

Towards autonomous software-defined Industrial IoT-Edge Communication Networks

A case of offshore wind farms

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Dr. Mikkel Gryning (Ørsted, Denmark)

SESSION GUIDE

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



About Me

□ 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



AGRIPPINA MWANGI (Ph.D. Candidate)

Copernicus Institute of Sustainable Development
Utrecht University,
The Netherlands

Innovative Tools for Cyber-Physical Energy Systems (InnoCyPES)

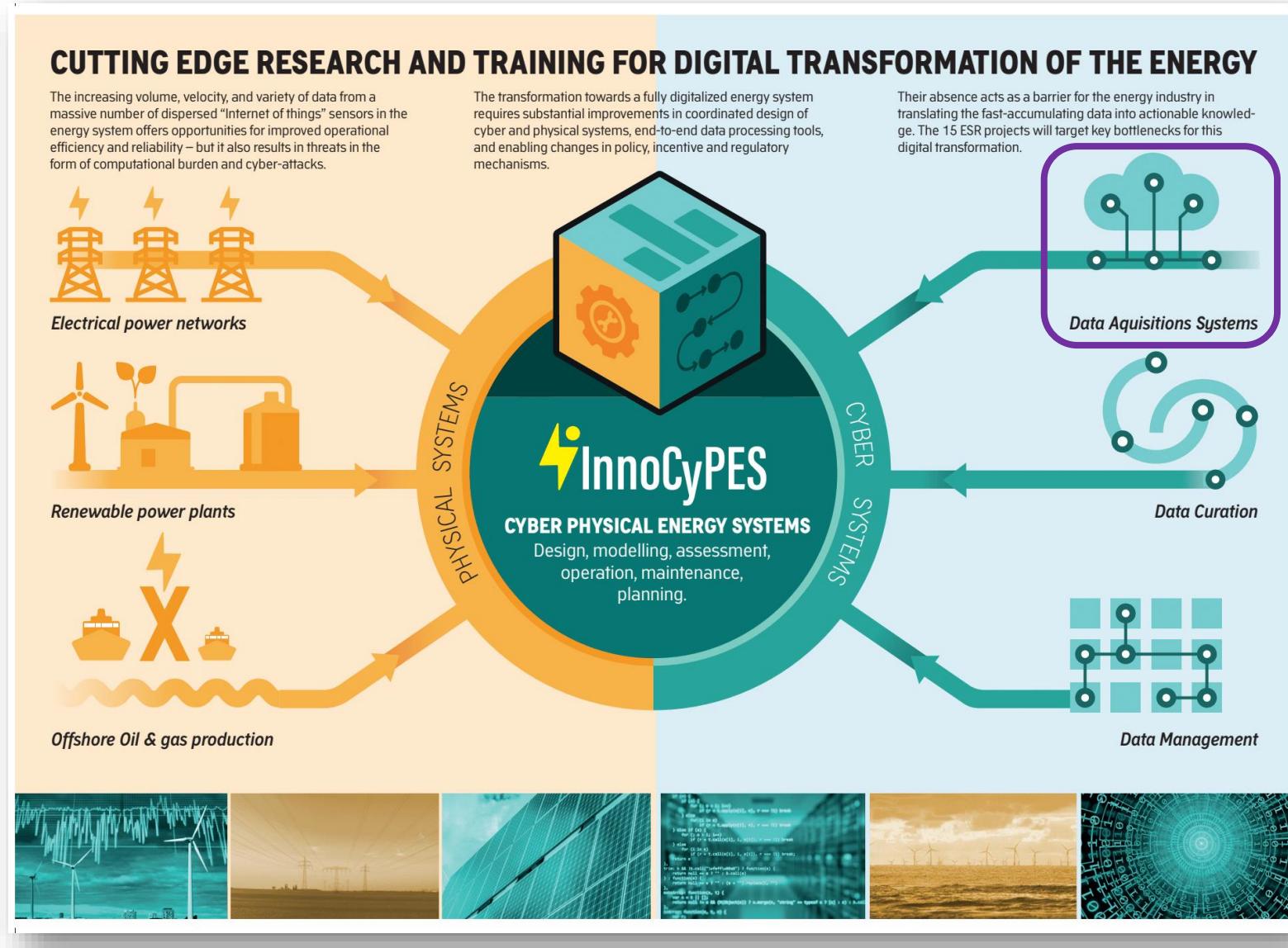
The overall goal of the project is to deliver a decision-making tool to enable energy companies to optimally design and utilize the ICT infrastructure and develop digital solutions, considering end-to-end data lifecycle and solution.

Research Work Scope: Data Acquisition Systems

Application Scenario: Offshore wind farms
("wind farms of tomorrow")



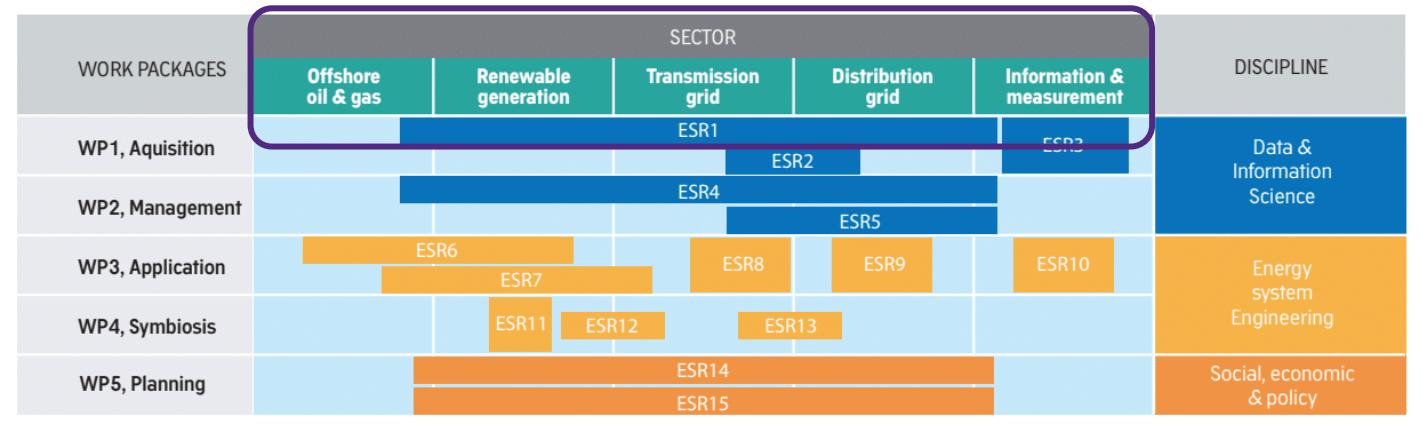
This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska Curie grant agreement No. 956433.



Innovative Tools for Cyber Physical Energy Systems (InnoCyPES)

Interdisciplinary and intersectoral research on digitalization of energy sector

Developing tools addressing the life-cycle of both cyber and physical infrastructure.



Host Institution:



Key Partners and beneficiaries:

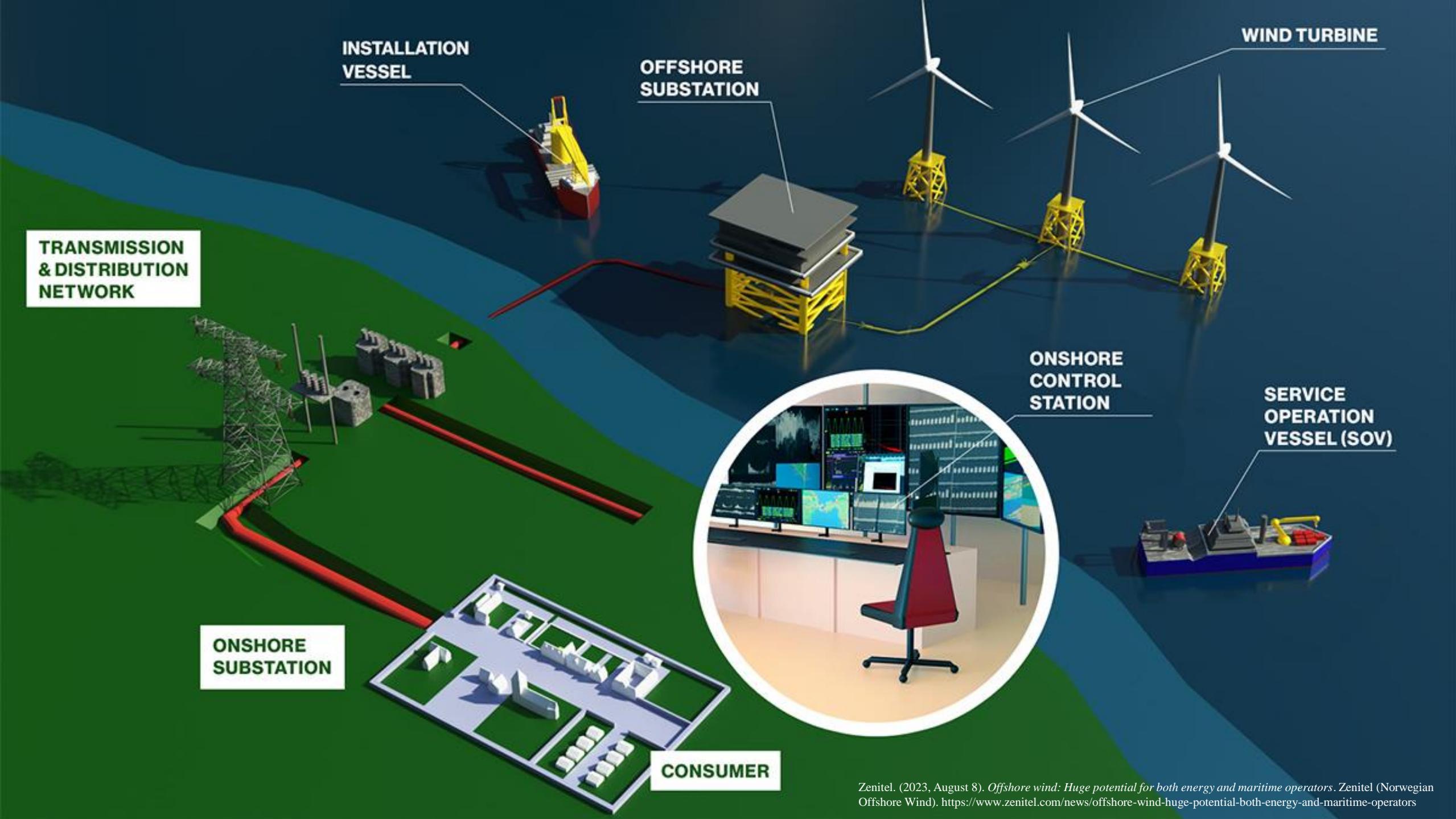


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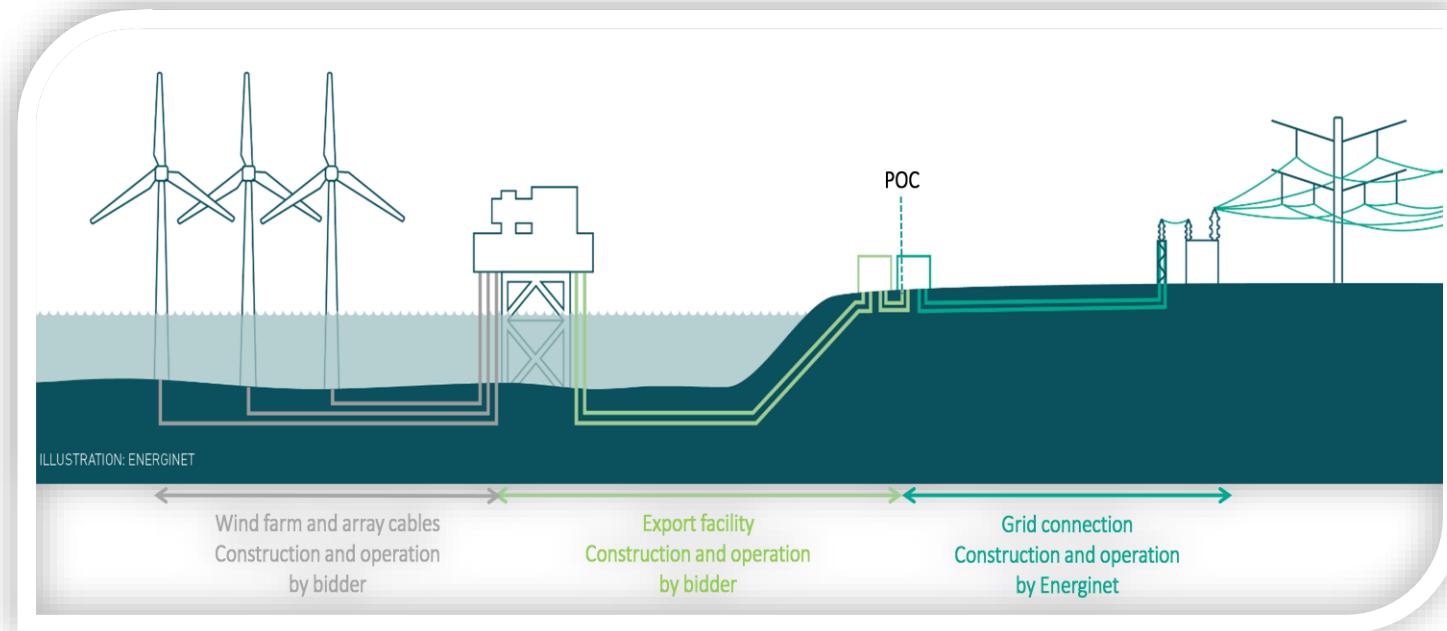
PART I

Next-generation data acquisition systems in offshore wind farms:
(Disrupting the status quo)



Offshore Wind Farms

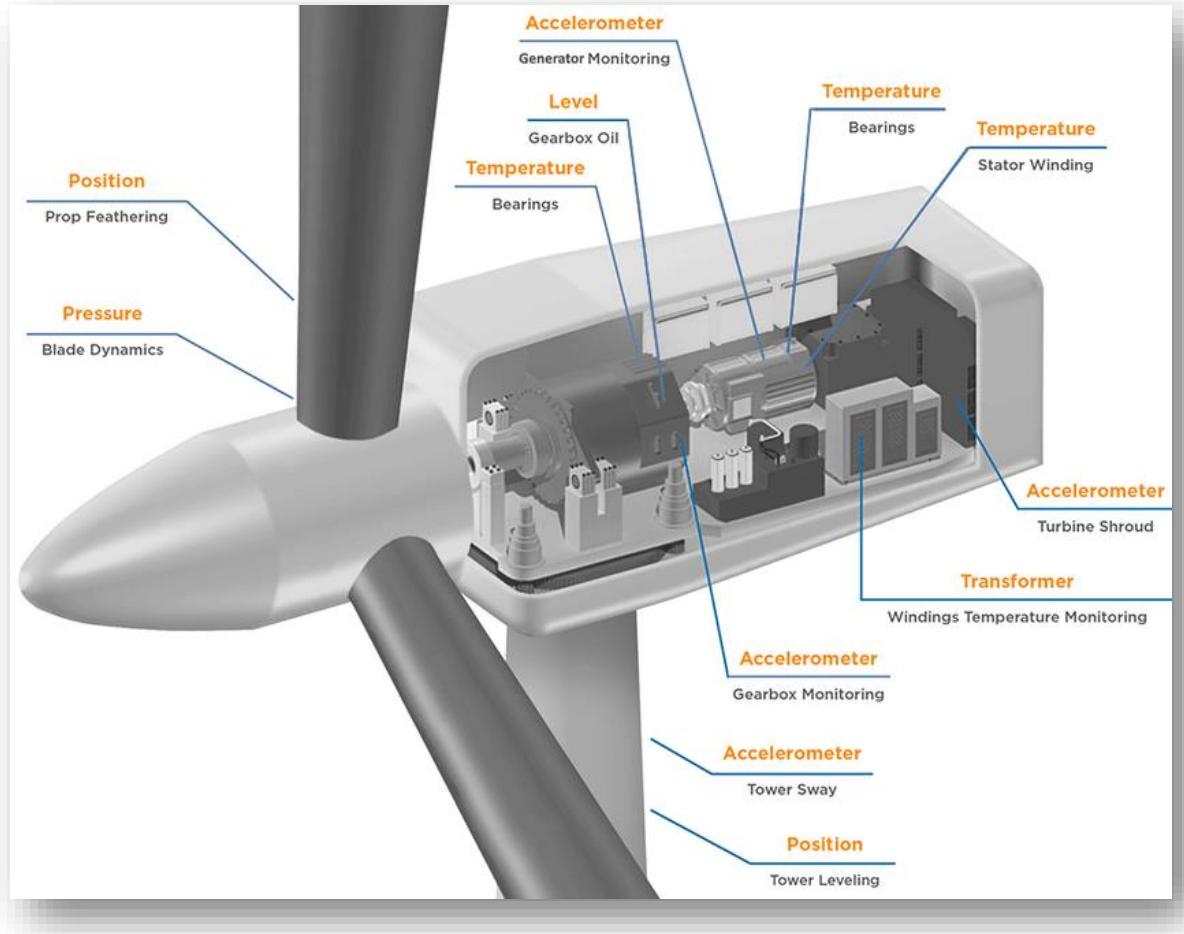
- ❑ Offshore wind farms are growing in complexity and size, expanding deeper into maritime environments to capture stronger and steadier wind energy.
- ❑ The intricacies of sea environments such as unpredictable weather patterns and the long distance from shore make manual monitoring and maintenance 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. [\[Source\]](#)

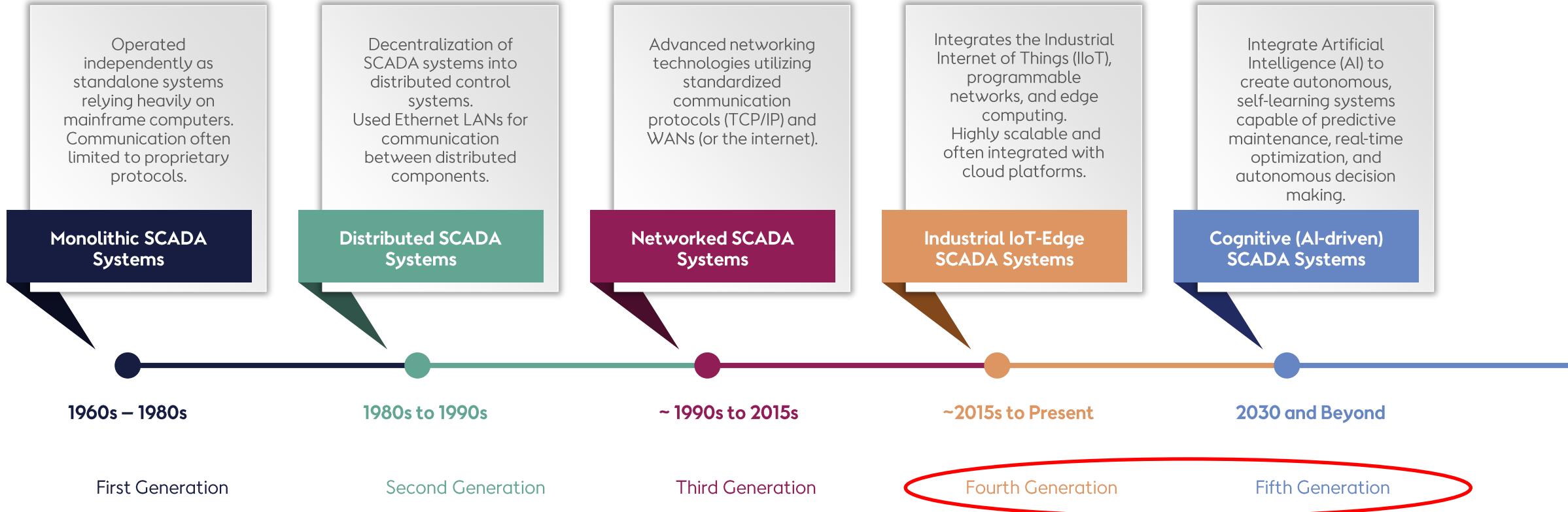
Some statistics here about offshore wind farms (to be updated)– cost of wind farms globally

Data Acquisition Systems in Offshore Wind Farms (Status Quo)



- 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 serve as SCADA suppliers.
- These suppliers retain administrative control to support and manage system upgrades, which is essential for meeting the Service Level Agreements (SLAs) during the operation and maintenance phase following the commissioning of the wind farm.

Data Acquisition Systems in Offshore Wind Farms (Status Quo)

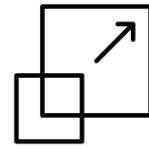


The evolution of Supervisory Control and Data Acquisition (SCADA) Systems

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



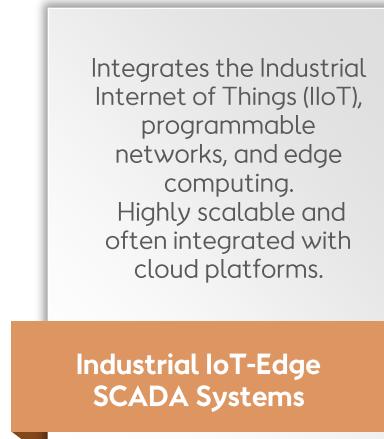
- Enhanced scalability and flexibility



- Reduced Operational Expenses (OPEX)

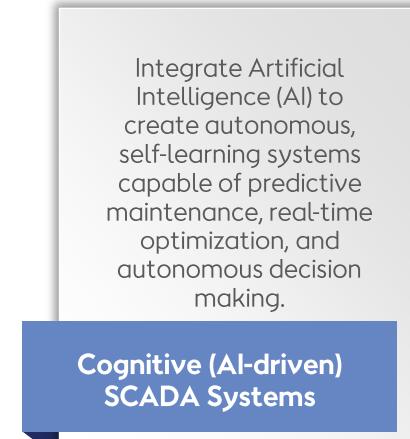


- Regulatory compliance and grid integration requirements



~2015s to Present

Fourth Generation



2030 and Beyond

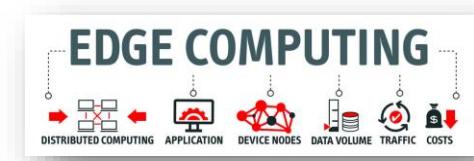
Fifth Generation

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



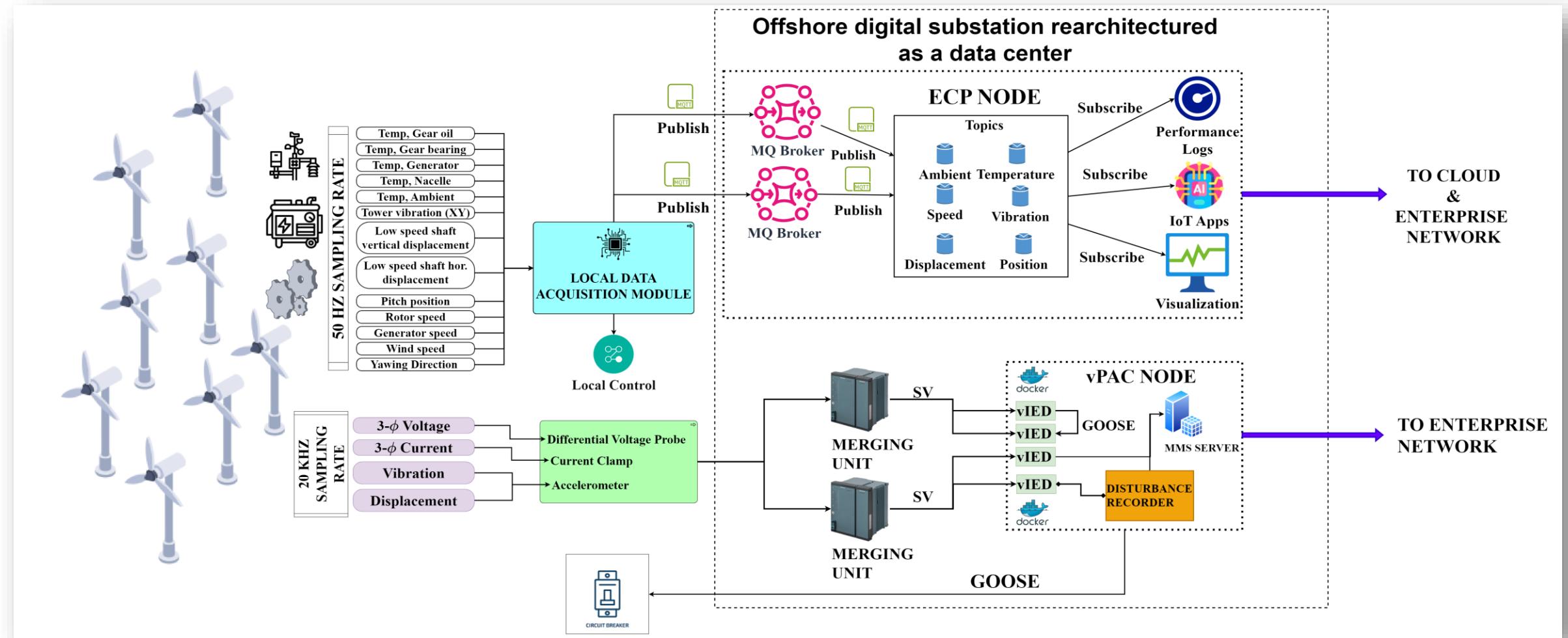
VIRTUALIZATION

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

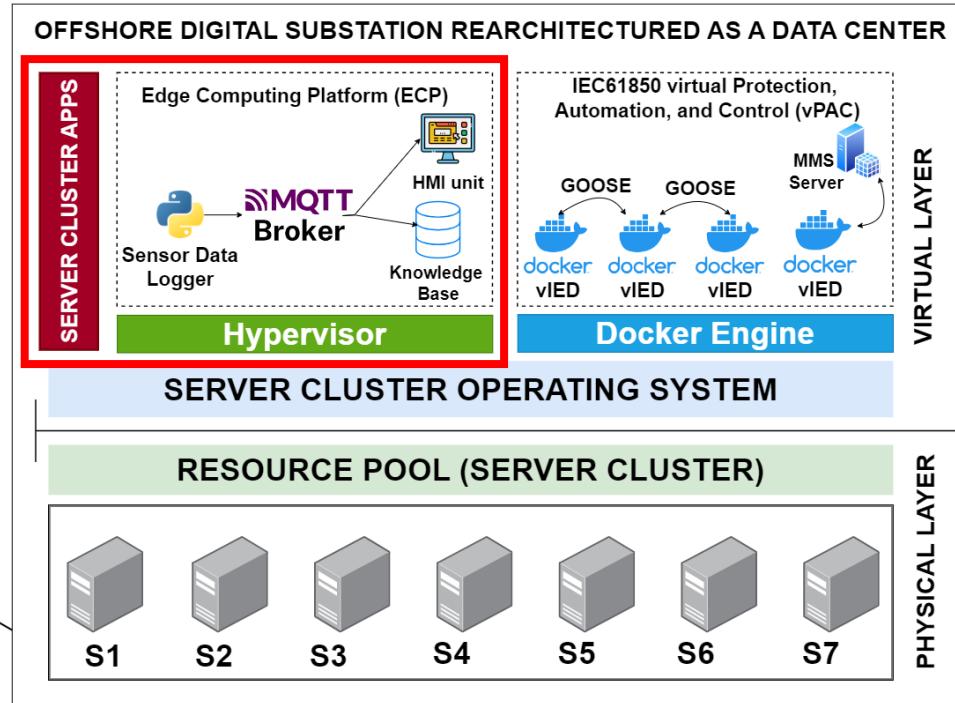
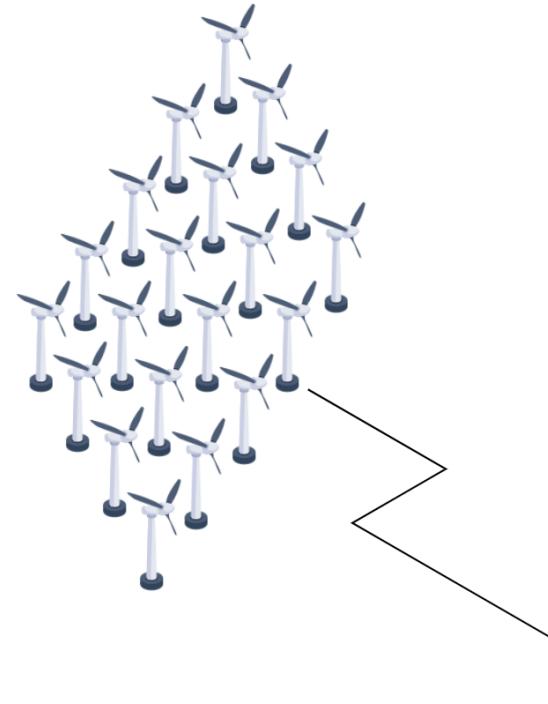


Software-defined networks where network engineers can modify the behavior of the network using programming interfaces.

Next-generation data acquisition systems in offshore wind farms (Industrial Internet of Things - IIoT)



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

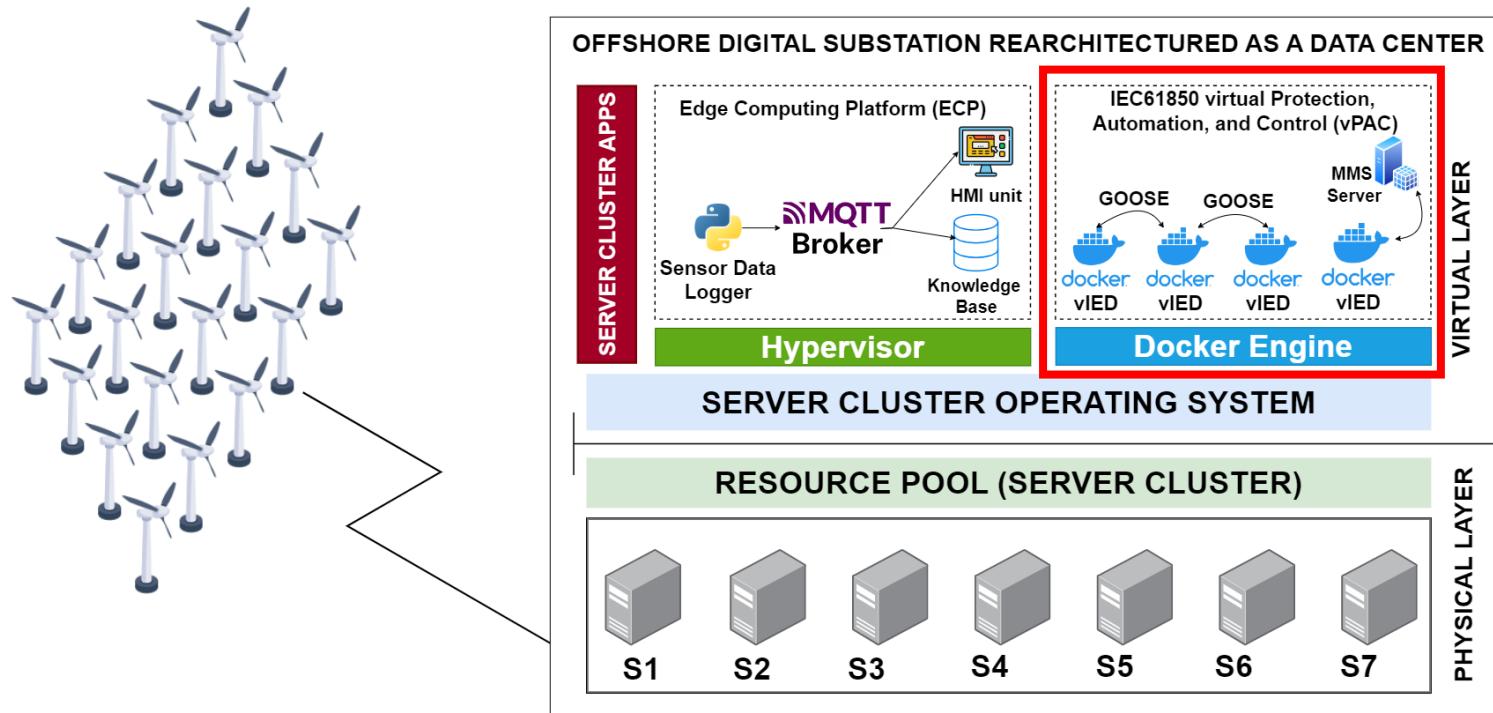


Choosing an edge computing platform over the traditional IoT-to-cloud model reduces data transmission latency, enhances data security, and enables real-time decision making.



Next-generation data acquisition systems in offshore wind farms

(Virtualization in offshore substations)



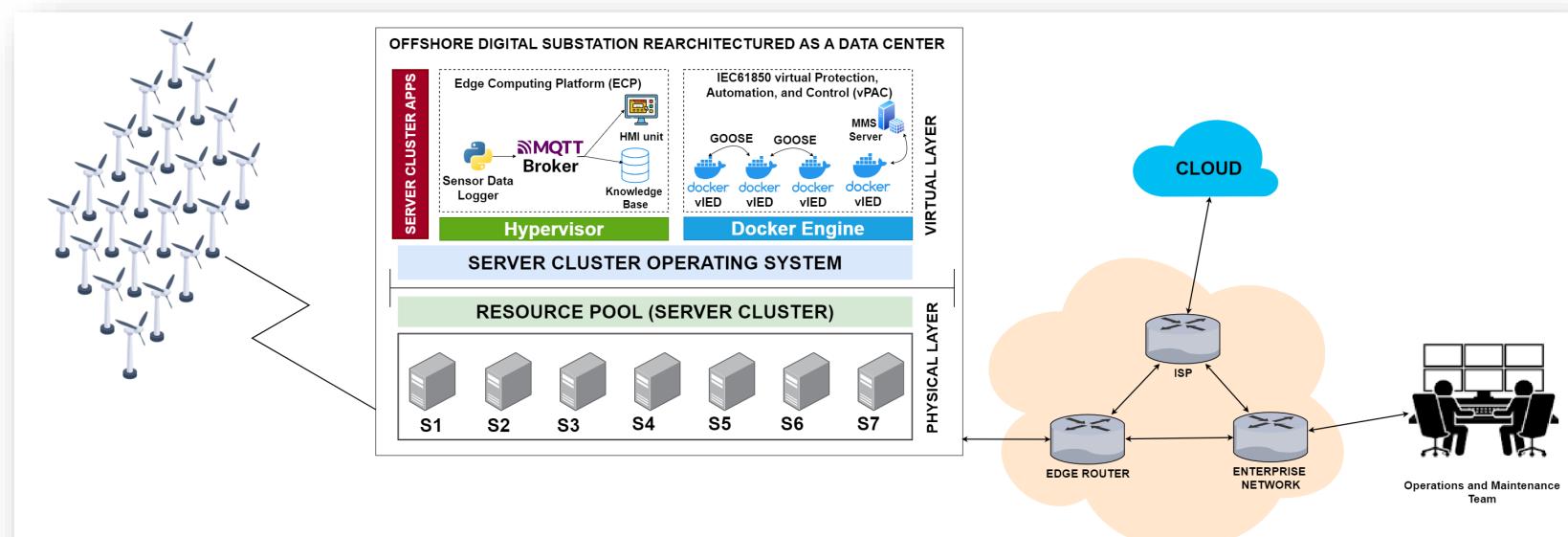
Virtual Protection Automation and Control (vPAC) Alliance is advocating for flexible, manageable, and interoperable platforms that are based on open



Challenge!



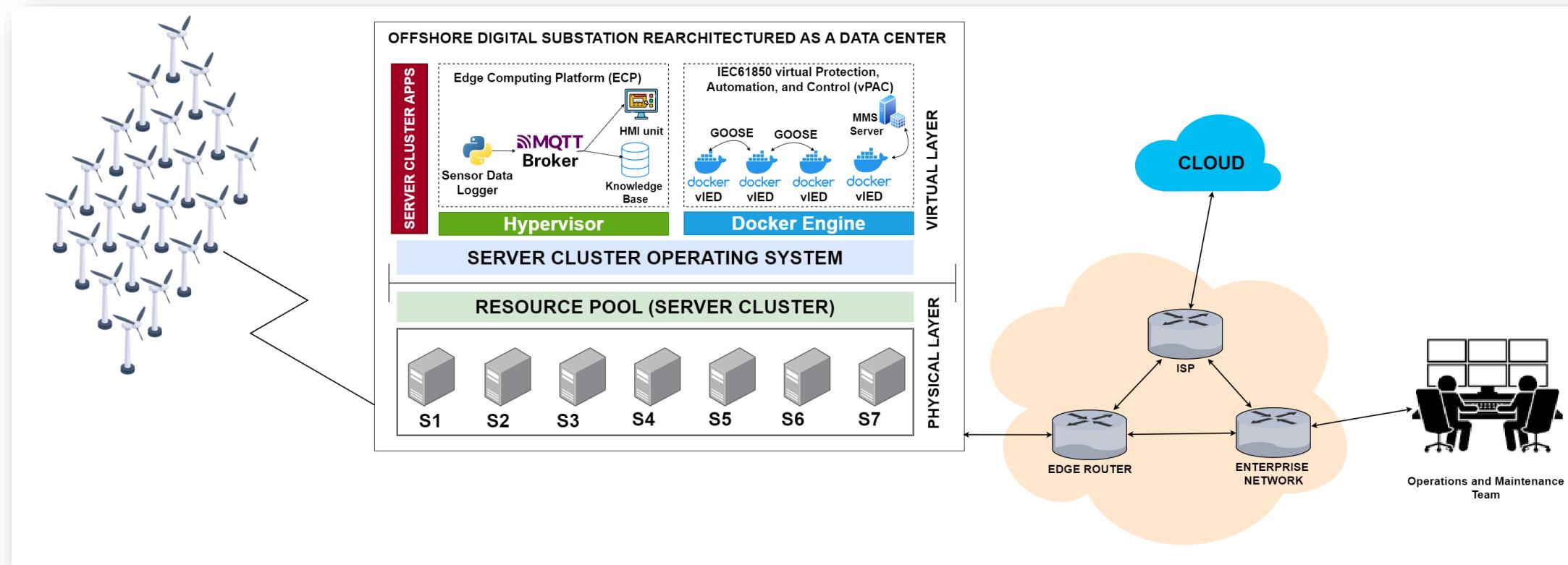
How can offshore wind farm Operational Technology (OT) communication networks be **designed and optimized** to handle the increased data traffic from IIoT devices while maintaining low latency, high reliability, and robust security?



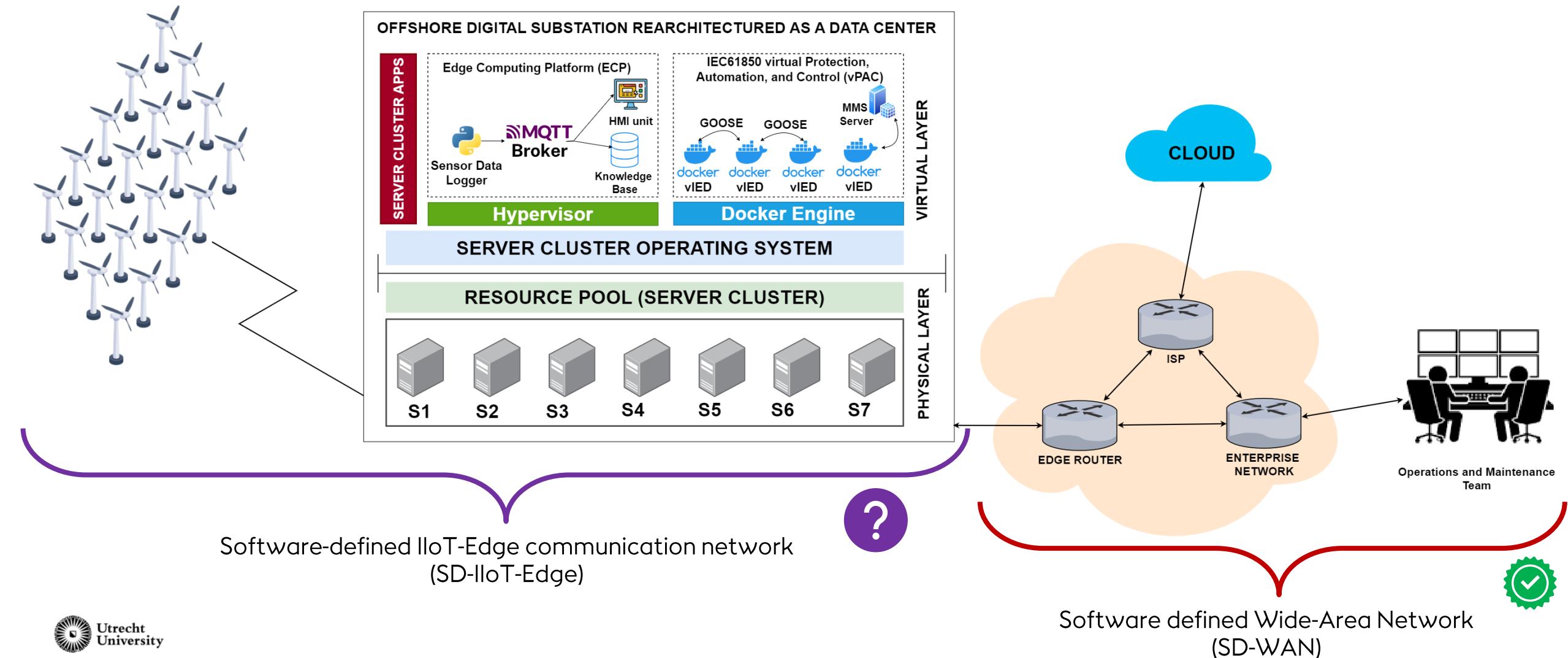
Building resilient communication networks for next-generation offshore data acquisition systems

"Orchestration of these Industry 4.0 technologies hinges on resilient communication networks."

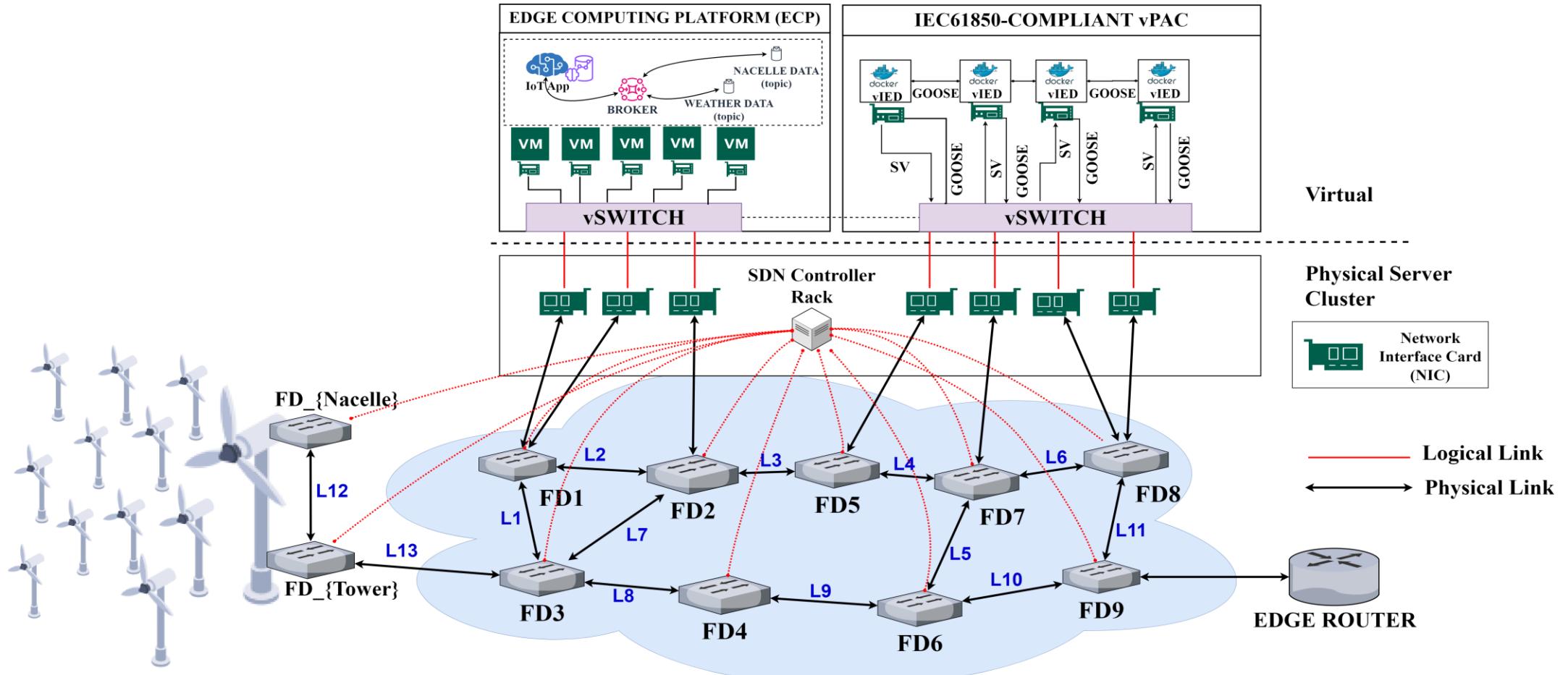
This research designs and validates software-defined communication networks capable of meeting the stringent performance requirements for efficient coordination of offshore wind farm services.



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

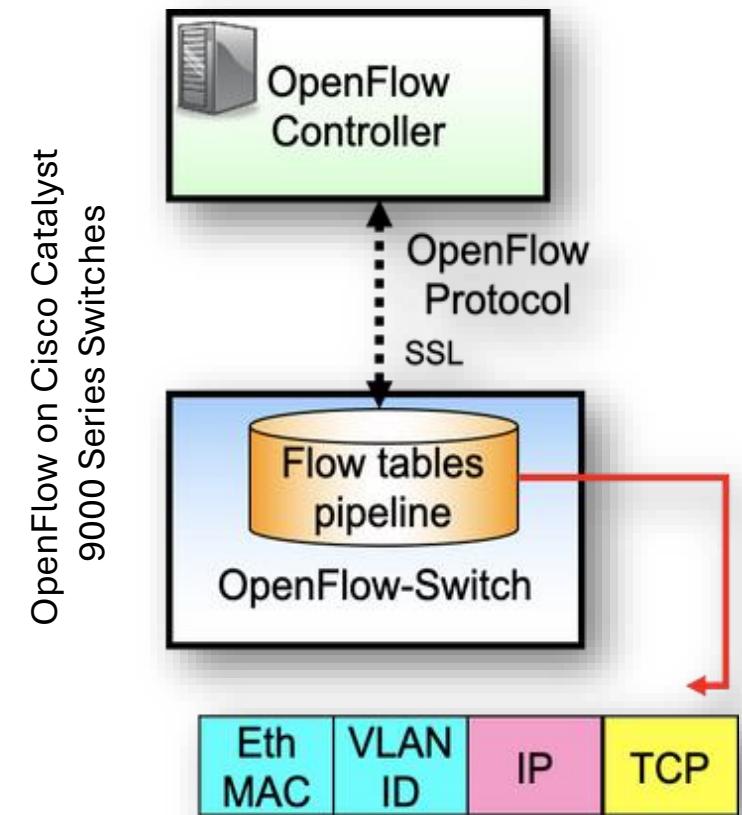


Software-defined Industrial IoT-Edge communication networks (SD-IIoT-Edge)

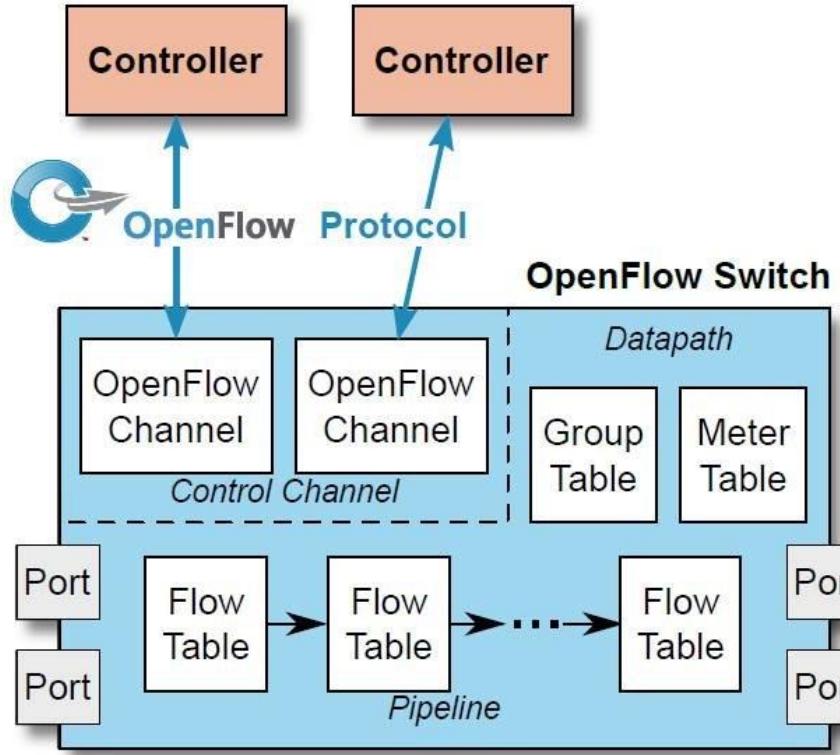


Software-Defined Networking (SDN) Architecture

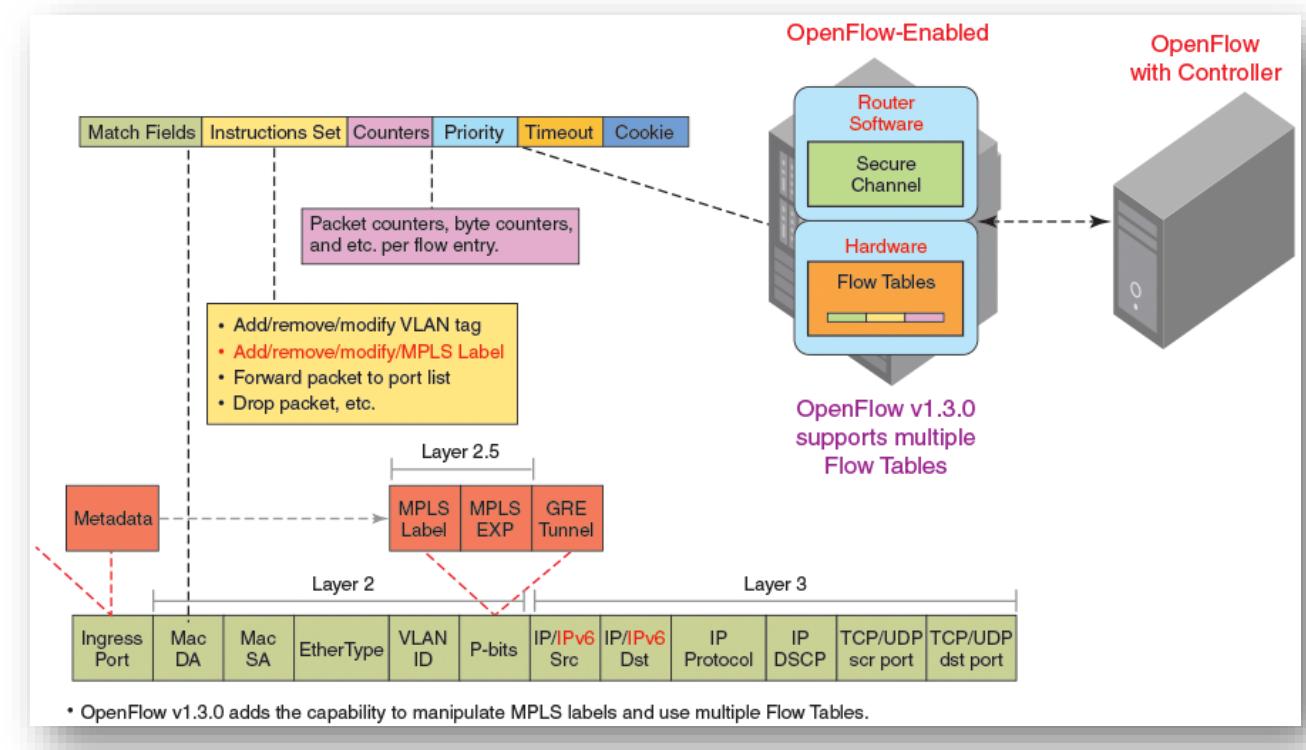
- In principle, software defined networks decouples the control plane from the data plane so that the network transforms from a distributed architecture to a centrally managed architecture.
- Industrial IoT-Edge Networks can become vendor-agnostic with SDN. Network engineers focus on more innovative 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 is a L2 communication protocol (Southbound Interface) that gives access to the data plane.



Software-Defined Networking (SDN) Architecture

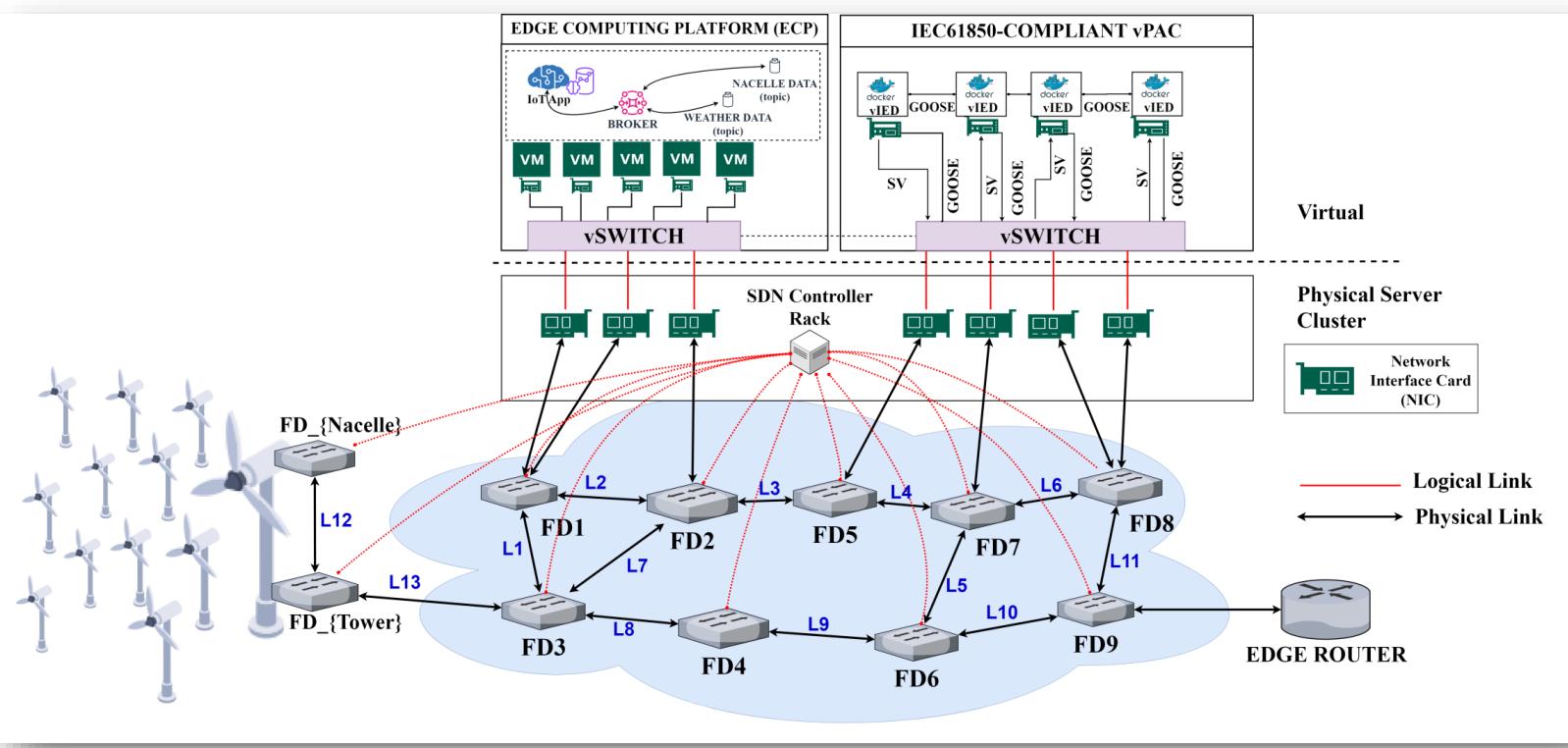


- ❑ An OpenFlow switch maintains one or more flow tables, which are used for packet processing. The switch performs the actions listed in the table entry corresponding to the matched flow.
- ❑ Further, Overlaying SD-WAN on the IP/MPLS backhaul is the perfect architecture for enterprises. The two technologies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



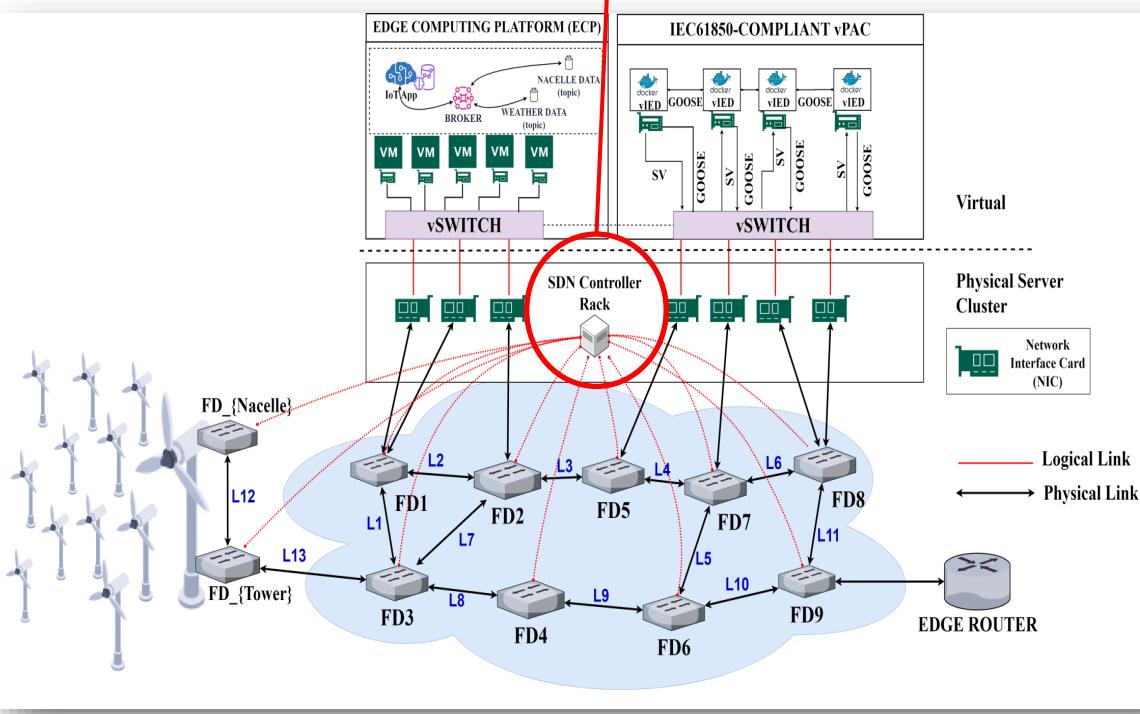
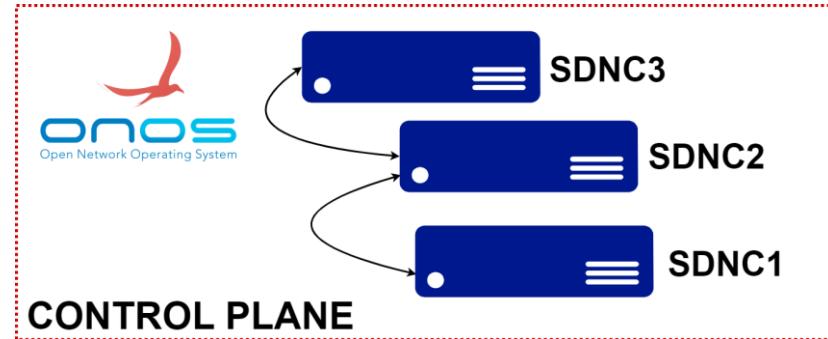
Software-defined Industrial IoT-Edge communication networks: (Challenges and mitigation strategies)

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

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
```

Performance in software-defined IIoT-Edge communication networks

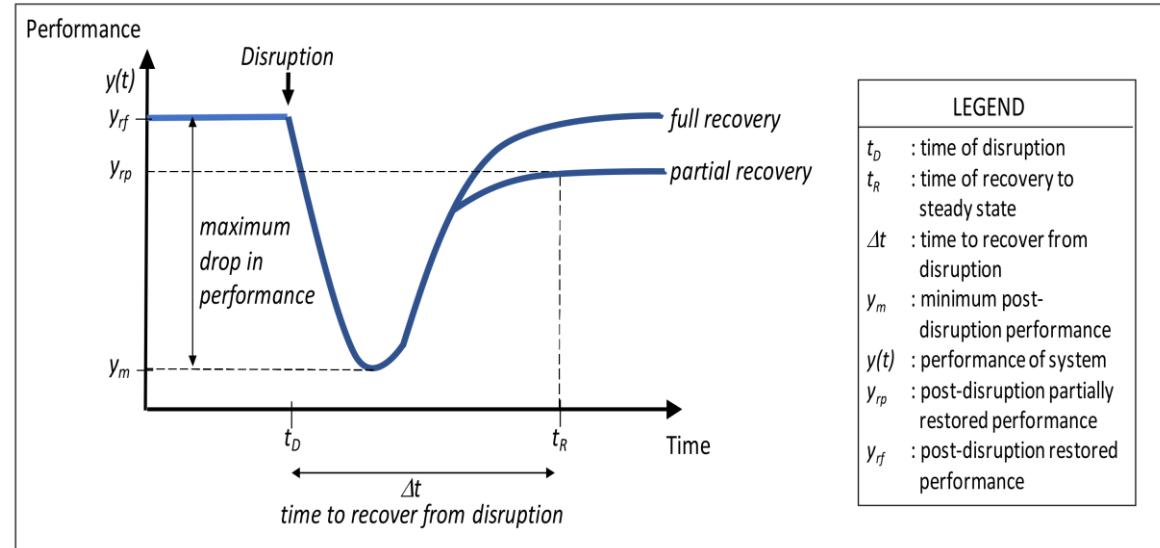
- ❑ It is important for the software-defined IIoT-Edge network to meet the performance requirements for the different data traffic types.
- ❑ These data traffic types are categorized into:
 - ❑ Critical, time-sensitive data traffic (protection, control, analogue measurements, status information, and 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 IIoT-Edge network is susceptible to stochastic disruptions of different form:
 - Control-plane specific:
 - Data-plane specific:

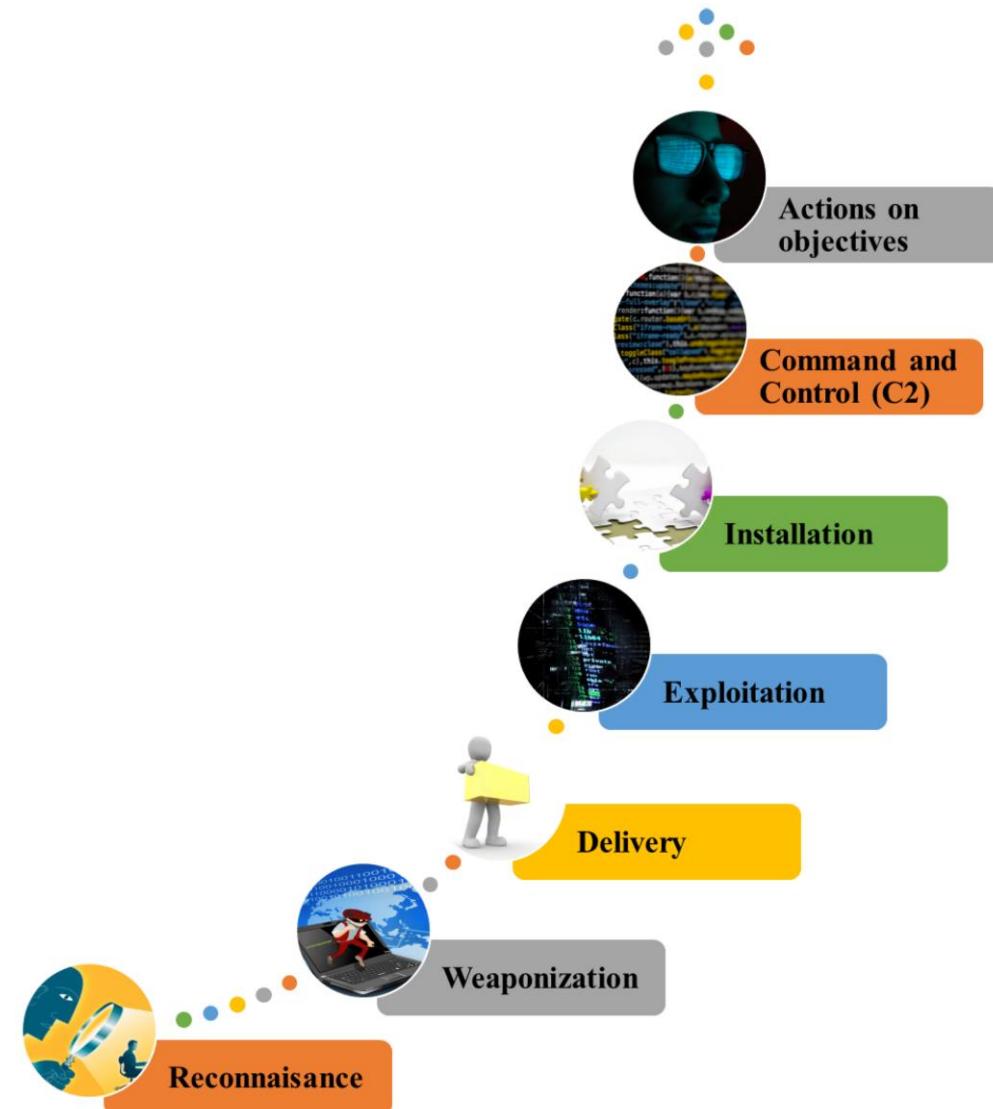


Performance in software-defined IIoT-Edge communication networks



Reliability in software-defined IIoT-Edge communication networks

Security in software-defined IIoT-Edge communication networks



ISA/IEC62443 Industrial Control System Cyber-kill chain



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

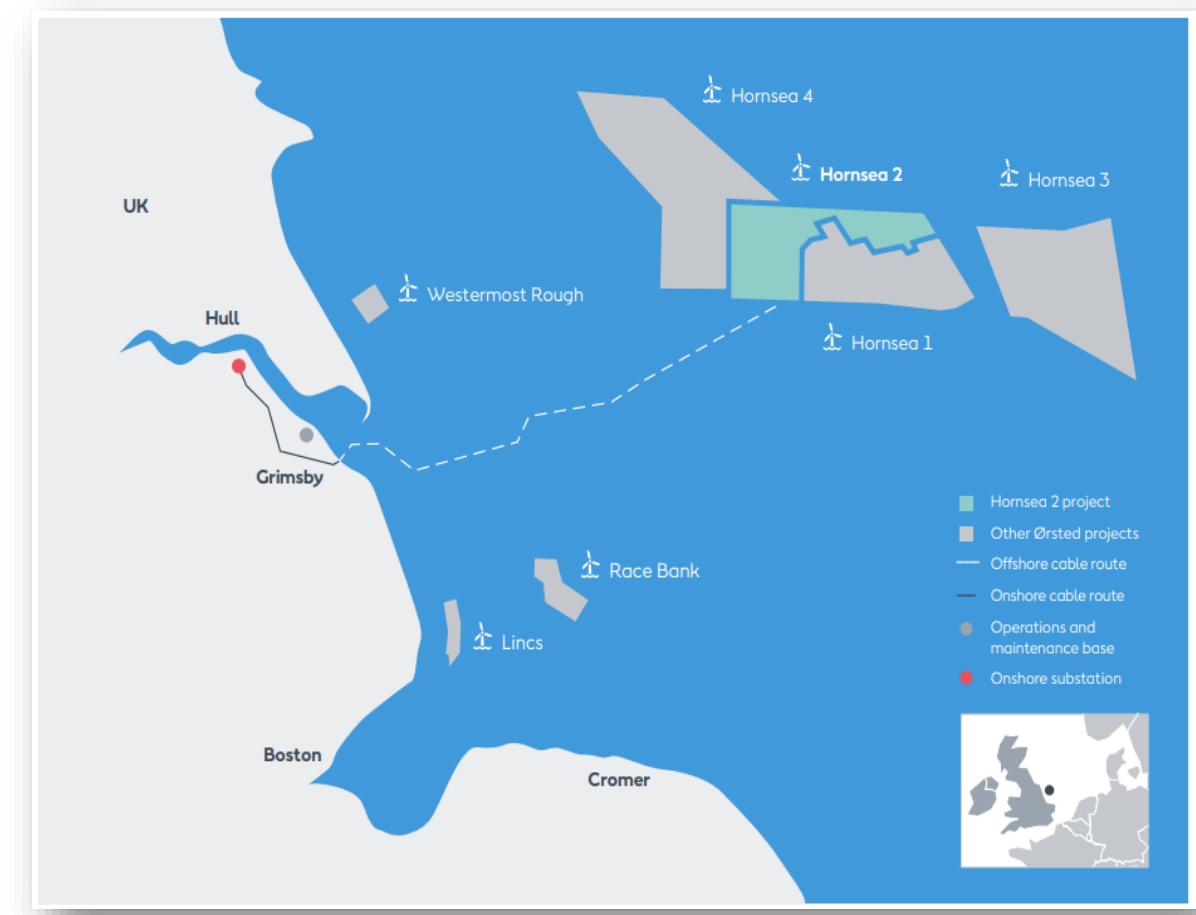
- European Telecommunication Standards Institute defines self-X (self-configuring, **self-healing**, self-optimizing, and self-protecting) network and service management framework¹.
- Self-healing focuses on the network's ability to automatically detect, diagnose, and resolve faults to maintain service continuity. It essentially ensures the network remains operational despite unexpected failures or issues, acting reactively to correct problems as they occur².

"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)



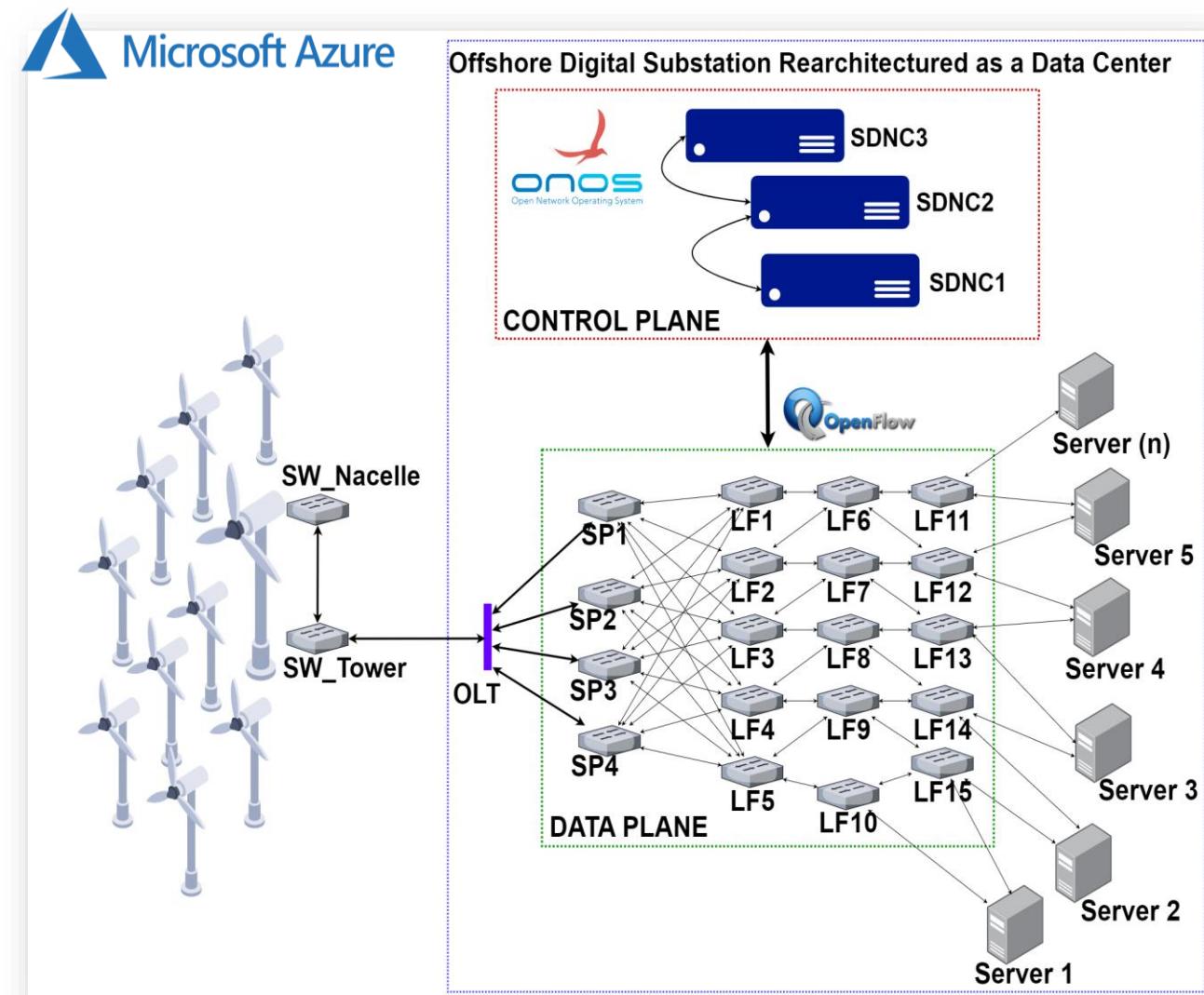
Application Scenario

- ❑ Offshore wind farm developers are increasingly building clustered wind farms because such setups provide technical, operational, and financial benefits. Consider the Hornsea (Ørsted, UK) project comprising 4 offshore wind farms (WFs).
- ❑ Each WF comprises a fleet of wind turbine generators (WTGs) communicating with a single offshore digital substation (OSS) and an offshore reactive compensation substation (RCS). From the OSS/RCS, an export cable connects to the mainland (herein, Grimsby).
- ❑ Proposed architecture:
 - ❑ Redesign each Operations Support System (OSS) as a data center.
 - ❑ 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.



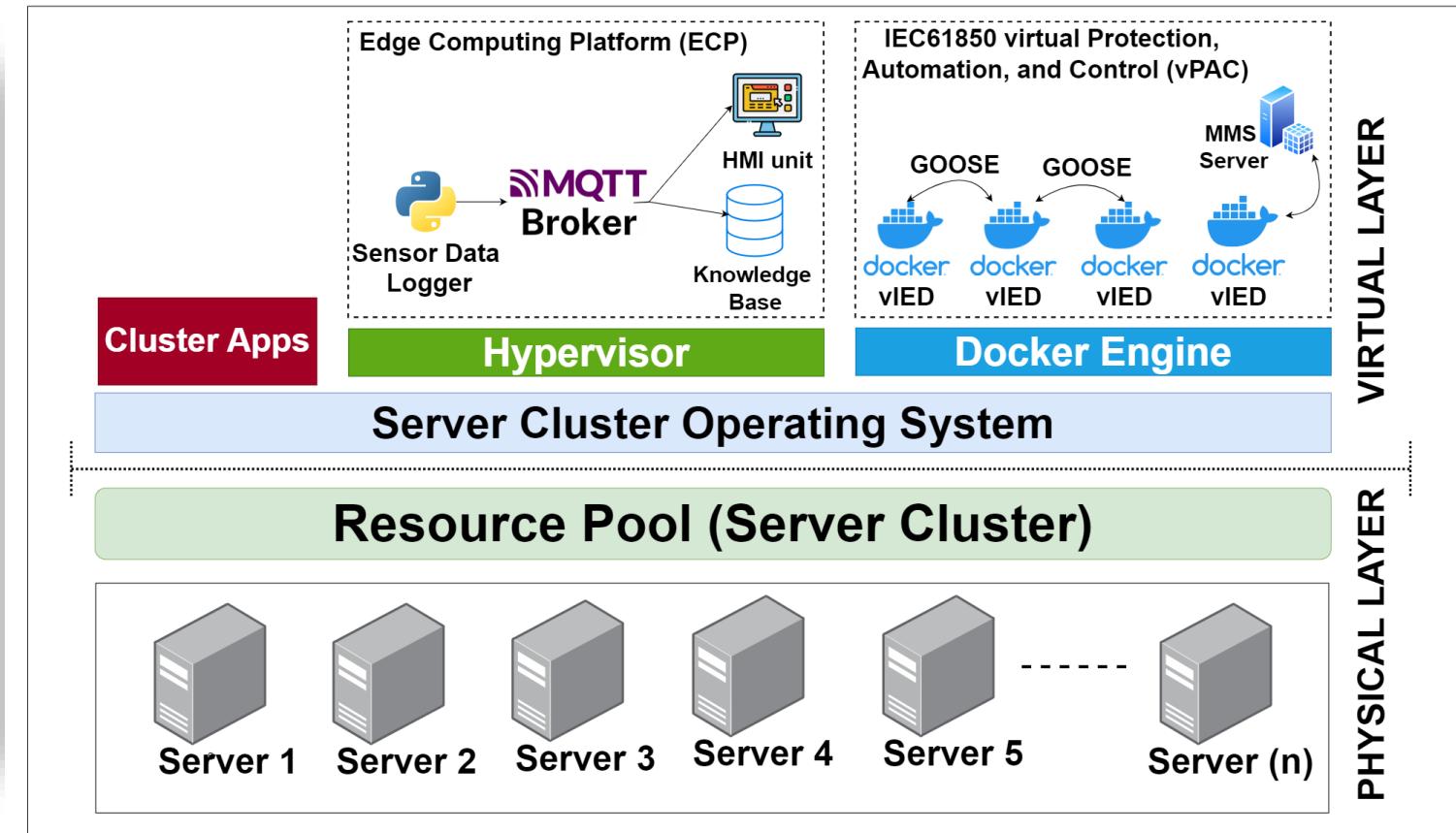
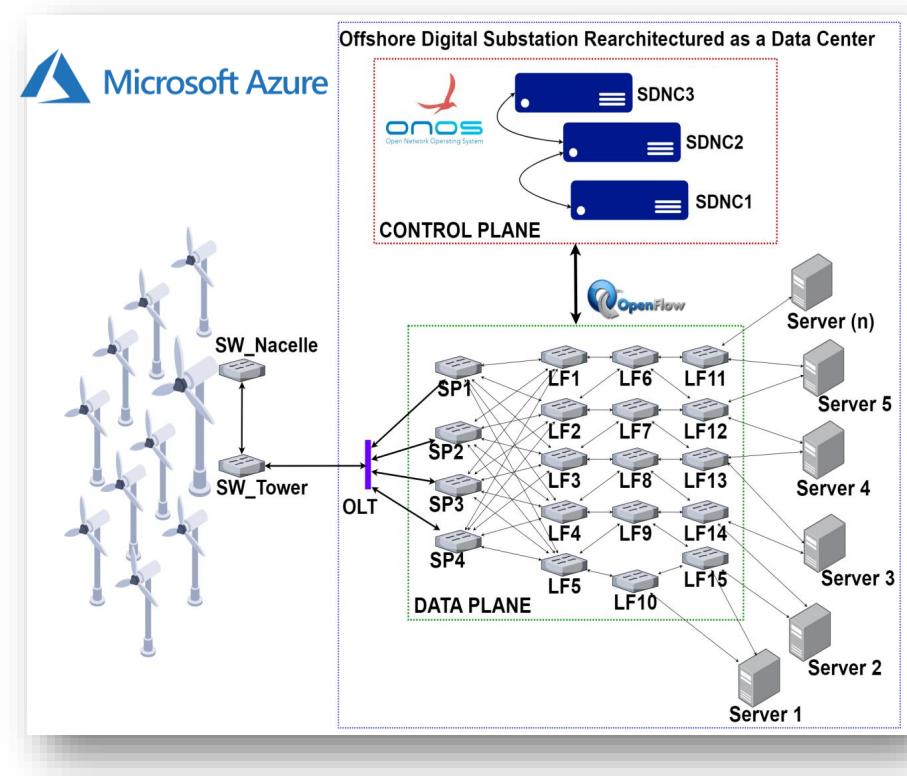
Ms-Azure proof-of-concept Testbed Design

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



Ms-Azure proof-of-concept Testbed Design

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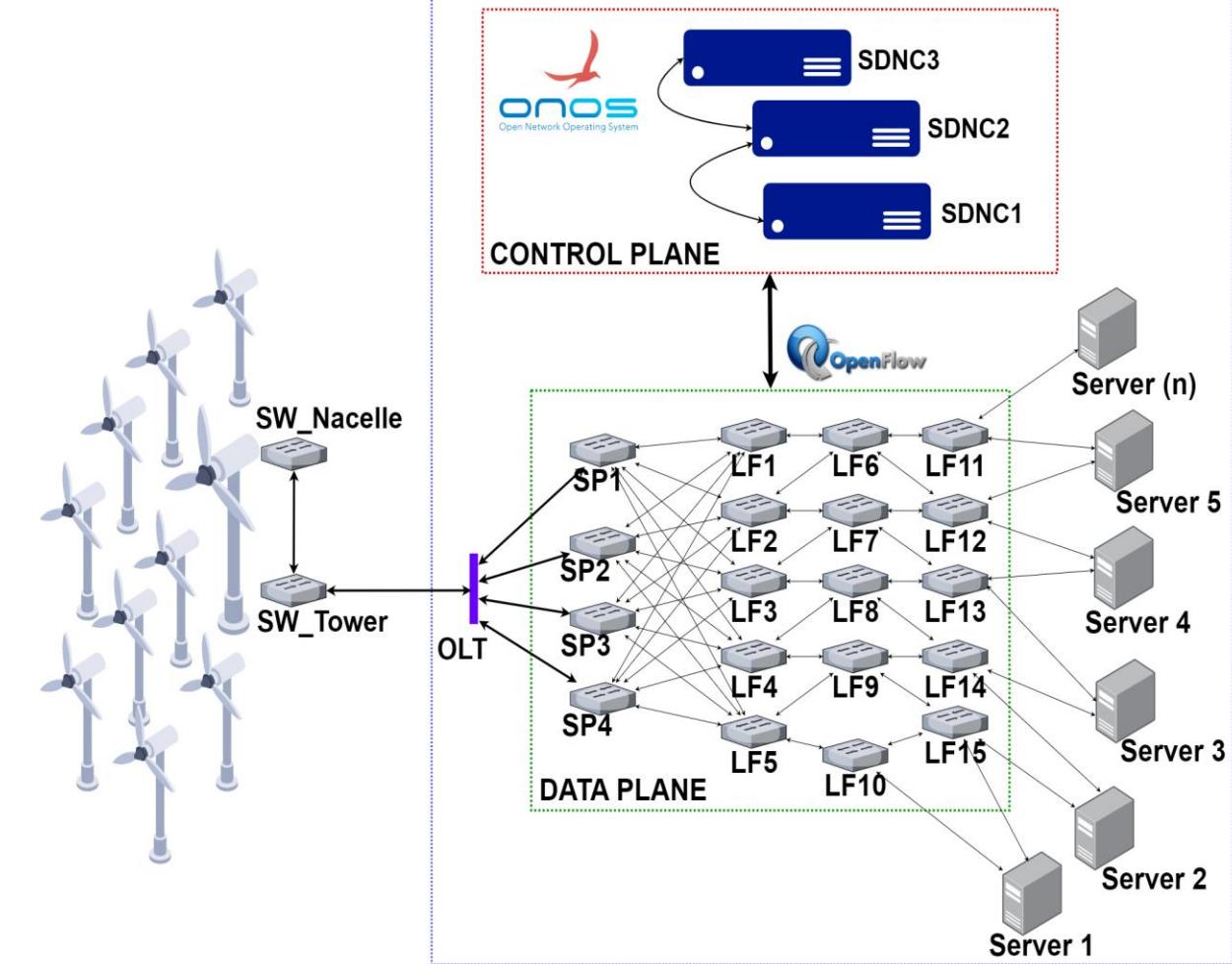
Ms-Azure proof-of-concept Testbed Design

- 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. [\[Source\]](#)

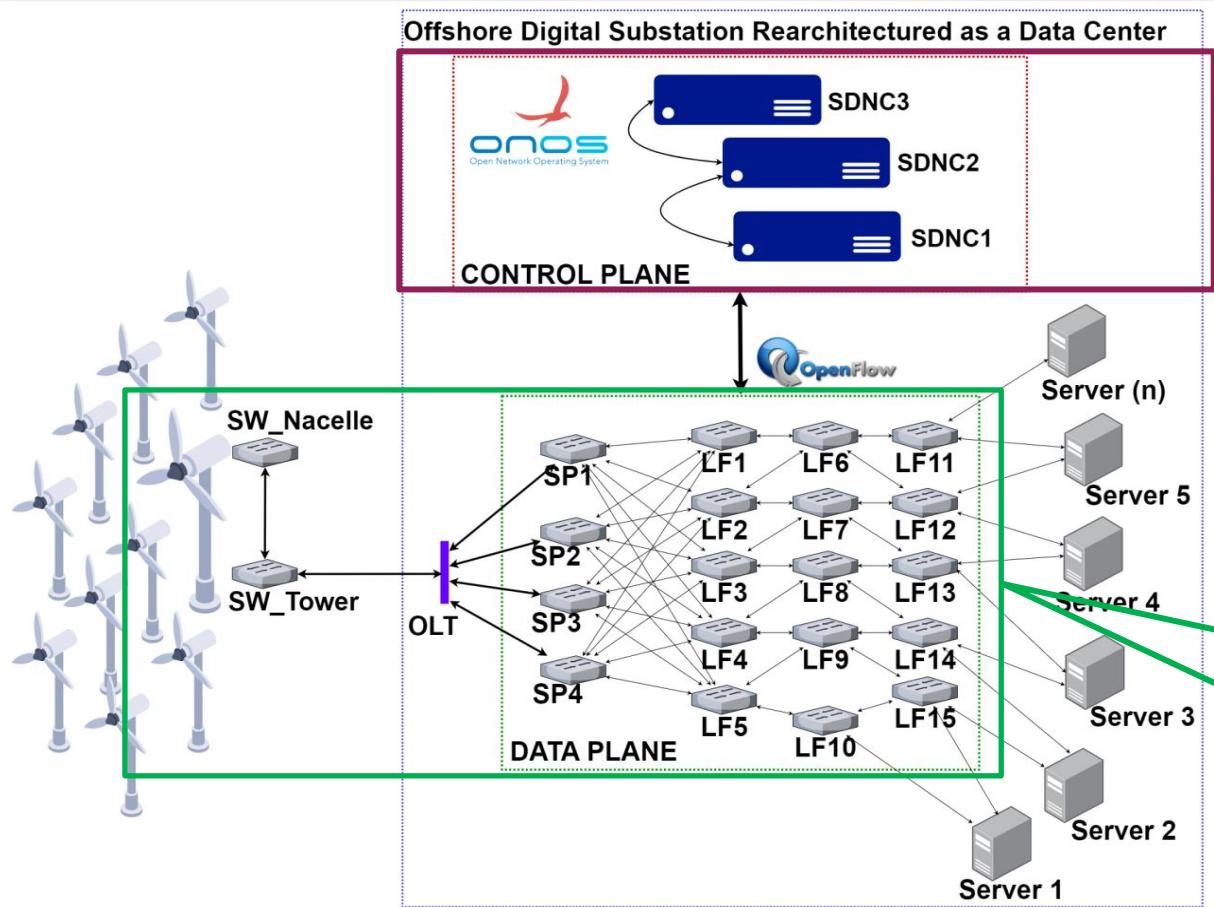
WPP Data Service	Nodes	Type
Turbine Operational Data (e.g. power output, rotor speed, wind speed and direction)	WTG → ECP	- Critical - Time sensitive
Control traffic	vIED → WTG	
Protection traffic	WTG → vIED	
Condition monitoring data (e.g. vibration)	WTG → ECP	- Critical - Delay tolerant
Meteorological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



Offshore Digital Substation Rearchitected as a Data Center

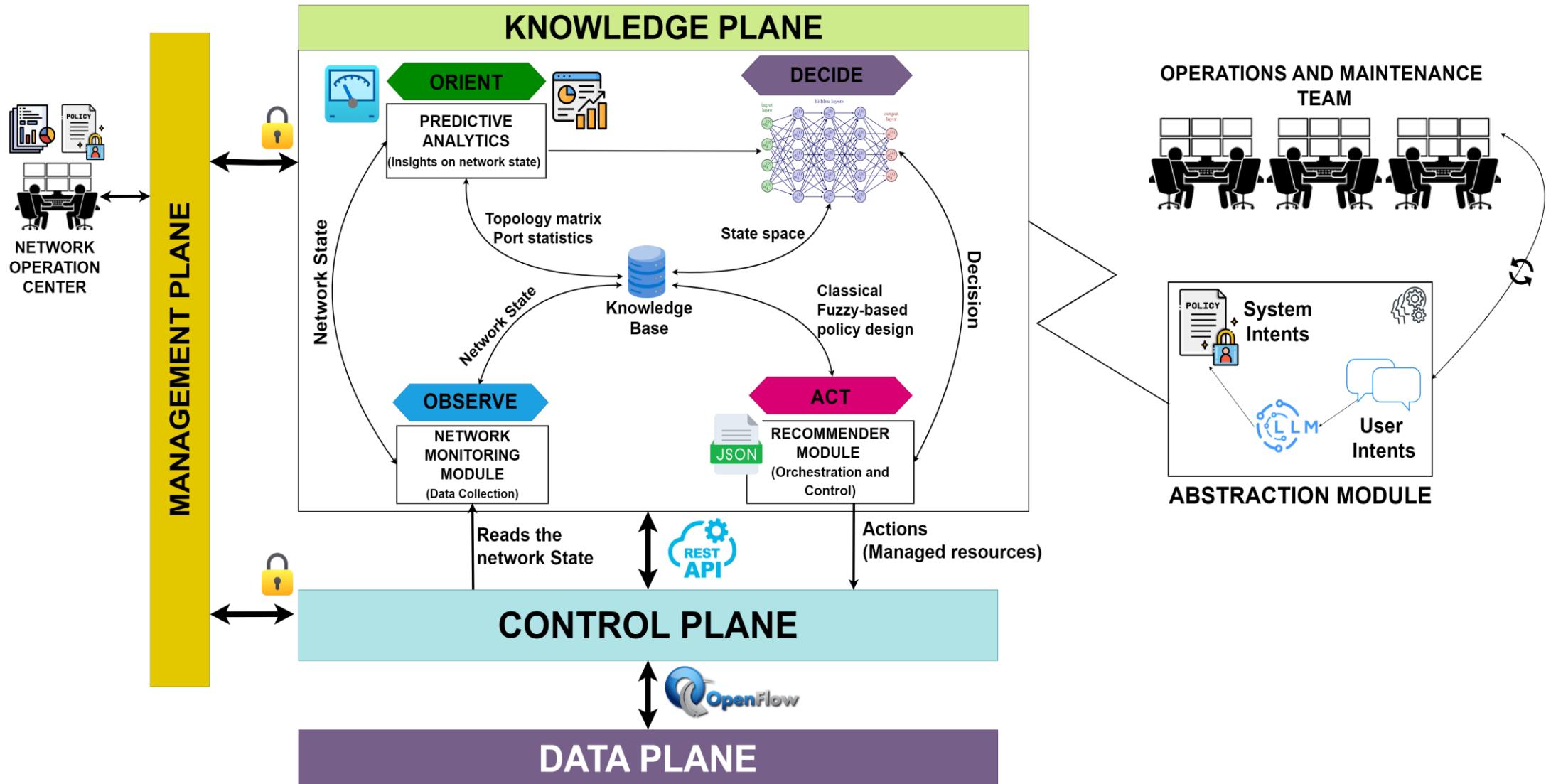


Why self-heal?



- 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.

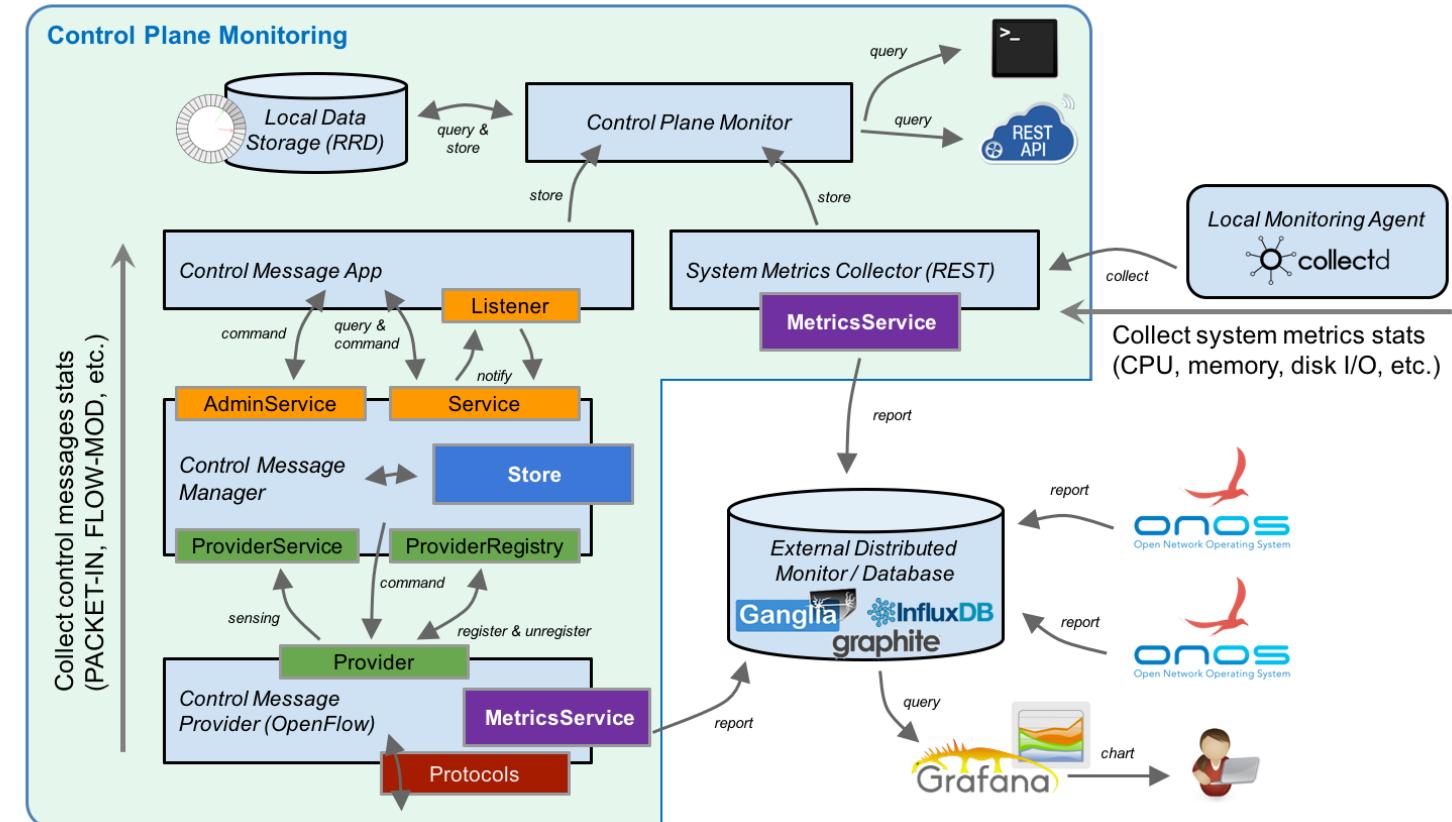
Self-healing framework for clustered offshore wind farm



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

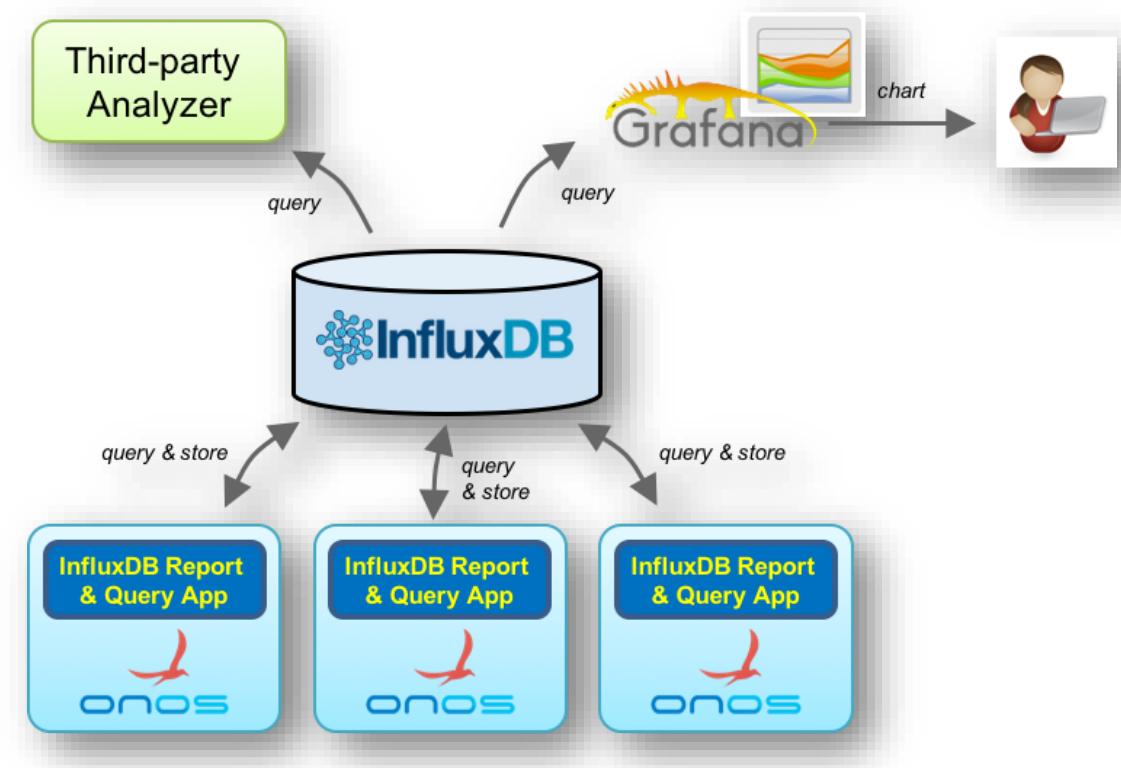
OBSERVE Module

- The Observe Module reads the current network state from the control plane's topology, statistics, and flow rule manager.

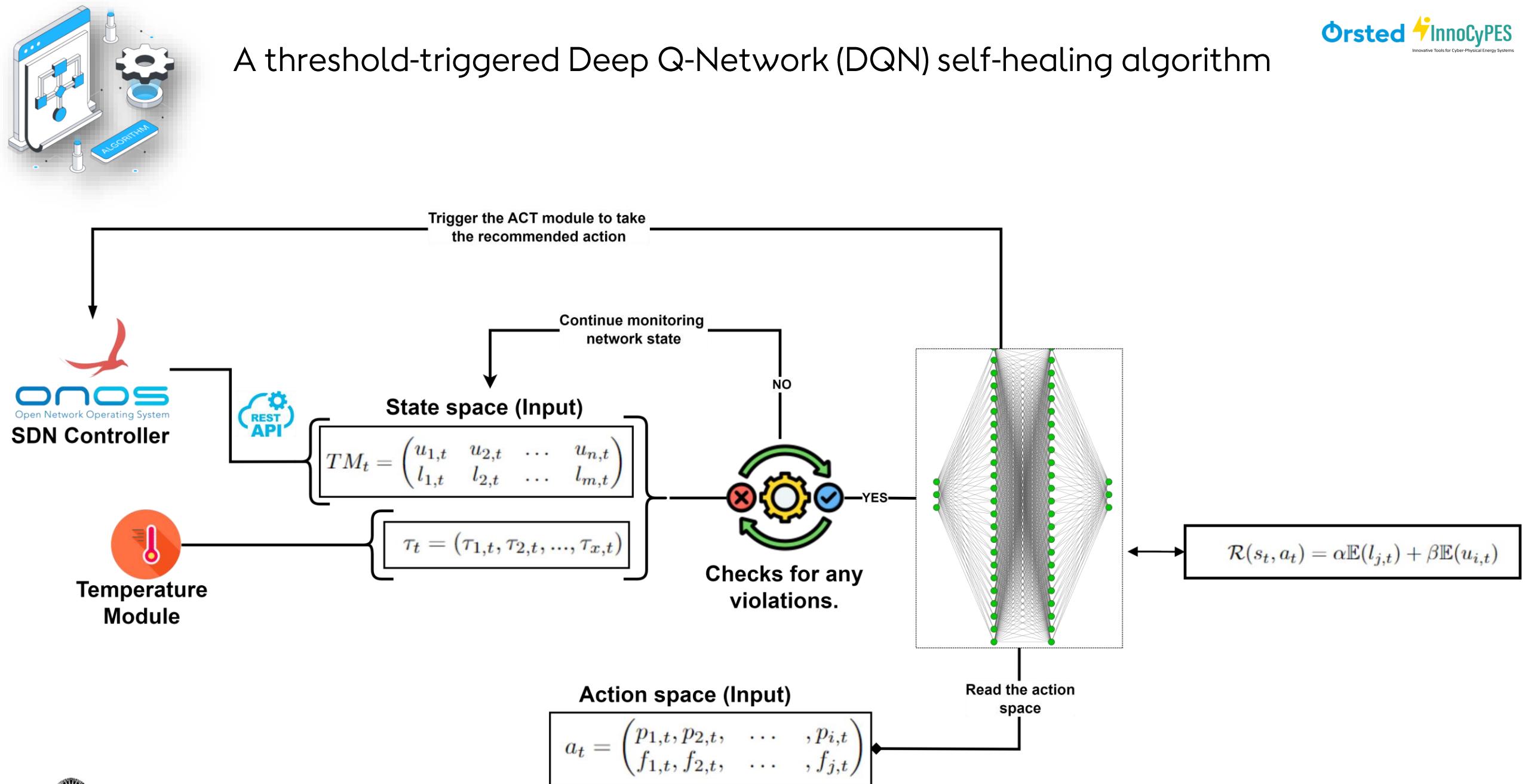


"Observe-Orient-Decide-Act" Closed Control Loop Cycle Knowledge Base (InfluxdB)

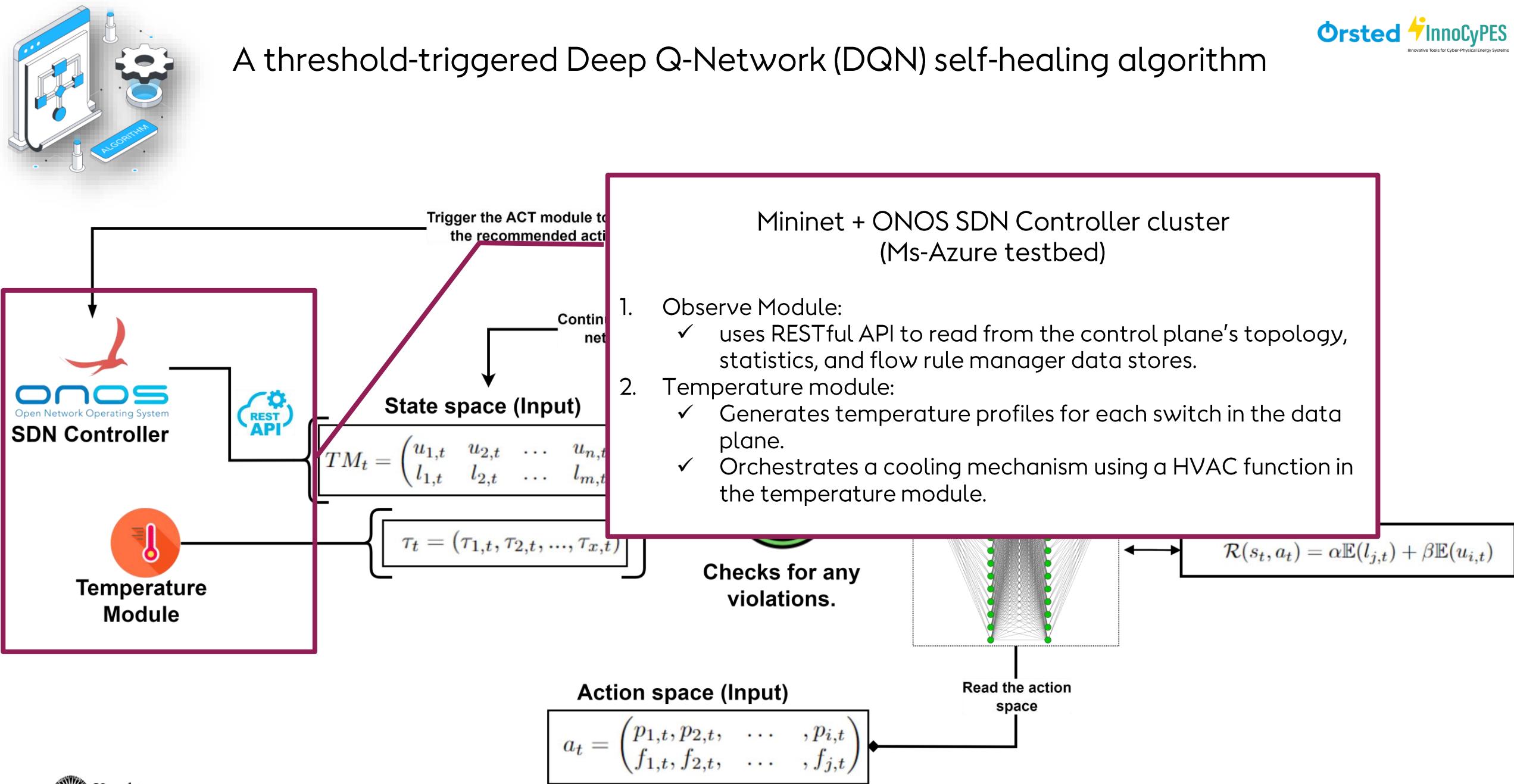
- ❑ InfluxDB is a distributed time-series database written in GO language and is optimized for storing time-series data while supporting clustering. It is a powerful database solution for applications that require high-performance and scalable storage and querying of time-series data.
- ❑ Each ONOS instance 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.



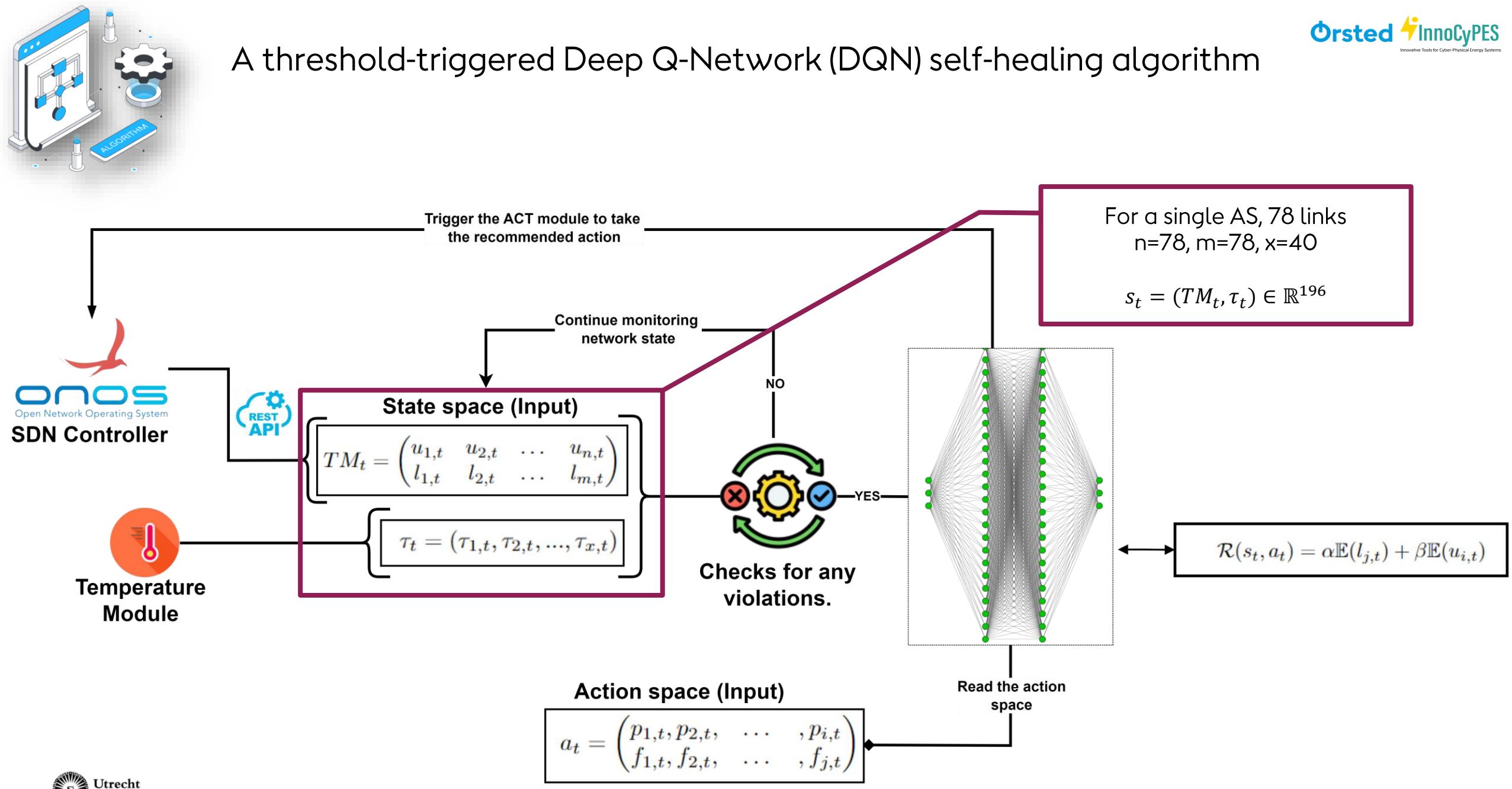
A threshold-triggered Deep Q-Network (DQN) self-healing algorithm



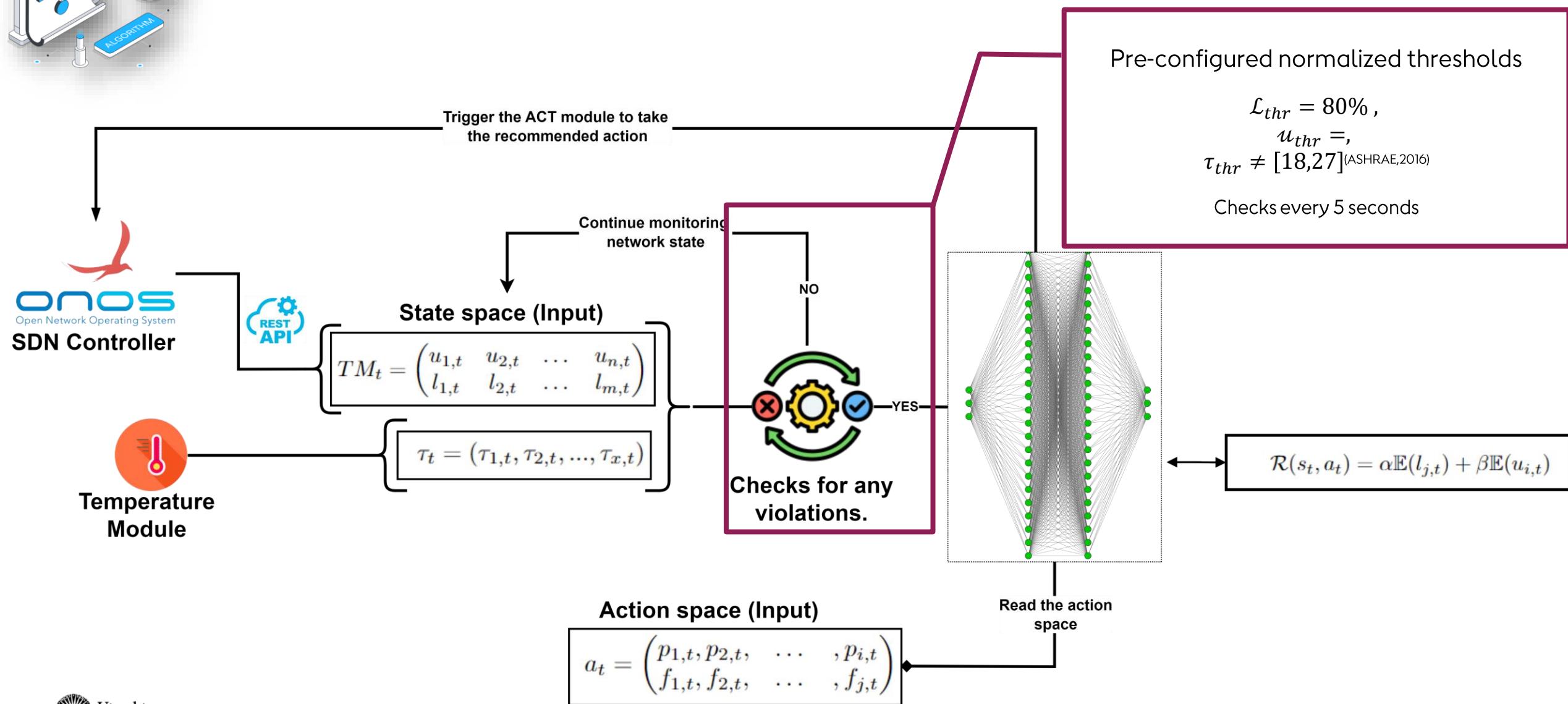
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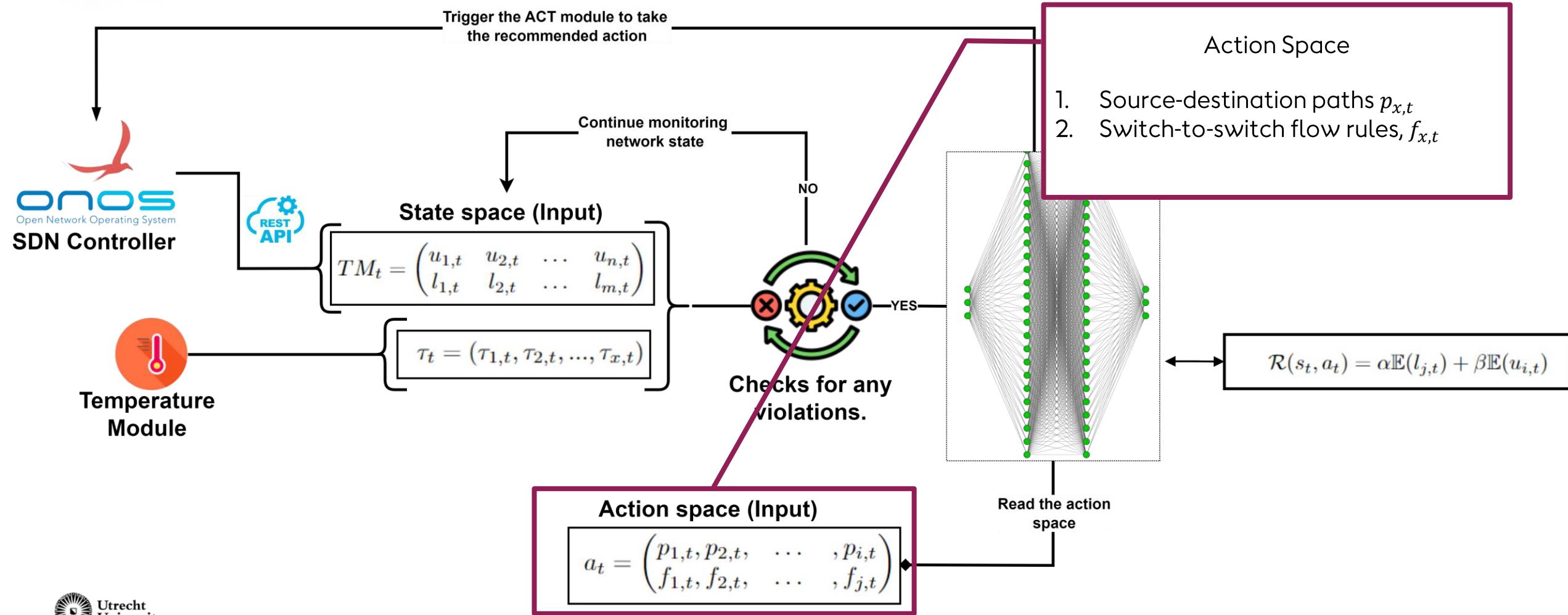
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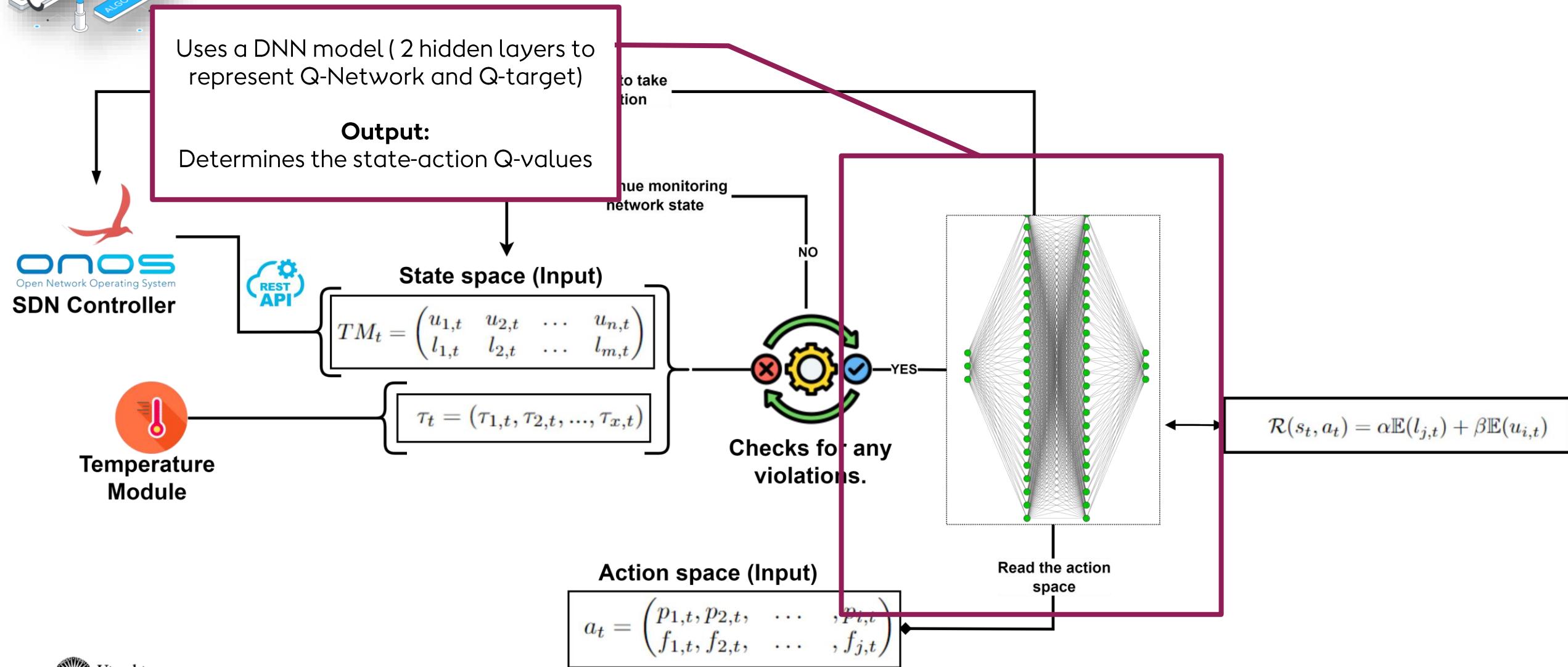
A threshold-triggered Deep Q-Network (DQN) self-healing algorithm



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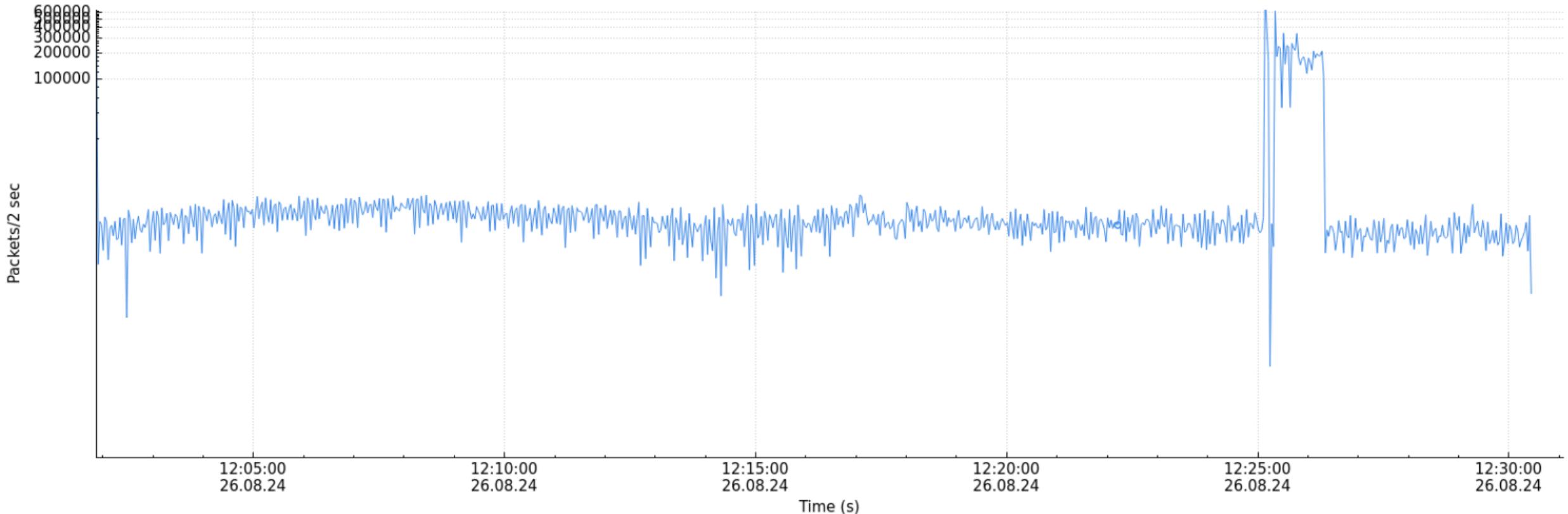


A threshold-triggered Deep Q-Network (DQN) self-healing algorithm



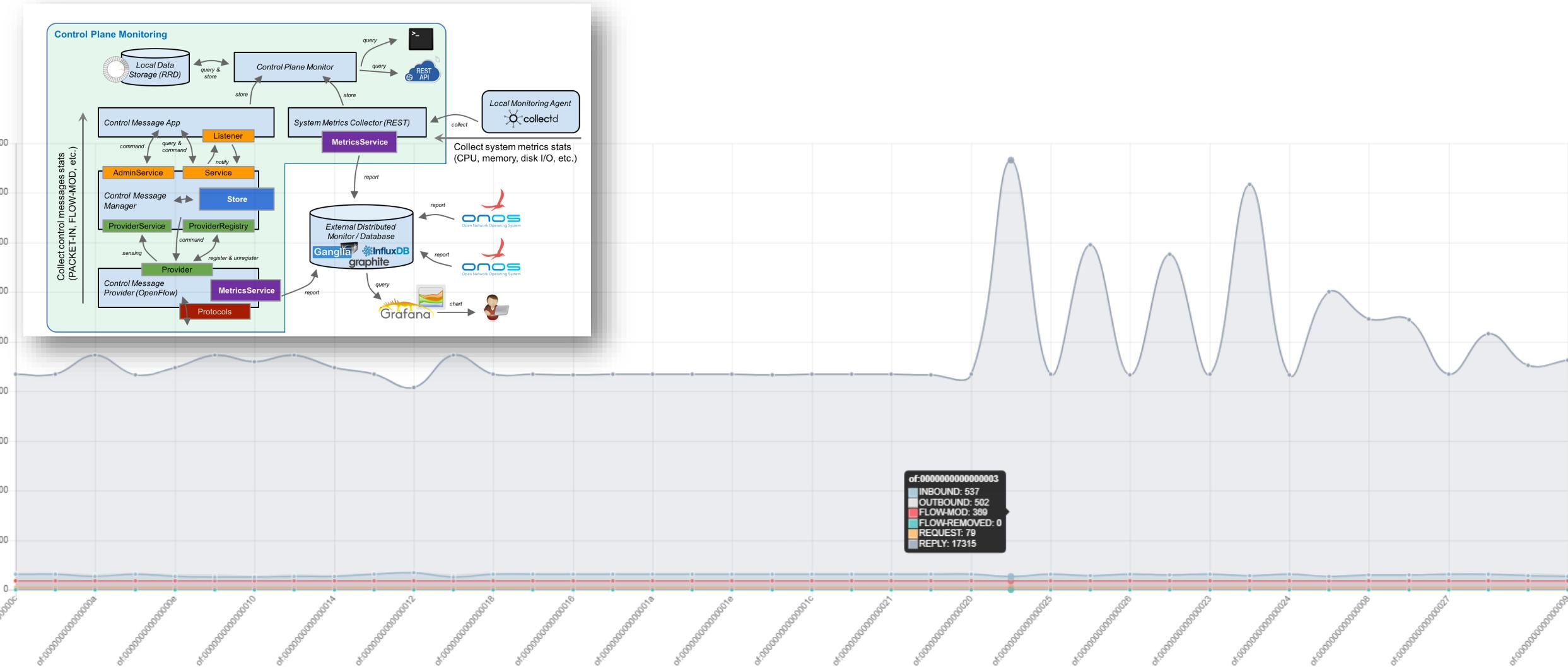
Key Findings

Plot of flash events of benign traffic flows captured on AS2 network



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

OBSERVE Module



Resources

DISSEMINATION

- 1) **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>
- 2) **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>
- 3) **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>

TESTBED DOCUMENTATION

- 1) Microsoft Azure (Ms-Azure) Testbed Design for the European Telecommunication Standards Institute (ETSI) self-healing framework ([Github Repository](#))



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