Optimisation of Fog Computing for Industrial IoT applications

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Abstract— **Industrial IoT is revolutionizing many industries, improving performance, but it still suffers from the high-latency and intermittent connections between cloud and end device terminals. In order to combat high-latency, Fog computing has been adopted to extend computing and storage to the network edge. The main objective of Fog computing is to bring selected cloud computing capabilities to the edge of the network, closer to the end devices, to improve latency, enhance location awareness, and provide mobility support among other advantages that are missing in cloud computing as is this stage. On the other hand, to combat intermittent connections requires Fog computing to operate autonomously to ensure uninterrupted services even when there are unreliable connections with the cloud, but it is also required to fully integrate with the cloud when the full resource connectivity is restored. These calls for an efficient scheme for the Fog computing, that will be able to improve performance. In this paper, we propose a scheme that makes use of machine learning algorithm among other techniques to improve latency, provide distributed decision-making and provide adaptive uplink management. The proposed scheme utilizes a hidden Markov model from the unsupervised machine learning algorithms. The scheme promises improved performance in terms of latency and efficient resource utilization compared to cloud computing.**

***Keywords*—Fog computing, Industrial Internet of things (IIoT)**

I. Introduction

Internet of Things (IoT) is expected to provide a quantum leap for the manufacturing industry with the market potential for industrial applications projected to be $913 billion by 2018. Industry analysts are projecting that there will be up to 50 billion connected devices with a market potential of between $10.6 to 14.2 trillion by 2030 [1]. The application of IoT in the manufacturing industry is normally referred to as the Industrial Internet of Things (IIoT). This phenomenon is to revolutionize many industries and manufacturing is not an exception. Manufacturers have already started to digitize their overall businesses processes, finding new ways to engage with customers and optimizing operations. This process of digitizing manufacturing processes has been referred to as smart manufacturing [2].

Manufacturing companies that have adopted smart manufacturing in their operations are already seeing improved results with 82% increased operational efficiency and improved product quality with 49% fewer product defects, according to Microsoft research in [3]. In addition to this, the American Society for Quality states that connecting devices and analyzing the data collected enables manufacturers to reduce overhead, conserve resources, increase profits and optimize operational efficiencies [3]. The greatest value being experienced from smart manufacturing stems from monitoring industrial operations, solving complex logistics and predicting the downtime of equipment.

As more factory processes adopt smart manufacturing, the data velocity and volume increases, moving the big data from factory sensor/actuators to the cloud might not be efficient, or even feasible due to bandwidth and network connection constraints. While on the other hand, smart manufacturing is required to support time-sensitive and location-aware applications, such as real-time manufacturing applications, making the distant cloud not be able to satisfy the low latency requirements of these applications. Proving low-latency response, distributed decision-making, or scaling to the resources to the magnitude of the data generated becomes a challenge in these scenarios. Moreover, in some applications, sending the data to the cloud may not be a feasible solution due to privacy concerns (e.g. intellectual property in a manufacturing plant). Therefore, to address these challenges, Fog computing has been one of the solutions that have been proposed [4].

Fog computing has been proposed by both industry and academia [5,6] to address the above issues and to quench the need for computing paradigm closer to connected devices. Fog computing bridges the gap between the cloud and IoT devices by enabling computing, storage, networking, and data management on the network nodes within the close vicinity of IoT devices. Therefore, computation, storage, networking, decision making, and data management occur along the path between IoT devices and the cloud, as data moves to the cloud from the IoT devices. These characteristics makes Fog computing to be a suitable technology for smart manufacturing applications.

Fog computing has the potential to support delay sensitive service requests with low traffic congestion, low energy consumption and minimum bandwidth with an aim to reduce the burden on cloud data centers. Fog computing, which is not a replacement for cloud computing, extends the computation, communication, and storage facilities from cloud to edge of the networks. Although Fog computing is a viable solution towards sustainable development of the IoT market, many unsolved issues still exist [7][8]. In this study, we will focus on improving performance in terms of latency, for Fog computing to be able to cater to the stringent requirements of IIoT applications such as smart manufacturing.

In this paper, we present a scheme that uses artificial intelligence, machine learning to be specific to enhance decision-making and improve latency by defining Fog computing as an autonomous system which can be able to provide its own computing and storage functionality and an additional network selection functionality to provide connectivity on primary link failures or unavailability.

The rest of the paper is outlined as follows: Section II provides the background and definition of key terms used in the paper, Section III reviews related research work in optimizing the Fog computing in IIoT, with the specific focus on smart manufacturing. Section IV describes our proposed scheme in steps to address these Fog computing, and provide a review of similar research work that addresses challenges of Fog computing in IIoT applications. Section V details the evaluation of the proposed scheme, covering experimental setup, results, and discussion, while Section VI provides the conclusion and highlight of future work.

II. Background

In this section we will outline the key areas covered in this paper, being Fog computing, Industrial IoT and Smart manufacturing.

A. Fog computing

Cloud computing leverages on geographical centralized data centers using relatively homogeneous commoditized hardware. The cloud computing infrastructures were not designed to cater for the processing, storage, and data generated by billions of distributed endpoints operating in often dynamic environments with intermittent network connectivity, as these are turning out to be with the continuous increase in adoption of IoT [9]. In response to this challenge, Fog computing offers a decentralized computing architecture where data is processed and stored between the source of origin and cloud infrastructure. This results in the minimization of data transmission overheads, and subsequently, improves the performance of computing in Cloud platforms by reducing the requirement to process and store large volumes of superfluous data [10]. In this paper, we focus on the application of Fog computing in IIoT

B. Fog computing and Industrial IoT

Internet of Things (IoT), which has emerged a few years ago, has been embraced by industry, resulting in what is known as the Industrial Internet of Things (IIoT). IIoT refers to making industrial processes and entities part of the Internet. Restricting the definition of IIoT to manufacturing yields another subset of IoT, known as Industry 4.0 [11]. In this paper, we are just going to refer to this phenomenon as IIoT. As outlined above, Fog can provide local processing support with acceptable latency to actuators and robots in the manufacturing industry. As such Fog computing has gained increasing attention in processing the computing tasks of the IIoT [12]. In this paper, we discuss this in detail and then propose how latency can be further improved and connectivity to the cloud be enhanced for improved reliability.

C. Smart Manufacturing

Smart industry is a synonym for Industry 4.0 or industrial transformation in the fourth industrial revolution within which smart manufacturing de facto fits. As such smart manufacturing aims to take advantage of advanced information and manufacturing technologies to enable flexibility in physical processes to address a dynamic and global market.:

As the primary field of application our proposed scheme, considers the use of Fog computing in the IIoT domain as a whole and Smart manufacturing environments in specific.

III. Related Work

Recently, there has been a number of promising research initiatives focused on solving issues related to IoT and Fog computing. One of our previous research works in [13] [14], also covered this area, proposing the design of efficient resource management and orchestration and enhancement of Fog computing based autonomous management systems. In this paper, we will focus on the research work that addresses the challenges of Fog computing in addressing Industrial IoT applications.

The application of Fog computing in IIoT with a specific focus in Smart Factories and cyber-physical system was studied by de Brito et. al. in [15]. In this study, the authors used container-based orchestration mechanisms to enable cyber-physical systems to be programmable, autonomous, and to communicate peer-to-peer. They focused on ultralow latency, robustness, and node programmability. In deploying programmable Fog Nodes on the shop floor, they argued that the approach can improve flexibility, reliability, and efficiency. Their paper established that Fog computing can improve production on the shop floor. This work did not cover the details of autonomous systems in Fog computing, such as autonomous decision-making, which we are planning to cover in this paper.

Deploying Fog computing in IIoT was studied in detail by Aazam et. al. [11] in their review paper, this study highlighted how Fog can be used to provide local computing support in the IIoT environment. In their review paper authors also listed emerging research challenges related to IIoT and Fog computing. In their review paper authors highlighted, fast processing of the sensed data to generate instructions for the actuators and robots within some acceptable latency as one of the challenges. The other challenge noted was data structuring and filtering to avoid sending unnecessary data to the core and the cloud. In this paper, we are indirectly addressing these challenges by proposing a scheme that will provide reduced latency and computing at the edge and reducing the use of the uplink to the cloud.

Fog computing is gaining increased attention in processing the computing tasks in IIoT with different service popularity. Li et. al in [12] proposed a service popularity-based smart resources partitioning scheme for Fog computing-enabled IIoT to improve delay time and fault tolerance. Their proposed scheme demonstrated improved performance. It was tested simulated using iFogSim [16], a similar simulator that has been adopted in this paper.

In providing more computing at the edge of the network and reducing data that is sent to the cloud. The work by Chekired et. al. in [17] stated that the collected and sensed data from IIoT need to be scheduled in real-time, especially for big factories. In response to this challenge, the authors proposed a hierarchical Fog servers' deployment at the network service layer across different tiers. In their study, the authors compared the benefits of their proposed scheme with conventional flat design and demonstrated improved performance. This study proved that processing data closer to the edge does improve performance in IIoT applications. In our proposed scheme, we are going to take a leaf in this work by also proposing computation at the edge node using machine learning algorithms.

As adoption of IIoT increase, a large amount of data is being generated continuously by different sources at the edge of the network. As Fu et. al. in [18] highlighted the challenges of data processing, secure storage, efficient retrieval and dynamic data collection in IIoT. The authors argued that storing all the IIoT data raw is unwise considering that the end devices energy and storage space is limited in these devices. In this, they proposed the integration of Fog computing for improved IIoT performance. Their scheme selectively processes data based on latency requirements, where the raw data is pre-processed in the Fog and then the time-sensitive data are used and stored locally, while the rest is sent to the cloud. The results of their scheme demonstrated improved efficiency and security of data storage and retrieval in IIoT. A similar approach is going to be employed in this paper, but with the focus of improving latency and enhancing autonomous decision-making.

Ashjaei et. al. in [19] proposed a Fog computing platform to enhance maintenance in IIoT. In their study, the authors identified four IIoT requirements for maintenance which are low latency, high reliability, security, and privacy. After this the proposed a Fog-based scheme to fulfill the mentioned requirements. Their proposed scheme has the potential of addressing the challenges. The scheme only focused on maintenance in manufacturing plants, not the normal day-to-day operation. A similar approach is going to be adopted in this paper with additional machine learning used to enhance decision-making.

Chen et. al. in [20] addressed the problem of distributed decision making, but this work focused on the challenge of service hosting where Fog nodes are required to be adaptively configured to host services for sensor nodes. The authors proposed the use of an online distributed algorithm, called adaptive Fog configuration (AFC), to optimize service hosting and task admission decisions in this case. Also, Shi et. al. in [21] proposed a scheme that integrates Fog computing to the cloud-based IIoT architecture to build ultra-low latency cloud-Fog computing for IIoT. This study used modeling to analyze and demonstrate how reliability can be improved in the cloud-Fog network architecture.

Another challenge in Fog computing is guaranteeing stable communication between Fog nodes and the cloud. Castellano et. al. in [22] analyzed the applicability of Fog computing in a real IIoT environment, highlighting challenges of unreliable and intermittent network connectivity. In addition, the authors proposed an architecture that enables disruption-tolerant communication over challenged networks. In our scheme, we address this by defining network states to respond to different network conditions, like our previous work in [14].

IV. PROPOSED SCHEME

In this section, we present the architecture of our Fog computing framework as depicted in Figure 1. The framework enables the enactment of IoT services in an arbitrary Fog landscape. This allows optimizing resource provisioning in the Fog, as discussed in Section IV.

A. System Architecture

In the design of the proposed scheme, we followed the basic structure of Fog computing as presented in [23]. This is the framework that has been outlined in previous related work such as [13] [14]. The proposed scheme will sit in the edge node and provide additional intelligence to improve decision making in the edge. Limited computation and storage will be performed in the edge node to reduce the latency by not sending all the data for computation at the centralized cloud, this is outlined in detail in the latency optimization subsection.

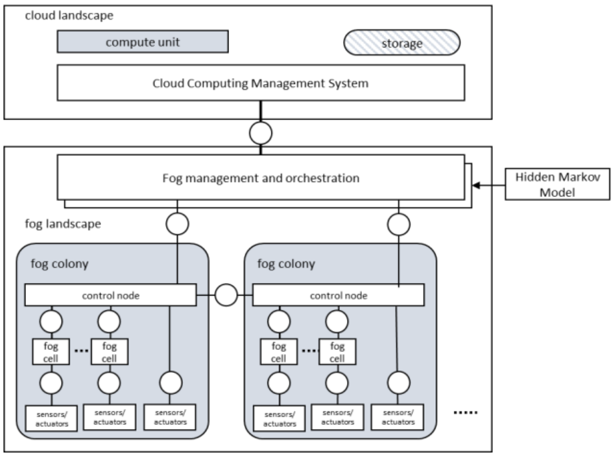

Figure 1: Fog Computing Framework Overview

In the proposed scheme, we introduce the hidden Markov module to help with state transitions. This component adds intelligence in the edge, allowing the edge to be able to autonomously make a decision in the absence of Fog computing.

B. Latency Optimisation

In this subsection, we outline how the proposed scheme is planning to reduce the overall latency in the system. As outlined in Figure 2, the average delays that are expected from the sensor/actuator to the cloud. Additional computation will be performed at the edge node for selected real-time data, other data will be sent to the cloud. In order to optimize the use of limited resources, as outlined by Fu et. al. in [18] data will be processed and computed in the cloud, with limited raw data to be sent over to the cloud at a suitable time to reduce the over-burdening of the backhaul. Figure 2 outlines the current average delays that contribute to the increased latency in Fog computing applications.

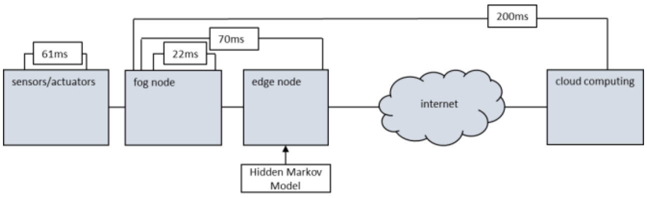

Figure 2: Average Loop delay outline

As outlined in Figure **2**, above the computational delay that will be added by the edge node computation will be 30ms, the current Fog computing on its own is at 173ms. When we add the proposed scheme computation this moves to 213ms. This provides much-improved performance compared to the cloud's 273ms. In addition, our proposed scheme provides improved performance over an unreliable network as it selects when to send data to the cloud as outlined below.

The proposed scheme will provide computing at the edge, the scheme selectively chooses the computing. The edge node will perform delay sensitive computing, and the module will send the none sensitive data to the cloud. In this, the average latency for operations is expected to improve.

C. Network Consumption

The use of Fog computing in IIoT might not be as suitable as required as in some smart manufacturing scenarios such as mining operations, building sites, precision agriculture, communication occurs over unreliable network, because of the absence of fixed and reliable network infrastructure as highlighted in [22]. The proposed scheme will be sitting at the edge of the autonomous network as shown in Figure **2** above. It will monitor the state of the autonomous network. If the network performance indicators are not satisfying the network user requirements, the proposed scheme will automatically change the state of the network

The proposed scheme will have the following states:

- independent autonomous network
- integrated edge with unreliable backhaul
- end-to-end integrate edge

The end-to-end integrated edge state is the best state in terms of computing and storage metrics, but because of the location of the cloud, there may be higher latency and cost of using backhaul network in addition to the cost of cloud services. The design goal is to have the network spend more time at the independent autonomous state and transition to another state when required.

V. Evaluation

In order to test the performance of the proposed scheme and the expected improvements, the system has to be set up and compared with a similar scheme in a close to live environment as much as possible. The proposed scheme proposed to improve latency for Fog computing to be suitable for IIoT applications.

A. Simulator

Simulation has been used extensively to simulate traditional network infrastructures. While Fog computing is still a new phenomenon, as such there has not been many well-developed simulators in this subject [24]. Although there are a number of simulators that can be used the most adopted in research recently has been iFogSim [16] and FogNetSim++ [27]. In order to compare the performance of both the resource management scheme for the study, we found that iFogSim would be the most suitable simulator to be used for simulation of resource management, specifically scheduling policies between Fog computing and cloud computing with varying network configurations. iFogSim is not without its limitations. While it enables the definition of the location of devices getting service from the Fog servers, this information is static and not updated by any mobility model.

B. Metrics

In Figure 2 above sensor/actuator delay is estimated to be at 61ms, this is the processing or computation delay. In the Fog node, 22ms is the computation delay, the proposed scheme's module will sit in the edge node and its delay is assumed to be 30ms. The delay between devices is expected to be 22ms for sensor/actuator to Fog node, 70ms for Fog node to edge node and 200ms for Fog node to cloud.

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TABLE I
SIMULATION PARAMETERS

Source	**Destination**	**Latency**
Sensor/Actuator	Fog Node	61ms
Fog Node	Fog Node	22ms
Fog Node	Fog Node	70ms
Edge Node	Edge Node	30ms
Edge Node	Cloud	200ms

C. Experimental Setup

As the delays are outlined in Table 1 above. The processing of the sensors/actuators is configured to be at million instructions per second (MIPS) within 5ms intervals. The setups were grouped into 6 groups with each group connected to one Fog node. The number of sensor actuator was varied from 1 to 64. The performance metrics reviewed in this study are network usage, and latency (the average latency of control loop), as outlined and defined in sub-section D below.

D. Experiments

As IIoT applications need to perfom most of its computing closer to the sensor/actuator and with limited external network in terference as possible. The proposed scheme model was simulated with limited number of sensor/actuators connected to the Fog node, with computing being done in Fog Node, Edge Node and Cloud. Figure 3 below displays the comparison between the centralized (centralised) and distributed management (fog and edge node) model average latency of the control loop.

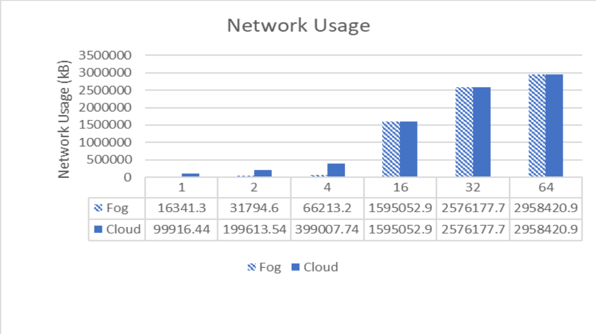

Figure 3: Network Consumption

The results demonstrates that distributed management provides lower latency when compared to centralized management in nodes below 16. This shows that when there are more than 16 nodes connected the system may have to trigger a centralized management model in order to improve latency.

Figure 4 below displays the comparison of latency from fog node, edge node and cloud.The edge node demonstrated that it can be able to handle the computational gap between the fog node and the cloud.

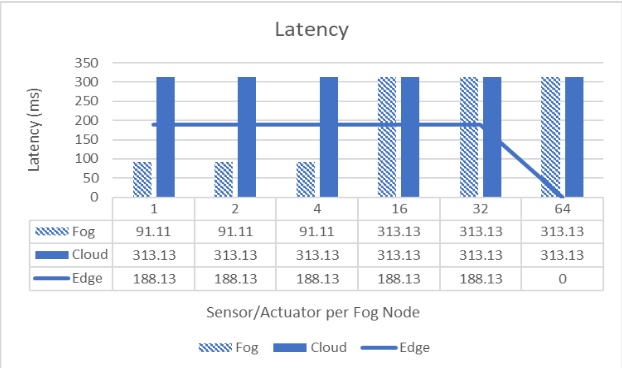

Figure 4: Latency Comparison

Figure 4 above outlines that the proposed scheme can provide and optimised latency of 183ms for sensor/actuator of up to 32. The proposed scheme edge node had limited capabilities and it was not able to handle computational requirements for sensor/actuatoes above 32, with limited functionality of handing over to the cloud compare to the Fog nodes that possess built-in functionality of handing over computing to the cloud.

E. Results and Discussion

The results highlight that there is a need for both orchestration (centralized management) and choreography (distributed management) in a Fog computing environment. In addition to this, we believe that there is a need for an intelligent switching between the centralized and distributed mode in order to enhance performance and reduce latency. The results were limited by the linear modelling of latency by the simulator.

VI. Conclusion and Future Work

In this paper, we presented a scheme that proposed an additional component in the edge node that used machine learning's hidden Markov model to predict the probability of change in availability of resource and prepare accordingly to avoid and reduce system downtime. The proposed scheme showed better performance compared to cloud implementation, but it adds more computational time to the current Fog computing schemes when they are on their own. This additional computational time provides the trade-off with a more reliable system with lower average latency compared to Fog computing on its own, and resiliency relating to uplink connectivity.

Nevertheless, there are some problems still to be addressed in this research. In the next steps, the latency values between devices and nodes will be improved to be randomly distributed to be as close as possible to real industrial application, also the computational delays will be aligned to a specific Smart Factory application. A stochastic distribution will be adopted for simulations to vary latency randomly based on the chosen model. Furthermore, details of computational resources utilized by the hidden Markov component of the scheme will be quantified.

VII. Acknowledgement

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