
PharmaChain 3.0: Blockchain Integrated Efficient QR Code Mechanism for Pharmaceutical Supply Chain

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Outline

- Counterfeit in HealthCare
- Blockchain Technology
- PharmaChain
- PharmaChain 2.0
- PharmaChain 3.0
- Working Flow of PharmaChain 3.0
- Implementation and Validation
- Conclusions & Future Work

Counterfeit in Healthcare

Counterfeit Medicines is a Problem



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



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

- 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

Image Source: <https://www.stabroeknews.com/2019/09/06/business/ga-fdds-occasional-fake-drugs-disclosures-may-be-tip-of-the-iceberg/>

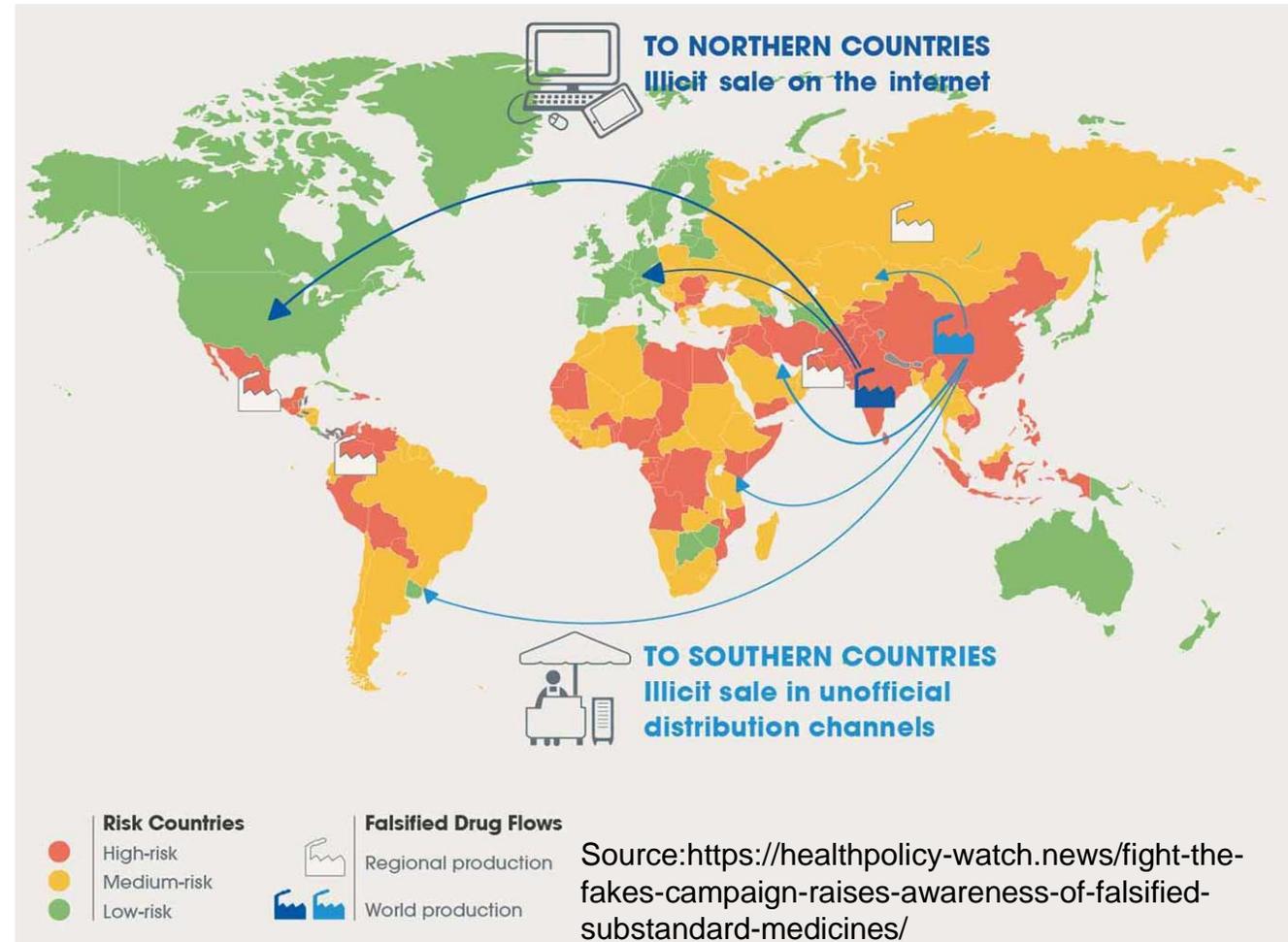
Fake Medicine - Serious Global Issue

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

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/>



Counterfeits in Healthcare → Severe Direct Impact



Authentic



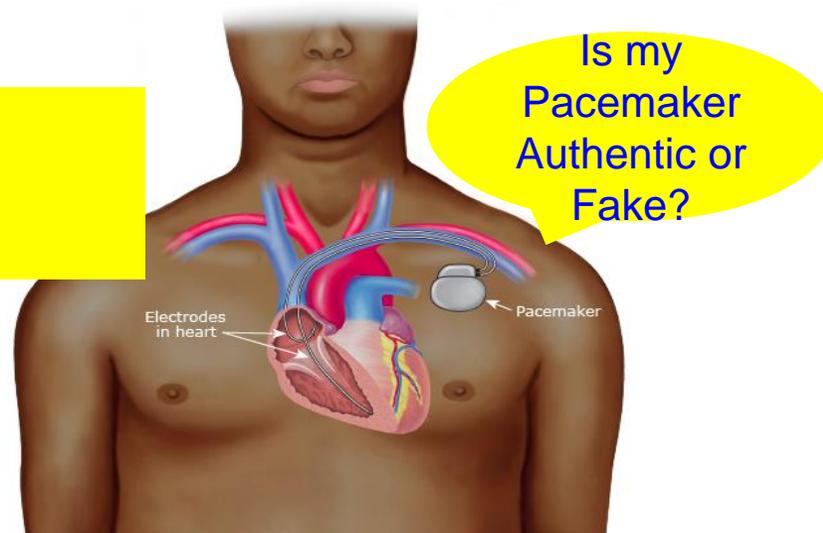
Fake

An implantable medical device

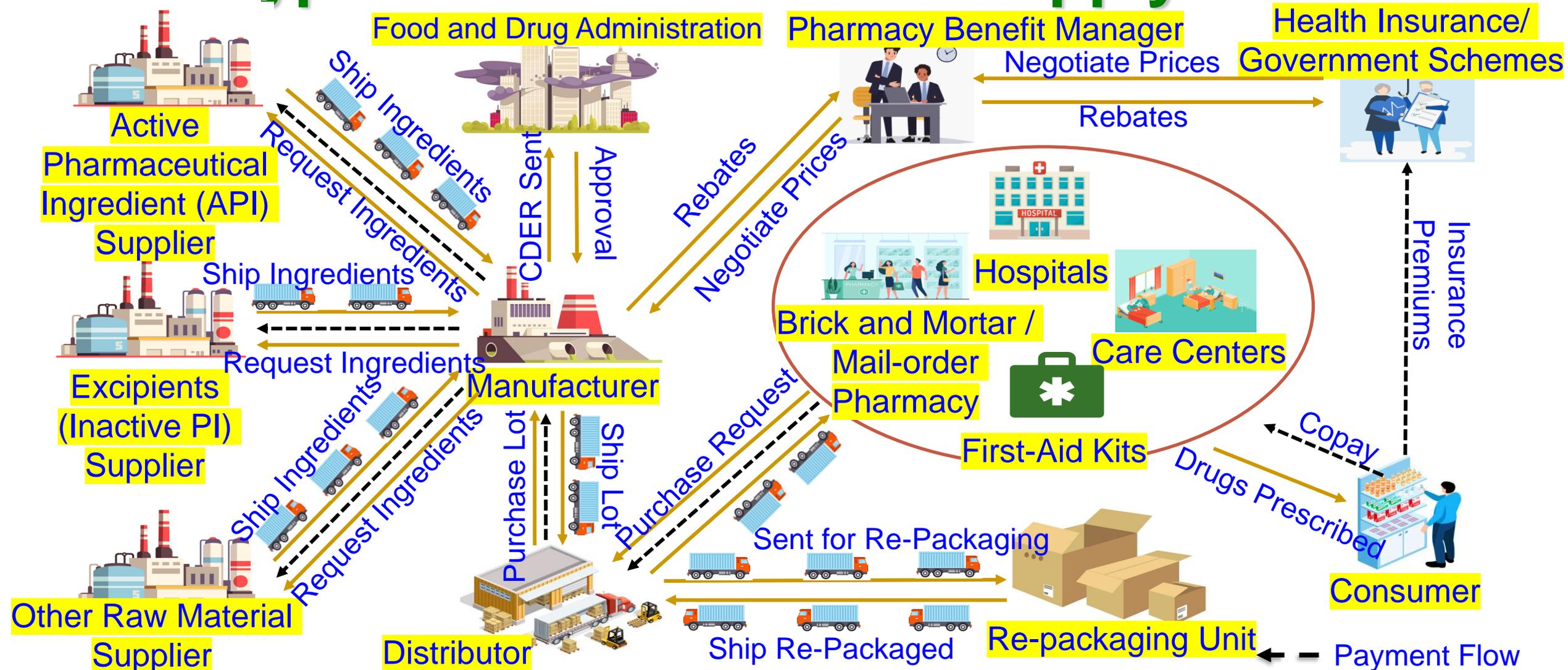


Fake data by adversaries

- Consumers are always in dilemma
- Health Security issues

An infographic titled "THE NEGATIVE IMPACTS OF FAKE MEDICINE" from the International Pharmaceutical Students' Federation (IPSF). It lists several negative impacts: increased mortality and morbidity, development of drug resistance, increased 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, and economic loss for patients and health systems. The infographic includes icons for each impact and a source link: <https://apro.ipsf.org/>

Typical Pharmaceutical Supply Chain



Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

Issues in Traditional PSC



News Source: Affairs, O. of R. (n.d.). *Press releases*. U.S. Food and Drug Administration. Retrieved November 15, 2022, from <https://www.fda.gov/inspections-compliance-enforcement-and-criminal-investigations/criminal-investigations/press-releases>

08/22/2022

BEAUMONT, Texas – A Florida-based pharmaceutical president has pleaded guilty to federal **drug trafficking violations** in the Eastern District of Texas, announced U.S. Attorney Brit Featherston today.

11/12/2021

A federal grand jury in Beaumont has returned a three-count indictment charging nine individuals in **drug trafficking conspiracy** in the Eastern District of Texas, announced Acting U.S. Attorney Nicholas J. Ganjei today.

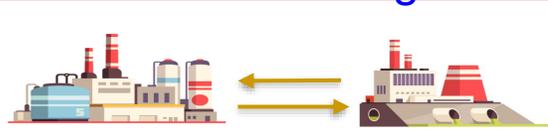
08/24/2021

ALEXANDRIA, Va. – An Inverness, Florida, man was sentenced today to three years in prison for selling **hundreds of thousands of counterfeit prescription drug pills** through the Internet.

PharmaChain - Counterfeit Free Pharmaceutical

Enterprise Resource Planning

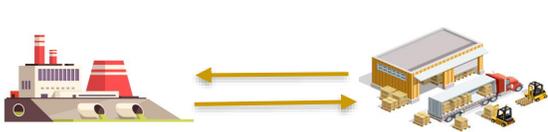
Transaction Ledger



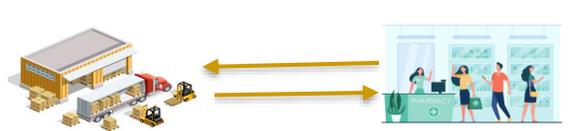
Blind Parties



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

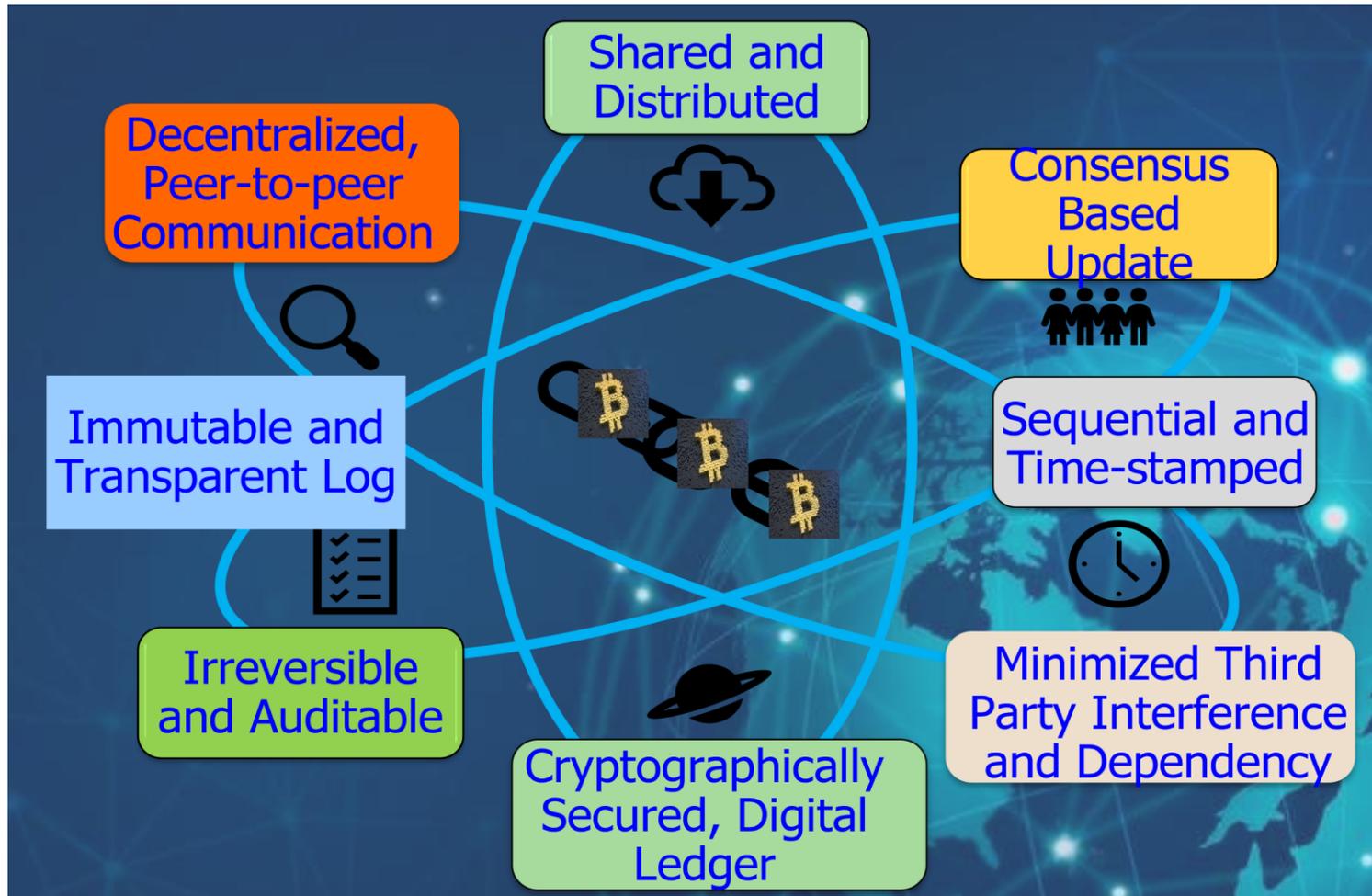


Pharmacy

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)

Blockchain Technology

Blockchain Definition



Technical Definition: A blockchain is a **linked list** that is built with **hash pointers** instead of regular pointers.

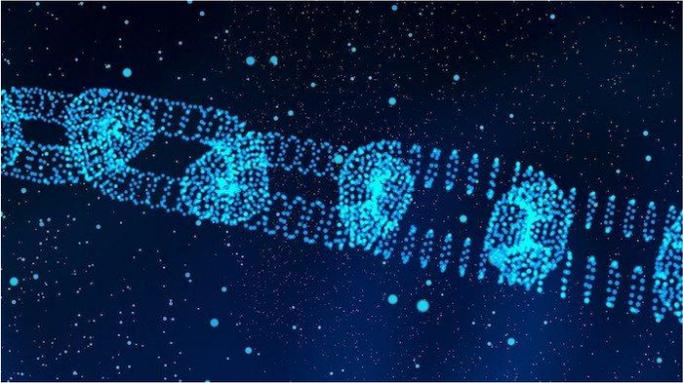
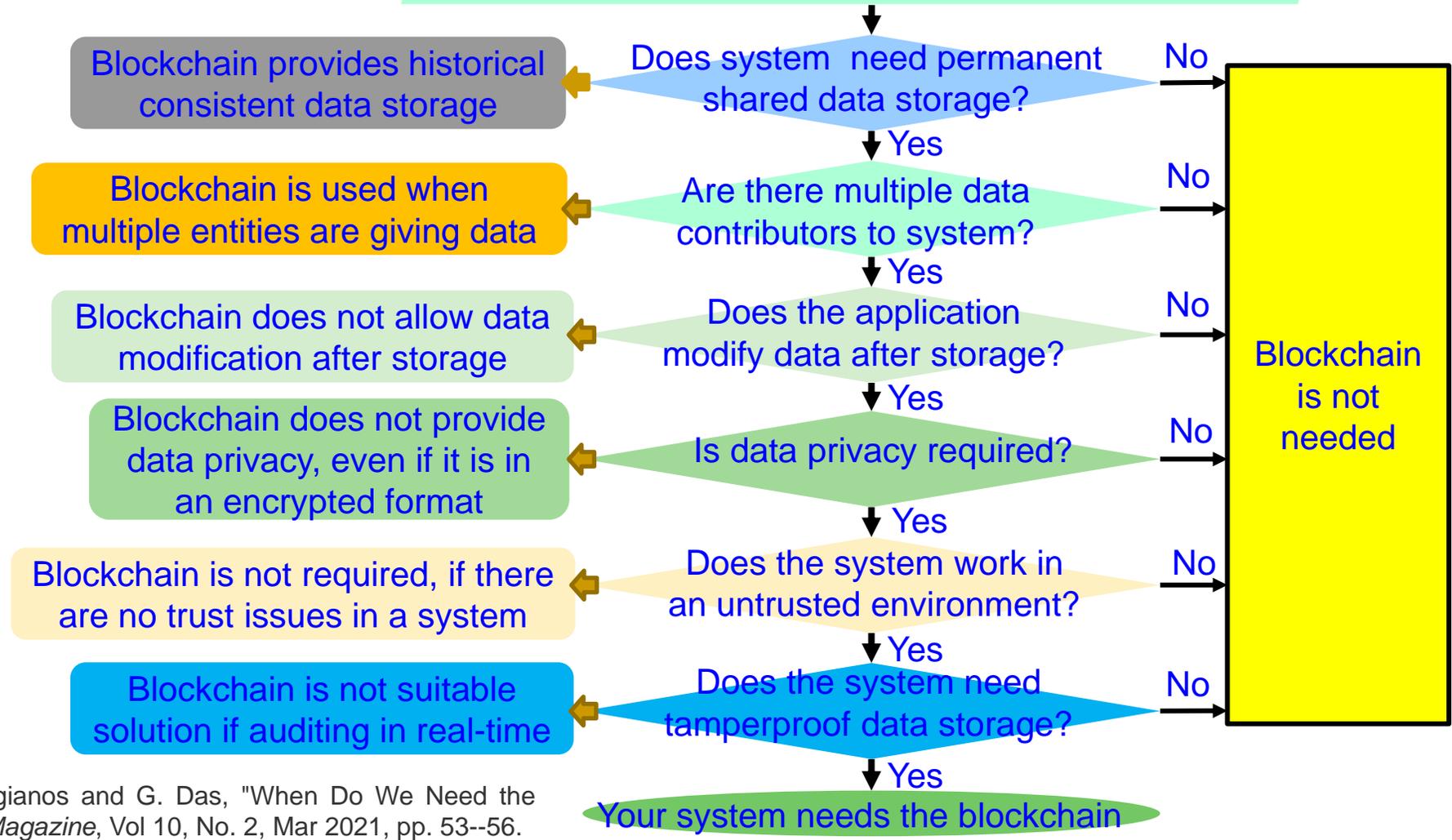
Socio-Political–Economic Definition: A blockchain is an **open, borderless, decentralized, public, trustless, permissionless, immutable** record of transactions.

Financial – Accounting Definition: A blockchain is a **public, distributed ledger** of **peer-to-peer** transactions.

Source: D. Puthal, N. Malik, S. P. Mohanty, E. Kougianos, and C. Yang, "The Blockchain as a Decentralized Security Framework", *IEEE Consumer Electronics Magazine (CEM)*, Volume 7, Issue 2, March 2018, pp. 18--21.

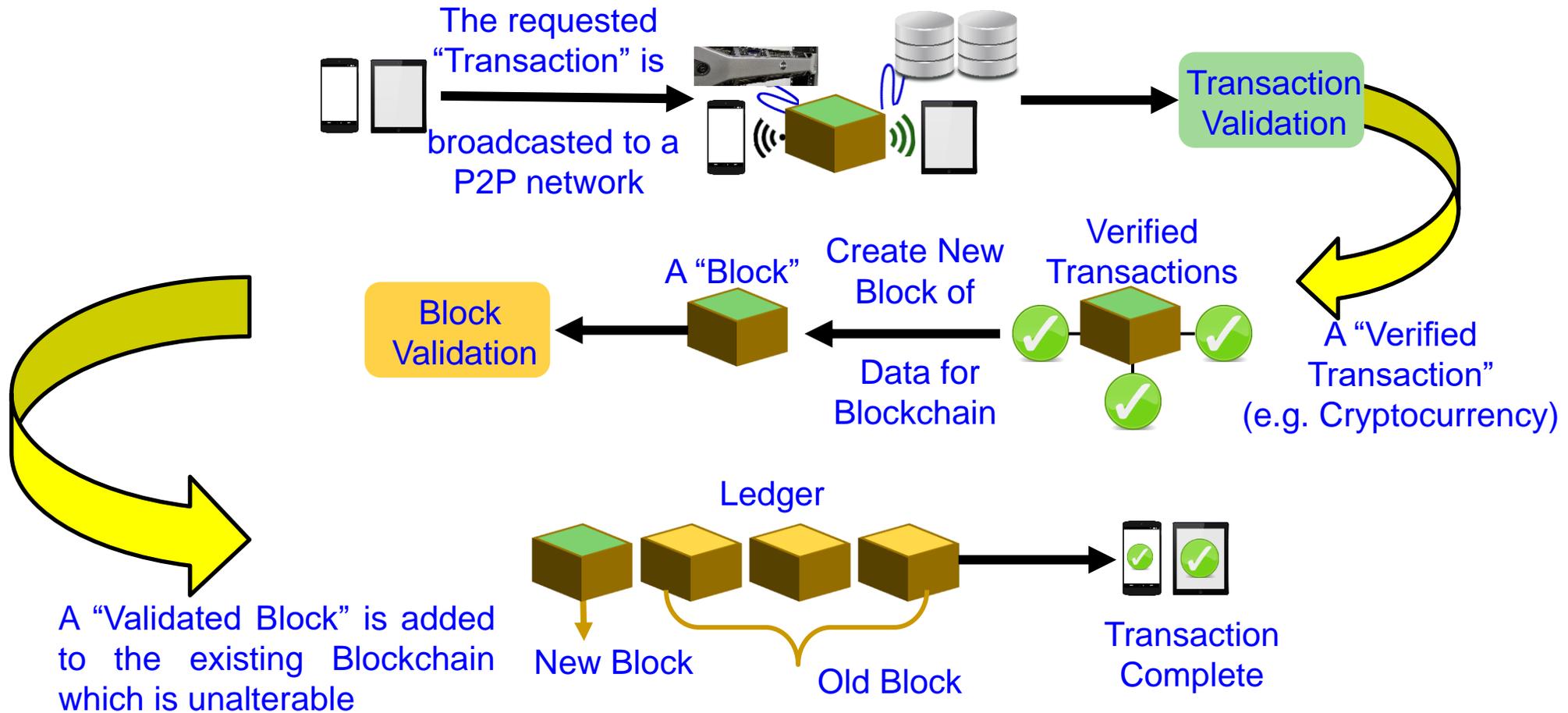
When do You Need the Blockchain?

Information of the System that may need a blockchain?



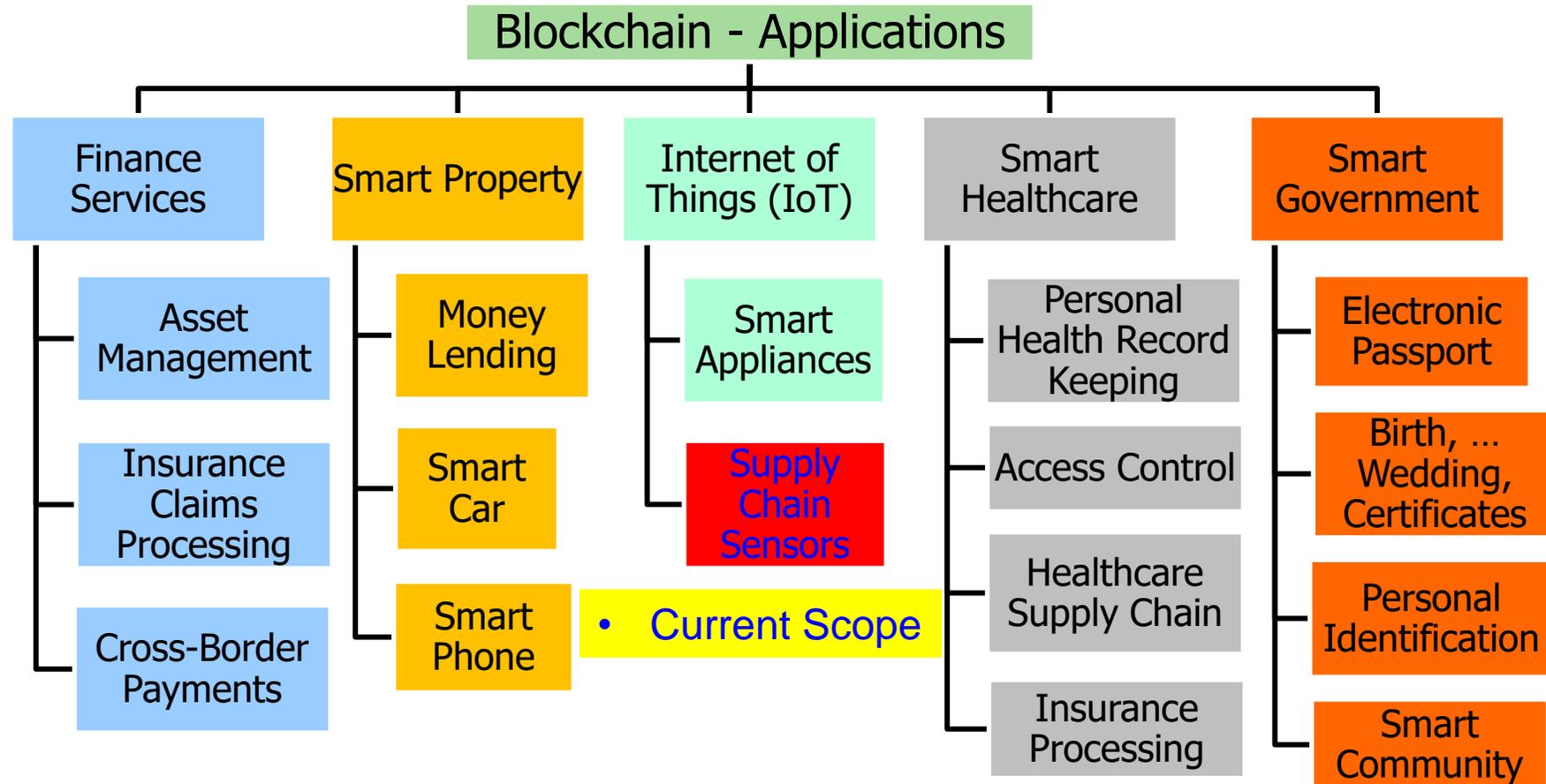
Source: D. Puthal, S. P. Mohanty, E. Kougianos and G. Das, "When Do We Need the Blockchain?," *IEEE Consumer Electronics Magazine*, Vol 10, No. 2, Mar 2021, pp. 53--56.

Blockchain Transaction Steps



Source: Deepak Puthal, Nisha Malik, Saraju P. Mohanty, Elias Kougianos, and Gautam Das, "Everything you Wanted to Know about the Blockchain", *IEEE Consumer Electronics Magazine*, Vol. 8, No. 4, pp. 6--14, 2018.

Blockchain Applications



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 (CEM)*, Volume 7, Issue 4, July 2018, pp. 06--14.

Blockchain Leveraged Healthcare CPS

↔ Manufacturers and Ingredient Suppliers Interactions

↔ Distributor and Manufacturers Interactions

Network Communication Protocols

Network of Ingredient Suppliers

Network of Manufacturers

Network of Distributors

Network of Healthcare

Facilities

Healthcare Facility Nodes

Distributors Nodes

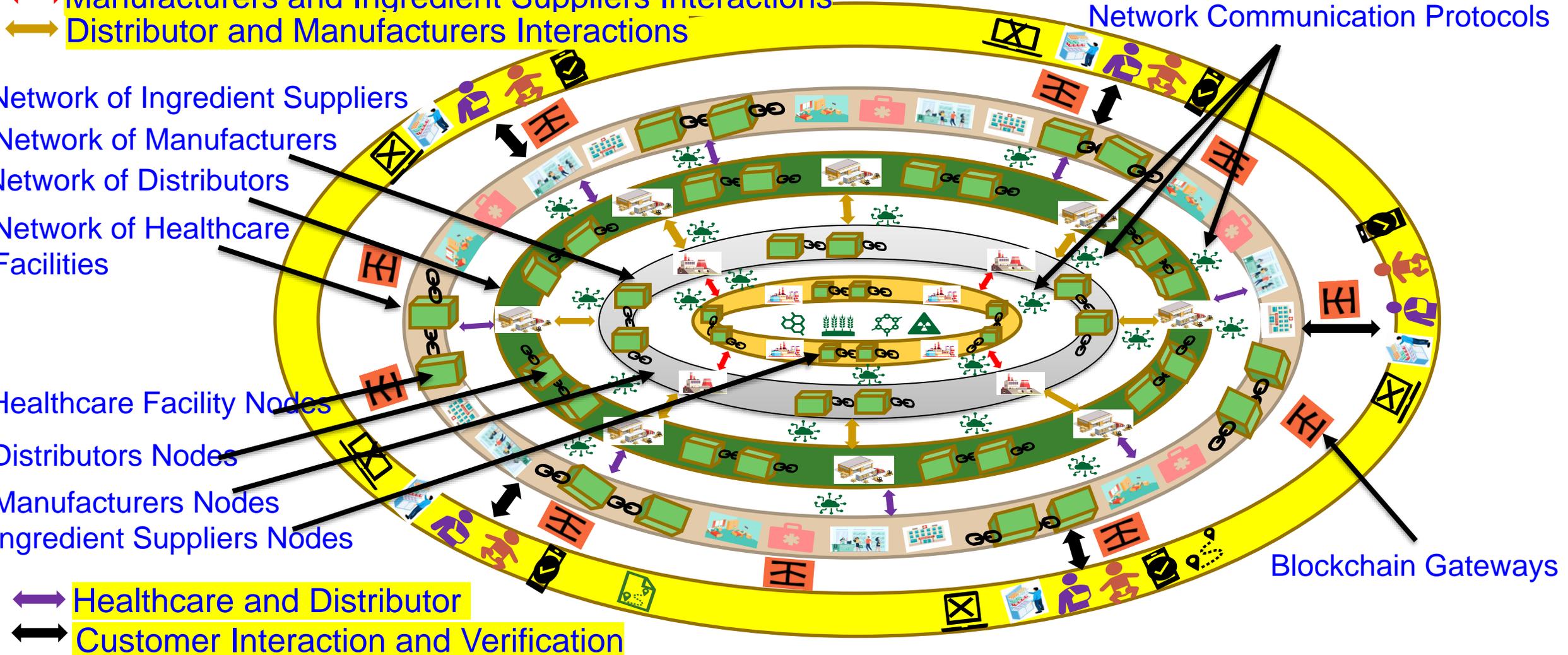
Manufacturers Nodes

Ingredient Suppliers Nodes

↔ Healthcare and Distributor

↔ Customer Interaction and Verification

Blockchain Gateways

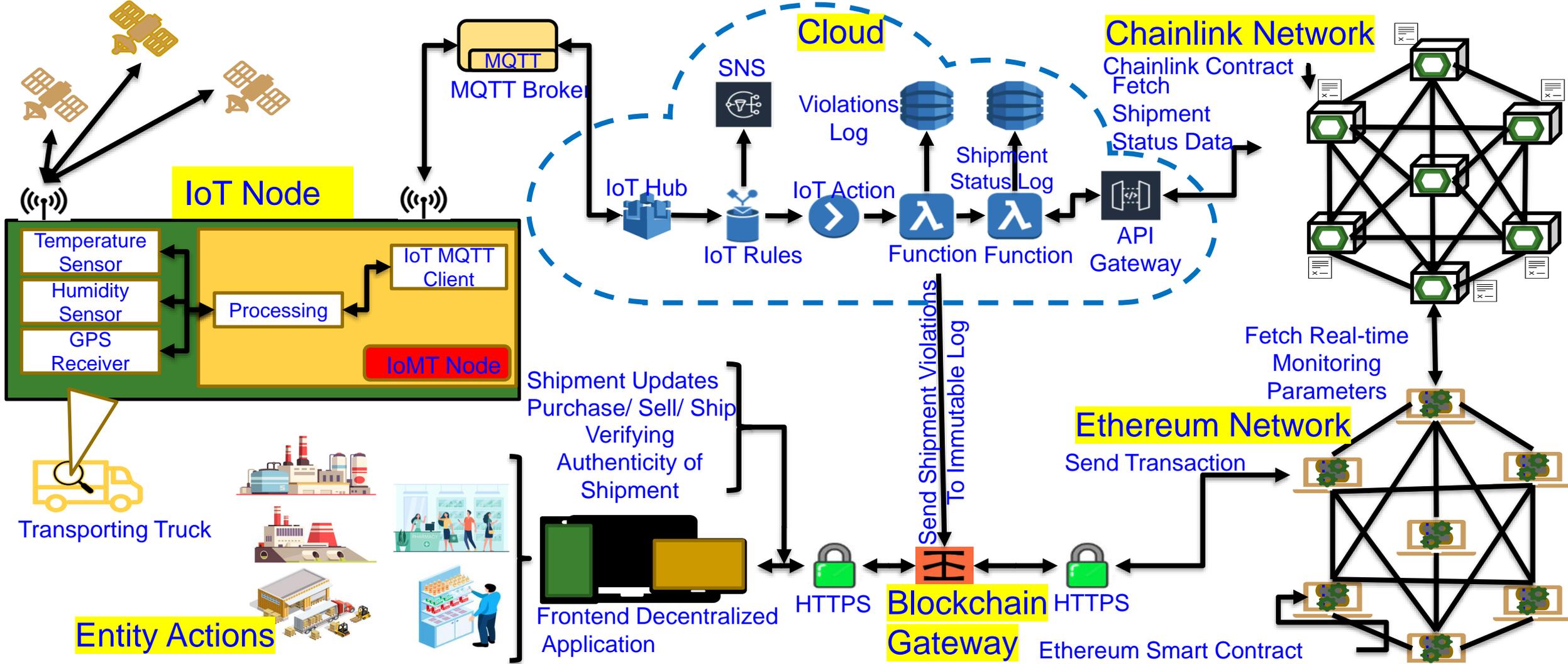


Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

Our First Work to Transparent Pharmaceutical Supply Chains

PharmaChain: A Blockchain to Ensure Counterfeit-Free Pharmaceutical Supply Chain

Architectural Overview of PharmaChain

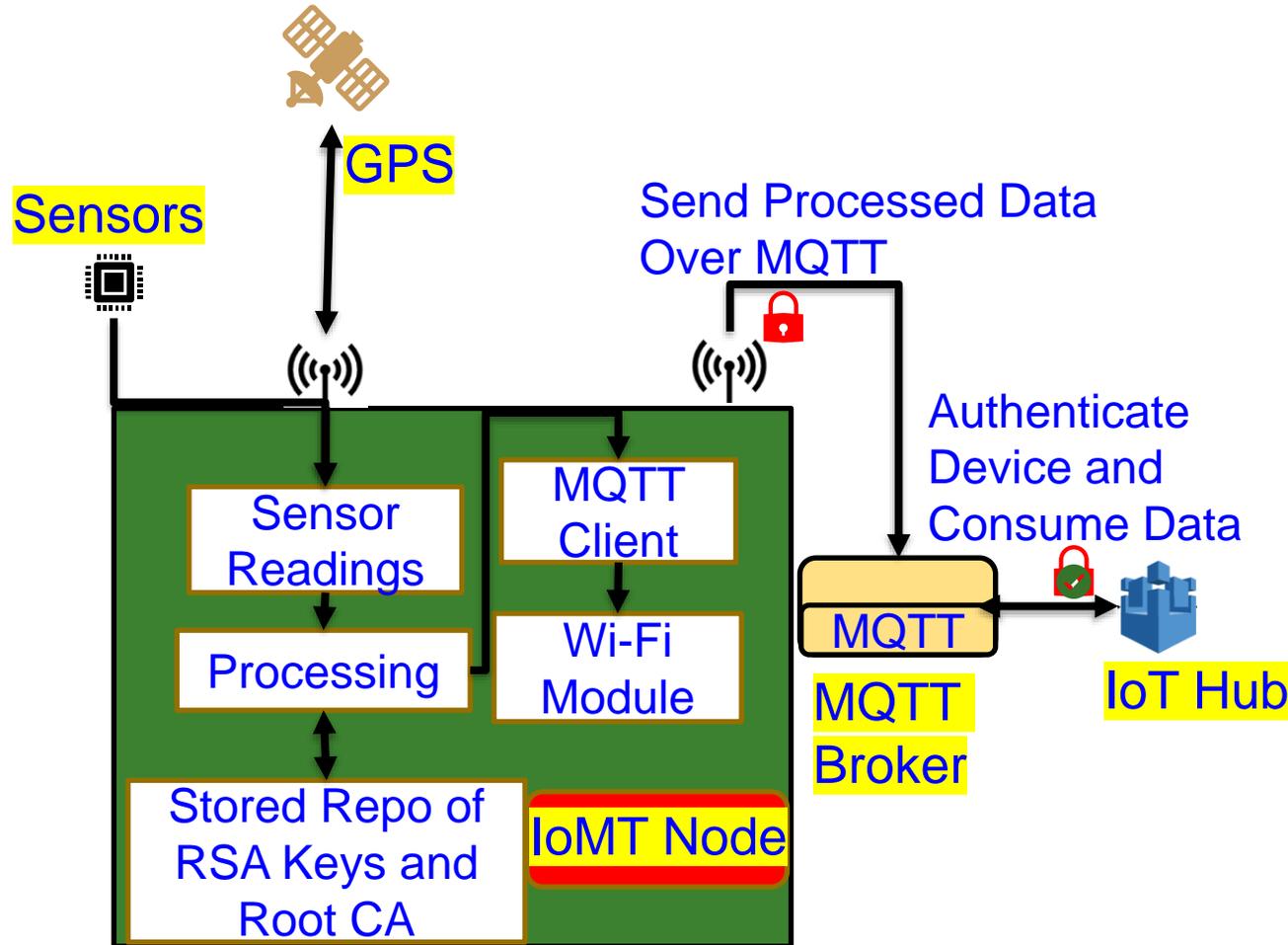


Source: A. K. Bapatla, S. P. Mohanty, E. Kougianos, D. Puthal, and A. Bapatla, "PharmaChain: A Blockchain to Ensure Counterfeit-Free Pharmaceutical Supply Chain", *IET Networks*, Vol. XX, No. YY, ZZ 2022, pp. Accepted on 24 June 2022, DOI: <https://doi.org/10.1049/ntw2.12041>. (Dataset for Research: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

Novel Contributions

- Expedite the order processing and prompt decision making
- Information fragmentation issue is addressed
- Detecting counterfeits easily in the supply chain
- Increasing accountability of participating entities
- Drug recall process made easier
- Real-time decision support tool is provided for pharmaceutical supply chains

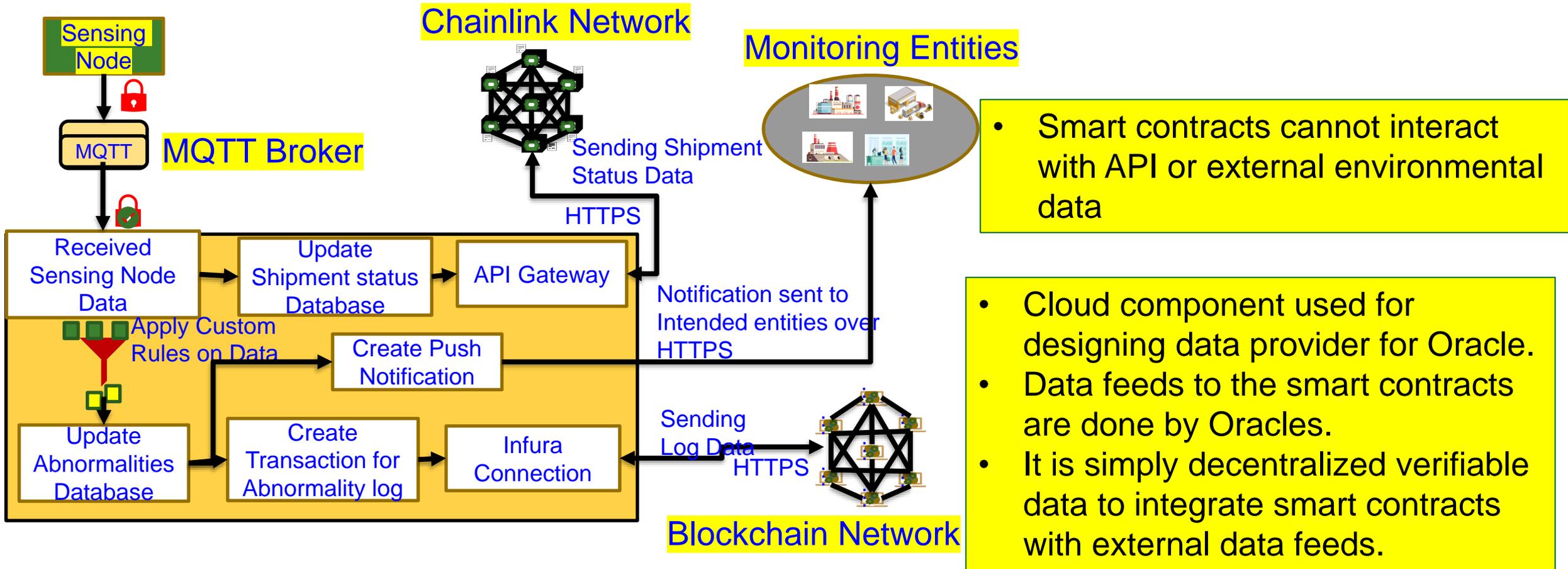
PharmaChain Sensing Node



- Designed to monitor important parameters for pharmaceutical shipment which include temperature, humidity along with GPS coordinates of the shipment
- Monitoring data from sensing nodes will be processed and formatted into a JSON file before being sent to the cloud component
- Lightweight Message Queuing Telemetry Transport (MQTT) protocol and topics are used

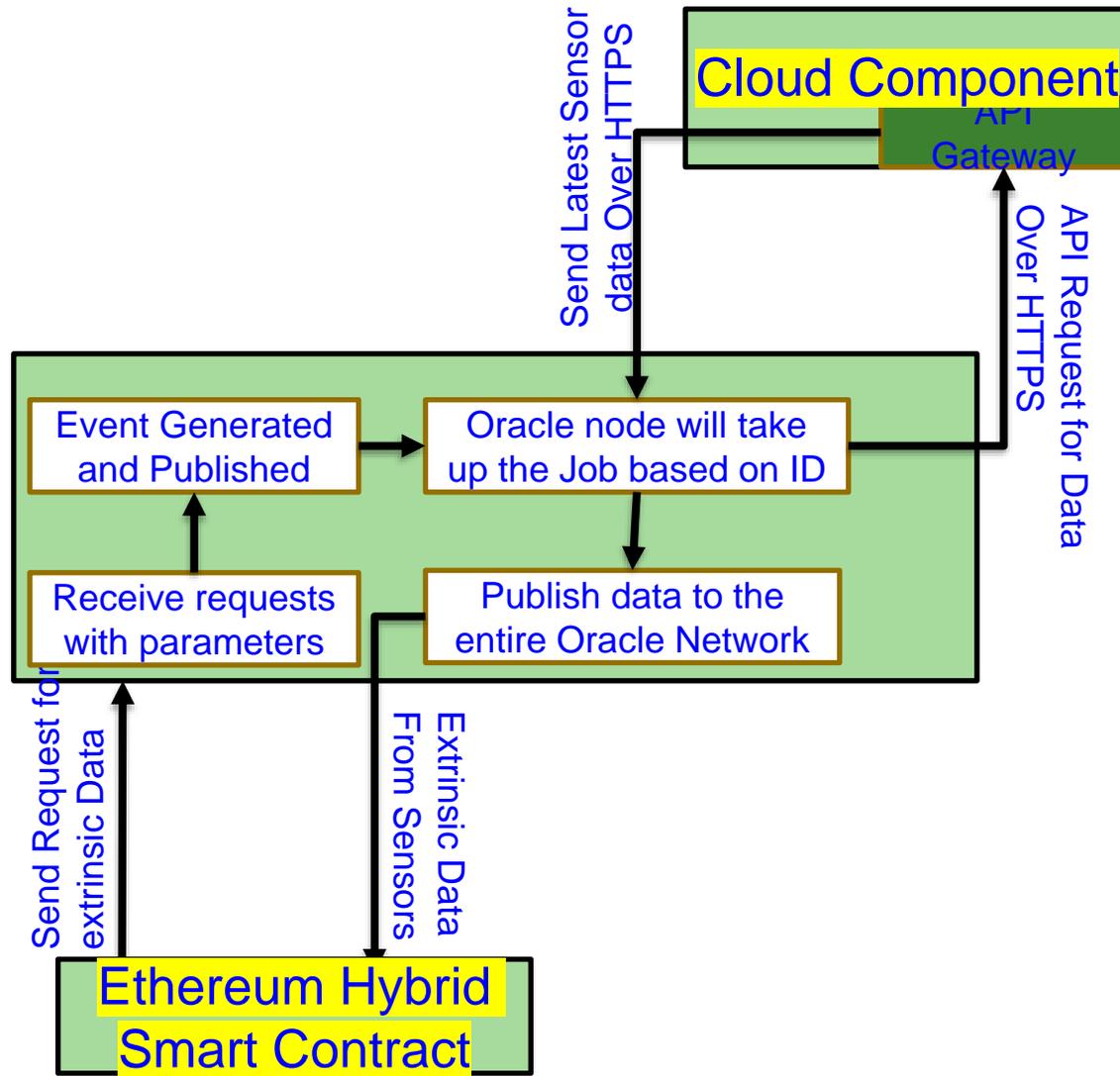
Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

PharmaChain Cloud Component



Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

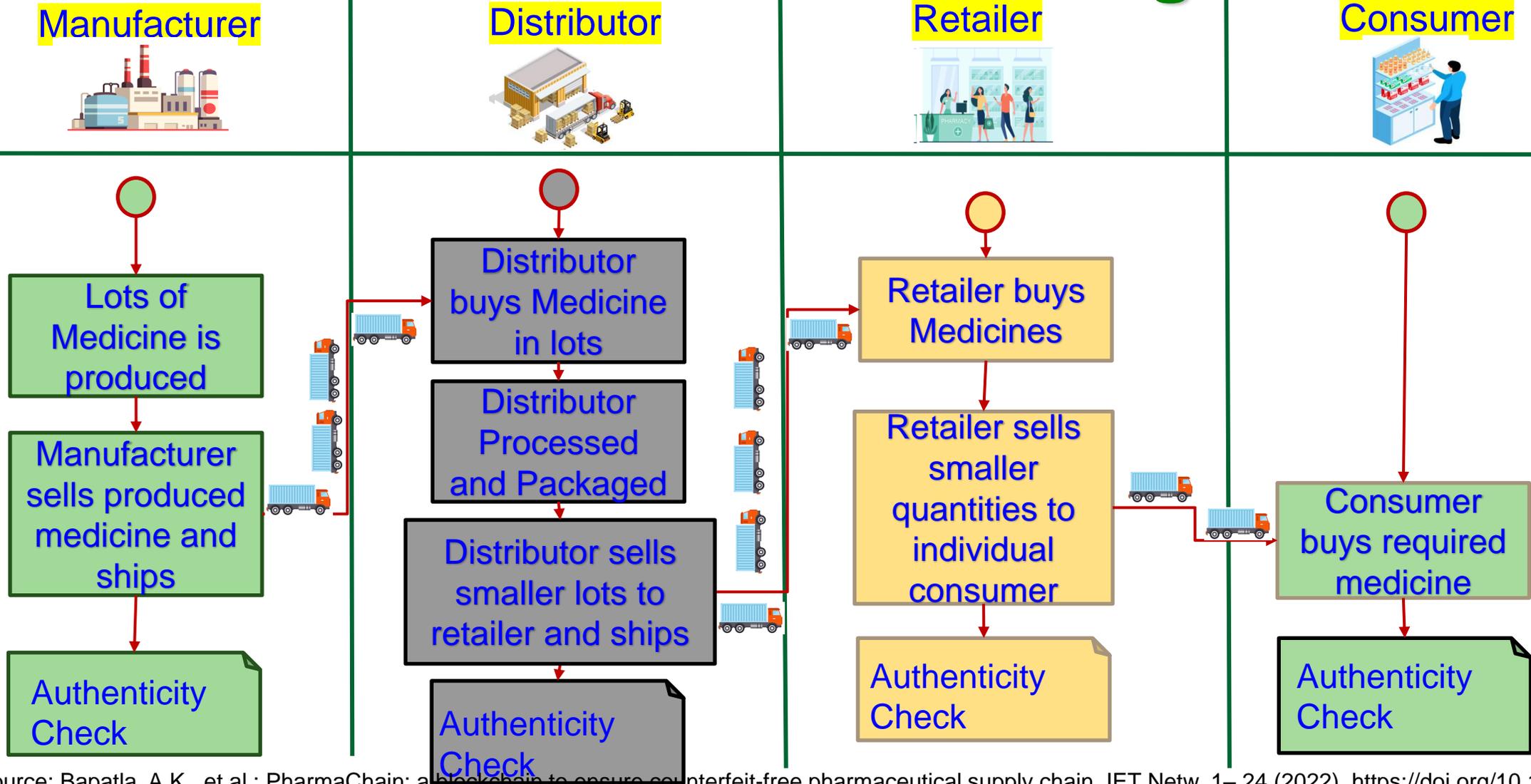
PharmaChain Oracle Component



- Multiple jobs are executed to fetch the data instead of a single job
- Results from multiple jobs are aggregated
- Aggregated data is published to hybrid smart contract

Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

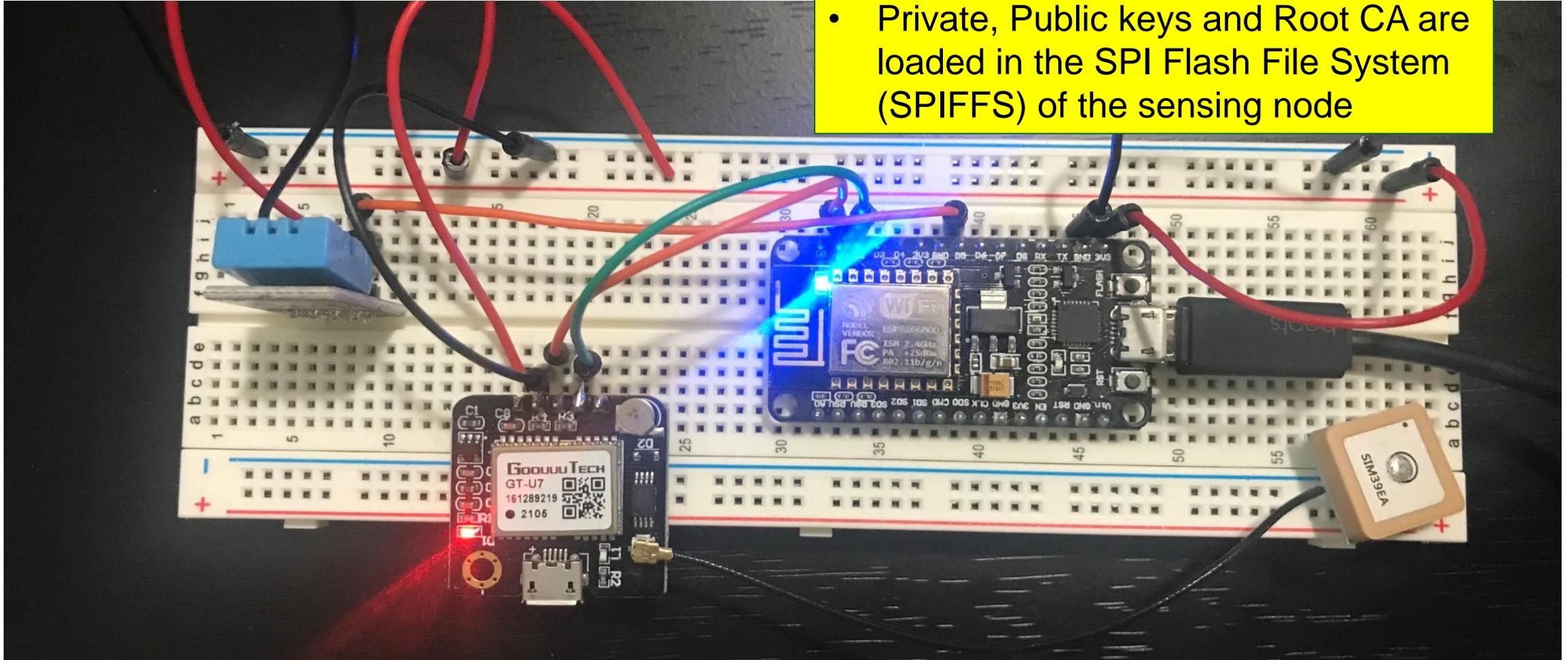
PharmaChain Entity Diagram



Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

Designed Sensing Node

- Private, Public keys and Root CA are loaded in the SPI Flash File System (SPIFFS) of the sensing node



Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

Sensing Node Data

```
COM3
....scandone
state: 0 -> 2 (b0)
.state: 2 -> 3 (0)
state: 3 -> 5 (10)
add 0
aid 1
cnt

connected with LifeEhOkaZindagi, channel 11
dhcp client start...
ip:192.168.1.62,mask:255.255.255.0,gw:192.168.1.1
.
WiFi connected
IP address:
192.168.1.62
Heap: 32632
Successfully opened cert file
cert loaded
Successfully opened private cert file
private key loaded
Successfully opened open ca
ca loaded
Heap: 29016
Attempting MQTT connection...pm open,type:2 0
connected
Publish message: {"timestamp": " ", "latitude":0,"longitude":0,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.5,"humidity":60}
Heap: 23584
Publish message: {"timestamp": " ", "latitude":0,"longitude":0,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.5,"humidity":60}
Heap: 23696
Publish message: {"timestamp": "11 / 01 / 2022 04 : 27 : 01 AM ", "latitude":33.21301,"longitide":-97.15771,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.5,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 27 : 18 AM ", "latitude":33.213,"longitide":-97.15753,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.5,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 27 : 28 AM ", "latitude":33.21297,"longitide":-97.1575,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.5,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 27 : 33 AM ", "latitude":33.21295,"longitide":-97.15753,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.4,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 27 : 40 AM ", "latitude":33.21297,"longitide":-97.15757,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.4,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 27 : 49 AM ", "latitude":33.21296,"longitide":-97.15765,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.4,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 28 : 02 AM ", "latitude":33.21296,"longitide":-97.15772,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.4,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 28 : 02 AM ", "latitude":33.21296,"longitide":-97.15772,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.4,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 28 : 28 AM ", "latitude":33.21297,"longitide":-97.1575,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.4,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 28 : 35 AM ", "latitude":33.21297,"longitide":-97.15747,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.4,"humidity":61}
Heap: 23592
Publish message: {"timestamp": "11 / 01 / 2022 04 : 28 : 42 AM ", "latitude":33.21297,"longitide":-97.15752,"sku":2112101,"lot":547863250,"drugname":"Mucinex","temperature":21.4,"humidity":61}
Autoscroll Show timestamp
Hexline 115200 baud Clear output
```



Loading all necessary RSA Key and Certificate files and establishing secure connection before publishing data



Published data from Sensing Node

Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>



Implemented Cloud Component

- IoT Custom rules to send real-time data to the API

The screenshot shows the configuration for a rule named 'APIUpdate'. The source is a Kinesis stream 'esp32/pub' with the SQL query 'SELECT * FROM 'esp32/pub''. The action is 'Send a message to a Lambda function' with the function name 'updateDB'.

- Adding abnormal temperatures to DB

```
const AWS = require("aws-sdk");
const dynamo = new AWS.DynamoDB.DocumentClient();

exports.handler = function (event, context, callback) {
  console.log(event);
  var params = {
    Item: {
      timestamp: event['timestamp'],
      latitude: event['latitude'],
      longitude: event['longitude'],
      sku: event['sku'],
      lot: event['lot'],
      drugname: event['drugname'],
      temperature: event['temperature'],
      humidity: event['humidity']
    }
  };
  const TableName = 'TemperatureAbnormalNotification';
  dynamo.put(params, function(err, data) {
    if(err) {
      callback(err, null);
    } else {
      callback(null, null);
    }
  });
};
```

- IoT Custom rules to check abnormal temperatures

The screenshot shows the configuration for a rule named 'PharmaChainNode_IoTRule'. The source is a Kinesis stream 'esp32/pub' with the SQL query 'SELECT * FROM 'esp32/pub' where temperature > 25'. The actions are 'Send a message as an SNS push notification' and 'Send a message to a Lambda function' with the function name 'AddPharmaChainTemperatureAbnormalDB'.

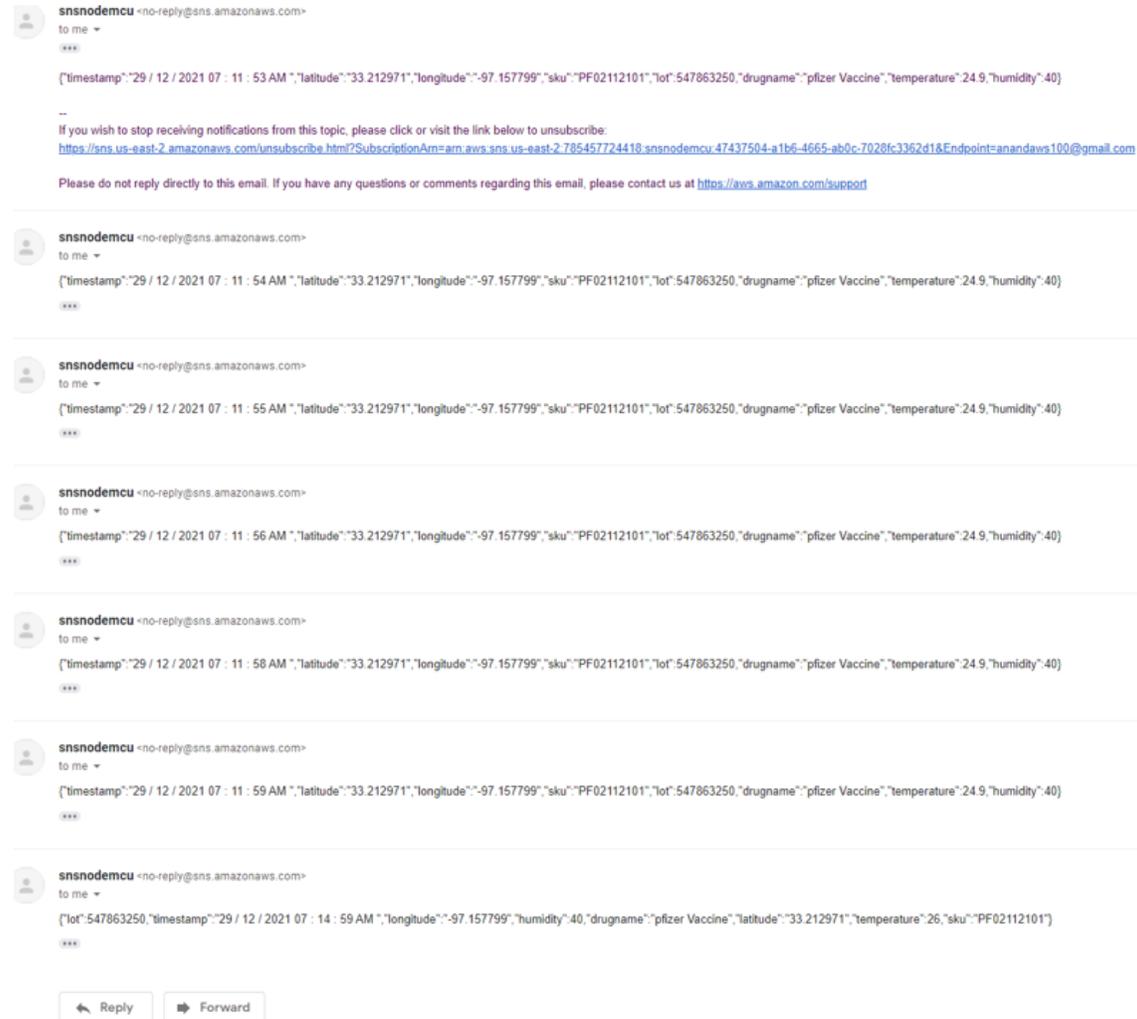
- API Gateway

```
const AWS = require("aws-sdk");
const dynamo = new AWS.DynamoDB.DocumentClient();

exports.handler = async (event, context) => {
  let body;
  let statusCode = 200;
  const headers = {
    "Content-Type": "application/json"
  };
  try {
    switch (event.routeKey) {
      case "GET /items/{sku}":
        let params = {
          // Specify which items in the results are returned.
          FilterExpression: "sku = :sku",
          // Define the expression attribute value, which are substitutes for the values you want to compare.
          ExpressionAttributeValues: {
            ":sku": parseInt(event.pathParameters.sku),
          },
          // Set the projection expression, which are the attributes that you want.
          //ProjectionExpression: "*",
          TableName: "PharmachainSKULatestDB",
        };
        body = await dynamo.scan(params).promise();
        console.log(event.pathParameters.sku);
        console.log(params.ExpressionAttributeValues);
        break;
        default:
          throw new Error("Unsupported route: " + event.routeKey);
    }
  } catch (err) {
    statusCode = 400;
    body = err.message;
  } finally {
    return {
      statusCode,
      body,
      headers
    };
  }
};
```

Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

Alerts Generated



Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

Web DApp Interface

- Manufacturer View

- Distributor View

- Retailer View

- Consumer View

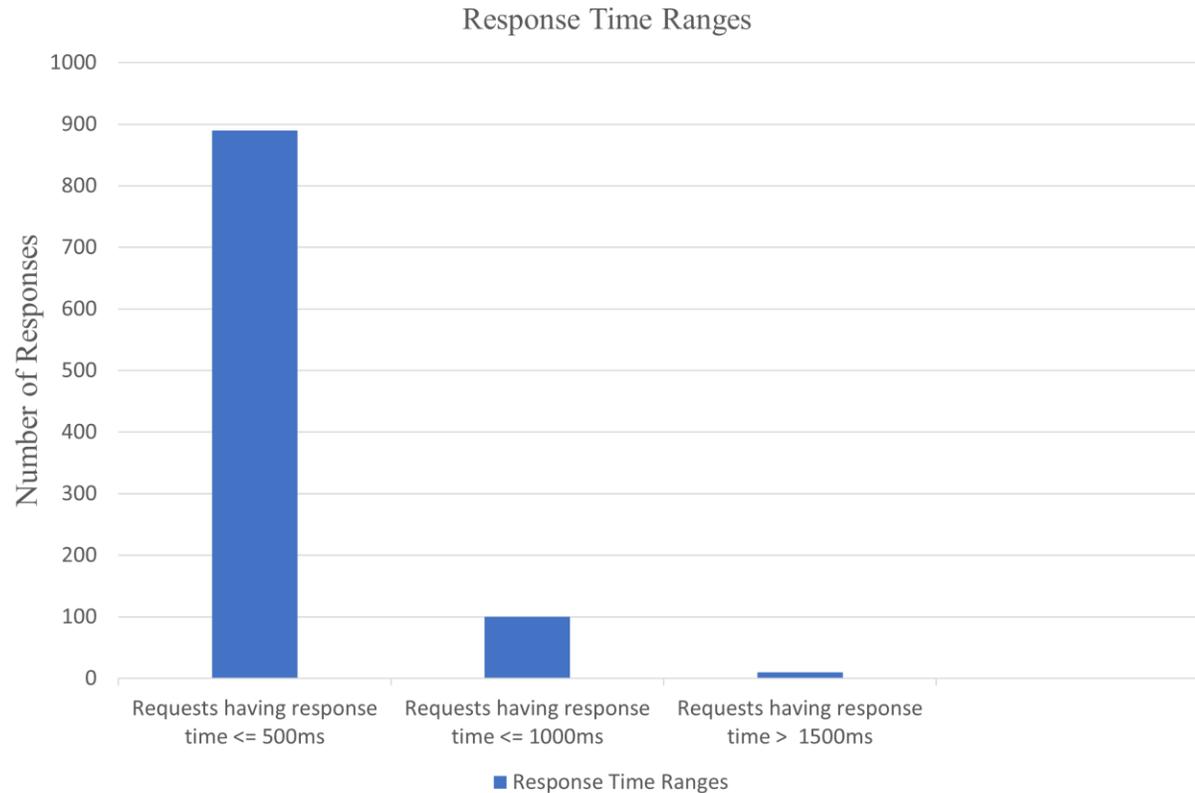
Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

Consumer Verifying Authenticity

The screenshot displays the PharmaChain web interface. At the top left, the logo 'PharmaChain' is shown in red. At the top right, the text 'logged in as:' is followed by a long alphanumeric string: '0xD46c558431c9CA642A85885509FBf6dA4Ba60435'. The main content area is divided into three sections by horizontal lines. The first section, 'Purchase Item By Consumer:', contains a text input field for 'Universal Product Code(UPC):', a 'submit' button, and a background image of a face mask. The second section, 'Verify Authenticity of Product:', contains another 'Universal Product Code(UPC):' input field and 'submit' button. Below this, it displays the following information: 'UPC: 547863250', 'SKU: 2112101', 'Verified transfer from manufacturer to distributor at block number : 29223086', 'Verified transfer from distributor to retailer at block number : 29223296', 'Verified transfer from retailer to consumer at block number : 29223390', and 'Product is verified ✓'. The third section, 'Fetch Item Details:', contains a third 'Universal Product Code(UPC):' input field and 'submit' button. At the bottom left of the interface, the text '© Copyrights SESL' is visible. The background of the interface features various medical icons like a heart with a pulse line, a ribbon, and a pill.

Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

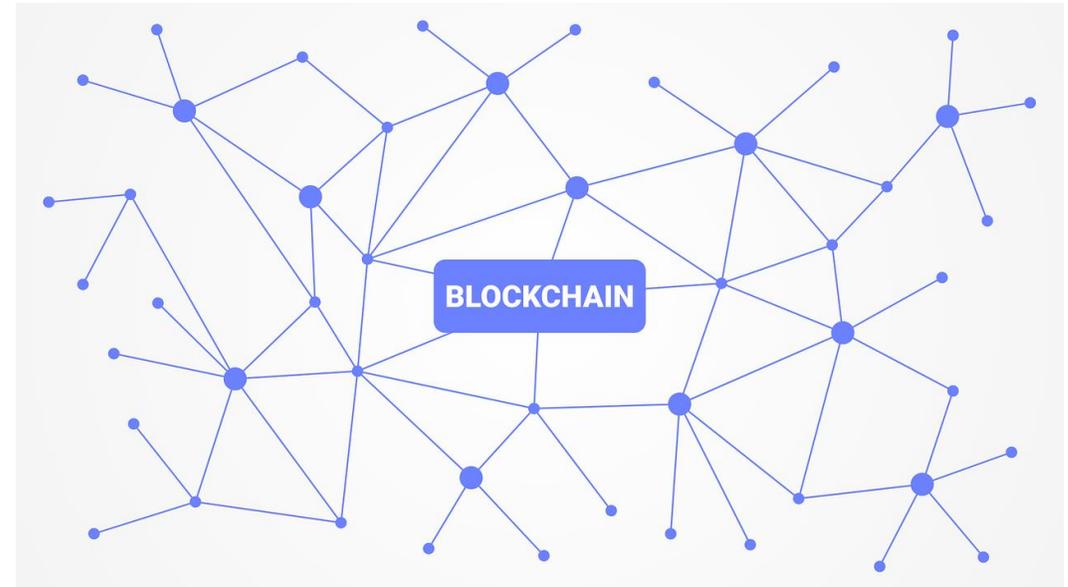
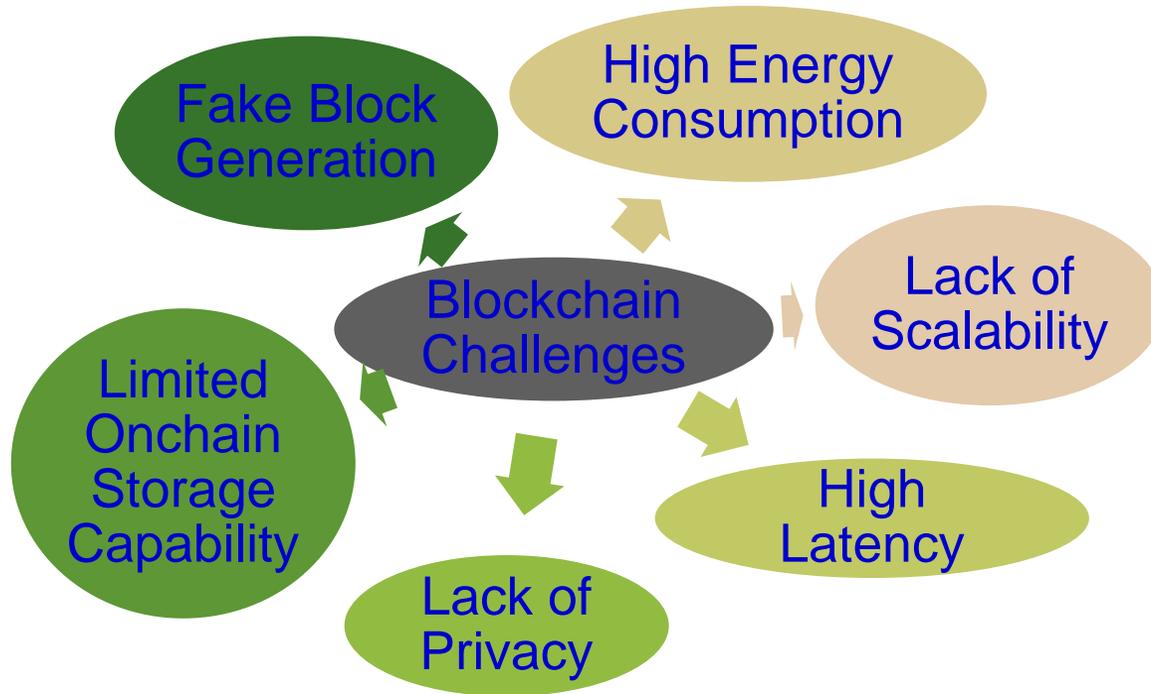
Performance and Cost Analysis



Parameters	Value
Number of Oracle Requests sent	1000
Load Duration	2 Seconds
Failed Requests	0
Percentage of Error	0%
Average Response Time (ms)	285.196 ms
Maximum Response Time (ms)	78ms
Throughput (requests/sec)	16.66

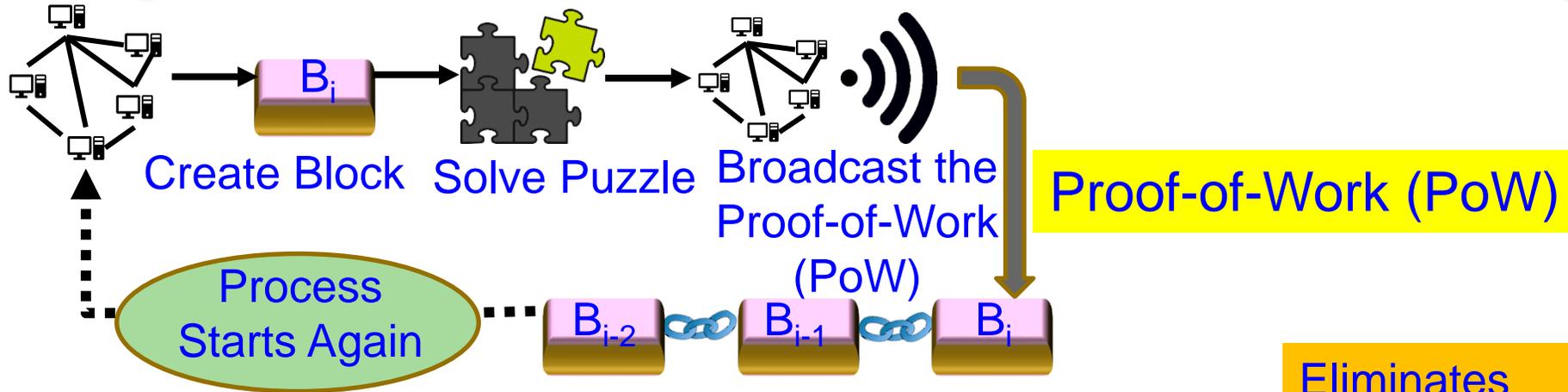
Source: Bapatla, A.K., et al.: PharmaChain: a blockchain to ensure counterfeit-free pharmaceutical supply chain. IET Netw. 1– 24 (2022). <https://doi.org/10.1049/ntw2.12041>

Blockchain has Many Challenges

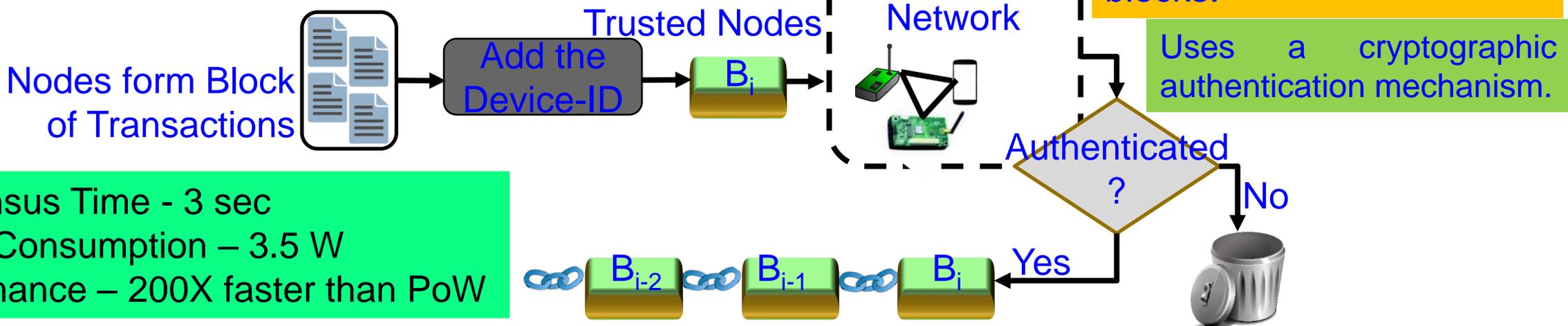


Source: D. Puthal, N. Malik, S. P. Mohanty, E. Kougianos, and G. Das, "Everything you Wanted to Know about the Blockchain", *IEEE Consumer Electronics Magazine (CEM)*, Volume 7, Issue 4, July 2018, pp. 06--14.

Our EasyChain: Proof-of-Authentication (PoAh)



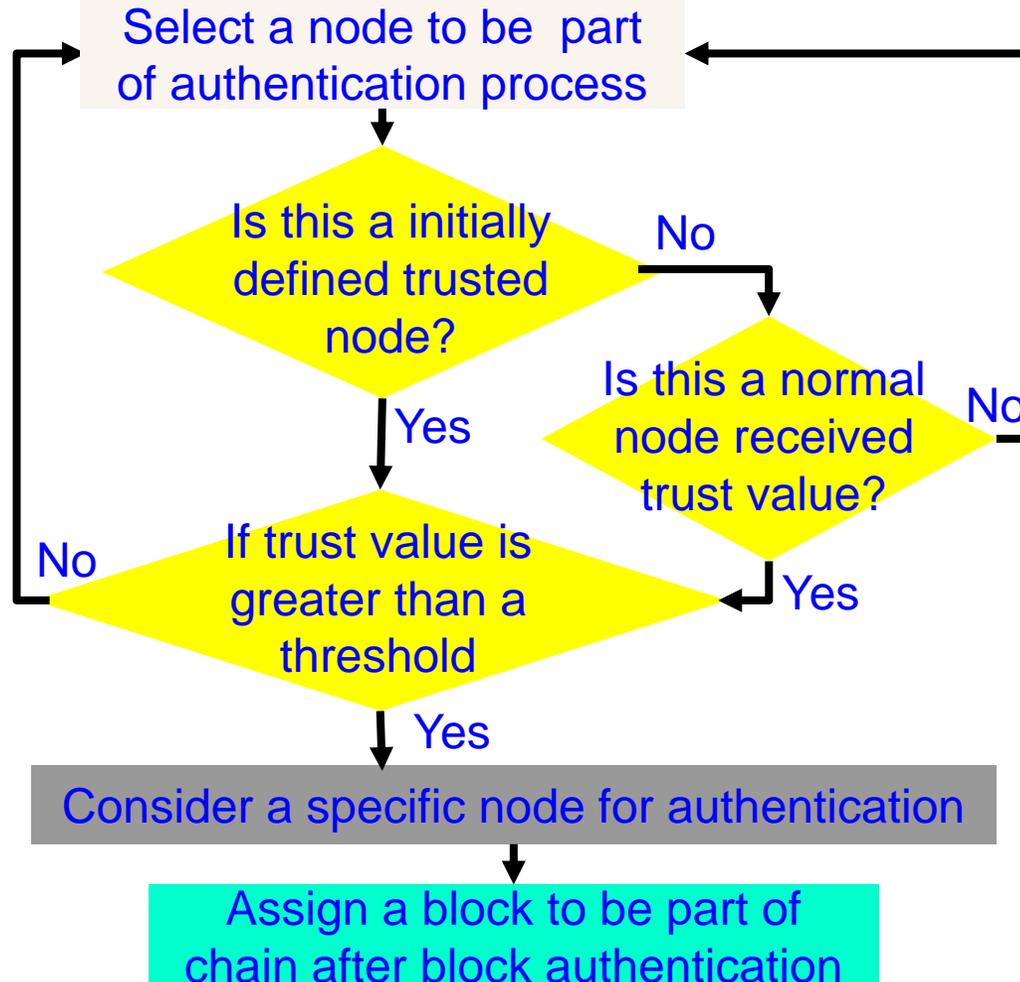
Proof of Authentication (PoAh)



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

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: PoAh Authentication Process



Algorithm 1: PoAh Block Authentication

Provided:

All nodes in the network follow SHA-256 Hash

Individual node has Private (PrK) and Public key (PuK)

Steps:

(1) Nodes combine transactions to form blocks
(Trx⁺) → blocks

(2) Blocks sign with own private key

$S_{PrK}(\text{block}) \rightarrow \text{broadcast}$

(3) Trusted node verifies signature with source public key

$V_{PuK}(\text{block}) \rightarrow \text{MAC Checking}$

(4) If (Authenticated)

$\text{Block}||\text{PoAh}(\text{ID}) \rightarrow \text{broadcast}$

$H(\text{block}) \rightarrow \text{Add blocks into chain}$

(5) Else

Drop blocks

(6) GOTO (Step-1) for next block

Steps to find a Trusted Node which will Authenticate a Block.

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.

Addressing Blockchain Scalability Issues and Control During Transport

PharmaChain 2.0: A Blockchain Framework for Secure Remote Monitoring of Drug Environmental Parameters in Pharmaceutical Cold Supply Chain

Issues in Traditional PSC



News Source: Affairs, O. of R. (n.d.). *Press releases*. U.S. Food and Drug Administration. Retrieved November 15, 2022, from <https://www.fda.gov/inspections-compliance-enforcement-and-criminal-investigations/criminal-investigations/press-releases>

08/22/2022

BEAUMONT, Texas – A Florida-based pharmaceutical president has pleaded guilty to federal **drug trafficking violations** in the Eastern District of Texas, announced U.S. Attorney Brit Featherston today.

11/12/2021

A federal grand jury in Beaumont has returned a three-count indictment charging nine individuals in **drug trafficking conspiracy** in the Eastern District of Texas, announced Acting U.S. Attorney Nicholas J. Ganjei today.

08/24/2021

ALEXANDRIA, Va. – An Inverness, Florida, man was sentenced today to three years in prison for selling **hundreds of thousands of counterfeit prescription drug pills** through the Internet.

Motivation

- Temperature-controlled drug's life cycle includes:
 - **Monitoring and controlling** the temperature during the storage of medicines in warehouses.
 - **Maintaining the temperature ranges** during the transportation of drugs.
 - Packaging should be taken care of **following all recommended procedures**.
 - Pharmacies and care sites should be **properly equipped** to maintain the medication temperature until dispensed.

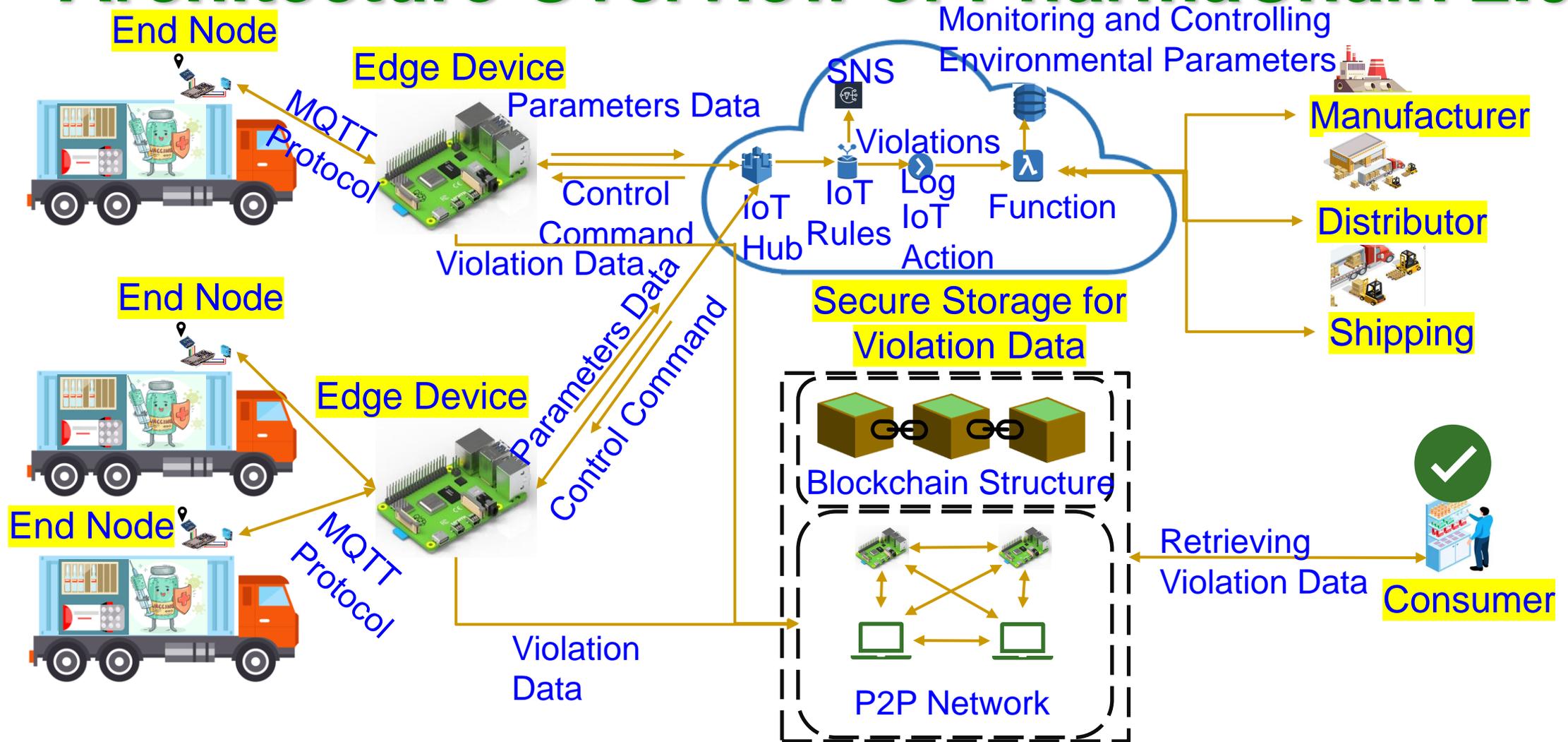
Novel Contributions

- **Near real-time data** will be propagated in the P2P network. Hence, prompt action can be taken to prevent decreases in drug efficacy.
- Consensus in the proposed P2P network will make the system more **robust to different security threats**.
- PharmaChain 2.0 makes use of IoT systems to provide **continuous monitoring and control throughout** the drug life cycle in the supply chain.
- **Data security** is provided by using the immutable characteristic of blockchain.
- PharmaChain 2.0 provides a **cost-efficient infrastructure** that can be adapted on a large scale as cold supply chains are huge.

PharmaChain Versus PharmaChain 2.0

PharmaChain	PharmaChain 2.0
Ethereum Blockchain Used for Tracking and Tracing in Pharmaceutical Supply Chain	PoAh Consensus Based Blockchain, used for both Tracking & Tracing along with Monitoring and Controlling Temperature Excursions
Proof-of-Authority (PoA) with less throughput compared to PoAh	Proof-of-Authentication (PoAh) with higher throughput
Private Blockchain with only nodes participating from Entities	Private Blockchain with only nodes participating from Entities
Not IoT friendly Consensus	IoT Friendly Consensus with less power and computations
The average transaction processing time is 5.6 sec.	The average transaction time has been improved significantly to 322.28ms

Architecture Overview of PharmaChain 2.0



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.

Proposed Algorithms – Log Generation

Algorithm 1 Proposed Violation Data Log Generation Algorithm For PharmaChain 2.0

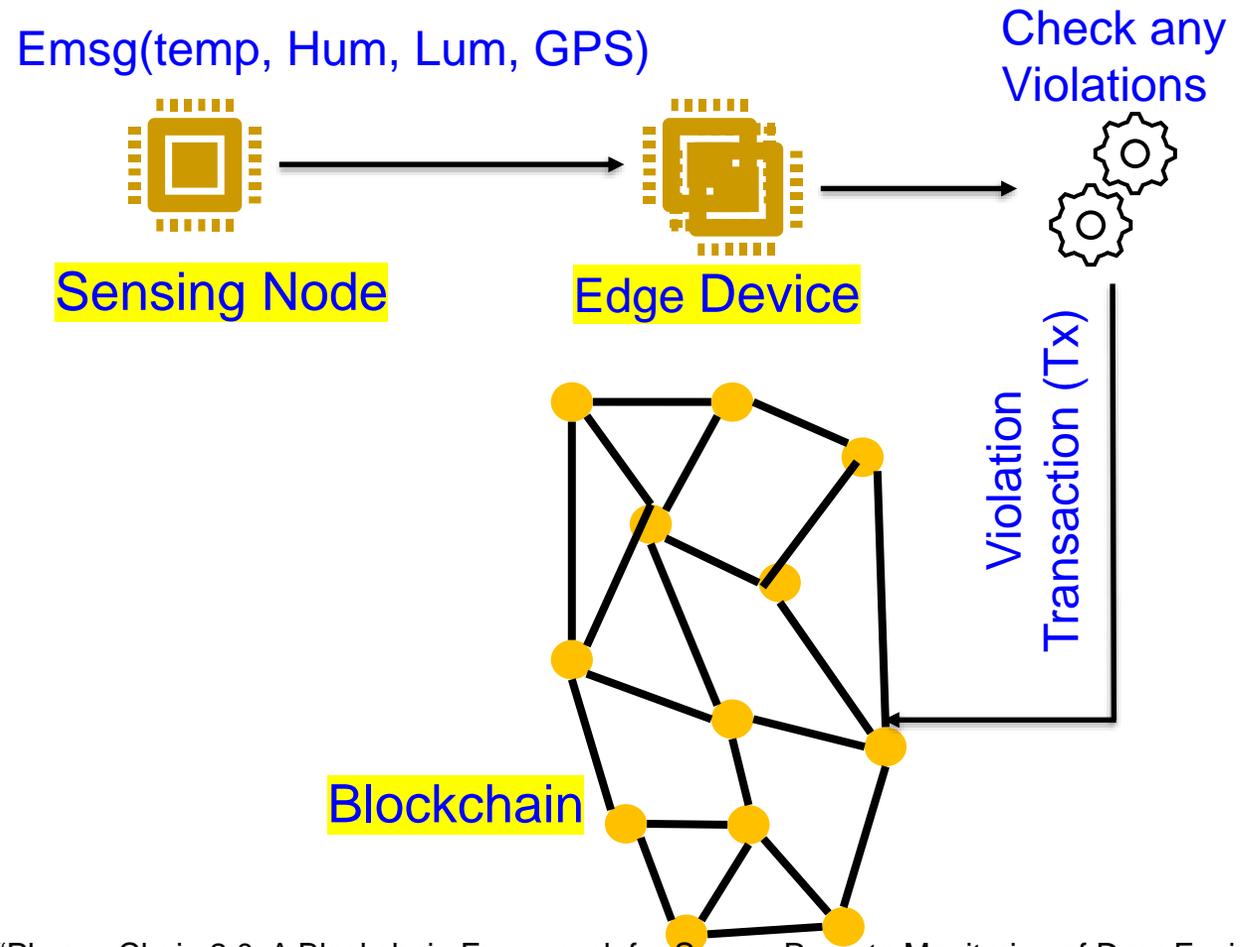
Input: Temperature, Humidity, Luminosity and GPS Position data from End node

Output: Violation data transaction published to blockchain network and cloud layer

- 1: End node E prepares a message E_{msg} with all the environmental parameters Temperature (temp), Humidity (hum), Luminosity (lum) and GPS position data(gps)
- 2: Prepared message is published to the topic τ of edge device using light weight pub-sub protocol
- 3: E.Publish(τ, E_{msg} (temp,Hum,lum,GPS))
- 4: Edge device E_e consumes the messages sent by the end nodes
- 5: $E_e.consume(\tau)$

Phase 1 – Edge Device Processing

- 6: **procedure** EDGE DEVICE PROCESSING
- 7: **for** Every message E_{msg} **do**
- 8: Check the pre-defined conditions on Temperature, Humidity, Luminosity
- 9: **if** Any Violation Detected **then**
- 10: Publish violation data V_E to both cloud
- 11: $E_e.Publish(V_E)$
- 12: Prepare and send transaction to blockchain network
- 13: $Tx \leftarrow E_e.prepareTransaction(V_E)$
- 14: $E_e.generateTransaction(Tx)$
- 15: **end if**
- 16: **end for**
- 17: **end procedure**



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.

Proposed Algorithm – Log Generation

Phase 2 – Cloud Layer Processing

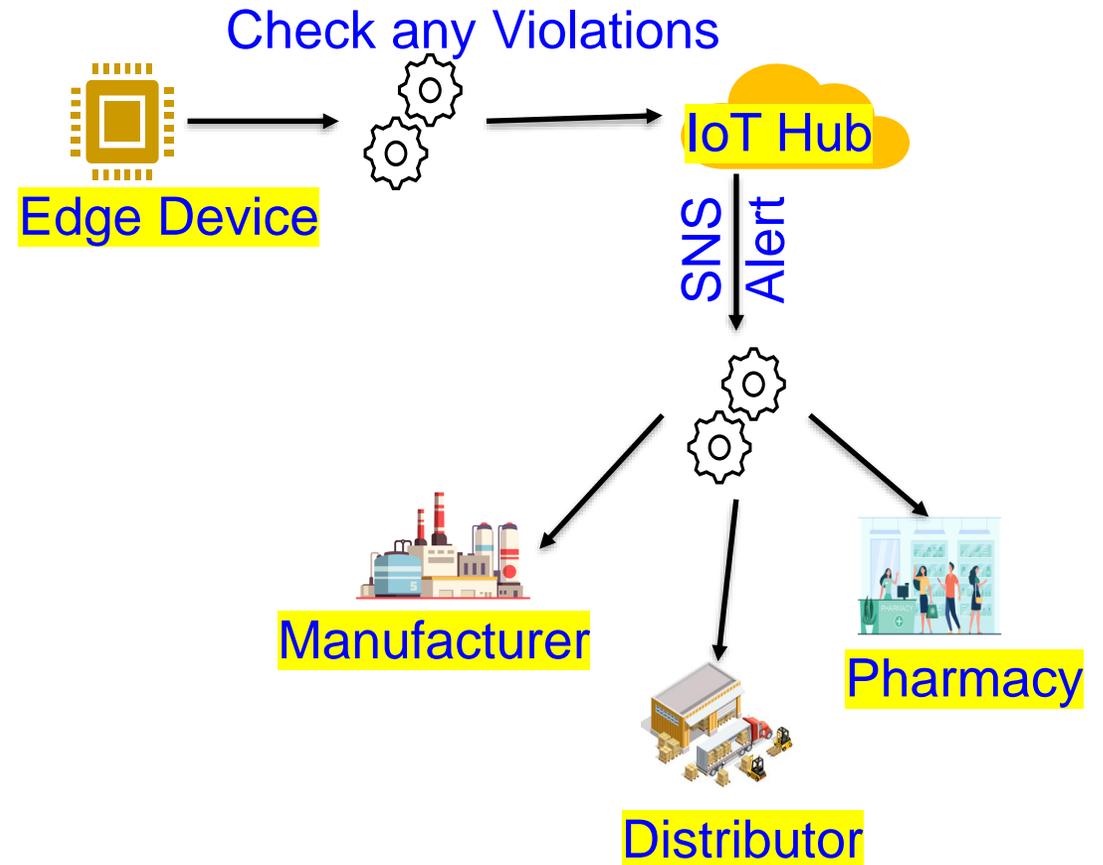
```

18: procedure CLOUD LAYER PROCESSING
19:   for Every Violation Data  $V_E$  received do
20:     Consume the message
21:     IoTHub.consume( $V_E$ )
22:     Generate an alert using SNS (Simple Notification
    Service) to the registered entities
23:     SNS.generateAlert( $V_E$ )
24:   end for
25: end procedure
  
```

Phase 3 – Blockchain Layer Processing

```

26: procedure BLOCKCHAIN LAYER PROCESSING
27:   Generated transaction is received into unconfirmed
    transactions pool (UTx)
28:   UTx.append(Tx)
29:   Miner picks transaction from UTx pool and creates a
    block
30:   Mining performed based on PoAh consensus protocol
31:   New block is added to the chain at all the participating
    nodes in the network creating an immutable violation data
    log
32:
33: end procedure
  
```

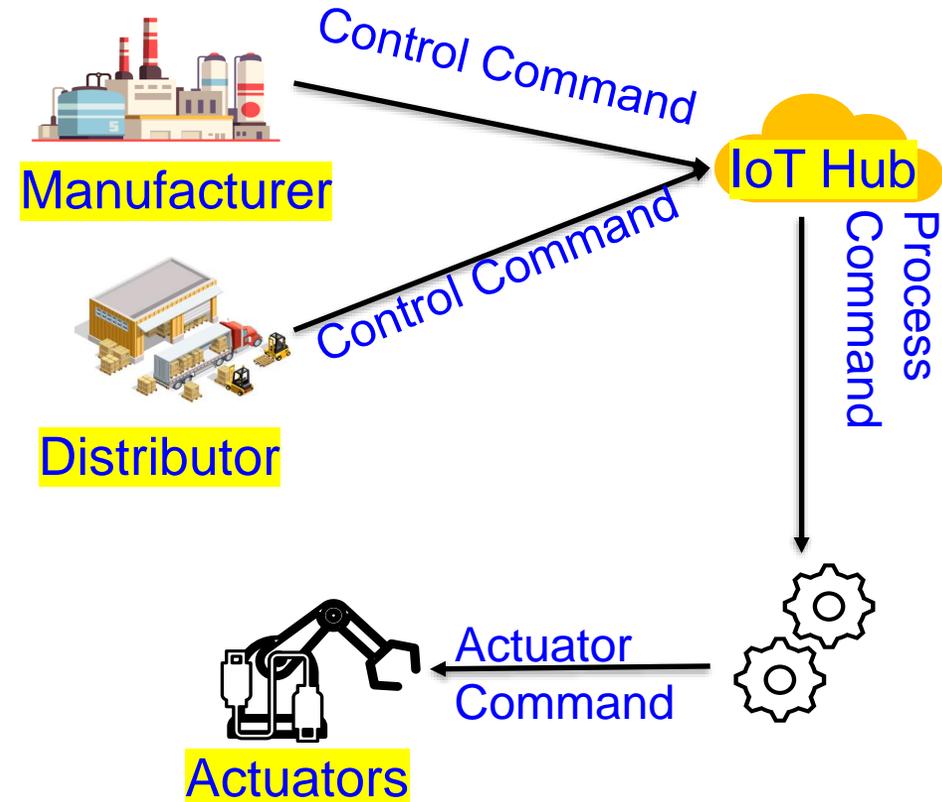


Source: A. K. Bapatla, **S. P. Mohanty**, E. Kougianos, and D. Puthal, "PharmaChain 2.0: A Blockchain Framework for Secure Remote Monitoring of Drug Environmental Parameters in Pharmaceutical Cold Supply Chain", in *Proceedings of the IEEE International Symposium on Smart Electronic Systems (iSES)*,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

Proposed Algorithm- Control Algorithm

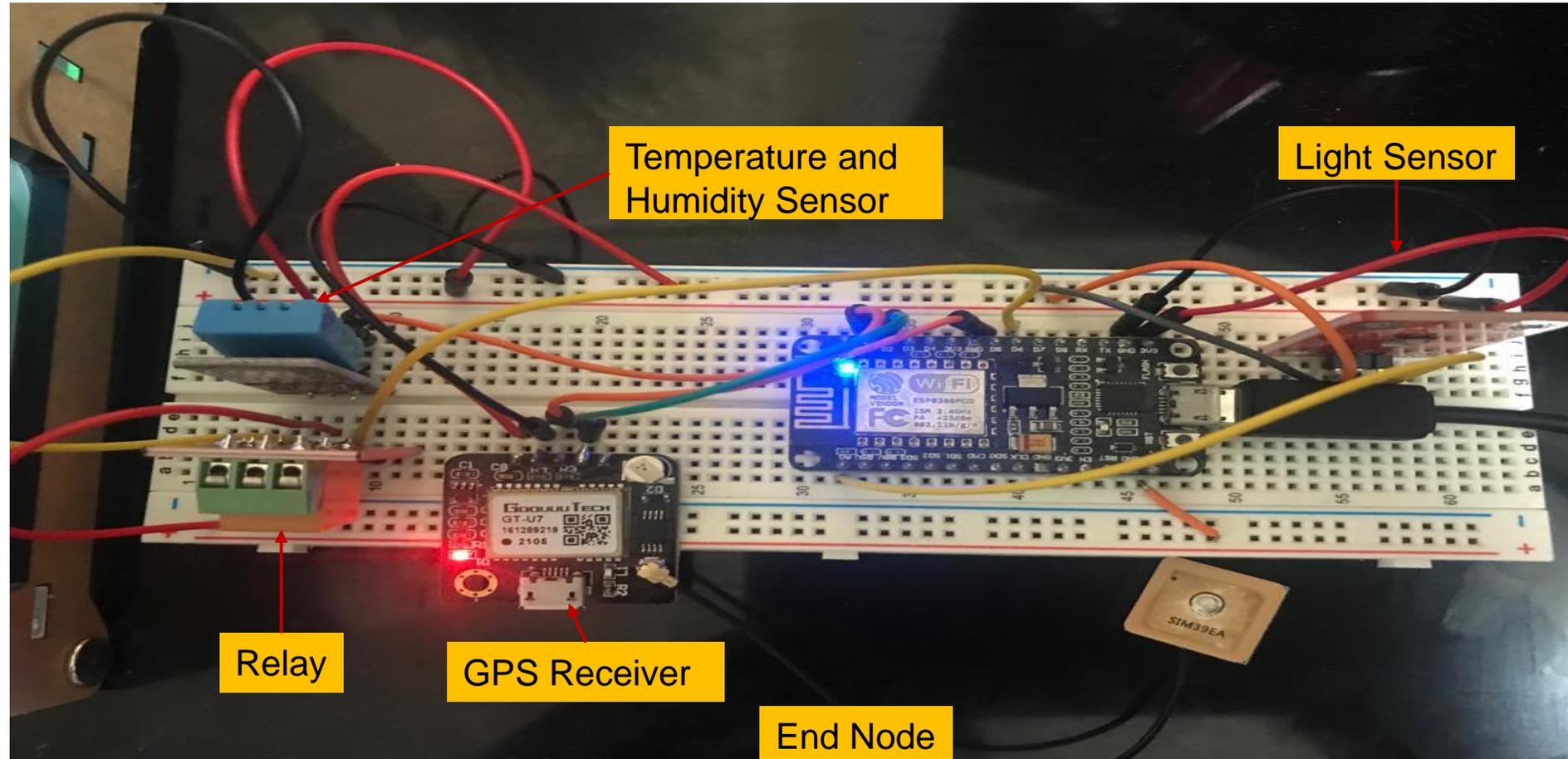
Algorithm 2 Proposed Control Algorithm For PharmaChain 2.0

- 1: **for** Each violation alert received **do**
- 2: Alert is reviewed by the responsible entity in the cold supply chain network
- 3: Control command CC_e for actuator is prepared by the entity
- 4: $CC_e \leftarrow$ Entity.prepareCommand(Control Instructions)
- 5: Control command is published to the cloud layer
- 6: Entity.publish(CC_e)
- 7: Cloud Layer processes the command and prepares control instructions for end node
- 8: $CC_e^+ \leftarrow$ IoTHub.process(CC_e)
- 9: Cloud layer published the processed control command to the edge devices
- 10: IoTHub.publish(CC_e^+)
- 11: Edge devices will send control instructions to the corresponding end devices
- 12: **for** Received Control Instructions by End Node e **do**
- 13: $e.consume(CC_e^+)$
- 14: Process and turn ON/OFF the actuators
- 15: $e.process(CC_e^+)$
- 16: **end for**
- 17: **end for**



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.

Implemented Sensing Node



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.

Implementation and Validation

```
pi@raspberrypi2: ~/Desktop/Implementation_python
login as: pi
pi [REDACTED]'s password:
Linux raspberrypi2 5.10.92-v7l+ #1514 SMP Mon Jan 17 17:38:03 GMT 2022 armv7l

The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*/copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.
Last login: Tue Feb 1 19:03:56 2022
pi@raspberrypi2:~$ cd Desktop/Impl*
pi@raspberrypi2:~/Desktop/Implementation_python$ python3 app.py 1234 1
* Serving Flask app 'app' (lazy loading)
* Environment: production
WARNING: This is a development server. Do not use it in a production deployment.
Use a production WSGI server instead.
* Debug mode: off
* Running on all addresses.
WARNING: This is a development server. Do not use it in a production deployment.
* Running on http://[REDACTED]:1234/ (Press CTRL+C to quit)
```

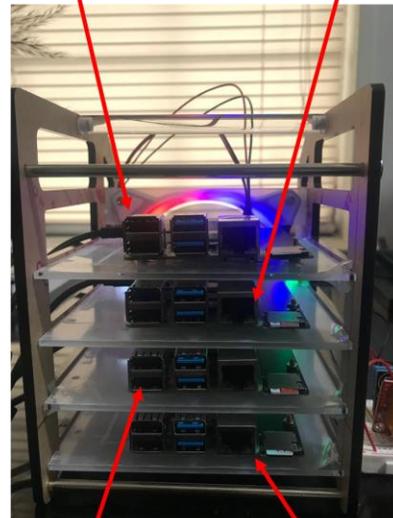
(a) Edge Device Running Proof of Authentication Based Blockchain

```
login as: pi
pi [REDACTED]'s password:
Linux raspberrypi2 5.10.92-v7l+ #1514 SMP Mon Jan 17 17:38:03 GMT 2022 armv7l

The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*/copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.
Last login: Tue Feb 1 22:42:31 2022
pi@raspberrypi2:~$ cd /Desktop/Implementation_python
-bash: cd: /Desktop/Implementation_python: No such file or directory
pi@raspberrypi2:~$ cd Desktop/Implementation_python
pi@raspberrypi2:~/Desktop/Implementation_python$ python3 app.py 3456 3
* Serving Flask app 'app' (lazy loading)
* Environment: production
WARNING: This is a development server. Do not use it in a production deployment.
Use a production WSGI server instead.
* Debug mode: off
* Running on all addresses.
WARNING: This is a development server. Do not use it in a production deployment.
* Running on http://[REDACTED]:3456/ (Press CTRL+C to quit)
```

(b) Edge Device Running Proof of Authentication Based Blockchain



(e) Implemented Four Node Prototype for PharmaChain 2.0

```
pi@raspberrypi1: ~/Desktop/Implementation_python
login as: pi
pi [REDACTED]'s password:
Linux raspberrypi1 5.10.17-v7l+ #1403 SMP Mon Feb 22 11:33:35 GMT 2021 armv7l

The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*/copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.
Last login: Tue Feb 1 22:31:44 2022 from 192.168.1.235
pi@raspberrypi1:~$ cd Desktop/Implementation_python
pi@raspberrypi1:~/Desktop/Implementation_python$ python3 app.py 2345 2
* Serving Flask app 'app' (lazy loading)
* Environment: production
WARNING: This is a development server. Do not use it in a production deployment.
Use a production WSGI server instead.
* Debug mode: off
* Running on all addresses.
WARNING: This is a development server. Do not use it in a production deployment.
* Running on http://[REDACTED]:2345/ (Press CTRL+C to quit)
```

(c) Edge Device Running Proof of Authentication Based Blockchain

```
pi@raspberrypi3: ~/Desktop/Implementation_python
login as: pi
pi [REDACTED]'s password:
Linux raspberrypi3 5.10.63-v7l+ #1459 SMP Wed Oct 6 16:41:57 BST 2021 armv7l

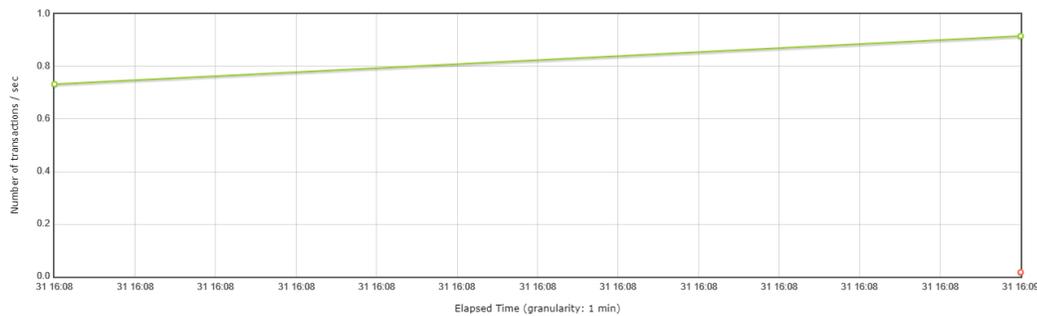
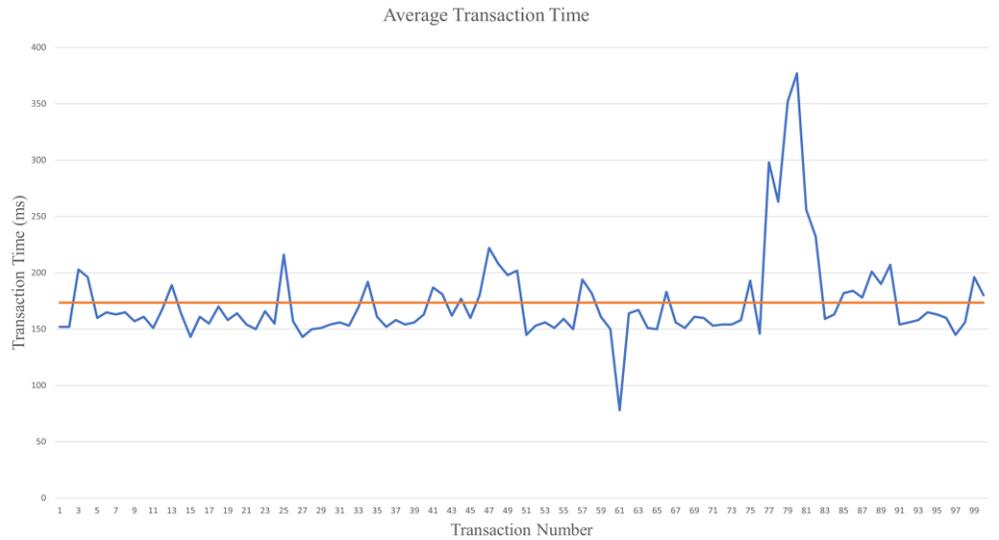
The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*/copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.
Last login: Tue Feb 1 22:42:32 2022
pi@raspberrypi3:~$ cd Desktop/Impl*
pi@raspberrypi3:~/Desktop/Implementation_python$ python3 app.py 4567 4
* Serving Flask app 'app' (lazy loading)
* Environment: production
WARNING: This is a development server. Do not use it in a production deployment.
Use a production WSGI server instead.
* Debug mode: off
* Running on all addresses.
WARNING: This is a development server. Do not use it in a production deployment.
* Running on http://[REDACTED]:4567/ (Press CTRL+C to quit)
```

(d) Edge Device Running Proof of Authentication Based Blockchain

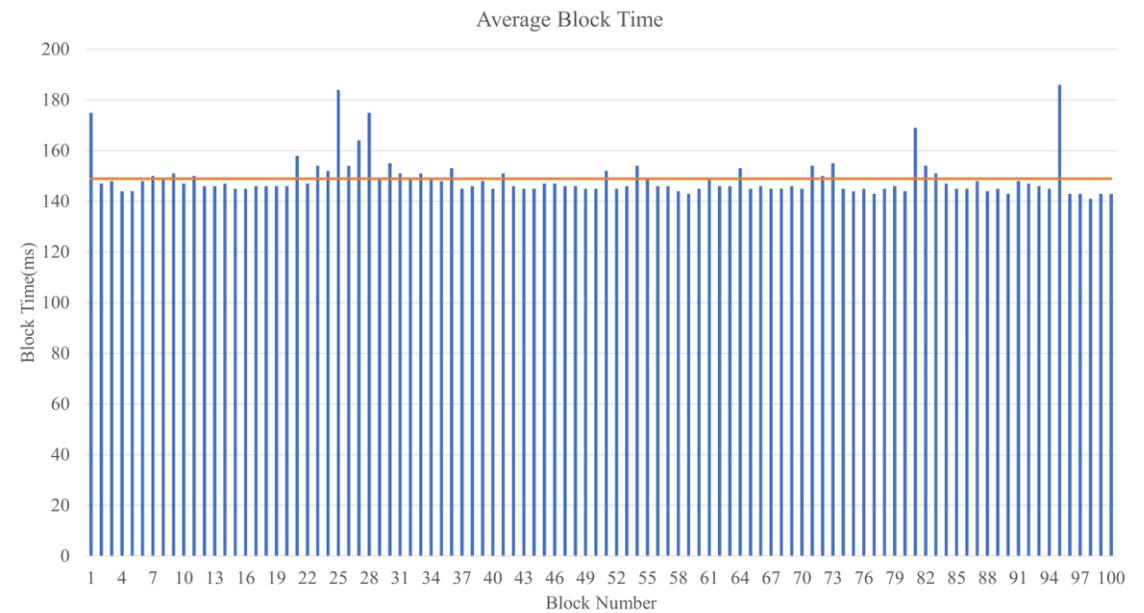
- Two nodes act as a miner nodes which are responsible for creating blocks from the unconfirmed

Testbed Evaluation



	Transacti on Time	Block Time	Total Time
PharmaChain 2.0	173.39ms	148.89 ms	322.2 8ms

Analysis Summary of PharmaChain 2.0



Comparative Analysis with Existing Solutions

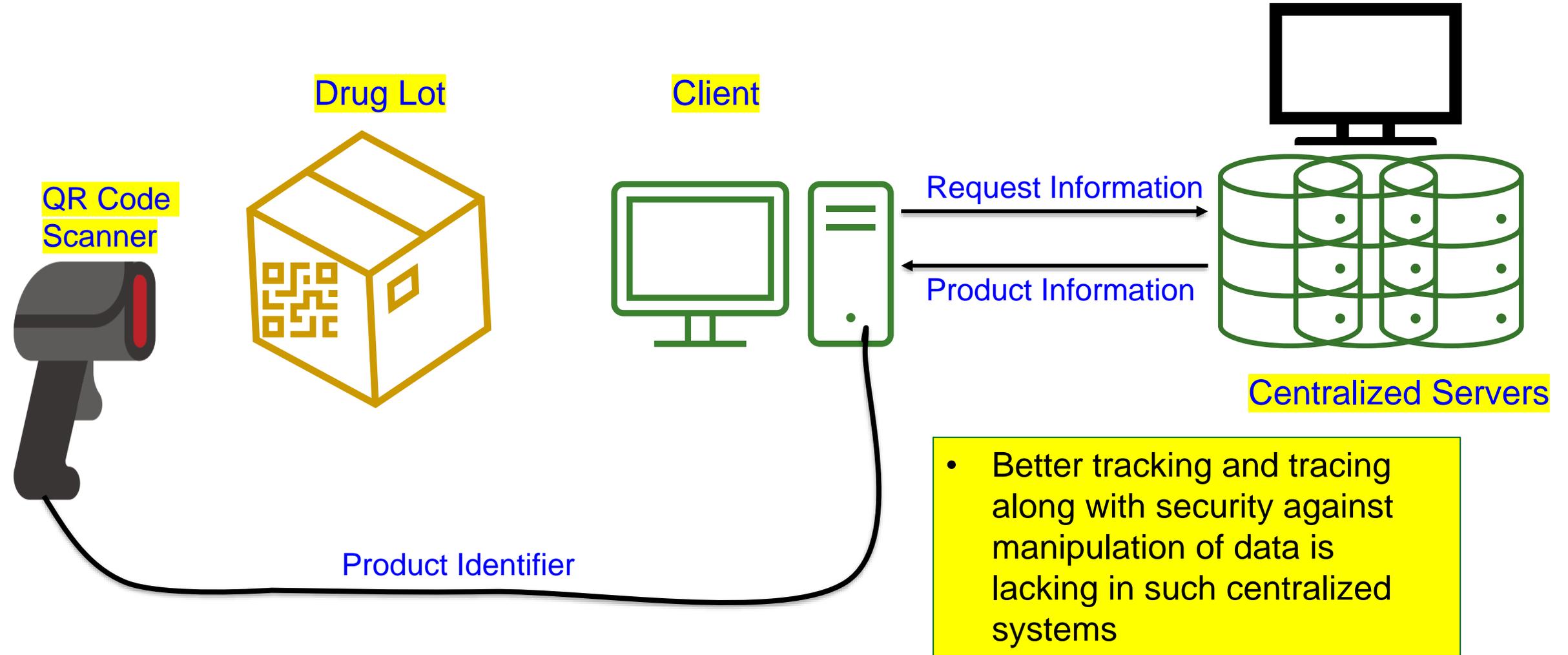
Comparison of Proposed PharmaChain 2.0 solution with Existing Solutions

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

Ease of Integrating Blockchain in Pharmaceutical Supply Chain

PharmaChain 3.0: Blockchain Integrated Efficient QR Code Mechanism for Pharmaceutical Supply Chain

Typical QR Code System



Issues Traditional Tracking

Removing
Centralized
Authorities

Response
Times

Consumer
accessibility of
Drug
Information

Data Security

Data Integrity

No End-to-End
Transparency

Fragmentation
of Information

Novel Contributions

- P2P network and consensus-based updates used in PharmaChain 3.0 **remove the centralized entities** and need for centralized databases for retrieving drug information.
- Shared ledger proposed in PharmaChain 3.0 provides **high availability** of data providing **low latency** for data retrieval.
- With the proposed QR Code integrated with the Blockchain mechanism, various **drug information** along with track and trace information can be stored in a single place and can be accessed using a **single QR Code scan**.
- Due to the immutability nature of blockchain, various threats like **data security** and **unauthorized modifications** are eliminated.

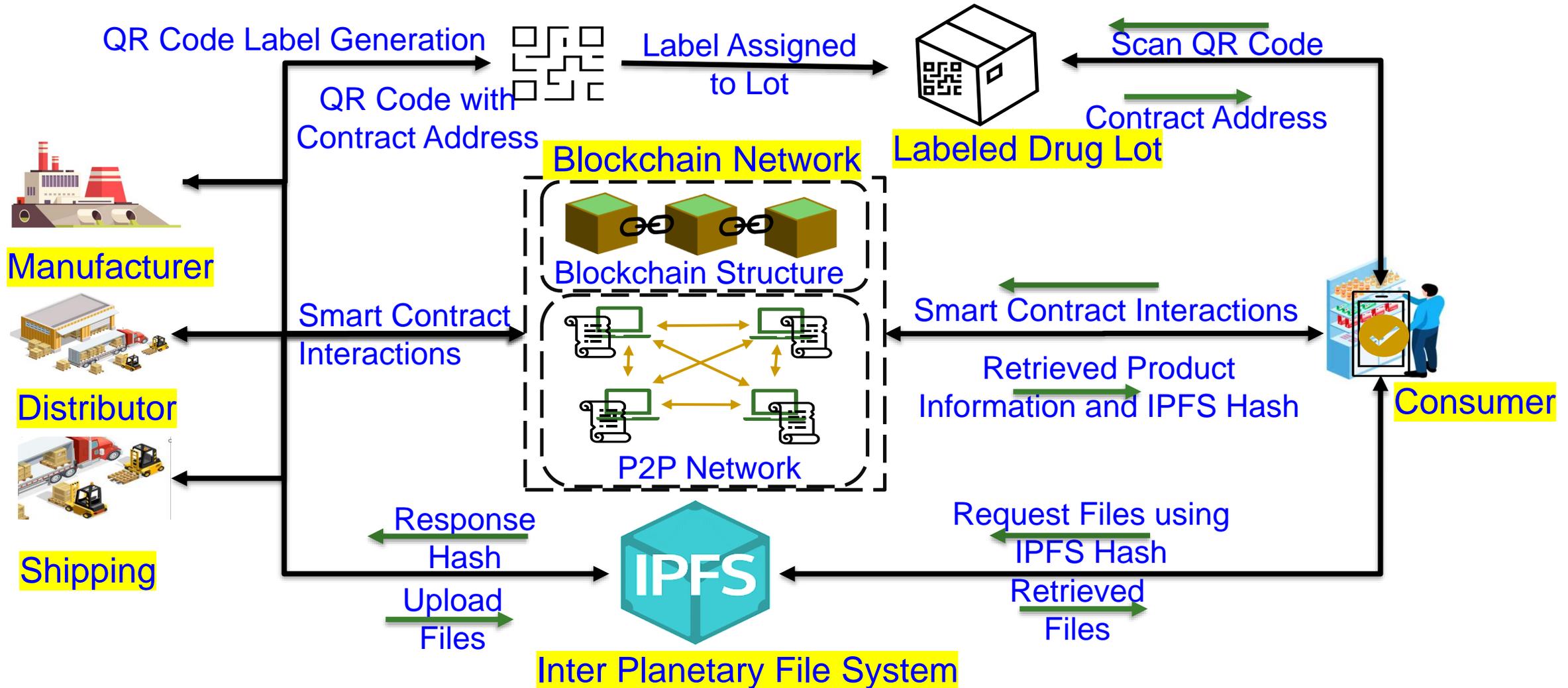
PharmaChain 2.0 Versus PharmaChain 3.0

PharmaChain 2.0	PharmaChain 3.0
PoAh Consensus Based Blockchain, used for both Tracking & Tracing along with Monitoring and Controlling Temperature Excursions	Integrating Ethereum Blockchain into IoT Systems through QR Code Mechanism for easy Tracking and Tracing and Drug Information
Proof-of-Authentication (PoAh) with higher throughput	Proof-of-Stake (PoS) Consensus mechanism is used with lesser throughput than PoAh
Private Blockchain with only nodes participating from Entities	Private Blockchain with only nodes participating from Entities
IoT Friendly Consensus with less power and computations. Doesn't support smart Contracts .	P2P nodes are maintained by the entities and are computationally capable. No need for IoT-Friendly Consensus
The average transaction time is 322.28ms	The average Transaction time is 16.2 Sec
Less information storage capabilities	More information can be stored

Related Research

Proposed	Methods Used
Modum.io	Used Sensory tags MAC address for track and trace. Mainly looks at track and tracing.
A. Musamih et.al.	Smart contracts to track and trace. Integration using QR codes is not considered.
CryptoCargo	Similarly, considered track and tracing using blockchain but integration of QR codes is not implemented.
M. Dave et.al., P.Sylim et.al., D. Sinclair et.al.	Hyper ledger-based solution for track and tracing using Chain codes, however integration of IoT environment is not addressed.

Architectural Overview of PharmaChain 3.0



Proposed Algorithms

Each Manufactured Lot

Algorithm 1 Data Upload and QR Code Generation Algorithm for Proposed PharmaChain 3.0

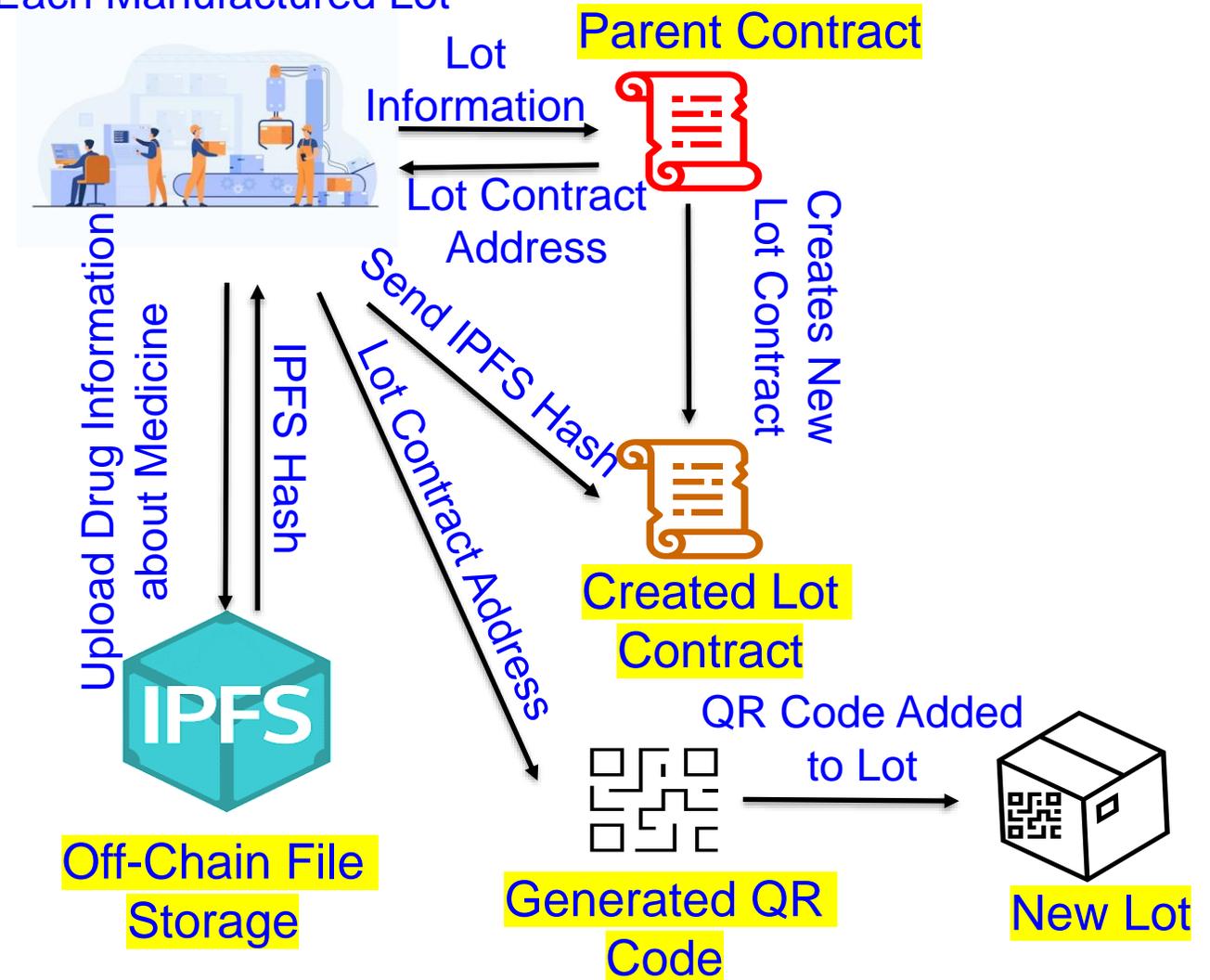
Input: Newly manufactured drug lot information files, shipping updates by entities in supply chain.

Output: Unique QR Code specific for newly manufactured lot and Immutable ledger of shipment updates.

Phase 1 – QR Code Generation

```

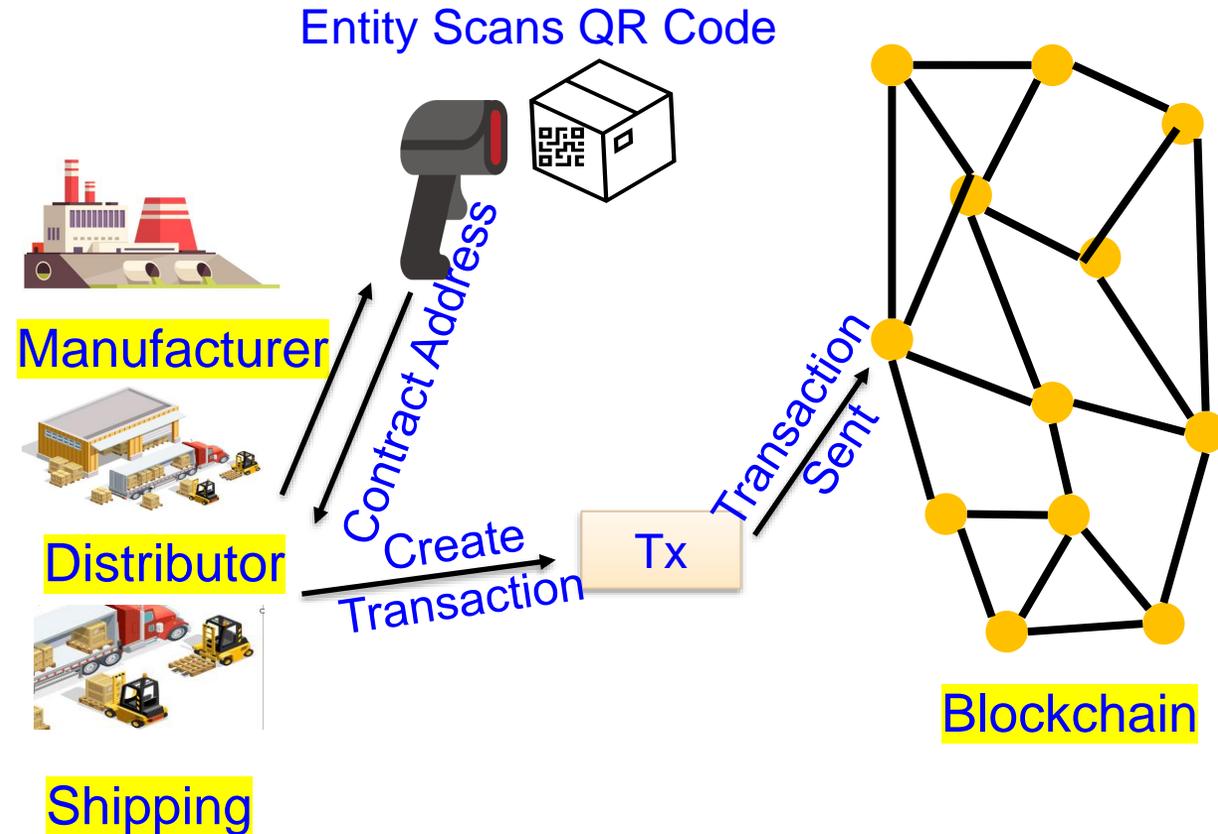
1: procedure QR CODE GENERATION
2:   for Each Drug Lot Manufactured do
3:     Lot specific contract is created by calling parent contract
4:      $Contract_{lot} \leftarrow Contract_{parent}.createNewLotContract()$ 
5:     Manufacturer uploads all required information about medicine on to IPFS system
6:     for Each Data File do
7:       Upload each individual file on IPFS
8:        $IPFSHash_{file} \leftarrow IPFS.add(File)$ 
9:       Returned hash is then updated in the newly created drug lot smart contract
10:       $Contract_{lot}.addIPFSHash(IPFSHash_{file})$ 
11:    end for
12:    Create a QR Code with newly created lot contract address information
13:     $QRCode.embed(Contract_{lot} \text{ Address})$ 
14:    Generated QR Code is assigned to the newly created drug lot
15:  end for
16: end procedure
  
```



Proposed Algorithms

Phase 2 – Track and Trace Updates

```
17: procedure TRACK AND TRACE UPDATES
18:   for Each Shipment Update in Supply Chain do
19:     Entity scans the QR Code to retrieve the lot
        contract address
20:      $Contract_{lot} \leftarrow QRCodeScan()$ 
21:     New transaction is generated and contract call is
        done to update the information of lot
22:     Newly generated transaction will be added to the
        unconfirmed transaction pool
23:     Group of unconfirmed transaction will be picked
        by miner and a new block is created after performing
        consensus
24:     New block is added at each and every node partic-
        ipating in the network creating immutable ledger of trail
        of ownership data
25:   end for
26: end procedure
```



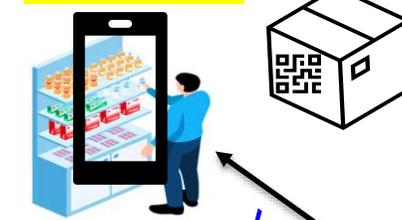
Proposed Algorithms

Algorithm 2 Algorithm for Drug Information Access and Authenticity Verification of Drug in Proposed PharmaChain 3.0

- 1: User scans the QR Code to get the lot contract address
- 2: $Contract_{lot} \leftarrow QRCodeScan()$
- 3: IPFS hashes are retrieved from the lot contract call
- 4: $IPFSHashes_{file} \leftarrow Contract_{lot}.getHashes()$
- 5: **for** Each IPFS hash **do**
- 6: Retrieve each information file
- 7: $FileData \leftarrow IPFS.get(IPFSHash_{file})$
- 8: **end for**
- 9: To verify authenticity, check the entities information updated in the smart contract
- 10: $TrailInformation \leftarrow Contract_{lot}.getTrailInformation()$
- 11: Authenticity of product can be checked along with all required drug information can be accessed.

Consumer Scans

QR Code

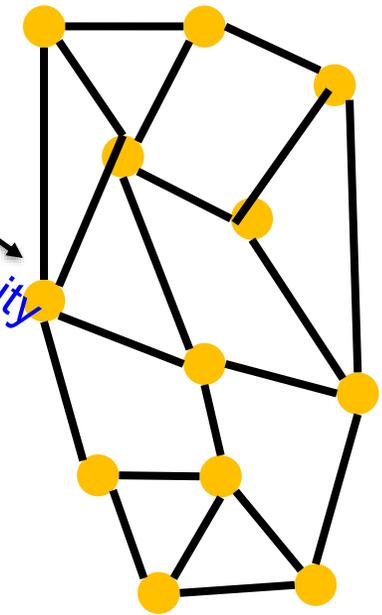


File
Retrieval



Off-Chain File
Storage

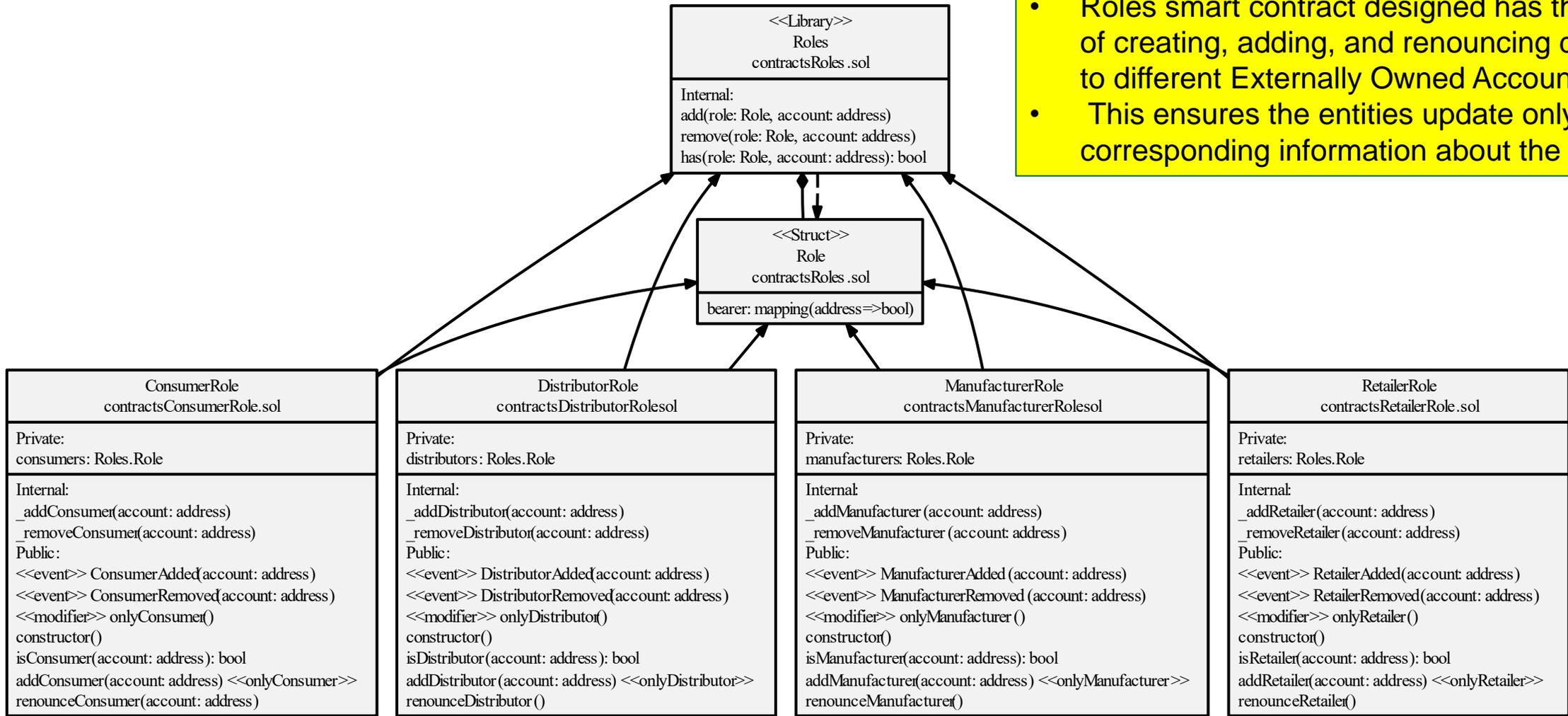
Verify Authenticity



Blockchain

Role Based Access Control Mechanism

- Roles smart contract designed has the capability of creating, adding, and renouncing different roles to different Externally Owned Accounts (EOA).
- This ensures the entities update only the corresponding information about the drug



Factory Smart Contract

- LotFactoryContract which generates a unique lot contract for each newly manufactured lot

LotContract LotContract.sol
Public: lotNumber: uint256 manufacturerID: address distributorID: address retailerID: address files: mapping(uint256=>address) numberOfFiles: uint256
Public: constructor(_lotnumber: uint256) storeLotNumber(num: uint256) retrieveLotNumber(): uint256 setManufacturerID(_address: address) retrieveManufacturerID(): address setDistributorID(_address: address) retrieveDistributorID(): address setRetailerID(_address: address) retrieveRetailerID(): address updateIPFHash(_address: address) retrieveAllFileHashes(): address[]

Factory LotContractFactory.sol
Public: contractAddresses: mapping(uint256=>address)
Public: CreateNewLotContract(_lotnumber: uint256) getLotContractAddress(_lotnumber: uint256): address



Implementation and Validation

- Ganache local blockchain is used to implement PharmaChain 3.0.
- Web3.js and Reactjs were used to develop the UI component.
- IPFS is used for providing distributed storage of large amounts of data.

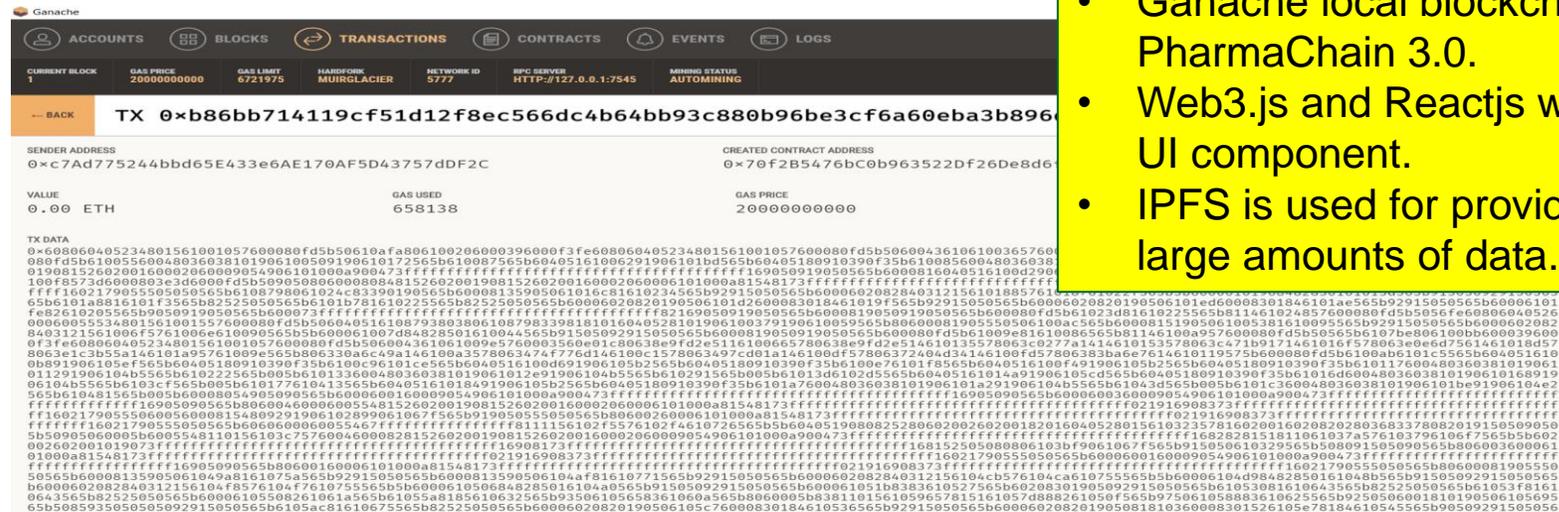


Fig. a. Factory Contract Creation

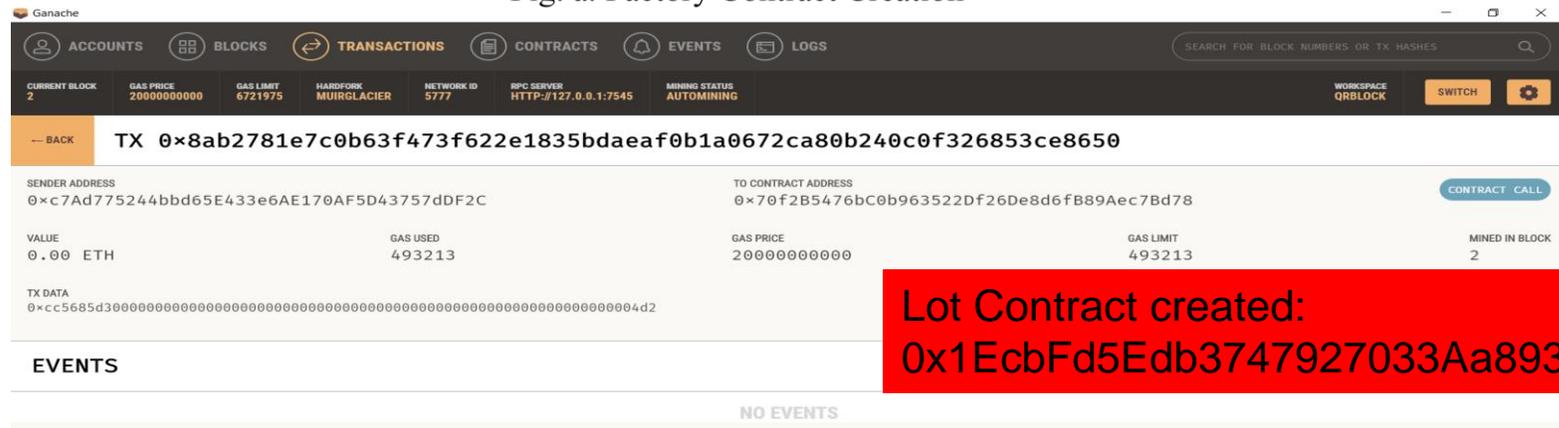


Fig. b. New Lot Contract Creation Transaction

Lot Contract created:
0x1EcbFd5Edb3747927033Aa893416e4aD01DF0c6E



Implementation and Validation

0x1EcbFd5Edb3747927033
Aa893416e4aD01DF0c6E

Lot Contract Address



QR Code Generated for Lot Labelling

New Lot Contract Address Converted to QR Code for Labeling

Implementation and Validation

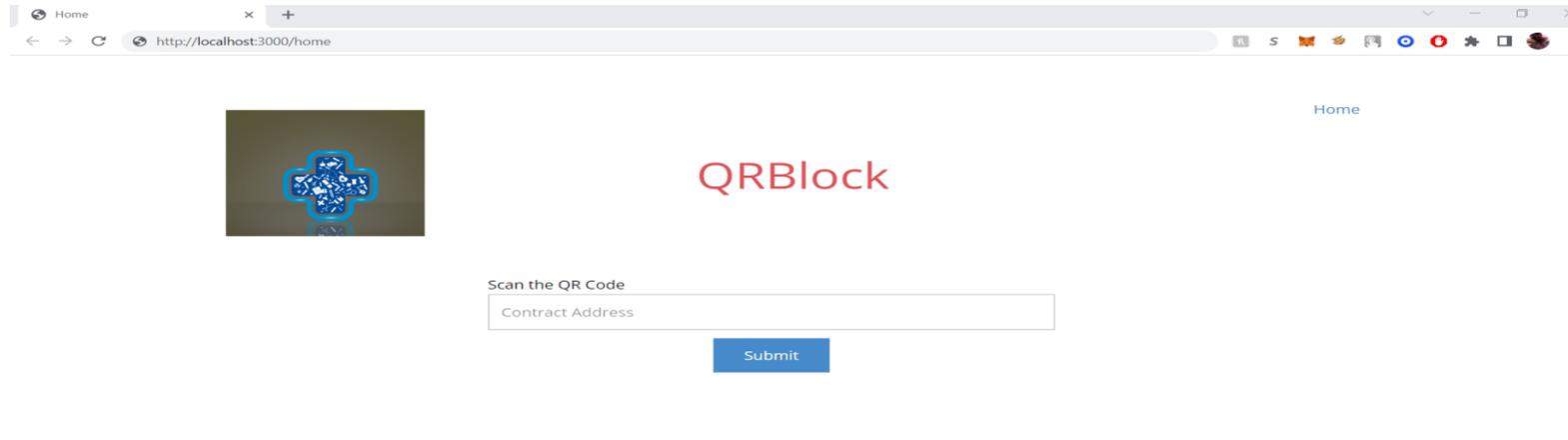


Fig. a. Scanning the QR Code to Get Contract Address



Fig. b. Fetching Drug Trail and IPFS Hashes

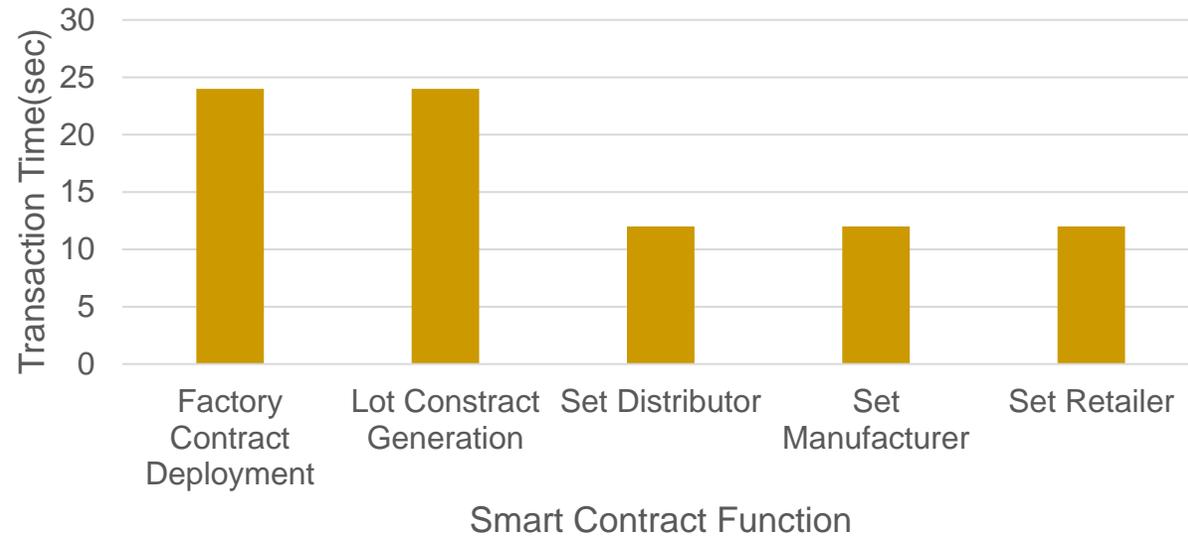
Security Analysis

- Threat 1: **Counterfeit Drugs** introduced into the supply chain by a malicious entity.
- Solution: Each transaction generated in the proposed PharmaChain 3.0 must be signed by the **entity's private key** before sending it to the blockchain.

- Threat 2: **Data Integrity Attacks** to manipulate data within the network
- Solution: Proposed PharmaChain 3.0 makes use of **distributed shared ledger**, each entity node participating in the network will have its copy of the ledger.

Timing and Cost Analysis

Smart Contract Function vs Transaction Time



Smart Contract Function vs Transaction Cost



Comparative Analysis

	Blockchain	Consensus Mechanism	Less Computational Needs	Openness	QR Code Integrated	Storage	Handling large data
Crypto Cargo [11]	Ethereum	Proof-of-Work (PoW)	No	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)	Yes	Private	No	On-Chain and cloud	No
PharmaChain 2.0	PoAh consensus-based blockchain	Proof-of-Authentication (PoAh)	Yes	Private	No	On-Chain and cloud	No
Current Solution (PharmaChain 3.0)	Ethereum	Proof-of-Stake (PoS)	Yes	Private	Yes	On-chain and off-Chain	Yes

Summary

- PharmaChain 3.0 presents a novel solution of embedding the smart contract addresses as the QR codes which will increase the accessibility of the **tamper-proof information**.
- This ensures the right medicines reach the consumer instead of counterfeits and **increase consumer confidence**.
- It also addresses the issue of uploading **large data** drug information files onto the blockchain by introducing an **IPFS distributed storage system**.
- Results from the analysis have shown that the proposed PharmaChain 3.0 is a feasible solution.

Future Research

- As future work, mechanisms to **avoid the duplication of the QR Codes** will be included.
- More **user-friendly GUI** will be provided in future work.
- **Increasing efficiency** in terms of cost and response times will be addressed in future work.
- Automating more **complex interactions** in the supply chain thereby reducing the latencies.

Thank You !!