Toward Self-Adaptive Software defined Fog Networking Architecture for IIoT and Industry 4.0

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***Abstract*—Industrial Internet of Things (IIoT) interconnects unconventional objects, such as sensors, actuators, robots, and control systems, with the information systems and the business processes to improve the operational efficiency and productivity. In IIoT, diverse, distributed and huge number of devices are collaborating and connecting over the Internet and the Cloud by generating a high and diverse data rate. In addition, industrial networks will be highly heterogeneous since it will connect heterogeneous devices through various communication technologies. Consequently, the industrial processes set new requirements such as reliability, scalability, and low latency that can not be managed by traditional technologies. The advent of Software Defined Networking (SDN) concept, by decoupling control and data planes, enables flexible and dynamic network architecture management by supporting horizontal scalability through distributed SDN controllers. Moreover, Fog computing is recently emerging as the best technology to provide local processing support with acceptable latency for IIoT devices. In this new rich evolving context, we propose an integration of SDN and Fog computing to provide a flexible and scalable solution granting low delays required by IIoT applications. More precisely, we present a novel architecture for IIoT based on SDN-Fog and then we detail the structure of our proposed Fog node enhanced by SDN. We also show some relevant experimental results that assess the performances of the proposed fog node in terms of latency and throughput.**

***Index Terms*—Industry 4.0, Fog computing, SDN, IoT, IIoT, Containerization.**

I. Introduction

Internet of Things (IoT) is an emerging concept that designates the ubiquitous connection to the Internet. The integration of IoT with the Cyber-Physical System (CPS) introduces the concept of Industrial IoT (IIoT). IIoT is about connecting the industrial assets, namely, machines and control systems with the information systems and the business processes, to improve the operational efficiency and productivity of industrial systems [1]. While IIoT focuses specifically on the industrial domain, IoT covers various domains defining IIoT as an IoT application. However, IIoT has diverse properties and requirements that distinguish it from IoT, citing the types of smart connected things, network technologies and quality-of-service requirements, and the IIoT application characteristics [2].

IIoT network technologies were different from the other IoT application. In fact, in the last decades, communication systems for industrial automation were mostly designed to locally interconnect sensors, actuators, and controllers using Fieldbus technology or Ethernet. More recently, the industrial environment started exploring the introduction of new wireless technologies solution in the shop floor. IEEE 802.11 standard and Bluetooth are not suitable for IIoT as they were for other IoT applications (e.g. Smart homes), since they can not guarantee the latency and reliability requirements of IIoT. Therefore, specific wireless solution such WirelessHART and ISA100.11a have been introduced [3]. However, the large scale characteristics of the IIoT network represent a big challenge for those technologies. First, the size of the industrial system can reach the thousands of connected things (sensor, actuators and controller) that they can be geographically distributed over a wide area like in the smart factory [4]. Second, sensors, actuators and controllers are connected automatically, possibly without human intervention. So, response time, network latency, and reliability are crucial for IIoT requirements. Third, some IIoT applications, such as emergency or safety and closed loop control applications with classes 0 and 1 (according to ISA-SP100 classification), require packet error rate (PER) under 10^{-9} and latency under 1ms. Therefore, now the direction in the industry is the use of 5G technologies.

Moreover, IIoT application proprieties and challenges and IIoT network and communication technologies are surveyed by several researches like [5] [4] [3] [1]. But, limited proposals are published. In this paper, we propose a software defined Fog networking architecture for managing and controlling the IIoT and Industry 4.0 network. Software defined networking (SDN) with the concept of decoupling of the control plane from the data plane, enhance the network configuration and flexibility. The dissociation and centralization of the control plane enables the programmability of the network, that simplifies the deployment of new forwarding strategies and the use of heterogeneous network technologies, that can be changed and updated independently. Thus, scalability and flexibility can be addressed with SDN. Some researches are proposed in this context [6] [7]. Otherwise, with the severe IIot application requirements, SDN alone can not response to all challenges such as the latency that should be in some IIoT application under 1ms. Moreover, Fog computing or edge computing has been proposed as middleware to reduce latency. Fog node with the ability to perform computation tasks such as data analytics and local processing can influence the performances of the IIoT system [8].

In our previous work, we proposed a self-adaptive framework able to take autonomous management decisions depending on existing network and controller conditions and application requirements from the business layer for IoT environment. In this work, while taking in consideration the specific requirements and proprieties of IIoT domain, we integrate Fog computing with our previous work. The proposed Fog node contains sub-modules that provide computation resources to analyze distributed IIoT data that can not be processed at the end devices such sensors and actuators for some IIoT application and enable the integration of SDN equipment (switch) to improve management performances. The main goal of our proposed architecture enabled by SDN model and structured fog node, is that combining the two technologies enhance the autonomous and automatic management and control of the IIoT network and promises the reliability and flexibility required by the IIoT environment. Firstly, we propose a self-adaptive Software Defined Fog Networking architecture. Then, we describe a deployment scenario that manages and deploys the fog nodes dynamically in a distributed IIoT network. Finally, we evaluate the deployment scenario with ONOS, a distributed SDN controller. So, we propose a self-Adaptive Software Defined Fog Networking Architecture for IIoT and Industry 4.0.

This paper is organized as follows: Section II discusses the related work. Section III present our proposed architecture. Section IV presents our deployment scenario and shows details of our test environment and experimental results. Finally, Section V concludes our work and discusses directions of future work.

II. Related work

IoT has created a revolution in networking and communication technologies. And by integrated IoT with the Cyber Physical System, it revolutionized the industrial sector. Recently, several researches are investigating on the characteristics, challenges and technologies of the IIoT concept. Xu et al. [4] surveyed IIoT architecture, applications and characteristics. The autors cited the different existing research efforts on control, networking and computing systems in IIoT, as well as challenges and future research needs. In this survey, the researchers study the IIoT from the point of view of cyber physical system. Also, some works [1] [5] studied the IIoT enabling technologies, applications and directions. Sisinni et al. [1] focused first on the difference between IIoT, IoT and Industry 4.0, while Li et al. [5] give more details on the network layer and different communication technologies. Addressing the different IIoT challenges that has been studied in previous mentioned works, few new solutions are proposed.

Henneke et al. [9] surveyed the different challenges of IIoT and the potential of SDN in resolving most of them. Also, Wan et al. [7] studied IIoT architecture and proposed an SDN based architecture to manage physical devices. All previous cited researches proposed an SDN based architecture for IIoT. However, Aazam et al. [8] discussed the potential of Fog computing as a middelware in resolving different IIoT challenges. Authors of [10] proposed a platform to provide end-to-end manageability of the enabling Fog Computing infrastructure according to the operational requirements of industrial processes. Our work is different from the previous cited works by proposing the idea of integrating SDN and Fog computing and enhancing their properties using their advantages in addressing the IIoT challenges. Also, the structure of our fog node that uses containerization technique to enable the reuse and multitasking (or decomposition) of the node functionalities.

III. SDN-Fog based architecture for IIoT

This section presents our proposed Software Defined Fog Networking architecture. We will present the scheme of emerging the SDN technology and Fog computing to respond to the IIoT requirements in terms of reliability, delay and scalability. And we will detail the structure of the proposed fog node.

A. Self-Adaptive SDN-Fog based architecture for IIoT

Industrial IoT network has the same characteristics of an IoT network: large-scale, heterogeneous, complex, and hard to manage and control. Therefore, a flexible and scalable architecture is required. Traditional network architecture that integrates the control and data plane in each device, can not handle the requirements of IIoT network, especially with the requirements and constraints of the IIoT application layer in terms of reliability and latency.

On other hand, SDN has the potential to handle some of IIoT network challenges. The fact that SDN proposes the concept of decoupling the control plane from the data plate, it gives the network the capability of programmability that simplifies the deployment of new forwarding strategies. Hence, it guarantees the flexibility of the network in order to be changed and updated independently the network forwarding and communication technologies. Also, with the distributed controller, SDN provides scalability for large-scale network as the IoT and IIoT networks. However, IIoT system is characterized by a process that is carried out automatically and without human intervention where possible. So, the network must be managed and controlled dynamically according to the industrial process and application.

Figure 1 represents our self-adaptive Software Defined Fog Networking architecture for IIoT and Industry 4.0. Our proposal is composed of three main structures: SDN Controller, Self-Adaptive Framework and Fog node.

SDN controller represents the network control plane. we propose the use of a distributed SDN controller that provides scalability for the large scale IIoT network. It defines the

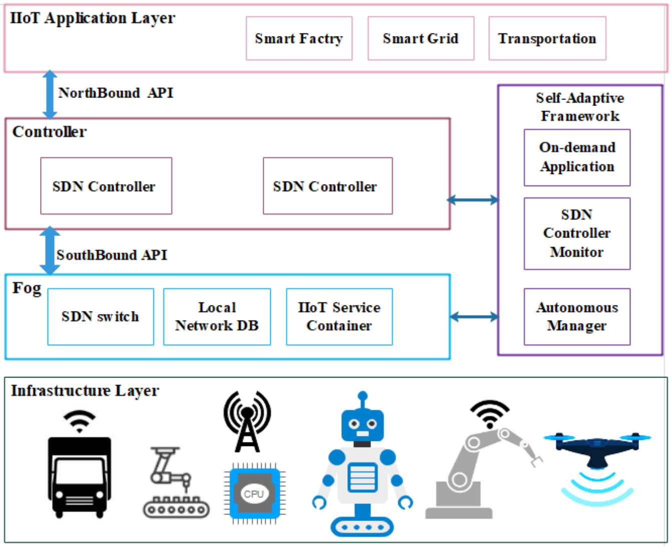

Fig. 1. SDN-based Fog architecture for Industrial Internet of Things.

forwarding strategies of the network.

Self-Adaptive Framework is responsible of controlling the SDN controller performances and the network state and decides the appropriate network communication strategies. According to the requirements of the application layer that are defined by the *On-demand application* module, the network topology state delivered by the network topology state Monitor and the controller available resources delivered by the SDN Controller module. The *Autonomous Manager* module will decide the appropriate network topology and the required number and location of the SDN controller.

Fog node is a lightweight device that contains sub-modules that provide computation resources to analyze distributed IIoT data that can not be processed at the end devices and enable the integration of SDN equipment (switch) to improve management performances.

In the next section, we will detail the structure and functionalities of the proposed fog node.

B. Fog Computing Node Structure

In this subsection, we detail the structure of the proposed Fog node. The IIoT system generates a high amount of data that is analyzed to generate information for control of devices and the processing of industrial operation. Generally, the analysis of the industrial big data is done at the cloud. However, the latency required by some industrial application impose the use of the fog as the best solution to reduce the latency. Moreover, industrial devices are resources limited. Fog computing would be a solution for data processing. As we mentioned previously, industrial devices are geographically distributed in a wide area, but they are centrally processed. So, integrating a broker in Fog to offer a pub/sub service can enhance processing task. Consequently, the proposed fog node designed to meet some requirements such flexibility to manage different services, interoperability and low latency.

The structure of our proposed Fog node for IIoT environment is depicted in Figure 2.

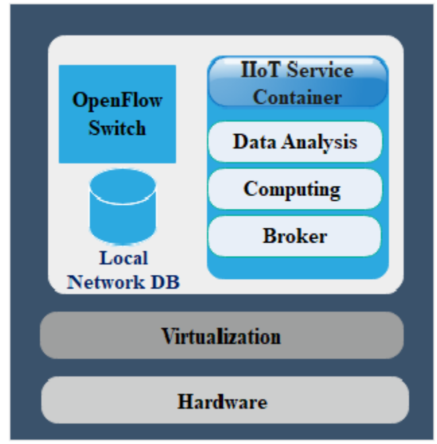

Fig. 2. Structure of the proposed Fog node.

The Fog node combines an SDN switch and a database for monitoring the state of network, and provides some IIoT services such data analysis, computing, and a broker. Lightweight virtualization technology (i.e. Docker) is the best technique to deploy the presented structure. Docker guarantees a light virtualization compared to virtual machine and an isolation between different instances.

OpenFlow Switch: we propose to use an OpenFlow switch in the fog node in order to connect it to the controller. So, the fog nodes will be controlled and managed by the SDN controller which makes the architecture more flexible and scalable.

Local Network Database: we propose the use of database in the fog node in order to store the information of the current state of the network. It will act as a local cloud for network topology information.

IIoT Services: we propose to integrate IIoT services in a lightweight container. The IIoT services can be a data analysis, computing and a broker. The IIoT devices are generally a limited computation ressources. This is why the deployement of a local data analysis service is better in terms of latency.

IV. Performance Evaluation

This section describes the deployment scenario, the testbed environment, and then it presents a set of experimental results.

A. Deployment scenarios

As we cited previously, the fog computing is the best solution to reduce the latency. We propose a self-Adaptive Software Defined Fog Networking architecture for IIoT and Industry 4.0 that proposes an enhancement of the fog nodes with SDN equipment in order to guarantee the flexibility of management of the fog nodes and response dynamically to the changes of the network topology. Thus, we propose two deployment scenarios of managing dynamically the fog nodes. In the first scenario, we propose to add dynamically a local fog node. In the second scenario, we propose to add dynamically a distributed fog node that could be at distance. We are considering the distributed nature of IIoT network, proposing those two scenarios. In the first scenario, our proposed framework adds dynamically a fog node to the existed IIoT network and then modifies the network topology by detaching some IIoT devices and re-directs them to the new fog node. The fog node in the first scenario is located in the same geographic area of the IIoT devices. In the second scenario, we propose a geographically distributed topology. In this scenario, we have a distributed network that covers two distributed areas that are deployed in two different virtual machines with Mininet. The two topologies distributed on the two virtual machines are connected with a GRE tunnel.

B. Test Environment

To deploy the scenario described in Section IV-A, we used three virtual machines that have been installed on a PC with Intel i3-3110 CPU 2.4 GHZ and 8 GBytes of memory. In two virtual machines, we implemented Mininet to create the distributed network topology. In the third machine, we deployed ONOS controller. Mininet [11] [12] is a container-based network emulator. It runs various kinds of hosts such as end terminals, switches, routers, and links on a single Linux kernel and it provides the capability of instantiating a set of virtual nodes, which can be connected to form any arbitrary network. In Mininet, the host behaves like a real machine in which the running programs can send packets through an Ethernet and/or a WiFi interface behaving like a real interface, with a given link speed and delay. It is also able to create OpenFlow enabled switches required for the SDN environment. For ONOS, we used the version 1.5.

C. Experimental results

Latency, jitter, and throughput are the performance parameters that we choose to evaluate the two deployment scenarios of the fog nodes. All the fog nodes are managed by ONOS controller. Figure 3 represents the results of latency of the two simulated scenarios. It is clear that the latency in the second scenario where the topology is distributed is higher.

As Figure 3 depicts the average latency of the scenario one (local deployment of fog node) is about 0.045 ms without counting the delay of the first packet. In general, the latency of the first packet is always the highest, since it discovers the network topology. Though, the average latency of the scenario two is about 0.45 ms. And it is higher due to the fact of the fog node located in a distributed area.

Figure 4 depicts the results of deploying dynamically the fog nodes in terms of throughput for the two scenarios. We can notice that the throughput of the first scenario that deploys the fog node locally in the same geographical area of the existed network is most important. The throughput of the first scenario is between 8.76 Gbits/s and 12.2 Gbit/s. While the throughput of the second scenario is maintained stable with an average of 230 Mbits/s.

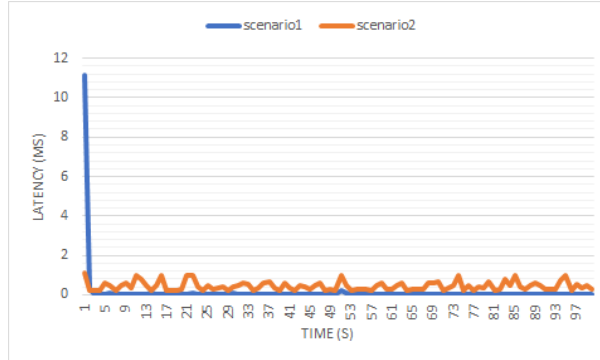

Fig. 3. Latency of deployment of Fog node.

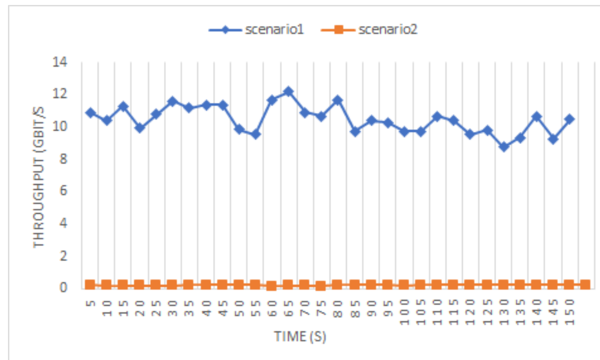

Fig. 4. Throughput of deployment of Fog node.

As shown in Figure 5 for the second scenario, the distributed deployment has the larger jitter, it is varied between 0.1 ms and 0.7 ms. In contrast, the jitter of the scenario one that deploys the fog locally is stable.

The simulation results have shown clearly that the distributed deployment of the fog node has the worst performances.

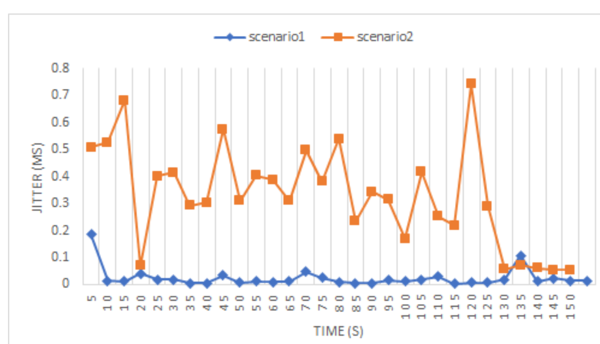

Fig. 5. Jitter of deployment of Fog node.

V. Conclusion

In this paper, we addressed the IIoT requirements in terms of delay, reliability and scalability. First, we proposed a self-Adaptive Software Defined Fog Networking Architecture for IIoT and Industry 4.0 that guarantee the control, management and the self-adaptive of the IIoT and Industry 4.0 network automatically. We extend our previous work by integrating a Fog node to decrease the latency. Second, we described the structure of the proposed fog node. It comprises sub-modules that provide computation resources to analyze distributed IIoT data that can not be processed at the end devices such sensors and actuators for some IIoT application and enables the integration of SDN equipment (switch) to improve management performances. Then, we evaluate a deployment scenario of managing dynamically the fog nodes. Simulation results show that the deployment of fog node locally have best evaluation results.

In our ongoing work, in one hand, we are implementing the entire modules of our proposed self-adaptive framework and we are trying to increase the intelligence of the autonomous management facility by using artificial intelligence and Machine Learning (ML) methodologies and tools. In the other hand, we are studying the possibility to replace the SDN equipment in the fog node which is the OpenFlow switch in this work by an instance of a controller.

References

[1] E. Sisinni, A. Saifullah, S. Han, U. Jennehag, and M. Gidlund, "Industrial internet of things: Challenges, opportunities, and directions," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 11, pp. 4724–4734, 2018.

[2] S. Schneider, "The industrial internet of things (iiot) applications and taxonomy," *Internet of Things and Data Analytics Handbook*, pp. 41–81, 2017.

[3] J. Rüth, F. Schmidt, M. Serror, K. Wehrle, and T. Zimmermann, "Communication and networking for the industrial internet of things," in *Industrial Internet of Things*. Springer, 2017, pp. 317–346.

[4] H. Xu, W. Yu, D. Griffith, and N. Golmie, "A survey on industrial internet of things: A cyber-physical systems perspective," *IEEE Access*, vol. 6, pp. 78 238–78 259, 2018.

[5] J.-Q. Li, F. R. Yu, G. Deng, C. Luo, Z. Ming, and Q. Yan, "Industrial internet: A survey on the enabling technologies, applications, and challenges," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 3, pp. 1504–1526, 2017.

[6] Y.-W. Ma, Y.-C. Chen, and J.-L. Chen, "Sdn-enabled network virtualization for industry 4.0 based on iots and cloud computing," in *2017 19Th international conference on advanced communication technology (ICACT)*. IEEE, 2017, pp. 199–202.

[7] J. Wan, S. Tang, Z. Shu, D. Li, S. Wang, M. Imran, and A. V. Vasilakos, "Software-defined industrial internet of things in the context of industry 4.0," *IEEE Sensors Journal*, vol. 16, no. 20, pp. 7373–7380, 2016.

[8] M. Aazam, S. Zeadally, and K. A. Harras, "Deploying fog computing in industrial internet of things and industry 4.0," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 10, pp. 4674–4682, 2018.

[9] D. Henneke, L. Wisniewski, and J. Jasperneite, "Analysis of realizing a future industrial network by means of software-defined networking (sdn)," in *2016 IEEE World Conference on Factory Communication Systems (WFCS)*. IEEE, 2016, pp. 1–4.

[10] V. Gazis, A. Leonardi, K. Mathioudakis, K. Sasloglou, P. Kikiras, and R. Sudhaakar, "Components of fog computing in an industrial internet of things context," in *2015 12th Annual IEEE International Conference on Sensing, Communication, and Networking-Workshops (SECON Workshops)*. IEEE, 2015, pp. 1–6.

[11] Introduction to mininet. [Online]. Available: https://github.com/mininet/mininet/wiki/Introduction-to-Mininet

[12] B. Lantz, B. Heller, and N. McKeown, "A network in a laptop: rapid prototyping for software-defined networks," in *Proceedings of the 9th ACM SIGCOMM Workshop on Hot Topics in Networks*. ACM, 2010, p. 19.