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Design Algorithm for Improving Propagation (Delay) of Industrial Internet of Things Systems based on Superframes Structure

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ABSTRACT

Industrial Internet of Things (IIoT) is the dominant technology overall technologies in the globe, which is widely used in smart factories, to control and manage the manufacturing environment, monitor production lines, and measure the consumption of engines by the hour. IIoT systems are responsible for capturing the information from sensors, processing and provide services to the end-user and production decision perspectives. However, one of the most important issues overall IIoT system is an energy consumption by IoT devices, which can be affected by throughput and the network delay. To tackle these issues, a new algorithm is proposed, design, and implement for reducing superframes based on the IEEE 802.15.4e protocol, to guarantee and enhance the performance of the sensors for the IIoT networks. This article attempts to implement and investigate the performance parameters such as energy consumption, throughput and the packet delay time utilizing simulations. Experimental results from extensive measurements showed that the proposed algorithm gives more energy efficiency for the IIoT systems that are deployed in a smart factory. This paper carefully presents the performance analysis of smart sensors that are available for IIoT applications. The proposed algorithm can be minimized the overall energy consumption with up to 60.2 %. Simulation outcomes support the proposed algorithm and show significant improvement over state-of-the-art techniques.

Keywords :- Industrial Internet of Things, Smart Sensors, IEEE 802.15.4e, Smart Factory, COOJA, and Industry 4.0.

I. INTRODUCTION

IIoT [1] is an emerging technology to enhances the efficiency of the production through analysis of big data, which is captured by smart sensors in a factory with the IoT platforms [2]. IIoT is a technology for the interconnection of the IoT devices that built-in smart manufacturing; these devices are extremely subject to energy constraints, memory, and resources [3]. The IIoT also defines as applications of IoT in the industrial domains, which is considered the cornerstone of industry 4.0 [4]. Industry 4.0 [5], [6] refers to the next era in the evolution of the organization and control of manufacturing operations. Also, it was developed by German scientists in 2011 [5], related to implementing the smart factories to manage more efficiently of their resources and to incorporate enough flexibility to adapts it to the production needs [7].

IIoT networks have long used wired networks and wireless networks for connectivity for high safety, durability, and reliability. However, adding new sensors to the network is so very difficult and costly to install and maintain wired networks [8]. To tackle these problems, WirelessHART, ISA100.11a, and IEEE 802.15.4e [9] have emerged as alternatives to the existing wired network. IEEE 802.15.4e unlike WirelessHART [10] and ISA100.11a [11]. IEEE 802.15.4e is only medium access control (MAC) layer protocol [8]. Various issues of industrial sensors deployed in industries, one of the most issues of these sensors are energy consumption [12], [13]. Many research effort has been made aimed to address those issues [14], [15], and [16].

The motivation of this work, there are many studies discussed the energy usage of the nodes in the literature. However, these works focused on analyzing energy aspects of specific events, such as packet reception, idle or wakeup. To decrease the energy consumption of the IIoT systems based on the IEEE 802.15.4e MAC layer protocol, a new algorithm has been proposed for grouping superframes based on the IEEE 802.15.4e protocol. This algorithm was designed and implemented for reducing the superframes and minimizes the timeslot. Then decreases the sensor nodes that are connected to the sensor board. Moreover, this paper attempts to investigate the performance of the smart sensors that are available for the IIoT networks under the Cooja simulator. To validate this algorithm, different experiments have been done by using two types of industrial sensors running Contiki OS. The proposed algorithm gives energy efficient for real-time applications of the IIoT systems.

The rest of the paper is structured as follows. Related work was discussed in section 2, section 3 provides IIoT background and IIoT architecture system for smart factories, the smart factory concepts also discussed in section 4, section 5 introduces the IIoT network model, section 6 offers a design algorithm for energy conservation, performance evaluation of the proposed scheme followed by a crucial implementation for both nodes, then experiments set up are overviewed, simulation measurement and simulation results from a more thorough discussion on the benefits of a new protocol to energy modeling were provided by section 7, conclusions, and future work were discussed in section 8.

II. RELATED WORKS

The authors in [15] have been proposed an Energy-Efficient Internet of Things technique for reducing the energy consumption in a significant manner on the IoT devices. To maximize energy efficiency for IoT nodes, they are provided in [17] both centralized optimal and distributed heuristic strategies that formulated to intelligently adjust the number of wakeup events. The simulation outcomes demonstrate that such optimization is necessary to minimize the overall network energy consumption with up to 25%. Work in [18] proposed an energy-aware routing scheme to achieve minimal energy consumption of industrial wireless sensor networks (IWSNs) for the Internet of Things (IoT) systems. The proposed scheme takes transmission distances and residual energy of nodes into account for selecting a relevant cluster head. Then, the data captured by cluster heads can be forwarded through the lowest energy consumption path to the sink. Also, they have been proposed in [19] a Data-aware energy-efficient distributed clustering protocol for IoT (DAEECI) by saving cluster head (CH) selection energy using active tags of RFID.

As observed in the literature, several techniques can be applied to reducing energy consumption. However, all these mechanisms were limited to energy harvesting but did not provide detailed discussion for other parameters such as throughput and network latencies.

III. IIOT BACKGROUND

IIoT is a term now being used to describe the interconnection of industrial manufacturing and process equipment using IoT technologies [20]. IIoT networks [21] are typically used for monitoring systems and supporting control loops, as well as for movement detection systems, process control and factory automation [22]. To this end, data generated by monitoring IoT devices are collected, elaborated and send it to controllers and actuators. The routing of data from IoT sensors to actuators is an integral part of any large-scale industrial network for maintaining critical delay requirements [23].

3.1 Key Technologies of IIoT

The architecture of the IIoT systems, which can be deployed to manage the smart factories is consisting of three tangible layers, the sensing layer, network layer, and application layer [24], [25], [26]. The sensing layer is mainly used for identifying the physical world by sensing data from their around objects, which are connected to the IIoT systems. The devices connected to the sensing layer include all kinds of sensors, Radio Frequency Identification (RFID) readers, image and video cameras[27]. Objects in this layer can be enabled to talking to each other via communication technologies such as BlueTooth, WiFi, LoRaWAN, SigFox, 4G, LTE, and 5G. The main task of the sensing layer is to generate a huge amount of data, then routing these data to a static node called a gateway, to store it for processing or forward it to the cloud platforms [28].

3.2 Communication Protocols of the IIoT

IIoT network has supported various types of communications stack protocols [29], [30] such as IEEE 802.15.4e, which it is only a MAC protocol [31], [32], it has been developed for achieving high energy efficiency, and to tackle the drawbacks of the IEEE 802.15 [33]. IIoT should support new protocols and new data formats with high flexibility and scalability, whereas the IWSNs bring new opportunities for the development of the industrial network. Additionally, there are other relevant technologies such as OLE for Process Control

Unified Architecture (OPC UA), Software-defined Networks (SDNs), and Device-to-Device (D2D) communication) have been introduced for guaranteeing the QoS of the IIoT network, reliable communication, and cooperation among equipment [34]. The main application of the IIoT system is a smart factory [5], [35], [36], [1].

IV. Smart Factory

Smart factory [37] can transmit data and services of industrial through remote monitoring of the machine operations, products, temperature, noise generation of running machines, factory areas, and speed of manufacturing process in real-time. These data routed based on short-range communications technologies such as Wi-Fi, ZigBee, 6LoWPAN, and Bluetooth. Or long-range communication technologies such as that mentioned in section 3.1. Based on the digital and automated factory, the smart factory uses information technology, cloud platform, and IIoT systems to improve the management of manufacturing resources and QoS [38], [39]. When building a smart factory, production and marketing should improve, control the production process, and minimize manual intervention in routine work [40].

4.1 Smart Factory Implementation

To implement smart factories, the IIoT is employed to integrate the underlying equipment resources. Accordingly, the manufacturing system should be capable of perception, interconnection, and data integration. The data analysis and scientific decisions are used to achieve production schedules, equipment service and quality control of products in the smart factory. Furthermore, the Internet of Services (IoS) was presented to virtualize the manufacturing resources from a local database to the cloud server.

4.2 IIoT Network Architecture for Smart Factory

In the context of Industry 4.0, intelligent manufacturing attracts enormous interest from government, enterprises and academic researchers [41]. Therefore, the construction patterns of the smart factory are widely discussed. According to the architecture of smart factories [34], [42], [43], [44], [45] includes four tangible layers are physical resource layer, network layer, cloud service layer, and terminal layer.

The physical resources layer consisted of intelligent sensors, conveyor equipment, packing products, which need to have support for real-time information acquisition, and communication devices should provide high-speed transmission of heterogeneous information [34].

The network layer was used to connect layers within the smart factory. Regarding the distributed control, the connection between controller and actuator was implemented by field bus, Modbus, and EtherCAT. The connection between equipment was achieved by the combination of Ethernet and DDS, which formed a self-organized network. Also, the connection of equipment and cloud platforms was implemented by integration of Ethernet and OPC UA, which provided data interaction [44].

The cloud service layer is the massive manufacturing data gathered with smart sensors, upload it to the cloud platform through the industrial wireless network for processing. Predix is a software for cloud platforms, which provided data analytics, storage, and services to end-users [45].

The terminal layer is used to connect end-users devices such as PCs, smartphones, and tablets to the smart factory, which is deployed to support remote monitoring of operations, maintenance, and diagnosis, even remotely through the internet. Also, customers can access the order provided by the cloud in real-time using the intelligent terminal [45]. Figure 1 illustrated the IIoT network architecture for the smart factory.

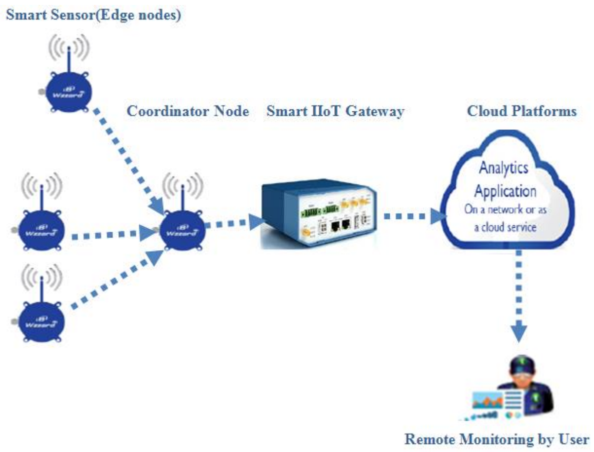

Fig. 1 IIoT Network Architecture for Smart Factory.

In the context of the smart factory, every sensor uses the channel access mechanism for transmitting data frames to the network layer. The node in the network is dedicated to the specific timeslot for successful transmission; we assume that all IIoT sensors are sending data to a sink node then forwarded it to the smart IIoT gateway, as depicted in Figure 1. After transmission/receiving through timeslots, the nodes are being in energy conservation mode.

V. IIOT NETWORK MODEL

The smart sensors in the IIoT network can be presented as illustrated in [27]. The nodes in the IIoT network are collecting information from their neighboring sensors, then reroute it to a smart gateway in the network layer of the IIoT architecture system. As that demonstrated in figures 2, where figure 2a, shows the sensor map for Zolertia Z1 mote, and figure 2 b shows the sensor map for Tmote Sky, in which there were twelve nodes; eleven of which represent as the sensor node and one of them acted as the sink node (this role also applied in different scenarios in this paper).

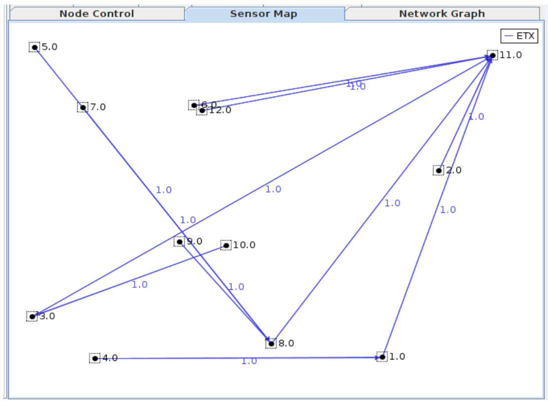

Fig. 2.a Sensor Map of Z1 Mote

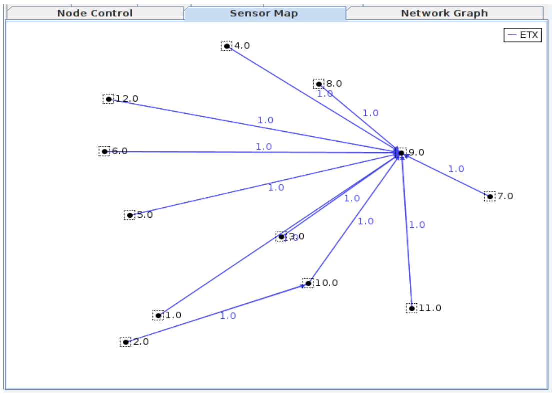

Fig. 2.b Sensor Map of Sky mote

VI. PROPOSED ALGORITHM FOR IMPROVING ENERGY CONSUMPTION

To address the energy consumption of the IIoT networks, which considered is one of the most important issues of the current IIoT nodes. This paper proposed a new algorithm based on a superframe structure for decreasing energy consumption. The proposed algorithm can enable grouping many superframes of the channel access mechanism based on the IEEE 802.15.4e MAC protocol into single or multiple groups of superframes, which minimizing the nodes in the network that gives more energy efficiency of the network. This algorithm also enhances the throughput of the nodes in the network, and then reduced the packets delay time. Moreover, it can be provided the capability of sending and receiving frames for all transmissions without losing packets. To adapt this algorithm to the specific platform requires to take into account the parameters of that platform and configuration. Based on the methodology, a new algorithm can group the superframes according to the following expressions:

$$R = k+1 \qquad (1)\text{, where } k=2.$$

$$G= (S \bmod R) + P \qquad (2)$$

where S is the number of superframes, R is constant, G is the number of group/s, P is the prime number, starting by 1 if the number of superframes is equal to eight. When the number of superframes is increased to 16, the prime number is increased to the value 3. The prime number is equal to 5 value when the number of superframes is maximized to 32. There are a different number of superframes of the IEEE 802.15.4e. every superframe has many timeslots that assign to a specific sensor. If there are no superframes available, this operation can return to zero, then, it grouping the number of superframes, the process reiterates until a common superframe is equal to zero. The detailed procedure of the proposed mechanism is given in the following algorithm.

Algorithm for grouping the superframe /s

```
Inputs: Number of superframes in the channel (S) and time
slot/s, k; k // constant value
        Require: Grouping the superframes in the channel,
        Results: Compute the superframe (G);
            If Noeverysuperframe then
                Return 0,
                Else if
        Do  // group the superframes in the network structure
            R = K+1;  // compute the constant R
                G= S mod R +P  // grouping the superframes
                    Until superframe/s = 0;
                        Return G;
                        end if
                            end if
```

When a sensor wants to send frames to the network, it sends the signal to all available timeslots of the channel, if the timeslot is available; the sensor can join the network over this timeslot.

. The following steps present how the proposed algorithm can reduce the number of superframes.

Step 1: Inters the number of superframes in the channel (S) and time slot/s, and k, where k is constant value as inputs.

Step 2: Algorithm is checking the superframes, if there is no superframe available, then return zero. Go to step 1.

Step 3: Compute the constant value of R. Where R is equal to K+1, and K has a constant value (2).

Step 4: Checking the available number of superframes, grouping the superframes in the channel access until the superframes are being zero.

Step 5: Compute the superframe, and return the overall process to the number of superframes after grouping (G).

VII. PERFORMANCE EVALUATION

This section is, performed to evaluate the results by dividing into three subsections, the first is to introduce the experimental setup, the second section discusses the experiment's measurements, and finally, practically show the actual experimental results of the simulation over Zolertia Z1 and Tmote Sky as IIoT sensors, analytically show the performance improvements of our proposed algorithm.

1.1 Experiment Setup

To evaluate the performance of these works, different experiments testbeds were conducted operate under Windows 10 Service Pack 3 operating system (64 bits), processor core i3, RAM 4 GB running over VMware 12 player Linux, Ubuntu 16.04, to perform that, 12 nodes in the first scenario were used, 32 nodes in the second scenario which are deployed in a star topology. Zolertia Z1 mote and Sky mote are especially used based on IEEE802.15.4e radio chipsets [46], CC2420 micro-controller, and IPv6. To evaluate the performance of the parameters of the node (energy consumption, delay time, and throughput), the Cooja simulator is used, run on the Contiki OS as the operating system for IIoT sensors, random deployment in the area of 100m2.

1.2 Simulation Measurements

Through these experiments, there are different measurements have been done: energy consumption, throughput, and packet delay.

1.2.1 Energy Consumption Measurement

The methodology used to measure energy consumption by the industrial devices in the network is so necessary adaptations to the Contiki OS that allowed performing the measurements. It was then continued by giving the value of the energy consumption in the transmission, reception, LPM, and CPU ON states.

Where the CPU refers to the energy computation by the node. LPM power refers to the energy used when the sensor in the idle state, RX is the listening energy required when the sensor is ready to receive the data packet from its neighbor nodes, and the TX is a transmit energy, refers to the energy required by the sensor to transmit the data packet to its neighbors, The energy consumption was measured in two scenarios, the scenario A has represented the proposed algorithm, which consisting of twelve of Z1 and Sky motes, scenario B also included in table 1, which composed of 32 of Z1 and Sky motes. In the scenario A, the average energy consumption of the values of Tx, Rx, LPM, and CPU of each sensor node including the node sink was reduced by 1.137 mW. These scenarios were conducted by consideration to observe the energy consumption by every sensor node in the network.

This paper can adopt the definition of a consumption profile as a sum of energy consumption contributions from each running peripheral. The total energy consumption by every timeslot in the Cooja simulator that can be computed according to the values illustrated in table 1.

Table 1: Shows the average Energy Consumption with IIoT networks.

Nodes/ Parametrs	**Z1**		**Sky**	
No. of Nodes	**12**	**32**	**12**	**32**
Tx Energy	0.092	0.277	0.036	0.119
Rx Energy	0.468	1.348	0.412	0.861
LPM Energy	0.163	0.160	0.153	0.151
CPU Energy	0.030	0.104	0.359	0.402
Avg. Energy Consumption	**0.752**	**1.889**	**0.959**	**1.533**

1.2.2 Throughput measurement

Throughput was measured experimentally based on two scenarios, the throughput of the IIoT system that as formed in table 2, these experiments running on two platforms are Z1 and Sky motes, under specific duration time.

Table 2: Throughput of the IIoT Network:

Motes/Parameters	No. of Nodes	Duration Time	Throughput
Z1	12	30 Minutes	143 Packets
	32	30 Minutes	62 Packets
Sky	12	30 Minutes	364 Packets
	32	30 Minutes	238 Packets

1.2.3 Network Delay Measurement

Table 3 depicts the various values for the packet delay time of the IIoT nodes in two simulation scenarios (in NanoSecond), the packet generation length is 4 bytes; operate on Z1 and Sky motes.

Table 3: Packet delay of Industrial IoT Network

Motes/Parameters	No. of Nodes	Duration Time	Packet Delay
Z1	12	30 Minutes	434 NanoSecond
	32	30 Minutes	2165 NanoSecond
Sky	12	30 Minutes	361 NanoSecond
	32	30 Minutes	802 NanoSecond

1.3 Simulation Results and Discussion

Energy consumption, throughput, and packet delay of the IIoT network were measured that depicted in figure 3, figure 4, and figure 5.

1.3.1 Energy Consumption

The energy consumption was measured by the Cooja simulator based upon four parameters are CPU power, LPM power, Listening Power, and Transmit Power. The results of the measurements of the parameters of CPU Power, the parameter of LPM Power, parameter of Listening power, and parameter of Transmit Power are provided by fig. 3 a and fig. 3b (Scenario A), and fig. 3c to fig. 3d (Scenario B), respectively. The tests based on the parameters of sensor node (Fig. 3a and fig. 3b), there is a significant difference of the values of average energy consumption between scenario A and scenario B, in which the values in the scenario A is equal to the 0.752 mW and scenario B also is equal to the 1.889 mW (Z1). In addition to the values of the average energy consumption with Sky mote in two scenarios are 0.959mW and 1.533mW that as shown in fig. 3c and fig. 3d.

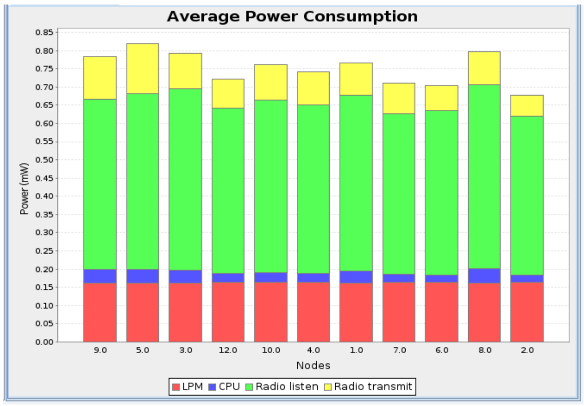

Fig.3a: Energy Consumption by Z1 in Scenario A

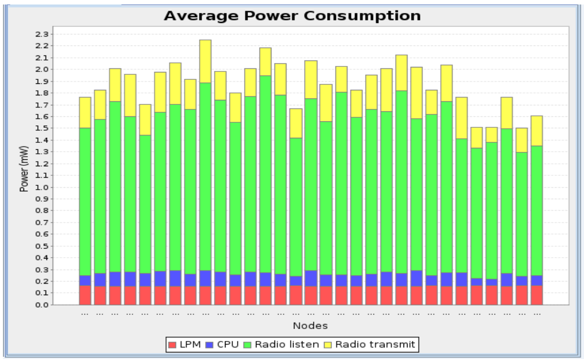

Fig.3b: Energy Consumption by Z1 in Scenario B

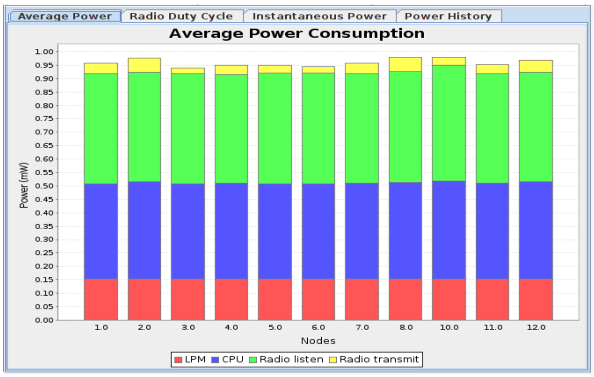

Fig. 3c: Energy Consumption by 12 nodes Sky Mote

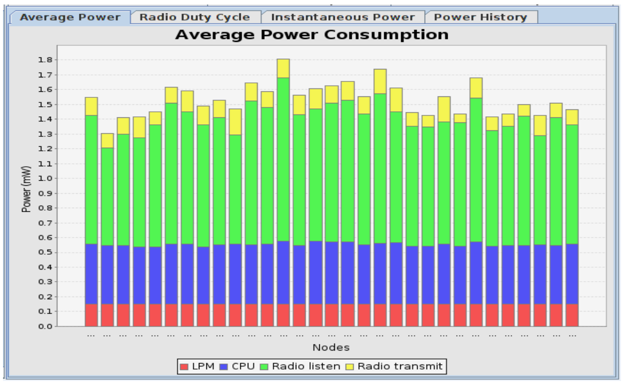

Fig. 3d: Energy Consumption of 32 nodes of Sky Mote.

1.3.2 Throughput

Measurement of throughput in the IIoT network can be presented as the following figures. In this experiment, the throughput was measured according to the scenario A and scenario B. The duration time of the simulation is kept at 30 minutes; four independent experiments were done when using two types of sensor nodes. Fig. 4a and fig. 4d are showing the variation of the throughput for different packets received by the base station with two scenarios.

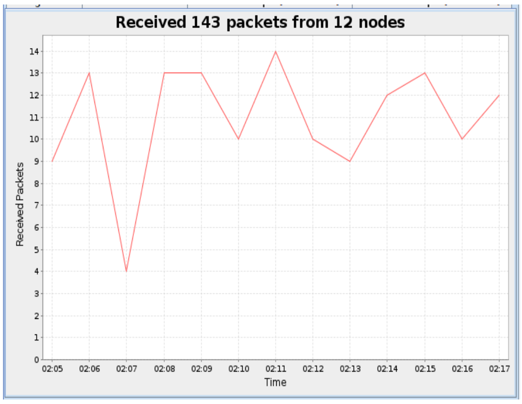

Fig. 4a: Throughput of 12 Z 1 Mote

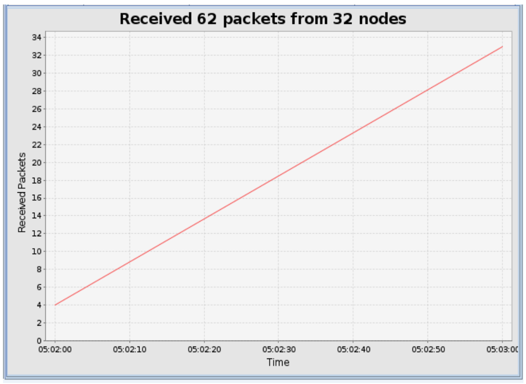

Fig. 4b: Throughput of 32 Z 1 Mote

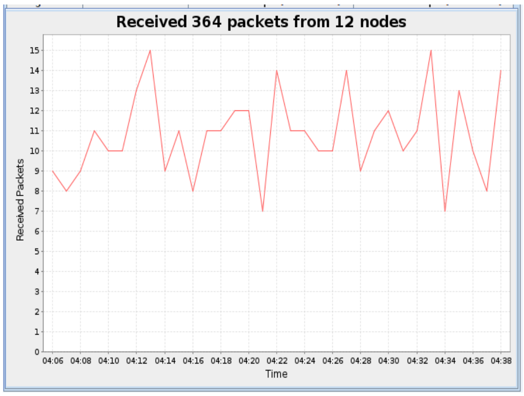

Fig. 4c: Throughput of 12 Sky Motes

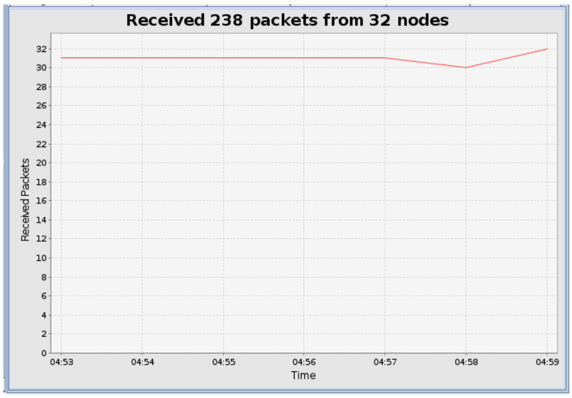

Fig. 4d: Throughput of 32 Sky Motes

1.3.3 Packet Latency Time

Network latency defined as the time was taken by the packet to reach it is destination [47]. Several factors affect latency such as a link quality, which commonly depends on the value of the signal to noise ratio, a weak link increases the number of retransmission and latency, and also hop-count is another factor that increases the network delay. The plots provided by the figures (5a to 5d) below are illustrated the delay time for transmitting packets with the different scenarios. the proposed technique has achieved an optimal packet delay time, which is equal to 434 Nanosecond, however, for all previous experiments, can observe that the delays are approaching zero seconds as it is observed in the following figures.

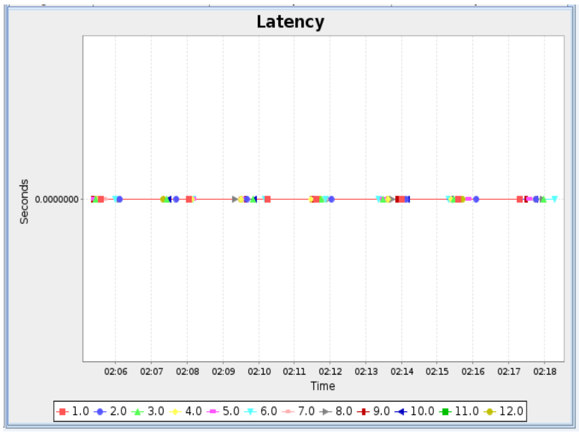

Fig. 5a: Packet Delay of 12 Z 1 Mote

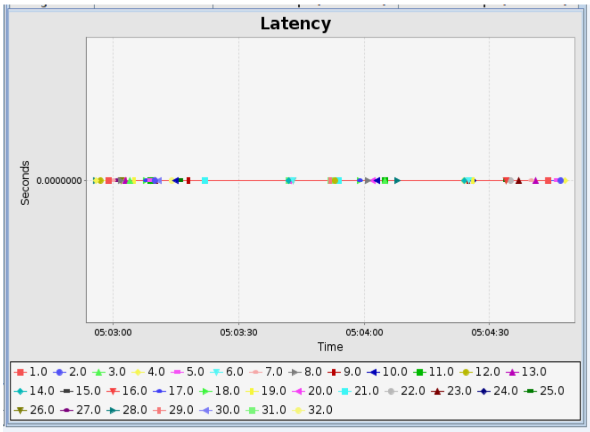

Fig. 5b: Packet Delay of 32 Z1 Mote

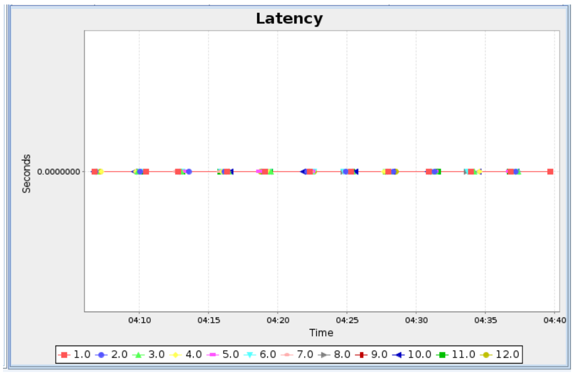

Fig. 5c: Packet Delay of 12 Sky Mote

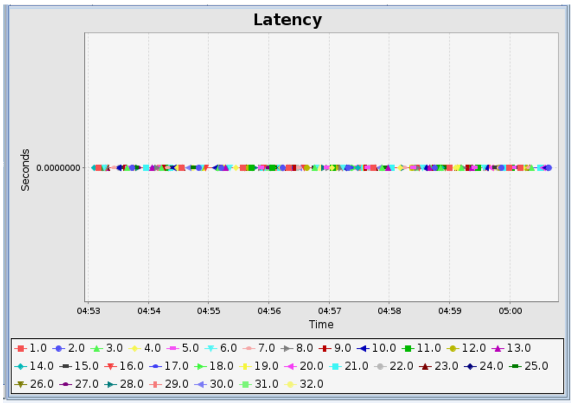

Fig. 5d: Packet Delay of 12 Sky Mote

To evaluate the proposed algorithm, several experiments were conducted based on the Cooja. After measuring the energy consumption for different testbeds in the two scenarios, Table 1 illustrated that. Different parameters such as CPU, LPM, radio transmission, and radio reception are taken into account. comparisons of the energy consumption have been done depends on scenario A with Z1 and scenario B. As presented in fig. 3a and fig. 3b illustrates that the proposed algorithm significantly reduces energy consumption in the IIoT network. Throughput also has been maximized as shown in fig. 4a and fig. 4b. In addition to the network, the delay was decreased, Table 2 illustrated the network latency.

Moreover, there have been different experiments were conducted, analyzed, and then evaluated the performance of two types of a popular sensor platform for IIoT applications.

The results of energy consumption for Sky mote are given separately in fig. 3c, due to the comparatively significant difference from Z1. From fig. 3a and fig. 3c, As observed in figure 3, the Sky mote is consumed more energy in the scenario A if compared to the Z1, for all scenarios, the CPU and radio listening are significantly larger energy consumption. On the other hand, Z1 is using less energy on the CPU state. The network measurements confirm that the Z1 achieves the best energy efficiency. AS showed in fig. 3b and fig 3d, an overall energy consumption of Z1 is much higher than that of the Sky mote. This can be explained by the high listen to the platform and active CPU energy from Sky mote, which required optimizing the behavior of its microcontroller, either in hardware or software platforms.

For all, the measurements show slightly higher energy consumption for RX scenarios; however, in this case, it is due to higher CPU utilization. On the other aspect, the CPU energy consumption of Sky mote is higher than that of Z1 in the same scenario. For all three parameters, the energy consumption minimized with the reduced number of nodes, because the number of sensors connected to the sensor board is reduced. The technique of energy model such that applied in scenario A has the highest throughput as compared with scenario B as presented in fig. 4a to fig. 4d, due to the hops count of the network which increases the packet delay.

As shown in Table 3, the proposed technique model obtained less packet delay. The sky mote is less delay time than that in the Z1 mote (scenario A). However, in scenario B, the Sky is higher delay time due to having retransmission, number of hops count. Most of the energy is spent listening, and more fine-tuning of CPU could further reduce the throughput, and decrease the network delay.

VIII. CONCLUSION AND FUTURE WORK

The critical concept of IIoT technology is used for making the use of engines and equipment for smart factories and smart manufacturing with high accuracy. Besides, the sensors can monitor the operating conditions to make more accurate predictions during preventive maintenance.

IIoT nodes have many challenges, one of the most challenges is energy consumption. To address this issue, a new algorithm has been proposed and implemented for energy conservation based on the structure of the superframe of the IEEE 802.15.4e protocol. The proposed algorithm can group the superframes of the channel access into single or multiple groups, this operation can reduce the number of sensors of the IIoT network. The proposed algorithm evaluated through different experiments based on the Cooja simulator. The proposed algorithm achieved low latency, energy consumption, and high throughput. All these metrics made the suggested stack an optimal fit for real-time applications for a smart factory.

Future Works aims to investigate in more detail the topology characteristics for those nodes, which observe an increase in their minimum energy consumption of constrained devices. The real testbed is also required in this works to test the proposed algorithm. The plan to run similar tests with the same hardware on different operating systems as OpenWSN and TinyOS will be needed, which supports the Z1 and Sky motes.

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