Towards autonomous software-defined Industrial IoT-Edge Communication Networks

A case of offshore wind farms

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SESSION GUIDE

Innovative Tools for Cyber-Physical Energy Systems

PART-I

09:30 – 10:20

Next generation data acquisition systems in offshore wind farms

(Disrupting the status quo)

BREAK-I

10:20 – 10:30

PART-II

10:30 – 11:00

Autonomous software-defined IIoT-Edge networks in offshore wind farms

(Self-healing cognitive AI tool)

BREAK-II

11:00 – 11:15

Utrecht University

About Me

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

❑ Academic Background

Utrecht University

Ph.D. in Engineering
- ❖ Research Interests: IIoT-Edge architectures, SDN/NFV, AI/ML, autonomous networks, and offshore wind

MSc. Electrical and Computer Engineering
- ❖ Major: Advanced Network Technologies
- ❖ Minor: Applied ML and Data Analytics

❑ Professional Background

Safaricom

CARREL TECHNOLOGIES

CISCO CERTIFIED CCNA

CHECKUPS medical hub

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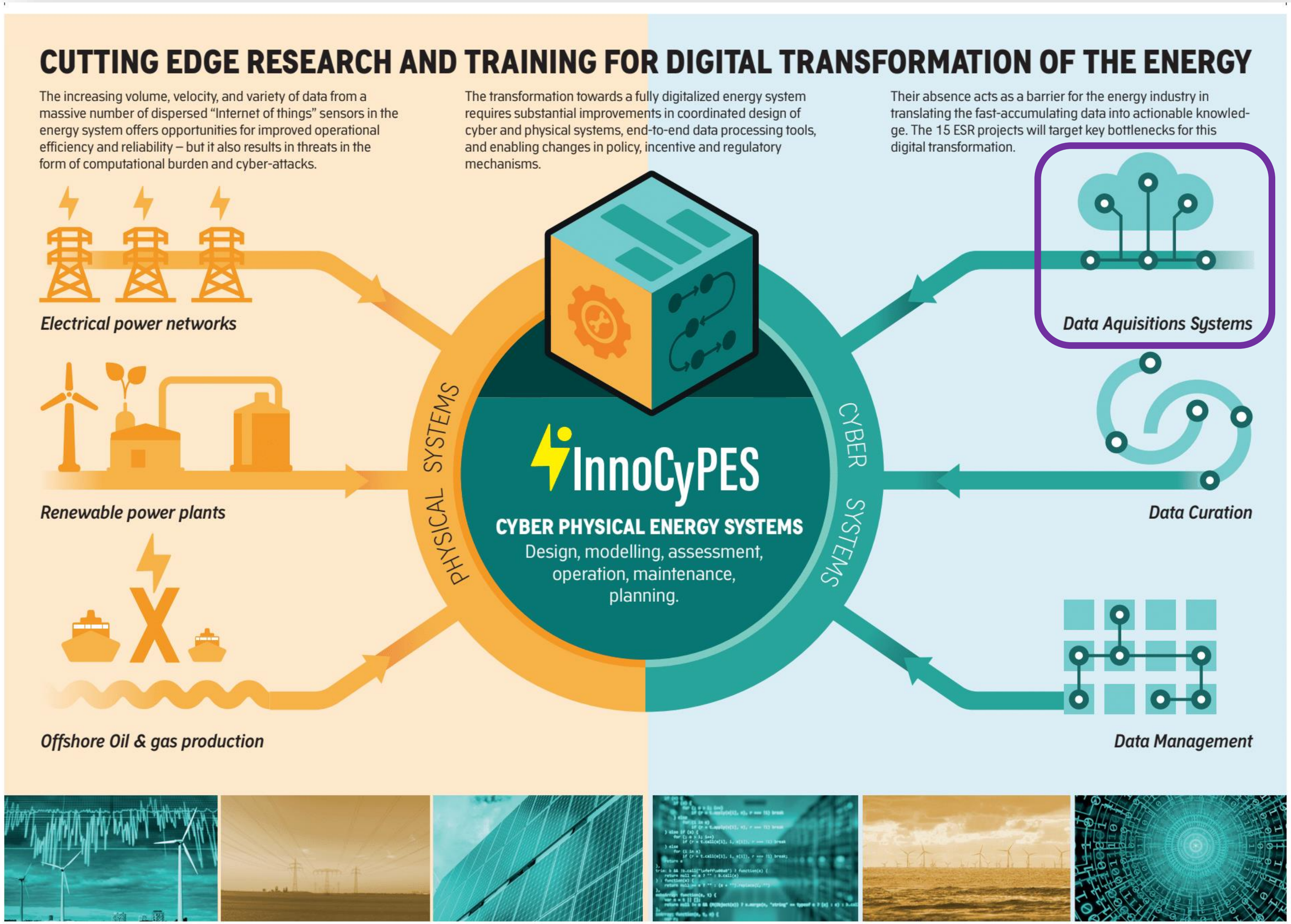
Innovative Tools for Cyber-Physical Energy Systems (InnoCyPES)

The overall goal of the project is to deliver a decision-making tool to enable energy companies to optimally design and utilize the ICT infrastructure and develop digital solutions, considering end-to-end data lifecycle and solution.

Research Work Scope: Data Acquisition Systems

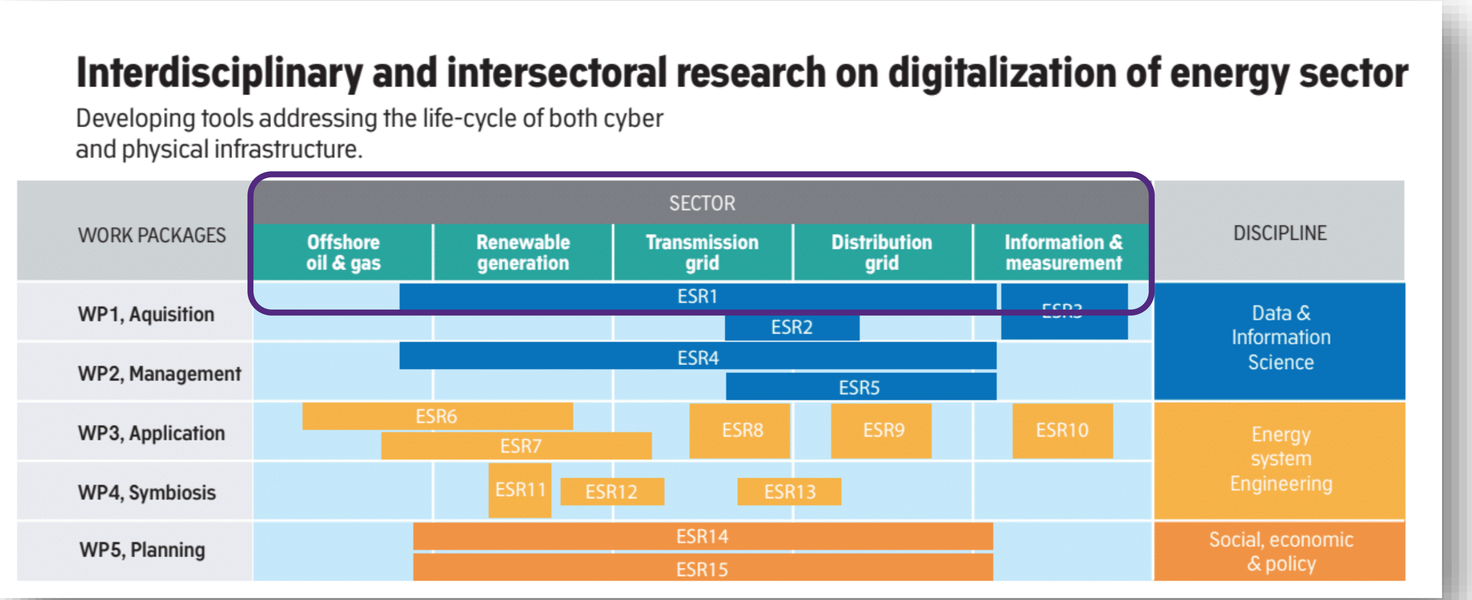
Application Scenario: Offshore wind farms

("wind farms of tomorrow")



This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska Curie grant agreement No. 956433.

Innovative Tools for Cyber Physical Energy Systems (InnoCyPES)



Host Institution:

Universiteit Utrecht

Key Partners and beneficiaries:

Ørsted EDF TU Delft

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956433.

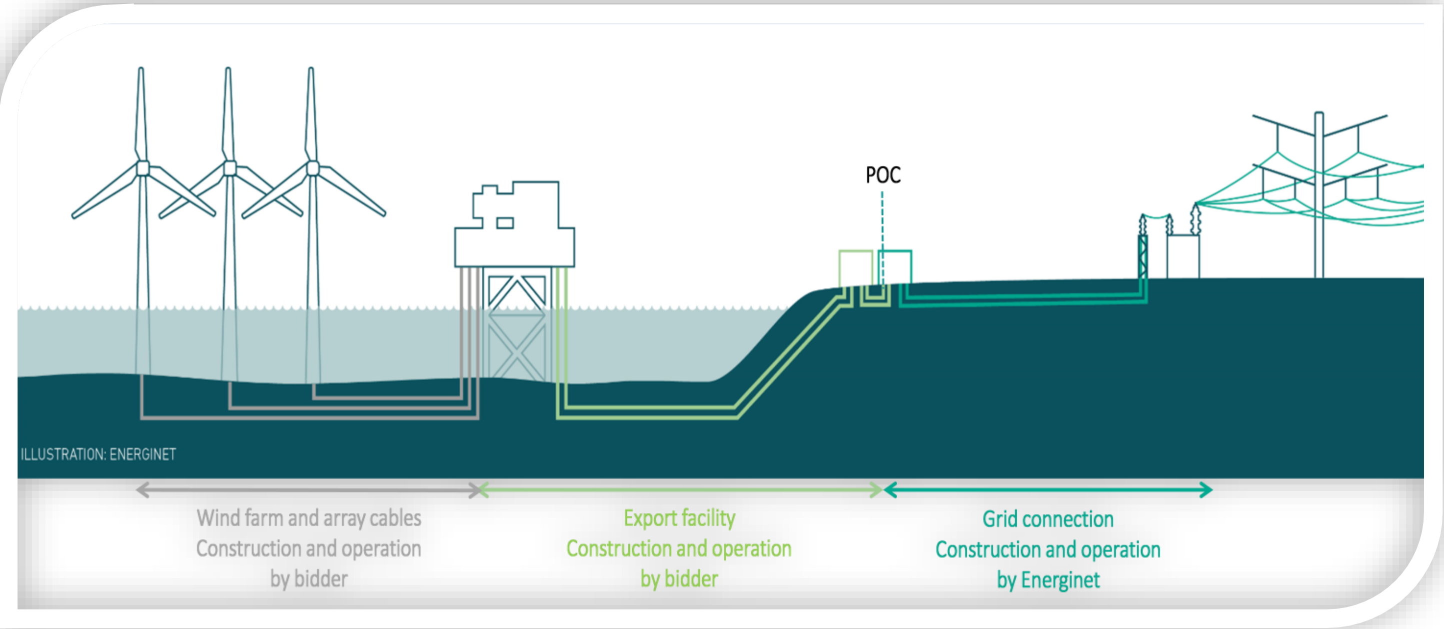
PART I

Next-generation data acquisition systems in offshore wind farms

(Disrupting the status quo)

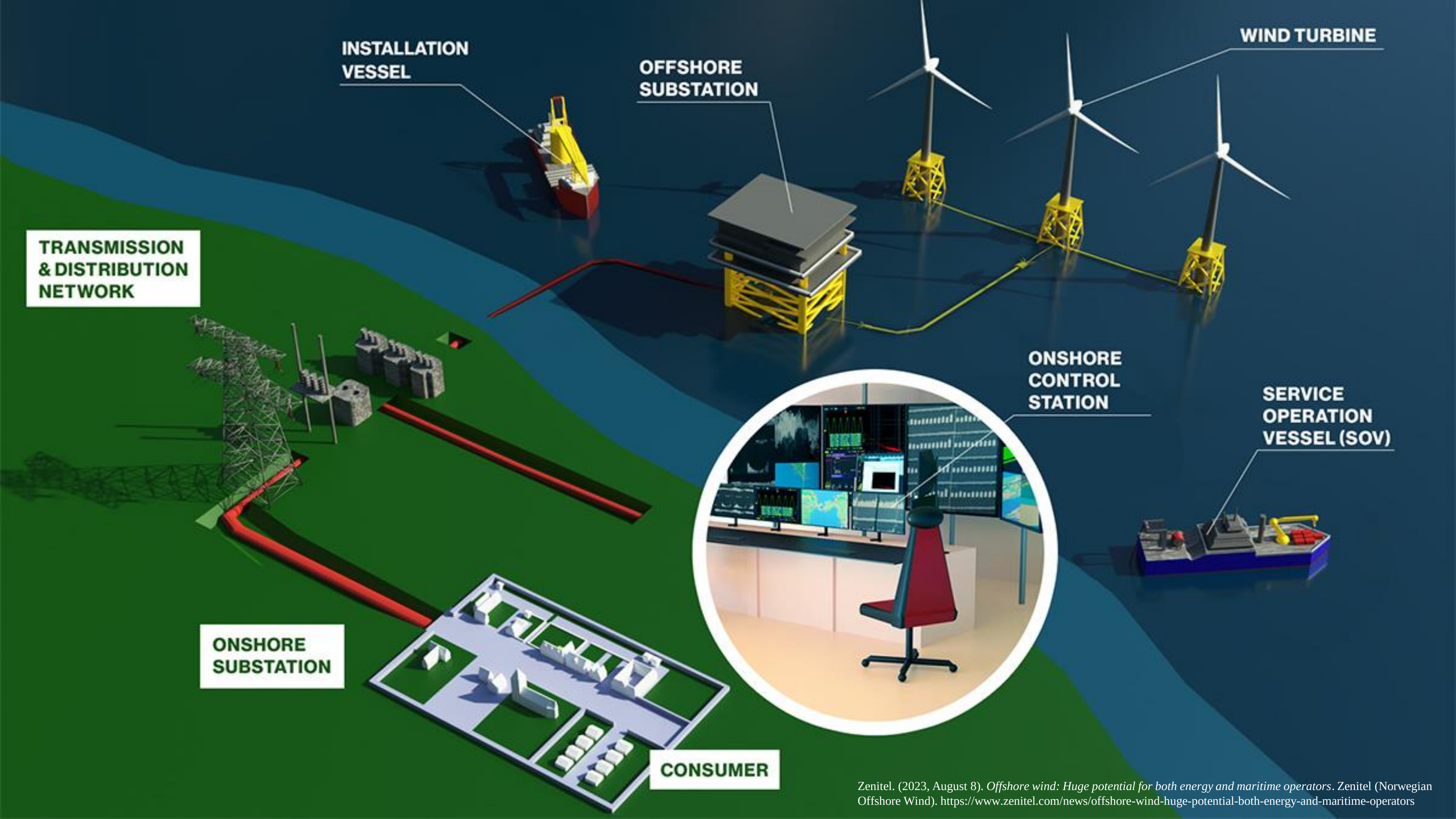
Offshore Wind Farms

- Offshore wind farms are growing in complexity and size, expanding deeper into maritime environments to capture stronger and steadier wind energy.
- The intricacies of sea environments such as unpredictable weather patterns and the long distance from shore make manual monitoring and maintenance a logistical challenge and economically draining.
- Distance between individual WTGs and offshore substation (tens of kms). Distance between offshore substation and onshore substation or control room (hundreds of kms).



Thor offshore wind farm (800MW-1000MW) established in the North Sea, West of Nissum Fjord, ~20km from shore of Thorsminde town. [Source]

a) Mwangi, A. W. (2023). *Horizon 2020: IoT Data Acquisition System Design Method* (Deliverable No. D1.2, Version 2.0, Project InnoCyPES). European Commission. Peer-reviewed by G. Yang, M. Gibescu, E. Fumagalli, M. Gryning, & F. Martin. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5f9455af8&appId=PPGMS
b) Mwangi, Agrippina, Rishikesh Sahay, Elena Fumagalli, Mikkel Gryning, and Madeleine Gibescu. 2024. "*Towards a Software-Defined Industrial IoT-Edge Network for Next-Generation Offshore Wind Farms: State of the Art, Resilience, and Self-X Network and Service Management*" Energies 17, no. 12: 2897. https://doi.org/10.3390/en17122897



Zenitel. (2023, August 8). *Offshore wind: Huge potential for both energy and maritime operators*. Zenitel (Norwegian Offshore Wind). https://www.zenitel.com/news/offshore-wind-huge-potential-both-energy-and-maritime-operators

Data Acquisition Systems in Offshore Wind Farms ("Nerve Center")

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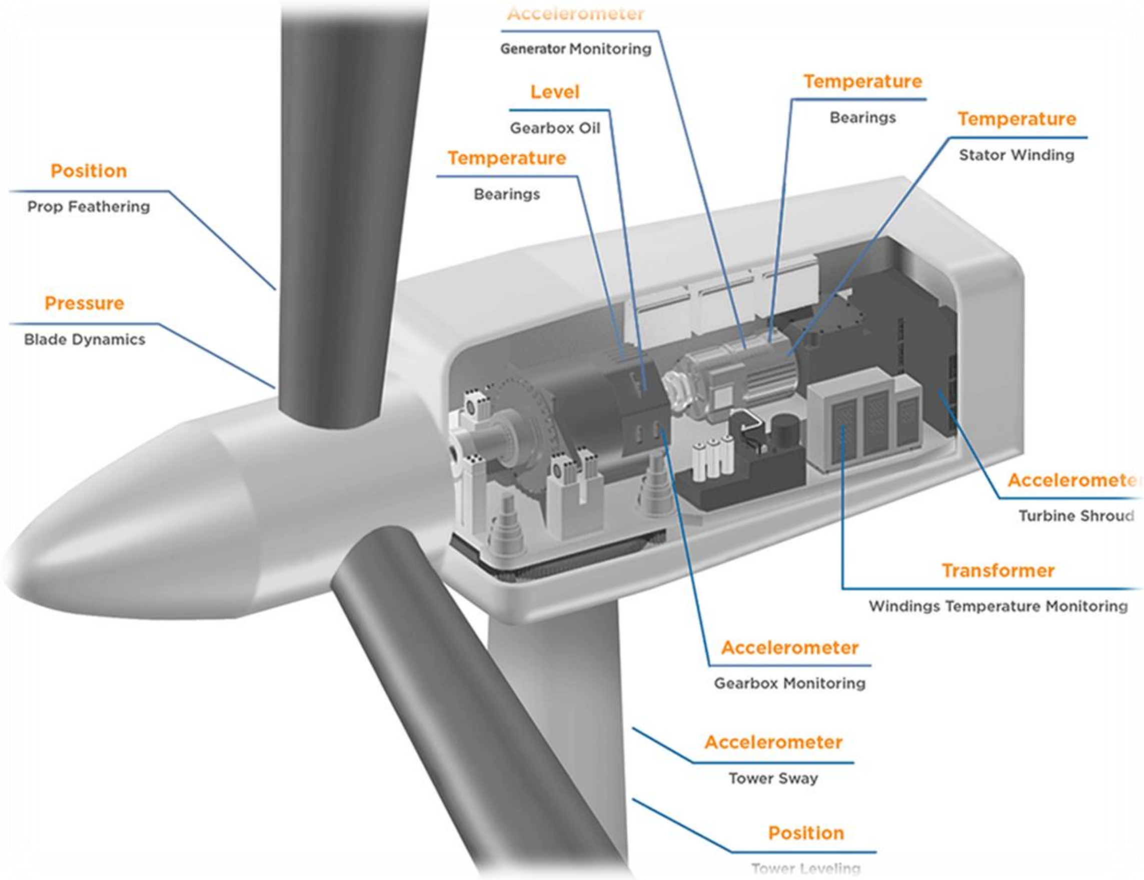

- The SCADA system are the "*nerve center*" for large-scale offshore wind farms, collecting data from wind turbine generators, digital substation components, and meteorological stations.
- These systems are vital for overseeing and controlling wind farm operations, offering comprehensive monitoring, control, and reporting functions. They accurately log events, improving the precision of alarm and event records, and reducing troubleshooting time.
- Offshore wind farm developers and operators usually procure SCADA systems from wind turbine manufacturers, who also double as SCADA suppliers.

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a) Marti-Puig, P.; Blanco-M, A.; Cárdenas, J.J.; Cusidó, J.; Solé-Casals, J. Feature Selection Algorithms for Wind Turbine Failure Prediction. *Energies* **2019**, *12*, 453. https://doi.org/10.3390/en12030453
b) Mwangi, A. W. (2023). *Horizon 2020: IoT Data Acquisition System Design Method* (Deliverable No. D1.2, Version 2.0, Project InnoCyPES). European Commission. Peer-reviewed by G. Yang, M. Gibescu, E. Fumagalli, M. Gryning, & F. Martin. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5f9455af8&appId=PPGMS

Data Acquisition Systems in Offshore Wind Farms (Status Quo)

Monolithic SCADA Systems

Operated independently as standalone systems relying heavily on mainframe computers. Communication often limited to proprietary protocols.

1960s – 1980s

First Generation

Distributed SCADA Systems

Decentralization of SCADA systems into distributed control systems.
Used Ethernet LANs for communication between distributed components.

1980s to 1990s

Second Generation

Networked SCADA Systems

Advanced networking technologies utilizing standardized communication protocols (TCP/IP) and WANs (or the internet).

~ 1990s to 2015s

Third Generation

Industrial IoT-Edge SCADA Systems

Integrates the IIoT, programmable networks, and edge computing.
Highly scalable and often integrated with cloud platforms.

~2015s to Present

Fourth Generation

Cognitive (AI-driven) SCADA Systems

Integrate AI to create autonomous, self-learning systems capable of predictive maintenance, real-time optimization, and autonomous decision making.

2030 and Beyond

Fifth Generation

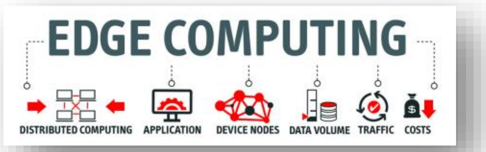
The evolution of Supervisory Control and Data Acquisition (SCADA) Systems

a) Mwangi, A. W. (2023). *Horizon 2020: IoT Data Acquisition System Design Method* (Deliverable No. D1.2, Version 2.0, Project InnoCyPES). European Commission. Peer-reviewed by G. Yang, M. Gibescu, E. Fumagalli, M. Gryning, & F. Martin. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5f9455af8&appId=PPGMS

Leveraging Industrial 4.0 technologies in next-generation data acquisition systems

"Embracing the digital era, the energy sector is undergoing a significant transformation that will see next-generation offshore wind farms leverage the power of technologies from the fourth industrial revolution (Industry 4.0) such as Industrial Internet of Things (IIoT), edge computing, and programmable networks to improve their data-acquisition systems." (Mwangi et al., 2024)

Monitor and manage offshore assets with unprecedented precision.



Process big data generated by IIoT devices closer to the offshore assets reducing dependency on distant data centers

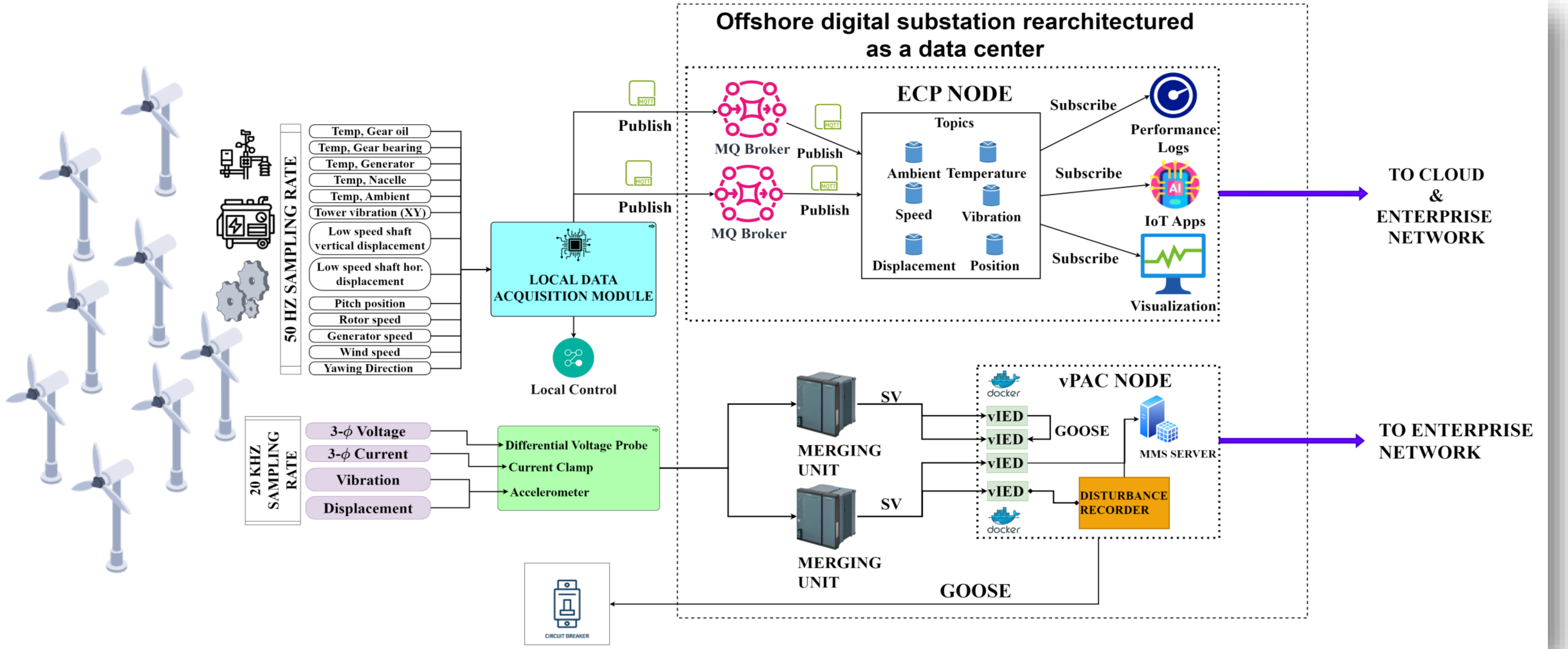
Virtualization creates virtual instances of physical assets enabling swift deployment, scalability, and management.

Software-defined networks where network engineers can modify the behavior of the network using programming interfaces.

a) Mwangi, Agrippina, Rishikesh Sahay, Elena Fumagalli, Mikkel Gryning, and Madeleine Gibescu. 2024. "*Towards a Software-Defined Industrial IoT-Edge Network for Next-Generation Offshore Wind Farms: State of the Art, Resilience, and Self-X Network and Service Management*" Energies 17, no. 12: 2897. https://doi.org/10.3390/en17122897

Next-generation data acquisition systems in offshore wind farms

(Industrial Internet of Things - IIoT)



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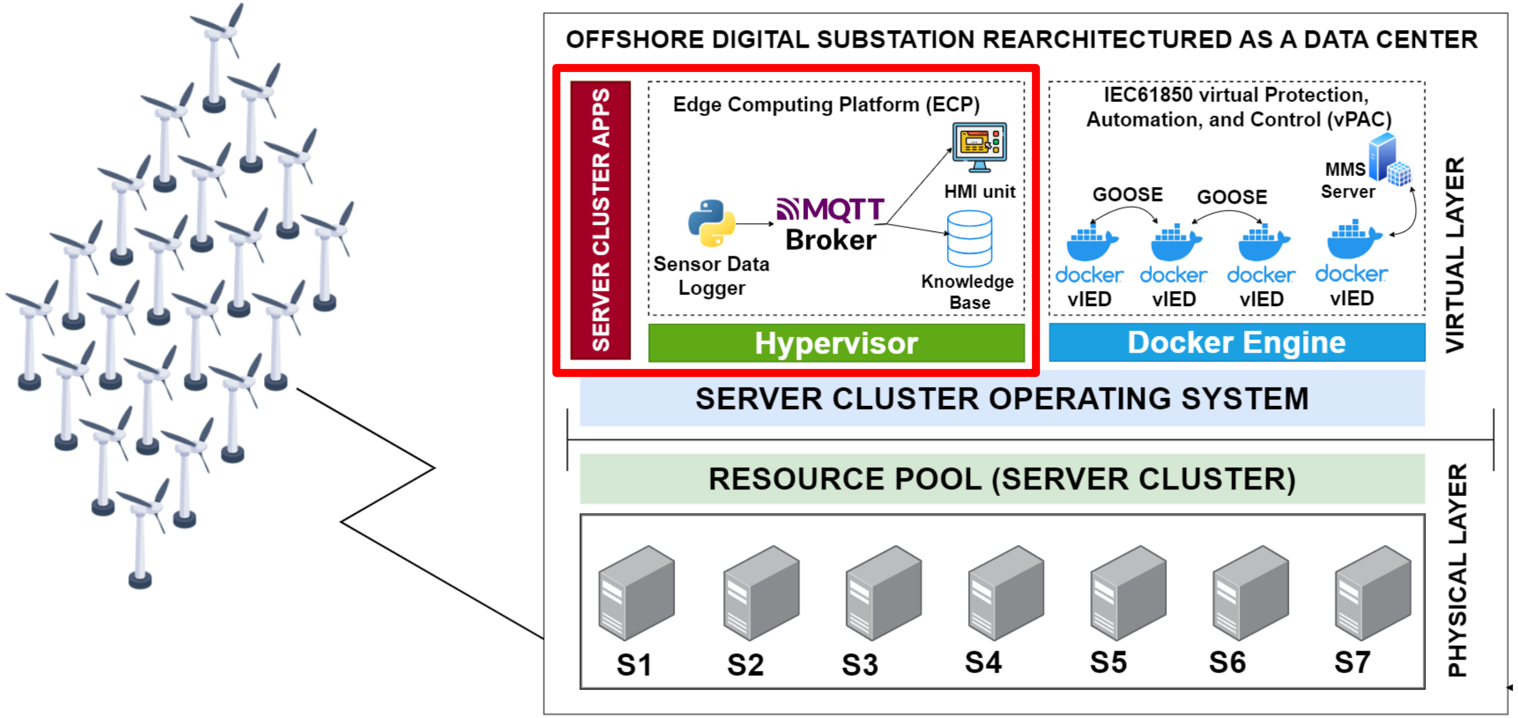
Next-generation data acquisition systems in offshore wind farms
(Edge computing platform for Industrial IoT)

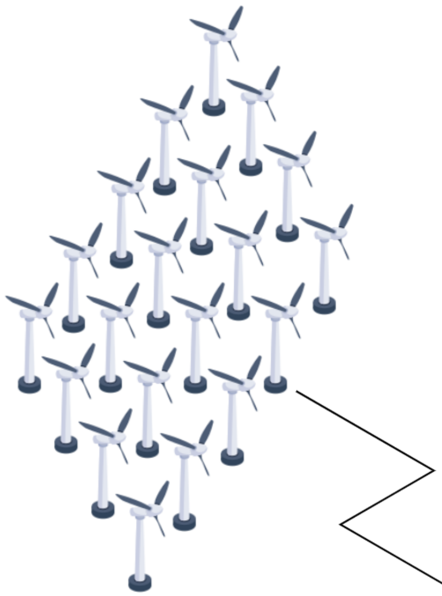


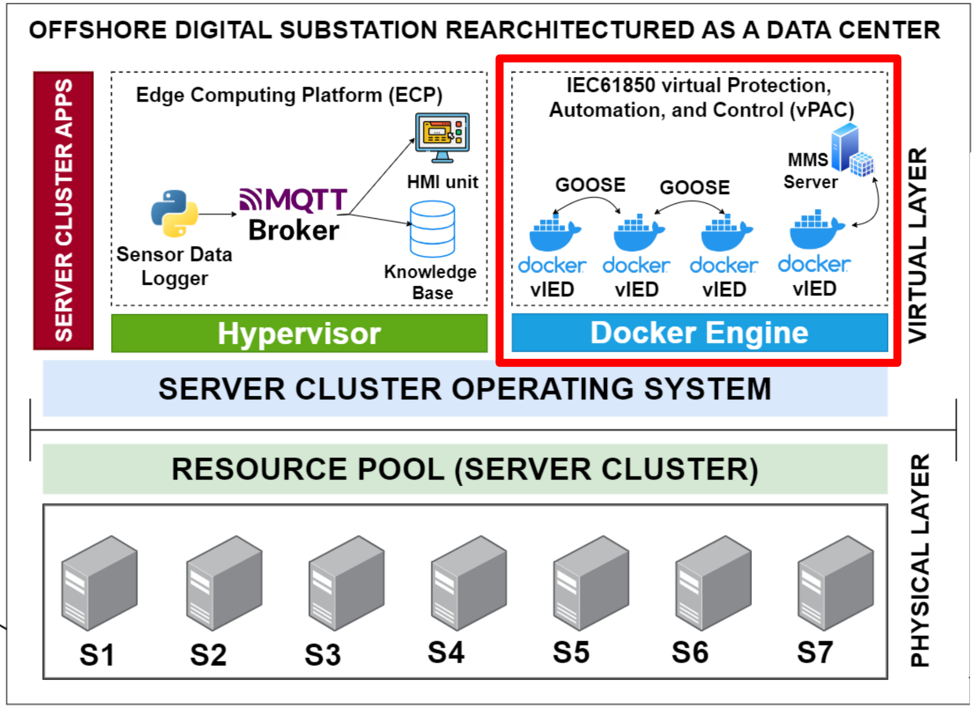
Choosing an edge computing platform over the traditional IoT-to-cloud model reduces data transmission latency, enhances data security, and enables real-time decision making.

Alliance for IoT and Edge Computing Innovation

Next-generation data acquisition systems in offshore wind farms

(Virtualization in offshore substations)





Virtual Protection Automation and Control (vPAC) Alliance is advocating for flexible, manageable, and interoperable platforms that are based on open

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a) VPA, "Virtual Protection Relay White Paper," Virtual Protection Alliance, May 12, 2022. [Online]. Available: https://vpacalliance.com/data/files/virtualprotectionrelaywp-v051222-3.pdf.

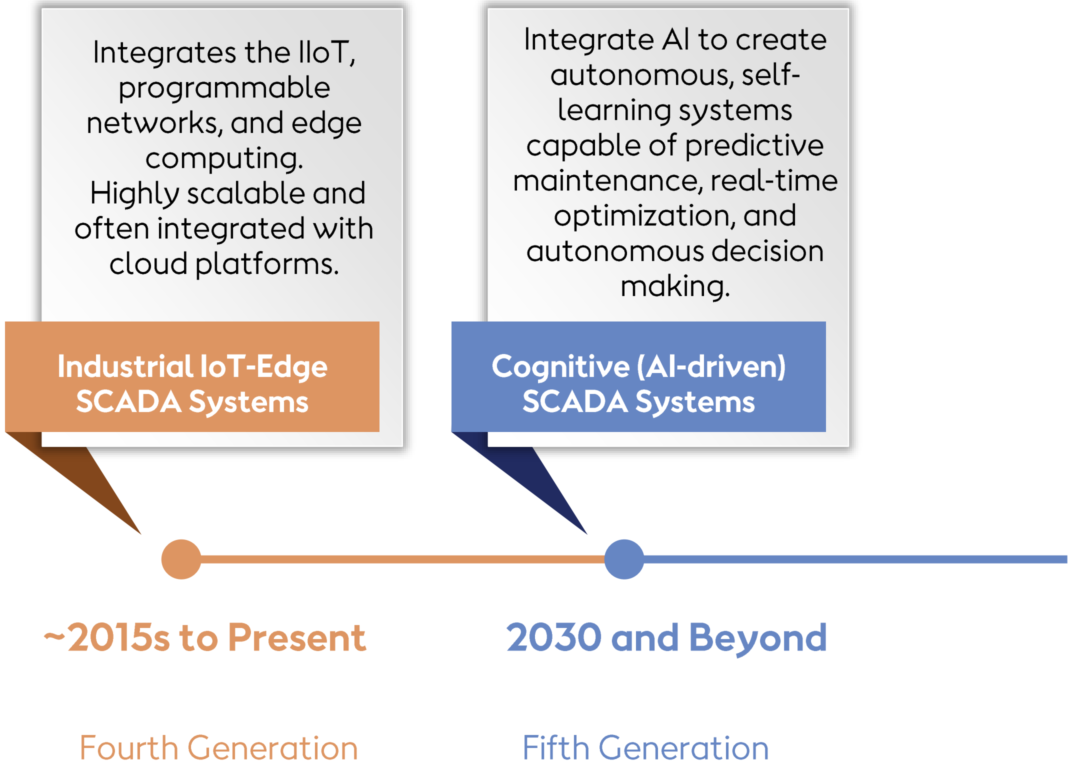
Key Drivers of Next-generation data acquisition in Offshore Wind Farms
(Unlocking innovation)

- ❑ Improved operational efficiency
- ❑ Enhanced Data Analytics and Decision making
- ❑ Enhanced reliability and predictive maintenance

- ❑ Enhanced scalability and flexibility

- ❑ Reduced Operational Expenses (OPEX)

- ❑ Regulatory compliance and grid integration requirements



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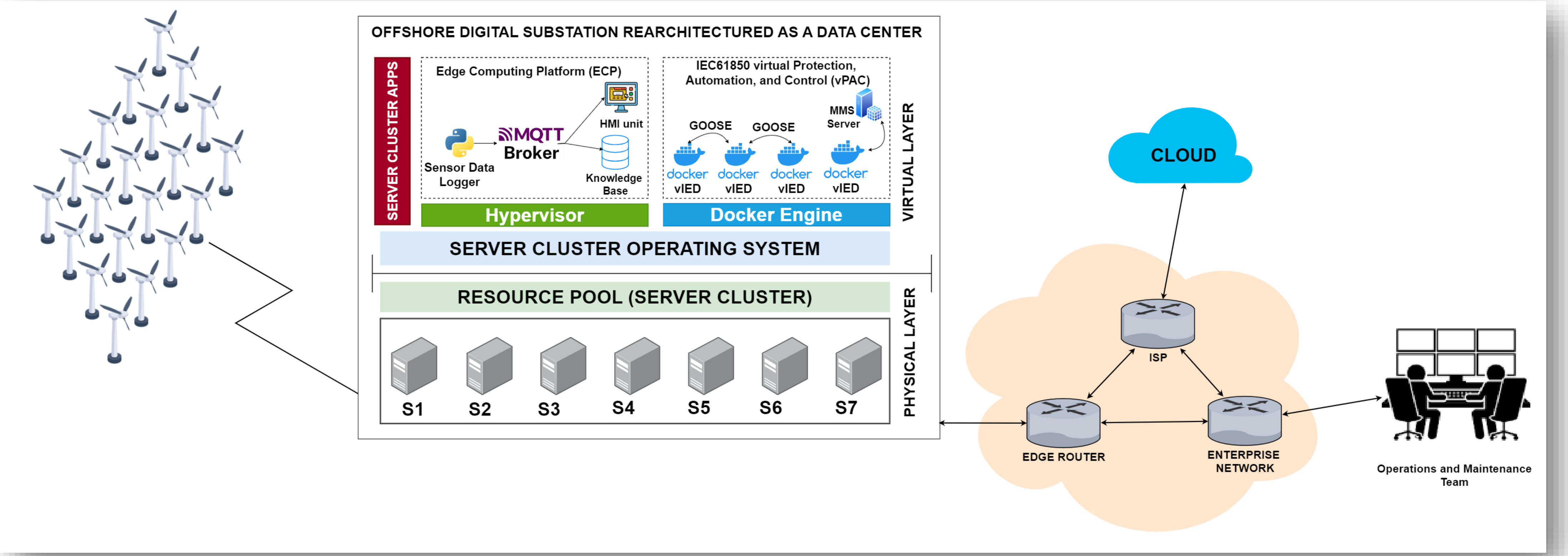
Building resilient communication networks for next-generation offshore data acquisition systems

"Orchestration of these Industry 4.0 technologies hinges on <u>resilient communication networks</u>."

This research <u>designs and validates</u> software-defined communication networks capable of meeting the stringent performance requirements for efficient coordination of offshore wind farm services.



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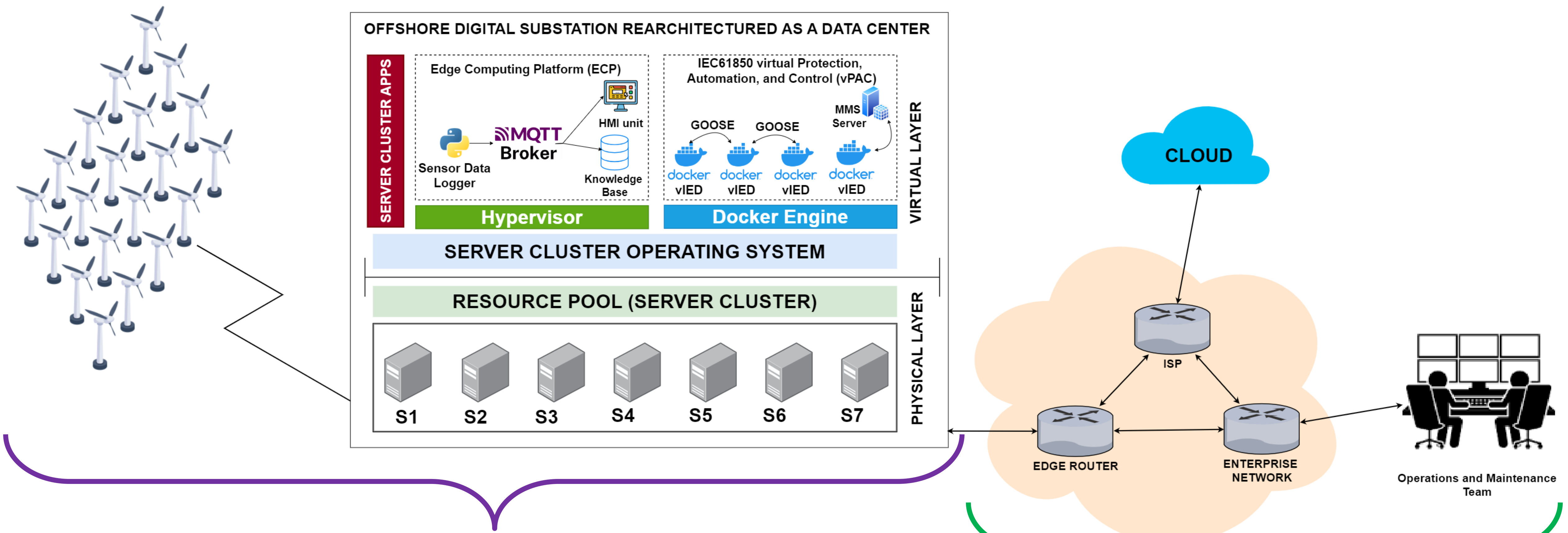
Building resilient communication networks for next-generation offshore data acquisition systems



Software-defined IIoT-Edge communication network (SD-IIoT-Edge)

?

Software defined Wide-Area Network (SD-WAN)

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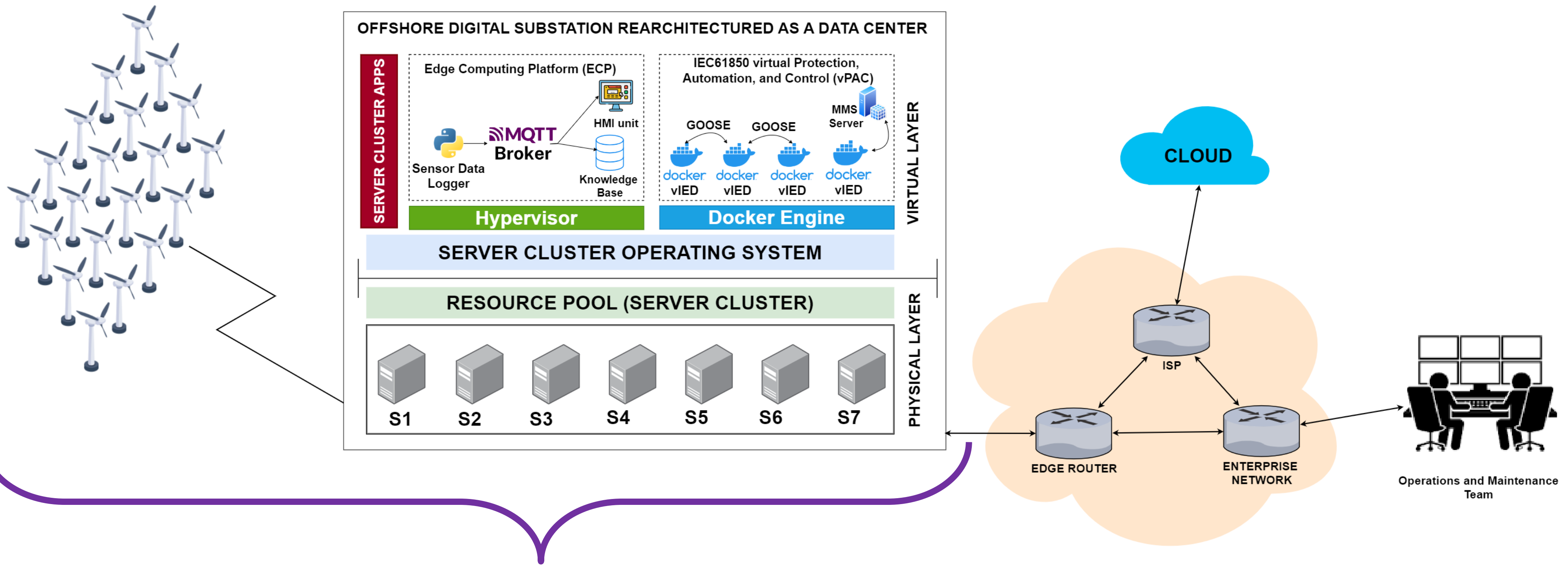
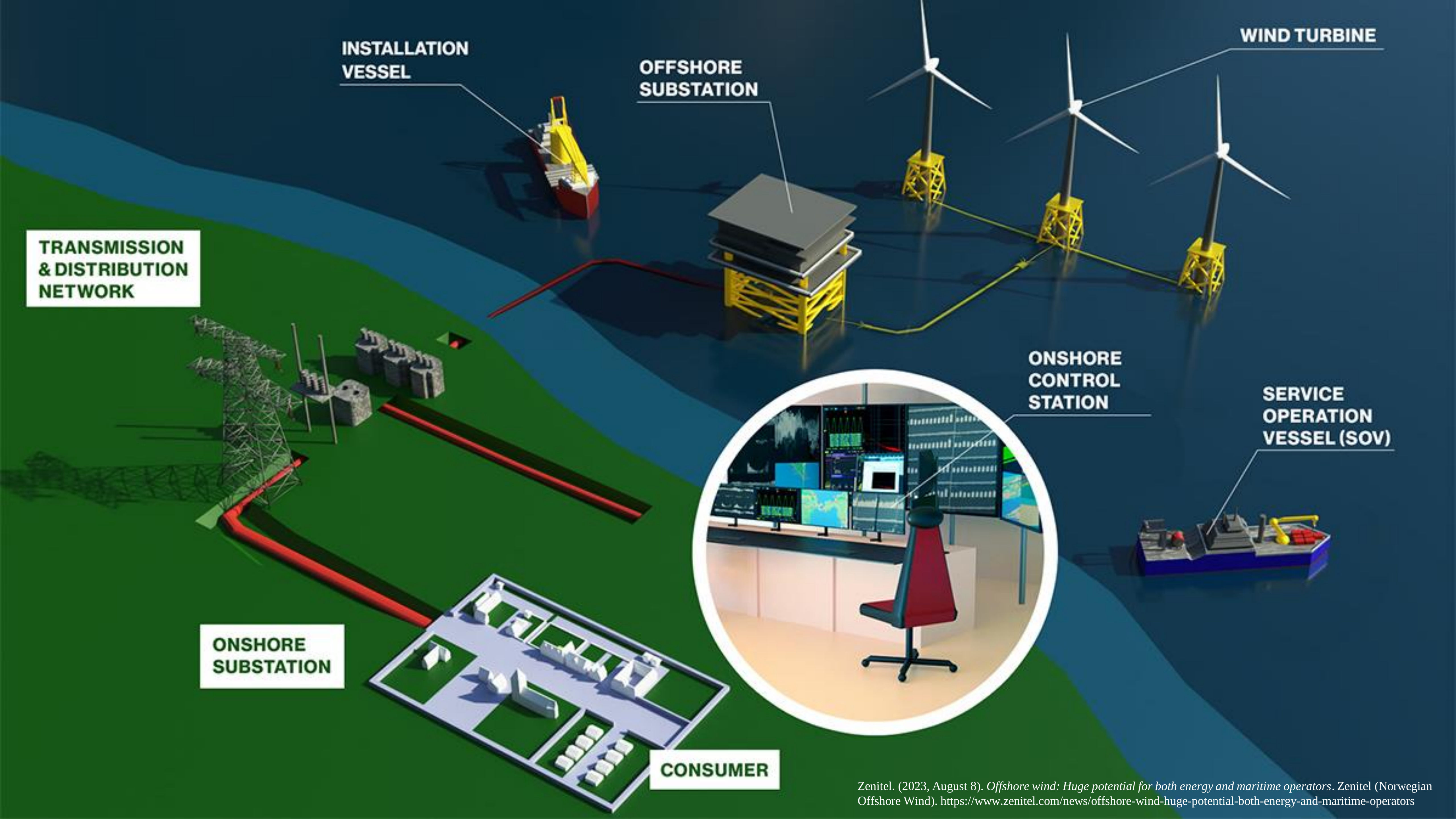
Challenge!

How can offshore wind farm Operational Technology (OT) communication networks be **<u>designed and optimized</u>** to handle the increased data traffic from IIoT devices while maintaining low latency, high reliability, and robust security?



Software-defined IIoT-Edge communication network (SD-IIoT-Edge)

?



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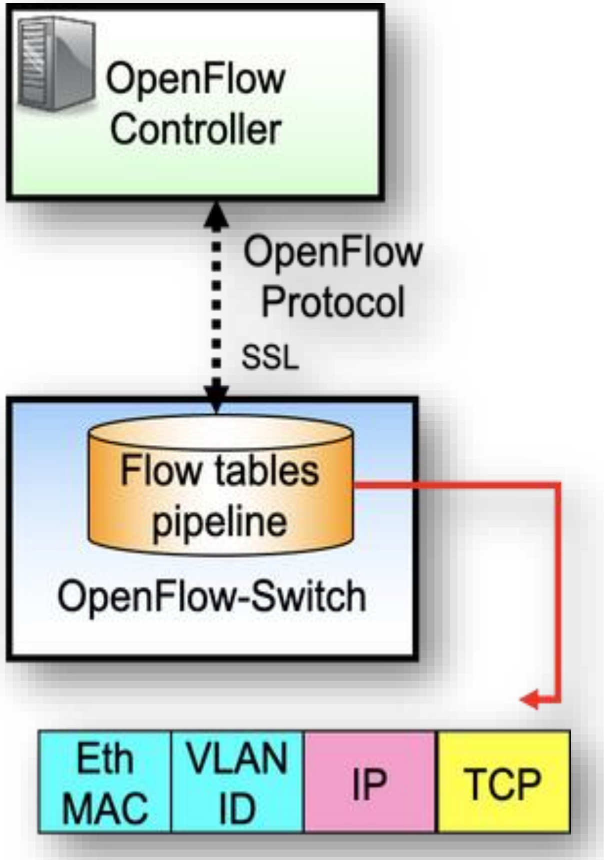
Software-Defined Networking (SDN) Architecture

- In principle, software defined networks decouples the control plane from the data plane so that the network transforms from a distributed architecture to a centrally managed architecture.

- Industrial IoT-Edge Networks can become vendor-agnostic with SDN. Network engineers focus on more innovative ways to manage their network services. Reduced OPEX with a one-off CAPEX.

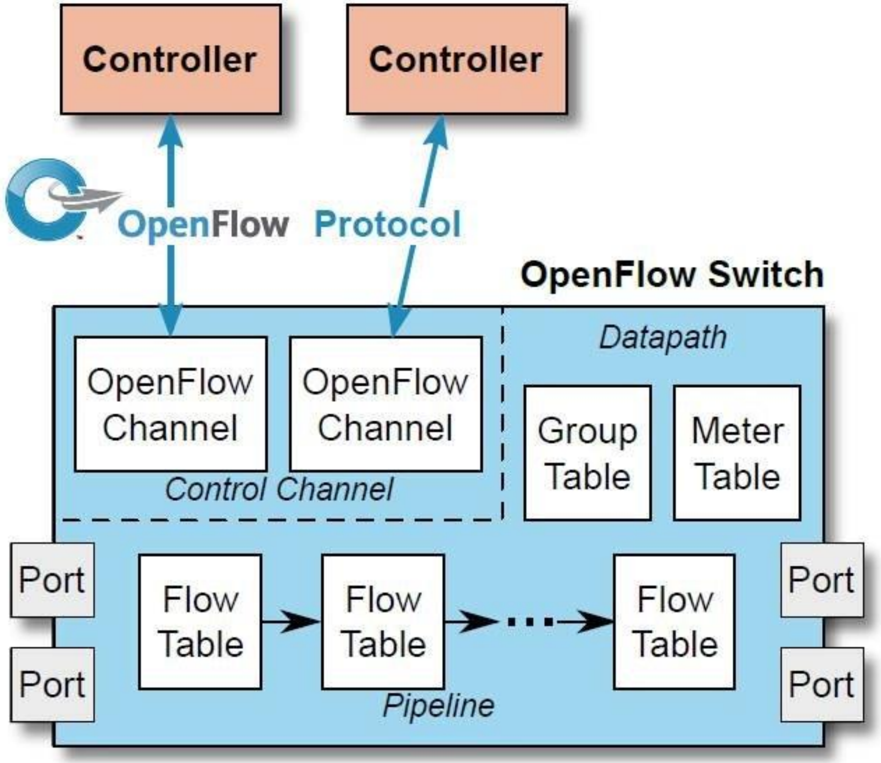
- Leveraging software defined networking in the design of future Industrial OT Networks aids network and service management. Enterprises have adopted network virtualization and SD-WAN to varying degrees but there are still a lot more traditional networks than software-defined ones.

OpenFlow on Cisco Catalyst 9000 Series Switches

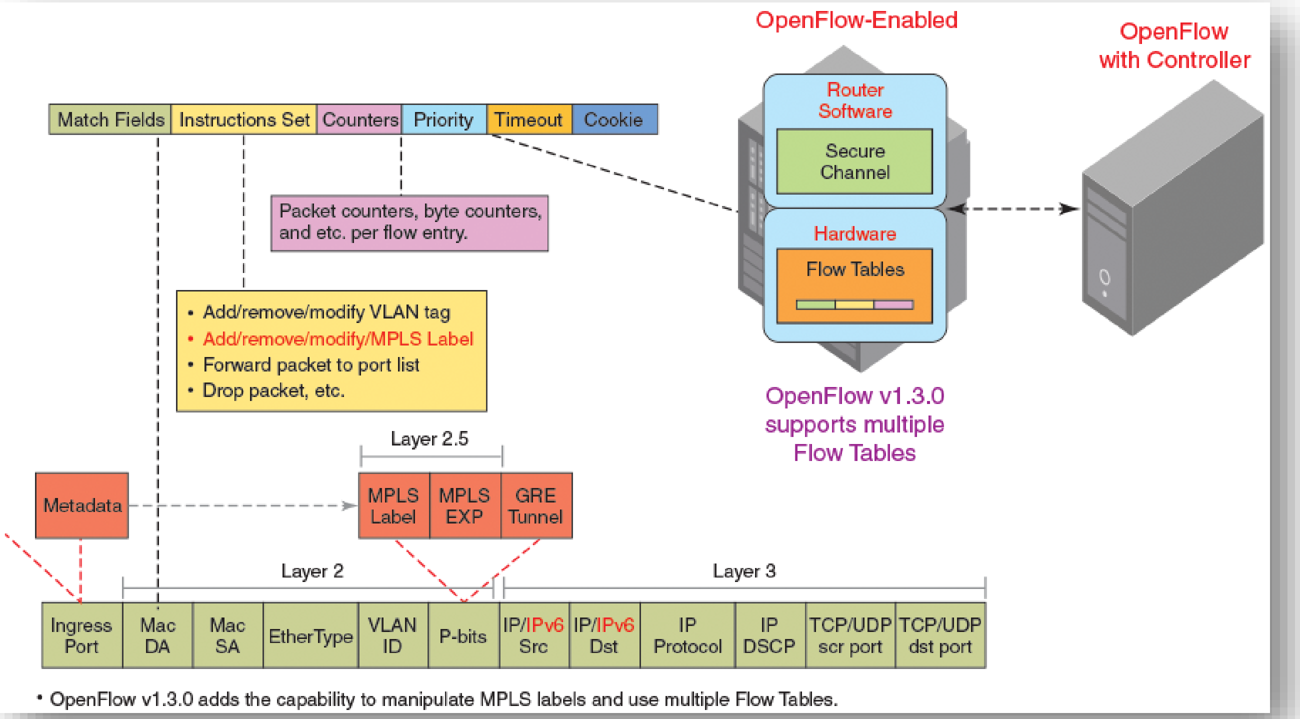


OpenFlow is a L2 communication protocol (Southbound Interface) that gives access to the data plane.

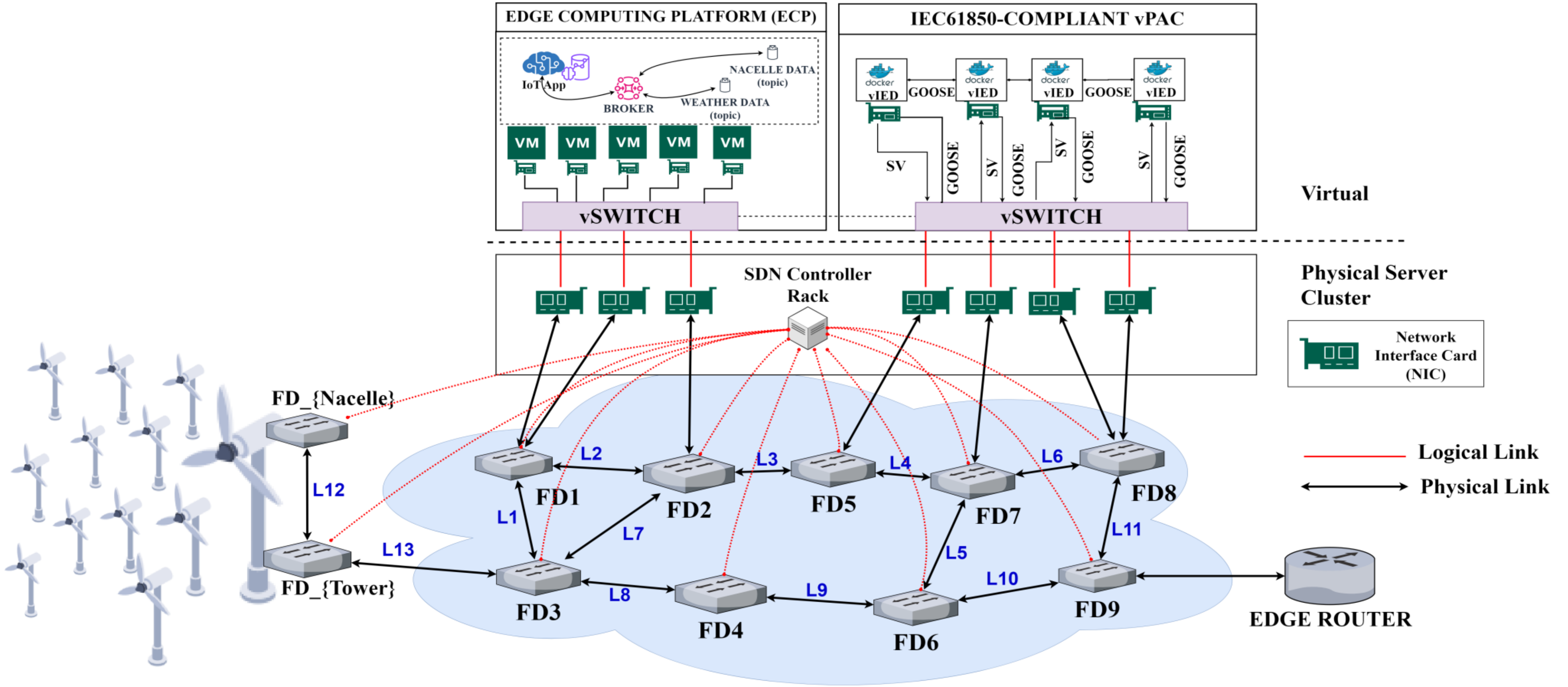
Software-Defined Networking (SDN) Architecture



- An OpenFlow switch maintains one or more flow tables, which are used for packet processing. The switch performs the actions listed in the table entry corresponding to the matched flow.
- Further, Overlaying SD-WAN on the IP/MPLS backhaul is the perfect architecture for enterprises. The two technologies are complementary where IP/MPLS defines the connectivity, and the SD-WAN manages the traffic.



Software-defined Industrial IoT-Edge communication networks (SD-IIoT-Edge)



An out-of-band control SDN-Enabled IIoT-Edge network schematic illustrating the fiber-optic-based connectivity between a fleet of wind turbine generator nacelle and tower switches connected to the offshore hub's data center switches FD{1,...,9} leading to the server cluster's physical network interfaces and virtualized networks within the ECP and vPAC nodes.

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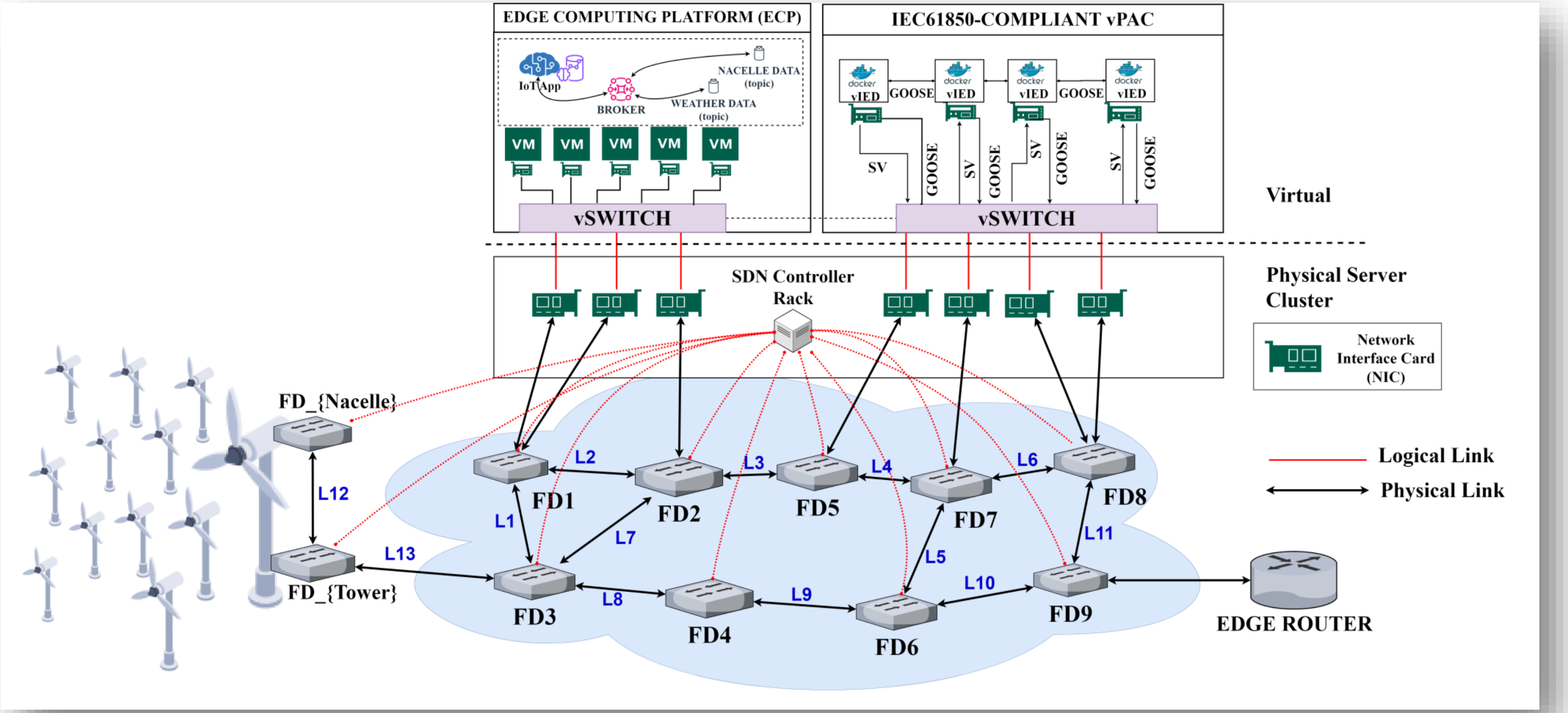
Software-defined Industrial IoT-Edge communication networks:
(Challenges and mitigation strategies)

While SDN/NFV architectures have demonstrated significant value in many application scenarios, there remains scalability, performance, reliability, and security concerns that hinder their implementation in mission critical applications such as offshore wind farms.



1 { • Scalability

2 { • Performance

3 { • Reliability

4 { • Security

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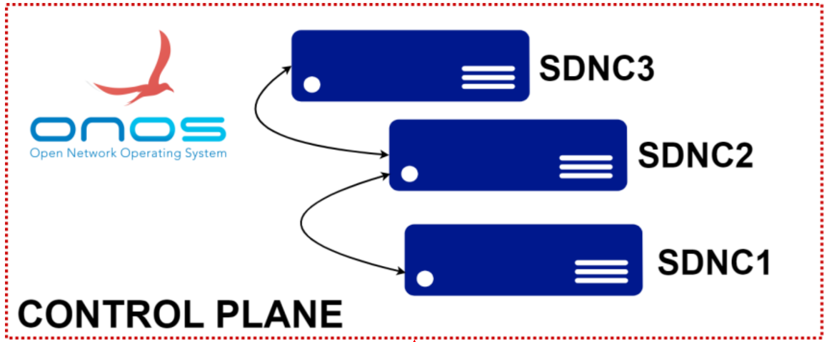
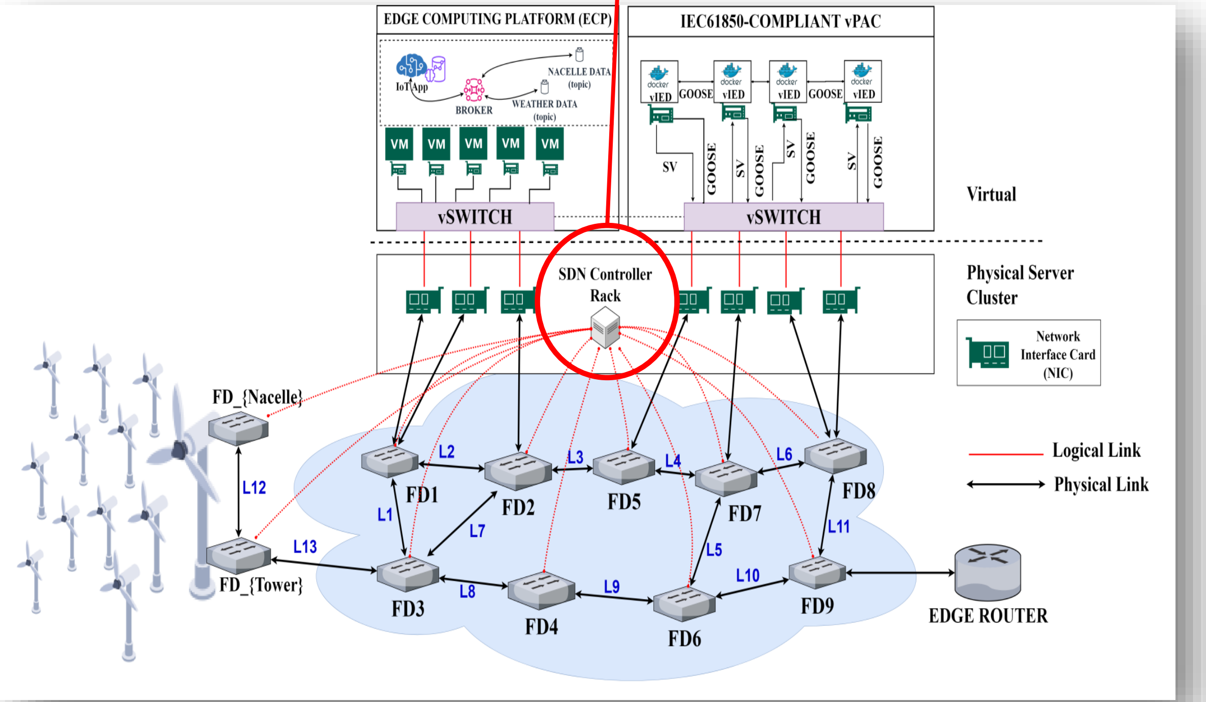
Scalability in software-defined IIoT-Edge communication networks






```
In [1]: runfile('C:/Users/amwangi254/JP3/ApplicationPlane/network_monitoring_module.py',
wdir='C:/Users/amwangi254/JP3/ApplicationPlane')
Enter the IP address of the ONOS controller (default is 192.168.0.7): 192.168.0.7
Enter the username for ONOS controller (default is 'onos'): onos
Enter the password for ONOS controller (default is 'rocks'): rocks
Data has been written to 'port_stats.csv'.
```

- ❑ SDN Clusters guarantee redundancy by deploying (n+1) SDN controller to manage the software-defined network. It is recommended to have a minimum of 3 SDN controllers for every network.

- ❑ Running the raft algorithm to assign leadership roles in the SDN controller cluster.

```
07:25:35.139 INFO  [atomix-0] Started
07:25:35.208 INFO  [atomix-0] Starting server for partition PartitionId{id=1, group=system}
07:25:35.538 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1} - Transitioning to FOLLOWER
07:25:38.446 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1} - Transitioning to CANDIDATE
07:25:38.448 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1}{role=CANDIDATE} - Starting election
07:25:38.461 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1} - Transitioning to LEADER
07:25:38.469 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1} - Found leader 192.168.0.6
07:25:39.147 INFO  [raft-partition-group-system-0] Started
07:25:39.310 INFO  [raft-partition-group-system-0] Starting server for partition PartitionId{id=1, group=raft}
07:25:39.435 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1} - Transitioning to FOLLOWER
07:25:42.042 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1} - Transitioning to CANDIDATE
07:25:42.043 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1}{role=CANDIDATE} - Starting election
07:25:42.061 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1} - Transitioning to LEADER
07:25:42.062 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1} - Found leader 192.168.0.6
07:25:42.921 INFO  [raft-partition-group-raft-3] Started
07:25:42.921 INFO  [raft-partition-group-raft-3] Started
07:25:43.087 INFO  [raft-partition-group-system-2] Started
07:25:43.089 INFO  [raft-partition-group-system-2] Started
07:25:43.090 INFO  [SCR Component Actor] Started
07:25:43.093 INFO  [FelixStartLevel] Updated node 192.168.0.6 state to ACTIVE
07:25:43.096 INFO  [FelixStartLevel] Started
```

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Performance in software-defined IIoT-Edge communication networks

- It is important for the software-defined IIoT-Edge network to meet the performance requirements for the different data traffic types.
- These data traffic types are categorized into:
  - Critical, time-sensitive data traffic (protection, control, analogue measurements, status information, and data polling WPP services).
  - Best-effort data traffic (reporting and logging, video surveillance, and wireless network connectivity for O&M personnel).

Service	Communication Direction	Priority	Data Rate	Latency	Reliability	Packet Loss Rate
Protection traffic	WTG → vPAC	1	76,816 bytes/s	4 ms	99.999%	$<10^{-9}$
Analogue measurements	WTG → vPAC/ECP	2	225,544 bytes/s	16 ms	99.999%	$<10^{-6}$
Status information	WTG → ECP	2	58 bytes/s	16 ms	99.999%	$<10^{-6}$
Reporting and logging	WTG → ECP	3	15 KB every 10 min	1 s	99.999%	$<10^{-6}$
Video surveillance	WTG → ECP	4	250 kb/s–1.5 Mb/s	1 s	99%	No specific requirement
Control traffic	vPAC → WTG	1	20 kbs/per turbine	16 ms	99.999%	$<10^{-9}$
Data polling	ECP/vPAC → WTG	2	2 KB every second	16 ms	99.999%	$<10^{-6}$
Internet connection	Internet → WTG/ECP/vPAC	3	1 GB every two months	60 min	99%	No specific requirement

Offshore wind farm data communication parameters between the wind turbine generators (WTG), the offshore hub-mounted data center components, and the Internet.

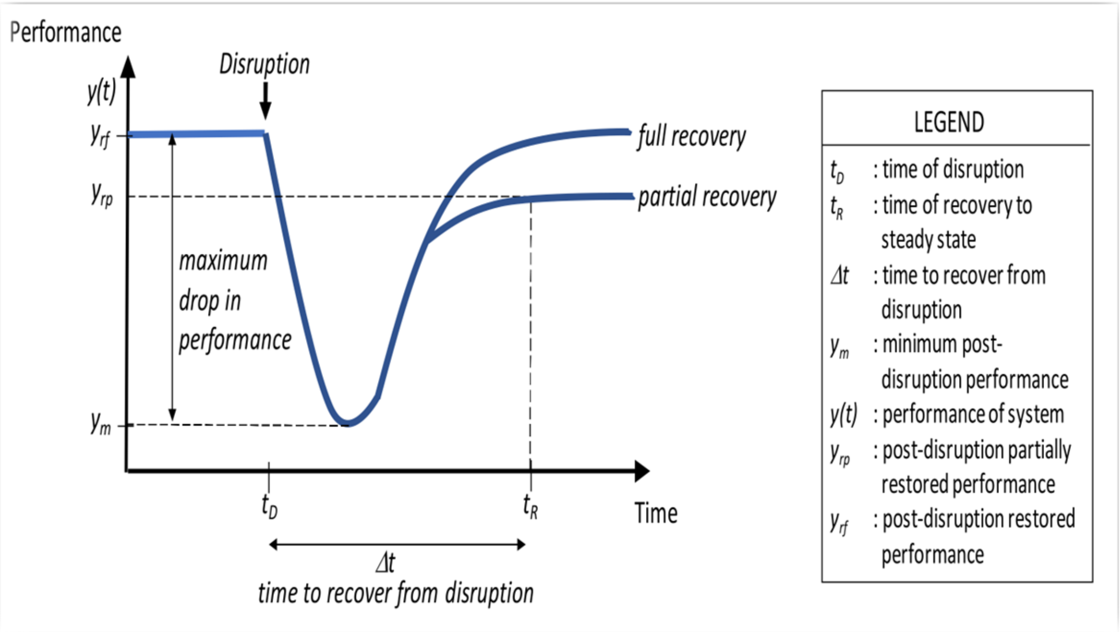
Performance in software-defined IIoT-Edge communication networks

- The software-defined industrial IoT-Edge, like other traditional networks, encounter stochastic disruptions in different forms.

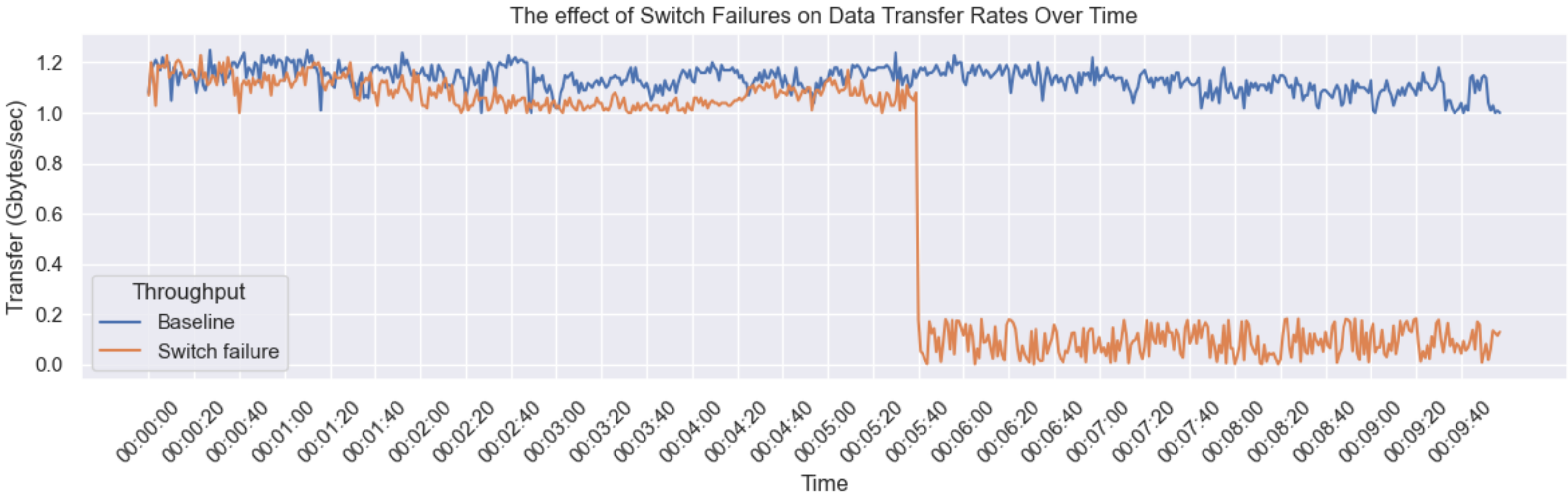
- These stochastic disruptions reduce the overall performance so that the network performance shifts from y_{rf} to y_m. When this happens, the network engineers engage several traffic engineering and other recovery strategies to restore the network to either y_{rf} or y_{rp}.

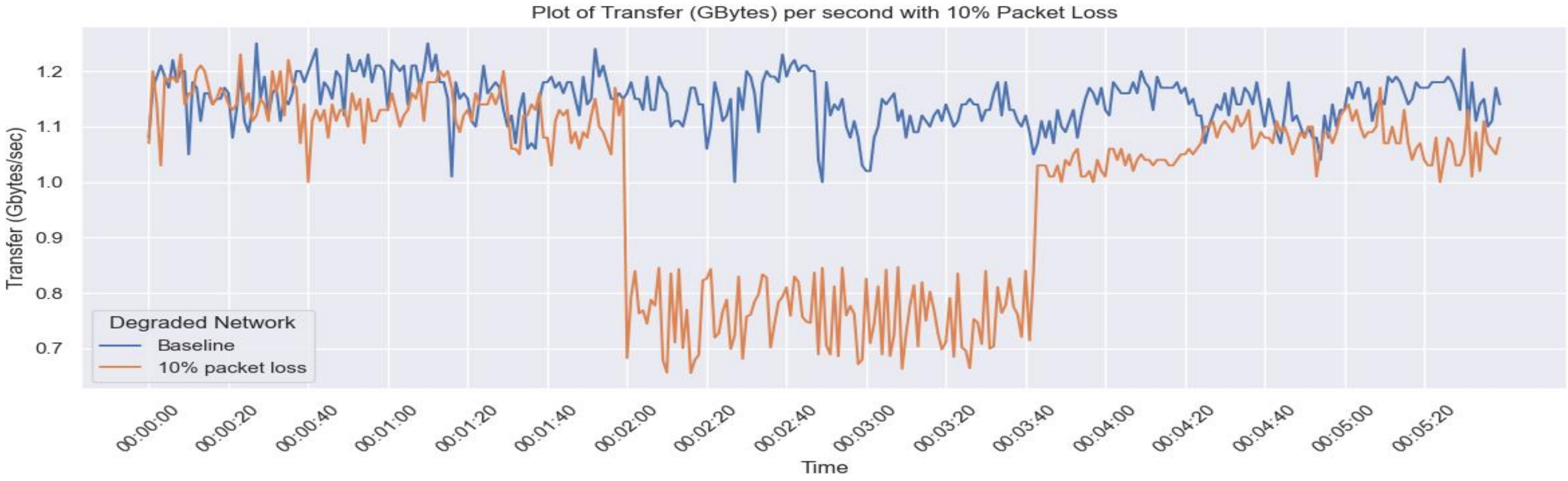
- Additionally, when the network performance drops, the time taken to recover the network to either y_{rf} or y_{rp} varies.

- While stochastic disruptions are inevitable, it is important to ensure that the approaches taken to restore the network ensure the least time to recovery from disruptions.



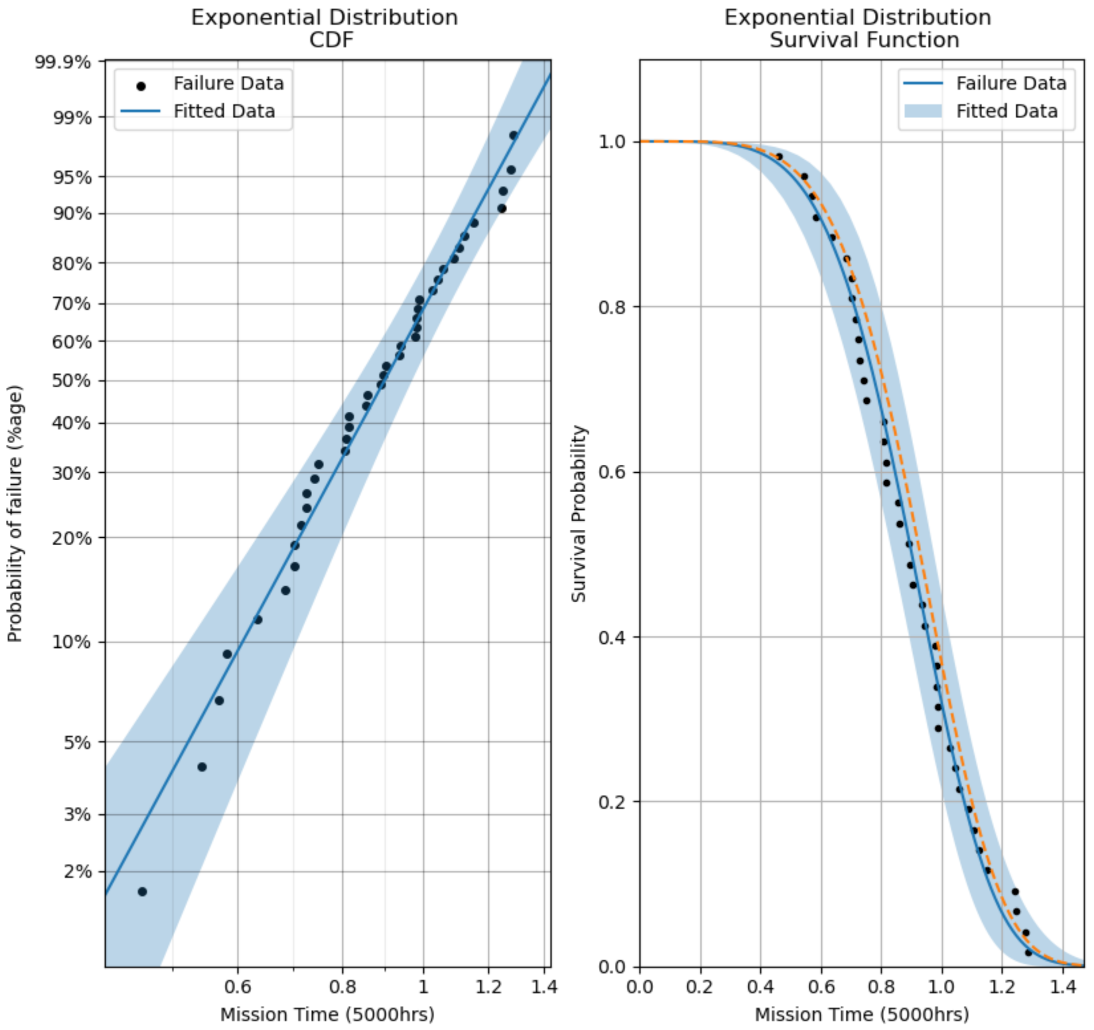
Performance in software-defined IIoT-Edge communication networks





Reliability in software-defined IIoT-Edge communication networks

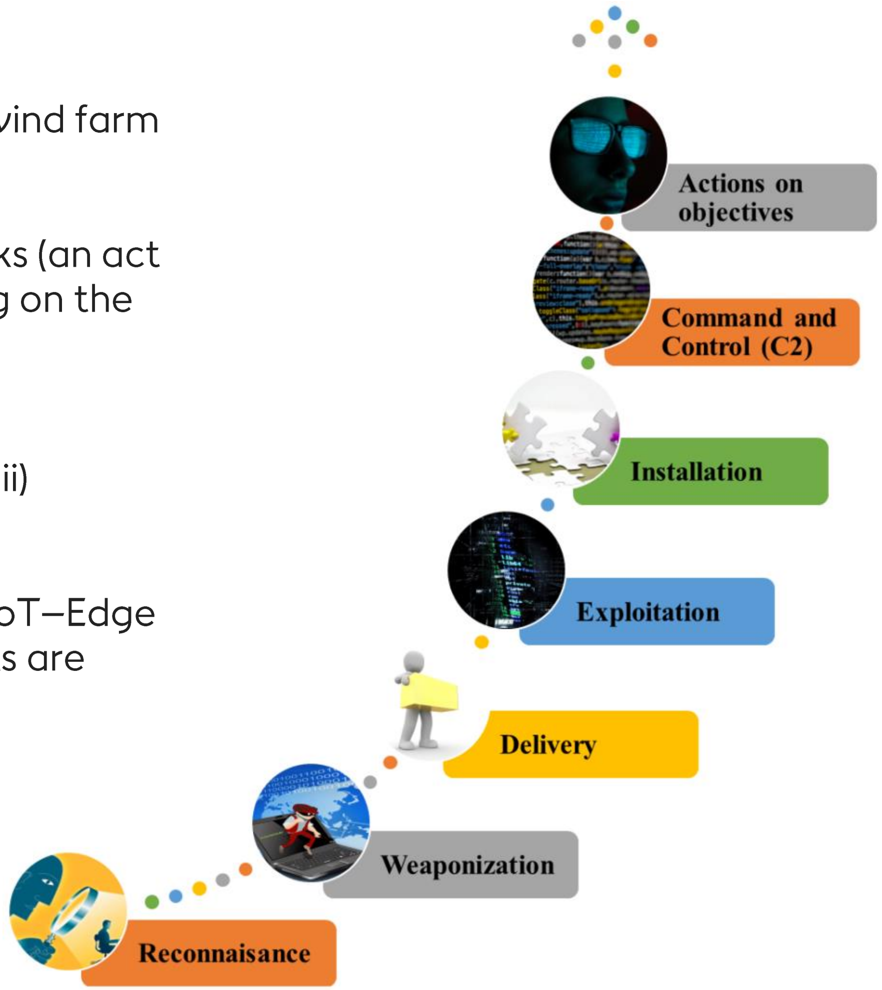
- The reliability of the software-defined IIoT–Edge network addresses architectural robustness, failover mechanisms, and performance under stress conditions.
- Given that these networks are deployed in extreme environments with unpredictable weather, there is a need to deploy ruggedized equipment that can withstand the harsh conditions of the offshore environment.
- The network reliability and availability are constantly affected, and, as a result, more advanced fast failover recovery methods are studied to tackle the availability issues by defining reliability or failure models and making inferences from the model results to determine the availability.



Security in software-defined IIoT-Edge communication networks

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

- Adopting software-defined IIoT–Edge networks exposes the critical wind farm infrastructure to cyber threats.
- Cyber threats (a potential risk of exploiting a vulnerability) and attacks (an act of exploiting a vulnerability) can either be passive or active depending on the objective of the intruder.
- The intruders who develop methods to exploit vulnerabilities in this communication network are motivated by (i) financial, (ii) espionage, (iii) disruption, (iv) political, and (v) retaliation reasons.
- To address the rising cybersecurity concern in this software-defined IIoT–Edge network, robust security policies, rules, and intrusion-detection models are adopted.



ISA-99/IEC62443 Industrial Control System Cyber-kill chain

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a) Mwangi, Agrippina, Rishikesh Sahay, Elena Fumagalli, Mikkel Gryning, and Madeleine Gibescu. 2024. "*Towards a Software-Defined Industrial IoT-Edge Network for Next-Generation Offshore Wind Farms: State of the Art, Resilience, and Self-X Network and Service Management*" Energies 17, no. 12: 2897. https://doi.org/10.3390/en17122897

Can we use AI to self-heal the software-defined IIoT-Edge networks?

PART II

Autonomous software-defined Industrial IoT-Edge communication networks

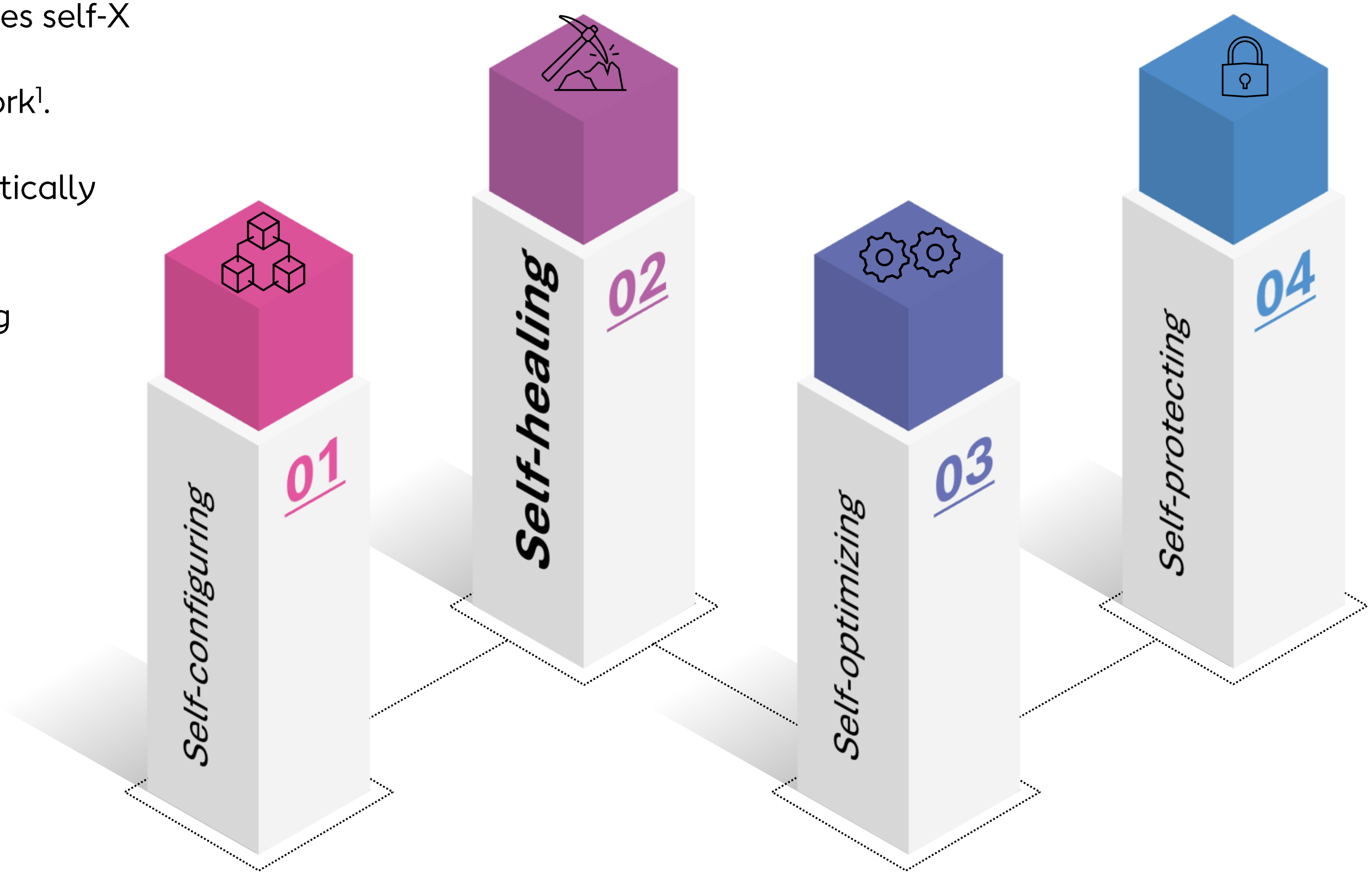
(Self-healing cognitive AI tool)

Autonomous software-defined Industrial IoT-Edge networks:
Self-healing as a concept

- European Telecommunication Standards Institute defines self-X (self-configuring, **self-healing**, self-optimizing, and self-protecting) network and service management framework[1].

- Self-healing focuses on the network's ability to automatically detect, diagnose, and resolve faults to maintain service continuity. It essentially ensures the network remains operational despite unexpected failures or issues, acting reactively to correct problems as they occur[2].

"An autonomous network (AN) is a network that self-operates according to the business goals with no human intervention beyond the initial supply of input (e.g., intent, goals, policies, certain configuration data) provided by the human operator." [1-2]
(ETSI, 2019)



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1. ETSI. ETSI White Paper No. 32: Network Transformation; Orchestration, Network and Service Management Framework: 1st Edition. 2019. Available at: https://www.etsi.org/images/files/ETSIWhitePapers/ETSI_White_Paper_Network_Transformation_2019_N32.pdf
2. Mwangi A, Sahay R, Fumagalli E, Gryning M, Gibescu M. Towards a Software-Defined Industrial IoT-Edge Network for Next-Generation Offshore Wind Farms: State of the Art, Resilience, and Self-X Network and Service Management. *Energies*. 2024; 17(12):2897. https://doi.org/10.3390/en17122897

Application Scenario

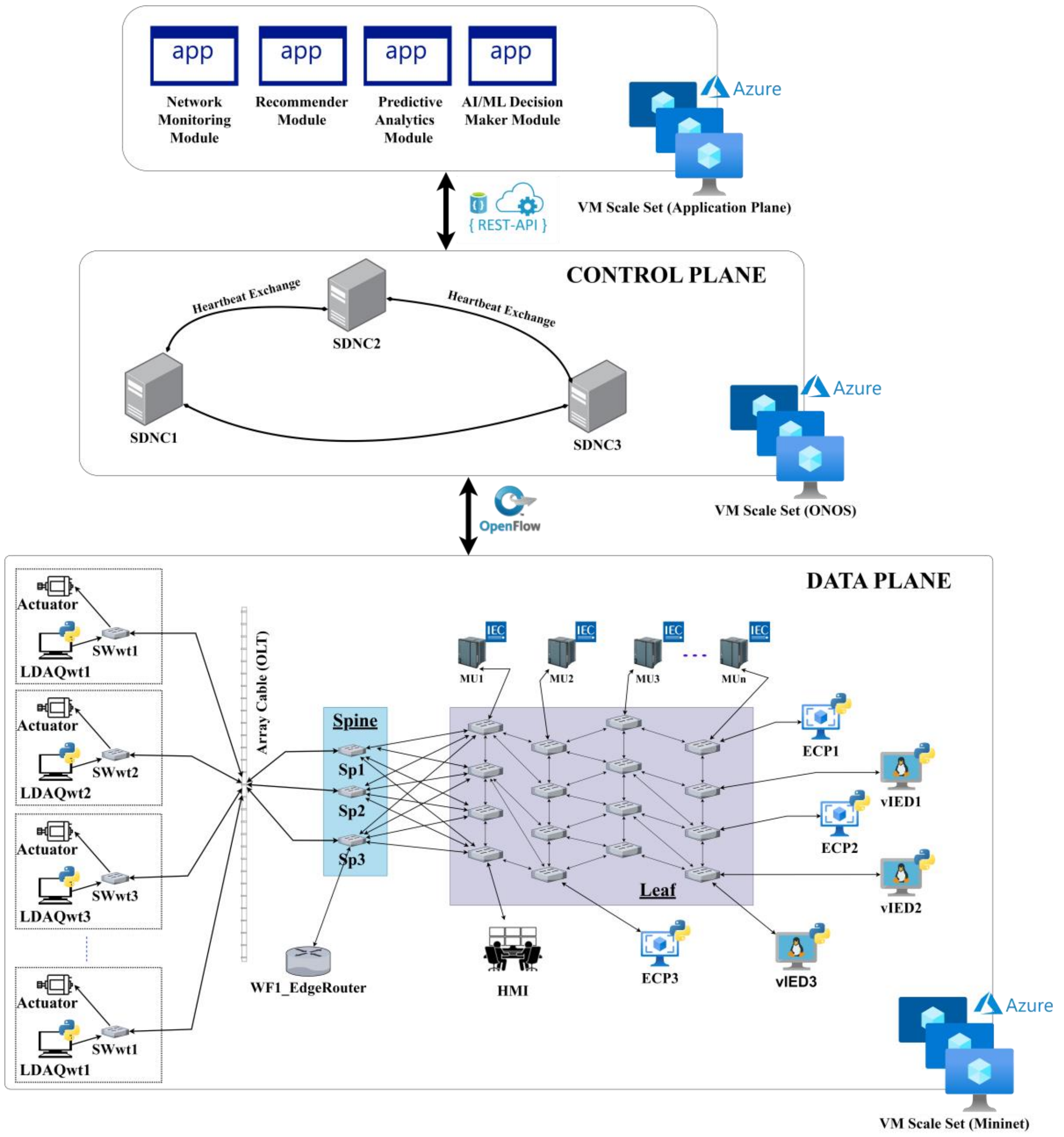
- A hybrid-band control (HBC) software-defined OT communication network was designed with the data plane utilizing Mininet and the control plane managed by the ONOS SDN Controller.

- Proposed architecture:

  - Redesign each Operations Support System (OSS) as a data center. The OSS uses a spine-leaf network topology, using programmable OpenFlow-hybrid IEEE802.1 Time Sensitive Networking (TSN) Ethernet switches at the data plane.

  - Redesign each mainland control center as a Central Office Re-architected as a Data Center (CORD).

  - Deploy software-defined networks (SDNs) at the Operational Technology (OT) layer, encompassing devices within the OSS, in a hybrid setup alongside WTG access networks operating on conventional networks



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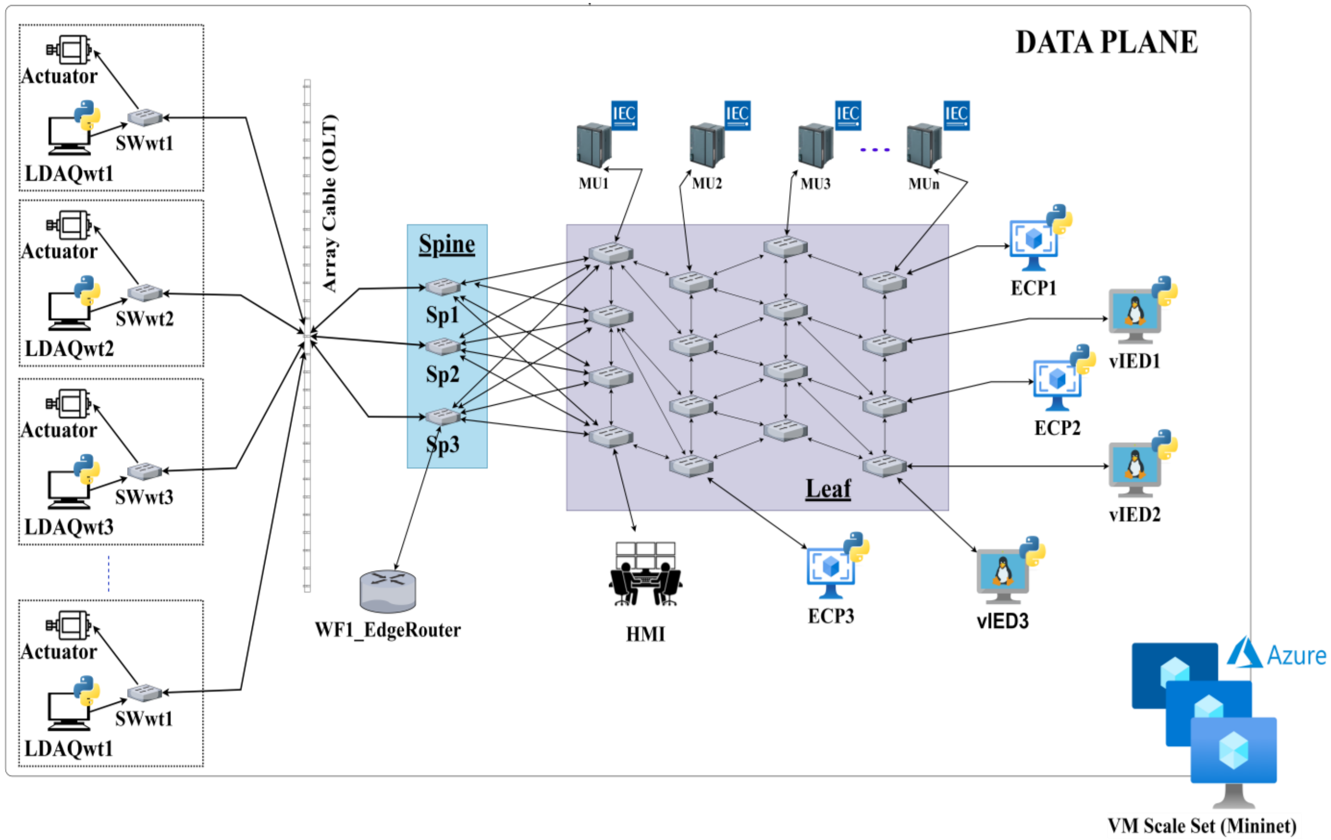
Traffic Generation



- The WPP data services (turbine operational data, condition monitoring data, meteorological data, and event-driven maintenance data) were generated using a customized publish/subscribe python (.py) script.
- Open-source LibIEC61850 for protection and control traffic. [Source]

WPP Data Service	Nodes	Type
Turbine Operational Data (e.g. power output, rotor speed, wind speed and direction)	WTG → ECP	- Critical - Time sensitive
Control traffic	vIED → WTG	
Protection traffic	WTG → vIED	
Condition monitoring data (e.g. vibration)	WTG → ECP	- Critical - Delay tolerant
Meteorological Data (e.g. temperature, humidity, atmospheric pressure)	WTG → ECP	- Best effort
Event-driven Maintenance Data (e.g. alerts, logs, and alarms)	WTG → ECP	

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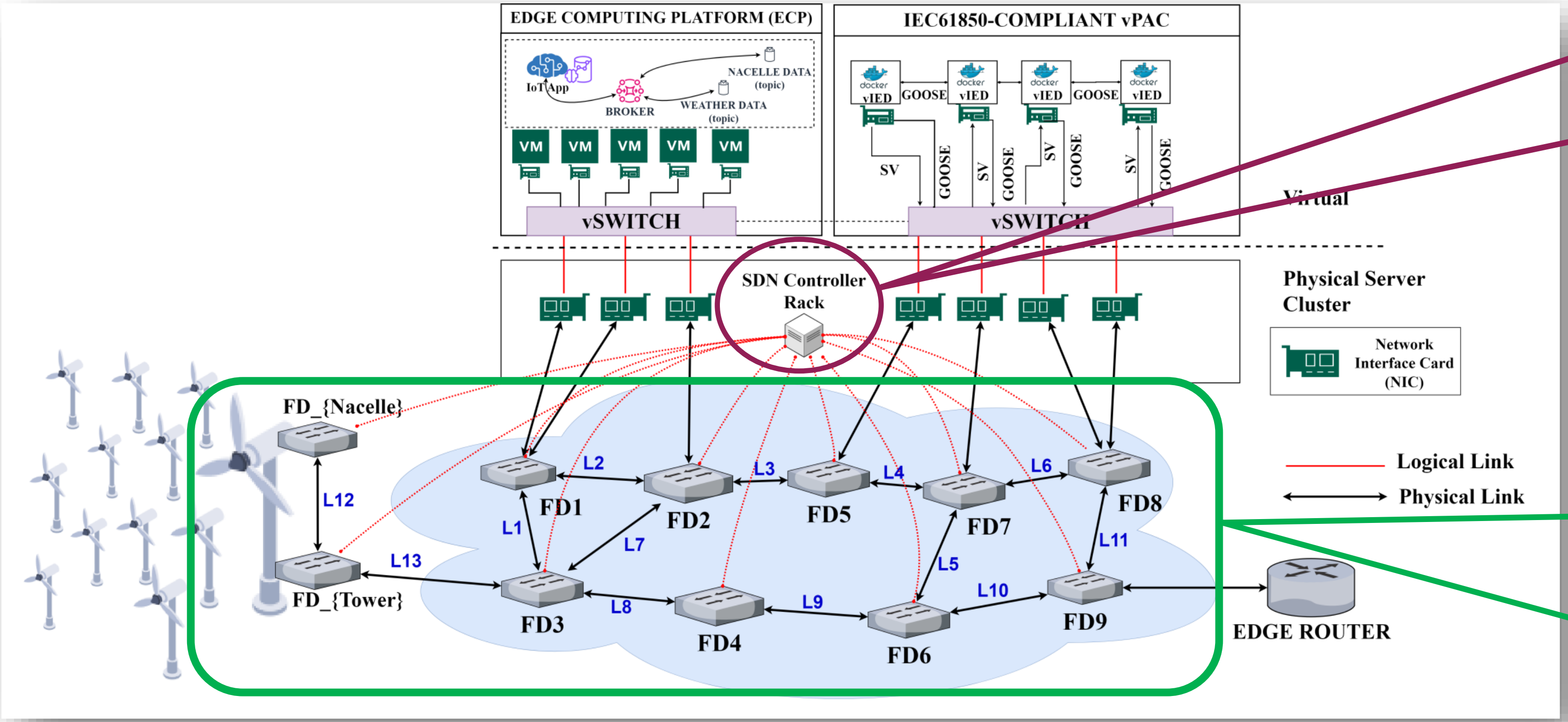
Why self-heal?



- ❑ Automatically detect and recover from controller crashes or malfunctions (VM and software).
- ❑ Resource exhaustion (Overconsumption of CPU and Memory Leakages)
- ❑ Identify and correct discrepancies in the network state to maintain accurate and consistent network operations.

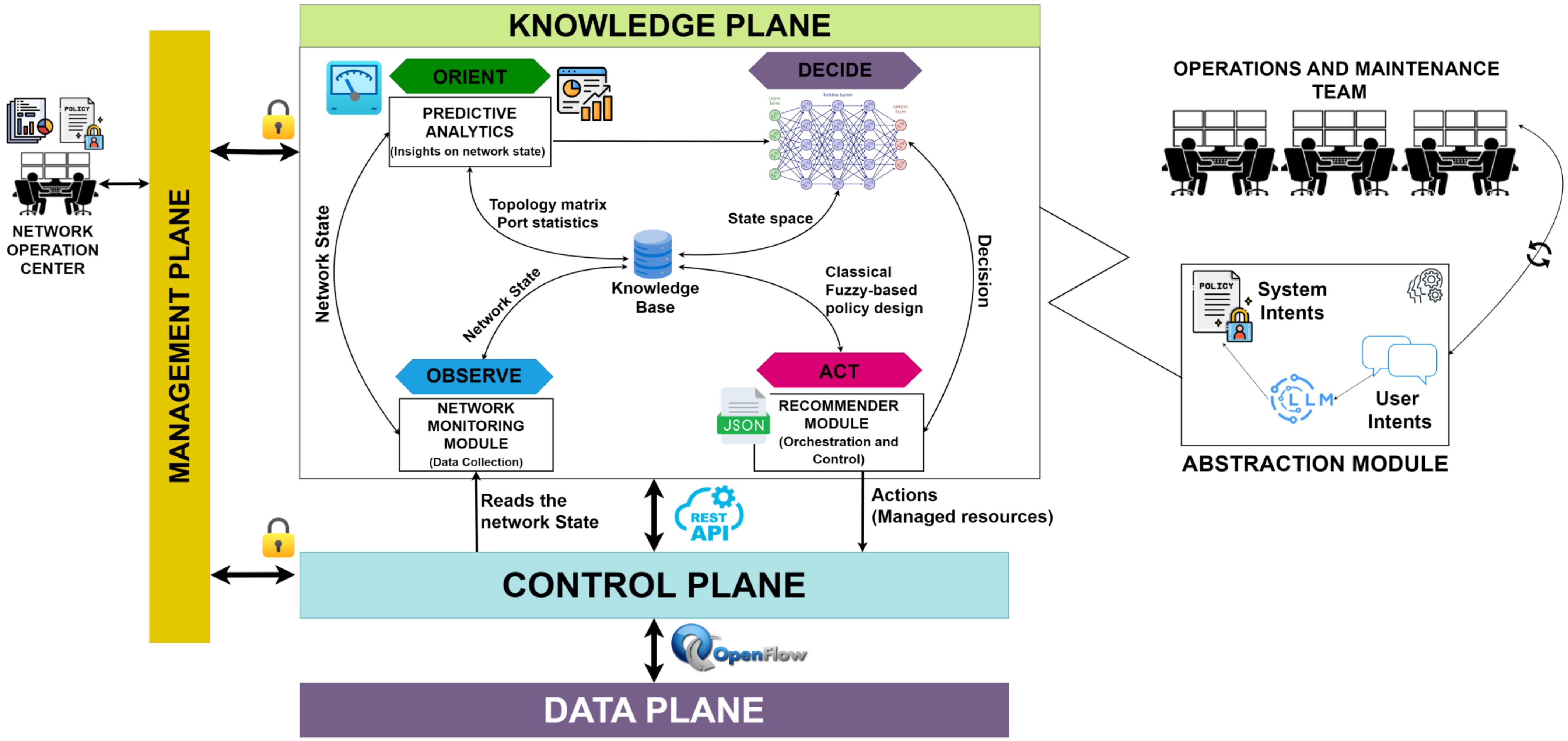
- ❑ Detecting and bypassing failed hardware components (switches and links).
- ❑ Automatically managing and alleviating network congestion to prevent bottlenecks and ensure smooth data flow.
- ❑ Automatically identifying and mitigating sources of increased latency and packet loss in the data plane to ensure optimal network performance.

NB:

1. The spine-leaf topology used here incorporates link aggregation for redundancy and a full mesh between the spine switches and the distribution leaf switches.
2. Server cluster application for server (1...n) ensures that Edge computing Platform (ECP) and IEC61850 virtual Protection, Automation, and Control (vPAC) services continue to run smoothly.

Self-healing framework for clustered offshore wind farm

(The "***Observe-Orient-Decide-Act***" closed control loop)



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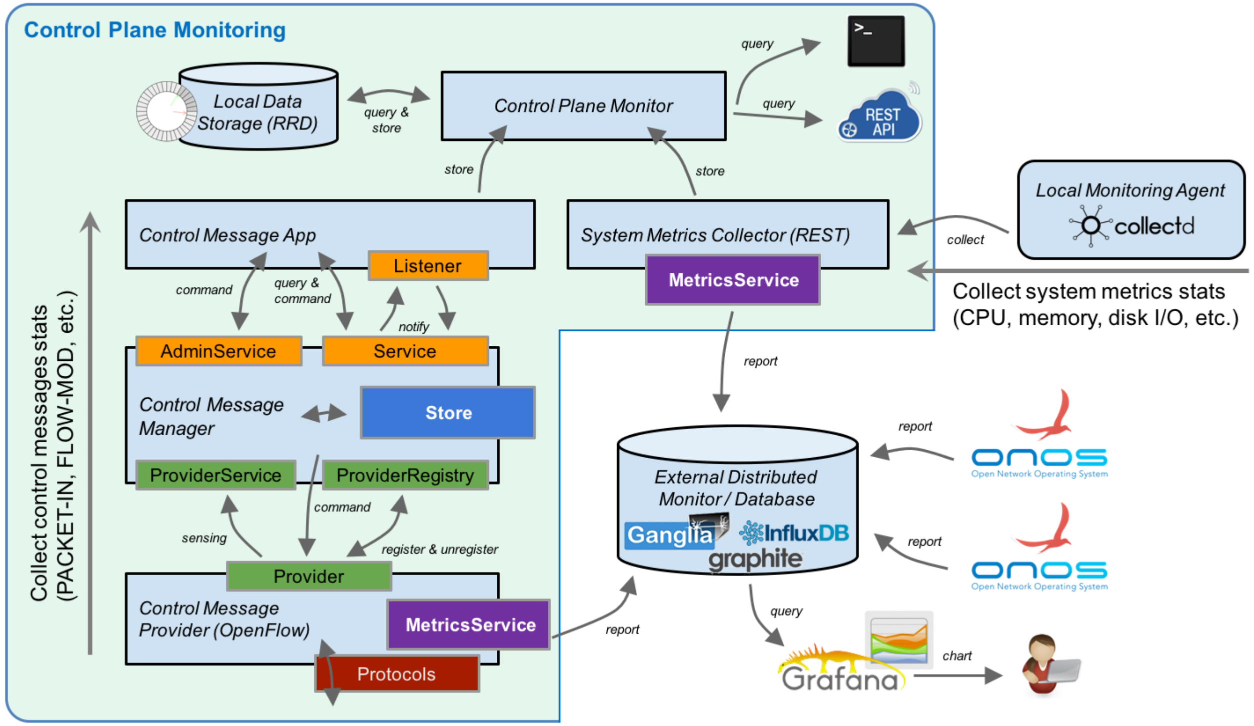
"Observe-Orient-Decide-Act" Closed Control Loop Cycle
OBSERVE Module

- The Observe Module reads the current network state from the control plane's topology, statistics, and flow rule manager.
- Accessing the ONOS SDN controller topology manager, statistics manager, and flow rule manager data stores using RESTful APIs to extract the data plane metrics (status of the network components) and the control plane metrics such as CPU consumption, Memory consumption, and Virtual Machine (VM) status.



The "OBSERVE" self-healing framework module showing interactions between control plane, *collectd*, InfluxDB, and Grafana for collecting, storing, and visualizing control and system metrics

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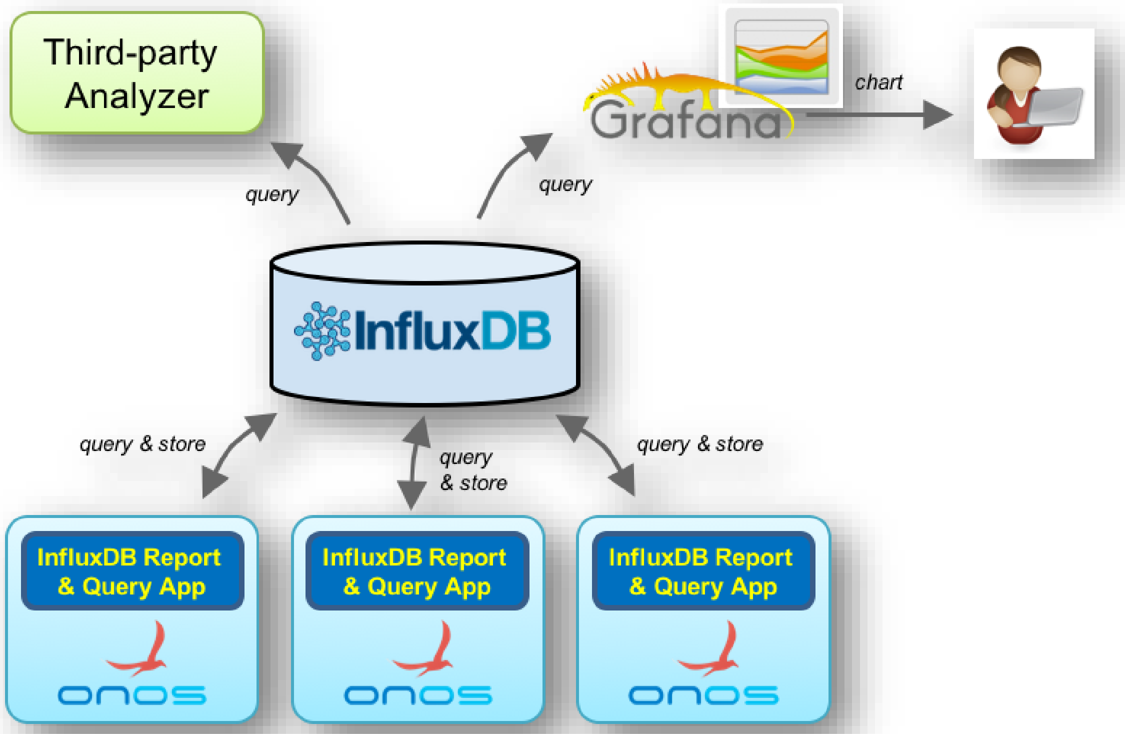
“Observe-Orient-Decide-Act” Closed Control Loop Cycle
Knowledge Base

- InfluxDB is a distributed time-series database written in GO language and is optimized for storing time-series data while supporting clustering. It is a powerful database solution for applications that require high-performance and scalable storage and querying of time-series data.
- Each ONOS instance can periodically report various metrics data to influxDB, and the network engineers can easily query global performance metrics from the knowledge base.
- This InfluxDB supports a dashboard built using Grafana and Graphite visualization tool.



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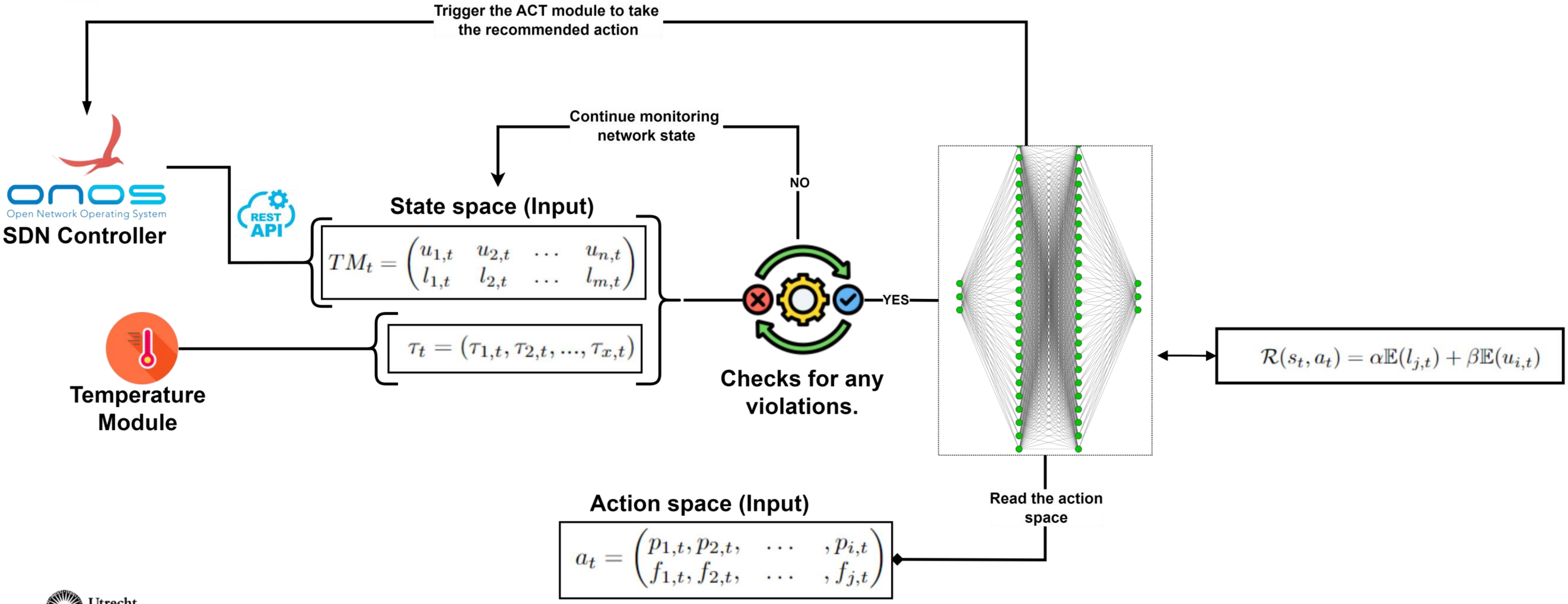
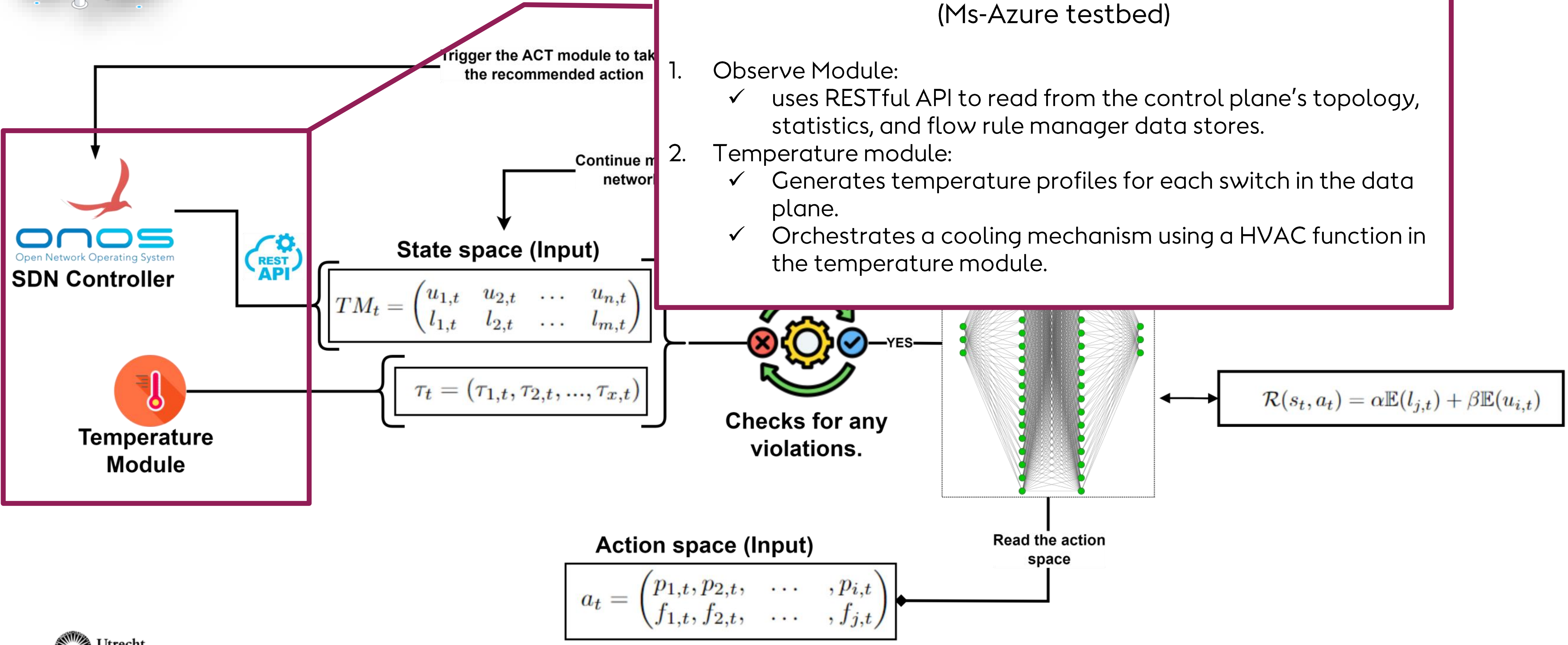
A threshold-triggered Deep Q-Network (DQN) self-healing algorithm



A threshold-triggered Deep Q-Network (DQN) self-healing algorithm

Mininet + ONOS SDN Controller cluster
(Ms-Azure testbed)

1. Observe Module:
   - ✓ uses RESTful API to read from the control plane's topology, statistics, and flow rule manager data stores.
2. Temperature module:
   - ✓ Generates temperature profiles for each switch in the data plane.
   - ✓ Orchestrates a cooling mechanism using a HVAC function in the temperature module.



A threshold-triggered Deep Q-Network (DQN) self-healing algorithm

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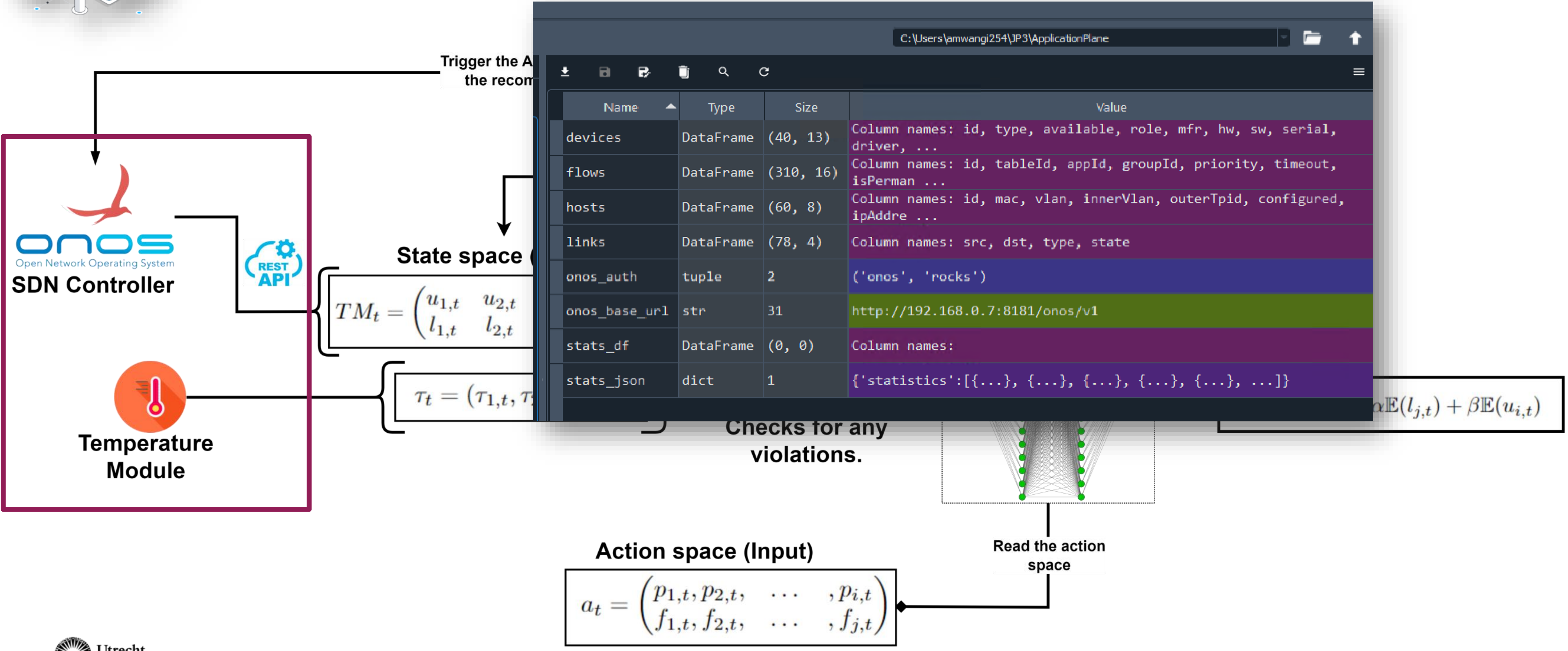

Name	Type	Size	Value
devices	DataFrame	(40, 13)	Column names: id, type, available, role, mfr, hw, sw, serial, driver, ...
flows	DataFrame	(310, 16)	Column names: id, tableId, appId, groupId, priority, timeout, isPerman ...
hosts	DataFrame	(60, 8)	Column names: id, mac, vlan, innerVlan, outerTpid, configured, ipAddre ...
links	DataFrame	(78, 4)	Column names: src, dst, type, state
onos_auth	tuple	2	('onos', 'rocks')
onos_base_url	str	31	http://192.168.0.7:8181/onos/v1
stats_df	DataFrame	(0, 0)	Column names:
stats_json	dict	1	{'statistics':[{...}, {...}, {...}, {...}, {...}, ...]}

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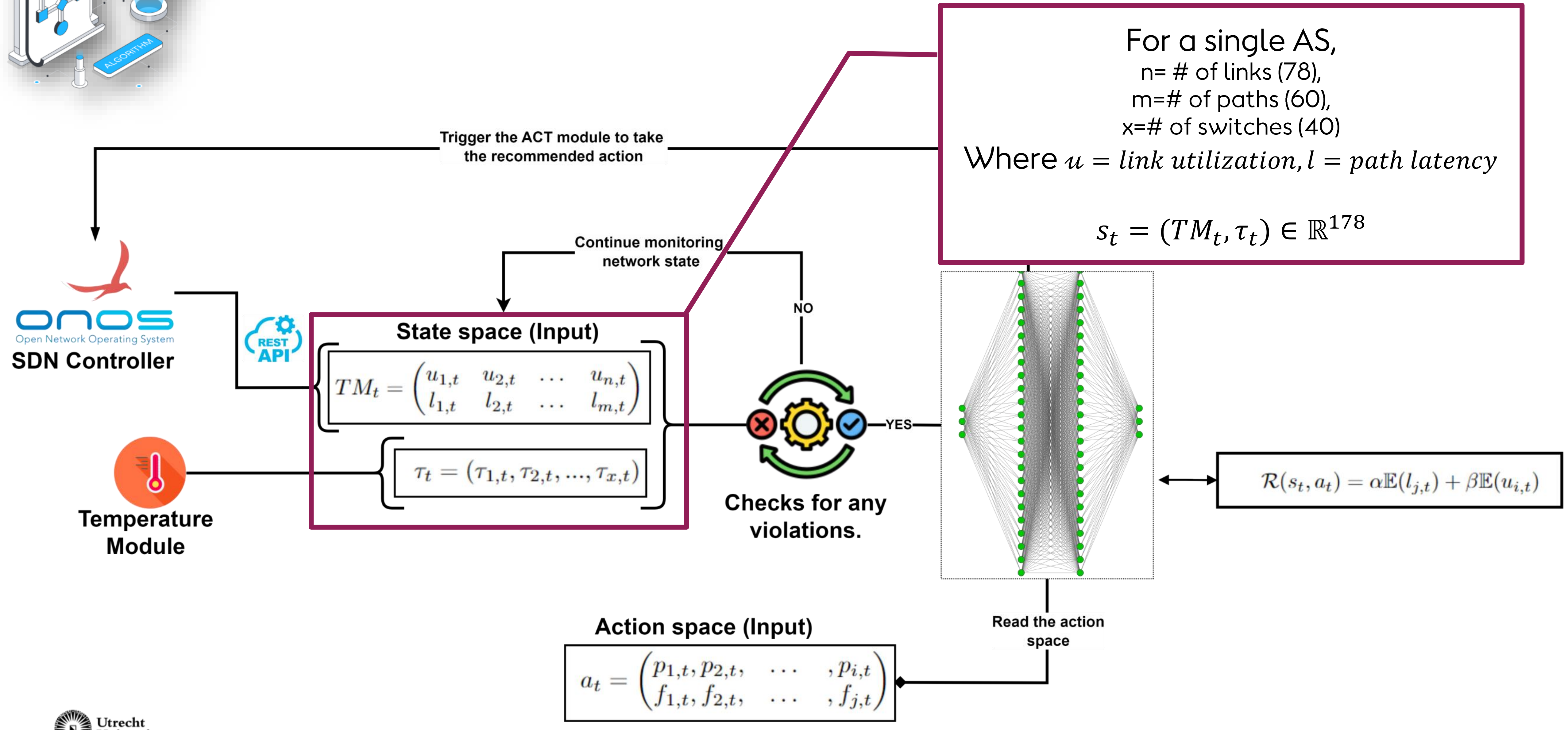

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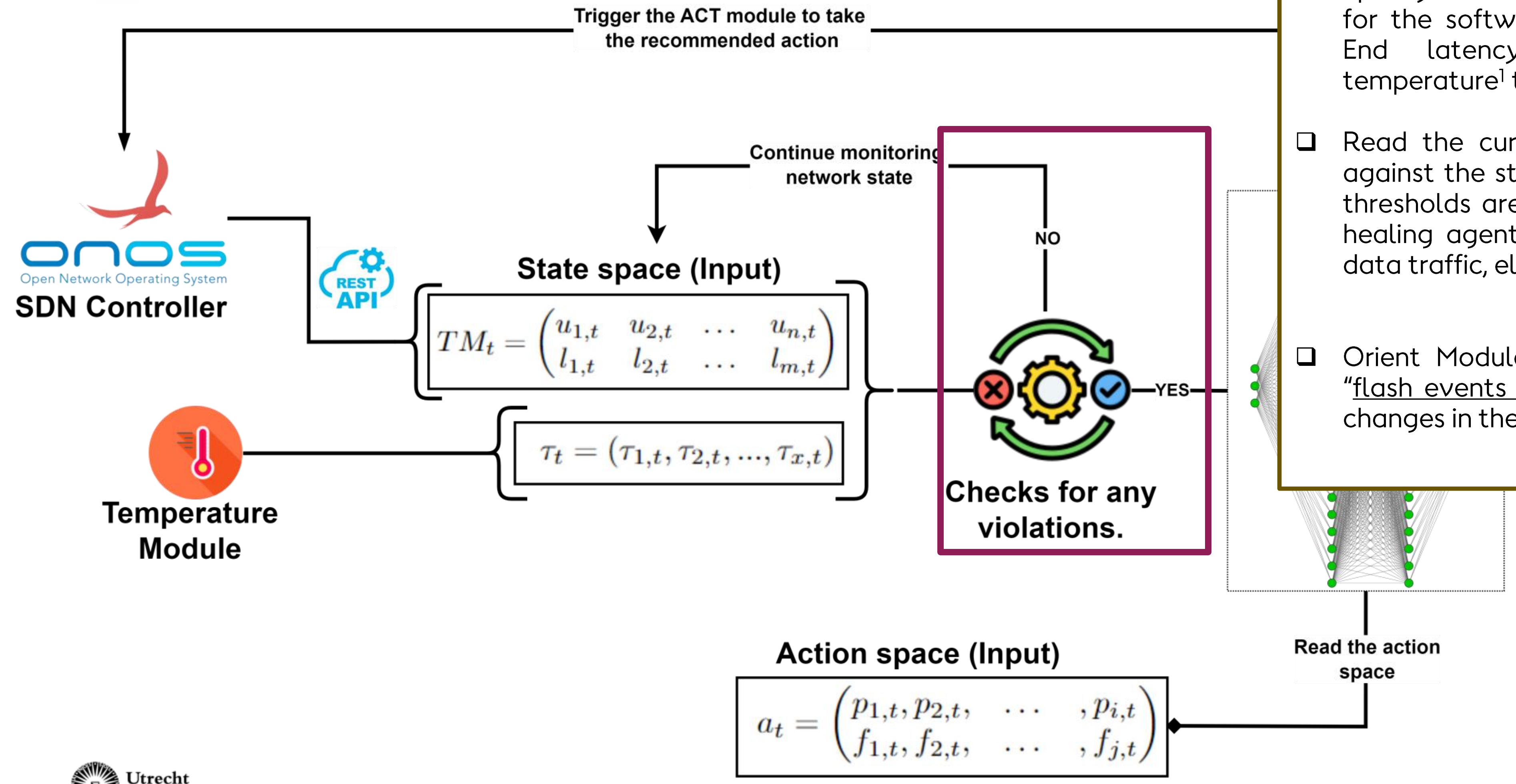
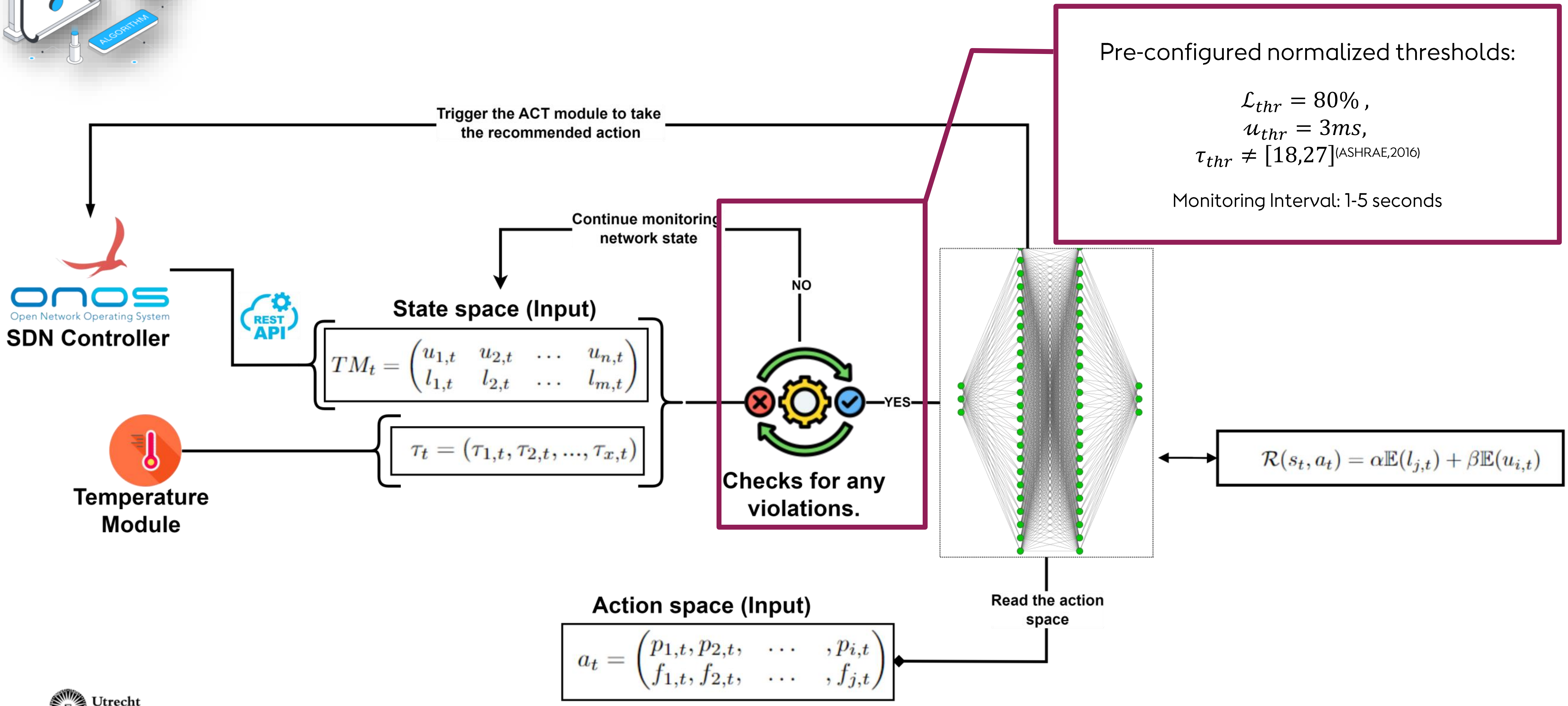


- Specify the QoS/SLA requirements *("system intents")* for the software-defined network such as End-to-End latency, Link utilization, and device temperature[1] thresholds.
- Read the current network state and compare it against the stipulated QoS/SLA thresholds. If these thresholds are violated, then trigger the DQN self-healing agent to find an optimal path to reroute data traffic, else, continue monitoring the network.
- Orient Module plays a critical role in identifying "flash events of benign traffic flows" by observing changes in the network's link parameters.

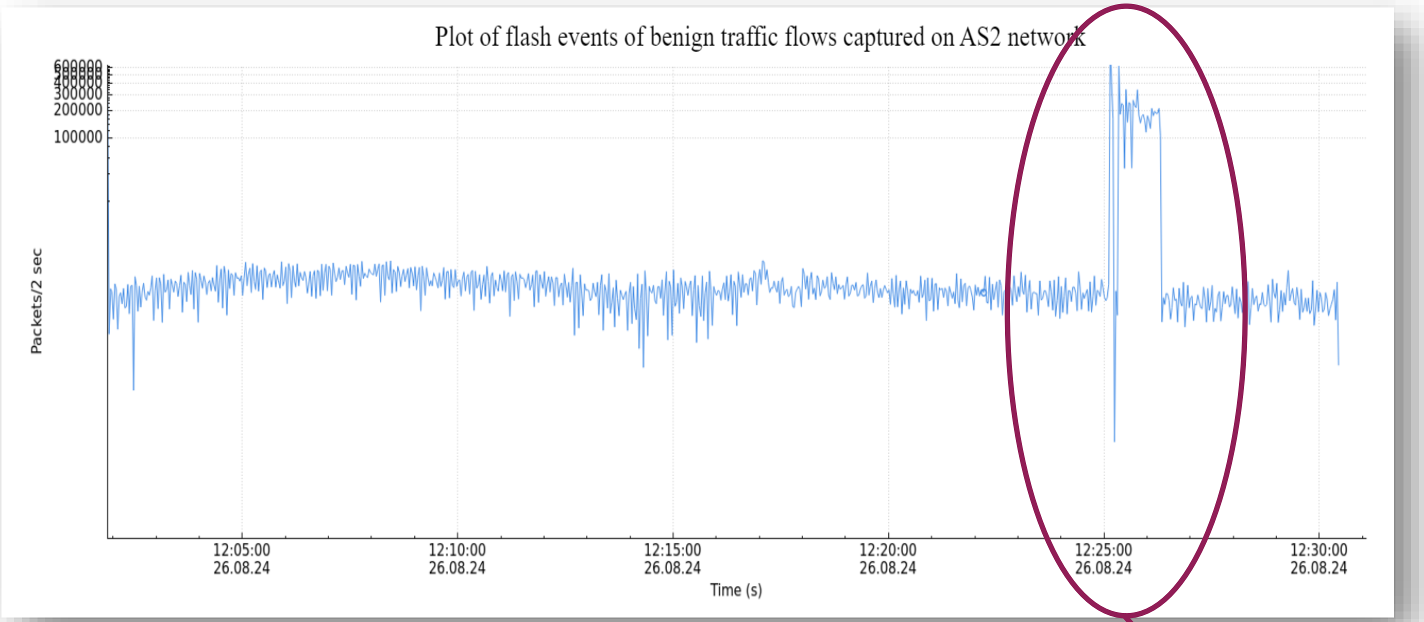
1. ASHRAE Technical Committee (TC) 9.9, "Data center power equipment thermal guidelines and Best practices.", 2016. Accessed: 2024-06-26 [Source]

A threshold-triggered Deep Q-Network (DQN) self-healing algorithm



1. ASHRAE Technical Committee (TC) 9.9, “Data center power equipment thermal guidelines and Best practices.”, 2016. Accessed: 2024-06-26 [Source]

Checking for violations
(why continuously monitor the network?)



What is flash events of benign traffic flows?

- ✓ Sudden, short-term surges of legitimate network traffic which last from a few seconds to a few hours.
- ✓ They increase the network traffic volume overwhelming the network resources.

What does this mean to an offshore WPP operator?

- ✓ Delayed or missed control commands leading to inefficiencies at the WTGs
- ✓ Inaccurate monitoring data (data losses)
- ✓ Increased latency leading to delayed response to critical issues in the WPP

What do we want to do?

- ✓ We want to catch the violations early, move around the network resources to adapt our network to respond swiftly to the stochastic disruption to mitigate the impact mentioned above.

Introducing flash events of benign traffic in the data plane.

- Caused network congestion
- Iperf3 (**3.13% - 5.27%**) loss of datagrams

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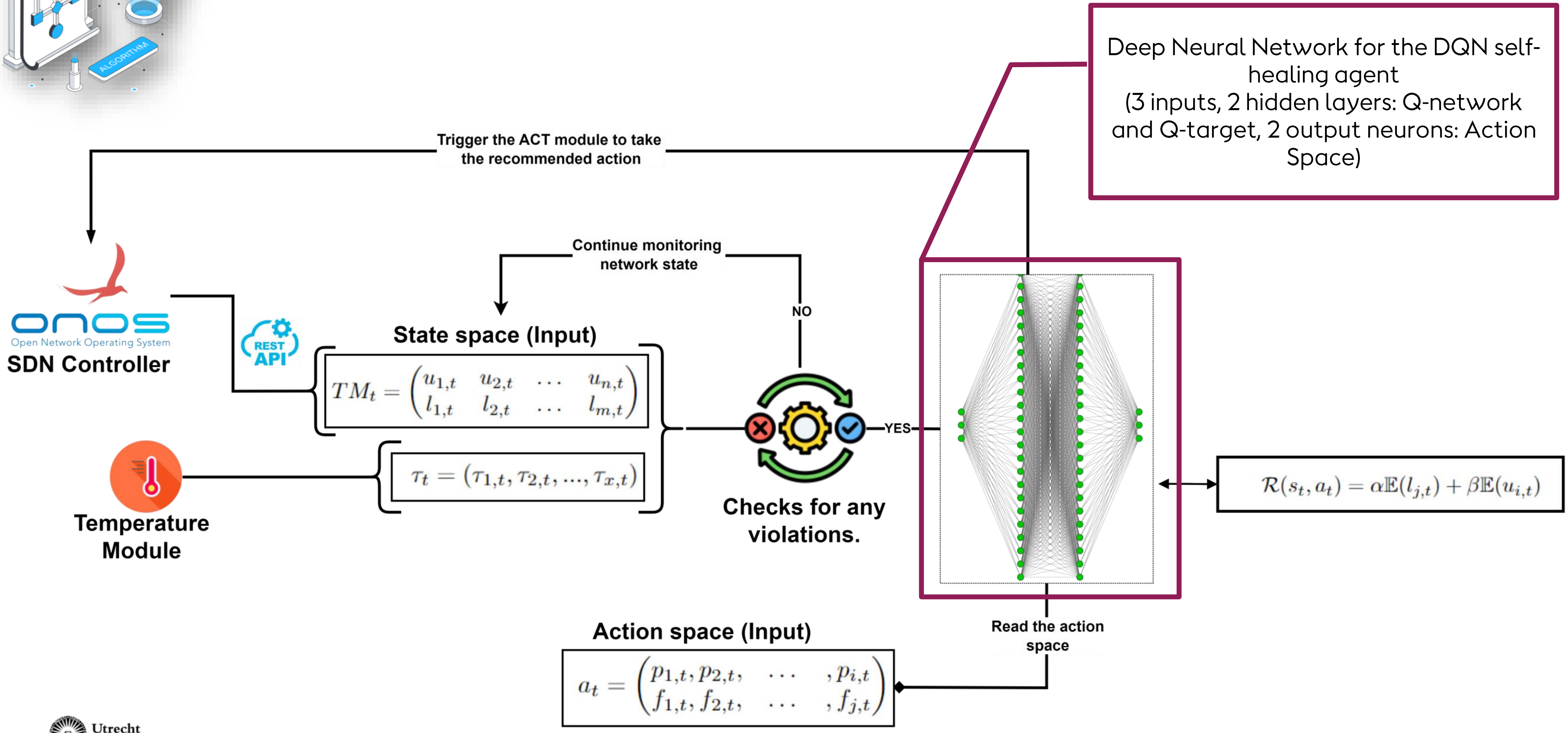

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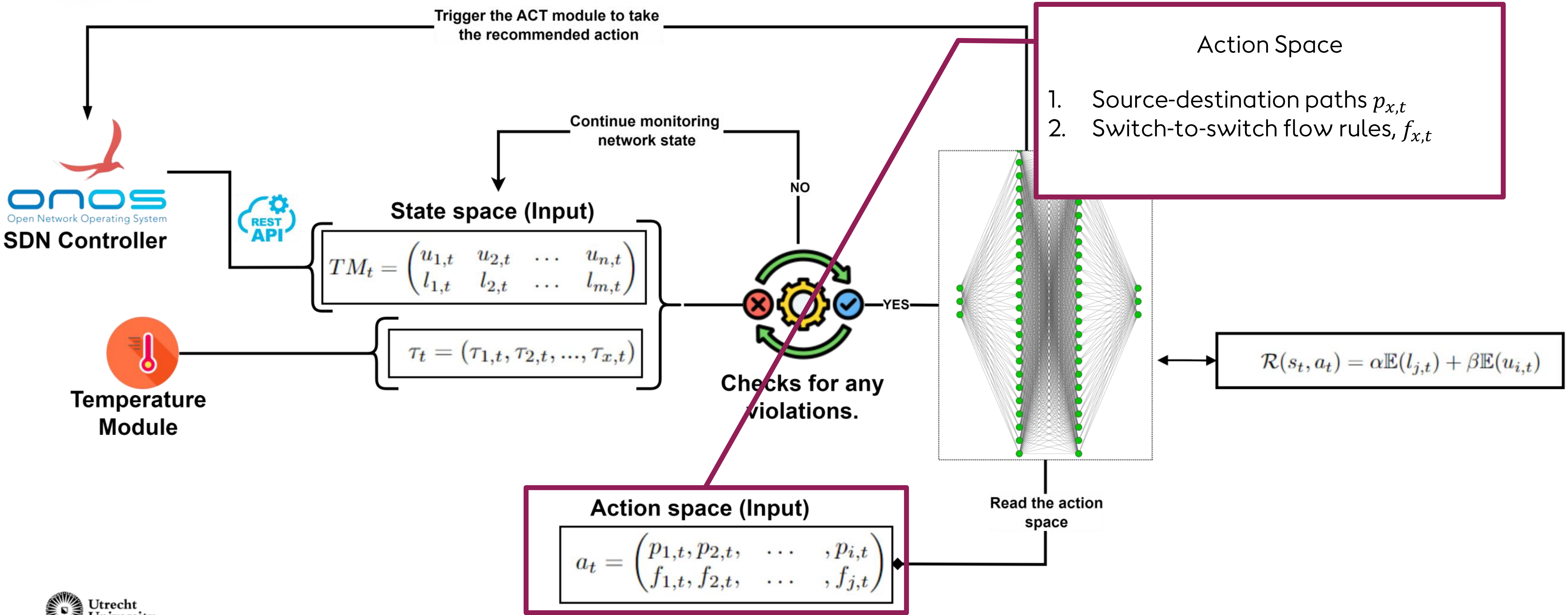

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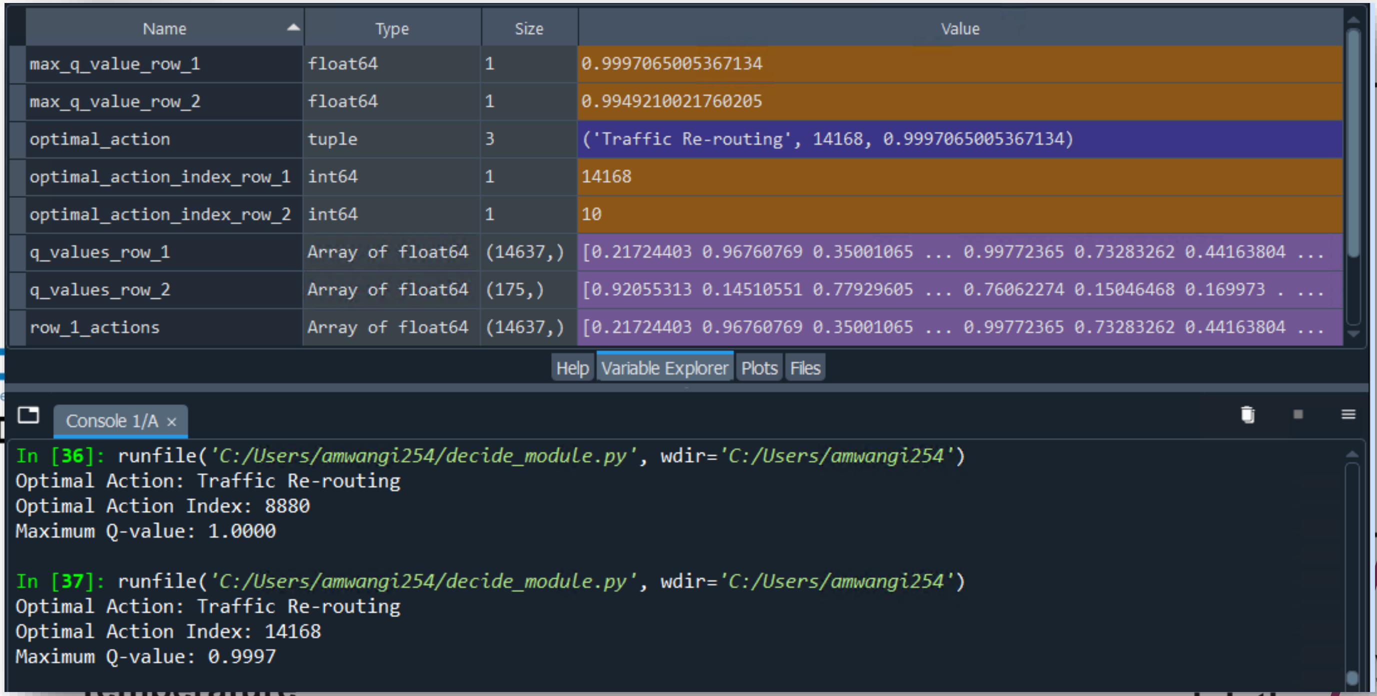


Name	Type	Size	Value
max_q_value_row_1	float64	1	0.9997065005367134
max_q_value_row_2	float64	1	0.9949210021760205
optimal_action	tuple	3	('Traffic Re-routing', 14168, 0.9997065005367134)
optimal_action_index_row_1	int64	1	14168
optimal_action_index_row_2	int64	1	10
q_values_row_1	Array of float64	(14637,)	[0.21724403 0.96760769 0.35001065 ... 0.99772365 0.73283262 0.44163804 ...
q_values_row_2	Array of float64	(175,)	[0.92055313 0.14510551 0.77929605 ... 0.76062274 0.15046468 0.169973 . ...
row_1_actions	Array of float64	(14637,)	[0.21724403 0.96760769 0.35001065 ... 0.99772365 0.73283262 0.44163804 ...

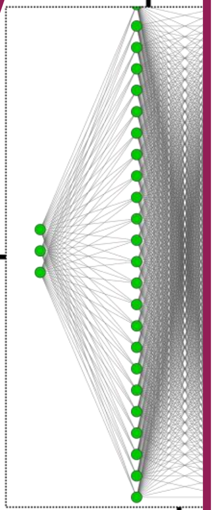

```
In [36]: runfile('C:/Users/amwangi254/decide_module.py', wdir='C:/Users/amwangi254')
Optimal Action: Traffic Re-routing
Optimal Action Index: 8880
Maximum Q-value: 1.0000

In [37]: runfile('C:/Users/amwangi254/decide_module.py', wdir='C:/Users/amwangi254')
Optimal Action: Traffic Re-routing
Optimal Action Index: 14168
Maximum Q-value: 0.9997
```

Module

violations.

YES



Action Space

1. Source-destination paths $p_{x,t}$
2. Switch-to-switch flow rules, $f_{x,t}$

The action space $\mathcal{A}$ comprises two actions:

- ✓ Traffic re-routing on pre-configured redundant paths (p)
- ✓ Throttle low-priority traffic (f) using service type classification as a metric.

For the select source-destination pairs:

- ✓ 14,637 paths overall
- ✓ 683 switch-to-switch flow rules
  - ✓ Low priority flows = 175
  - ✓ High priority flows = 508

Read the action space

Action space (Input)

$$a_t = \begin{pmatrix} p_{1,t}, p_{2,t}, & \cdots & , p_{i,t} \\ f_{1,t}, f_{2,t}, & \cdots & , f_{j,t} \end{pmatrix}$$

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1. ASHRAE Technical Committee (TC) 9.9, “Data center power equipment thermal guidelines and Best practices.”, 2016. Accessed: 2024-06-26 [Source]

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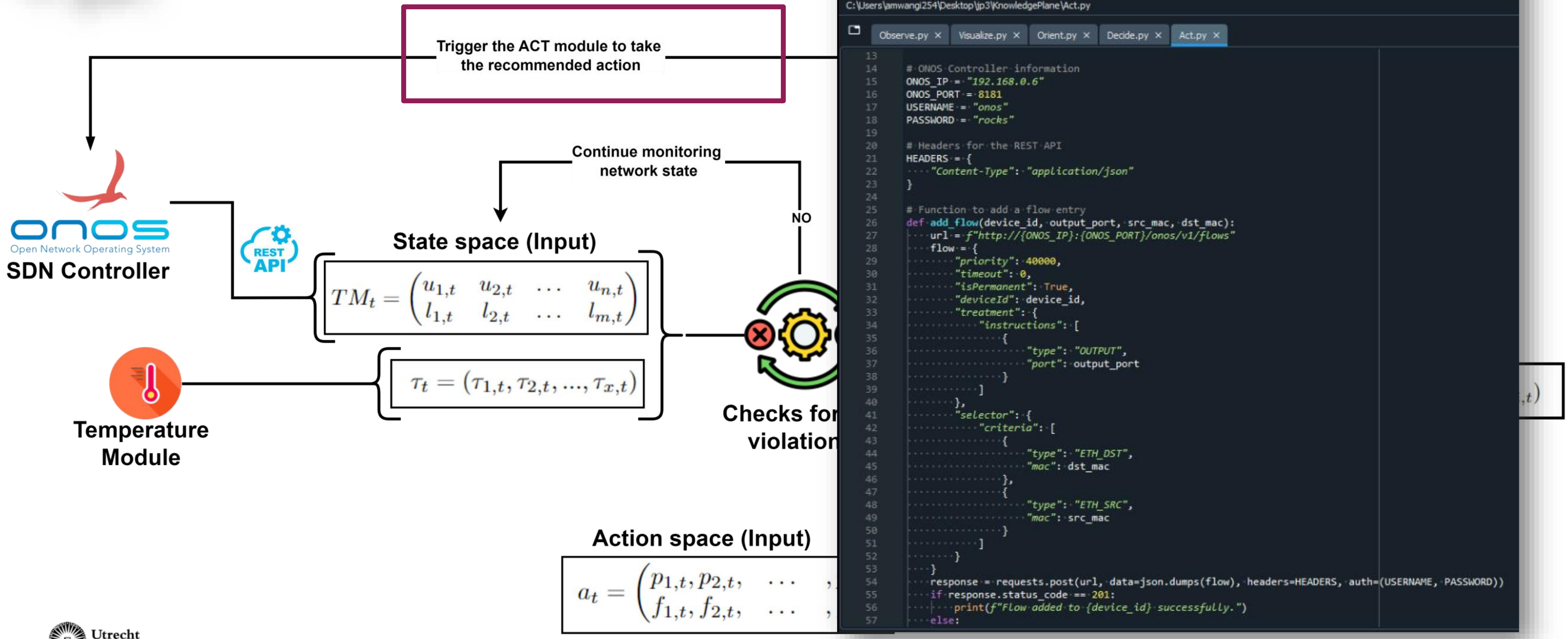

1. ASHRAE Technical Committee (TC) 9.9, “Data center power equipment thermal guidelines and Best practices.”, 2016. Accessed: 2024-06-26 [Source]

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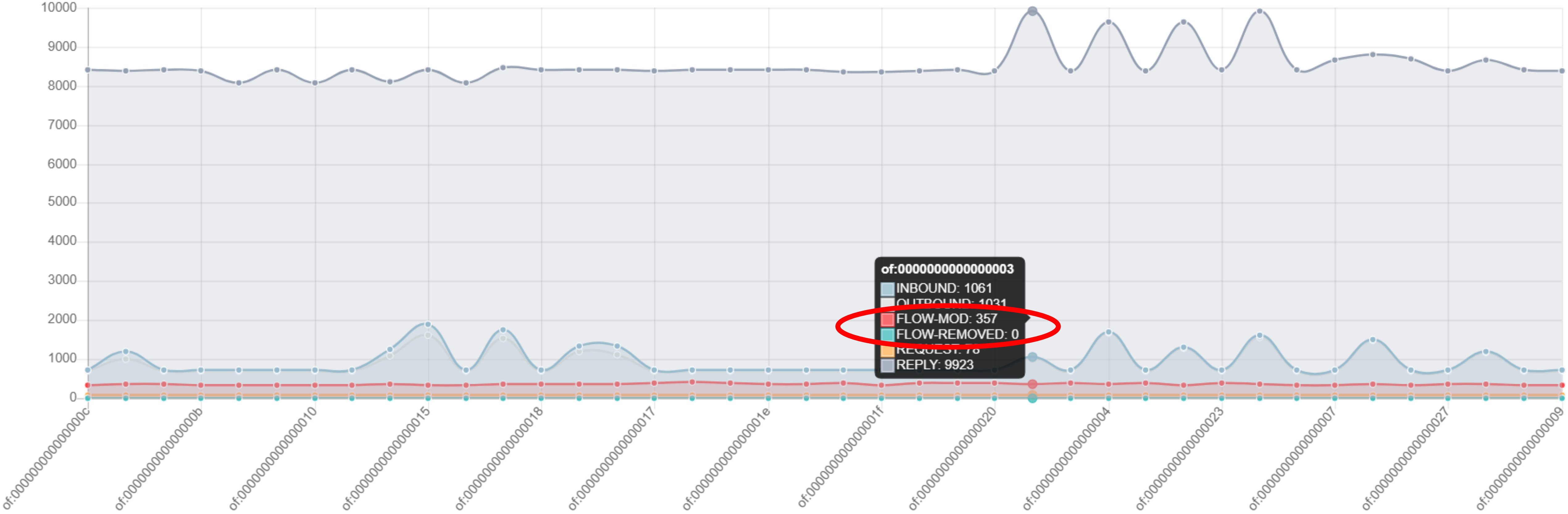
Monitoring the “ACT” Module and control plane’s flow rule manager

Key features to monitor:

- ✓ OpenFlow_MOD
- ✓ OpenFlow_REMOVED



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Resources

1) **Mwangi, Agrippina,** N.Kabbara, P. Coudray, M. Gryning, and M. Gibescu, "Investigating the dependability of software-defined IIoT-Edge networks in next-generation offshore wind farms", IEEE Transactions on Network and Service Management, 2024. [Link]

2) **Mwangi, Agrippina**, Rishikesh Sahay, Elena Fumagalli, Mikkel Gryning, and Madeleine Gibescu. 2024. "Towards a Software-Defined Industrial IoT-Edge Network for Next-Generation Offshore Wind Farms: State of the Art, Resilience, and Self-X Network and Service Management" Energies 17, no. 12: 2897. https://doi.org/10.3390/en17122897

3) **Mwangi, A.,** Fumagalli, E., Gryning, M., & Gibescu, M. (2023, October). Building Resilience for SDN-Enabled IoT Networks in Offshore Renewable Energy Supply. In 2023 IEEE 9th World Forum on Internet of Things (WF-IoT) (pp. 1-2). IEEE. https://ieeexplore.ieee.org/abstract/document/10539483

4) **Mwangi, A.,** Sundsgaard, K., Vilaplana, J. A. L., Vilerá, K. V., & Yang, G. (2023, June). A system-based framework for optimal sensor placement in smart grids. In 2023 IEEE Belgrade PowerTech (pp. 1-6). IEEE. https://ieeexplore.ieee.org/abstract/document/10202987

Ms Azure Proof-of-Concept Testbed Design for the European Telecommunication Standards Institute (ETSI) self-healing framework (Github Repository)

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