Blockchain Technology and Its Application to IoT-Enabled Internet of Drones for Secure Data Delivery and Collection [Practical Real-life Problem Based on NP-hardness]

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What is Blockchain?

- A blockchain is considered as a chain of blocks that are created from several blocks and it potentially consists of information.
- By the words “block” and “chain”, we actually specify in the context of digital information (“block”) which is stored in a public domain say database (“chain”).
- Since the digital information is stored in the form of “block” and it is linked in a “chain” form, the linked blocks constitute a chain, and hence, the name “blockchain”.
- The blockchain’s first block is known as the **Genesis block**.

What is Blockchain?

The reasons why the blockchain have gained so much admiration are that:

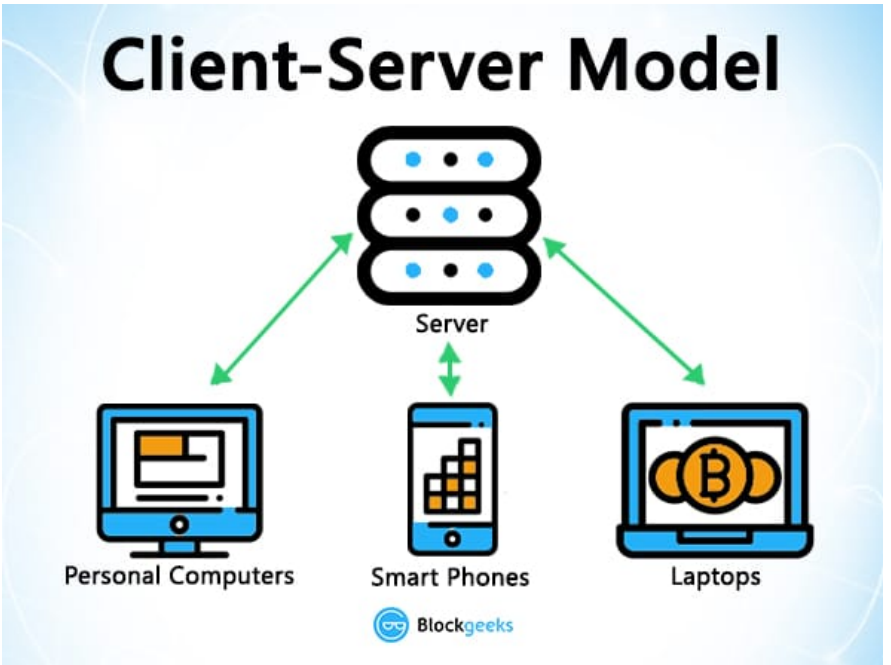
- It is not owned by a single entity, hence it is **decentralized**
- The data is **cryptographically** stored inside
- The blockchain is **immutable**, so no one can tamper with the data that is inside the blockchain
- The blockchain is **transparent** so one can track the data if they want to

Three Pillars of Blockchain Technology

- Decentralization
- Transparency
- Immutability

Pillar #1 : Decentralization

- Example of a centralized system is banks. They store all our money, and the only way that we can pay someone is by going through the bank.
- The traditional client-server model is a perfect example of this.
- When we google search for something, we send a query to the server who then gets back at us with the relevant information. That is simple client-server.



Pillar #1 : Decentralization

- In a decentralized system, the information is not stored by one single entity. In fact, everyone in the network owns the information.
- In a decentralized network, if you wanted to interact with your friend then you can do so directly without going through a third party.
- That was the main ideology behind Bitcoins. You and only you alone are in charge of your money. You can send your money to anyone you want without having to go through a bank.

Pillar #2 : Transparency

- While the person's real identity is secure, you will still see all the transactions that were done by their public address.
- This level of transparency has never existed before within a financial system.
- It adds that extra, and much needed, level of accountability which is required by some of these biggest institutions.

Pillar #3 : Immutability

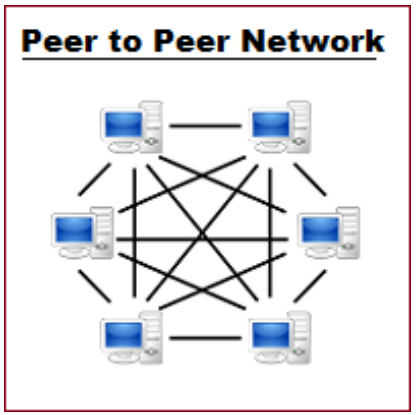
- Immutability, in the context of the blockchain, means that once something has been entered into the blockchain, it cannot be tampered with.
- The reason why the blockchain gets this property is that of cryptographic hash function.

INPUT	HASH
Hi	3639EFCD08ABB273B1619E82E78C29A7DF02C1051B1820E99FC395DCAA3326B8
Welcome to blockgeeks. Glad to have you here.	53A53FC9E2A03F9B6E66D84BA701574CD9CF5F01FB498C41731881BCDC68A7C8

INPUT	HASH
This is a test	C7BE1ED902FB8DD4D48997C6452F5D7E509FBCDBE2808B16BCF4EDCE4C07D14E
this is a test	2E99758548972A8E8822AD47FA1017FF72F06F3FF6A016851F45C398732BC50C

Maintaining the Blockchain – Network and Nodes

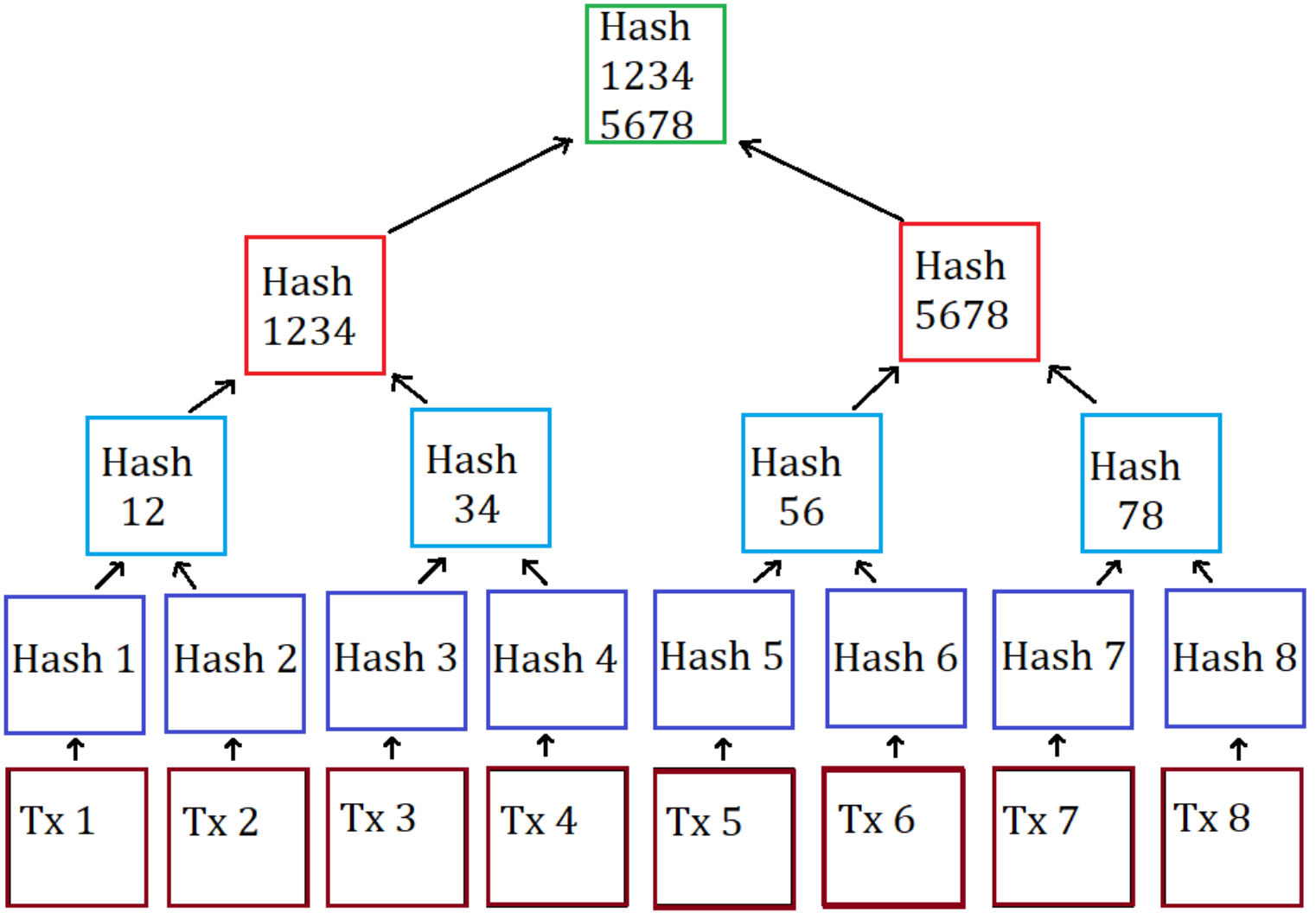
- The blockchain is maintained by a peer-to-peer (P2P) network.
- The network is a collection of nodes which are interconnected to one another.
- Nodes are individual computers which take in input and performs a function on them and gives an output.
- The blockchain uses a special kind of network called *peer-to-peer network* which partitions its entire workload between participants, who are all equally privileged, called *peers*.
- There is no longer one central server, now there are several distributed and decentralized peers.



Types of blockchain

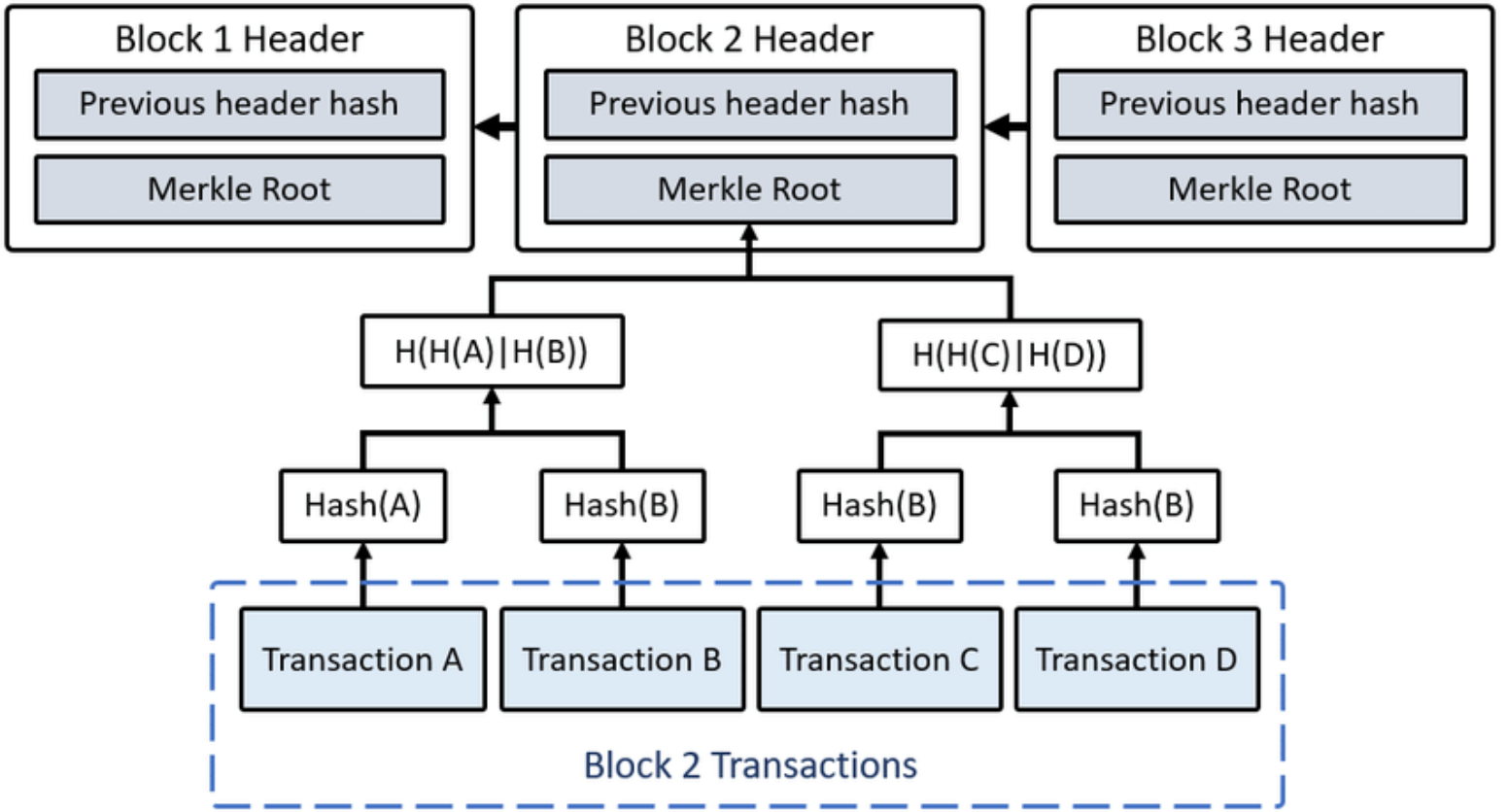
- **Public (Permissionless) Blockchain**: Everyone has the right to join, access, send, verify and receive transactions of the blocks in the blockchain to create a consensus. One widely successful permissionless blockchain is *bitcoin*.
- **Private (Permissioned) Blockchain**: The owner of the network decides which node to assign the right to access, send, receive, join and verify the block for creating an agreement between the nodes. Example: Healthcare Applications
- **Consortium or Hybrid Blockchain**: Internet of Vehicles (IoV) application

How to Make a Merkle Tree?

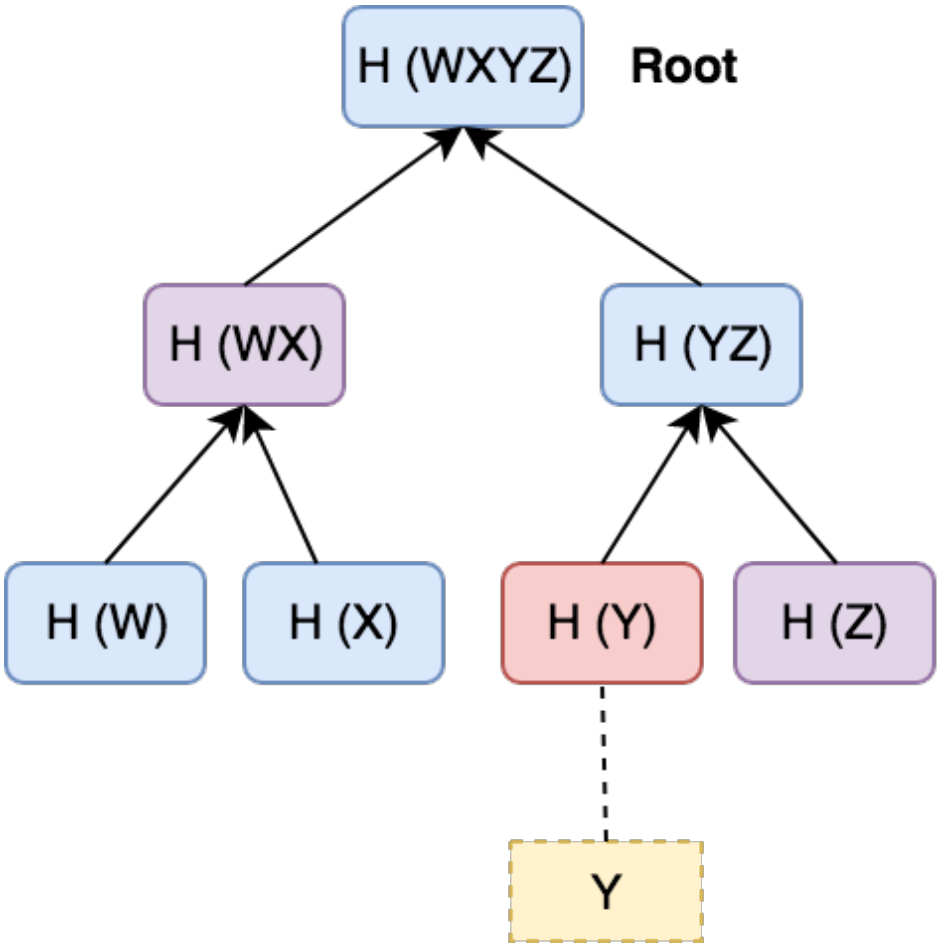


Tx_i: i^{th} transaction; H_i: Hash of i^{th} transaction ($H_{Tx_i} = H(Tx_i)$);
$H_{Tx_1 Tx_2} = H_{Tx_1} \oplus H_{Tx_2}$; $H_{12345678}$: Merkle root

Use of Merkle Tree in Blockchain



Verifying Transactions Using the Merkle Root



To confirm transaction Y, one only needs to know: $H(WX)$, $H(Y)$, $H(Z)$ and $H(WXYZ)$; $H(\cdot)$: hash function

Types of blockchain

Block Header	
Block Version	BV
Previous Block Hash	PBHash
Merkle Tree Root	MTR
Block Type	Public
Timestamp	TS
Owner of Block	ES_l
Public key of signer (ES_l)	Pub_{ES_l}
Block Payload (Transactions)	
Transaction #1	Tx_1
Transaction #2	Tx_2
⋮	⋮
Transaction #n_t	Tx_{n_t}
Current Block Hash	CBHash
Signature on block using ECDSA	BSign

a) Formation of a block on public blockchain

Block Header	
Block Version	BV
Previous Block Hash	PBHash
Merkle Tree Root	MTR
Block Type	Private
Timestamp	TS
Owner of Block	ES_l
Public key of signer (ES_l)	Pub_{ES_l}
Block Payload (Encrypted Transactions)	
Encrypted Transaction #1	$E_{Pub_{ES_l}}(Tx_1)$
Encrypted Transaction #2	$E_{Pub_{ES_l}}(Tx_2)$
⋮	⋮
Encrypted Transaction #n_t	$E_{Pub_{ES_l}}(Tx_{n_t})$
Current Block Hash	CBHash
Signature on block using ECDSA	BSign

b) Formation of a block on private blockchain

Block Header	
Block Version	BV
Previous Block Hash	PBHash
Merkle Tree Root	MTR
Block Type	Hybrid
Timestamp	TS
Owner of Block	ES_l
Public key of signer (ES_l)	Pub_{ES_l}
Block Payload	
Encrypted Transaction #1	$E_{Pub_{ES_l}}(Tx_1)$
Transaction #2	Tx_2
⋮	⋮
Encrypted Transaction #n_t	$E_{Pub_{ES_l}}(Tx_{n_t})$
Current Block Hash	CBHash
Signature on block using ECDSA	BSign

c) Formation of a block on consortium blockchain

Consensus mechanisms

Consensus mechanisms are used to verify transactional data between the nodes in a P2P network.

- **Byzantine Fault Tolerance (BFT)**: An agreement protocol which helps to tolerate the Byzantine failures in a network. BFT maintains the reliable record of transactions in a transparent and tamper-proof way, as long as the number of traitors does not exceed one-third of the general network nodes.
- **Practical Byzantine Fault Tolerance (PBFT)**: This consensus mechanism is used when BFT fails to tolerate the faults in a network system. The algorithm for PBFT works in asynchronous systems and is optimized to achieve high performance along with an impressive overhead runtime.

Practical Byzantine Fault Tolerance (PBFT)

For adding a block in the blockchain, the following procedures in PBFT are required:

- A leader acting as a miner will select by the leader selection algorithm for adding a block.
- Leader receives a block with block adding request from any nodes (or client) into the blockchain.
- Leader sends this block to every node in the network for verifying the transactions.
- After successful verification of the transaction in the block, each received node sends a valid reply for adding that block.
- Leader counts the received reply and checks the number of counts (say, RCount) if it is greater that the twice number of the faulty nodes, i.e., $RCount > 2n_f + 1$ or the two-third nodes give the same reply. The $2n_f + 1$ non-faulty or valid replies provide the liveness of the system, that is, the message delay need to be bounded in due course. If this condition is satisfied, the leader will add the block into the blockchain and broadcasts a commit for adding the block into their respective blockchain for backup purposes.

Consensus mechanisms

- **Proof-of-Work (PoW):** This is the original consensus mechanism used to verify the transactions and produce new blocks in the blockchain. Mining is a complex process, and miners need to demonstrate that they can validate the transaction block. Here, the miners are financially rewarded if they perform verification. Thus, as the complexity increases in the mining process over time, the power consumption also increases. In other words, PoW is a costly process as the miners compete with each other to solve a mathematical problem.
- **Proof-of-Stake (PoS)**: In 2017, Ethereum began the process of switching from a PoW mechanism to a PoS system. The latter was designed to mitigate the limitations of PoW, in terms of energy, cost, and processing time. Specifically, it adopts a forging process rather than the mining process to validate transaction blocks.

Consensus mechanisms

- **Delegated Proof-of-Stake (DPoS):** This is a fast, efficient, flexible and most decentralized consensus mechanism. DPoS holds the power of stakeholder for the approval of voting and resolving the consensus issues in an honest and representative way. The deterministic selection of witnesses allows the transactions to be confirmed on an average of just 1 second. This consensus mechanism is designed to protect all the participants in a free, fair, and transparent environment.
- **Proof-of-Burn (PoB)**: An alternative consensus protocol for PoS and PoW. In PoB mechanism, the miners prove that they burn one cryptocurrency to create another currency, i.e., they are sent to a bitcoin address which is unsupendable. Its significance depends on the burning tokens in an unrecoverable manner. As comparative to PoW/PoS, it is easily verifiable and hard to undo.

Ripple Protocol Consensus Algorithm (RPCA)

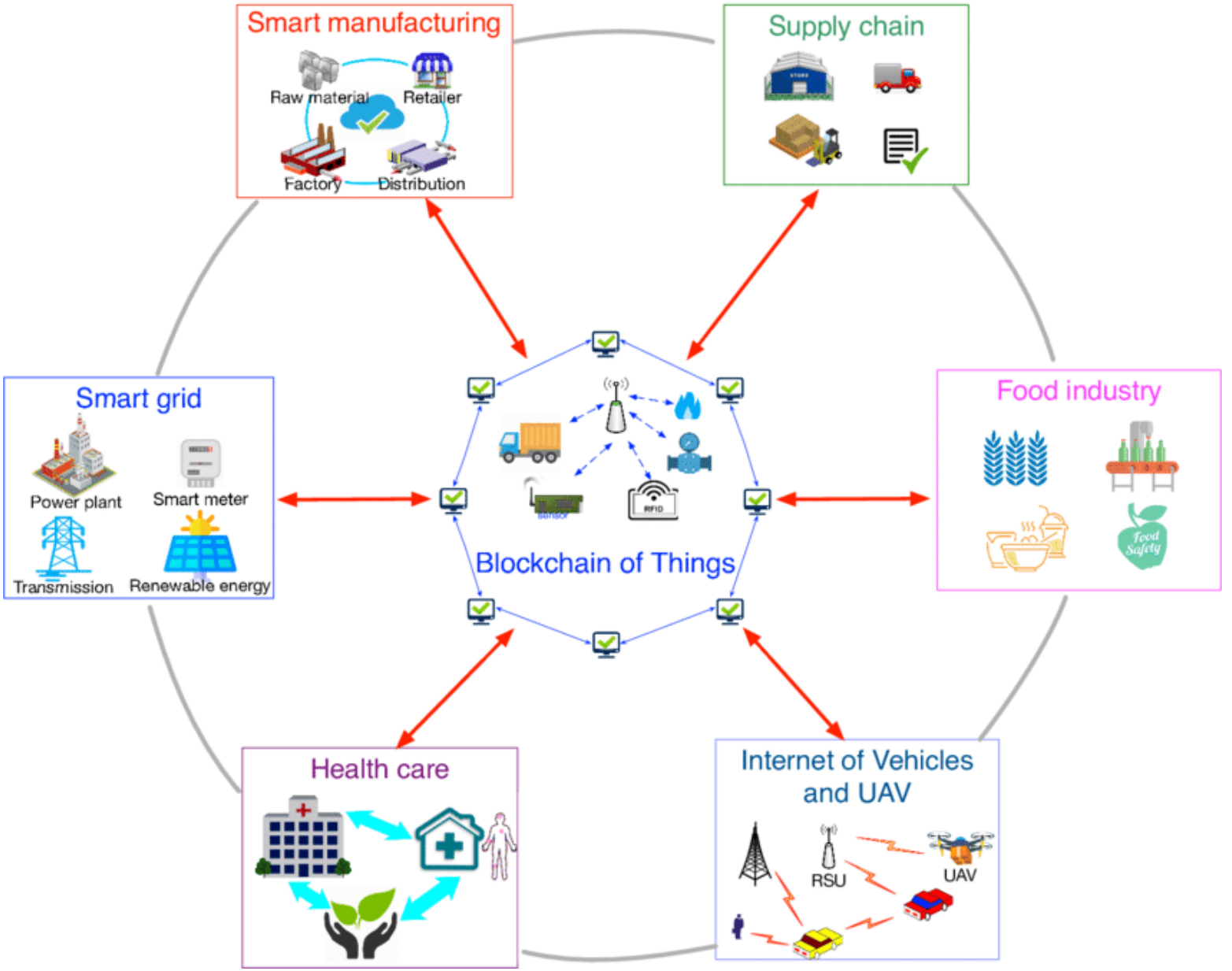
- It is a voting based consensus algorithm proposed in the literature in order to achieve high accuracy of a correct agreement for adding a block into a blockchain over unreliable distributed network.
- RPCA achieves an agreement in the voting process.
- Every participant node in the voting process maintains a unique node list (UNL), where each node in the list is considered as trusted one.
- The protocol executes with the help of the following steps:
  - In voting process, every participant node constantly receives the transaction. If the transaction is valid, the node integrates the transactions into a set or list, called a “candidate set”.
  - Every participant node dispatches its own candidate set to other participant node as a proposal.

Ripple Protocol Consensus Algorithm (RPCA) (Continued...)

- The remaining steps are as follows:
  - The participant node receives the proposal from other nodes. The node will then check whether the sender node belongs to its UNL list or not. If it is there, the node will verify the transactions with its own local candidate set. If all are valid, the transactions will gain a vote. Only when the transaction gets more than 50% of vote, the transaction will enter into the next round.
  - Next, the participant node sends the transaction that it gains more than 50% of the votes than the others and if it increases to 60% of vote, it needs to wait until it reaches to the threshold of 80% of the votes.
  - Finally, the participant node records the transaction confirmed by the 80% UNL nodes to be added into its ledger data.

The transaction is accepted only if 80% of the votes in the UNL of a participant node agrees with it. Thus, 80% of the UNL is honest, that is, the percentage of the faulty nodes in the UNL is less that for the 20% of the UNL. When the UNL contains d number of nodes in the network, and the RPCA will maintain its correctness as long as $n_f \leq \frac{d-1}{5}$, i.e., $d \geq 5n_f + 1$ where n_f is the Byzantine failure persisted nodes in the network.

Applications of Blockchain Technology



Important References: Blockchain Applications

- Basudeb Bera, Sourav Saha, Ashok Kumar Das, Neeraj Kumar, Pascal Lorenz, and Mamoun Alazab. "Blockchain-Envisioned Secure Data Delivery and Collection Scheme for 5G-Based IoT-Enabled Internet of Drones Environment," in ***IEEE Transactions on Vehicular Technology***, Vol. 69, No. 8, pp. 9097-9111, 2020, DOI: 10.1109/TVT.2020.3000576.
- Jangirala Srinivas, Ashok Kumar Das, and Athanasios V. Vasilakos. "Designing Secure Lightweight Blockchain-Enabled RFID-Based Authentication Protocol for Supply Chains in 5G Mobile Edge Computing Environment," in ***IEEE Transactions on Industrial Informatics***, Vol. 16, No. 11, pp. 7081-7093, 2020, DOI: 10.1109/TII.2019.2942389.
- Anusha Vangala, Ashok Kumar Das, Ankush Mitra, Sajal K. Das, and YoungHo Park. "Blockchain-Enabled Authenticated Key Agreement Scheme for Mobile Vehicles-Assisted Precision Agricultural IoT Networks," in ***IEEE Transactions on Information Forensics and Security***, Vol. 18, pp. 904-919, 2023, DOI: 10.1109/TIFS.2022.3231121. (2021 SCI Impact Factor: 7.231) [This article is one of the top 50 most frequently accessed documents for Popular Articles (February 2023)]
- Prakash Tekchandani, Indranil Pradhan, Ashok Kumar Das, Neeraj Kumar, and Youngho Park. "Blockchain-Enabled Secure Big Data Analytics for Internet of Things Smart Applications," in ***IEEE Internet of Things Journal***, Vol. 10, No. 7, pp. 6428-6443, April 2023, DOI: 10.1109/JIOT.2022.3227162. (2021 SCI Impact Factor: 10.238)
- Prithwi Bagchi, Raj Maheshwari, Basudeb Bera, Ashok Kumar Das, Youngho Park, Pascal Lorenz, and David K. Y. Yau. "Public Blockchain-Envisioned Security Scheme using Post Quantum Lattice-Based Aggregate Signature for Internet of Drones Applications," in ***IEEE Transactions on Vehicular Technology***, Vol. 72, No. 8, pp. 10393-10408, August 2023, DOI: 10.1109/TVT.2023.3260579. (2022 SCI Impact Factor: 6.8)

Case Study: Blockchain-Envisioned Secure Data Delivery and Collection Scheme for 5G-Based IoT-Enabled Internet of Drones Environment

Basudeb Bera, Sourav Saha, **Ashok Kumar Das**, Neeraj Kumar, Pascal Lorenz, and Mamoun Alazab. "Blockchain-Envisioned Secure Data Delivery and Collection Scheme for 5G-Based IoT-Enabled Internet of Drones Environment," in ***IEEE Transactions on Vehicular Technology***, Vol. 69, No. 8, pp. 9097-9111, 2020, DOI: 10.1109/TVT.2020.3000576. (2022 SCI Impact Factor: 6.8)

Full research paper can be downloaded at:
`https://ieeexplore.ieee.org/document/9110761`

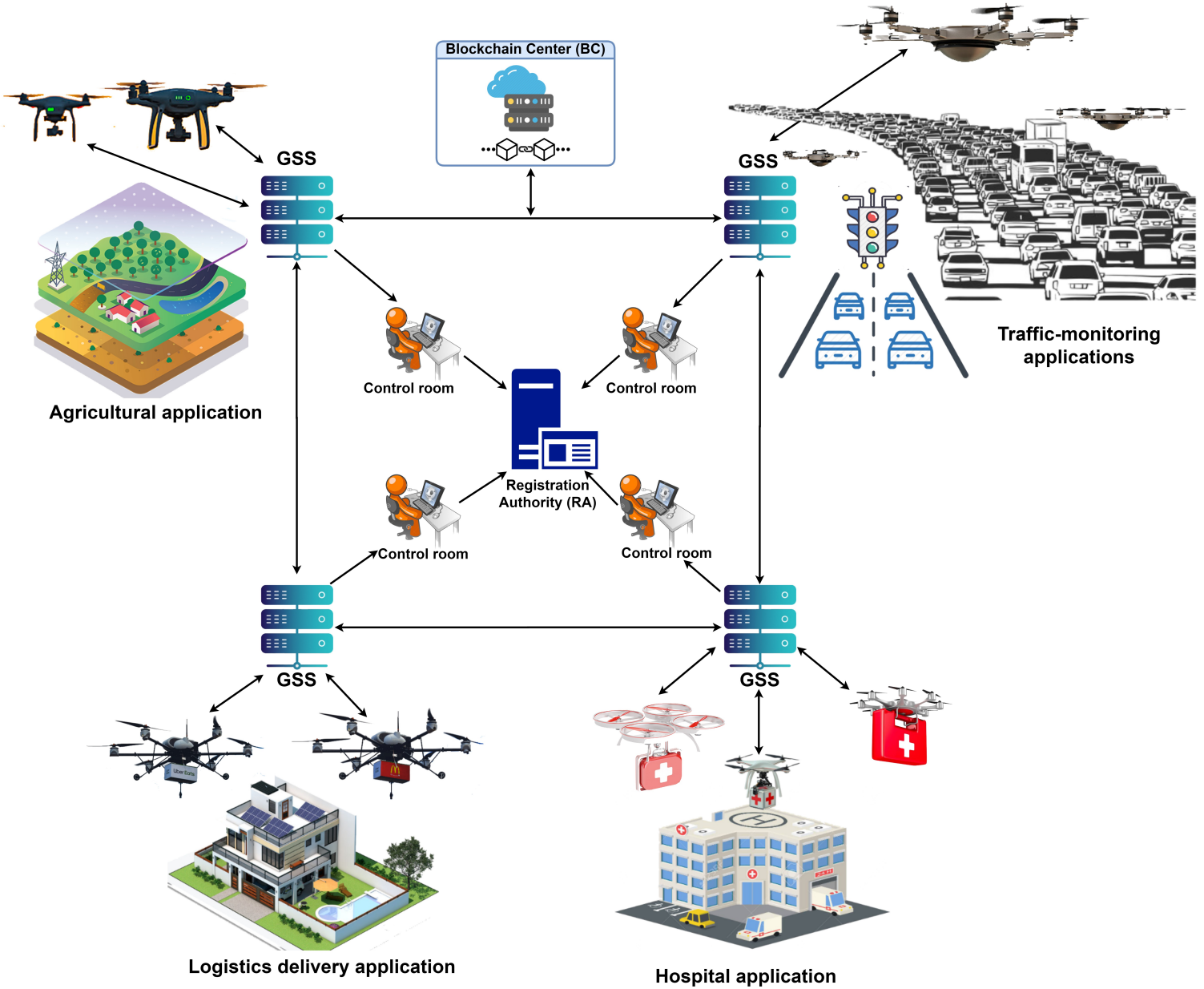
Internet of Drones

- The Internet of Drones (IoD) is a “layered network control architecture”.
- Primarily designed to co-relate access of Unmanned Aerial Vehicles (UAVs) (which are also called *drones*) for controlling airspace and providing support to various navigation activities [5].
- Due to increase of commercial drones applications, recent forecasts indicate that there will be a 100 USD billion market opportunity over the coming years based on the drones ([1]).
- Several applications of drones: ranging from military, newsgathering (for example, videography and photography), security, agricultural and logistics deployments, surveillance, medicine to traffic-monitoring applications ([4],[7]).

Secure Data Delivery and Collection: Need of the Hour

- In recent years, a drone delivery service has been established in London due to people demands, which can permit to exchange packages weighing up to 500g. In addition, Germany's express delivery company, Deutsche Post (DHL) also use the drones, called "parcelcopters" for the emergency delivery (for instance, high-priority goods like medicines to remote areas).
- A delivery system in the IoD environment was built upon the trust among the delivery service provider(s) and their customers ([6]). A service provider believes that their customers will not repudiate the delivery confirmation after successfully delivered the items in the proper destination. The customers need to also trust that the service provider will not deliver an item without presence of them or delivered an item in front of the door is stolen.
- In such kind of cases, it is very hard to maintain the responsibility. Due to such reasons, security plays a very important role in the IoD environment. This leads to design a secure data delivery and collection mechanism with the help of deployed drones.
- However, we need to maintain several security requirements, such as confidentiality, authentication, access control, non-repudiation, availability, freshness, etc. Apart from these requirements, we also face various security challenges in an IoD environment including "remote hijacking of drone", "privacy", "replay and man-in-the middle attacks", "impersonation attack", "privileged-insider attack", "physical drone capture attack", etc. as in other networks ([3, 2]).

Blockchain-envisioned 5G-enabled IoD environment

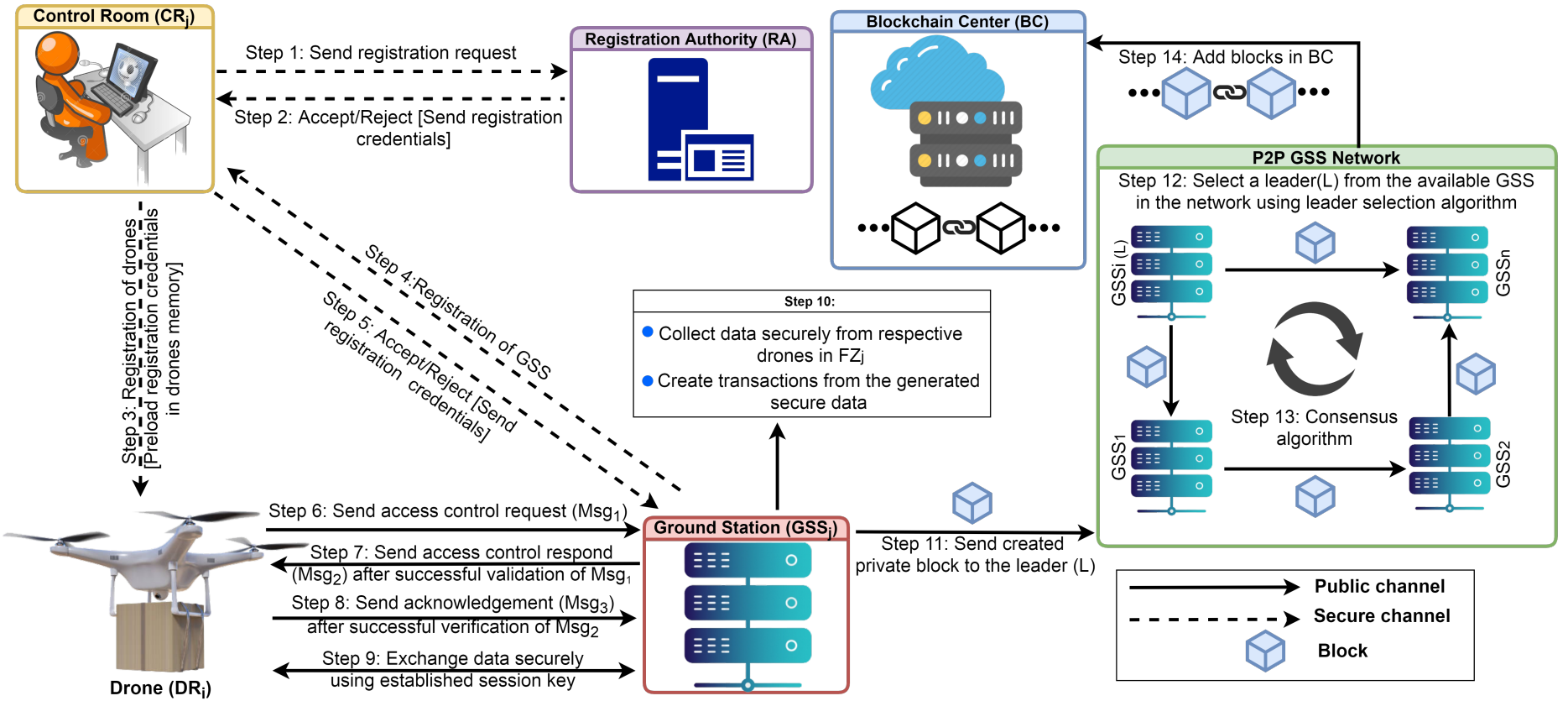


BSD2C-IoD: Blockchain-Based Secure Data Delivery and Collection Scheme

Different Phases:

- system initialization phase
- registration phase
- access control phase
- secure data delivery and collection phase
- block creation, verification and addition in blockchain center phase
- dynamic drones addition phase

Overall process in the proposed BSD2C-IoD



Registration phase for control room, ground station server and drones

(a) Registration of a controller room (CR_j) for an IoT application

Registration Authority (RA)	Control room (CR_j)
• Select $E_p(u, v)$ over $GF(p)$ with base point G, $h(\cdot)$ • Select random private key $r_{CR_j} \in Z_p^*$ and compute $Pub_{CR_j} = r_{CR_j} \cdot G$ for CR_j • Pick its own master (private) key $r_{RA} \in Z_p^*$ and compute public key $Pub_{RA} = r_{RA} \cdot G$ • Select identity ID_{RA}, and identity ID_{CR_j} for each CR_j • Create certificate for each CR_j as $Cert_{CR_j} = r_{CR_j} + h(ID_{CR_j} \|ID_{RA} \|Pub_{RA} \|Pub_{CR_j} \|RTS_{CR_j}) * r_{RA} \pmod p$ • Publish $\{Pub_{RA}, Pub_{CR_j}, E_p(u, v), h(\cdot), G\}$ as public	• Store in each CR_j: $\{ID_{CR_j}, ID_{RA}, Cert_{CR_j}, Pub_{RA}, Pub_{CR_j}, E_p(u, v), h(\cdot), G\}$ • Pick random master key $mk_{CR_j} \in Z_p^*$ and compute public key $Pk_{CR_j} = mk_{CR_j} \cdot G$ • Store $\{mk_{CR_j}, Pk_{CR_j}\}$ in its database and make Pk_{CR_j} as public

(b) Registration of Ground Station Server GSS_j

Control Room CR_j	Ground Station Server GSS_j
• Pick identity ID_{GSS_j} and compute its pseudo-identity $RID_{GSS_j} = h(ID_{GSS_j} \|RTS_{GSS_j} \|mk_{CR_j})$ • Pick random private key $r_{GSS_j} \in Z_p^*$ and compute public key $Pub_{GSS_j} = r_{GSS_j} \cdot G$ • Create certificate for GSS_j as $Cert_{GSS_j} = r_{GSS_j} + h(RID_{GSS_j} \|ID_{CR_j} \|Pub_{CR_j} \|Pub_{GSS_j}) * mk_{CR_j} \pmod p$ • Store RID_{GSS_j} and $Cert_{GSS_j}$ in GSS_j • Make Pub_{GSS_j} as public; and delete ID_{GSS_j} and r_{GSS_j} • Store $\{Pk_{GSS_j}\}$ for each GSS_j in its database	• Select another private key (decryption key) $k_{GSS_j} \in Z_p^*$ and compute public key (encryption key) $Pk_{GSS_j} = k_{GSS_j} \cdot G$ • Pre-load $\{RID_{GSS_j}, ID_{CR_j}, Cert_{GSS_j}, Pub_{CR_j}, Pub_{GSS_j}, (k_{GSS_j}, Pk_{GSS_j}), Pk_{CR_j}, E_p(u, v), h(\cdot), G\}$ in GSS_j

(c) Registration of drones DR_i in a flying zone FZ_j

Control Room CR_j	Drone DR_i
• Pick identity ID_{DR_i} and pseudo-identity $RID_{DR_i} = h(ID_{DR_i} \|ID_{CR_j} \|mk_{CR_j} \|RTS_{DR_i})$ for each drone DR_i • Select private certificate key $r_{DR_i} \in Z_p^*$ and compute public key $Pub_{DR_i} = r_{DR_i} \cdot G$ for each drone DR_i • Select private signature key $k_{DR_i} \in Z_p^*$ and compute public signature key $Pk_{DR_i} = k_{DR_i} \cdot G$ for each drone DR_i • Generate certificate for each DR_i as $Cert_{DR_i} = r_{DR_i} + h(RID_{DR_i} \|Pub_{CR_j} \|Pub_{GSS_j} \|Pub_{DR_i}) * mk_{CR_j} \pmod p$ • Delete ID_{DR_i} and r_{DR_i} from its database	• Store $\{RID_{DR_i}, Cert_{DR_i}, (k_{DR_i}, Pk_{DR_i}), Pk_{CR_j}, E_p(u, v), h(\cdot), G\}$ in DR_i prior to deployment in flying zone FZ_j

Access control phase

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Access control between a ground station server GSS_j and its drones (DR_i) in a flying zone FZ_j

Drone (DR_i)	Ground Station Server (GSS_j)
available information: $\{RID_{DR_i}, Cert_{DR_i}, (k_{DR_i}, Pk_{DR_i}), Pk_{CR_j}, E_p(u,v), h(\cdot), G\}$	available information: $\{RID_{GSS_j}, ID_{CR_j}, Cert_{GSS_j}, Pub_{CR_j}, Pub_{GSS_j}, (k_{GSS_j}, Pk_{GSS_j}), Pk_{CR_j}, E_p(u,v), h(\cdot), G\}$
• Select random secret $r_1 \in Z_p^*$ & generate current timestamp TS_1 • Compute $r_1' = h(RID_{DR_i} \|\| r_1 \|\| Cert_{DR_i} \|\| k_{DR_i} \|\| TS_1)$, $A_{DR_i} = r_1' \cdot G$ • Generate signature Sig_{DR_i}	
$Msg_1 = \{RID_{DR_i}, A_{DR_i}, Cert_{DR_i}, Sig_{DR_i}, TS_1\} \rightarrow$ (via public channel)	
	• Verify timestamp TS_1, and certificate by $Cert_{DR_i} \cdot G = Pub_{DR_i} + h(RID_{DR_i} \|\| Pub_{CR_j} \|\| Pub_{GSS_j} \|\| Pub_{DR_i}) \cdot Pk_{CR_j}$. • If timestamp and certificate are valid, verify signature by $Sig_{DR_i} \cdot G = A_{DR_i} + h(Pk_{DR_i} \|\| RID_{DR_i} \|\| Pk_{CR_j} \|\| Pub_{GSS_j} \|\| A_{DR_i} \|\| TS_1) \cdot Pk_{DR_i}$ • Generate random number $r_2 \in Z_p^*$ and current timestamp TS_2 • Calculate $r_2' = h(RID_{GSS_j} \|\| ID_{CR_j} \|\| r_2 \|\| Cert_{GSS_j} \|\| k_{GSS_j} \|\| TS_2)$, $B_{GSS_j} = r_2' \cdot G$, $DHK_{GSS_j,DR_i} = r_2' \cdot A_{DR_i} (= (r_2' * r_1') \cdot G)$, session key as $SK_{GSS_j,DR_i} = h(DHK_{GSS_j,DR_i} \|\| RID_{DR_i} \|\| RID_{GSS_j} \|\| Pk_{DR_i} \|\| Pub_{GSS_j})$, and session key verifier $SKV_{GSS_j,DR_i} = h(SK_{GSS_j,DR_i} \|\| RID_{DR_i} \|\| RID_{GSS_j} \|\| B_{GSS_j} \|\| Cert_{GSS_j} \|\| TS_1 \|\| TS_2)$
	$Msg_2 = \{RID_{GSS_j}, Cert_{GSS_j}, B_{GSS_j}, SKV_{GSS_j,DR_i}, TS_2\} \leftarrow$ (via public channel)
• Check validity of TS_2, and certificate as $Cert_{GSS_j} \cdot G = Pub_{GSS_j} + h(RID_{GSS_j} \|\| ID_{CR_j} \|\| Pub_{CR_j} \|\| Pub_{GSS_j}) \cdot Pk_{CR_j}$ • If timestamp and certificate are valid, compute $DHK_{DR_i,GSS_j} = r_1' \cdot B_{GSS_j} (= (r_1' * r_2') \cdot G = DHK_{GSS_j,DR_i})$ and session key as $SK_{DR_i,GSS_j} = h(DHK_{DR_i,GSS_j} \|\| RID_{DR_i} \|\| RID_{GSS_j} \|\| Pk_{DR_i} \|\| Pub_{GSS_j})$ and session key verifier, $SKV_{DR_i,GSS_j} = h(SK_{DR_i,GSS_j} \|\| RID_{DR_i} \|\| RID_{GSS_j} \|\| B_{GSS_j} \|\| Cert_{GSS_j} \|\| TS_1 \|\| TS_2)$ • Check if $SKV_{DR_i,GSS_j} = SKV_{GSS_j,DR_i}$. If so, generate current timestamp TS_3 and compute $ACK_{DR_i,GSS_j} = h(SK_{DR_i,GSS_j} \|\| TS_2 \|\| TS_3)$	
$Msg_3 = \{ACK_{DR_i,GSS_j}, TS_3\} \rightarrow$ (via public channel)	
	• Verify the received timestamp. If timestamp is valid, compute $ACK_{GSS_j,DR_i} = h(SK_{GSS_j,DR_i} \|\| TS_2 \|\| TS_3)$ • Verify if $ACK_{GSS_j,DR_i} = ACK_{DR_i,GSS_j}$. If valid, session key is established
Both DR_i and GSS_j establish the same session key $SK_{DR_i,GSS_j} (= SK_{GSS_j,DR_i})$	

Block Creation, Verification and Addition in Blockchain Center Phase

Details of various transactions Tx_i

Type of Transaction	Description
$Tx_{CR-GSS-req}$	It represents a transaction between a control room (CR_j) and its GSS_j. It is the data delivery request from CR_j to GSS_j.
$Tx_{GSS-DR-req}$	It means a transaction between GSS_j and its drones DR_i. It denotes the data delivery request from GSS_j to DR_i in a particular flying zone FZ_j.
$Tx_{DR-GSS-res}$	It denotes a transaction between DR_i and its GSS_j. It is the data delivery/collection response from DR_i to GSS_j.
$Tx_{DR-GSS-data}$	It means a transaction between GSS_j and its drones DR_i. It represents the collection message from GSS_j to DR_i in a particular flying zone FZ_j.

Structure of a block $Block_i$ based on transactions

Block Header	
Block Version	$BVer$
Previous Block Hash	PBH
Merkle Tree Root	MTR
Timestamp	TS
Creator of Block	CB_{ID} (Identity of one of the GSSs, say GSS_j in P2P GSS network)
Public key of Signer GSS_j	Pk_{GSS_j}
Block Payload (Encrypted Transactions)	
List of t_n Encrypted Transactions $\#i$ (Tx_i)	$\{E_{Pk_{GSS_j}}(Tx_i) \mid i = 1, 2, \cdots, t_n\}$
Current Block Hash	$CBHash$
Signature on $CBHash$	$BSign = ECDSA.Sig_{k_{GSS}}(CBHash)$, where $ECDSA.Sig(\cdot)$ and $ECDSA.Ver(\cdot)$ represent ECDSA signature generation and verification algorithms, respectively

Consensus for block verification and addition

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Algorithm 1 Consensus for block verification and addition in blockchain

Input: A block $Block_i$ as shown in Fig.7 and $n_{f_{GSS}}$: the number of faulty GSS nodes in the P2P GSS network
Output: Commitment and addition of block $Block_i$ into blockchain after its successful validation

1: Assume L, say GSS_l, is selected as the leader and it wants to add $Block_i$ into blockchain
2: L generates current timestamp TS_{GSS_j} for each follower ground station server node GSS_j and performs voting process
3: L encrypts voting request $VotReq$ as $E_{Pk_{GSS_j}}(VotReq, TS_{GSS_j})$ and sends a message containing the same block, and $E_{Pk_{GSS_j}}(VotReq, TS_{GSS_j})$ to each follower node GSS_j, $(j = 1, 2, \cdots, n_{GSS}, \forall j \neq l)$, where $E(\cdot)$ and $D(\cdot)$ are the encryption and decryption functions, respectively
4: Assume the message from L is received by each follower GSS_j in the P2P GSS network at time $TS^*_{GSS_j}$
5: **for** each follower node GSS_j **do**
6: Decrypt the message as $(VotReq', TS_{GSS_j}) = D_{k_{GSS_j}}\ [E_{Pk_{GSS_j}}(VotReq, TS_{GSS_j})]$
7: Verify timestamp, Merkle tree root, current block hash, and signature on received block $Block_i$
8: If all checks are verified successfully, send the voting reply $VotRep$ and block verification status $BVStatus$ as $\{E_{Pk_L}(VotReq', VotRep, BVStatus)\}$ to L
9: **end for**
10: If $VCnt$ denotes the vote counter, initialize $VCnt \leftarrow 0$
11: **for** each received response message $\{E_{Pk_L}(VotReq', VotRep, BVStatus)\}$ from the responded follower GSS_j **do**
12: Compute $(VotReq', VotRep, BVStatus) = D_{k_L}[E_{Pk_L}\ (VotReq', VotRep, BVStatus)]$
13: **if** $((VotReq' = VotReq)$ and $((VotRep = valid)$ and $(BVStatus = valid)))$ **then**
14: Set $VCnt = VCnt + 1$
15: **end if**
16: **end for**
17: **if** $(VCnt > 2.n_{f_{GSS}} + 1)$ **then**
18: Send the commit response to all follower nodes
19: Add block $Block_i$ to the blockchain
20: **end if**

Security Analysis

Elliptic curve-based computationally hard problems

We discuss three well-known computationally hard problems under elliptic curve cryography (ECC) as follows.

Definition (Elliptic Curve Discrete Logarithm Problem (ECDLP))

Let $E_q(m, n)$ be an elliptic curve over a finite field $GF(q)$ of the form: $y^2 = x^3 + mx + n \pmod{q}$ and $P \in E_q(m, n)$ be a point in it, where q is a large prime and $m, n \in Z_q^*$ such that $4m^3 + 27n^2 \neq 0 \pmod{q}$. The ECDLP states that given two points P and $Q \in E_q(m, n)$, where $Q = c \cdot P$, to find the discrete logarithm c.

Note that the security of the ECC solely depends on the intractability of ECDLP. Although, there exist various algorithms to solve ECDLP, namely Pollard's rho method and baby-step giant-step strategy, but these algorithms take exponential or sub-exponential execution time. Till date no algorithm exists in the literature to solve this problem in polynomial time. ECDLP is then NP-hard problem.

Elliptic curve-based computationally hard problems

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Definition (Elliptic curve computational Diffie-Hellman problem (ECCDHP))

Let R be a point in $E_q(m, n)$ and given two points $i \cdot R \in E_q(m, n)$ and $j \cdot R \in E_q(m, n)$. Then, to compute $(i * j) \cdot R$, it is computationally intractable, where $i, j \in Z_q^*$ and $Z_q^* = \{1, 2, \cdots, q-1\}$.

Definition (Elliptic curve decisional Diffie-Hellman problem (ECDDHP))

Let R be a point in $E_q(m, n)$ and given a quadruple $(R, i \cdot R, j \cdot R, k \cdot R)$, decide whether $k = i * j$ or a uniform value, where $i, j, k \in Z_q^*$.

Elliptic curve-based computationally hard problems

It is known that ECDLP, ECCDHP and ECDDHP are computationally intractable when q is large. More precisely, the value of q should be selected at least 160-bit prime to ensure that ECDLP, ECCDHP and ECDDHP are computationally infeasible.

Lemma

ECDLP $\leq_p$ *ECCDHP* $\leq_p$ *ECDDHP.*

Proof.

* Let R be a point in $E_q(m, n)$ and given two points $i \cdot R \in E_q(m, n)$ and $j \cdot R \in E_q(m, n)$. Given $i \cdot R$ and $j \cdot R$, using the ECDLP, one can determine $i, j \in Z_q^*$, if ECDLP can be solved in polynomial time. Hence, we can compute $(i * j) \cdot R$. Thus, ECDLP $\leq_p$ ECCDHP.
* Let R be a point in $E_q(m, n)$ and given a quadruple (R, $i \cdot R$, $j \cdot R$, $k \cdot R$). If the ECCDHP can be solved in polynomial-time, we can determine $(i * j) \cdot R$ from $i \cdot R$ and $j \cdot R$. Then, we can check if $(i * j) \cdot R = k \cdot R$. If it is so, $k = i * j$. Thus, ECCDHP $\leq_p$ ECDDHP. □

Formal Security Analysis under Random Oracle Model

Theorem

Let an adversary $\mathcal{A}$ running in polynomial time t_{poly} attempt to compute the session key SK_{DR_i,GSS_j} $(= SK_{GSS_j,DR_i})$ shared between a drone DR_i and an GSS_j for a particular session in the proposed protocol, BSD2C-IoD. If q_h, $|Hash|$, and $Adv_{\mathcal{A}}^{ECDDHP}(t_{poly})$ denote the number of "Hash queries", the range space of "a one-way collision-resistant hash function $h(\cdot)$", and the advantage of breaking the "Elliptic Curve Decisional Diffie-Hellman Problem (ECDDHP)" respectively, then

$$Adv_{\mathcal{A}}^{BSD2C-IoD}(t_{poly}) \leq \frac{q_h^2}{|Hash|} + 2Adv_{\mathcal{A}}^{ECDDHP}(t_{poly}).$$

Security Analysis

- Replay Attack
- Man-in-the-Middle (MiTM) Attack
- Drone/GSS Impersonation Attacks
- Privileged-Insider Attack
- Physical Drone Capture Attack
- Ephemeral Secret Leakage (ESL) Attack

Formal Security Security Verification using Automated Validation of Internet Security Protocols and Applications (AVISPA) tool

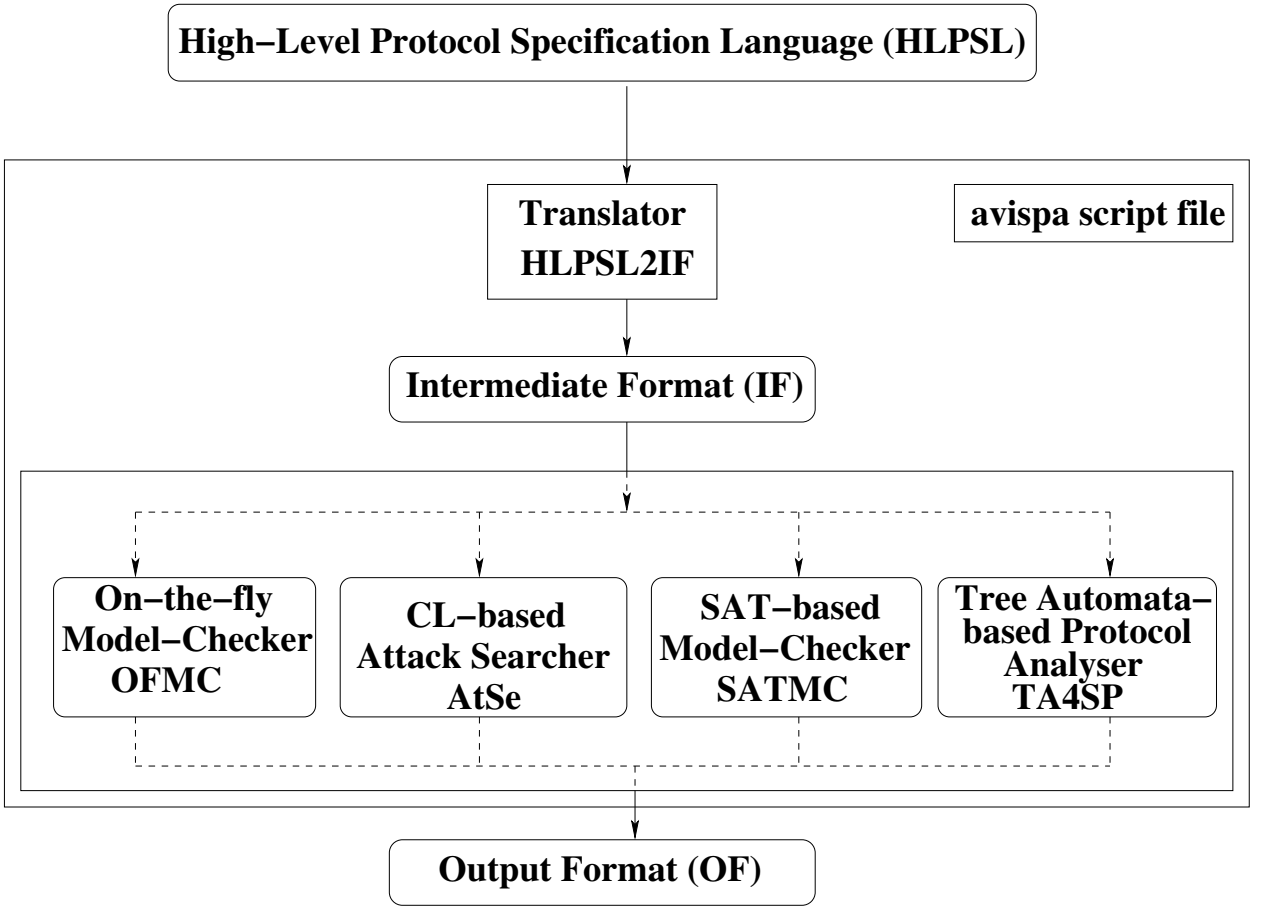

Figure: Architecture of AVISPA (`http://www.avispa-project.org/`)

Simulation results of BSD2C-IoD under OFMC and CL-AtSe backends

```
SUMMARY
  SAFE

DETAILS
  BOUNDED_NUMBER_OF_SESSIONS

PROTOCOL
  /home/akdas/Desktop/span/
  testsuite/results/IoD-acc.if

GOAL
   as specified

BACKEND
  OFMC

STATISTICS

  TIME 395 ms
  parseTime 0 ms
  visitedNodes: 86 nodes
  depth: 6 plies
```

```
SUMMARY
  SAFE

DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
  TYPED_MODEL

PROTOCOL
  /home/akdas/Desktop/span/
  testsuite/results/IoD-acc.if

GOAL
  As specified

BACKEND
  CL-AtSe

STATISTICS
  Analysed   : 1 state
  Reachable  : 0 state
  Translation: 0.17 seconds
  Computation: 0.00 seconds
```

Testbed Experiments using MIRACL under a server

- Multiprecision Integer and Rational Arithmetic Cryptographic Library (MIRACL)
- **Platform #1.** The first platform considered for MIRACL here for a server with the setting as follows: Ubuntu 18.04.4 LTS, with memory: 7.7 GiB, processor: Intel Core i7-8565U CPU @ 1.80GHz $\times$ 8, OS type: 64-bit and disk: 966.1 GB. The experiments on each cryptographic primitive are performed for 100 runs. After that we calculate the maximum, minimum and average time (in milliseconds) for each cryptographic primitive from these 100 runs.

EXECUTION TIME (IN MILLISECONDS) ON A SERVER FOR CRYPTOGRAPHIC PRIMITIVES USING MIRACL

Primitive	Max. time (ms)	Min. time (ms)	Average time (ms)
T_h	0.149	0.024	0.055
T_e	0.248	0.046	0.072
T_{ecm}	2.998	0.284	0.674
T_{eca}	0.002	0.001	0.002
T_{bp}	7.951	4.495	4.716

Experimental setup using Raspberry PI 3

Testbed Experiments using MIRACL under Raspberry PI 3

- **Platform #2.** The second platform that we have considered for MIRACL is as follows: Raspberry PI 3 B+ Rev 1.3, with CPU: 64-bit, Processor: 1.4 GHz Quad-core, 4 cores, Memory (RAM): 1GB, and OS: Ubuntu 20.04 LTS, 64-bit. The experiments on each cryptographic primitive are also executed for 100 runs. We then calculate the maximum, minimum and average run-time (in milliseconds) for each cryptographic primitive from these 100 runs.

EXECUTION TIME (IN MILLISECONDS) ON A RASPBERRY PI 3 FOR CRYPTOGRAPHIC PRIMITIVES USING MIRACL

Primitive	Max. time (ms)	Min. time (ms)	Average time (ms)
T_h	0.643	0.274	0.309
T_e	0.493	0.178	0.228
T_{ecm}	4.532	2.206	2.288
T_{eca}	0.021	0.015	0.016
T_{bp}	32.79	27.606	32.084

Comparative study on communication costs

- Assume that "identity", "random number", "elliptic curve point" $P = (P_x, P_y) \in E_p(u, v)$ where x and y coordinates of P are P_x and P_y respectively, hash output (here SHA-256 hashing algorithm), and timestamp are 160, 160, (160 + 160) = 320, 256 and 32 bits, respectively.
- It is assumed that 160-bit ECC provides the same security level as that for 1024-bit RSA cryptosystem.

Scheme	No. of messages	Total cost (in bits)	Gain
Luo et al. [38]	2	3040	36%
Li et al. [39]	2	3488	56%
Tian et al. [40]	2	$384s$ + 11712	509%
BSD2C-IoD	3	2240	–

Note: s: "no. of pseudonyms of an UAV (drone) in Tian et al.'s scheme" [40] $(s = 5)$

Comparative study on computational costs

- T_h: time required to execute a "one-way cryptographic hash function"
- T_{ecm}: time required to execute an "elliptic curve point multiplication"
- T_{eca}: time required to execute an "elliptic curve point addition"
- T_{bp}: time required to execute a "bilinear pairing"
- T_e: time required to execute a "modular exponentiation"

Scheme	Smart device/drone cost	Gain for a smart device/drone	GSS/server cost	Gain for GSS/server
Luo *et al.* [38]	$T_{bp} + T_h$ ≈ 32.393 ms	194%	$3T_{ecm} + 3T_{bp} + 3T_h + T_{eca} + T_e$ ≈ 16.409 ms	275%
Li *et al.* [39]	$T_{bp} + T_h$ ≈ 32.393 ms	194%	$3T_{ecm} + 4T_{bp} + T_h + 2T_{eca}$ ≈ 20.945 ms	378%
Tian et al. [40]	$8T_e + 9T_h$ ≈ 4.605 ms	–	–	–
BSD2C-IoD	$6T_h + 4T_{ecm} + T_{eca}$ ≈ 11.022 ms	–	$6T_h + 6T_{ecm} + 2T_{eca}$ ≈ 4.378 ms	–

Comparative study on functionality & security attributes

Attribute (A)	Luo *et al.* [38]	Li *et al.* [39]	Tian et al. [40]	BACS-IoD
FSA_1	✓	✓	✓	✓
FSA_2	✓	✓	✓	✓
FSA_3	×	×	×	✓
FSA_4	✓	✓	✓	✓
FSA_5	✓	✓	✓	✓
FSA_6	✓	✓	N/A	✓
FSA_7	✓	✓	✓	✓
FSA_8	×	×	✓	✓
FSA_9	✓	✓	×	✓
FSA_{10}	×	×	×	✓
FSA_{11}	×	×	✓	✓
FSA_{12}	×	×	×	✓

FSA_1: "replay attack"; FSA_2: "man-in-the-middle attack"; FSA_3: "mutual authentication"; FSA_4: "key agreement"; FSA_5: "device/drone impersonation attack"; FSA_6: "GSS/server impersonation attack"; FSA_7: "malicious device deployment attack"; FSA_8: "resilience against drone/device physical capture attack"; FSA_9: "formal security verification using AVISPA tool"; FSA_{10}: "ESL attack under the CK-adversary model"; FSA_{11}: "support dynamic drone/device addition phase"; FSA_{12}: "support blockchain-based solution"

✓: "a scheme is secure or it supports an attribute"; ×: "a scheme is insecure or it does not support an attribute"; N/A: means "not applicable" in a scheme.

Blockchain Implementation

- **Scenario 1:** We assume that the total number of peer-to-peer (P2P) nodes in the CS network is 5. It is worth noticing that the computational time (in seconds) differs for the varied number of blocks mined into a blockchain, where each block contains a fixed number of transactions as 60.

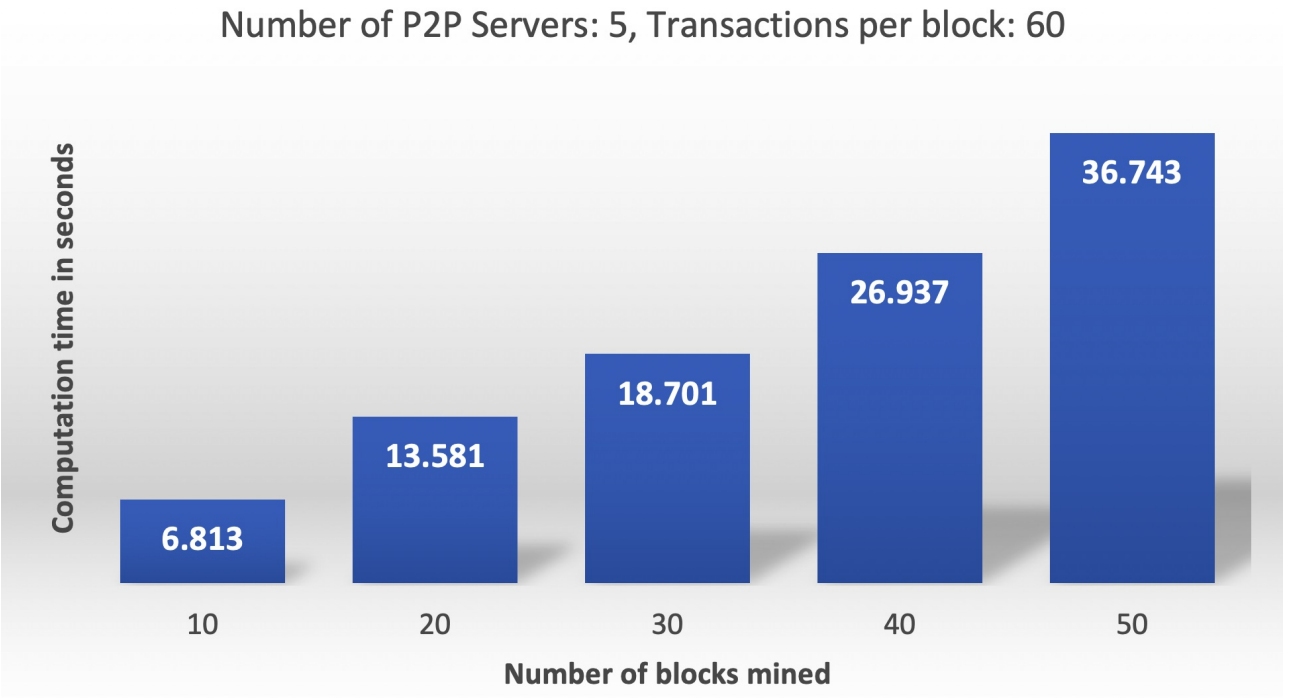

Figure: Blockchain simulation results for Scenario 1

Blockchain Implementation

- **Scenario 2:** In this situation, the total number of peer-to-peer (P2P) nodes in CS network is also considered as 5. We have considered a fixed number of mined blocks as 30. The simulation results show the computational time (in seconds) also differs based on the number of varied transactions pushed per block.

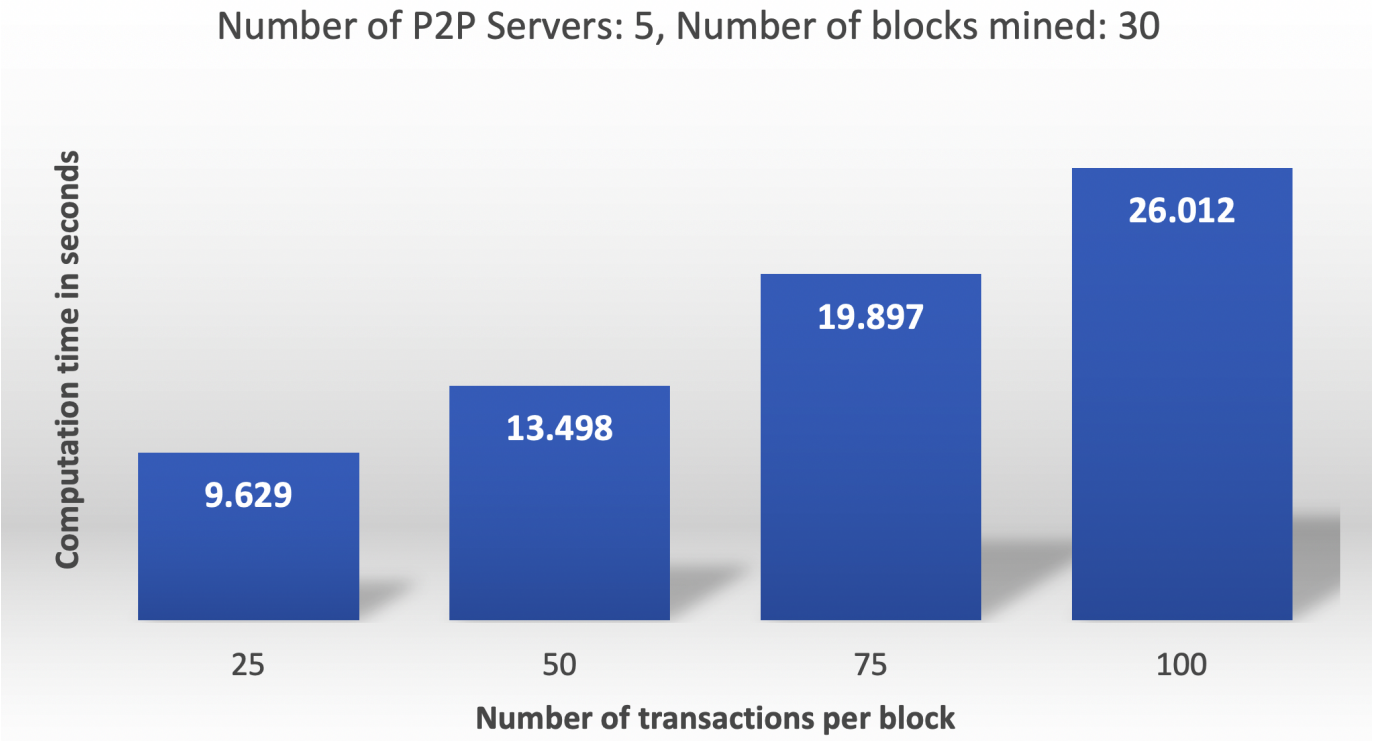

Figure: Blockchain simulation results for Scenario 2

Testbed Experiments

- Under this testbed experiment, we executed the access control scheme.
- The access control mechanism has been implemented in a client-server model paradigm with the socket programming environment in python3 language.
- Each drone *DR* is considered as a client and the ground station server (*GSS*) is assumed to be a server.
- The configuration of each *GSS* is considered as a Laptop configuration under the environment: “Ubuntu 20.04 LTS , 64-bit OS with Intel Core i5-4210U CPU @ 1.70GHz, 4 GB RAM, 130 GB memory partition”.
- Raspberry Pi 3 configuration is “Ubuntu 18.04, Quad-Core 1.2GHz Broadcom BCM2837 64bit CPU, 1GB RAM, 16 GB memory”.

Continuing...

Continuing...

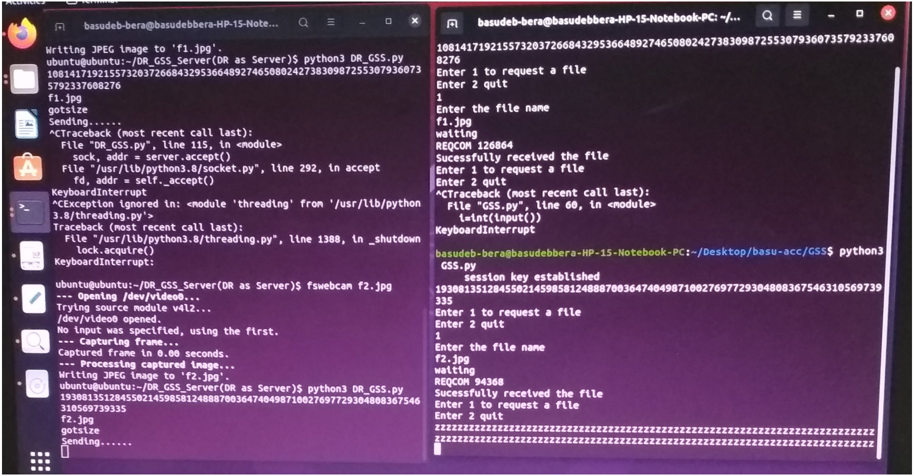

Figure: Testbed experimental results

Continuing...

- It is noticing that the established session key from both sides (*DR* and *GSS*) is the same.
- Once the session key is established between them, *DR* takes a real image (stored in a file, say “f2.jpg”).
- Then sends the image file to the *GSS* by encrypting the image with the same session key.
- The encryption is used here, a symmetric encryption (in this case, we considered the “Advanced Encryption Standard (AES-256)”).

Conclusion and Future Works

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Blockchain:

- Blockclain technology and its various applications

Case Study:

- Discussed a novel blockchain-envisioned secure data delivery and collection scheme for 5G-enabled IoD environment (BSD2C-IoD).
- BSD2C-IoD not only provides access control mechanism among the drones and the *GSS* in the flying zones, it also provides secure transactions among the drones, the *GSS*s and the *CR*s in the IoD environment, which are then used to form various blocks by the respective *GSS*.
- Applied ECC-based signature and the security depends on solving ECDLP (in turn ECDDHP, which is NP-hard) and collision-resistant one-way hash function.
- Achieves better security, and requires low communication and computational overheads.

References

Drones reporting for work.
Goldman Sachs Research, Accessed on January 2020.

Debiao He, Neeraj Kumar, and Jong-Hyouk Lee.
Privacy-preserving data aggregation scheme against internal attackers in smart grids.
Wireless Networks, 22(2):491–502, 2016.

Neeraj Kumar, Rahat Iqbal, Sudip Misra, and Joel J.P.C. Rodrigues.
An intelligent approach for building a secure decentralized public key infrastructure in vanet.

Journal of Computer and System Sciences, 81(6):1042–1058, 2015.

Thomas Lagkas, Vasileios Argyriou, Stamatia Bibi, and Panagiotis Sarigiannidis.
UAV IoT Framework Views and Challenges: Towards Protecting Drones as "Things".
Sensors, 18(11), 2018.

B. Li, Z. Fei, and Y. Zhang.
UAV Communications for 5G and Beyond: Recent Advances and Future Trends.
IEEE Internet of Things Journal, 6(2):2241–2263, 2019.

Seung-Hyun Seo, Jongho Won, Elisa Bertino, You Sung Kang, and Dooho Choi.
A security framework for a drone delivery service.
In *2nd Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use (DroNet'16)*, pages 29–34, Singapore, 2016.

Attila Takacs, Xingqin Lin, Stephen Hayes, and Erika Tejedor.
Drones and networks: Ensuring safe and secure operations, 2018.
Ericsson white paper, GFMC-18:000526, Accessed on January 2020.

Thank You
For Your Attention