# Project: Incorporating Blockchain/P2P Technology into an SDN-Enabled Cybersecurity System to Safeguard Fossil Fuel Power Generation Systems

Project Number: DE-FE0031742


**University of North Dakota**
**College of Engineering and Mines**


Annual Technical Review (Spring 2022)
May 20th, 2022

# Project Description and Objectives

## Overview

- **This project aims to strengthen the security protection of software defined networking (SDN) for facilitating its deployment in fossil fuel power generating systems.**
  - The security protection solution makes use of the blockchain and the peer-to-peer (P2P) technologies.
  - This project is in response to Area of Interest 2 of DE-FOA-0001991.
  - AOI 2: "*investigate how cutting-edge network technologies such as blockchain may be leveraged and integrated into industrial monitoring and process control systems for optimized, cybersecure operation of electricity generating units.*"
- **This project aims to produce two deliverables:**
  - A cloud-based networking platform for prototyping and experimenting various designs of safeguarding the software-defined networks deployed in electric power systems.
  - A blockchain/P2P-based technology for detecting the compromised controllers in a software defined network.
    - The application will operate in the cloud-based networking platform.
- **The outcomes of this project will serve in**
  - Meeting the general security requirements of the electric power generating systems.
  - Mitigating the security risks targeting the vulnerabilities of SDN-enabled operational networks.

UNIVERSITY OF NORTH DAKOTA

# Project Description and Objectives

## Strategic Alignment of Project to Fossil Energy Objectives (1)

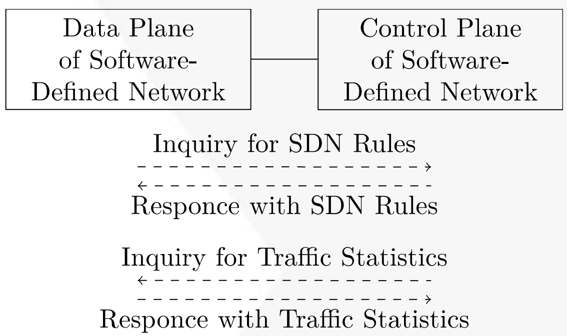
- **Serving for Meeting the General Security Requirements of Electric Power Systems**
  - Safe operations of power systems rely on the fundamental security mechanisms
    - Authentication, Authorization, and Anti-spoofing.
- **Serving for Facilitating the Deployment of SDN-Enabled Operational Networks**
  - Software Defined Network (SDN) technologies will be increasingly adopted to support data communications in electric power systems.
  - The Department of Energy had sponsored research projects on
    - Applying SDN technology to support the device-to-device communications;
    - Prototyping a dashboard application for providing the operators with a global view of the SDN-enabled operational networks.
- **Serving for Addressing the Threats Targeting the SDN-Enabled Operational Networks**
  - SDN paradigm faces new security threats and attacks.
  - <u>Our project addresses the security risks targeting SDN technology and the protection solutions.</u>

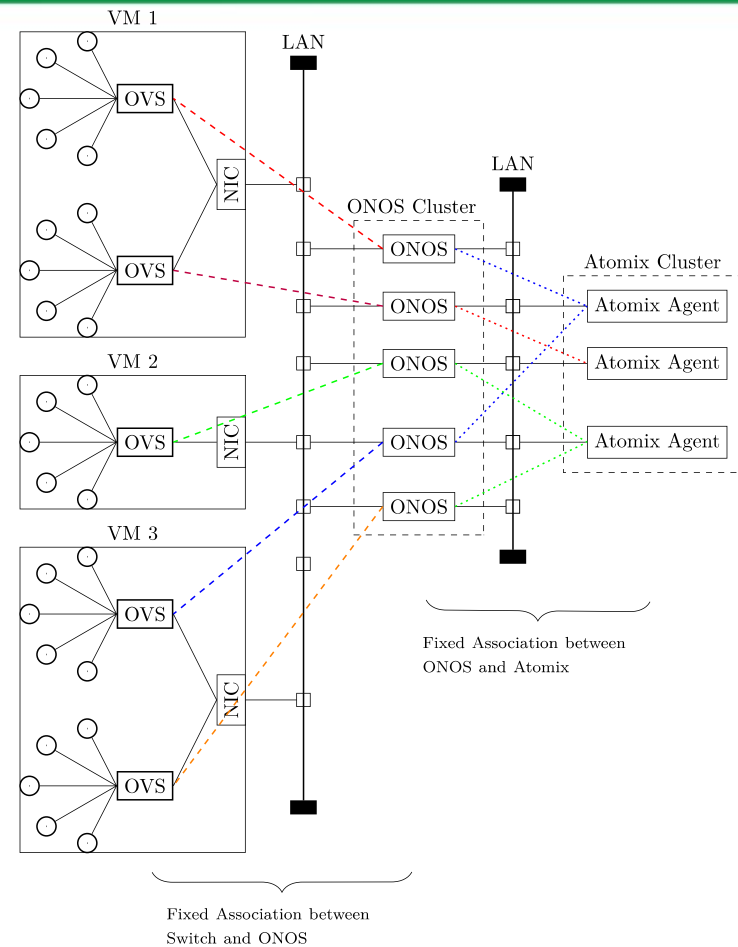
UND UNIVERSITY OF NORTH DAKOTA

# Project Description and Objectives

## Strategic Alignment of Project to Fossil Energy Objectives (2)

System Diagrams of traditional Software-Defined Network




- Key vulnerabilities
  - Lack of detection on security breaching.
  - Lack of effective mechanism for excluding compromised SDN controllers from a SDN.

# Project Description and Objectives

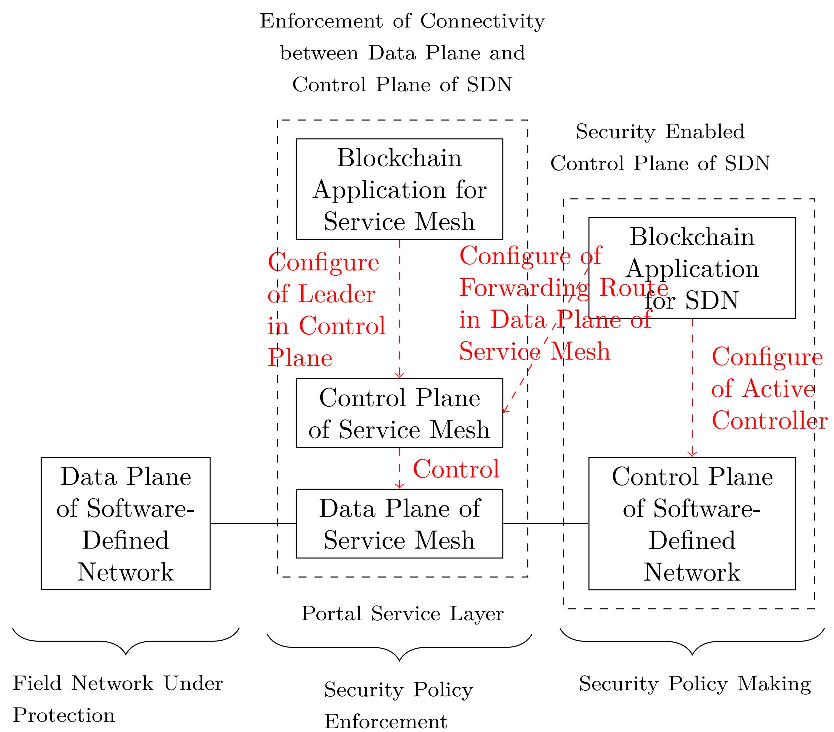
## Technology Benchmarking (1)

- This project aims to construct
  - A cloud-based networking platform which can be used for
    - Studying the threats targeting SDN-enabled operational networks deployed in electric power systems, and
    - Prototyping security protection solutions thwarting the attacks targeting the control plane, the forwarding plane, and the communications between the control plane and the forwarding plane.
  - A blockchain/P2P-based technology for detecting the compromised controllers in software defined networks.
- Industry/input or validation
  - This project is in collaboration with *Minnkota Power Cooperative.*
  - *Minnkota Power Cooperative* helps to facilitate decision-makings on the scientific and technical direction of the project and will be a user of the cloud-based networking platform.
  - This project has also attracted attentions by a cybersecurity marketing firm and a network equipment supplier serving for data communications used in power generation and transmission.

# Project Description and Objectives

## Technology Benchmarking (2)

- This project aims to enable security protection for SDN.
  - ❑ Enabling detection of compromised SDN controllers by constructing blockchain applications.
  - ❑ Enabling exclusion of compromised SDN controllers by decoupling the direct and fixed connectivity between the data plane and control plane in SDN.
    - ❖ A portal service layer is used to decouple the two planes.



# Project Description and Objectives

## Overview of Major Efforts (1)

- We have conducted 8 efforts in this project.
  - Efforts made before 2021 Review Meeting
    - **Effort #1**: Determined the overall structure of the security-enabled SDN system.
    - **Effort #2**: Constructed a private cloud platform over 3 Dell servers.
      - The testbed supports simultaneous run of multiple SDN simulations.
    - **Effort #3**: Constructed the SDN with a controller cluster.
      - Mininet is used for simulating the data plane of the SDN.
      - A cluster of ONOS controllers is used for the control plane of the SDN.
    - **Effort #4**: Constructed the portal service layer to bridge the data plane and the control plane of an SDN.
      - The portal service layer is materialized in the form of a service mesh which consists of
        - A data plane: a set of *Envoy* proxies.
        - A control plane: a set of *Consul* agents.

# Project Description and Objectives

## Overview of Major Efforts (2)

- We have conducted 8 efforts in this project.
  - Efforts made since 2021 Review Meeting
    - **Effort #5**: Added the Discovery Service (xDS) in the portal service layer to dynamically forward SDN traffic.
    - **Effort #6**: Constructed the base blockchain system running on top of a peer-to-peer (P2P) data storage
      - Adopted the InterPlanetary File System (IPFS) as the P2P data storage.
      - Adopted Hyperledger Fabric (HLF) software (version 2.4) as the base blockchain system.
      - Added Orbit-DB as the key-value store of (key=readable event name, value=block ID).

# Project Description and Objectives

## Overview of Major Efforts (3)

- We have conducted 8 efforts in this project.
  - Efforts made since 2021 Review Meeting
    - **Effort #7**: Programmed an Application Programing Interface (API) server to facilitate the application of malicious attack detection to access the HLF blockchain sub-system.
      - The API server serves the requests sent from the application through performing a sequence of operations on the HLF and IPFS sub-systems.
      - The API server provides the responses with respect to the application's requests.
    - **Effort #8**: Performed the literature study on BFT consensus and the theoretical preparation on constructing an information-theoretic framework of an efficient BFT consensus.

# Project Description and Objectives

## Current Status of Project

- This project started on September 1st, 2019 for a 3 years duration.
- This project , and there is no available comparison with known benchmark.
- There is no major change in the project goals/objectives.
- We have made some changes in the actual implementation of the tasks.
  - We have decided to construct the originally proposed testbed in the form of a cloud-based networking platform.
  - We have decided to adopt the proof-of-reputation consensus model for detecting the compromised network controllers in SDN networks.
  - We have simplified the structure of the system of detecting the compromised network controllers.

UND UNIVERSITY OF NORTH DAKOTA

# Project Description and Objectives

## Current Status of Project

- This project started on September 1st, 2019 for a 3 years duration.
- Timeline of major tasks and milestones

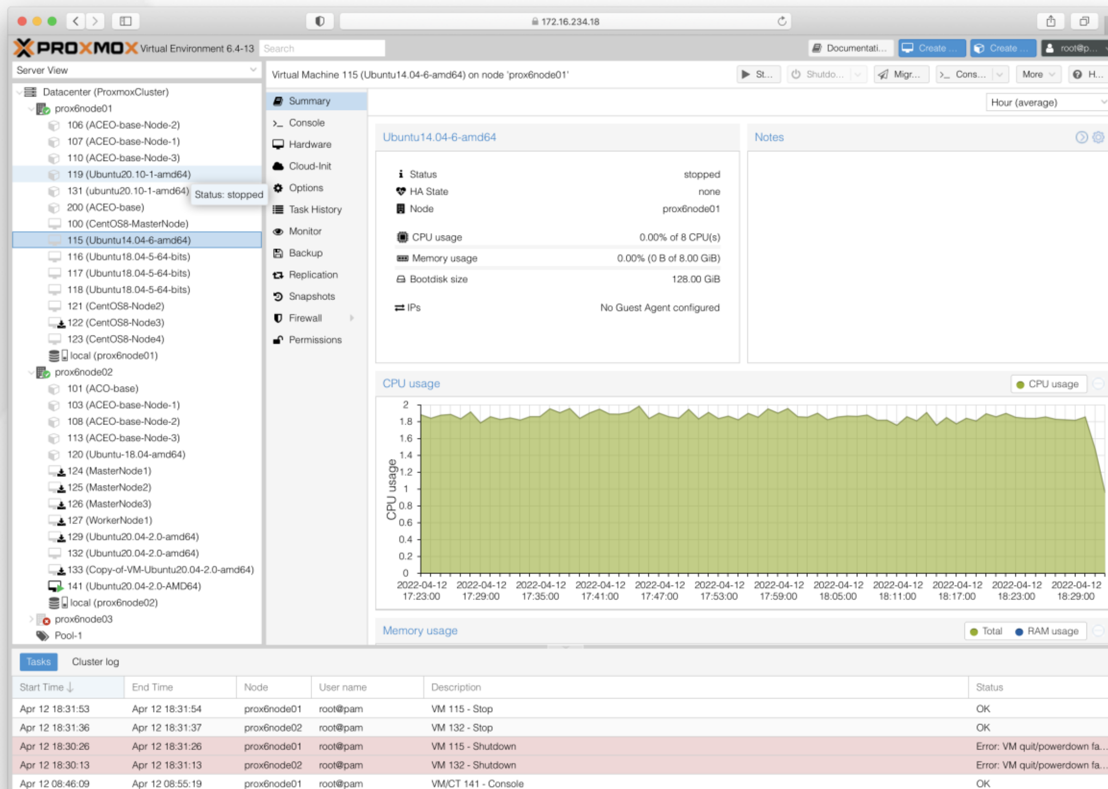
| Task Description | Planned | | Achieved | |
|---|---|---|---|---|
| | Start Date | End Date | Start Date | End Date |
| Task 1.0 -- Update project management plan | 9/1/19 | 9/30/19 | 9/1/19 | 9/30/19 |
| Task 2.0 -- Demonstration of Sample Runs of an SDN System | 10/1/19 | 4/30/20 | 10/1/19 | 5/30/20 |
| Subtask 2.1 -- Demonstration of Installation of Software on Controllers and Switches | 10/1/19 | 11/30/19 | 10/1/19 | 12/31/19 |
| Subtask 2.2 -- Demonstration of Traffic Flows Between SDN Switches | 12/1/19 | 1/30/20 | 12/1/19 | 2/28/20 |
| Subtask 2.3 -- Demonstration of Query for Rules | 2/1/20 | 2/28/20 | 2/1/20 | 3/31/20 |
| Subtask 2.4 -- Demonstration of Traffic Flow Handling Based on Rule Specifications | 3/1/20 | 4/30/20 | 3/1/20 | 5/30/20 |
| Task 3.0 -- Demonstration of a P2P Inquiry Platform in the SDN System | 5/1/20 | 4/30/21 | 5/1/20 | 4/20/21 |
| Subtask 3.1 -- A Justification Report of the Choice of a P2P Open-Source Package | 5/1/20 | 5/30/20 | 5/1/20 | 6/15/20 |
| Subtask 3.2 -- Demonstration of Querying Rules from the P2P System | 6/1/20 | 11/30/20 | 6/1/20 | 3/15/21 |
| Subtask 3.3 -- Making SDN Forwarding Switches to Query Rules from the Inquiry Platform | 12/1/20 | 4/30/21 | 12/1/20 | 4/20/21 |
| Task 4.0 -- Demonstration of Use Case of Identifying a Compromised Controller | 5/1/21 | 8/31/22 | 2/1/21 | |
| Subtask 4.1 -- Demonstration of a Blockchain System Running on Top of a P2P System | 5/1/21 | 10/1/21 | 2/1/21 | 3/15/22 |
| Subtask 4.2 -- Demonstration of Replicated Rules in Blockchain System | 11/1/21 | 1/30/22 | 12/1/21 | 3/31/22 |
| Subtask 4.3 -- Demonstration of Storing Replicated Data Chunks in Blockchain System | 2/1/22 | 6/1/22 | 3/15/22 | |
| Subtask 4.4 -- Demonstration of Identifying a Compromised Controller | 7/1/22 | 8/30/22 | | |

UNIVERSITY OF NORTH DAKOTA

# Project Description and Objectives

## Accomplishments Before 2021 Review Meeting (1)

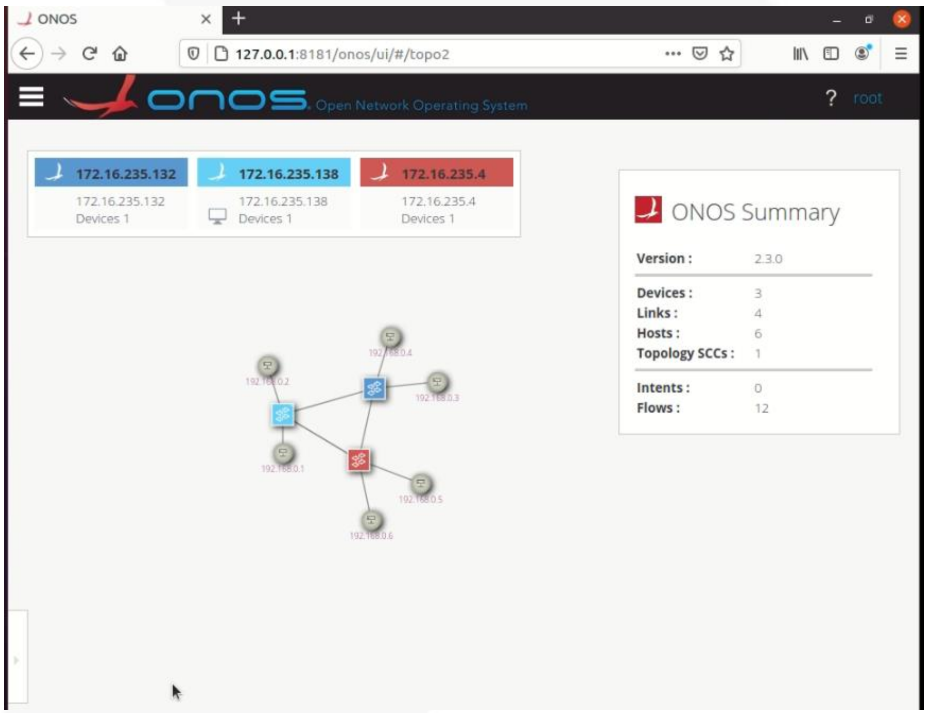
- All software development is performed in a cloud infrastructure running across 3 servers
  - Hardware: 3 high-end Dell servers (Model PowerEdge R540).
  - Software: Proxmox Virtual Environment (PVE) and OpenStack.

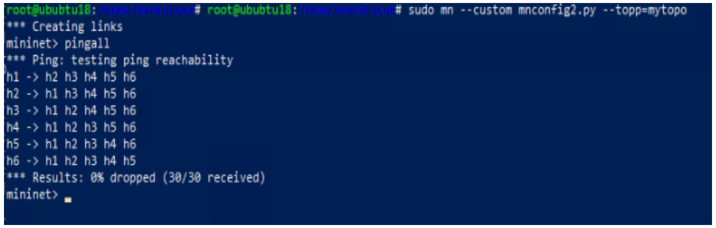


# Project Description and Objectives

## Accomplishments Before 2021 Review Meeting (2)

- Constructed the SDN with a controller cluster.
  - Mininet is used for simulating the data plane of the SDN (DP-SDN).
  - A cluster of ONOS controllers is used as the control plane of the SDN (CP-SDN).
  - A cluster of Atomix agents is needed for forming a cluster of ONOS controllers.



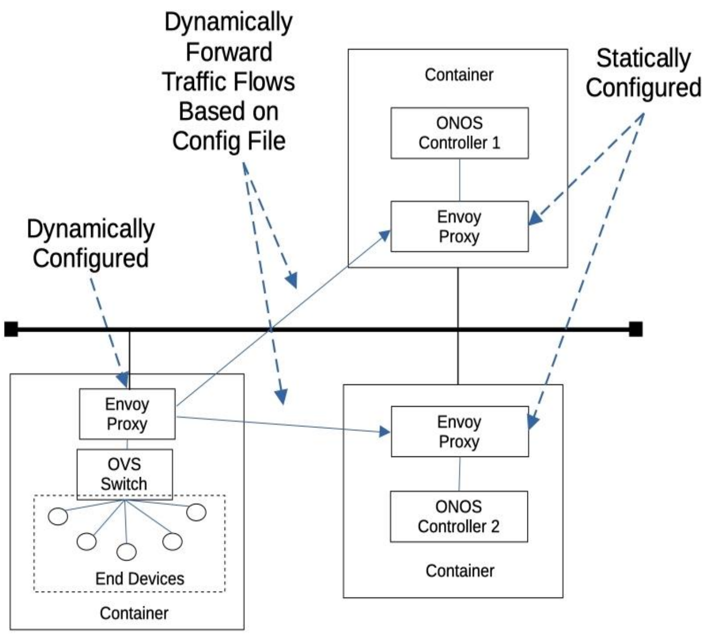




UND UNIVERSITY OF NORTH DAKOTA

# Project Description and Objectives

## Accomplishments Before 2021 Review Meeting (3)

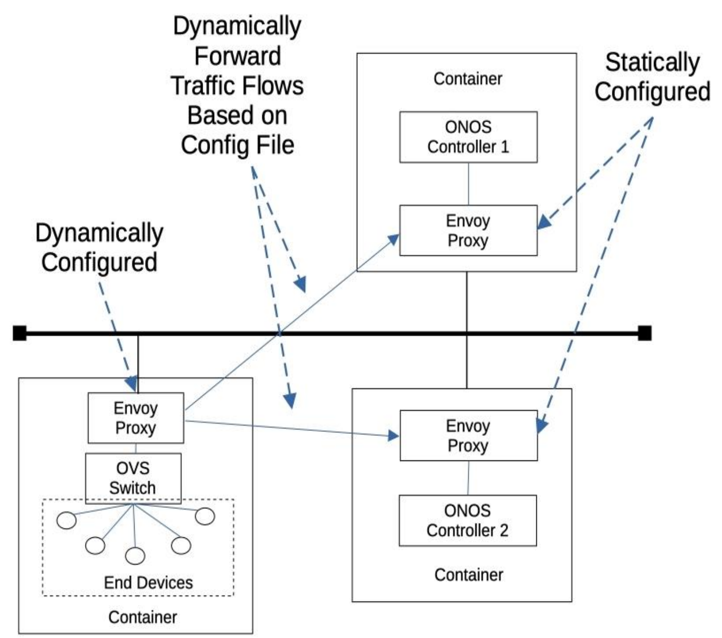
- Constructed the portal service layer to bridge the data plane and the control plane of an SDN.
  - The portal service layer is materialized in the form of a service mesh which consists of
    - A data plane: a set of *Envoy* proxies.
    - A control plane: a set of *Consul* agents.
  - OVS switches interact with ONOS cluster through the portal service layer.
    - Only the data plane (Envoy proxy) has been successfully functional.
    - Envoy proxy has been manually configured to dynamically forward SDN traffic to a target ONOS controller.



# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting (1)

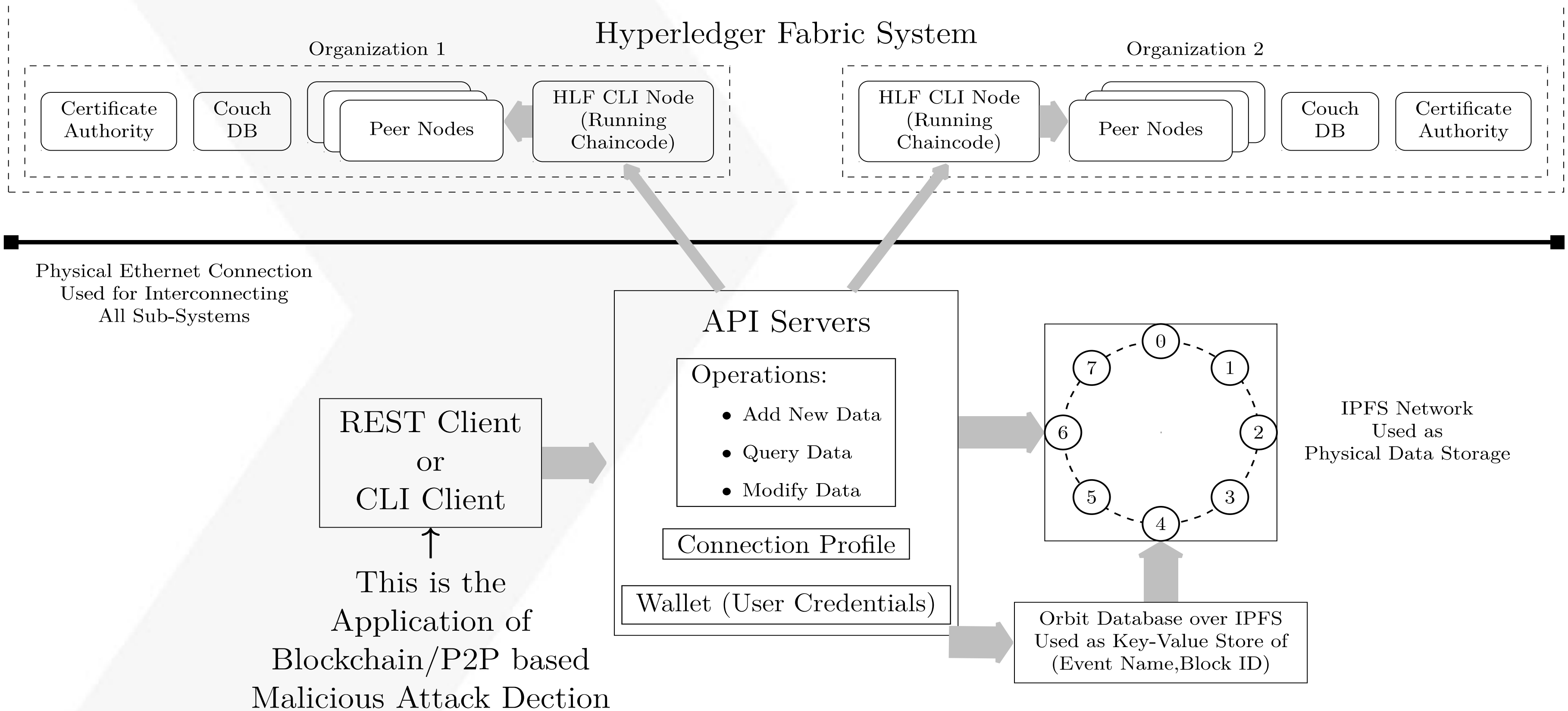
- Added a cluster of Consul agents as the control plane of the portal service layer.
- Consul agents maintain the configurations of the routing paths between an OVS switch and an ONOS controller.
  - Configurations can be dynamically changed to exclude the compromised SDN controllers after being detected by the detection program.
- Envoy proxy is configured to obtain rules of forwarding SDN traffic from the (currently active) Consul agent in a Consul cluster.



# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting (2)

### Structure of the Hyperledger Fabric/IPFS sub-System

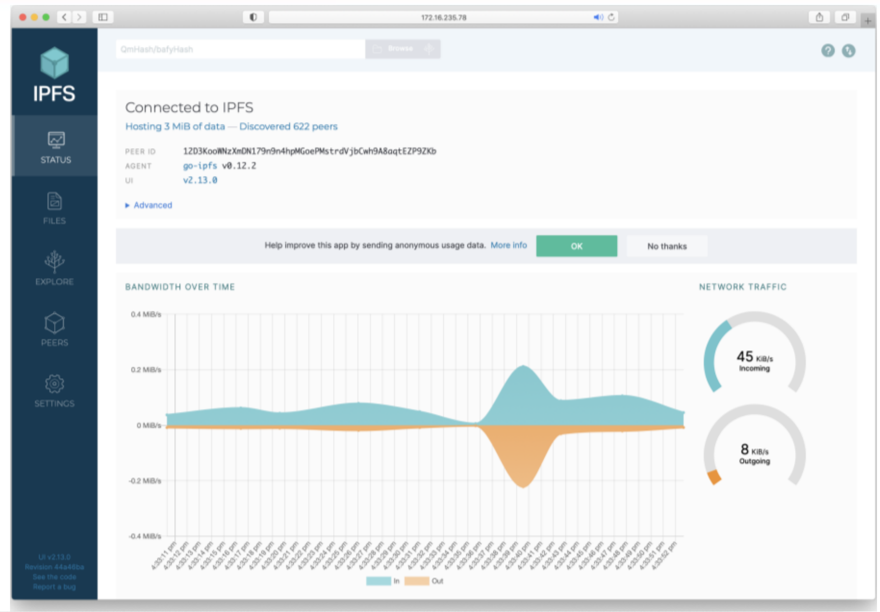



UND UNIVERSITY OF NORTH DAKOTA

# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting (3)

- Deployed the InterPlanetary File System (IPFS) docker container.
  - Interaction with the IPFS data storage can be made through command-line interface through using the curl command.
  - Web user-interface of the IPFS data storage is accessible from remote hosts.




Figures — -bash — 80×7

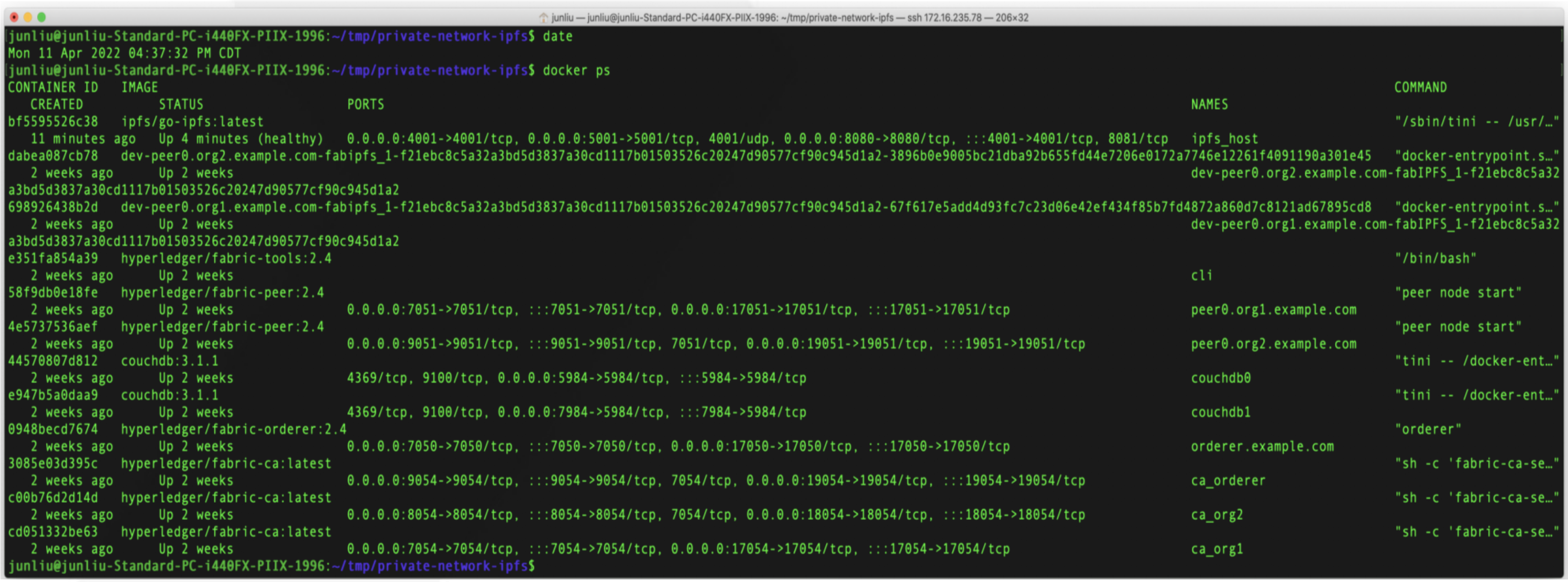
```
localadminsimac:Figures junliu$ curl -F file=111 http://172.16.235.78:5001/api/v0/add
{"Name":"QmewtY21Ufyqa166AWXrSC3Y3FMqKMhpRRPH2tqTNMUALE","Hash":"QmewtY21Ufyqa166AWXrSC3Y3FMqKMhpRRPH2tqTNMUALE","Size":"11"}
localadminsimac:Figures junliu$ curl -X POST "http://172.16.235.78:5001/api/v0/cat?arg=QmewtY21Ufyqa166AWXrSC3Y3FMqKMhpRRPH2tqTNMUALE"
111localadminsimac:Figures junliu$
```

UND UNIVERSITY OF NORTH DAKOTA

# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting (4)

- The entire docker cluster of a HLF/IPFS sub-system can be launched through running a single bootstrapping script.
  - More peers or organizations can be added by modifying the bootstrapping script.



# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting (5)

- Command-line interaction can be supported between the CLI client and the API server.

```
junliu — junliu@junliu-Standard-PC-i440FX-PIIX-1996: ~/tmp/fabric-samples/chaincode/fabIPFS/javascript/lib — ssh 172.16.235.78 — 207×11
 1811  curl http://localhost:8080/get
 1813  curl http://localhost:8080/api/queryallblocks
 2111  curl -H "Content-Type: application/json" -d '{"filename": "./111"}' -X POST http://localhost:9090/api/addblock/
 2215  curl http://localhost:9090/api/query/1
 2222  curl http://localhost:9090/api/orbit-db-init
 2223  curl http://localhost:9090/api/init-db
 2224  curl -H 'Content-Type: application/json' -d '{"username":"name1"}' http://localhost:9090/api/init-db
 2227  curl -H 'Content-Type: application/json' -d '{"username":"name1"}' http://localhost:9090/api/dbget
 2230  curl http://localhost:9090/api/dbget
 2251  curl http://localhost:9090/api/dbget/userone
junliu@junliu-Standard-PC-i440FX-PIIX-1996:~/tmp/fabric-samples/chaincode/fabIPFS/javascript/lib$
```

- Sample Run: the client sends a request to the API server for adding a file to the HLF blockchain.
  - At client: curl command sent to API server and the response received from API server.

```
junliu — junliu@junliu-Standard-PC-i440FX-PIIX-1996: ~/tmp — ssh 172.16.235.78 — 129×5
^C
junliu@junliu-Standard-PC-i440FX-PIIX-1996:~/tmp$ curl -H "Content-Type: application/json" -d '{"filename": "./111"}' -X POST htt
p://localhost:9090/api/addblock/
Transaction has been submitted
junliu@junliu-Standard-PC-i440FX-PIIX-1996:~/tmp$
```

  - API server: serving client's request and displaying the response received from IPFS and HLF.

```
junliu — junliu@junliu-Standard-PC-i440FX-PIIX-1996: ~/tmp/fabric-samples/fabIPFS/javascript — ssh 172.16.235.78 — 125×14
junliu@junliu-Standard-PC-i440FX-PIIX-1996:~/tmp/fabric-samples/fabIPFS/javascript$ node ./apiserver-Fabric-IPFS.js
listening on port 9090
{ hash_val: '11111', updated: 1649904636667 }
addBlock
Wallet path: /home/junliu/tmp/fabric-samples/fabIPFS/javascript/wallet
typeof dataJson: object
typeof dataString: string
dataJson: { filename: './111' }
dataString: {"filename":"./111"}
filename: ./111
received: 5
QmYt2LHNpx6gcBNULAqZscSasMsfLpWvjtRHX2eDK6WAeS
Transaction has been submitted
```

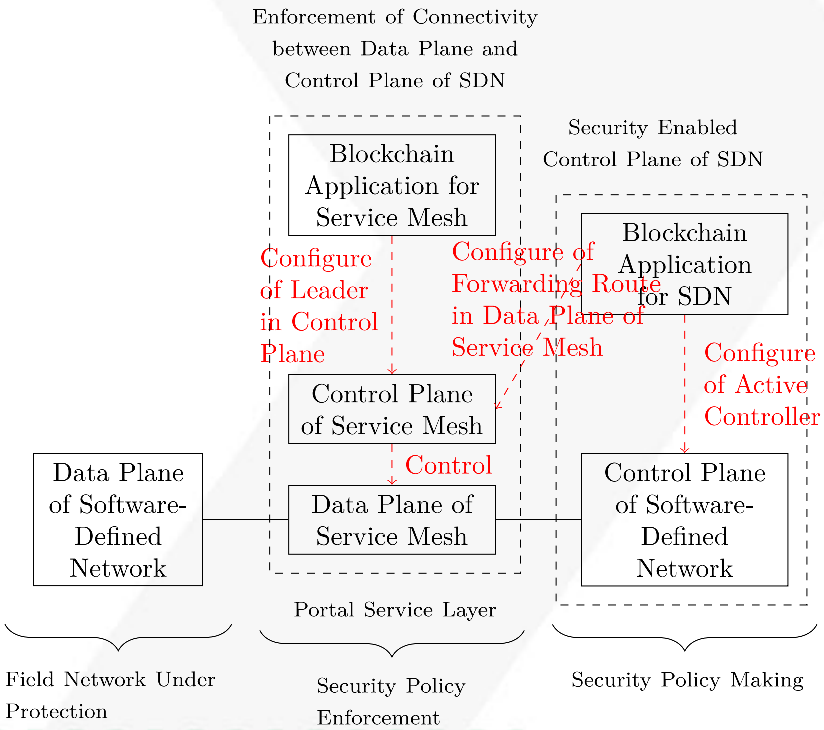
UND UNIVERSITY OF NORTH DAKOTA

# Project Description and Objectives

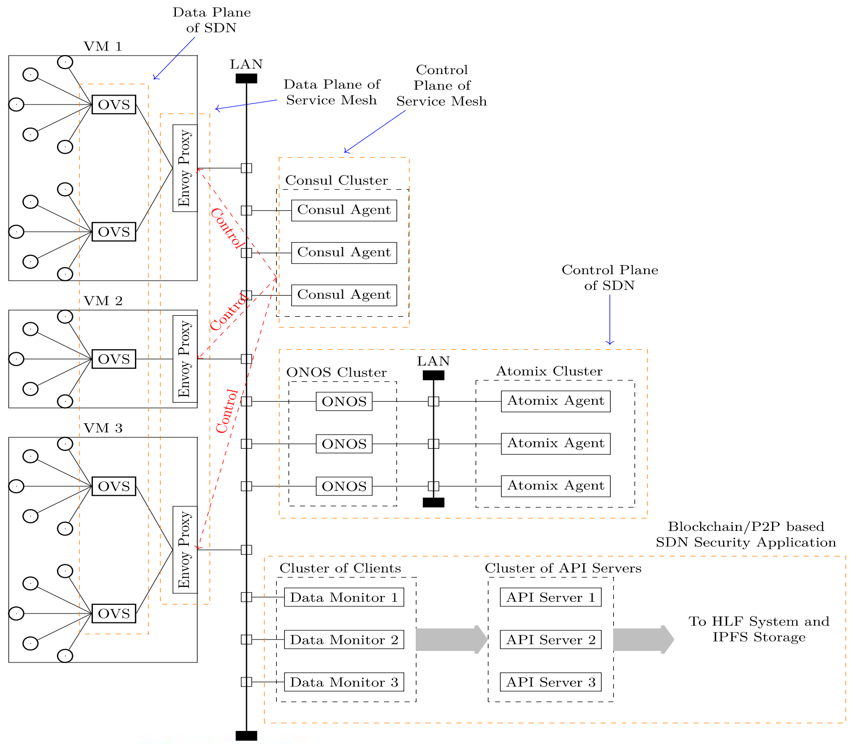
## Accomplishments Since 2021 Review Meeting (6)

Following the deployment of HLF/IPFS sub-system, simplification has been made to the structure of the testbed of detecting compromised SDN controllers.

### Logical Structure




### Physical Testbed

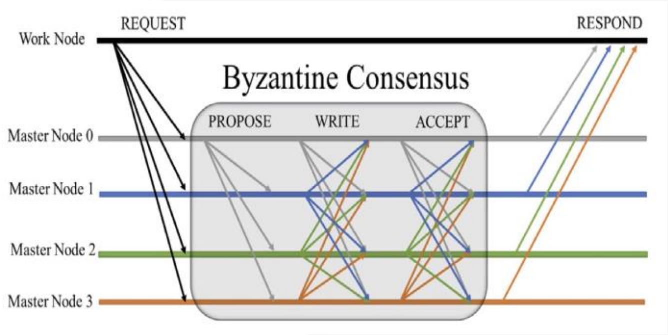



UND UNIVERSITY OF NORTH DAKOTA

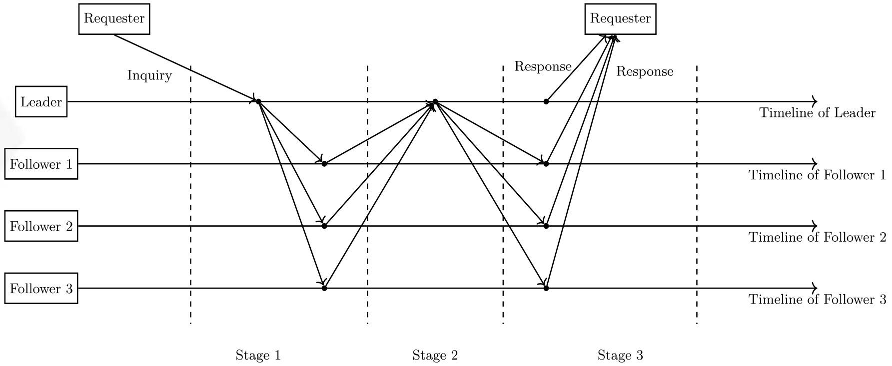
# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting (7)

- Performed the literature study and the planning step toward an efficient BFT consensus mechanism..




Predominant BFT consensus mechanism.
(Figure is from a public website).




Planned BFT consensus mechanism

# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting (8)

- Developed a basic analytical framework as the basis for constructing an efficient cryptographic BFT consensus mechanism.
- The basic analytical framework is an information-theoretic scheme which can provide unconditional security, rather than computational security.
- In this analytical framework, two parties individually derive their own local outcomes using the private values and the publicly disseminated values.
- This analytical framework can be converted to establish different cryptographic solutions, as well as being extended to more than 2 parties.
- This analytical work is still under development. Proof of correctness and security analysis are very challenging.

# Project Description and Objectives

## Next Steps (1)

- Develop a BFT consensus algorithm with linear communication overhead.
  - We are close to finish developing a 2-rounds group key agreement protocol which allows a group of participants to agree upon a common secret value.
  - The communication overhead of this group key agreement protocol is linear in the number of participants.
  - We plan to convert this group key agreement protocol into a BFT consensus algorithm.
- Prototyping the BFT consensus algorithm by modifying the Raft code.
- Risk:
  - Prototyping the BFT consensus algorithm may be risky and time consumptive.
  - Many open-source implementations of practical BFT (pBFT) algorithm are incomplete.
- Risk mitigation:
  - Bottom line: we will ensure pBFT with quadratic communication overhead to be functional to provide BFT consensus in the application of detection.

# Project Description and Objectives

## Next Steps (2)

- To develop a blockchain/P2P based application for detecting and excluding a compromised SDN controller.
  - The detection application only relies on the passive snooping on network traffic.
    - In order to avoid technical complications, the application does not rely on obtaining operational data from ONOS/Atomix and Envoy/Consul service mesh.
  - Detection: A compromised SDN controller is the one which had issued inconsistent rule to SDN switches.
  - Exclusion: The blockchain application configures the Discovery Service in the Consul cluster to exclude a compromised SDN controller after the detection.

# Acknowledgment

This material is based upon work supported by the Department of Energy Award Number DE-FE0031742.



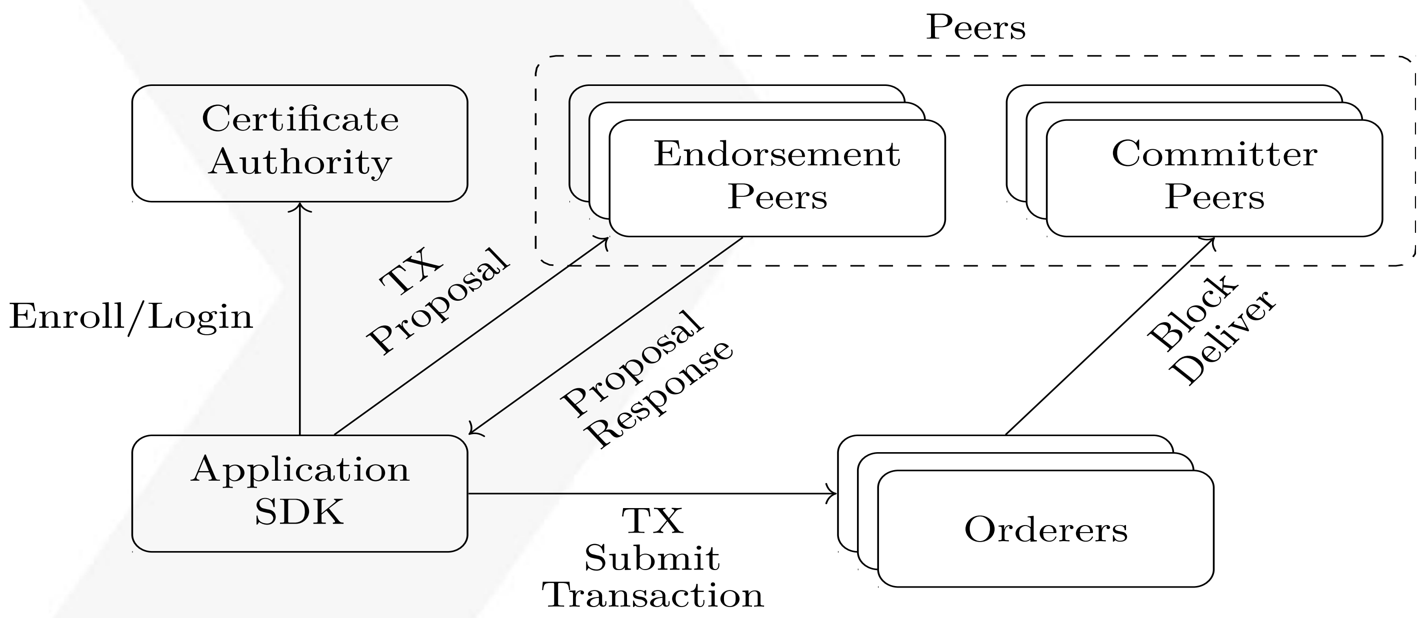
UND UNIVERSITY OF NORTH DAKOTA

# Backup Slides

# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting

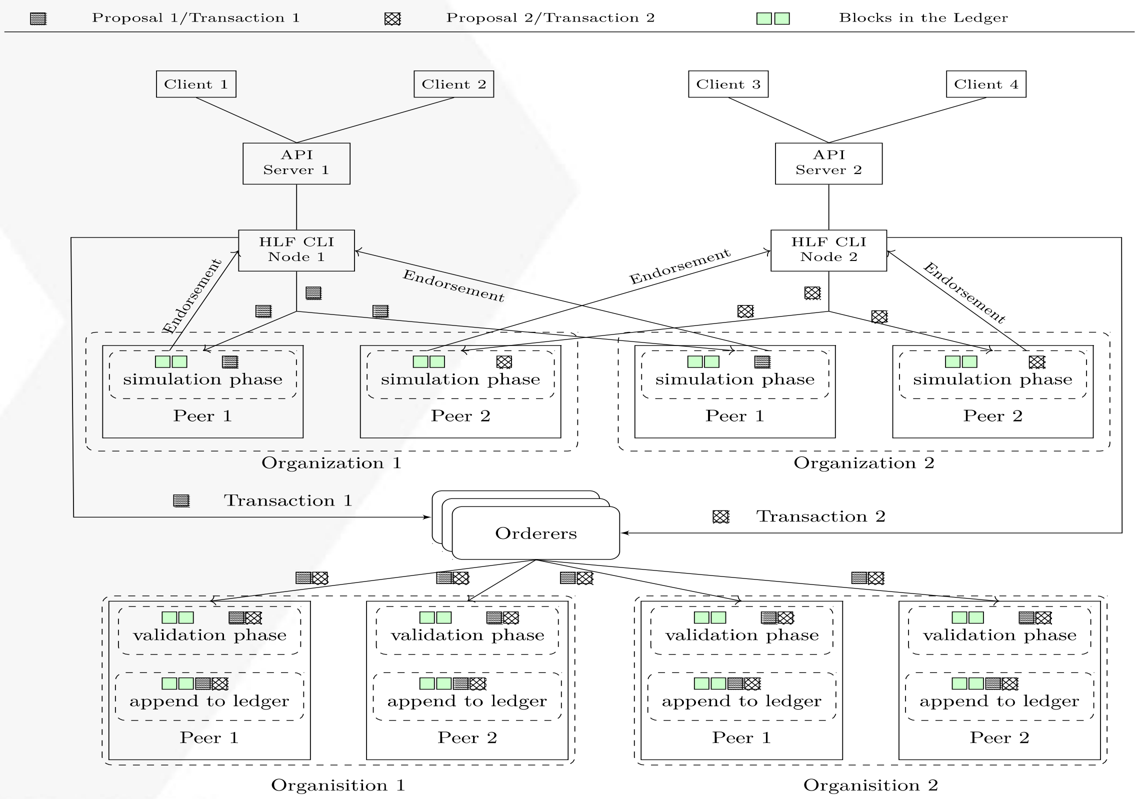
Logical flowchart of making a transaction in the Hyperledger Fabric framework



# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting

Actions taken for adding blocks in the Hyperledger Fabric framework



# Project Description and Objectives

## Accomplishments Since 2021 Review Meeting