A Lightweight Software Defined Network for Resilient Real-time Internet of Things

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Abstract

A real-time Internet of thing (RT-IoT) is the most emerging technology in which the processes, objects, machinery, and workers are monitored in order to have a real-time knowledge about the environmental event area. This eventually leads to achieve an efficient data collection, management, and decision-making at a very high speed and very low latency. However, traditional IoT does not support dynamic management and adaptive traffic control which are the crucial challenges of real-time IoT network. Software Defined Networking (SDN) came as a solution that separates the control plane from the data plane. Nevertheless, a resource constrained IoT device faces considerable challenges when a centralized SDN is implemented on IoT network. This is primarily due to IoT based on a centralized SDN causes jitter delay and higher overhead which can severely affect the performance of IoT traffic. This paper proposes a lightweight software defined network (LSDN) for a resilient real-time IoT (RT-IoT) based on optimization of control functions and reducing the duty cycle of the control plane. The proposed LSDN proposes an optimal SDN architecture and virtualization functions that preserve the resilient real-time and reduce the control overhead to practical levels. The finding in the experimental results shows that the developed LSDN outperforms the centralized SDN on RT-IoT. More importantly, the performance evaluation of LSDN guarantees an optimal QoS measurements in terms of control overhead, latency, and delivery ratio on RT-IoT.

Key words:

RT-IoT; LSDN; SDN.

1. Introduction

The exponential growth of the wireless devices that connected to the Internet has resulted to develop new IoT systems that can collect and exchange real-time information for providing intelligent services. The real-time IoT (RT-IoT) means that the messages of IoT are transmitted according to the constraint of end-to-end deadlines, which is useful in many applications such as health monitoring, industrial process management, vehicle traffic monitoring, household appliances control and monitoring, etc. Unfortunately, traditional network technologies are not capable of handling the requirements of IoT in an efficient, scalable, seamless, and cost-effective manner. Thus, the centralized software-defined networking (SDN) introduces a solution that separates the control plane from the data plane, and it facilitates the remote management and control of sensor devices according to the traffic type. Moreover, the SDN architecture has the SDN controller which has the capability to provide a complete knowledge of the IoT network and the flexibility to tune the components based on the IoT environment [1, 2, 3]. Also, the SDN offers a logical centralized and programmable method of IoT networks that resolve the weaknesses of traditional networks, such as troubleshooting and reconfiguration of connection for all devices in IoT, effective usage of network resources, reducing latency due to distributed mechanism etc. [4, 5, 6, 7]. Nevertheless, the IoT architect relies on two types of communication interfaces which are the micro IoT paradigm based on short-range radio technologies (e.g., IEEE 802.15.4/RFID/NFC/IEEE 802.11) which used in the sensor network interface, and the rising macro IoT paradigm, based on 3G/4G/5G technologies which used in the base station and IoT users devices[8, 9]. Hence, the centralized SDN is considered as an impractical solution for the micro IoT paradigm because of the resource-constrained and the overhead generated by SDN which can severely affect the performance of data traffic in terms of latency, and delivery ratio. Furthermore, the dynamic real-time applications that perform multiple tasks have many restrictions when they are implemented on micro IoT paradigm. For instance, the nature of predefined programmed of the sensor network does not permit the devices to perform real-time multi-task functions, although they are capable of doing so. Thus, it is required to change the functions of sensor devices based on the in real-time application. The recent solution for this problem is using the network function virtualization (NFV) that permits the sensor devices to accomplish multi-tasks, while altering their function in real-time [10, 11, 12, 13, 14].

1.1 Problem Statement

Since macro IoT paradigm devices have limited resources, the traditional SDN and NFV mechanisms are not a good fit for these constrained devices, especially when those approaches are applied to multi-task real-time applications. The SDN and NFV challenge in the RT-IoT system is to find a suitable solution for handling a large-scale of RT-IoT networks, establish complex routing topologies and simplify RT-IoT device operations. In addition, the direct

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applying of SDN and NFV on RT-IoT will increase the latency, jitter delay and overhead which can severely affect the performance of the RT-IoT traffic. Therefore, the aim of this paper is to propose a LSDN integrated with NFV mechanisms that tackles the aforementioned problems for RT-IoT Network.

The paper is structured as follows: Section 2 presents the related works on a LSDN solution for IoT network. The system design of LSDN is explained in Sections 3. Section 4 describes the performance analysis and the discussion of the obtained results. Finally, Section 5 concludes the paper.

2. Related Work on SDN for RT-IoT

Although many researches study the SDN solution for RT-IoT, a limited number of researches exploit the tiny SDN to resolve the problem of performance degradation when a centralized SDN is applied without modification to the RT-IoT. The related work in this paper entry focuses on the research studies that concern about the modification of SDN to to fit the resource-constraint of IoT. José L. et al. [15] proposed an open-source software architecture solution based on OpenDaylight (ODL) SDN controller, for orchestrating an industrial IoT scenario. The research in [15] highlights the critical aspects of the SDN controller architectural choices to precise IoT interfaces and the difficulties of covering the wide range of communication protocols in industrial contexts. The most related research is presented in Z. Zhang et al. [16] proposed an Optimal Control Channel (OCC) strategy to determine the optimal number of nodes to establish a stable OpenFlow channel between the IoT nodes and the Controller which will reduce the performance degradation by unstable IoT nodes. Furthermore, OCC is responsible for the control message aggregation to further decrease the SDN-inherent control overheads. The research presented in M. Baddeley et al. [17] proposed μSDN, a lightweight SDN framework with the combination of overhead reduction functions for the Contiki OS with both IPv6 and underlying routing protocol interoperability, as well as optimizing a number of elements within the SDN architecture to work in a constrained environment. Moreover, J. Pan and et al. [18] discussed the edge cloud and edge computing technologies which are promising to address multiple challenges with the current cloud computing model facing with the IoT network. Also, I. Bedhief et al. [19] introduced the comparative study for the performance of SDN with using multiple SDN controllers and traditional network. The results in terms of throughput prove that SDN-based outperformed the traditional network. The authors concluded that the Ryu is the most stable controller regardless the network. T. Theodorou et al. [20] demonstrated CORAL-SDN, an SDN solution for WSNs which uses a smart centralized controller to change the functions of protocol dynamically, resolves the challenging requirements of the WSNs and improves the IoT network management and operation in terms of performance and resource utilization. Furthermore, F. F. J. Lasso et al. [21] proposed SD-WSN6Lo, a software-defined wireless management solution for 6LoWPAN networks that aims to reduce the management complexity in WSN's. S. S. Bhunia et al. [22] proposed an SDN-based framework called Soft-Things for detection of anomaly closer to the edge of the network instead of detection at the core or higher level of the IoT network. The authors in [22] used the machine learning techniques to detect anomalies in the traffic.

The limitations of previous literature studies [15-22] are basically divided into three points: Firstly, most of the research studies developed the SDN architecture on the wireless sensor networks while the outstanding architecture of IoT does not considered. Secondly, the reduction in the duty cycle of the SDN controller has not been investigated. Finally, the smart traffic shaping on the data plane of IoT devices does not considered in the previous literature researches [15-22].

2.1 Summary of Contributions

This paper reports the following contributions. Firstly, it proposes a lightweight SDN (LSDN) integrated with NFV mechanism for RT-IoT that can be used to provide flexible management and centralized control to resolve the problem of concurrency of multi-task application in real-time. Secondly, it proposes a virtualization function that that permits the sensor devices to accomplish multi-tasks, while altering their function in real-time. Finally, the proposed LSDN mechanism provides an optimal number of SDN functions that preserves resilient real-time and reduces the control overhead to practical levels. LSDN consists of several optimization functions such as reduction of duty cycle for control plane and adaptive traffic shaping for data plane. The performance evaluation of LSDN guarantees a comparable QoS measurements in terms of control overhead, latency, and delivery ratio on RT-IoT.

3. System Design of LSDN

The proposed LSDN architecture is like the SDN on separation of the lightweight control plane, which also called network operating system that hosted at the base station (sink) from the lightweight data plane (forwarding plane) that hosted in the IoT devices. In contrast to SDN, the lightweight control plane makes decisions about the flow of packets through the macro IoT paradigm and the lightweight data plane moves packets through the micro IoT paradigm. Furthermore, LSDN reduces the latency and control packet overhead using two mechanisms:

optimization of control functions and reducing the duty cycle of the control plane. Fig.1 illustrates the architecture of LSDN in which the lightweight data plane manages the sensor devices in different types of real-time application and the lightweight control plane (base station) provides the necessary functions for micro IoT paradigm. Moreover, Fig. 1 depicts the centralized SDN that can be used to manage and control the macro IoT paradigm (SDN controller and IoT devices).

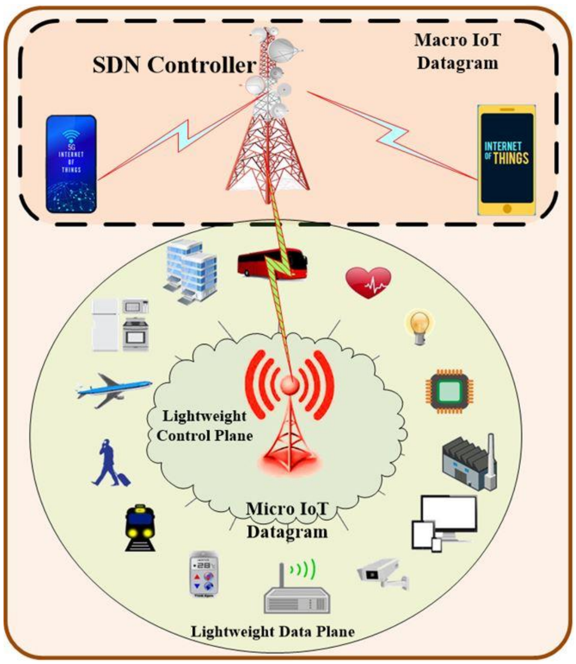


Fig. 1 System design of LSDN framework

3.1 Lightweight Control Plane

The main purpose of lightweight control plane which could be uploaded to the base station or sink is to provide flexible management and control to resolve the problem of real-time concurrent programming. Each sensor device must transmit the sensed data to the base station or sink for further processing and manipulating before sending to the IoT devices. Meanwhile, the lightweight control plane communicates with the remote IoT devices through the centralized SDN controller which have the full control functions such as: security management, traffic management, resource management, mobility management, etc. In addition, the lightweight control plane mitigates the effect of control packet overhead using the following mechanisms:

- **Optimization of Control Functions**. The lightweight control plane eliminates the redundant control packets and discontinues the congested control function, e.g., If traffic management, real-time programming management and mobility management functions are working in a congested situation, the lightweight control plane will stop the least two important function based on the application-specific requirements. Moreover, the lightweight control plane uses NFV to perform multi-tasks on each sensor device, while changing their functions in the real-time.
- **Reducing Duty Cycle of Control Plane.** The lightweight control plane will reduce the duty cycle of the LSDN controller based on the demand of the lightweight data plane. As well known that the sensor devices spent most of the time in the sleeping mode which involves the lightweight data plane to decrease the dissemination of sensed data. Consequently, the LSDN controller at the lightweight control plane also decreases the exchange of control packet overhead to practical levels.

3.2 Lightweight Data Plane

The main purpose of the lightweight data plane is to transfer the sensed data from the sensor nodes to the base station or the sink which will forward it to the IoT devices. Also, it is responsible for carrying the control requests from the base station or IoT devices to the sensor nodes. In this context, the real-time routing protocols, load distribution, and adaptive traffic shaping for wireless sensor networks are the most important functions of the lightweight data plane in order to achieve an optimal QoS measurements in terms of control overhead, latency, and delivery ratio on RT-IoT.

- **Real-time Routing Protocols.** The sensor devices demand real-time forwarding which means the sensed data in the network are delivered to the remote IoT devices according to their end-to-end deadlines (packet lifetime). The lightweight data plane will use the concept of real-time routing based on the optimal cost of the next hop toward the base station as can be shown in [23].
- **Load Distribution.** The lightweight data plane estimates the remaining power in each sensor device that contributes in dissemination of the sensed data traffic to the remote IoT devices [23, 24].
- **Adaptive Traffic Shaping.** The lightweight data plane will use a token bucket traffic shaping to reshape the variable bit rate traffic to find a trade-off between buffering delay and the constrained channel capacity on the sensor networks. For more details, the reader is advised to read the literature research works that are available in [24].

4. Implementation of LSDN and Evaluation

To demonstrate the LSDN for RT-IoT functionality, several experiments have been conducted using Mininet-IoT emulation software [25]. Mininet-IoT is an emulator that developed based on Mininet [26] to emulate SDN environment over IoT system. Moreover, the wireless OpenFlow/SDN is emulated on Miniinet-IoT to allow high fidelity experiments which replicate the real-time network environments. The OpenFlow designated the communication protocol in SDN networks which allows the SDN controller to interact with the forwarding devices such as a base station, switches and routers. In this research, IoT network was comprised of ten sensor devices (sen1 to sen10) making a mesh topology, one lightweight controller (LWC), three IoT device (IoT1 to IoT3) connected with wireless switch (WS1) and a centralized controller (controller). Each sensor device can communicate with LWC directly using 6LowPAN protocol. The header length size and the maximum transfer unit in 6LowPAN is 40 bytes and 127 bytes respectively [27, 28]. The proposed LSDN used the OpenFlow messages to implement the lightweight control plane functions and lightweight data plane functions. Moreover, LSDN used the OpenFlow protocol version 1.3 to manage the traffic and forwarding table between the controllers (LWC and the centralized controller) and WS1. Also, it is used to monitor the packet statistics at the controllers and switches. As can be shown in Fig. 2, the IoT device can communicate with the sensor devices through the connection between the controller and LWC. The network topology has been developed using a graphical tool in Mininet-IoT that called MiniEdit.

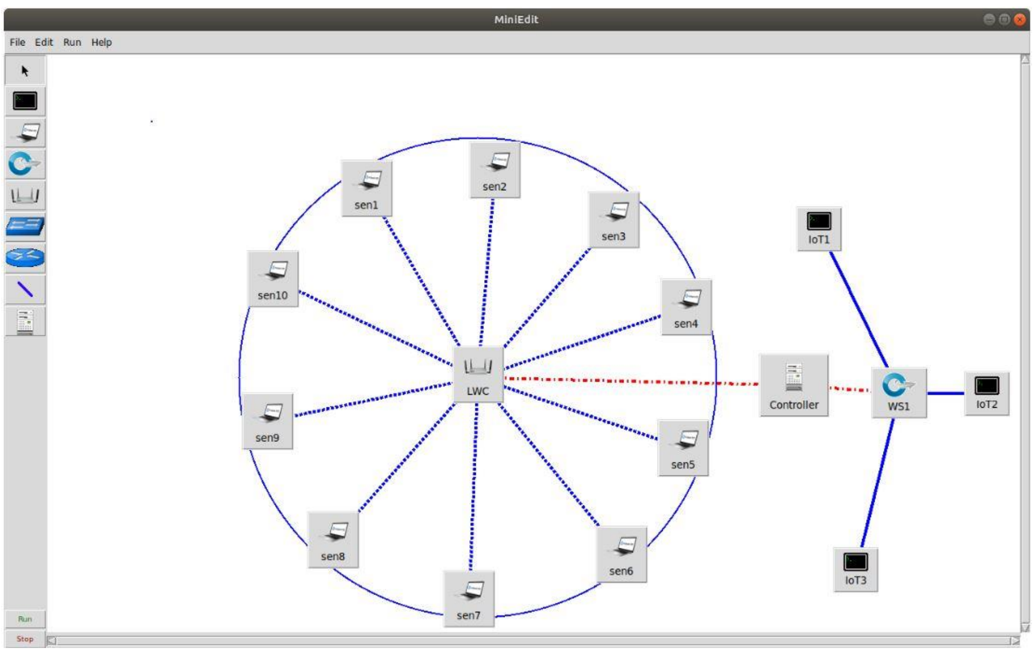


Fig. 2 IoT emulation topology

Table 1 shows the details about the emulation configuration parameters and setting. In this table, 802.15.4_hwsim and 802.11_hwsim models have been selected to implement RT-IoT environment. Also, the signal propagation mechanism is selected based on shadowing model to reflect the actual signal degradation due to interference in the propagation path. The emulation time has been set to 1000s and the traffic type is selected based on Constant bit rate (CBR).

Table 1: Emulation Configuration Parameters.

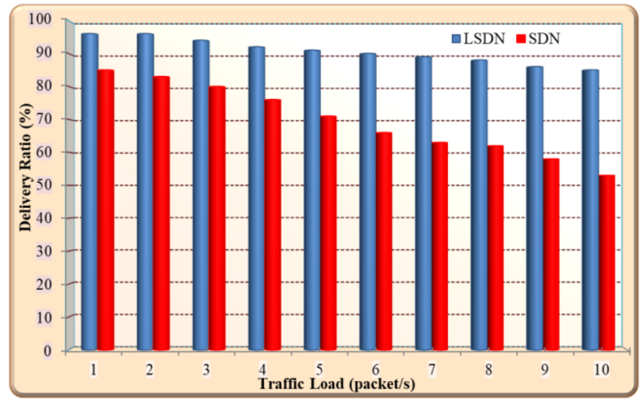
Parameter	Values
MAC and PHY	802.15.14_hmsim and 802.11_hmsim
Propagation Model	Shadowing
Path loss exponent	3.0
Shadowing deviation (dB)	3.0
Range of IoT device	150m
Radio range of BaseST1	250m
Protocols used	UDP, ICMP
Traffic Emulator	Iperf with UDP
Traffic Type	Constant bit rate (CBR)
Traffic Load	1-10 packet per second (packet/s)
Performance metrics	Latency, control overhead, and delivery ratio
Emulation duration	1000s

4.1 Performance Evaluation and Results Discussion

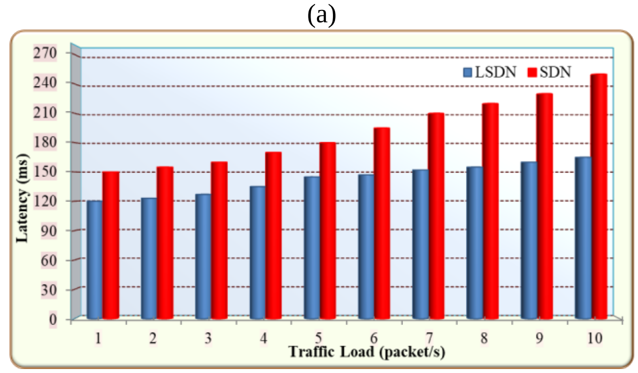
In this section, the performance of using LSDN architecture has been analyzed in terms of latency, control overhead, and delivery ratio on the RT-IoT network. The RT-IoT has been emulated using the traffic of constant bit rate and user datagram protocol (UDP) which is more suitable for real-time applications. Moreover, the comparison between the proposed LSDN and SDN algorithms has been investigated. The throughput can be defined as the amount of data transferred successfully to the destination in a given period. The delivery ratio is defined as the ratio of the number of receiving packets to the total number of sending packets. The packet latency is the time period between the transmission and the reception of the packet. Normalized control packet overhead can be defined as the number of control packets sent in the IoT network for each data packet received.

Impact of Proposed LSDN Architecture on RT-IoT Performance

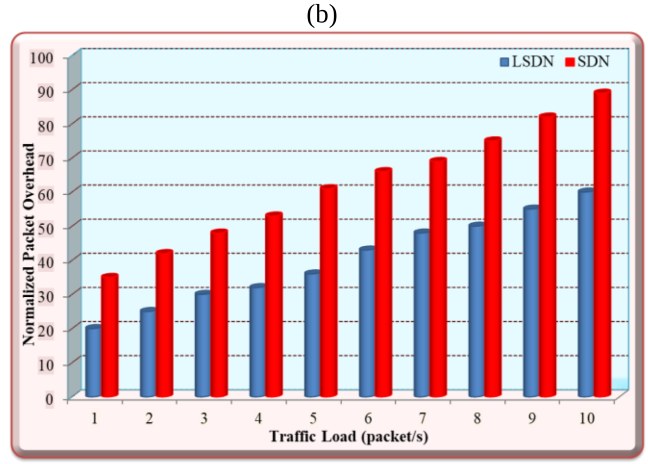
In this experiment, the effect of using LSDN architecture on RT-IoT has been evaluated using the Iperf of IPv6 standard tool to measure the performance of conducting UDP data traffic. In order to create data streams to measure the performance between IoT devices and sensor devices, the Iperf client function has been run in the sensor 1 (sen1) and the Iperf server function has been run in IoT1. Fig.3 shows the performance results of using the LSDN architecture on IoT network. In Fig.3(a), the LSDN architecture experiences on average 32.4% higher delivery ratio than the centralized SDN architecture. Moreover, Fig.3(b) shows that the LSDN architecture experiences 24.8% less time latency compared to the centralized SDN architecture. Also, Fig.3(c) illustrates that the LSDN architecture experiences 36.6% less packet overhead compared to the centralized SDN architecture. This is mainly due to the following reasons. Firstly, the LSDN architecture uses two optimization mechanisms which are optimization of control functions and reducing the duty cycle of the control plane. The first optimization mechanism eliminates the redundant control packets and discontinues the congested control function. The other optimization mechanism reduces the duty cycle of the LSDN controller based on the demand of the lightweight data plane. Secondly, the lightweight control plane in LSDN uses NFV to perform multi-tasks control on each sensor device, while changing their functions in the real-time which will increase the delivery ratio of sensor devices. Finally, the lightweight data plane uses three important functions which are real-time routing protocols, load distribution, and adaptive traffic shaping for wireless sensor networks. Overall, the performance of LSDN architecture outperforms the centralized SDN and it achieves an optimal QoS measurements in terms of control overhead, latency, and delivery ratio on RT-IoT.



(a)



(b)



(c)

Fig. 7 Impact of LSDN architecture on RT-IoT Performance (a) Delivery Ratio; (b) Latency; (c) Normalized Packet Overhead

5. Conclusion and Future Work

This paper presents the LSDN architecture which consists of lightweight control plane and data plane which implement an optimal SDN architecture and virtualization functions. The LSDN uses the OpenFlow protocol to implement the optimization of control functions and reducing the duty cycle of the control plane which preserve the resilient real-time and reduce the control overhead to practical levels. The finding in the experimental results shows that the developed LSDN outperforms the centralized SDN on RT-IoT in terms of delivery ratio, latency and packet overhead. The future work of this research will focus on developing tiny OpenFlow protocol to reduce the message change between the controller and the forwarding plane which will increase the performance of the LSDN architecture on RT-IoT networks.

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