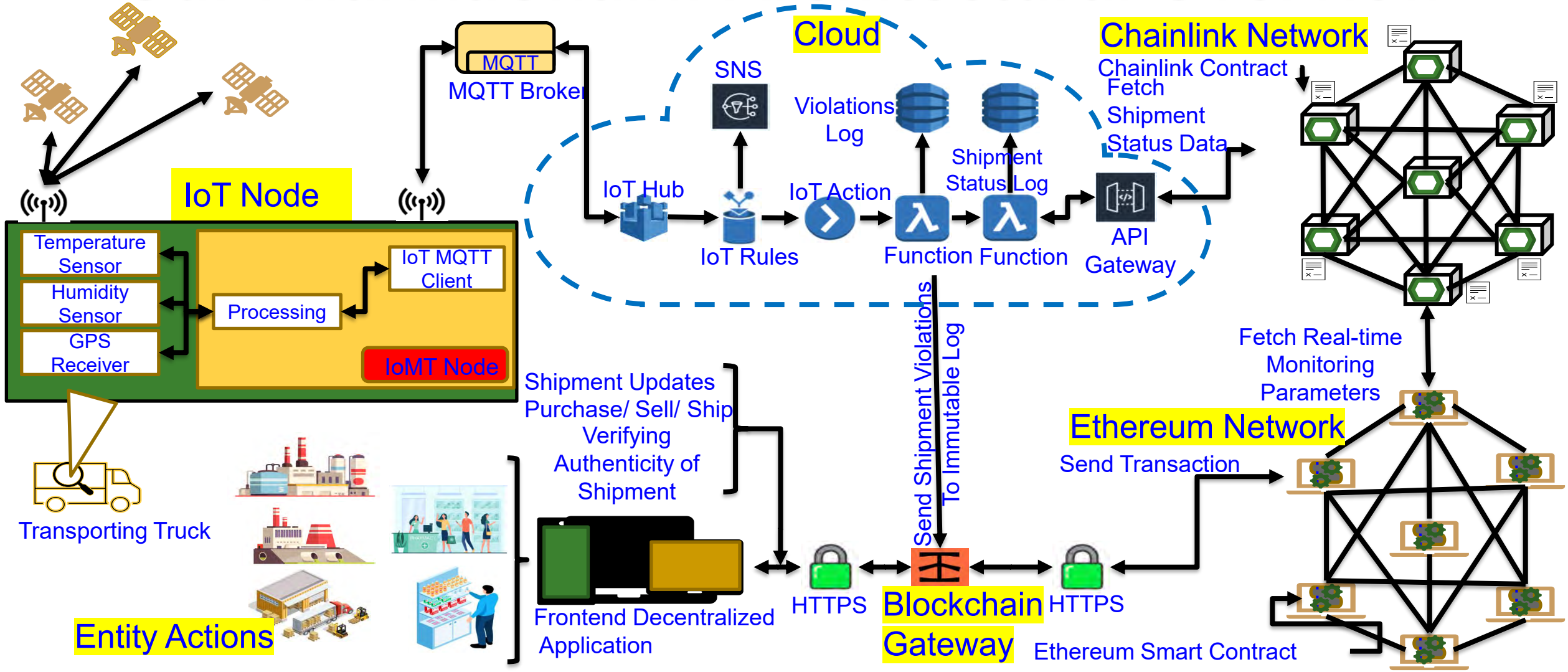
Source: https://healthpolicy-watch.news/fight-the-fakes-campaign-raises-awareness-of-falsified-substandard-medicines/

PharmaChain - Counterfeit Free Pharmaceutical



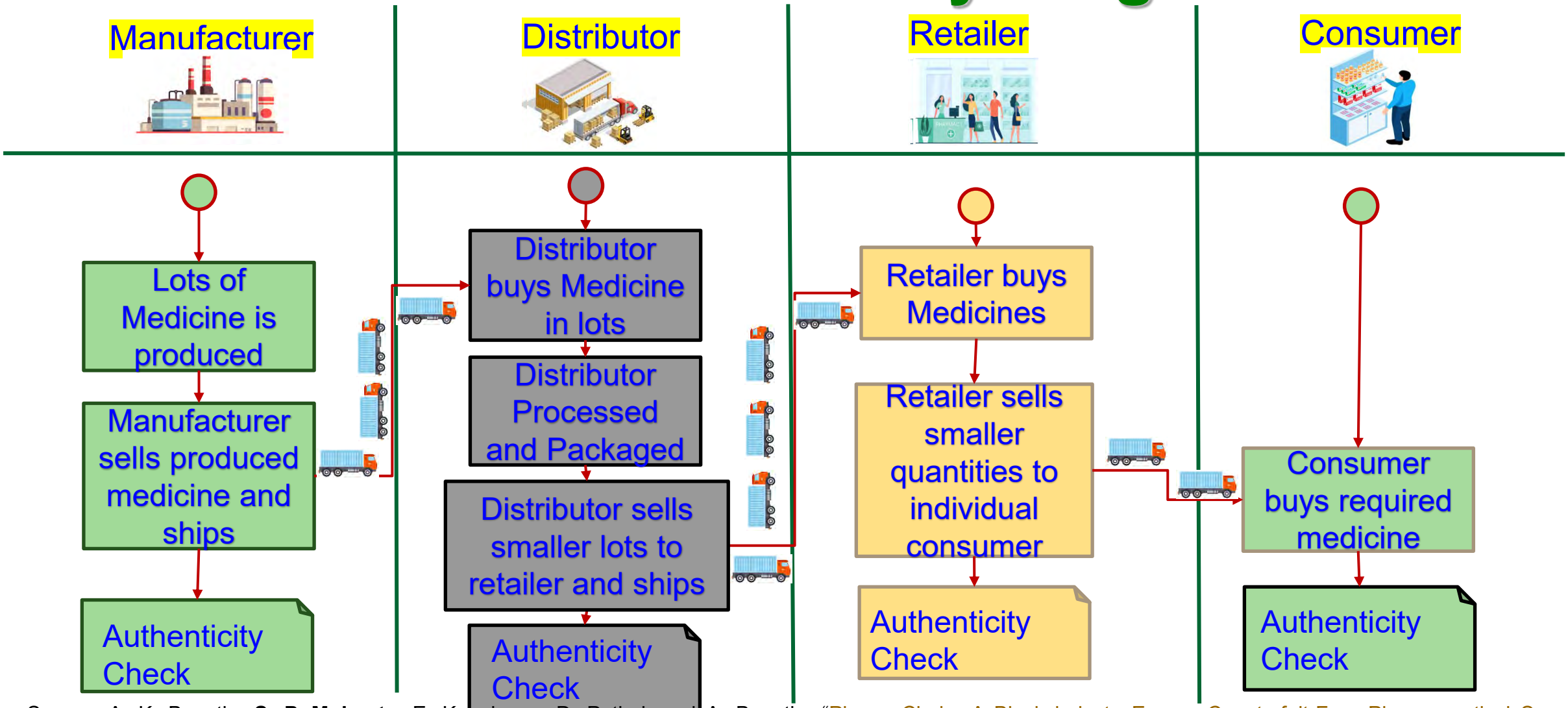
Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, D. Puthal, and A. Bapatla, "PharmaChain: A Blockchain to Ensure Counterfeit-Free Pharmaceutical Supply Chain", *IET Networks*, Vol. XX, No. YY, ZZ 2022, pp. Accepted on 24 June 2022, DOI: https://doi.org/10.1049/ntw2.12041. (Dataset for Research: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

Our PharmaChain: Architectural Overview



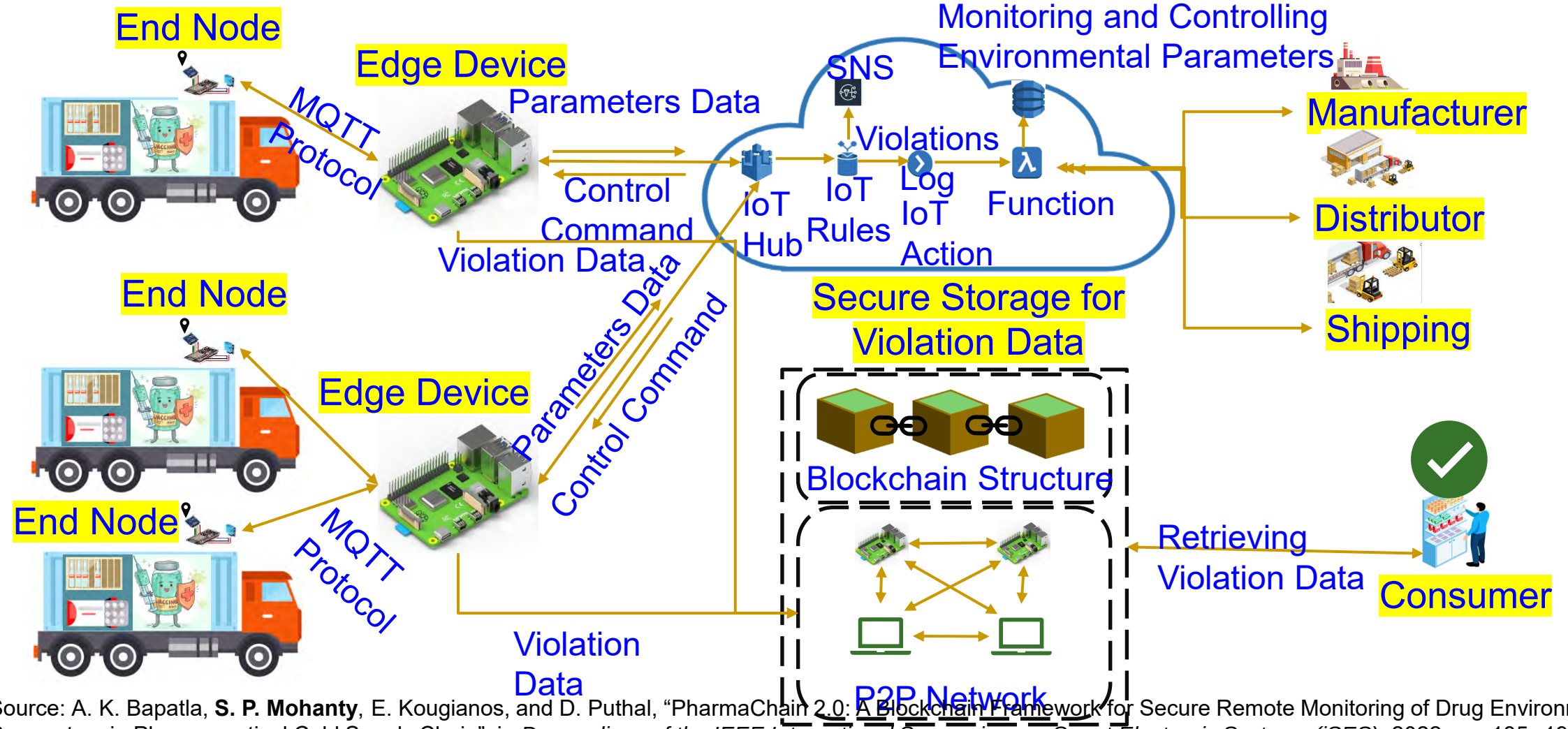
Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, D. Puthal, and A. Bapatla, "PharmaChain: A Blockchain to Ensure Counterfeit-Free Pharmaceutical Supply Chain", *IET Networks*, Vol. 12, No. 2, March 2023, pp. 53--76, DOI: https://doi.org/10.1049/ntw2.12041. (Dataset for Research: GitHub)

PharmaChain Entity Diagram



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



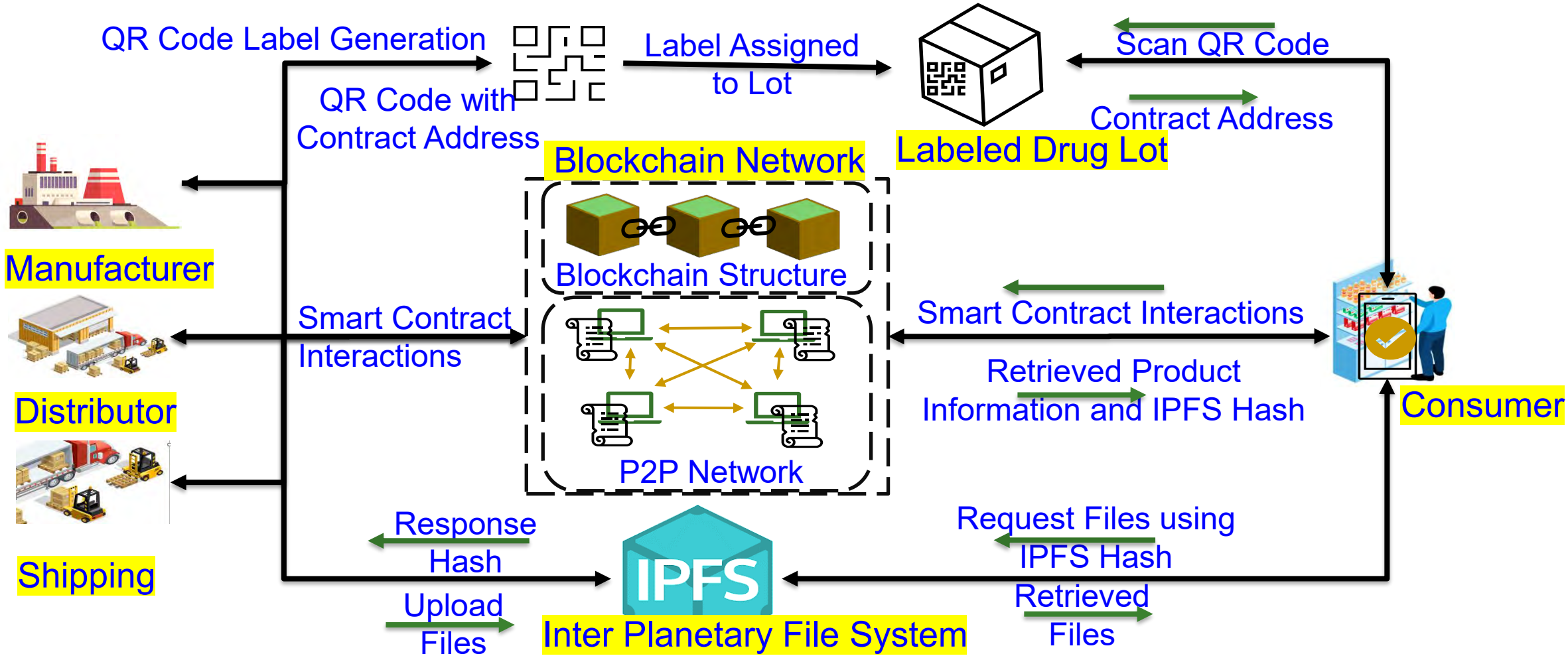
Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, and D. Puthal, "PharmaChain 2.0: A Blockchain Framework for Secure Remote Monitoring of Drug Environmental Parameters in Pharmaceutical Cold Supply Chain", in *Proceedings of the IEEE International Symposium on Smart Electronic Systems (iSES)*,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

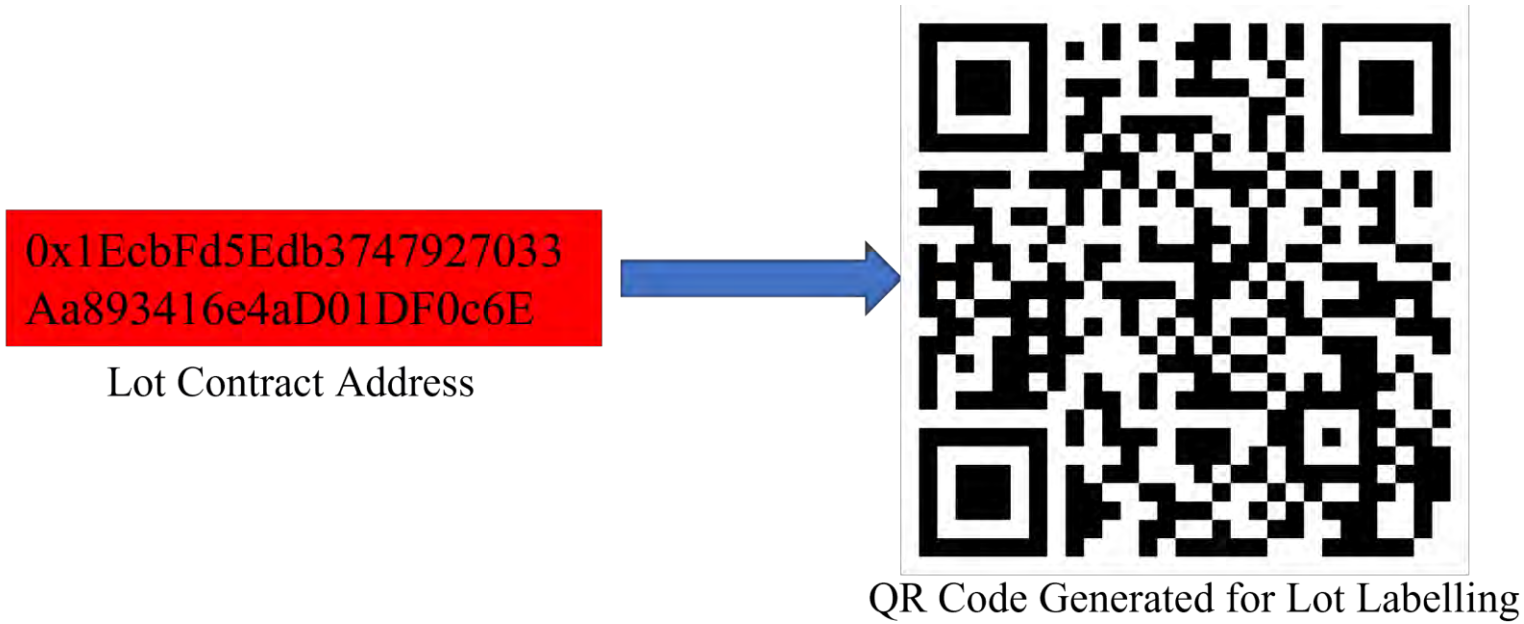
Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, and D. Puthal, "PharmaChain 2.0: A Blockchain Framework for Secure Remote Monitoring of Drug Environmental Parameters in Pharmaceutical Cold Supply Chain", in *Proceedings of the IEEE International Symposium on Smart Electronic Systems (iSES)*,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



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

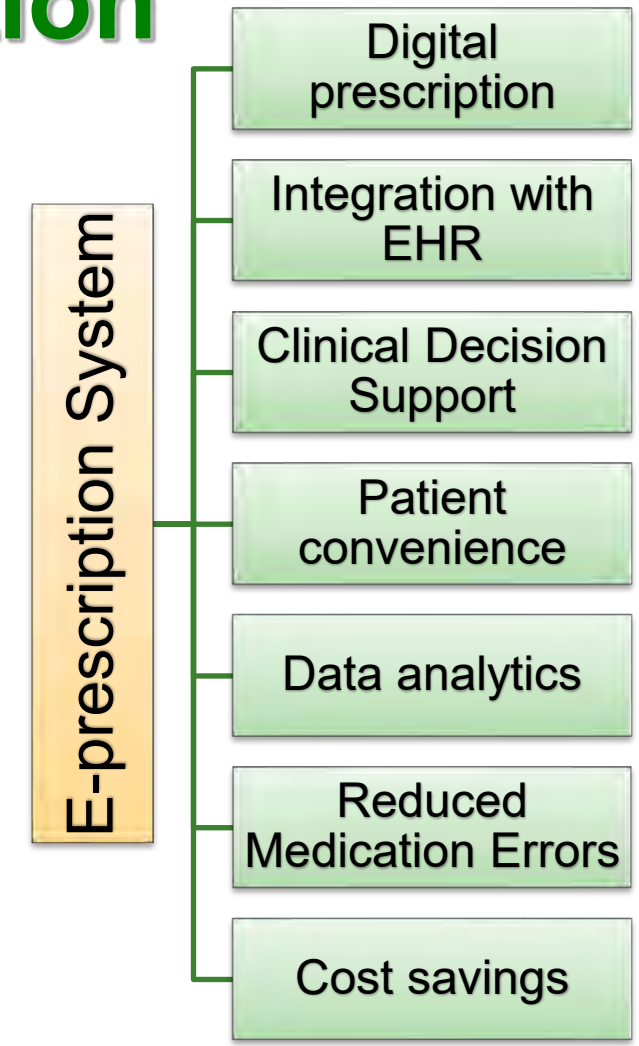
Works	Blockchain	Consensus Mechanism	Computational Needs	Openness	QR Code Integrated	Storage	Handling Large data
Crypto Cargo [11]	Ethereum	Proof-of-Work (PoW)	High	Public	No	On-Chain and Cloud	No
Kumar et.al. [9]	NA	NA	NA	NA	Yes	On-chain	No
PharmaChain [12]	Ethereum	Proof-of-Authority (PoA)	Low	Private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

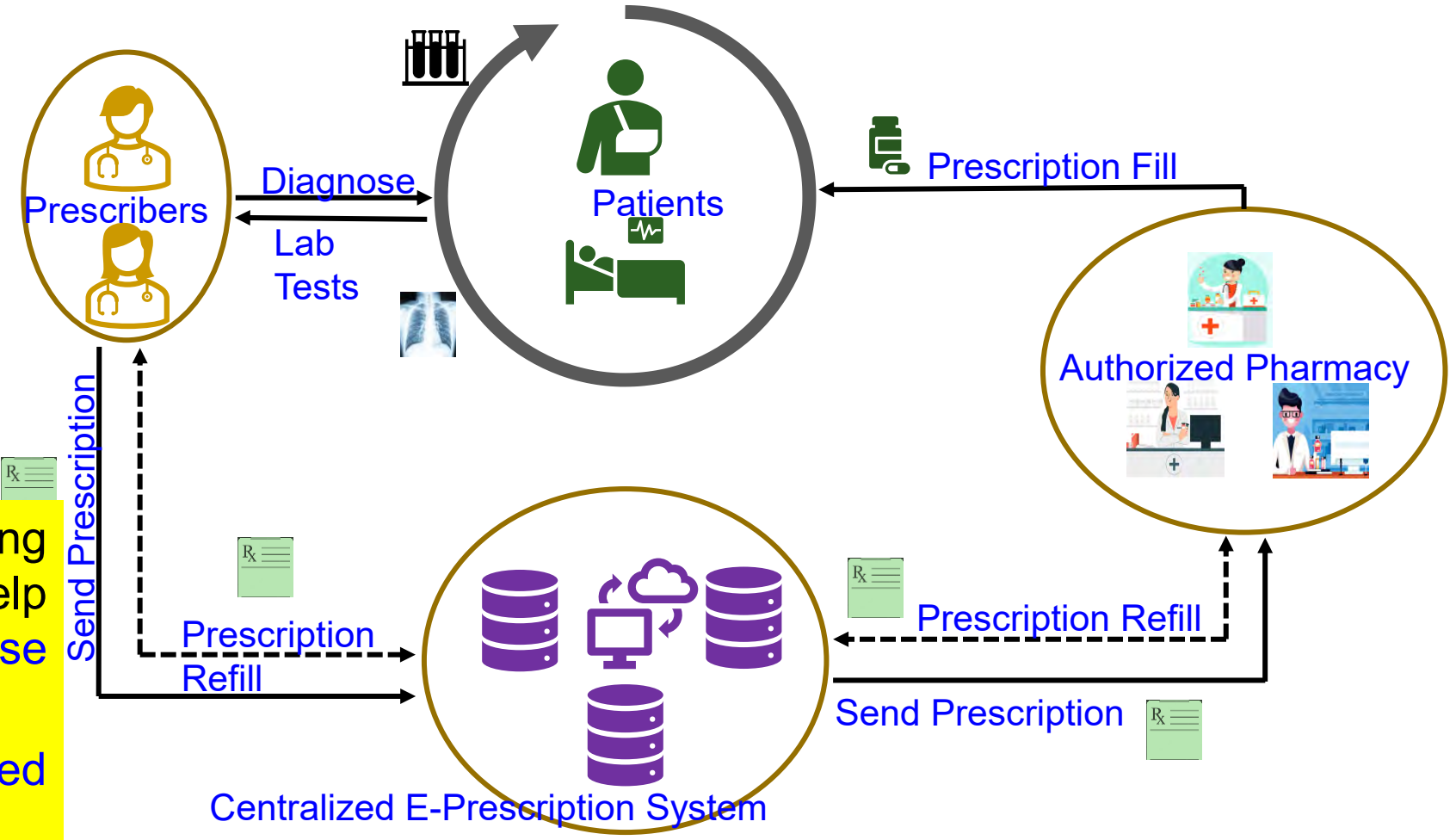
- More than 100,000 reports of medication errors (FDA)
- 40% of Americans report being involved in medical errors (Institute for Healthcare Improvement/NORC at the University of Chicago)
- 1 in 5 doses of medication provided during patient visits is administered incorrectly



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

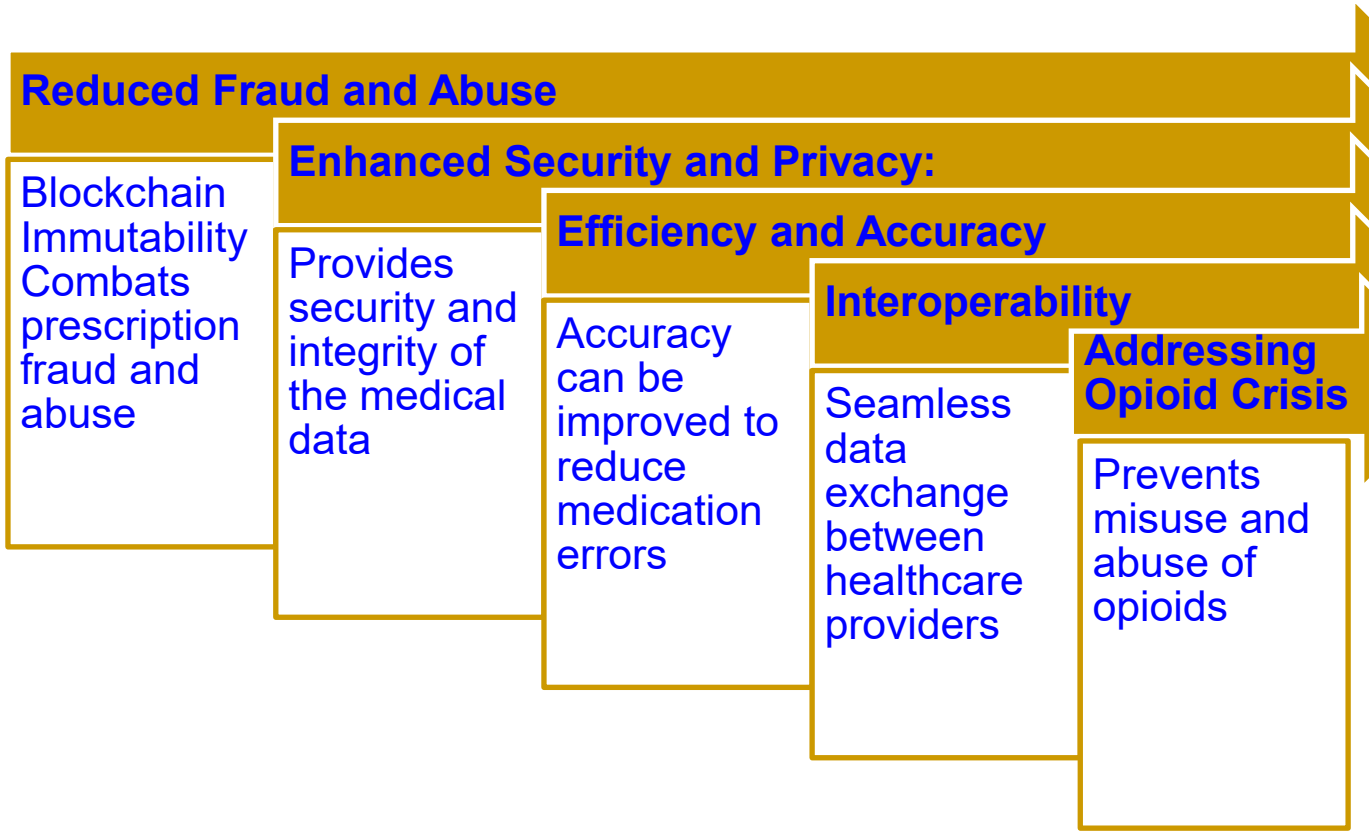
- Single Point of Failure (SPOF)
- Data Security
- Privacy Concerns
- Interoperability Concerns (PDMP)
- System availability Issues



- 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

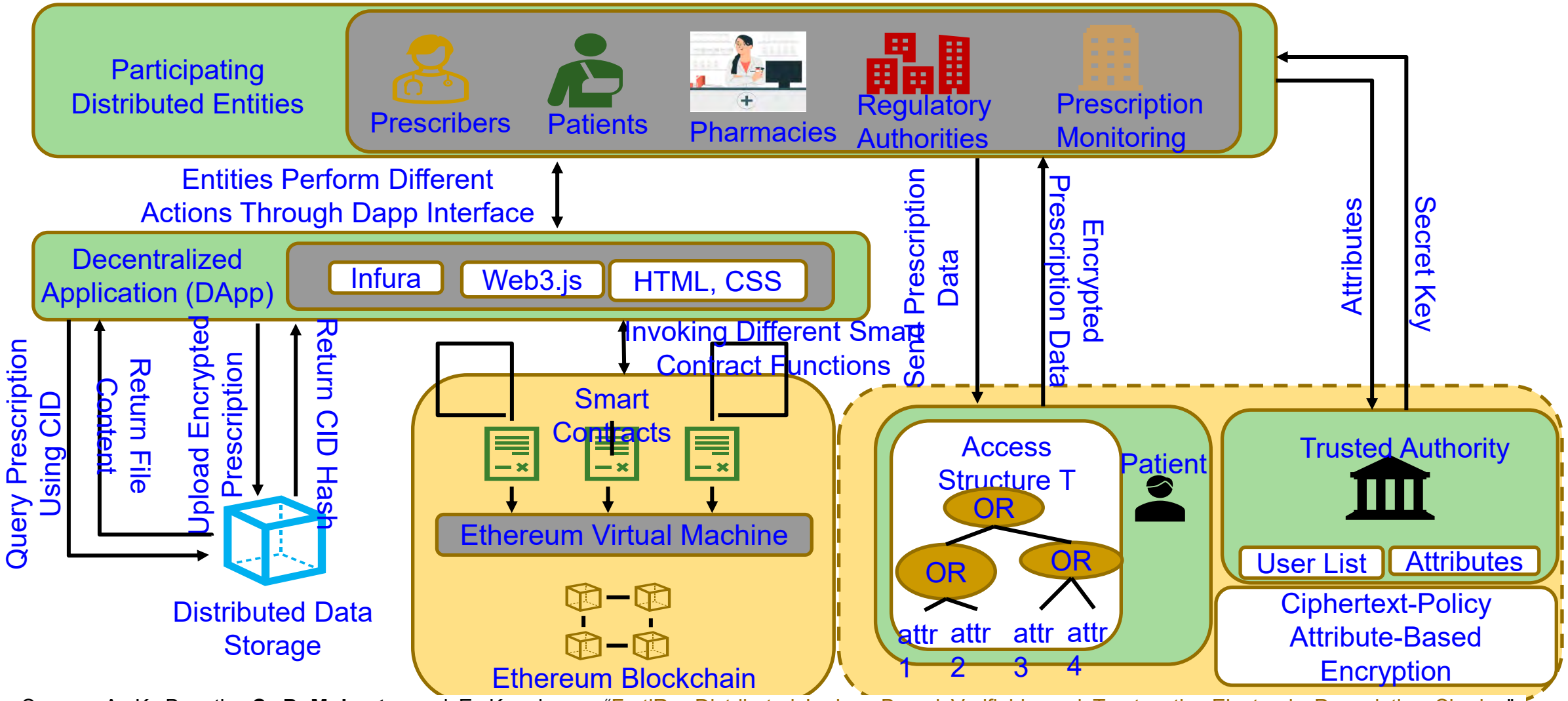


Prescription Drug Type	Annual Abusers	% Among Rx Abusers	% Among Americans
Painkillers	9.7 million	59.5%	3.43%
Opioids Alone	9.3 million	57.1%	3.29%
Sedatives	5.9 million	36.2%	2.08%
Stimulants	4.9 million	30.1%	1.73%
Benzodiazepine Alone	4.8 million	29.4%	1.70%
All Prescription Drugs	16.3 million	100%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



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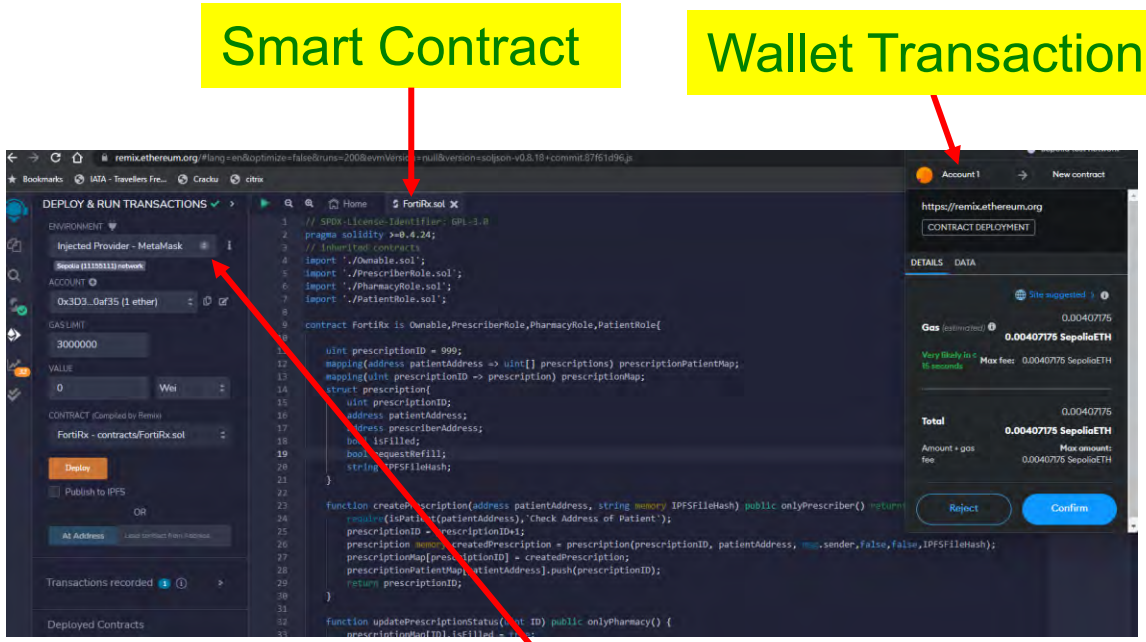
FortiRx: Smart Contract Deployment

Deployment in Sepolia

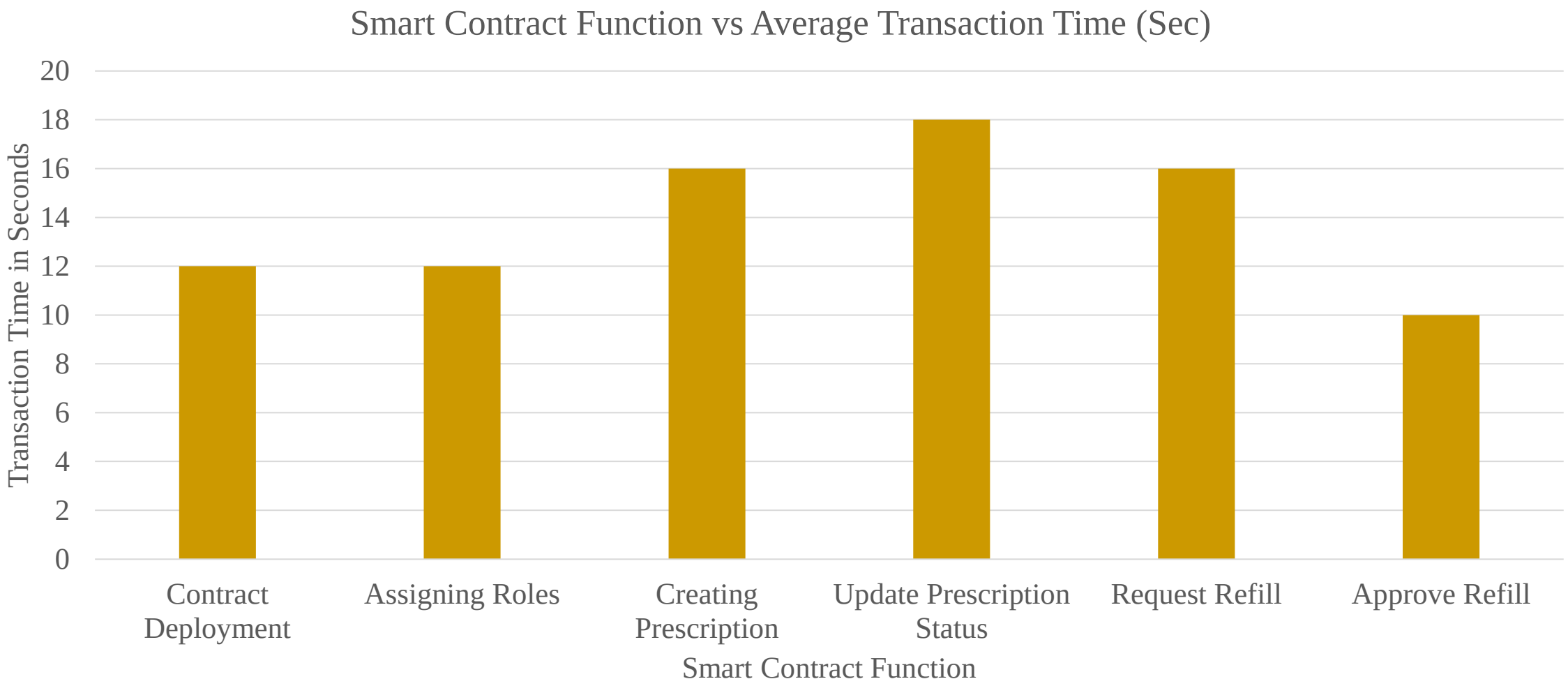


Ethereum Addresses with Roles

Feature	Value
Physician Account Address	0x3d352313f4f5561d0ffbfda205b52a3c3b70af35
Pharmacy Account Address	0x3D352313F4f5561D0fFBfda205B52A3c3b70af35
Patient Account Address	0x2a9884dfa7E6890FE8AA99FE2486c613C32b697a
Contract Deployment Hash	0x798d1f5ff49f9df09b9856db2646cebc2029d5cd2a45c5ef0c1b9acb9f217c6f
Prescription Content ID	Qme7Sq8gLmE875kE79QyWWFy9wqQ4yHnTEHMur511PrZfF
Prescription Creation Hash	0xda5bd0ce943325696e91bfe140bd8cdd60eafdca6f2a41b07221e499bfe7f1f7

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



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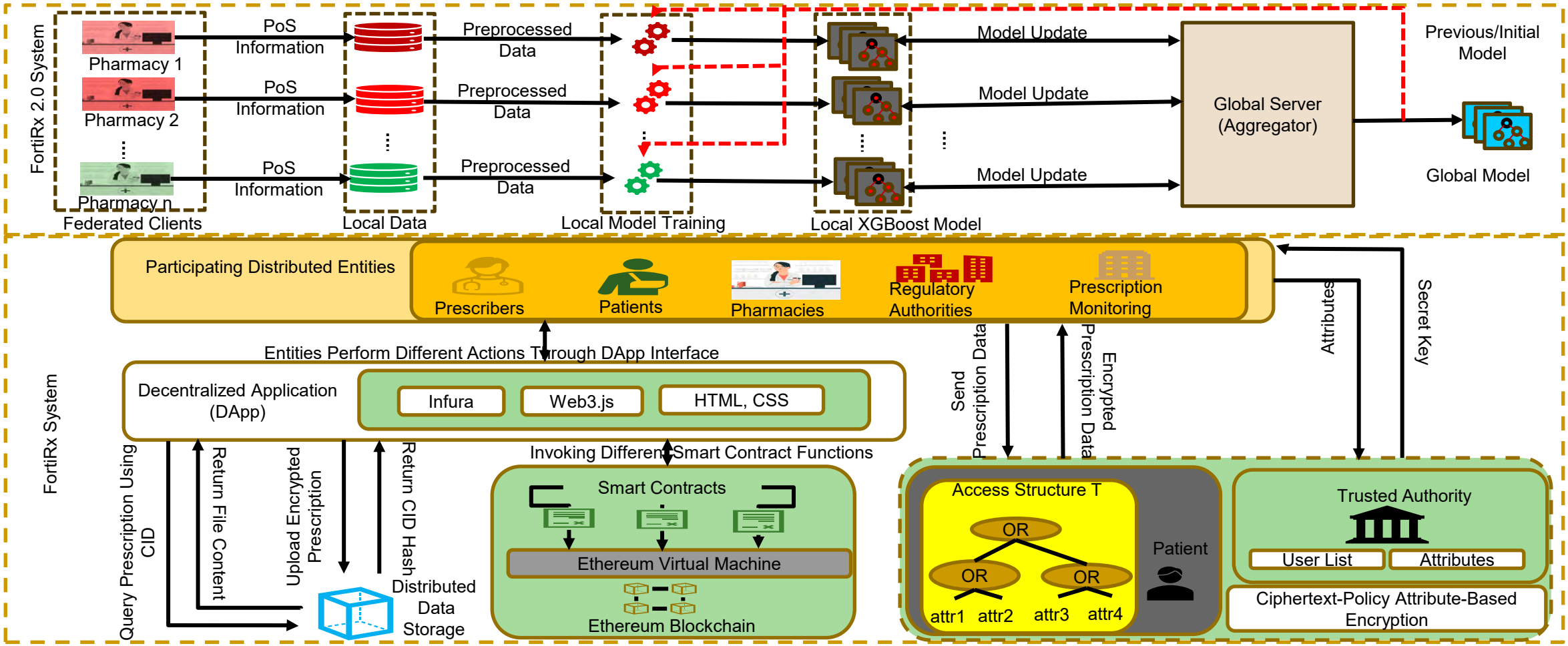
Our FortiRx 2.0: Architecture



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.

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.