Bulletin of Electrical Engineering and Informatics
Vol. 11, No. 3, June 2022, pp. 1706~1714
ISSN: 2302-9285, DOI: 10.11591/eei.v11i3.3227

A smart water grid network for water supply management systems

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Article Info

Article history:

Received Oct 5, 2021
Revised Apr 12, 2022
Accepted May 23, 2022

Keywords:

Cloud computing
Fog computing
Smart water grid
Water quality monitoring
internet of things

ABSTRACT

This paper proposes a smart water grids network (SWGN) architecture that combines the advantages of fog computing, internet of things (IoT), long range wide area network (LoRaWAN), and Software-defined networking (SDN). The main aims of the SWG architecture are to optimize data routing and monitor water supply and quality in real-time. SWGN handles a vast amount of data that is collected by IoT devices from different points related to water supply and quality. The data is processed in a distributed way by a number of fog servers that are located at the edge of the network. The fog controllers are deployed at the fog layer in order to take action locally for frequent events. The cloud layer has a cloud controller to take actions globally for infrequent events. The LoRaWAN provides communication technology that allows devices to operate regularly. The SDN technology decouples network traffic to control data routing decisions efficiently. A primitive evaluation under the Mininet emulator, focusing on SDN, shows the feasibility and efficiency of the architecture.

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1. INTRODUCTION

The world's urban population has increased from 1.019 billion in 1960 to 4.117 billion in 2017 and is expected to reach around 9.7 billion by 2050 [1]. This exponential growth of the world's population already causes water problems in some countries around the world. Approximately 700 million people are currently affected by water scarcity in 43 nations. By 2025, in 48 countries, around 2.8 billion people will face water stress because of the growth of the number of water scarcity regions [2]. Unified platforms have been introduced for digital water cycle transformation [3]. These platforms are integrated with advanced information technologies such as fog and cloud computing, the internet of things (IoT), and smart grid to construct smart water grids (SWGs). Unfortunately, the existing data routing approaches fail in some scenarios, such as finding the shortest path in multi-hop networks if required [4], [5]. Moreover, because of the increasing complexity of water-related water-related problems, water scarcity, water pollution, leakages, and aging of the water components (pipelines, reservoirs, pumps, etc.), traditional water management methodologies have been shown their inability and limitations. Overexploitation of natural resources, climate change, and industrial activities exacerbate the problems related to water scarcity [6]. Therefore, urgent sophisticated solutions are needed in order to tackle the current issues related to water scarcity and then improve water management efficiency.

Designing and developing a smart grid management system for real-time data collection is a challenge. Particularly for the SWG context, Mutchek and Williams [7] reviewed how smart technologies can be integrated into the water distribution systems and therefore contribute to the efficient management of this system. One main challenge with using information and communications technology (ICT) in water systems is the enormous amount of data collected by sensing devices and event detection devices (leakage detection nodes) and how this data is communicated and processed across all the components of the water grid [8], [9].

During the past few years, some communities have started to deploy SWG in order to enable water utilities to optimize the operation system, effectively control and manage leakages, optimize water consumption, and monitor real-time water quality parameters [6]. Before we present our proposed architecture, in this section, we discuss the architectures of the pilot deployments already available and the architectures proposed by researchers for SWG applications deployment. We also investigate numerous researchers routing approaches to allow multi-hop communication in LoRa. Some communities such as [10]-[12] have begun to develop SWG applications, and real-world deployments are available. These deployments enable water utilities to efficiently manage leaks in order to reduce both economic losses and water losses caused by leakages, enhance optimization of system operation, monitor real-time water quality parameters to reduce diseases spread by water pollution, and real-time water consumption monitoring using smart water meters into the water grids. All these deployments and others available in the literature are cloud-based systems, where the huge amount of data collected is transmitted to the cloud services for storage, processing, and decision making.

Because of the energy constraint of SWG devices, it is crucial to use a low power consumption technology for data communication, and LoRaWAN is a perfect data networking solution according to the state-of-the-art [13]. However, in the official LoRaWAN specification, one-hop communication has been adopted. The end devices to reach one or more gateways employ just one-hop communication. Due to the fact that links in Lo- RaWAN networks can be kilometers long, the signals sent by LoRaWAN transceivers (gateways and end-devices) may be attenuated by obstacles like trees mountains, impacting negatively the packet delivery ratio. To improve Lo-RaWAN performance, different studies [4], [14], [15] proposed LoRaWAN multi-hop networks as a suitable solution and therefore implemented different routing strategies. Unfortunately, there are still challenges in terms of efficient routing approach to use. The existing routing approaches fail in some scenarios, such as finding the shortest path if required [4]. Therefore, efficient, robust, flexible, easy, and secure routing algorithms are required to root data of a specific SWG device efficiently to an own fog server or even to a fog server nearby. Software defined networking (SDN) can be used to address routing issues in the LoRaWAN network based on fog computing [16].

Therefore, this article proposes a smart water grids network (SWGN) architecture for SWG communication based on fog computing, LoRaWAN, and SDN. An enormous amount of data collected by SWG devices is processed in a distributed way by fog servers deployed along with the water distribution network. The LoRaWAN technology is employed to allow the battery-powered devices to operate for a longer period. We use SDN to make routing decisions easily, efficiently, securely, and flexibly. As the size of the network increases, we propose to deploy SDN controllers in a distributed manner at the fog layer to manage frequent events and an SDN controller at the cloud layer to take global decisions for rare events. Our goal in this paper is to provide a system for SWG applications where data collected by SWG devices are processed locally in order to tackle the difficulties of the cloud-based solutions while at the same time providing a suitable solution, through the SDN concept, to the routing issues of LoRaWAN network widely used in SWG applications. Our contributions are listed as follows: i) survey on existing SWG communication architectures and routing approaches for LoRaWAN; ii) propose an SWGN communication architecture based on fog computing, LoRaWAN, and SDN.

In the next section, we discuss the architectures of the SWGN projects that are in operation and architectures proposed by researchers, followed by a review of LoRaWAN routing approaches. Then, we provide a quick overview of the methods and technologies involved in our proposed SWGN architecture and present our proposed SWGN architecture. The primitive evaluation of the proposed architecture is provided in section 3, including the advantages of our architecture over the existing solutions. It then addresses and discusses the challenges of implementing our proposed architecture. The conclusion and future research work are finally provided in section 4.

2. THE PROPOSED SMART WATER GRIDS NETWORK ARCHITECTURE

Due to the vast use of the water distribution system, many SWG devices will be connected for monitoring purposes. Because of the exponential growth of the population in the urban area combined with urbanization, the number of houses in cities continues to grow. By assuming that each house is equipped with a water meter, the quantity of smart water meters connected is great. In addition, the sensor nodes will be deployed to tanks along with the water distribution network for events detection and water quality monitoring. As the network size increases, the use of a sole controller to manage the forwarding devices results in several issues such as response time, infrastructure support, scalability, and availability [17]. Therefore, as discussed by authors of [16], large-scale networks can be divided into multiple controller domains, and it is feasible to deploy multiple SDN controllers where each SDN controller is responsible for managing a specific area.

Our proposed architecture comprises a set of controllers that aims to locally and globally control the SWGN. Each controller could be physically distributed or centralized. Due to issues encountered by physically centralized architecture such as a single point of failure, scalability issues, etc., recent studies shifted to the physically distributed architecture, especially [18], [19]. A physically distributed architecture can be divided into logically distributed or centralized. The logically centralized architecture considers a single controller which is suggested to be a single failure point. The logically distributed architecture considers different controllers with different responsibilities. Every controller has responsibility for a specific domain and therefore manages it. This paper proposes physically and logically distributed SDN architecture to address routing issues in LoRaWAN multi-hop networks for SWG applications. The fog servers process SWG devices' data at the network's edges. Our architecture aims to have local control of the network view by using SDN controllers deployed at the fog layer and global network control by using a single controller installed at the cloud layer. The proposed SWGN architecture consists of four layers, as shown in Figure 1.

2.1. SWG devices layer

The SWG devices layer, also called the IoT layer, consists of SWG devices connected with each other and generating heterogeneous data. These devices can be smart water meters, smart valves, leaks detection sensor nodes, water quality sensor nodes, etc. In this paper, we simply considered smart water meters as IoT objects, but in real-world deployment, water quality and leaks detection nodes can be used, and the principle will be the same. Because of energy constraints, distance from the gateways, and security issues, some nodes cannot communicate directly with LoRa gateways. Therefore, some devices can act as relay nodes (RNs), as shown in Figure 1, in order to relay the neighbor data. Therefore, only RNs play the role of forwarding devices, and routing decisions are realized over them. In order to provide LoRa communication, each device must be equipped with a LoRa module. It is worth mentioning that the topology proposed in this paper aims to extend the communication range and efficiently manage the routing process through SDN controllers.

2.2. Fog layer

The fog layer consists of four main components: The LoRa gateways, the LoRaWAN network server, the fog servers, and the fog controllers. It is worth noting that fog controllers are just some fog servers that play the controller role. The LoRa gateways task is to transfer data sent by RNs to the LoRaWAN network server. This research work suggests equipping a dedicated network server with each LoRa network. This enables us to introduce in the same location the Fog servers, where the incoming data are processed immediately after having been received, as shown in Figure 1. The data are processed with low latency and are stored temporarily by fog servers. The fog servers are connected to the cloud server located in the cloud layer. For permanent data storage and processing that requires high computing, the fog servers periodically send some data to the cloud server. In the fog layer, fog controllers are deployed and perform different responsibilities. Fog servers and LoRa transceivers are equipped with an Open Flow protocol. These fog servers are controlled by fog controllers located at the fog layer. Each fog controller controls and manages a specific region assigned to it. Therefore, each fog controller has a local view of part of the network assigned to it. Because fog servers and LoRa transceivers are controlled and managed locally, the forwarding components can be applied with routing decisions such (RNs and LoRa gateways) faster, easier, flexibly, and securely which locally through fog servers, the time for data transmission and the amount of transmitted data considerably reduced.

2.3. Cloud layer

The cloud layer contains a cloud server that collects data from the fog servers for processing and permanent storage. In Figure 1, we did not indicate the communication between the cloud server and the fog servers because of overload reasons. Still, there is perfect communication between these components. Additionally, the cloud layer includes a cloud controller responsible for controlling and managing the entire network. As shown in Figure 1, the cloud controller communicates with the fog controllers. The cloud controller is responsible for global decisions while the fog controllers take decisions locally. For frequent events, the fog controllers make decisions locally and ask the cloud controller for global decisions.

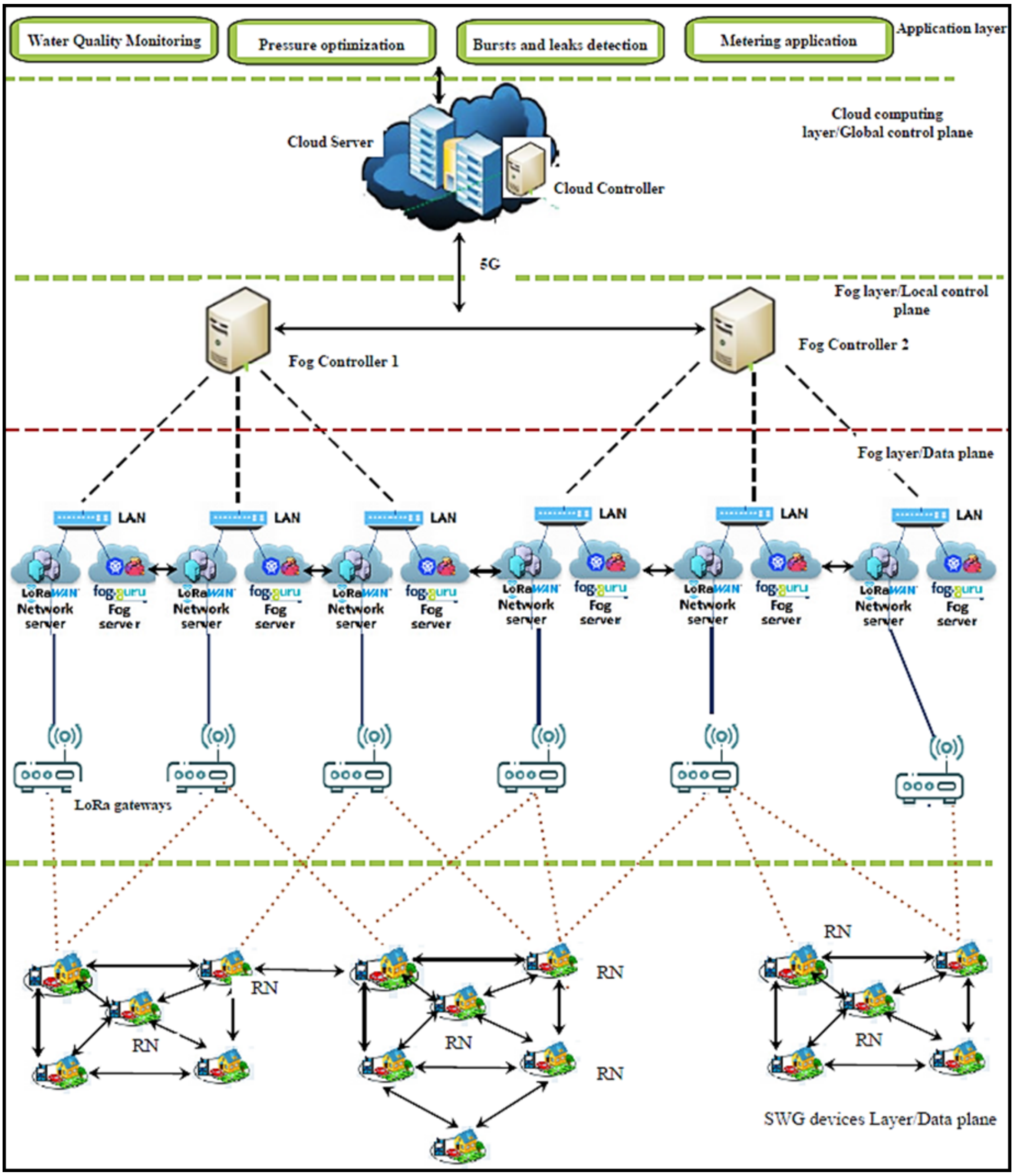


Figure 1. Our proposed SWGN architecture

2.4. Application layer

The application layer consists of pressure optimization, leakages detection, and smart water metering applications. These applications exploit data collected by smart devices of the IoT layer. It is also important to note that fog servers can serve applications that require real-time processing locally. By realizing the routing process over forwarding devices, our proposed solution is able to solve routing issues, especially for downlink communication where the shortest path is required during data communication. Once the routing rules are defined at the SDN controllers as flow tables, the shortest path will be easily found for data communication. In order to take action during data communication, each forwarding device performs the following process: (1) Firstly, by examining the results of incoming data packets, each forwarding device verifies its flow tables to take action. (2) Each forwarding device then finds the highest priority match. In the case where there is a match, the forwarding device quickly and easily processes the data packets. It forwards them to the destination address with very low latency, which is an important metric for leakages detection in the SWG communication system. In the case where there is no match, the device will communicate with its local controller. For instance, if the shortest path is required for downlink communication and the RN has no idea regarding the shortest path information, it sends a request to its local fog controller to have this information, and when this one responds, the forwarding device will just follow the instructions coming from this fog controller.

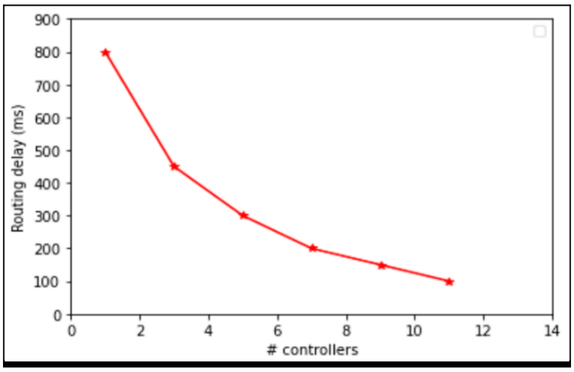
In some cases (rare events, for example), the local controller may not have the information that the forwarding device requests, of course, according to its flow table. Therefore, the local fog controller must communicate with the cloud controller and ask him to take a global decision. The cloud controller will take a global decision, and the fog controller will relay this one. Then, this decision is sent to the forwarding device. Our proposed approach is expected to find the shortest paths for data communication through SDN controllers at the fog and cloud layer, reduce data traffic processing via the fog computing concept, extend the SWG devices' batteries life through the LoRaWAN solution, and enable real-time communication due to reducing latency. In the next section, a primitive evaluation of our model is provided.

3. RESULTS AND DISCUSSION

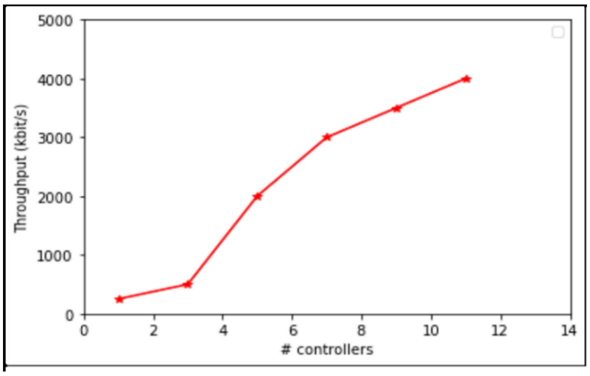
In this section, we evaluate our solution primitively in order to show its performance and feasibility. Specifically, we focus on SDN and use the Mininet emulator for evaluation. We consider a simple scenario where smart water meters are connected through the LoRaWAN network, and the multi-hop mechanisms can be employed to send data to extend the network coverage. Therefore, the shortest path is needed for data communication from source to destination. We consider in our evaluation that, for any communication, information about the shortest route is mandatory, but the forwarding devices know nothing about that information. We use Dijkstra's algorithm to find the shortest path. This evaluation aims to show how our proposed architecture can help find the shortest path for data transmission. The evaluation is performed under Mininet. Mininet is an open-source SDN emulator. It already contains all components (controllers, hosts, and others) we need to configure our network easily. The communication between SDN controllers and network switches is performed through the OpenFlow protocol.

As Mininet contains hosts, smart water meters in our simulations are represented by these hosts. We consider a network containing 30 switches, four communicating hosts, and varying controllers (1, 3, 5, 7, 9, 11). The lower link (the connection between hosts and switches) bandwidth is set to 5 Mbps, while the upper link bandwidth is set to 10 Mbps. The lower link delay is set to 5 ms, while the upper link delay is set to 10 ms. The lower link loss is set to 1%, while the upper link loss is set to 2%. The transmitted packet types are IP and ICMP. Each simulation time is set to 60 seconds. Ping and Iperf tools are tested to see the performance of the proposed architecture.

- Packet delivery radio: the results show that the increase in send interval increases the packet delivery ratio. The high traffic load frequently causes radio collision and congestion at buffers which ultimately case loss of packets.
- Network energy consumption: similar to network energy consumption, network energy consumption is highly affected by the frequency of application messages. The increase of application messages increases power consumption, and on the contrary, the rise of send interval linearly decreases the energy consumption.
- End-to-end delay: our proposed architecture is expected to reduce the routing delay if the shortest path is used during data transmission. We first measure the delay metric with the varying number of SDN controllers in the network, assuming that the host h1 communicates with the host h2 and the shortest path must be used. We denote the routing delay for this scenario d1. Secondly, we assume that the host h2 communicates with the host hl and d2 denotes the delay. Then, the communication delays between h1 and h3 are respectively denoted by d3 and d4. The communication delays between h2 and h3 are respectively denoted by d 5 and d6. And so forth, the communication between hosts is simulated individually, and the delays are obtained (via taking the average). With a high number of controllers, our proposed solution is able to provide SWG services with low delay as the actions are taken locally by SDN controllers. The shortest paths during data communication are found locally by SDN controllers and sent to the forwarding devices. As expected, it is clearly shown in Figure 2(a) that when the number of controllers increases, the routing delay decreases.
- Throughput: lastly, we measured the throughput according to the number of controllers (1, 3, 5, 7, 9, 11). Again, the average throughput is taken for each value of the number of controllers. The efficiency of the architecture is confirmed in Figures 2(a) and (b).



(a)



(b)

Figure 2. The performance evaluation (a) delay and number of controllers and (b) throughput and number of controllers

Subsequently, we compare our proposed solution to the traditional cloud-based solutions that consider neither SDN nor LoRaWAN in the SWG communication system and theoretically discuss our proposed solution's advantages. In contrast to existing SWG deployments mentioned in section 2, our architecture benefits from fog computing capabilities and uses SDN to address routing issues. Most existing SWG deployments use cloud computing services for data processing and permanent storage. Additionally, apart from [11], existing SWG deployments employ conventional cellular networks and short-range networks for data communication. Cellular networks are greedy in terms of power consumption, while short-range networks are just able to communicate over short distances. To extend the communication range, multi-hop communications are allowed in such networks, raising routing and power consumption issues. Specifically, our proposed architecture offers the following advantages over existing SWG deployments:

- Sensing node structure: SWG devices are usually used in adverse terrains like underground pipelines, where accessibility is very difficult. Therefore, the only way to power these devices is through the use of batteries. The use of the LoRaWAN protocol in our proposed architecture will significantly reduce the power consumption of SWG devices during data communication and enable them to operate over a long time. It was reported in [8] that devices equipped with the LoRa interface could operate for ten years and more with batteries. Additionally, as SWG devices can communicate over long distances with the LoRaWAN protocol, a few numbers of gateways will need to install, resulting in a decrease in the total cost of the network.
- Security and privacy: our proposed architecture eliminates the continuous transmission of sensitive data on the cloud servers through the fog computing paradigm. As we have mentioned in different studies, water consumption data collected by smart water meters are the users' private information. This sensitive data is regularly transmitted to the centralized cloud server for permanent storage in existing SWG deployments [20]. In this context, an adversary can easily extract users' lifestyle profiles from the detailed consumption data collected by using a NILM [21]. In contrast, in our proposed architecture, the real-time user data are stored and analyzed at the fog server by using fog computing. Only critical events are transmitted to the cloud server, preserving thus user privacy. From the security perspective, the complicated security protocols are deployed between fog and cloud servers instead of establishing direct connections between the SWG devices and the cloud. The Fog layer acts as an authentication center between SWG devices and the cloud.
- Low latency burst and leaks detection: in existing SWG deployments mentioned in section 2, it is typical for SWG devices to store periodic data and transmit these data once a day to the cloud for processing. The goal of transmitting devices data once a day is to reduce the power consumption as the communication task consumes more energy [22], [23]. However, this results in delayed burst detection. In our proposed architecture, as bursts and leaks detection data are processed at the edges of the network by fog servers, better alarming with low latency is provided in the case of a burst. Additionally, transmitting data regularly on fog servers will not negatively impact energy consumption because of the use of LoRaWAN, which provides deficient power consumption.

Using shortest path during data communication: As our solution proposes the distribution of controllers both at the fog layer and cloud layer, during data communication, the shortest path can be easily found by local controllers as each controller has a view of the domain that it is responsible for. The shortest route is sent to the forwarding devices that accept rules or policies from controllers [24], [25]. Table 1 shows the comparison of the proposed architecture with the related work.

Table 1. The comparison between SWGN and architectures of the related work

Issues	Reviewed architectures	SWGN
Sensing node	Hight power consumption	Low power consumption
Security and privacy	Medium	Hight
Latency burst	Hight	low
shortest path	Difficulty founded	Easily found

This research encountered some challenges during implementation that need to be addressed. These challenges are summarized in the following:

- Packet deduplication: As it is clearly remarked, our proposed architecture employs multiple LoRaWAN net-work servers. One obvious drawback is that we cannot solely depend on a single centralized network server in using a numerous network servers scheme, as in classical cloud-based architecture, to detect and filter redundant data received by multiple gateways. Therefore, innovative techniques need to be developed to enable these numerous network servers to communicate with each other to realize the same function in a distributed way.
- Fog and cloud are complementary elements located in different layers: Different jobs are assigned to these levels, and the distribution of tasks directly influences routing performance. The issue that arises in the collaboration of fog and cloud is "which tasks will be done at the fog layer and which will be done at the cloud layer." The requirements of a specific task need to be accurately analyzed and transmitted to the corresponding computing layer. Such tasks with high computational cost and large storage space must be sent to the cloud layer, while tasks requiring real-time processing must be sent to the fog layer. In a nutshell, the challenge is to accurately define which tasks will be processed at the fog layer and which one will be sent to the fog servers.
- Location of fog controllers: The location of each controller at the fog layer needs to be determined in order to increase the reliability and resiliency of the network. This problem can be solved through multi-objective optimization approaches.

4. CONCLUSION

This paper has presented an IoT communication architecture based on fog computing and software-defined networking (SDN) to monitor and control water distribution systems. The proposed SWGN architecture introduces an intermediate layer between the remote cloud data centers and the SWG devices. This layer consists mainly of fog servers and fog controllers. Fog servers are responsible for collecting and processing SWG devices data with less latency and storing that data temporarily while the fog controllers take action locally for frequent events. The fog servers periodically transmit data that require high computing and permanent storage to the cloud server for further processing and storage. Additionally, the cloud layer contains a cloud controller for global decision-making. Since the fog controllers make decisions locally for frequent events, the fog controllers ask the cloud controller to take decisions globally for rare events. To extend the batteries life of SWG devices, SWGN architecture employs a new emerging data networking solution called LoRaWAN for data communication, and the SDN concept is used to optimize the routing process in such a network. Under the Mininet emulator, the feasibility of SWGN architecture is shown by evaluating two important metrics of an IoT service, specifically, the delay and the network throughput. As future work, we plan to perform an experimental test-bed to evaluate our proposed architecture's performance.

ACKNOWLEDGMENTS

The authors would like to thank the Center of Intelligent and Autonomous Systems (CIAS), Faculty of Computer Science and Information Technology, Universiti Tun Hussein Onn Malaysia (UTHM), for supporting this work.

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