Demo: An SDN-driven Active Queue Management Architecture for Assisting Mission-Critical Traffic Flows in Industrial Automation Systems

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ABSTRACT

"Cloud-Fog Automation" envisages a fully digitalized and network-centric paradigm in next-generation industrial automation systems with the goal of providing network determinism. To this end, we designed a Software-Defined Networking (SDN)-based experimental testbed to implement Active Queue Management (AQM) schemes to assist mission-critical flows in a smart factory environment. In this demo, we showcase SDN's Open vSwitch (OVS) capabilities to dynamically configure and control interface-specific AQM schemes, and demonstrate our proposed queue management mechanism (*vSwitch-AQM*) for elevating the network performance of mission-critical flows in industrial environments.

CCS CONCEPTS

• **Networks** → **Cyber-physical networks**; **Programmable networks**; **Network management**; *Transport protocols*;

KEYWORDS

Software-Defined Networks, Active Queue Management, Industrial Automation Systems, Cloud-Fog Automation

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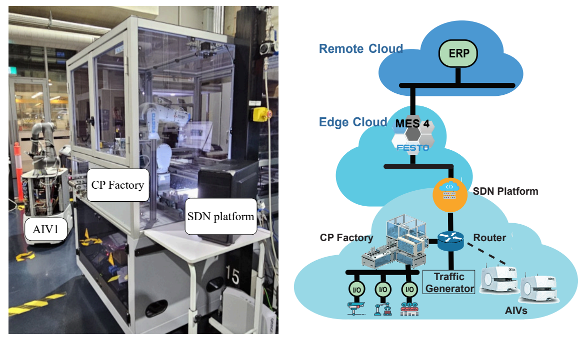


(a) Experimental testbed **(b) Network topology**

Figure 1: Our SDN-based industrial automation system testbed for emulating Cloud-Fog Automation [1].

1 INTRODUCTION

"Cloud-Fog Automation" is a new disruptive network-centric paradigm we recently proposed for next-generation industrial automation systems [1]. This paradigm enables industrial traffic flows to achieve determinism in connectivity, computing and control. In particular, network determinism is paramount for mission-critical flows, such as those that carry process control data, safety-related data, and control signals. These flows require bounded network latency and jitter guarantees, of which the failure to achieve these guarantees could potentially lead to catastrophic safety incidents [2].

A complete realization of Cloud-Fog Automation with network determinism guarantees require significant deployment efforts and costs in infrastructure upgrades. To drive this transition and ensure backward-compatibility with legacy systems, we propose the use of Software Defined Networking (SDN) [3] in conjunction with Active Queue Management (AQM) [4] to ensure mission-critical industrial traffic flows meet their stringent throughput, latency and jitter requirements [5]. With its 'global view' and programmable networking capabilities, SDN provides a centralized mechanism for efficient resource allocation [6], whereas AQM [7] ensures low-latency data transmission at network bottlenecks [8].

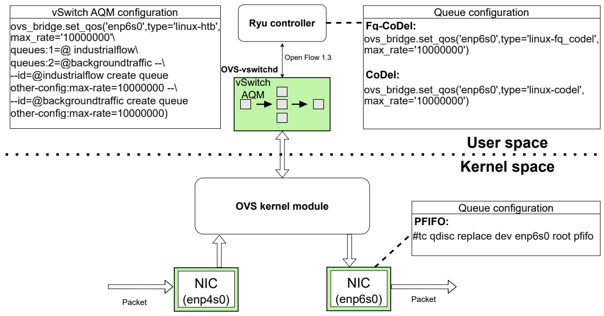


Figure 2: SDN-driven AQM architecture

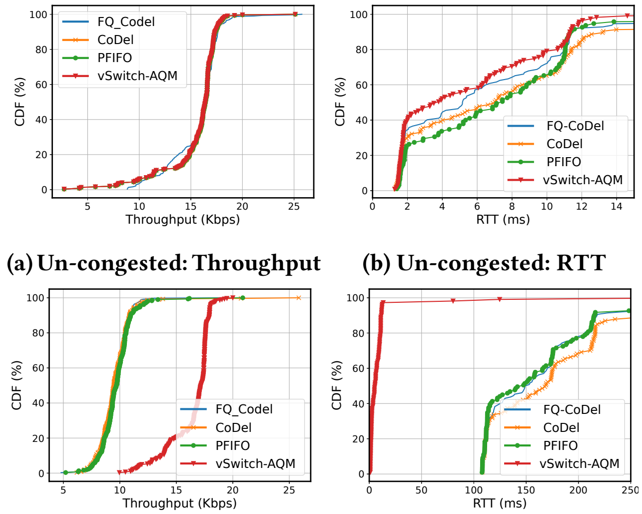
In this demo, we present an SDN-driven AQM architecture for assisting mission-critical traffic flows in industrial automation systems. Our SDN-based testbed dynamically configure and implement interface-specific PFIFO, CoDel [9], and FQ-CoDel [10] AQM schemes. Further, we proposed and deployed a queue management scheme (which we termed *vSwitch-AQM*), which significantly improved the network performance of mission-critical industrial traffic flows.

2 SYSTEM ARCHITECTURE

Industrial automation testbed. As depicted in Fig. 1, our experimental testbed comprises two Autonomous Intelligent Vehicles (AIVs), a FESTO® Cyber-Physical (CP) Factory system, and background traffic generator (running *iperf*). These components are connected to the Manufacturing Execution System (MES) and SDN platform via the MikroTik® router with a symmetric 10Mbps bottleneck link. We define AIV1's flow as mission-critical, where a robotic arm is attached to execute time-sensitive quality inspection procedures.

SDN platform. We use Open vSwitch (OVS) [11] to provide control and visibility interfaces to the virtual networking layer in our SDN platform. As demonstrated in Fig. 2, we attached two Network Interface Cards (NICs) to a computer running Linux Ubuntu 22.04, created a virtual bridge (*br*0) within OVS, and added two physical interfaces (*enp*4*s*0, *enp*6*s*0) as ports to *br*0. We use Ryu as our SDN controller (which communicates with OVS using OpenFlow [12]) to dynamically configure the AQM schemes at the outbound port (*enp*6*s*0), and implement our *vSwitch-AQM* mechanism.

SDN-driven AQM schemes. We control, configure and implement PFIFO, CoDel, FQ-CoDel, and our *vSwitch-AQM*) mechanism in OVS through the Ryu controller. CoDel and FQ-CoDel are implemented out-of-the-box, whereas PFIFO is implemented using Linux's traffic control (*tc*). *vSwitch-AQM* is implemented using Hierarchical Token Bucket (HTB), where industrial traffic flows are classified into three separate queues, i.e., *Queue 0* for mission-critical flows, *Queue 1* for other latency-sensitive industrial flows, and *Queue 2* for latency-tolerant traffic flows.



(a) Un-congested: Throughput **(b) Un-congested: RTT**

(c) Congested: Throughput **(d) Congested: RTT**

Figure 3: Throughput and RTT of mission-critical traffic flow in un-congested and congested environments.

3 DEMONSTRATION

Evaluation results summary: We measured AIV1's throughput and Round Trip Time (RTT) as performance benchmarks of our SDN-based AQM mechanisms' impact on mission-critical traffic flows. We evaluated the benefits and impact of PFIFO, interface-specific CoDel and FQ-CoDel AQM schemes, and our *vSwitch-AQM* mechanism in un-congested and congested environments (with and without elastic background traffic running TCP CUBIC generated by *iperf*).

In un-congested environments, AIV1's throughput remains nearly identical with ∼15Kbps across all queue disciplines (Fig. 3a). The corresponding RTT measurements (Fig. 3b) demonstrate the superiority of our *vSwitch-AQM* scheme, followed by FQ-CoDel, CoDel, then PFIFO in terms of latency performance. In congested environments, our scheme performs the best by preserving the throughput of AIV1 (Fig. 3c) with the lowest latency of ∼5ms (Fig. 3d), therefore ensuring AIV's smooth operation, whereas it is drastically interrupted and non-functional in other scenarios – entering 'fail-safe' mode with PFIFO, CoDel and FQ-CoDel as throughput dropped below ∼10Kbps and RTT spiked to ∼120ms.

Live demo: To showcase our work, we will package and present our virtualized testbed prototype, which runs the actual OVS software switch with Ryu controller for implementing interface-specific AQM schemes, and our *vSwitch-AQM* scheme. Traffic flows generated by industrial equipment and machineries will be emulated with Raspberry Pis with realistic traffic characteristics. We will also present our industrial automation system as a digital twin using CloudWorx® for real-time visualization and audience engagement.

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