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Practical Implementation of an OPC UA TSN Communication Architecture for a Manufacturing System

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ABSTRACT In modern manufacturing systems, various industrial communication systems (e.g., fieldbus systems and industrial Ethernet networks) have been used to realize reliable information exchange. However, these industrial communication solutions are largely incompatible with each other, which do not satisfy the new requirements of Industry 4.0. Recently Time-Sensitive Networking (TSN) has been developed to improve the real-time capabilities to the standard Ethernet, and is considered to be a promising real-time communication solution for Industry 4.0. In this work, we propose a communication architecture for a manufacturing system using the Open Platform Communications Unified Architecture (OPC UA) and TSN technologies. TSN is adopted as the communication backbone to connect heterogeneous industrial automation subsystems. The OPC UA is adopted to realize horizontal and vertical communication between subsystems in the field layer and the entities of the upper layers. We implement a laboratory-level manufacturing system to validate the proposed architecture. The experimental results demonstrate the feasibility and capability of the proposed architecture. Moreover, we evaluate the performance of a key TSN substandard, i.e., IEEE 802.1Qbv, in the laboratory-level manufacturing system. The evaluation results demonstrate that IEEE 802.1Qbv can indeed provide excellent real-time capabilities for industrial applications.

INDEX TERMS Industry 4.0, manufacturing system, OPC UA, TSN.

I. INTRODUCTION

In factory automation systems, one of the key elements is the reliable exchange of information among various controllers, sensors, and actuators [1]. To realize the exchange of information, various industrial communication networks have been used during the past several decades. In the early days, communication networks, the so-called fieldbus systems, e.g., Profibus or Interbus, which laid in the lower layers of the automation pyramid architecture of a manufacturing system, were adopted to overcome the limitations caused by point-to-point connections among controllers, sensors, and actuators. One of the challenges of using fieldbus systems in field-level networking was the integration problems between different levels of the automation pyramid architecture, i.e., fieldbus systems and Ethernet-based LANs, which are largely incompatible networking concepts [2]. These integration problems promoted the use of Ethernet on the field level. However, Ethernet per se lacks real-time capabilities; thus, device vendors started to develop industrial Ethernet solutions to improve the real-time communication capabilities to Ethernet. In the early stage of developing industrial Ethernet solutions, the related research works focused on compatibility and conformity. However, Ethernet-based solutions failed to be a unique industrial communication solution in the end; various industrial Ethernet solutions are incompatible, interoperability is not possible in a direct way, and some of these solutions are incompatible with the classical Ethernet standard [3].

The industrial automation scenario is continuously evolving. Recent Industry 4.0 revolutionizes the automation scenarios, enabling new production strategies (e.g., mass customization and efficient production of small lot sizes),

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better efficiency (e.g., energy usage optimization), higher flexibility, and rapid answers to the market requests. This poses challenges to industrial networks, i.e., providing better performance in terms of real-time capabilities, reliability, and connectivity, and requires a more uniform communication based on IP in all functional layers. Legacy industrial communication solutions are not interoperable with each other and cannot satisfy the requirements of Industry 4.0 [4].

Currently, Time-Sensitive Networking (TSN) [5] is being developed by the IEEE 802.1 working group, aiming to improve real-time capabilities to the standard Ethernet. TSN has many advantages: deterministic latency, low jitter, extremely low packets loss, and better interoperability among solutions from different manufacturers. Compared to the existing industrial Ethernet solutions, TSN enables a much higher determinism, and the real-time support is included directly in the Ethernet standard; thus, TSN is suitable to act as the communication backbone for horizontal and vertical communication in factory automation systems. TSN is considered to be a promising real-time communication solution for automation systems and has attracted considerable attention from the industrial automation and automotive domains ([6] and [7]).

In addition to pure data exchange, the description, data modeling and method of accessing data across platforms are equally important for the reliable exchange of information in an automation system. The Open Platform Communication Unified Architecture (OPC UA) [8], which is a neutral modeling approach, gradually becomes a company-independent information handling standard. The OPC UA can enable data modeling and information exchange among different industrial communication subsystems, and also support automation information transfer from the lower layers to the upper IT layers of the automation pyramid.

The combination of OPC UA and TSN promises to satisfy all requirements of Industry 4.0. Since OPC UA TSN is a promising solution, there is an interesting question whether OPC UA TSN will replace legacy industrial communication solutions. As we know, it is time-consuming and costly for manufacturing systems to replace all existing legacy industrial communication solutions with OPC UA TSN, which indicates that in the near future, legacy communication solutions and OPC UA TSN solution will be likely to coexist in manufacturing systems. Therefore, there is another question: how to introduce OPC UA and TSN into a manufacturing system and how to enable the coexistence of legacy industrial communication solutions and the OPC UA TSN solution?

In this work, we first adopt the TSN network as the communication network for realizing real-time services in industrial automation subsystems. Then, TSN is adopted as the communication backbone to connect heterogeneous industrial automation subsystems of the field layer (which use various industrial communication solutions) and the entities of the upper layers. The OPC UA is adopted to realize horizontal and vertical information exchange among heterogeneous subsystems in the field layer and the entities of the upper layers. The main contributions of this work can be summarized as follows.

- We proposed a two-tier OPC UA TSN communication architecture for a manufacturing system with heterogeneous networks.
- We implemented an experimental manufacturing system to validate the proposed architecture. The results demonstrate the feasibility and capability of the proposed communication architecture. The proposed architecture can act as a useful reference for developing more comprehensive architecture by adding more technologies, e.g., OPC UA pub/sub communication model and the Deterministic Networking (Detnet) technology.
- We evaluated the performance of a key TSN substandard, i.e., IEEE 802.1Qbv standard, in the implemented experimental manufacturing system, and the results show that if all TSN devices are time-synchronized, IEEE 802.1Qbv standard can indeed provide excellent real-time capabilities for industrial applications, even in the worst-case scenario.

The rest of this article is organized as follows. Section II introduces the related works about cyber-physical systems, industrial automation, TSN, and OPC UA. In Section III, an overview of the TSN technology is provided. Section IV introduces the OPC UA technology. In Section V, the proposed OPC UA TSN communication architecture for a discrete manufacturing system is described. The implementation and execution of the experimental manufacturing system are described in Section VI. In Section VII, the performance evaluation of the IEEE 802.1Qbv standard is demonstrated. Finally, Section VIII concludes this article.

II. RELATED WORK

Currently, the digital twin is considered a critical enabler for the cyber-physical production systems of Industry 4.0 [9], [10]. Lee *et al.* [11] proposed a 5-level cyber-physical systems architecture to define the structure and methodology of cyber-physical systems, to guide the implementation of cyber-physical systems in the industry. Each critical component has a digital twin in the architecture, capturing sensor data, and synthesizing future steps to enable the machine with self-prediction capability. With the advancement of cyber-physical systems, the technological evolution of machine tools was triggered, which is called Machine Tool 4.0 [12]–[14]. The authors in [15] proposed an OPC UA and MTConnect-based cyber-physical machine tools platform which enables interoperable data communication among tools and software applications, to improve the production efficiency. In [3], the authors reviewed how the Internet of Things (IoT) and cyber-physical systems affect the industrial automation from an Industry 4.0 perspective, provided a survey of the current state of TSN development, and clarified the role of fifth-generation (5G) telecom networks in automation. Finally, they pointed out that harmonization beyond networking is required in industrial automation. Vitturi *et al.* in [16] provided a comprehensive overview of modern industrial communication networks and then addressed new perspectives and trends for future development, focusing on novel technologies and standards (e.g., the TSN standards, the Industrial IoT systems, and industrial applications of 5G networks). In [17], Felser *et al.* introduced standardization bodies that develop Operation Technology (OT) and Information Technology (IT) standards and provided examples of OT and IT coexistence.

Currently, the novel TSN technology is regarded as a promising solution for industrial automation systems, and different aspects of TSN have been investigated. In [6], Bello *et al.* first performed an overview of TSN in industrial automation systems. Then, the authors discussed specific TSN standards, projects, industrial application fields, and future research directions in details. Samii *et al.* in [7] provided a review of the TSN standards for possible use cases in automotive systems which use in-vehicle Ethernet networks. Lee in [18] developed a TSN integrated environment simulator and analyzed the simulator to verify whether TSN can satisfy the traffic requirements of the in-vehicle network for autonomous driving. The synchronization quality of IEEE 802.1AS in the context of industrial automation networks was analyzed in [19]. The worst-case latency analysis for a TSN network using network calculus was studied in [20]. Nasrallah *et al.* compared the performances of the IEEE 802.1 time aware shaper and asynchronous traffic shaper in [21]. Jiang *et al.* developed a simulation model in compliance with the IEEE 802.1Qbv standard ([22] and [23]). A number of studies [24]–[29] have been conducted aimed at calculating schedules for configuring TSN devices in a TSN network.

The OPC UA is another promising technology for industrial automation systems. In [30], Kumar *et al.* described how to use the OPC UA technology to connect an automation system with an IoT infrastructure, and analyzed a security model of the OPC UA from an IoT perspective. Schleipen *et al.* in [31] presented various OPC UA-based scenarios and use cases to demonstrate the OPC UA as an enabling technology for Industry 4.0. In [32], Zezulka *et al.* introduced the basics of communication systems and examined the problem of a unified architecture (OPC UA over TSN) to comply with the principles of Industry 4.0 for future enterprises. The emergence of field device integration with the embedded OPC UA over TSN was investigated in [33]. Bruckner *et al.* in [4] introduced OPC UA TSN as a new technology, which could be used to establish a unified communication from sensors to the cloud, and presented the status, open challenges, and research directions of OPC UA TSN.

The state-of-the-art works indicate an urgent need to adopt OPC UA and TSN to fulfill industrial communication requirements of the Industry 4.0. However, because of the long lifespan of industrial manufacturing systems' infrastructures, the legacy industrial communication solutions will still be used in the manufacturing systems in the near future. It is costly and impractical to use the new OPC UA TSN solution to replace all existing legacy industrial communication solutions. There have not yet been works specifying an OPC UA TSN based communication architecture for a manufacturing system with heterogeneous networks, which introduces the OPC UA and TSN into a manufacturing system and enables the coexistence of legacy industrial communication solutions and OPC UA TSN technology. To bridge the research gap, we propose an OPC UA TSN based communication architecture for a manufacturing system with heterogeneous networks, which can satisfy the requirements of the Industry 4.0, relieve the cost pressure of replacing the existing legacy communication solutions, and enable the interoperability between different control subsystems using different communication solutions. An experimental manufacturing system is implemented to demonstrate the feasibility and capability of the proposed communication architecture.

III. OVERVIEW OF THE TSN TECHNOLOGY

TSN is a set of data link layer standards under development by the IEEE 802.1 TSN task group. It is designed to add real-time capabilities to the standard Ethernet. It enables time-critical control traffic flows and nontime-critical traffic flows to converge on a single network without disrupting the transmission of time-critical control traffic flows. It provides the following key benefits: deterministic latency and low jitter, ease of use, and better interoperability between solutions from different manufacturers [34].

TSN consists of a series of substandards, including distributed clock synchronization [35], scheduled traffic enhancement [36], frame preemption [37], per-stream filtering and policing [38], etc. Among these substandards, three particular substandards are considered to be the key for industrial automation systems:

- IEEE 802.1AS-rev [35] enables a network-wide precise time synchronization between TSN devices, which is a basic requirement for distributed automation and control.
- IEEE 802.1Qbv [36] defines a gate mechanism (a time-triggered gate) for egress ports of TSN devices. Based on precise time synchronization, the TSN devices are capable of forwarding time-critical control traffic according to a time schedule.
- IEEE 802.1Qcc [39] defines a central configuration model for configuring the related parameters in a TSN network. The central configuration model is particularly important for industrial applications, and it consolidates application requirements, calculates paths and time schedules for traffic flows, and distributes them to the relevant network infrastructure.

In general, a TSN system comprises non-TSN end stations (non-TSN talkers and listeners), TSN end stations (TSN talkers and listeners), TSN switches, a central network configurator (CNC), and a central user configurator (CUC) [34]. The composition of a TSN system is shown in Fig. 1. Before the whole TSN system starts working, the CUC collects stream information of the TSN end stations (including the

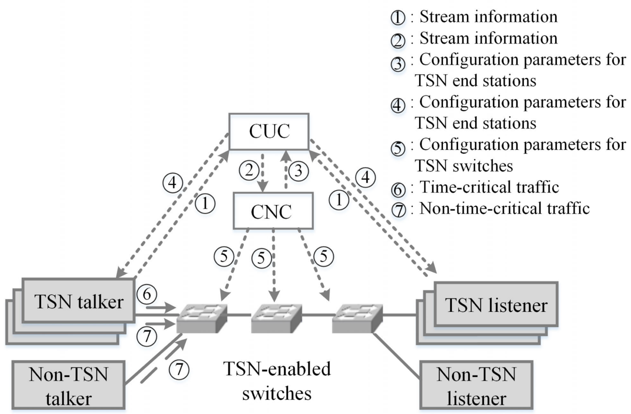


FIGURE 1. Composition of a Time-Sensitive Networking (TSN) system [34].

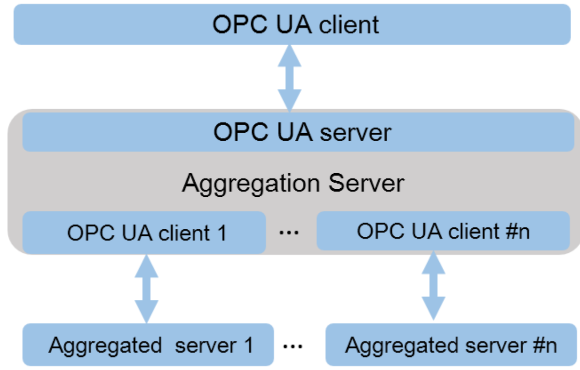


FIGURE 2. Aggregation architecture [40].

requirements of the maximum allowable delay and the frame length, etc.) and sends it to the CNC. Based on the stream information, the CNC computes configuration parameters for the TSN end stations and TSN switches. The CUC obtains the configuration parameters for the TSN end stations from the CNC and then configures the TSN end stations; meanwhile, the configuration parameters for the TSN switches are used by the CNC to configure the TSN switches.

IV. OPC UA TECHNOLOGY

The OPC UA [8] is the interoperability standard for the reliable information exchange in many industries, e.g., industrial automation. The OPC UA consists of 14 specifications and a number of companion specifications, which define the interface between clients and servers, servers and servers, including real-time data access, alarm monitoring, etc. Recently, a publisher/subscriber communication model has been added to the current OPC UA specification release to improve the real-time capability of the OPC UA by allowing time-triggered transmitting of multicast messages. The OPC UA has several advantages:

- Platform independence: It can be implemented on any platform, e.g., traditional PC hardware or microcontrollers.
- Good extensibility: New features can be added without affecting existing applications.
- Support of comprehensive information modeling: Even complex information can be modeled and defined.
- Secure communication: By using appropriate authentication methods, the OPC UA-based communication is secure.

Basically, the OPC UA technology consists of these elements:

- A metamodel for defining specific information models.
- Transport protocol specifications for data exchange between devices.
- OPC UA servers, which contain the information model related to real facility, e.g., the industrial automation process. The information model is a hierarchical structure composed of sets of nodes, e.g., objects, variables, which can represent real objects (i.e., software and hardware objects), and process information in industrial automation.
- OPC UA clients, which send/receive OPC UA messages to access data of the nodes in the OPC UA server information model.

As field devices and subsystems are becoming more and more powerful in terms of CPU performance and memory, there is a trend to embed the OPC UA server functionality inside field devices to provide direct data access to external OPC UA clients. Although this trend has its advantages, there are also drawbacks. In a scenario where multiple field devices and subsystems with embedded OPC UA servers exist, the connection between external OPC UA clients and embedded OPC UA servers need to be set up manually multiple times, which causes an enormous engineering effort and results in a system with meshed connections between clients and servers. To solve the problem, an aggregation architecture is proposed in [40] to reduce the above-mentioned complexity of connections, as shown in Fig. 2. An underlying aggregated server may either represent an embedded OPC UA server in a single field device or in a subsystem. The core of the aggregation architecture is the aggregation server, which connects to underlying aggregated servers via internal OPC UA clients and aggregates their information. Inside the aggregation server, there is an internal OPC UA server, which manages the aggregation and information of underlying aggregated servers, as well as provides the data access to the upper OPC UA client.

V. OPC UA TSN COMMUNICATION ARCHITECTURE FOR A DISCRETE MANUFACTURING SYSTEM

The system architecture of a manufacturing system can be divided into three layers by referencing [41], i.e., factory cloud layer, edge layer, and field layer. This section proposes a two-tier OPC UA TSN communication architecture for a discrete manufacturing system, i.e., factory-edge tier and edge-field tier, as shown in Fig. 3. TSN aims to add real-time capabilities to the standard Ethernet and has many advantages: deterministic latency, high communication bandwidth, and better interoperability between solutions from different

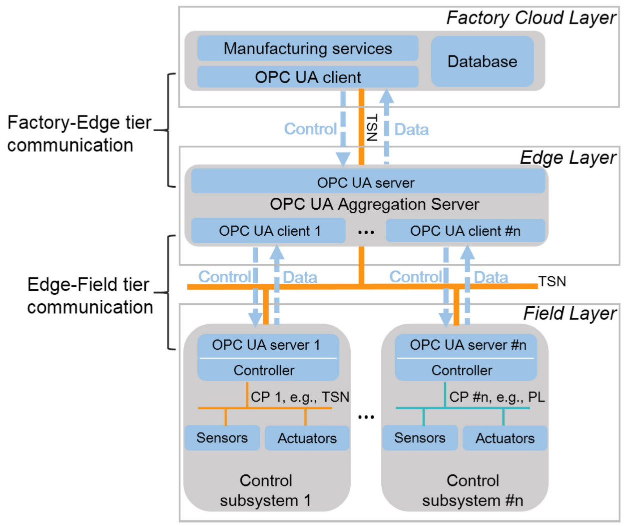


FIGURE 3. OPC UA TSN communication architecture for a discrete manufacturing system. CP represents communication profile, PL represents Powerlink.

manufacturers; thus, TSN is adopted as the communication backbone to connect different control subsystems in the field layer and the entities of the upper layers. OPC UA has the advantages of platform independence, good extensibility, supporting comprehensive information modeling, and secure communication. The requirements of Industry 4.0 can be satisfied by the combination of TSN and OPC UA; thus, OPC UA is adopted to realize horizontal and vertical information exchange between the entities of each layer. The infrastructures in industrial manufacturing systems usually have a long lifespan, and the legacy industrial communication solutions will still be used in the control subsystems of the manufacturing systems. To avoid fully meshed connections between data consumers (OPC UA clients) and data providers (OPC UA servers) resulting in the complexity and enormous engineering effort, the OPC UA aggregation architecture is adopted to connect the OPC UA servers inside the industrial control subsystems of the field layer.

In the factory cloud layer, various manufacturing services can be implemented, e.g., utilizing the big data technology and machine learning technology for analyzing data collected from the field layer, or providing a user interface to the system operator for monitoring and controlling devices of the field layer. The database service is also provided; thus, data produced during the manufacturing processes can be stored. After a large amount of data are collected, the collected data can be transformed into valuable knowledge for supporting optimal decision making. To realize the factory-edge tier communication, the OPC UA client is implemented as a communication interface to connect to the OPC UA aggregation server, thus establishing a communication channel between the factory cloud layer and the edge layer.

In the edge layer, an OPC UA aggregation server is implemented. The OPC UA aggregation server provides interfaces to the upper OPC UA client for establishing a connection of exchanging data. To realize the edge-field tier communication, the OPC UA aggregation server embraces a series of OPC UA clients, and each OPC UA client will establish a connection with the corresponding OPC UA server residing on each automation subsystem in the field layer. We regard this OPC UA aggregation server as a broker for establishing vertical data communication between the factory cloud layer and the field layer, this broker also provides horizontal data communication between each control subsystem in the field layer to enable interoperability.

The field layer contains various manufacturing process facilities and control subsystems, which may adopt different communication solutions for process control, i.e., TSN, the next-generation industrial Ethernet standard, or legacy industrial Ethernet solutions such as PROFINET [42], EtherCAT [43], and Powerlink [44]. Each control subsystem consists of devices such as sensors (e.g., distance sensors) that collect data from the manufacturing process, actuators (e.g., robot arms) that execute specific actions according to the control commands, and controllers (e.g., programmable logic controllers (PLCs)) to process the sensor data and accordingly change the actions of the actuators. To enable interconnectivity between the field layer and the edge layer, OPC UA servers are developed inside each control subsystem to implement two main functionalities, i.e., send the sensor data collected from the manufacturing process to the upper layer and receive the control strategy from the upper layer.

VI. SYSTEM IMPLEMENTATION AND EXECUTION

A. SYSTEM IMPLEMENTATION

In this section, a laboratory-level experimental manufacturing system was constructed consisting of all required software and hardware, to validate the proposed two-tier OPC UA TSN communication architecture. The conceptual framework of the experimental manufacturing system is shown in Fig. 4.

1) FACTORY CLOUD LAYER

The factory cloud layer was implemented on a NUC mini PC with Linux OS. The OPC UA client was developed by referencing an open-source OPC UA client software. It can perform the specific "write" function to send data to the OPC UA aggregation server in the edge layer and the specific "read" function to obtain data from the aggregation server. The obtained data will be stored in the MariaDB [45] database. Moreover, a visualized web user interface (UI) was implemented, which allowed the system operator to monitor and control the devices of the field layer, as shown in Fig. 5.

2) EDGE LAYER

In the edge layer, we implemented the OPC UA aggregation server on an embedded IoT platform with Linux OS. The aggregation server contains an internal OPC UA server and two internal OPC UA clients (i.e., Powerlink OPC UA

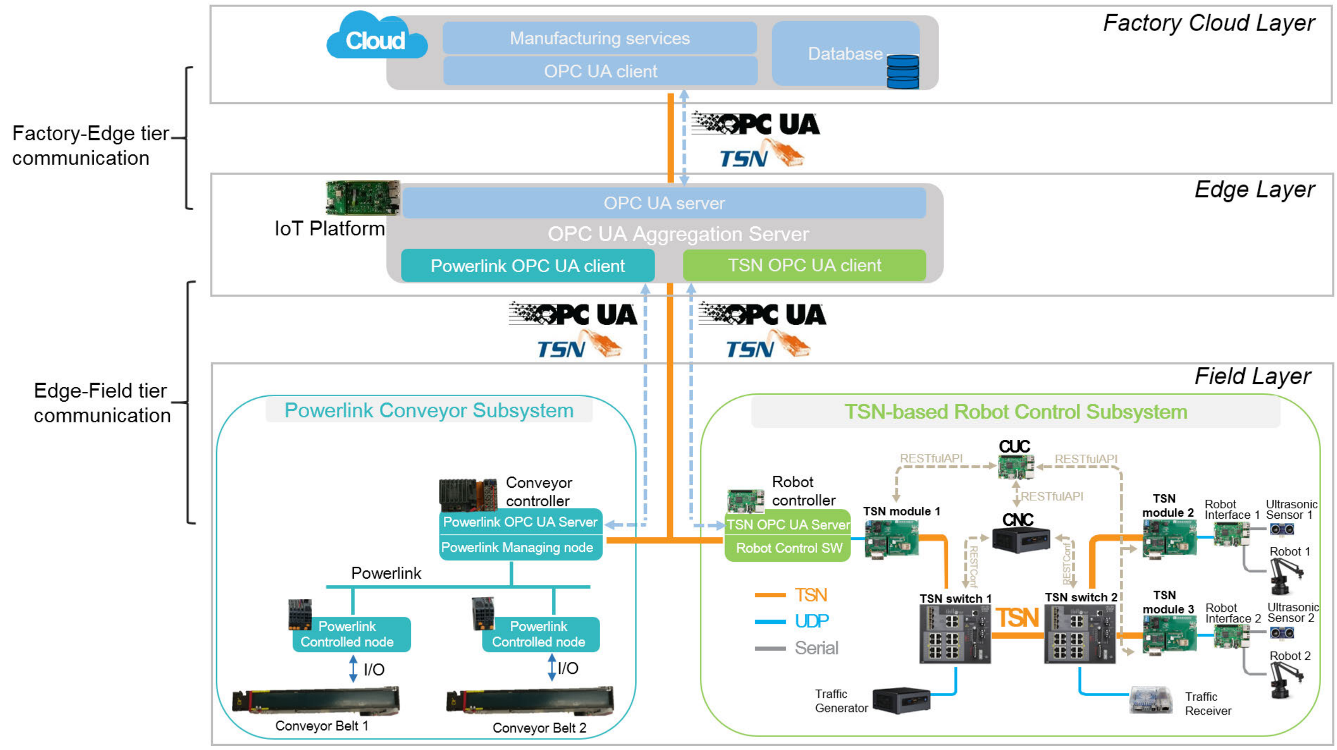


FIGURE 4. Conceptual framework of the experimental manufacturing system.

FIGURE 5. Web user interface for monitoring and controlling the experimental manufacturing system.

client and TSN OPC UA client). Each client establishes a connection with the corresponding OPC UA server in each subsystem to exchange data. The workflow in the OPC UA aggregation server is illustrated using a flowchart, as shown in Fig. 6.

3) FIELD LAYER

There are two types of subsystems in the field layer: a conveyor subsystem and a robot control subsystem. Therein, Powerlink is adopted as a representative of legacy industrial communication solutions for real-time communication in the conveyor subsystem. TSN technology is used for real-time communication in the robot control subsystem.

a: POWERLINK-BASED CONVEYOR SUBSYSTEM

In the conveyor subsystem, the Powerlink OPC UA server together with the Powerlink managing node was implemented on a PLC. For easier denotation, the Powerlink OPC UA server and the Powerlink managing node were conjunctively named as "Conveyor controller". The Conveyor controller exchanges data with two Powerlink controlled nodes via the Powerlink protocol, and each Powerlink controlled node

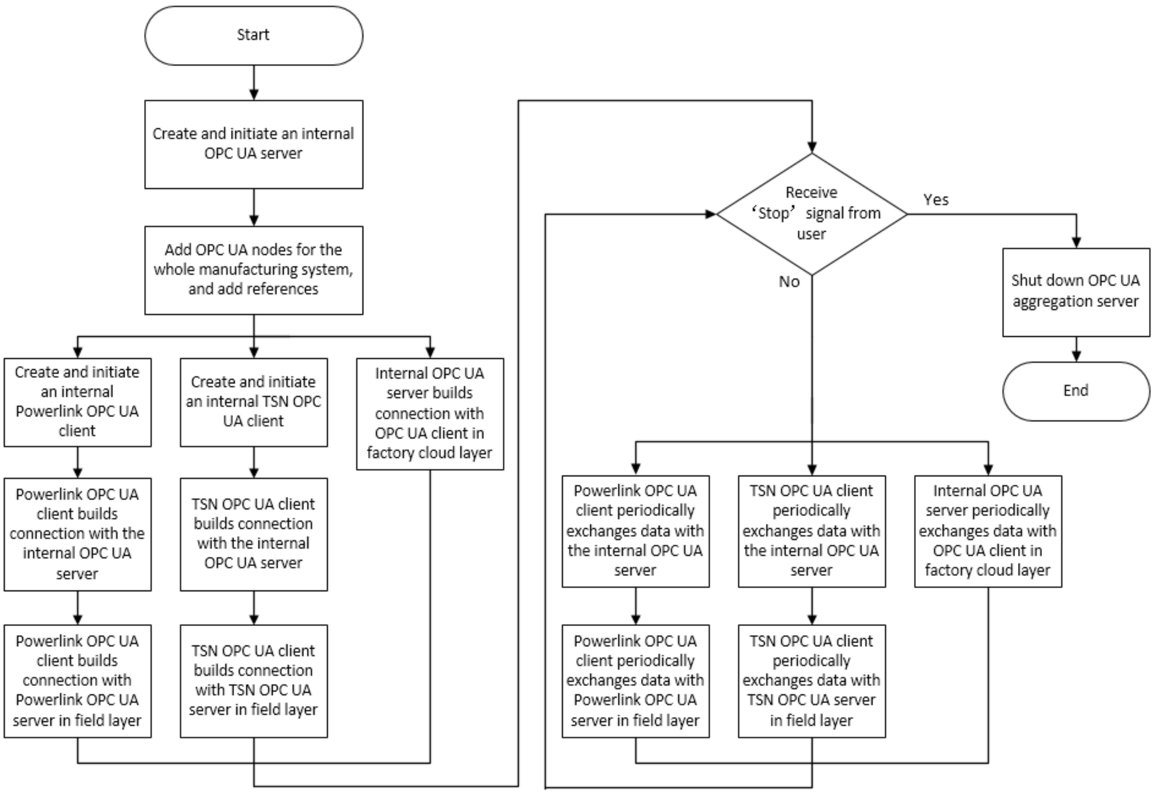


FIGURE 6. **Flowchart of the OPC UA aggregation server.**

controls the behavior of a conveyor belt through input/output (I/O) module.

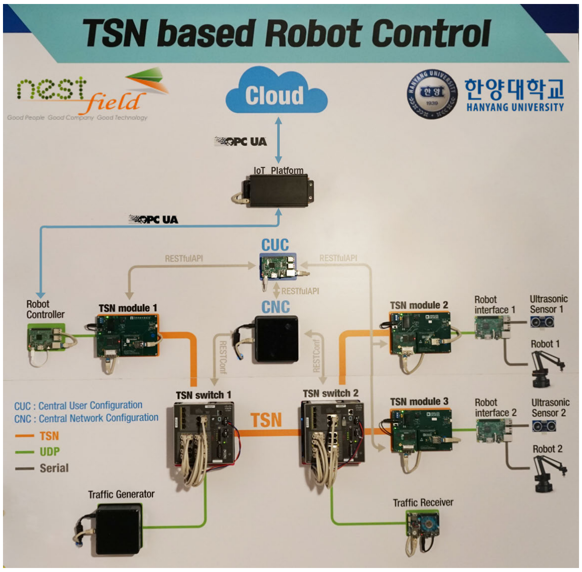
b: TSN-BASED ROBOT CONTROL SUBSYSTEM

In the robot control subsystem, the TSN OPC UA server together with the robot control software (based on UDP/IP) was implemented on an embedded device with Linux OS. For easier denotation, the TSN OPC UA server and the robot control software were conjunctively named as ''Robot controller''. Two Cisco Industrial Ethernet (IE 4K) TSN switches were connected through a 1Gb/s trunk link, TSN switch 1 was connected with the robot controller and a traffic generator, and TSN switch 2 was connected with two robot interfaces (the so-called robot drives) and a traffic receiver. The two robot interfaces were also developed on embedded devices with Linux OS, and they exchanged data with ultrasonic sensors and the robot arms through serial lines. Because the Ethernet port of the embedded device does not have TSN functionalities, we adopted a TSN module to provide the TSN proxy function (i.e., time synchronization function and traffic scheduling function). The embedded device was integrated with the TSN module via Ethernet, and the TSN module could transform the Ethernet frame generated by the embedded device into the TSN frame, and vice versa. Because the TSN module has a link speed limit of 100Mb/s, the speed of the links between the TSN modules and the TSN switches is 100Mb/s. We employed a NUC mini PC with Linux OS to run the Cisco CNC software to compute the schedules for the TSN switches and TSN modules. We developed the CUC software and ran it on an embedded device with Linux OS. The developed CUC software has a series of functionalities: collect the stream requirements from the robot controller and robot interfaces via RESTful protocol; send the collected stream requirements to the CNC via RESTful protocol; invoke the CNC to compute the schedule for the TSN switches and TSN modules; acquire the schedules for the TSN modules from the CNC and then use the schedule information to configure the TSN module via RESTful protocol; invoke the CNC to use the schedule information to configure the TSN switches via RESTCONF protocol; and check whether the TSN switches are configured successfully. We demonstrates hardware implementation of the experimental manufacturing system in Fig. 7.

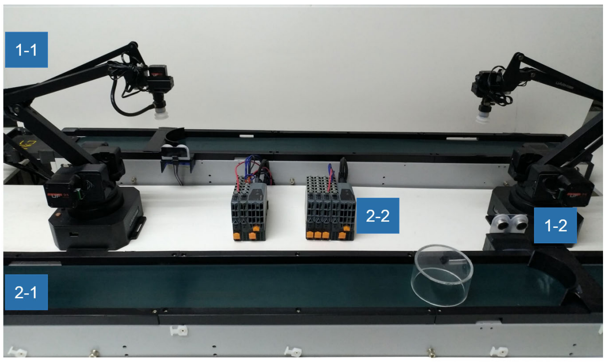
B. SYSTEM EXECUTION

This section describes the sequence diagram of the system execution for better understanding of the exchange process of the information flow among the entire system.

As shown in Fig. 8, eleven components are involved in the system execution, which are represented by the colorful boxes in the top. In this diagram, a single-direction blue arrow is used to represent the information flow between two adjacent components. First, the OPC UA aggregation server, Powerlink OPC UA server, TSN OPC UA server, and



(a)



Legends:
Label 1-1: Robot arm. *Label 1-2*: Ultrasonic sensor.
Label 2-1: Conveyor belt. *Label 2-2*: Powerlink PLC.

(b)

FIGURE 7. Hardware implementation of the experimental manufacturing system: (a)TSN-based robot control subsystem and (b) Powerlink-based conveyor subsystem.

database are initiated (here, to facilitate the understanding, the internal OPC UA server inside the OPC UA aggregation server is represented by the OPC UA aggregation server; the Powerlink OPC UA server together with the Powerlink managing node are represented by the Powerlink OPC UA server; and the TSN OPC UA server together with the robot control software are represented by the TSN OPC UA server). Next, the OPC UA client in the factory cloud layer discovers the OPC UA aggregation server and builds a connection with it. The Powerlink/TSN OPC UA client in the edge layer discovers the Powerlink/TSN OPC UA server in the field layer and the OPC UA aggregation server and then establishes connections with them.

Then, the system operator can operate the web UI to assign the upper control strategy to the OPC UA client of the factory cloud layer, which will then send the control strategy to the OPC UA aggregation server by invoking the "write" function. The Powerlink OPC UA client obtains the upper control strategy and the monitored ultrasonic sensor status data from the aggregation server by invoking the "read" function and sends them to the Powerlink OPC UA server in the field layer via the "write" function. Based on the obtained upper control strategy and the monitored ultrasonic sensor status data, the Powerlink OPC UA server computes a suitable control command to control the behavior of the conveyor belts. The monitored status data of the conveyor belts are returned to the OPC UA aggregation server via the reverse process. The TSN OPC UA client also obtains the upper control strategy from the aggregation server and sends it to the TSN OPC UA server in the field layer. Based on the upper control strategy and the monitored ultrasonic sensor status data, the TSN OPC UA server computes a suitable control command to control the behavior of the robot arms. The monitored status data of the robot arms and the ultrasonic sensors are returned to the TSN OPC UA server and OPC UA aggregation server via the reverse process. In the case the system operator does not assign a new upper control strategy, according to current upper control strategy and the obtained status data of the ultrasonic sensors, the Powerlink OPC UA server computes appropriate control commands to control the conveyor belts, and the TSN OPC UA server computes appropriate control commands to control the robot arms, which form an automatic process line via collaborative working.

The OPC UA client in the factory cloud layer periodically acquires all status data of the field devices from the aggregation server and stores them in the database. The manufacturing services fetch and process the status data from the database and show them on the web UI, so that the system operator can monitor the status of the field devices in any time. When necessary, the system operator can assign a new upper control strategy to change the behavior of the conveyor belts and robot arms. The experimental results have shown that the proposed communication architecture is not only feasible, but also enables the interoperability between different control subsystems using different communication solutions and can improve the management and analysis for field devices in the manufacturing system.

VII. PERFORMANCE EVALUATION OF THE IEEE 802.1Qbv STANDARD

As presented above, in the robot control subsystem, TSN network is used (herein, IEEE 802.1Qbv and 802.1AS standard are implemented) for the communication between the robot controller and the robot interfaces. Based on the robot control subsystem, we evaluated the real-time performance of the IEEE 802.1Qbv standard. When the robot controller sends two robot arm control data flows to two robot interfaces, the robot controller together with TSN module 1 are deemed as a TSN talker, and robot interface 1 together with TSN module 2/robot interface 2 together with TSN module 3 are deemed as TSN listeners. All TSN talker, TSN listeners, and TSN switches are time-synchronized using the IEEE

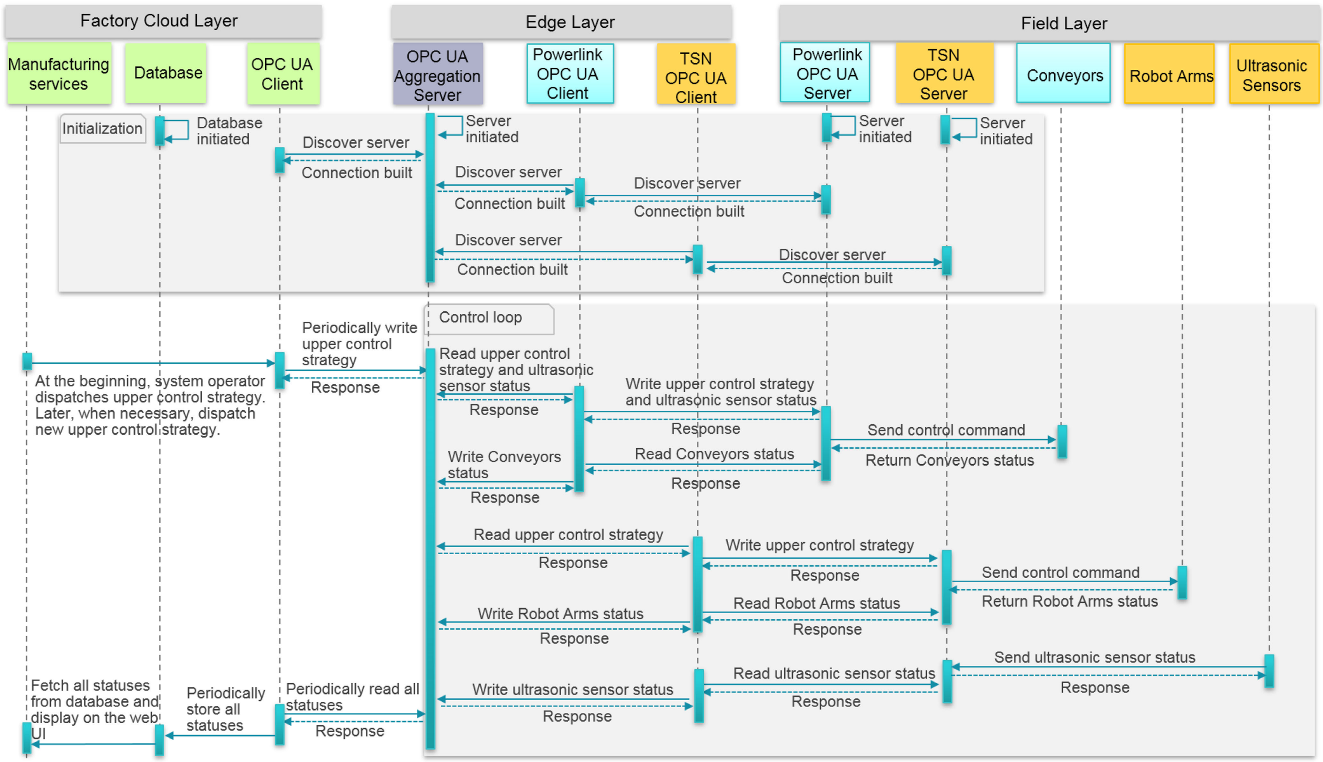


FIGURE 8. Sequence diagram of the system execution.

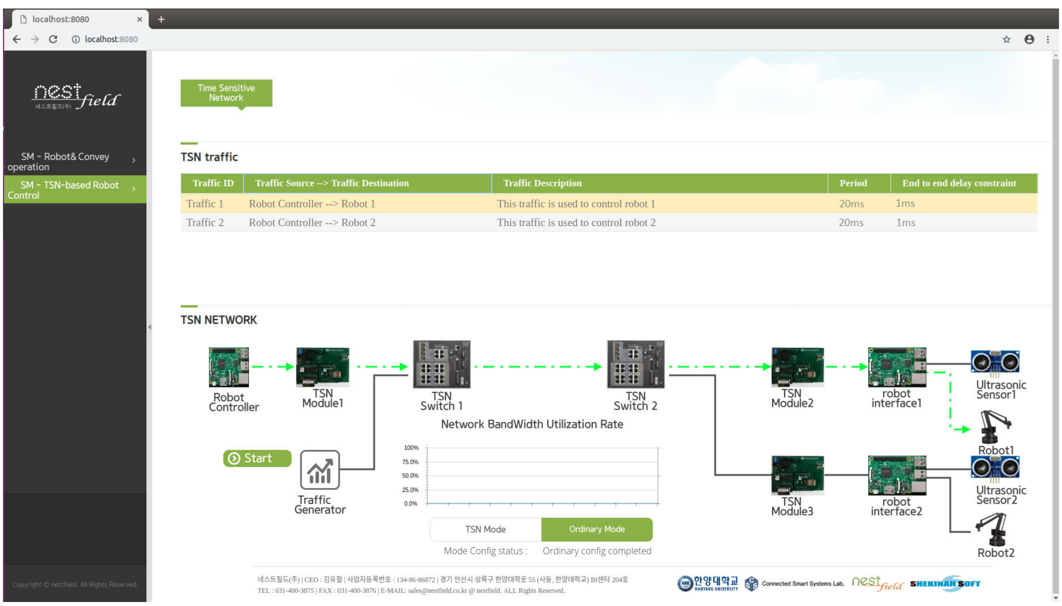


FIGURE 9. Graphical user interface for controlling the traffic generator and enabling the proxy function of the TSN modules.

802.1AS standard. The specifications of the generated two data flows are presented in Table 1.

We use traffic generator software Ostinato [46] to send a varying amount of interference UDP traffic to the traffic receiver by adjusting its packet transmission rate, between 100 Mbps-1 Gbps. Thus, the trunk link between the two TSN switches is occupied by the varied amount of interference UDP traffic. When the traffic generator generates 1 Gbit interference UDP traffic per second, the 1Gbps trunk link between the two TSN switches is fully utilized by the interference UDP traffic, which is considered the worst-case scenario. In this scenario, we validate whether the IEEE 802.1Qbv standard can prevent the transfer of the time-critical control data flows from being affected by the interference UDP traffic

TABLE 1. Specifications of the generated data flows.

Flow ID	Source	Destination	Period	e2e delay constraint	Payload size
Flow 1	robot contoller	robot interface 1	20 ms	1 ms	20 bytes
Flow 2	robot contoller	robot interface 2	20 ms	1 ms	20 bytes

TABLE 2. Schedule information obtained from the Cisco CNC.

	TSN talker		TSN switch 1		TSN switch 2	
Schedule (µs)	T_{Open}	T_{Close}	T_{Open}	T_{Close}	T_{Open}	T_{Close}
Flow 1	100	229	935	948	973	1101
Flow 2	231	359	949	961	1004	1132

and guarantee the latency of the time-critical data flows to be deterministic. We control the traffic generator and enable the proxy function of the TSN modules by our developed web UI, as shown in Fig. 9. When the "TSN mode" is selected, the TSN proxy function of the TSN modules is enabled, and the ordinary Ethernet frames generated by the robot controller are converted to TSN frames, or vice versa. When the "Ordinary mode" is selected, the proxy function is disabled, and the ordinary Ethernet frames are transmitted without being converted to TSN frames.

According to the specifications of the data flows listed in Table 1, the Cisco CNC was run to calculate the effective schedule information for each data flow, as summarized in Table 2. Table 2 shows the time instant at which the transmission window for a data flow is opened (T_{Open}) and closed (T_{Close}) at the TSN talker and TSN switches. After that, the CUC obtained the schedule information for the TSN talker from the CNC and then configured the TSN talker. Additionally, the CUC invoked the CNC to configure the TSN switches using the schedule information. Based on the schedule information, the TSN talker generated time-critical data flows the moment the transmission window was set to be opened, at T_{Open}, which minimizes the end-to-end latency T_{e2e}. Two dedicated transmission windows are allocated to the same egress port of TSN switch 1 to transmit time-critical data flows sent from the TSN talker. The two transmission windows do not overlap, thus avoiding interference from other traffic. Two TSN listeners are connected to two different egress ports of TSN switch 2; thus, the transmission window can be overlapped.

Afterwards, we measured T_{e2e} between the TSN talker and the TSN listeners. A traffic capture device called ProfiShark 1G+ [47] was adopted to measure T_{e2e}. Two ProfiShark 1G+ devices were deployed at the egress port of the TSN talker and the ingress port of the TSN listeners, respectively. When a data frame was sent from the egress port of the TSN talker, the timestamp was recorded, and when the data frame arrived at the ingress port of a TSN listener, the timestamp was recorded again. The difference between these two timestamps was taken as T_{e2e}. We calculated T_{e2e} of a data flow using equation (1):

$$T_{e2e} = T_{Dest} - T_{Src}, \tag{1}$$

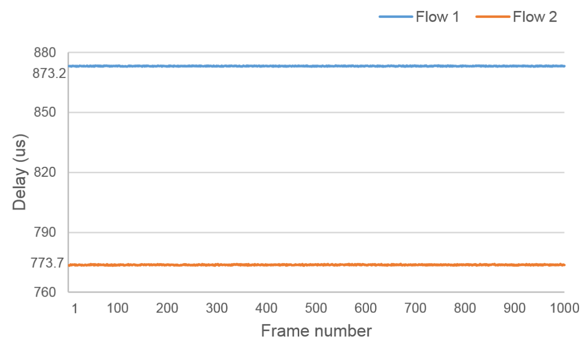


FIGURE 10. Measured real-time latency of two data flows in the worst-case scenario.

where T_{Src} and T_{Dest} are the timestamps recorded at the egress port of the TSN talker and the ingress port of the TSN listener, respectively.

First, T_{e2e} of two data flows was measured in the worst-case scenario (i.e., the traffic generator sent 1Gbit interference UDP traffic per second), with the "TSN mode" selected. The respective latencies (T_{e2e}) of 1000 frames of the two data flows are plotted in Fig. 10. We can see that even in the worst case, T_{e2e} of the two data flows were not affected by the interference UDP traffic and satisfied the real-time communication requirements (i.e., T_{e2e} is lower than e2e delay constraints of 1 ms, as presented in Table 1).

To verify the real-time performance of the IEEE 802.1Qbv standard further, we also evaluated T_{e2e} of the two data flows with the "Ordinary mode" or "TSN mode" selected, while varying the amount of the generated interference UDP traffic. The mean latencies of 1,000 frames of the two data flows were analyzed, as presented in Table 3. In the "Ordinary mode" case, the ordinary Ethernet frames of the two data flows were transmitted without being converted to TSN frames. When the data rate of the interference UDP traffic was not greater than 800 Mbps, T_{e2e} of the two data flows remained constant, because the trunk link was sufficiently idle, the transmission of the ordinary Ethernet frames of the two data flows was seldom affected by the interference UDP traffic, the overall latency only consists of the transmission latency, the propagation latency and the processing latency, which are constant value. As the amount of the interference UDP traffic increased (i.e., the data rate was greater than 800 Mbps), T_{e2e} of the two data flows increased drastically, because the transmission of the ordinary Ethernet frames of the two data flows became increasingly affected by the interference UDP traffic, which resulted in the increasing queueing delay in the switches. However, in the "TSN mode" case, i.e., the ordinary Ethernet frames of the two data flows were converted to TSN frames, we could see that T_{e2e} of the two data flows remained constant regardless of the amount of the generated interference UDP traffic, which indicates that the transmission of TSN frames is never affected by the interference UDP traffic. And the measured latency of the TSN frames conformed with the schedule information computed from CNC software, which indicated the transmission of the TSN

TABLE 3. Measured end-to-end latency of flows 1 and 2.

T_{e2e}	Flow ID	Data rate of traffic generator (Mbps)							
		200	400	600	800	850	900	950	1000
TSN mode	Flow 1	873.2 µs	873.2 µs	873.2 µs	873.2 µs	873.2 µs	873.2 µs	873.2 µs	873.2 µs
	Flow 2	773.7 µs	773.7 µs	773.7 µs	773.7 µs	773.7 µs	773.7 µs	773.7 µs	773.7 µs
Ordinary mode	Flow 1	36.6 µs	36.6 µs	36.6 µs	36.6 µs	710 µs	6.5 ms	70.1 ms	600 ms
	Flow 2	36.8 µs	36.8 µs	36.8 µs	36.8 µs	715 µs	6.6 ms	70.5 ms	600 ms

frames of the two data flows was indeed strictly controlled according to the computed schedule information. From the results of this performance evaluation, we can conclude that if all TSN devices are time-synchronized, the mechanism of IEEE 802.1Qbv indeed guarantees deterministic latency of TSN frames and satisfies the real-time communication constraints, even in the worst-case scenario. Moreover, the communication bandwidth of TSN is tested to be up to 1Gb/s, which is much larger than the bandwidth of legacy industrial Ethernet solutions (usually 100Mb/s). Thus, TSN is suitable for industrial automation applications and acting as the communication backbone to connect heterogeneous industrial automation subsystems of the field layer and the entities of the upper layers.

VIII. CONCLUSION AND FUTURE WORK

In this study, a two-tier OPC UA communication architecture for a manufacturing system with heterogeneous networks is presented. We adopt TSN as the communication backbone to connect heterogeneous industrial automation subsystems of the field layer and the entities of the upper layers. OPC UA is used to realize horizontal and vertical communication among subsystems in the field layer and the entities of the upper layers. In addition, a laboratory-level experimental manufacturing system is implemented. The sequence diagram of the system execution is described to clearly express the exchange process of the information flow among system components. The experimental results of system execution show that the proposed communication architecture is not only feasible, but also enables the interoperability between different control subsystems and can improve the management and analysis for field devices in the manufacturing system. Besides, we verify the real-time performance of the IEEE 802.1Qbv standard using the implemented robot control subsystem. The results of this performance evaluation show that if all TSN devices are time-synchronized, the mechanism of IEEE 802.1Qbv guarantees deterministic latency of TSN frames and satisfies the real-time communication constraints, even in the worst-case scenario. Moreover, the communication bandwidth of TSN is tested to be up to 1Gb/s, which indicates TSN can support the transmission of more data, e.g., sensors and background data. Thus, TSN is proven to be suitable for industrial automation applications and acting as the communication backbone to connect heterogeneous industrial automation subsystems and the entities of the upper layers. For the future work, the pub/sub communication model of the OPC UA will be further added into the proposed architecture. And we will extend to apply the proposed architecture for other types of manufacturing systems, e.g., a flexible manufacturing system. Besides, we will add the Detnet technology to our proposed communication architecture to connect the enterprise cloud or a public cloud through deterministic data paths, and evaluate the comprehensive performance of the proposed architecture.

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