Intelligent Edge Control with Deterministic-IP based Industrial Communication in Process Automation

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***Abstract*— In the past years, the Industry 4.0, also known as the Fourth Industrial Revolution, has emerged by the advancement of manufacturing technologies with the Internet of Things (IoT) to enable interconnected manufacturing machines and systems with higher productivity. One of the interesting scenarios in the context of I4.0 is to provide control from the edge, which will improve the efficiency and flexibility of the system at a reduced cost. The industrial automation, especially the process automation (PA) aims for a converged network for data communication. Traditionally internet protocol (IP) is being used for standard IT communication to connect machines to the enterprise network, but not used as much for field network due to lack of determinism. Recent, research has been focused on the design and development of deterministic IP communication, and some preliminary results have been standardized in the IETF Deterministic Network (DetNet) group. In this paper, we investigate on extending the deterministic IP communication to operational technology (OT) domain to support real time industrial Ethernet (RTE) communications. We have integrated IEC-61131-3 based soft PLC (Programmable Logic Controller) runtime system into an Edge computing gateway. The RTE frames are wrapped up with custom UDP/IP header by a proxy and delivered to the deterministic routers. The routers forward packets with a bounded delay of less than 30us per hop. We validate our approach using an experimental test setup, a virtualized PLC (vPLC) inside the edge device remotely controlling the PA application (bioreactor) by passing through proxies and deterministic routers in a heterogeneous network.**

Keywords— Deterministic IP, DetNet, Edge Computing, Industrial IP Communication, Profinet, Process Automation, Real Time Ethernet, vPLC

I. INTRODUCTION

Intelligent edge control is running virtual PLCs inside an edge device with the intention to reduce the cost and increase the system flexibility, as shown in Fig. 1.

In the past, industrial automation used conventional PLC's for exchanging control information between remote IOs and control hardware to accomplish process tasks [1]. The legacy industrial controllers (hardware-based PLC's) are good enough in performance and reliability. However, they have drawbacks in terms of flexibility and scalability. Also, every new PLC additionally increases Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) and requires higher operational and maintenance efforts [2] [3] [4].

In recent years, the automation industry has been explicitly adopted and implemented new automation and communication technologies in order to remain competitive [5]. The concept of "control-as-service" or "Plc-as-service" [2] [3] [6] [7] has emerged as a new paradigm providing service on demand from edge or cloud platform [2] [7] enables system flexibility and scalability for future smart manufacturing system. Another advantage of the edge control is that by moving the control function to the edge node, a massive amount of data have been sent to the edge, which enables data analysis and machine learning. Edge computing is a decentralized computing infrastructure [8] providing rapid processing of a large amount

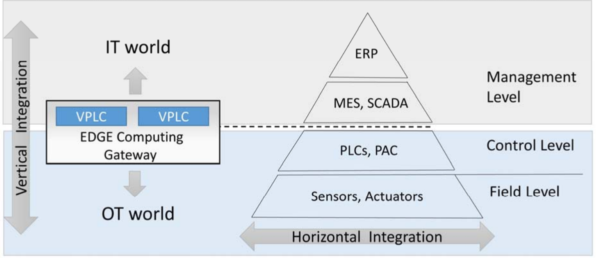

Fig. 1. Mapping of intelligent edge control into classical automation pyramid

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of data [9] locally close to a machine and sends only required data to the cloud. Thus it reduces transmission latency and provides high availability even in the scenario of disconnection from the cloud [8]. Meanwhile, this increases network security as the data processing is done locally on customer premise equipment. This prevents data from being leaked out when sending over internet.

Besides the cloud or edge-based control, ensuring deterministic communication from edge or cloud to field devices remains a challenge [7]. Emerging wired technology such as IEEE 802.1 Time-Sensitive-Networking (TSN) has been considered as a baseline technology for industrial automation applications providing interoperability and connectivity on a converged network [7][10][11]. The TSN standard has gained significant importance. However, technology is still challenging several issues for the requirements of different applications on the TSN network [12] i.e. self-configuration [13] and runtime configuration of scheduled traffic [14]. On the other hand, 3GPP standardization is pushing cellular technology for industrial wireless communication such as the existing narrowband Internet of Things (NB-IoT) introduced in the 3GPP Release-13 [7] [16] targeted to low cost and power, deeper coverage, and higher device density [7][17]. In contrast, the 5G new radio (5G-NR) intent to use ultra-reliable low latency communication (URLLC) [7] for time-critical IIoT use cases such as motion control or mobile robots [10]. There are several challenges 5G need to overcome, including potential side effects of uncontrolled coexistence of other wireless networks operated in unlicensed frequency bands such as Wi-Fi and MulteFire [17][18], integration with existing networking technologies on shop floor and cost issues [17].

Recently IETF DetNet group is standardizing deterministic communication technologies [19] to support real time service from OSI layer 3 and above [15]. In contrast to TSN and 5G, deterministic IP enables real-time communication between the subnets, provides simple network configuration and interoperability with the existing network infrastructure. In addition, it bridges the gap between OT/IT although traditional communication adopt layer 1 and 2 technologies. In this paper we would like to investigate on carrying the field level communication with deterministic IP technology to enable control from edge and facilitate big data analytics.

The rest of the paper is organized as follow: Section II presents background information on deterministic networking. Section III provides an overview of edge control. Section IV shows the proof-of-concept testbed, which includes an approach to IP tunnel for industrial Ethernet communications, edge based virtual control, and production module. Section V presents the performance evaluation of deterministic routers. Finally, Section VI concludes the paper and provides an outlook.

II. BACKGROUND

The purpose of deterministic network is to provide "TSN-like" performance available from layer 3 applications [20].

The DetNet working group collaborates with TSN (WG) to define a common architecture for layer 2 and layer 3 communication [19]. It offers real-time services on layer 3 in routed network using deterministic data paths where such paths can provide bounded latency, jitter, zero packet loss, and high reliability [19]. Three techniques are used by DetNet to provide Quality of Service (QoS) as shown in Fig. 2.

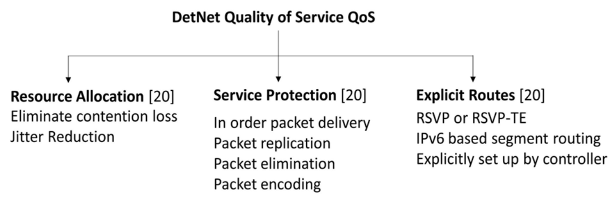

Fig. 2. Classification of DetNet Quality of Service (QoS)

A. *Resource Allocation*

The resource allocation addresses the QoS requirements of latency and packet loss. The bounded latency is achieved by reserving bandwidth and dedicated buffer resources for zero packet loss at each DetNet aware router [20]. The provision can be released or reused when they are no longer needed.

B. *Service Protection*

The service protection technique is used to improve reliability which aims to mitigate or eliminate packet loss by switching the explicit disjoint path after a failure is detected to re-stablish required DetNet service. However, route changes, even after the failure recovery can lead to the out of order delivery of the packets [20]. The DetNet service sub-layers includes the PREOF mechanism (Packet Replication, Elimination and Ordering Function). The packet ordering function re-orders packets that are received out of order [20].

C. *Explicit Routes*

To improve the deterministic latency, DetNet explicitly used specific path to each IP flow. These flows can be synchronous or asynchronous depending on the application. In synchronous flows DetNet enabled endpoint systems use time synchronized clocks. For asynchronous flows, a maximum

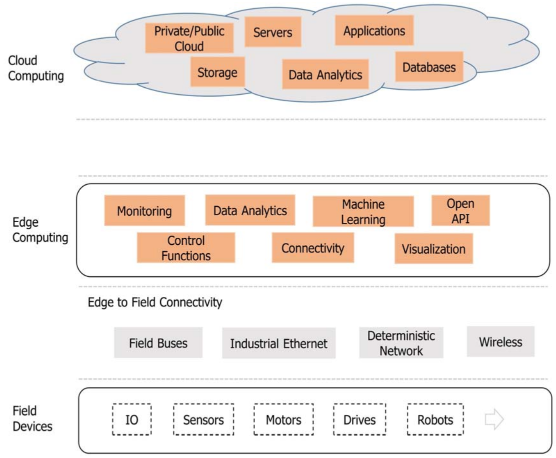

Fig. 3. Network architecture of edge/cloud computing to field network

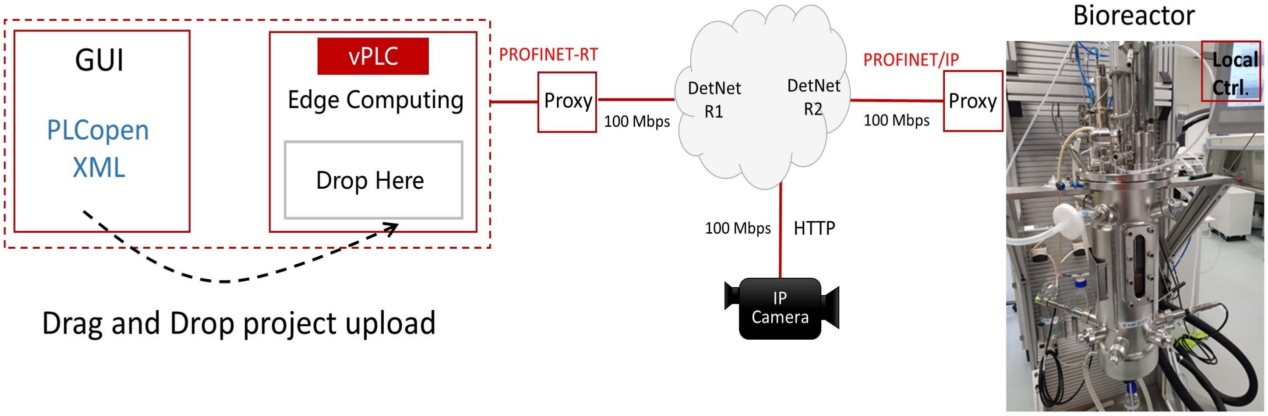

Fig. 4. Huawei and Festo edge control with deterministic IP based industrial hetrogeneous network demonstrator

packet size and maximum number of transmissions during the observation interval is used in conjunction with the information from protocol stack to reserve bandwidth for DetNet flows [20].

III. EDGE CONTROL

The edge computing technology has emerged to bring the functionality of cloud close to the network edge in a PA plant.

Besides the hardware-based PLC's, which have been used to control the automation tasks for the past several years, much attention has drawn to move control from field to edge in order utilize computing resources, enable new services and increase flexibility with reduced cost. As shown in Fig. 3. The edge computing device provides different applications and services to field devices such as virtual control functions, data analytics, visualization, etc. A virtual controller can communicate to field devices using wired or wireless networking technologies such as existing field buses, industrial Ethernet, emerging deterministic networking, and cellular networks.

Providing control from the edge has several advantages among others:

A. Flexbility

Edge computing can support and meet the dynamic requirements of the manufacturing using virtualization technology. Several vendor-independent virtual control function can be deployed and run in parallel on different virtual machines or containers on a single hardware platform, thus enables the system flexibility.

B. Enabling Data Analytics

With edge computing, big-data analysis and processing can also be done locally even at the control level and almost near real time.

C. Reducing Network Traffic

Computing at the edge mitigates the risk of network congestion because not all data needs to be transferred to the cloud. However, it only sends the required amount of data to cloud for further processing.

IV. PROOF OF CONCEPT

For proof of concept, a joint industrial testbed has been developed by Huawei and Festo, shown in Fig.4. In this setup, an experimental production module on the right-hand side is controlled in two different ways. Initially, the Festo local PLC controls the bioreactor. After some time the PLC is forced manually to stop and changed over to slave mode (only using remote IO).

Festo provides the bioreactor project application in terms of Codesys project in PLCopen XML schema. The project file is automatically uploaded into the vPLC running in edge computing device via a Graphical User Interface (GUI) by simple drag & drop mechanism. After the project file has been uploaded successfully, the vPLC is started which remotely controls the process parameters of the bioreactor via two deterministic IP routers. At the same time, an IP camera is turned on in order to demonstrate the mixed traffic scenario on a single deterministic IP network.

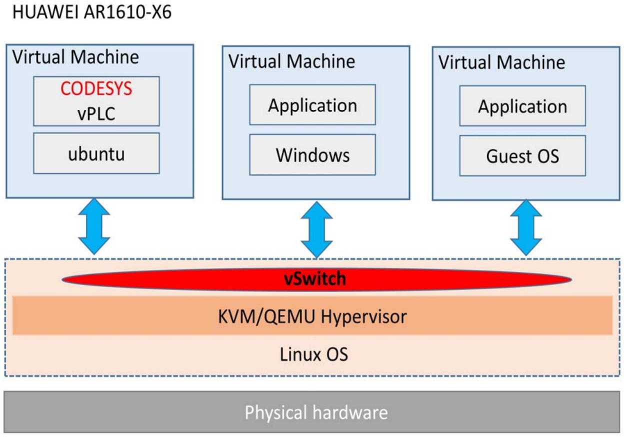

Fig. 5. Integration of Codesys vPLC into Huawei edge computing device

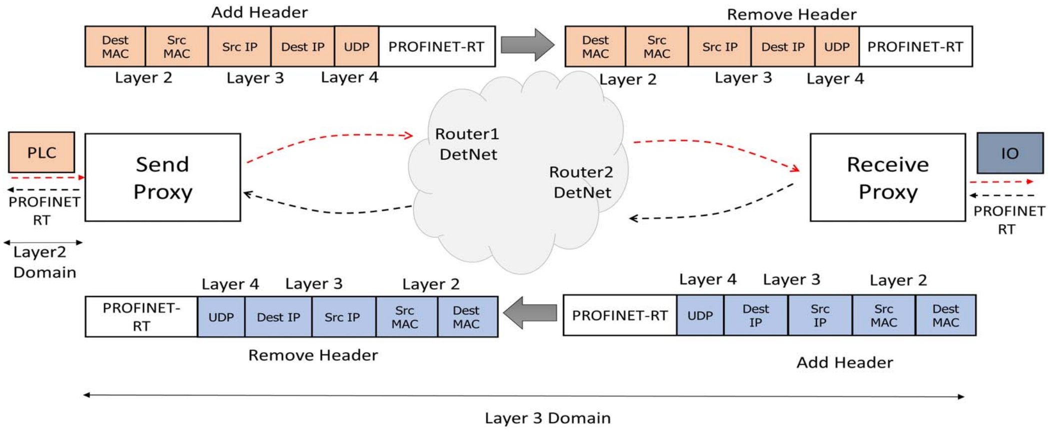

Fig. 6. IP tunnel for RTE industrial communications

A. *vPLC*

The concept of "vPLC" is realized by using the Huawei AR1610-X6 edge computing gateway as depicted in Fig. 5. The edge device is equipped with six physical cores, 32GB RAM, and 32GB built-in Hard Disk Drive (HDD), with 8xGE LAN and 2xGE WAN interface. The Ubuntu VM is assigned with a single CPU core, 4GB RAM, and 8GB HDD. For the virtual network interfaces, KVM (para-virtualized network driver) is used, which is modified in XML configuration of the guest OS.

The VM is managed by Huawei internal router commands or an external tool such as virsh. The tool provides several commands which include the start, restart and shutdown of VM's. The Codesys Profinet runtime system IEC-61131-3 implementation is used as a vPLC as shown in Fig 5. It supports the minimum cycle time of 1 millisecond for soft real-time applications. The runtime system is installed by using the development package via Codesys development system V3. A virtual switch (vSwitch) creates a bridge network and connect the virtual port of VM to the physical interface of the edge device, allowing Profinet-RT frames pass through the physical interface of the edge to an external network.

B. *Proxy*

The purpose of proxy is to transport RTE traffic on a converged IP-based network in order to provide WAN connectivity down to field level in industrial automation applications. The proxy is only intended for RTE protocols, which do not support IP-based real-time communication. For example, Profinet-RT completely replaces the higher layer TCP/IP stack for the real-time channel [21]. Although, Profinet standard has RT_CLASS_UDP for cross-subnet communication with a cycle time of 5 ms [22].

However, we used Codesys runtime for our implementation, which is currently not supporting Profinet-RT over UDP/IP. Therefore, we have developed a custom IP tunnel for layer 3 based industrial communications. As shown in Fig. 6. The Profinet frames are cyclically exchanged between the subnets. The send Proxy receives entire RTE frame from the vPLC and encapsulates it into the payload of a custom header of 42 bytes including (14 bytes MAC + 20 bytes IP + 8 bytes UDP). The modified packets are forwarded to the deterministic IP router which delivers the IP packets to the receive proxy. It removes the headers and sends the original RTE frame to IO device and vice versa. The worst case processing time of each proxy is 300us.

C. *Deterministic Routers*

The deterministic routers are high-performance network devices which are compliant to the DetNet standard [20]. In an experimental setup, as shown in Fig. 4, the two Huawei deterministic prototype routers were used in order to mimic the typical industrial application of carrying different traffic on the same network. For example, critical control traffic such as Profinet over UDP/IP and non-critical traffic such as a IP video camera. On each deterministic router, a dedicated

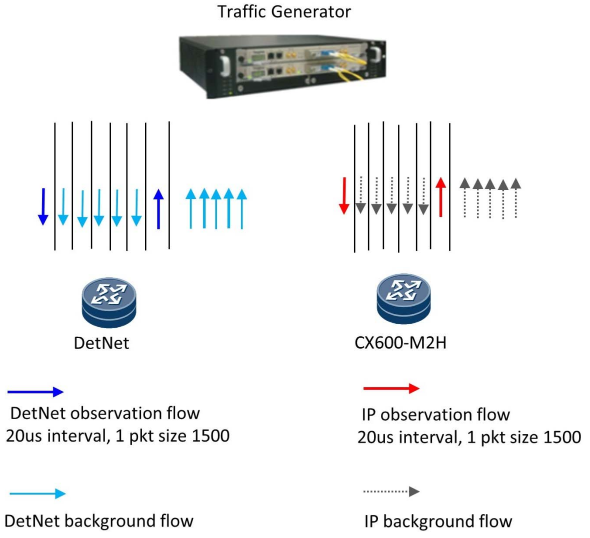

Fig. 7. Single hop test topology with and without DetNet solution

TABLE I. SINGLE-HOP LATENCY AND JITTER MEASUREMENT WITH AND WITHOUT DETNET SOLUTION

Flow model	DetNet min latency	DetNet avg latency	DetNet max latency	DetNet min Jitter	DetNet avg Jitter	DetNet max Jitter	IP min latency	IP avg latency	IP max latency	IP min Jitter	IP avg Jitter	IP max Jitter
Background flow interval 100us，5 pkt/interval	19.588	28.206	38.122	0	3.045	17.855	10.849	17.157	43.843	0	9.340	32.895
Background flow interval 200us，10 pkt/interval	19.601	28.282	38.141	0	1.541	17.842	10.830	22.934	74.830	0	10.690	63.839
Background flow interval 500us，25 pkt/interval	19.608	28.314	37.930	0	0.652	17.727	10.805	31.526	164.144	0	8.981	107.777
Background flow interval 800us，40 pkt/interval	19.608	28.334	38.192	0	0.454	17.739	10.856	57.602	264.410	0	11.636	112.735
Background flow interval 1ms，50 pkt/interval	19.595	28.327	37.891	0	0.371	17.733	10.830	66.641	326.811	0	11.361	111.493

unit = us

TABLE II. MULTI- HOP LATENCY AND JITTER MEASUREMENT WITH AND WITHOUT DETNET SOLUTION

Flow model	DetNet min latency	DetNet avg latency	DetNet max latency	DetNet min Jitter	DetNet avg Jitter	DetNet max Jitter	IP min latency	IP avg latency	IP max latency	IP min Jitter	IP avg Jitter	IP max Jitter
Background flow interval 100us，5 pkt/interval	49.304	62.528	77.127	0	2.386	24.175	21.655	26.069	44.110	0	5.923	22.179
Background flow interval 200us，10 pkt/interval	49.311	62.816	77.555	0	1.535	27.873	21.649	31.923	76.244	0	9.007	50.520
Background flow interval 500us，25 pkt/interval	49.330	62.988	77.395	0	0.658	25.320	21.616	47.724	171.175	0	9.864	127.698
Background flow interval 800us，40 pkt/interval	49.317	63.033	77.760	0	0.454	24.169	21.661	68.407	264.494	0	11.253	163.779
Background flow interval 1ms，50 pkt/interval	49.323	63.046	77.414	0	0.377	24.162	21.661	81.234	327.738	0	11.476	212.323

unit = us

network bandwidth (100Mbps) and the explicit route was allocated to provide deterministic service for control traffic and ensure that it prioritizes the Profinet/IP flow over standard TCP/IP communication.

D. Production module (Festo-Bioreactor)

The Festo bioreactor, shown in Fig. 4 on the right-handside, is an experimental production module capable of performing the cultivation of various microorganism like bacteria, yeast or mammalian cells. The setup consists of a vessel with an elaborate set of sensors to monitor the process parameters closely. Among the measured quantities are temperature, pressure, oxygen saturation and pH value of the culture medium. A local Festo PLC controls the process, regulates the entry of gas and different media used to regulate the fermentation. The reactor is mainly used to develop Process Analytical Technology (PAT) with a focus on automation, integration and advanced process control for biological cultivation processes.

The Festo bioreactor is automated according to the requirements of the VDI/VDE/Namur 2658 standard and is thus a Module Type Package (MTP) [23] compliant Production Module, allowing seamless software integration into modular production plants. Modular production with MTP is one of the major opportunities for process industries in the context of Industry 4.0 [24].

The demonstrator shows the feasibility of edge based control technology with deterministic IP communication using the deterministic routers carrying mixed types of traffic on a single network. The process IO data of vPLC are periodically transmitted over 100 Mbps link via a Gigabit Ethernet link which is shared between the two routers. The IP video camera is added into the loop as background traffic which sends video stream at 100 Mbps.

V. RESULTS

The latency and jitter performance of the DetNet and standard IP edge router are measured using the Huawei traffic generator and analyzer (Tesgine v2.0).

The test topology, shown in Fig.7 on the left-hand side is Huawei prototype DetNet capable router and on the right side

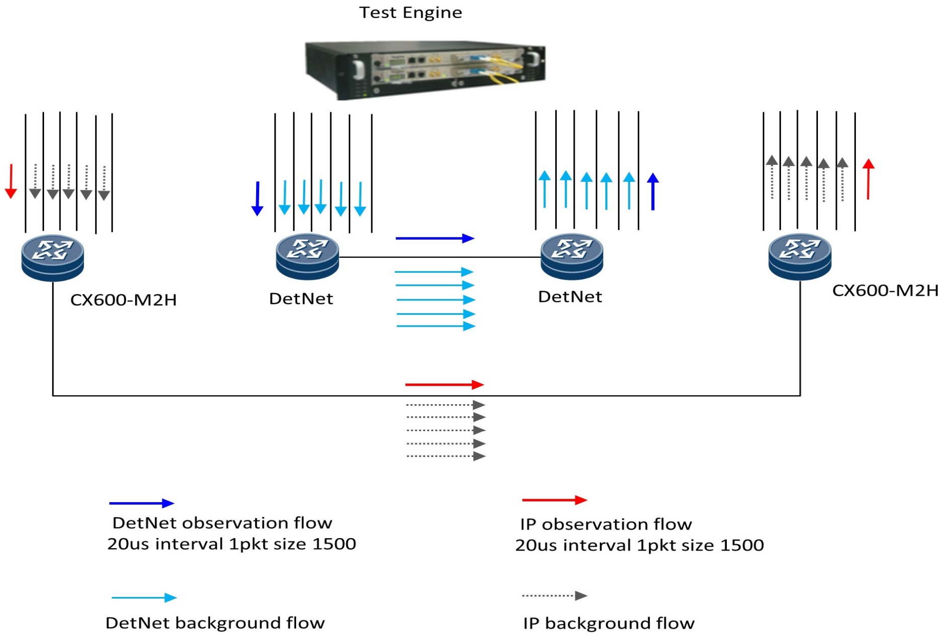

Fig. 8. Multi hop test topology with and without DetNet solution

is standard IP (CX600-M2H) router.

For configuration of the traffic generator, a tesgine V500R008C00SPC100 software is installed on a computer running Microsoft windows 10 which is connected to the traffic generator via a network cable. By using the software, we have generated different background flows with different intervals and packet rate and measures the latency and jitter of the observation flow with and without the DetNet solution.

A. *Test Case*

Generate five different background flows and one observation flow with and without the DetNet solution as depicted in the Fig.7. The background flows are generated with different Intervals (100us up to 1ms), packet rate (5 up to 50 packets per interval) and packet size 1500 bytes. While the observation interval is generated at constant 20µs interval with the maximum packet size is set to 1500 bytes. The observation flow remains the same with all flow model.

The minimum observation interval is set to 20us, in order to achieve the best performance with the DetNet routers.

B. *Test Criteria*

Measure the latency and jitter of the observation flow corresponding to each background flow with and without DetNet solution for single and multi-hop network topology.

As shown in Table.I for the flow model with different intervals and packet rate, the DetNet router providing the consistent forwarding capability, the average latency of the observation flow measured at 100us interval remain unchanged at 1ms with background flow of 50 “packets per interval,” and jitter is reduced from 3.045 to 0.371us. On the other hand, the average latency and jitter of the standard IP observation flow are increased as we increase the background flow.

The network topology is extended with one additional router as shown in Fig.8 and perform a similar test as we did with single hop scenario. The test results are shown in the Table. II, again it is worth mentioning that, the average latency for DetNet solution is quite stable and does not change with an increase in the background flow. However, the average latency is almost double as compared to single-hop scenario, and this is due to the fact that, the average processing time of each DetNet router is around 30us. The end to end latency will be increased as we increased the number of hop count. While for the standard IP, again the average latency is not deterministic however it is changed in single-hop from 17 to 81us in multi-hop topology.

The deterministic router has the advantage of providing bounded latency and jitter by explicitly allocating the route and bandwidth for packet streams using information from IP header and the number of transmissions during the observation interval. On average, the processing time of the single DetNet router is to deliver one packet within the delay of less than 30us while keeping the jitter as low as 0.371us.

VI. CONCLUSION AND OUTLOOK

In this paper, we have proven that the deterministic IP networking can be used at field level communications. We have successfully managed to carry RTE communication such as Profinet RT over DetNet in a heterogeneous network and control a realistic production module for PA applications. We have obtained significant results showing that deterministic IP routers process packets with bounded low latency and jitter.

The deterministic IP network enables new opportunities for industrial automation, providing deterministic layer 3 communication down to the field level, which has not been possible with traditionally IP communication.

Further evidence of the study confirmed the edge computing technology can be used to execute IEC-61131-3 applications from the edge for PA applications, which has typical timings requirements on the latency within the range of 50ms up to a few seconds [25]. However, the existing demonstrator as shown in the Fig.4 is capable to provide control from the edge with guaranteed end to end communication with minimum cycle time up to 4ms. Besides that, it increases system flexibility and reduces the cost.

Our future work will be focused on the factory automation applications which requires cycle time 1 to 2ms. In addition, the demo will be extended for redundant communication and realization of the distributed virtual control functions from the edge using container technology over deterministic IP network.

ACKNOWLEDGMENT

The authors would like to thanks for the collaboration of joint innovation between Huawei and Festo, the enterprise Huawei for providing edge computing gateway, deterministic routers and Testgine for latency and jitter measurements, and the Festo innovation group provides Bioreactor production module to be controlled from an edge over a deterministic network.

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