Design and Implementation of IoT Sensor Network Architecture with the Concept of Differential Security Level

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Abstract— **Internet of things sensor networks (ISNs) have been widely used in various fields. Especially, it is a key technology to design environmental monitoring solution in a building space. However, it is not easy to implement ISNs in a building space due to their spatial and structural complexity. Unlike a home space, a building has a variety of variables such as people, rooms, and different structures. Therefore, we considered diverse components of a building which influence 2.4GHz wireless communication and designed efficient ISN structure utilizing sensor node information to provide better network performance. We proposed the ZigBee sensor network system consisting of the environmental information sensor (EIS) and server, designed various user services, and implemented it in a test bed. To verify the efficiency of the system, we conducted two experiments about the network reliability and battery consumption of the EIS, and both results show improvements.**

Keywords- environmental monitoring; IoT sensor network; ZigBee communication; network reliability; differential security level

I. INTRODUCTION

Recently, Internet of things sensor networks (ISNs) have received much attention all over the world. Especially with the development of low power wireless communication and micro electro mechanical systems (MEMS), the ISNs can be configured on a large scale and applied in a variety of areas. ISN is a network in which sensor nodes with computing and wireless communication capabilities are deployed and configure autonomous network. This technology utilizes gathered information from the sensor nodes through wireless communication for monitoring and controlling other devices. Therefore, various services through configuring ISNs such as environmental monitoring, health care service and energy management service are being provided around us [1]. Nowadays, many studies are focusing on the developing environmental monitoring solution in buildings. ISN is key technology to design and develop environmental monitoring solution in buildings due to its ability to manage situational information. However, it is so difficult to implement the ISN in buildings due to their spatial and structural complexity.

A building has complex structural and spatial characteristics compared to a house. Furthermore, in the building, there are various types of people. Thus, there are many challenges to deploy ISNs for the environmental monitoring solution in the building. For example, too many sensors are needed in order to gather and manage the complex environmental and situational events, which inevitably increase costs. Furthermore, the sensor module is more affected by physical characteristics of the wireless link due to structural and spatial characteristics of the building.

In order to manage this complex building information, many researchers studied building information modeling (BIM). BIM [2] is the process of generating and managing building information. BIM encompasses building geometry, spatial relationships, geographic information, and quantities and properties of building components. Geographic information system (GIS) [3] is similar to BIM. GIS gathers the data related to geographic and location-based information. And then it analyzes this information in order to provide user-centric location based service (LBS). It is expected that these systems are evolving into the direction where existing models are applied to various fields such as sensor network management, architecture design, transportation services, etc.

As the number of buildings increases rapidly due to the population growth and industrial factors, there has been a growing interest in safety and energy saving in buildings. Accordingly, the importance of user-centric environmental monitoring services by collecting and analyzing environmental information in buildings is growing bigger and bigger. Therefore, like BIM and GIS, the environmental monitoring service should effectively gather environmental and situational information and provide new services by using gathered information. And this service needs to be operated with energy efficient way, safety of gathered information, and ISN structure suitable for buildings.

In this paper, we considered the design of ISN architecture with the concept of differential security level suitable for the buildings. We proposed the ZigBee-based and reliable sensor network system by utilizing information related to buildings and sensor nodes that configure the network. We utilized the ZigBee technology because of its low-cost and low-power characteristics [4]. Therefore, our system adaptively establishes the network topology, automatically discovers and recovers the faulty nodes according to building information and sensor node information. In this way, we can efficiently manage the ISN and strengthen security of the ISN. And we can also provide better services.

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II. PROBLEMS AND REQUIREMENTS OF CONFIGURING ISN IN THE BUILDING

As mentioned above, a building has complex structural and spatial characteristics compared to a house. Thus, there are many problems to configure ISNs for environmental monitoring solution in a building as follows.

- *Interference from other sources*: Radio source transmitting in the same frequency band will interfere with each other. In addition to interference from transmitting source, electromagnetic noise within the building environment can result in interference [5].
- *Multipath propagation*: This phenomenon occurs when portions of the electromagnetic wave reflect off objects and the ground, taking paths of different lengths between a sender and a receiver. This results in the blurring of the received signal at the receiver [5].
- *Faulty node detection and recovery*: Some sensor nodes may fail due to various reasons such as energy depletion, environmental interference, or malicious attacks. This often results in a non-uniform network topology and some nodes will lose contact with the rest of the network. Therefore, the sensor nodes should have a robust and reliable feature to detect faulty nodes and take appropriate measures to recovery from the failure status. This ability is essential to guarantee sensor network reliability and connectivity after one or more nodes are loss in connection with the network [6].

Configuring ISN in consideration of these problems that occur in buildings is essential. Therefore, ISN suitable for buildings needs to have the following requirements*:*

- *Adaptive network management*: Due to the complex structure and spatial characteristics of a building, adaptive network management is essential for securing network reliability. Therefore, in order to configure ISN in a building, various components of a building such as closed or open structure, the number of walls and the number of wireless LAN need to be considered. Furthermore, ISN is required to be managed by considering the status of each sensor node.
- *Energy Efficient Operation*: Extending lifetime of a sensor node in ISN is very important element. Discontinuity of data transmission due to the lack of battery reduces network reliability and can cause incorrect data transmission to users. Thus, battery condition of each node should be analyzed for configuring ISN, and data transmission path needs to be determined based on the battery conditions of surrounding nodes.

III. WIRELESS ENVIRONMENTAL IOT SENSOR NETWORK SYSTEM ARCHITECTURE

The architecture of the proposed system is shown in Figure 1. Environmental information sensor (EIS) consists of 6 type of sensors, such as temperature, humidity, motion sensor, carbon monoxide (CO), and illumination.

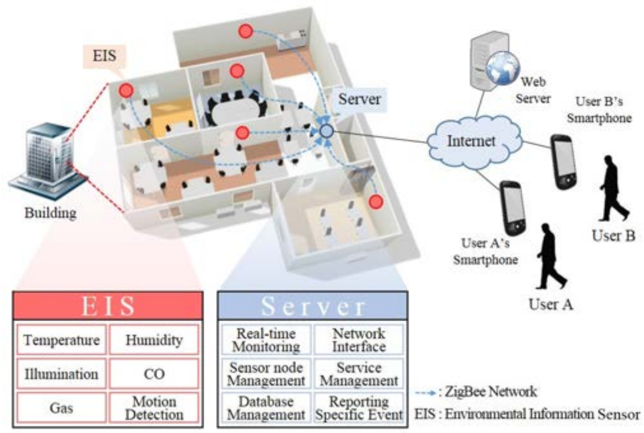

Figure 1. Overview of wireless environmental IoT sensor network system.

Moreover, it contains LEDs and a buzzer for notifying operation of current status. If every environmental sensor is included in the sensor node, it would be wasteful because some environmental sensors could not be used in some spots. Therefore, each sensor is designed to be detachable and also shut out power source in case of that some sensors are not used. Both EIS and server use ZigBee wireless communication for efficient energy use. The EIS plays a role of gathering environmental information about situations that occur in the buildings. The server analyzes and stores the information received from the EISs to provide user services. Users are able to confirm the analyzed data through smartphone application and web server.

A. *Network Structure of the Proposed System*

The whole network structure of the proposed system is optimized to consider various variables in building spaces.

1) *Network Initialization of the Proposed System*

A coordinator manages the certain number of sensor nodes or nodes in a particular space. However, in this structure of sensor networks, if a coordinator does not work, it influences the network performance which the coordinator manages. Therefore, each sensor node has the same middleware and hardware specification so that every node can play a role of the coordinator. Figure 2 shows network initialization of the proposed system. At the beginning of the network initialization, a coordinator is selected by the server, and it can be changed according to various cases. The selected coordinator gathers and stores the data from assigned nodes, and transmits to the server.

First, the server is installed, and each sensor node is distributed in a specific area. In this paper, the server uses connectivity between the sensor network and building area so 16 area codes that help to understand where it is deployed have to be selected in the nodes. By using a switch in the EIS node, users can change or choose one of the area codes, and the selected code is added to the event message of the coordinator. Therefore, the server can link the node position with a building floor plan.

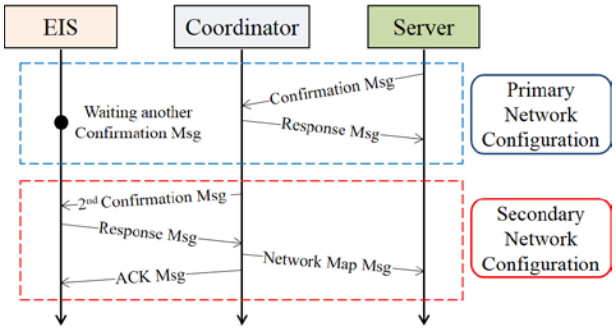

Figure 2. Network initialization of the proposed system.

For the network initialization, the server needs to select a coordinator among the nodes, and this process is as below. First, the server transmits the Confirmation Msg around itself, and the nodes receiving this Msg also send the Response Msg to the server. The selected nodes are candidates of the reserved coordinator. Secondly, these candidates transmit 2nd Confirmation Msg, and other nodes, which did not receive anything in the primary network configuration, send Response Msg to the candidates. The server repeats this process until every sensor node is found, and every node has graded level to be a coordinator. That is, the node connected during primary network configuration has the highest graded level. As described above, if multiple candidates of the reserved coordinator are selected, the server chooses one of them as a coordinator that is located in the largest area and has a wide coverage range, and other candidates gain a qualification of the reserved coordinator. Therefore, if the selected coordinator does not work, the server selects one of the candidates to maintain a certain network. Moreover, one of the EIS nodes, which are in the same section and have same area code, is selected as a sub-coordinator according to the coverage area, and this sub-coordinator collects and transmits data to the coordinator.

2) Building Elements Considered for Configuring Wireless Environmental IoT Sensor Network

For efficient wireless environmental IoT sensor network suitable for buildings, we considered several components of a building. First of all, we found factors which have effects on 2.4 GHz frequency in a building area. High frequency communications such as ZigBee and WLAN are influenced by various factors more compared with low frequency communications. Furthermore, positions where sensor nodes are placed would be important in network performance. Therefore, we analyzed researches related to ZigBee communication and chose some factors [7], and designed the proposed sensor network according to the factors. The types of evaluation factors are as follows.

- Coverage area: grasping the optimal number of nodes and service quality
- Closed or open structure: if a node is placed in a closed structure, the server least chooses the node as a coordinator
- Wall quality and the number of walls: if a node is placed near aluminum quality walls, the server least chooses the node as a coordinator
- The number of wireless LAN used in a space: related to communication interference in the same frequency band
- Degree of communication interference between floors: related to communication interference in different floors

3) Hierarchical Network Structure

In this paper, the wireless environmental IoT sensor network system is hierarchized based on the status of sensor nodes such as battery status, the number of performed events and node area. Figure 3 shows the hierarchical network composition. The green node means a coordinator, and colored nodes means hierarchical nodes according to the network initialization. For example, the blue node which is in the Alternative path is included in two common paths, and the server assigns this node in the one of the two networks, which has lower battery status. If a node placed near the Alternative path does not work, the coordinator replaces the node with one in the Alternative path. If there is no node in the Alternative path, the server reports that a node needs to be changed. And, each node has a differential security level. The coordinator has a high security level because it deals with a lot of information. Furthermore, in order to improve battery life and reliable data transmission, environmental sensors of the EIS nodes are controlled by the coordinator. If battery status of an EIS node is below 20%, the node turns off the environmental sensors according to the control command of the coordinator. By doing this, the node, which can be in a critical path, can save power and focus on data transmission instead of wasting power for sensing environmental information.

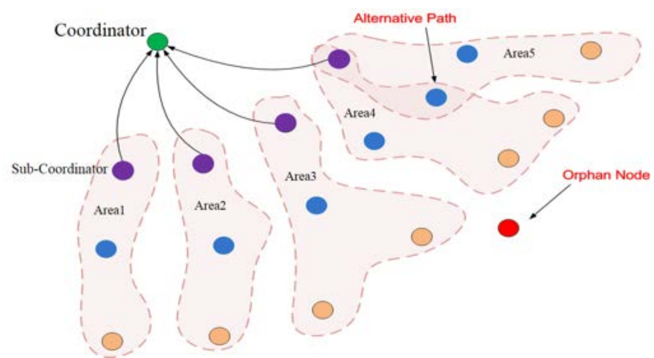

Figure 3. Area-code based hierarchical network structure.

In organizing the sensor network, the orphan problem is always an important issue. Especially, if a node is in a critical route path and has a problem, a network which is connected to the node cannot operate well. In a building space, it is not usual to place hundreds of sensor nodes at the same place so that the orphan problem is getting more important. In some cases like the red node, some nodes could not reply in the first network initialization and be included in the network, and this causes another type of the orphan problem. However, we designed this sensor network system by grouping the certain number of nodes in the same place like Figure 3, and users have to input the total number of nodes to compare the initial number of the nodes with the number of the installed ones. Thus, the server can detect how many nodes are not included in the network.

B. Data Packet Structure of the Proposed system

Figure 4 shows the data packet structure of the proposed system and management of the data packets in the server. The data packet of an EIS includes area code, data length, event code, environmental information and battery status. The coordinator creates data packets by gathering information from EISs and send them to the server. Since the coordinator does not have sufficient internal storage space and processing performance, all the data is translated into the hex codes and deleted after the data transmission. As described above, each node can select one of the 16 area codes by a switch and every area is also allocated for one of 16 area codes. After the network initialization, the server checks whether data is received or not through coordinators. That is, each coordinator checks and stores detailed network connections between a node and the coordinator. Therefore, these data are transmitted to the server, and the server figures out what events happen in each node and can analyze network statistics. Furthermore, the coordinator counts time by using internal timer so that time can be added to each event.

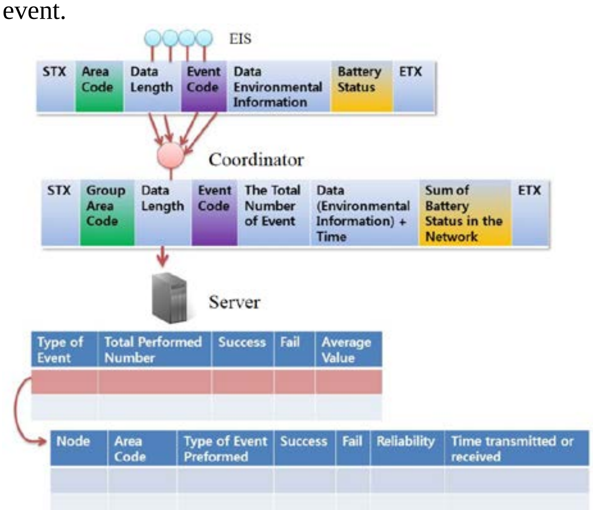

Figure 4. Data packet structure of the proposed system.

Basically, the server not only gathers environmental information but also analyzes the data packet so that every event can be inferred. For example, the EIS sends a temperature data periodically but motion-detection or gas data is transmitted when specific events are discovered. Furthermore, the coordinator also gathers a battery status of each node because a Micro Control Unit (MCU) of each node checks and sends the battery status. That is, if a specific node takes a role of a router and runs down battery, the server reports this data to replace the battery or change power source.

The server also can find communication problems in specific routes. For example, if the server knows the total number of temperature events in a node, it can also infer the ratio of data transmission success or fail. Furthermore, the server can find a period of each event based on the time counted by the coordinator. Therefore, the server arranges every event in time table so that it is easy to figure out what events happen at the same time and change a time schedule of events that have a problem.

IV. Service Provisions of the Proposed System

In this paper, we also designed various user services through the smart phone application and web service as shown in Figure 5. Especially, smart phone is widely used in these days to provide mobile services and various applications [8]. Furthermore, users do not need to be in limited places to access web sites, and it is available to confirm what they want to check in various places and let users know certain events by using push service.

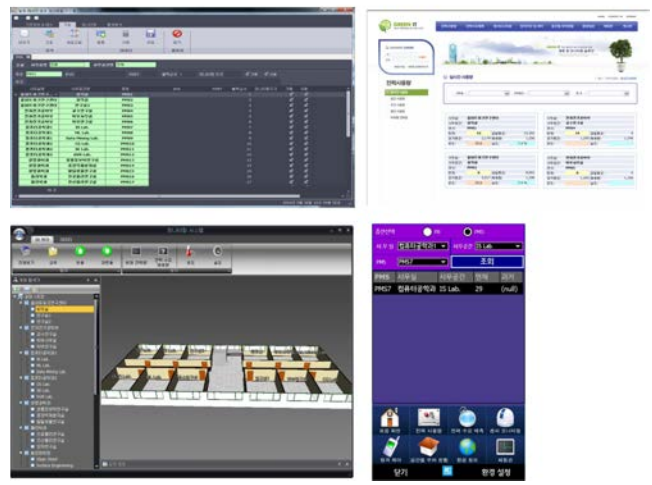

Figure 5. Management program, web site, and smartphone application

The services that the server and EIS provide are as follows.

- Provision of collected environmental information
- Sensor node management
- Reporting specific events

As we described above, total 6 environmental sensors are included in the EIS, and the system provides real time monitoring services, such as motion detection of users, and risk factors like gas and fire. According to the purpose and importance, the environmental information is divided into three parts, and each part is managed differently.

- General environmental information: Temperature, humidity, illumination
  - Indirectly used in other application
  - Periodically gathered
  - Low data grade
- Event-based environmental information: Motion detection
  - Detected when specific events happen
  - Indirectly or directly used in other application (crime prevention, people density)
  - Information period is not irregular
- High priority environmental information: CO, gas
  - Detected when specific events happen
  - Indirectly or directly used in other application

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- reported immediately to users or the server
- High data grade

The general environmental information is not used immediately but first gathered periodically to help to manage battery status in the EIS. This information is gathered by the coordinator, and sent to the server to provide real time environmental monitoring or used in additional services.

The event-based environmental information includes only the motion detection sensor, and it is gathered irregularly and used indirectly or directly according to applications. Therefore, according to services, the coordinator sends this information instantly or periodically to the server.

The high priority environmental information consists of two sensors, CO and gas. If a fire breaks out, CO is generated so that the server can detect fire by using a CO sensor. Therefore, CO and gas information have high priority because these are connected with risk factors in a building space. If some nodes are performing other events, all events are stopped, and the coordinator transmits this high priority information instantly to the server.

V. IMPLEMENTATION

First of all, figure 6 shows the hardware structure of the EIS. The EIS includes,

- MCU: controlling each part of the EIS
- Power Part: consisting of battery and power source
- Battery status part: checking the battery status
- Sensor part: including 6 types of environmental sensors and converting analog input to digital
- ZigBee part : ZigBee communication

The server is designed by using C++ based programming language, and a ZigBee module is attached to communicate with the EIS nodes.

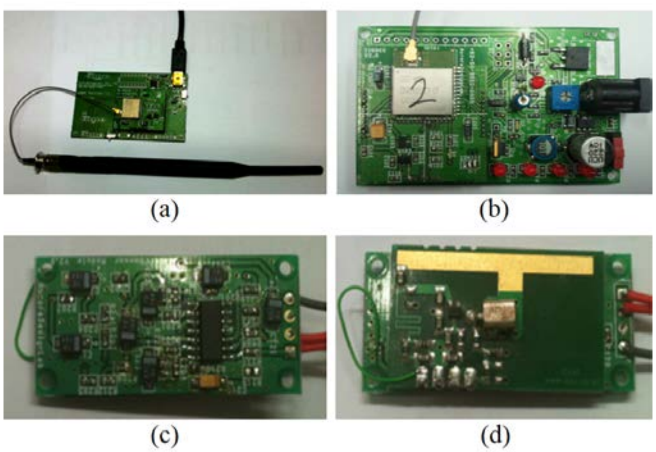

Figure 6. (a) ZigBee module with an antenna used in the server, (b) Hardware structure of an EIS, (c), and (d) Hardware structure of sensor part.

The EIS nodes and server are implemented in the test bed environment. Figure 7 shows the floor plan of the test bed. Through the network initialization, total 8 coordinators are selected in 8 areas, and the server is located in the red field. In each section, 10 EIS nodes with 6 types of environmental sensors are placed. Above this, the experimental environments are in Table 1.

TABLE I. EXPERIMENTAL ENVIRONMENT

Classification	
The Number of Used WLAN	1~3
Status of Wall Quality	Normal
Extent of Testbed	3200 m^2

The component about communication interference between floors is excluded because the test is performed in only one-story house. In summary, there are the total 8 sections and 80 EIS nodes with 6 types of environmental sensors, and we tested to monitor environmental information and control sensor nodes by using the server, web page, and smart phone application.

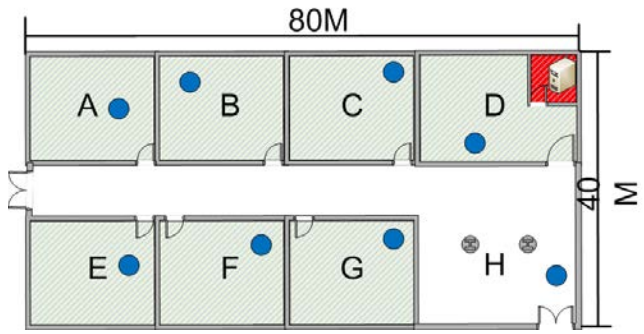

Figure 7. Testbed floor plan; blue points means coordinator, and the server is located in a red section.

VI. TEST AND RESULTS

Based on this test bed environment, we tested 2 experiments about reliability and efficiency of this system. Performed experiments are as follows:

- Network reliability of the proposed network structure
- Comparison of battery consumption

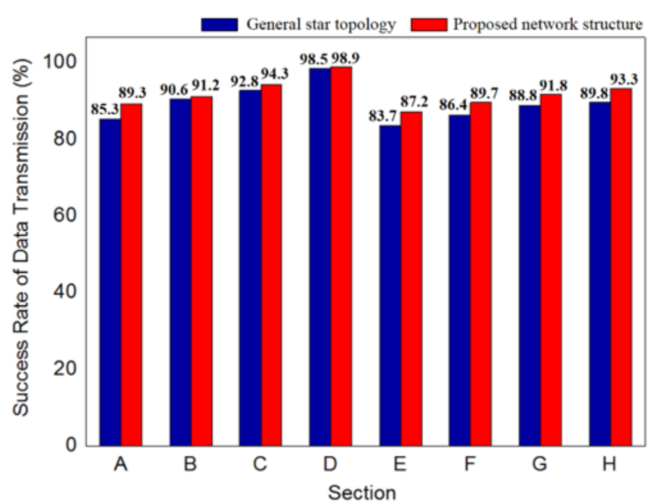

Figure 8. Comparison of data reliablility between two networks.

The first experiment describes how high the system provides network reliability. We compared a network, which uses general star topology, with the proposed network structure. Figure 8 shows the success rate of data transmission between each coordinator and the server. For this experiment, each coordinator transmitted 1000 data packets to the server, and we analyzed this result. The result shows that the highest rate is obtained the D section, and the lowest rate is obtained the E section in Table 2. This result means the number of walls and distances between the coordinator and the server influence the network performance, and the system improves it.

TABLE II. FIRST EXPERIMENTAL RESULTS ACCORDING TO DISTANCE AND THE NUMBER OF WALLS

Section	Distance	The Number of Walls	Success Rate (%)	
			General Star Topology	Proposed Network Structure
A	75M	4	85.3	89.3
B	55M	3	90.6	91.2
C	35M	2	92.8	94.3
D	15M	1	98.5	98.9
E	82M	5	83.7	87.2
F	60M	4	86.4	89.7
G	49M	3	88.8	91.8
H	35M	2	89.8	93.3

The second experiment shows how much the system improves battery life. The EIS node has a 900mAh battery, and the network operated for 1 day. To result this experiment, we compared the sum of battery amount of the two network cases described in the first experiment. Figure 9 shows the comparison of battery amount of two network cases.

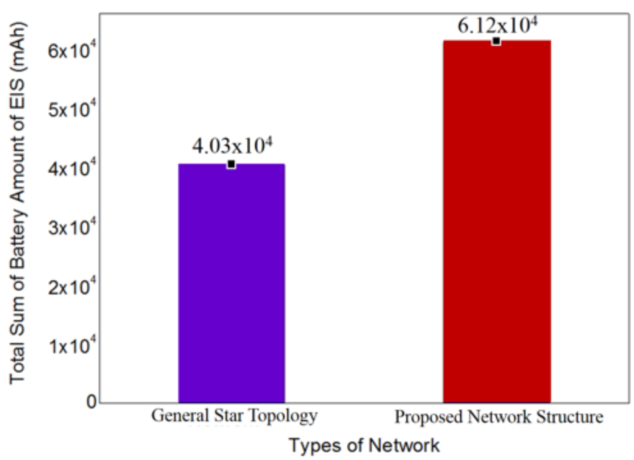

Figure 9. Comparison of battery amount.

This result shows that the proposed network structure saves about 34 % battery life. That is, the server checks service quality of each section and control power of used environmental sensors. Therefore, the proposed network can maintain the entire nodes' battery life longer.

VII. CONCLUSION

In this paper, we designed the wireless environmental IoT sensor network system by using the EIS and server in a building space. The main point is that this sensor network system considered various building elements which influence ZigBee communication and used sensor node information for providing better performance of the network. Users can confirm various environmental conditions such as temperature, humidity, illumination, CO, gas, and motion-detection through the smart phone application or web site. We implemented this sensor network system in the test bed and performed two experiments about performance of the system. The experimental results demonstrate the improved network reliability and longer battery life by using the proposed sensor network system.

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