Interconnecting ZigBee and 6LoWPAN Wireless Sensor Networks for Smart Grid Applications

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Abstract— **Although the ZigBee communication protocol is popularly adopted in wireless sensor networks (WSNs), it is rather immature compared with Internet Protocol (IP) which has been developed over the past 40 years. ZigBee networks can not directly communicate with current Internet. It always needs a gateway to collect required data from a ZigBee network and to convert the ZigBee protocol to IP. Moreover, it scales poorly on routing and network management. On the contrary, Internet Protocol, especially the new Internet Protocol version 6 (IPv6), is a more promising alternative as scalability is concerned. If a wireless sensor network is developed based on the IP protocol, it does not need an application-layer translator which is mandatory for ZigBee networks. This can greatly save developing time and improve the efficiency for end-to-end communications. Many existing IP-based services can thus be re-used to monitor WSNs status in real time. From a perspective on network management service, this paper compares the advantages and disadvantages of ZigBee and IP. Since ZigBee is only appropriate for small-scale networks and suffers from the scope expansion of a sensor network, our suggestion is that future deployment of wireless sensor network devices should be IP-based, so that they can be easily managed remotely. To allow legacy ZigBee networks to co-exist with IP networks, translators may be required during this migration phase.**

Keywords-IPv6; Internet of Things; Network Management; Smart Grid; Wireless Sensor Network; ZigBee

I. INTRODUCTION

Decades ago, only computers have the abilities to communicate over the Internet. After continuous development of modern technologies, the future trend is that any object in the real world can interact with one another to exchange messages through the Internet, so that management and communication can be easily carried on. The idea for all objects tied together is called Internet of Things (IoT). Any object including computers, mobile phones, and sensors will all have a unique IP address connecting to the Internet. In large scale IoT deployment there will be rich combination of sensors and intelligent management schemes. As a result, the research of wireless sensor networks (WSNs) [1] and related technology played a very important role in IoT.

WSN has wide applications in many fields such as smart energy, smart logistics, health care, home automation and so forth. To support these applications, a protocol IEEE 802.15.4 was proposed for wireless personal area network communication. It specifies the physical layer and data link layer, with short distance transmission, low power consumption and low cost characteristics. Based on IEEE 802.15.4, ZigBee [2] is a protocol widely used in smart grids. It deals with the upper network layer and application layer. Because ZigBee was designed for local networks in home environments, it does not directly communicate with servers on the Internet. If administrators want to remotely control ZigBee devices through the Internet, or ZigBee devices need to send collected data back to a managing server on the Internet, an additional mechanism is required.

For example, a gateway [3] can be deployed to connect a ZigBee network to the Internet. In a ZigBee network, end devices collect data and send data to the gateway, which then translates the data from ZigBee protocol format to Internet Protocol format, and vice versa. This allows ZigBee devices to communicate with servers on the Internet.

With rapid development of wireless network applications, how to efficiently manage WSN devices and monitor the status of WSNs is a very important topic. The aforementioned gateway mechanism only facilitates sending data from ZigBee networks to the Internet. On the other hand, it does not provide easy mechanisms to manage WSN devices from the Internet. This paper proposes using Session Initiation Protocol (SIP) [4], which is an application layer protocol, to manage WSNs.

II. RELATED WORK

The physical layer and data link layer of ZigBee are based on the existing IEEE 802.15.4 protocol, in order to achieve the goal of low-power and low-energy consumption. However, for the upper layer protocols (network layer and application layer), many development experiences show that ZigBee has some technical shortcomings, such as address allocation, scalability, management tools, routing mechanisms, and interoperability with the Internet.

One competitive alternative to ZigBee is 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) [5] [6]. As shown in Figure 1, at the physical layer and the data link layer, it uses the same IEEE 802.15.4 protocol as ZigBee. For the network layer, it uses Internet Protocol version 6 (IPv6). It supports 2^{128} IP addresses, so the numbers of addresses are more than sufficient. Even if there are a large number of devices deployed in a WSN, each device can also be assigned with a unique IP address. This feature makes it easy to support end-to-end communication.

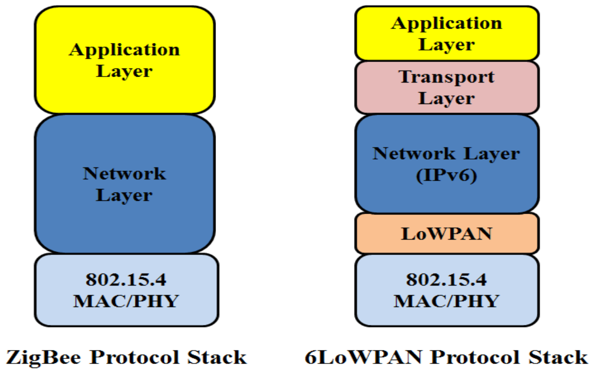

Figure 1. ZigBee / 6LoWPAN protocol stack

In the following, we compare ZigBee with IPv6:

A. Compatibility with Internet

If no extra conversion mechanism is deployed, ZigBee devices can not directly communicate with devices on the Internet. Currently there is no perfect solution for ZigBee/IP conversion. Proposed conversion mechanisms such as SOAP / REST, GRIP [7] and tunnel mechanism, will all impose extra cost, which will increases the total cost of the network. On the contrary, if WSN devices can support IP, it can directly communicate with servers on the Internet. This does not require any application-layer translation, so the cost and efficiency will be greatly improved.

B. Address allocation

. When a ZigBee node joins a network, its parent node will arbitrarily assign an unused random address to the newly added ZigBee node. From the perspective of network management, the randomly assigned ZigBee address is difficulty to control.

IPv6 has two address allocation approaches. One is the Stateful Auto-configuration mode, which utilizes DHCPv6 (Dynamic Host Configuration Protocol for IPv6) to assign addresses for specific devices. This makes it easy to manage sensors in a large deployment.

The other is the Stateless Auto-configuration mode. The device can use EUI-64 [8] method to obtain its own IPv6 address from the MAC address of its network interface card.

C. Network management

When the number of devices in a WSN gradually increases, and the deployment range gets larger, it is important to have a good tool to monitor and analyze the network. Otherwise, it is quite easy to waste lots of time and effort in trouble-shooting trivial problems.

Currently, a few software tools were developed for specific ZigBee platforms, such as ZigBee Sensor Monitor [9] developed by Texas Instruments. This tool supports ZigBee CC2530ZDK module delivered by Texas Instrument. It can also display ZigBee network topology and the temperature collected by sensors.

ZigBee Operator [10] is developed by the company Serial Port Tool; it can be used to manage WSNs built by Digi's XBee ZigBee modules. It can read the module information, set module parameters, and show the network topology. However, since ZigBee is still a new protocol, currently available management software is thus a little immature, especially when it is necessary to manage a large scale network.

In contrast, IP-based network management tool has been developed for decades. It is rather easy to find mature protocols to support network management in an IP network. For example, SNMP [11] (Simple Network Management Protocol) is an IP-based network management standard which can collect, modify and exchange network management information between network devices. With SNMP, it is easy to monitor and manage network devices. Another example is SIP (Session Initiation Protocol), which is currently a common protocol used in voice and video communications. In addition to making phone calls and starting video conferences, SIP can also display the on-line status of friends, and deliver instant text messages. Besides, it can also be applied to network management [12].

D. Routing

There are two ZigBee network routing protocols: Tree routing and AODV (Ad hoc On-Demand Distance Vector Routing) [13]. Tree routing mechanism is suitable for stationary devices or less mobile devices. The disadvantage is that the chosen path may not be optimal. Moreover, after a single node fails in the path, the data will not be sent to the destination. Therefore, it is less used. A more popular routing protocol AODV has the route repair mechanism, so it is suitable for mobile devices. When the routing path between two nodes fails, its route repair mechanism uses broadcasting to discover a new path. Therefore, it is likely to cause network congestion as the number of sensor nodes increases [14].

The proposed routing protocol for IPv6 wireless network is RPL (IPv6 Routing Protocol for Low power and Lossy Networks) [15]. According to [16], RPL is designed specifically for WSNs. When the distance is farther, and packets will be relayed through many nodes, AODV has larger packet loss rate and longer delay ratio, compared with RPL. For packet delivery success rate, using RPL routing protocol can achieve a ratio close to 99.9%, but AODV can only successfully send 37.3% packets to the destination. For average packet delay, the delay of AODV is also 11 times longer than the one of RPL.

According to the characteristics described above, it is clear that using ZigBee in a small area may not be a problem, but when the range of a WSN is expanded and the transmission distance gets farther, RPL is more suitable than AODV in WSN.

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E. Extensibility

Over the past decades, there are a lot of protocols developed based on the IP protocol. For example: SNMP, SIP, HTTP, NTP, and so on. If various manufacturers have to re-design all these features for ZigBee platforms, there will be compatibility problems among them. On the contrary, if a WSN deploys devices with IP support, we can easily select appropriate upper layer application protocols and incorporate them into a new platform.

Through these comparisons, we believe that WSN using IPv6 will be a viable and better option than ZigBee. Future trends will manage WSN devices through IPv6. The following sections describe the framework developed in our smart grid project [17] and the implementation of its communication system architecture.

III. SYSTEM ARCHITECTURE

Smart grid is a new generation of electric power network which uses advanced metering infrastructure (AMI)[18] to monitor and control power plants, substations, and power transmission lines. It can clearly oversee the status of the entire electrical power network, and adjust electric power scheduling for devices to increase energy utilization efficiency. Currently our research focuses on how to efficiently transmit electricity-related data (such as the power consumption of users) back to the back-end server, so that the server can make decisions to adjust the power network accordingly. For example, if a portion of the power network is suffering severe power loss, this implies there must be something wrong with those electrical devices or transmission lines. Some actions must be taken quickly to remedy the problem.

A. ZigBee-based smart grid system architecture

ZigBee is a popularly adopted communication technology in smart grid systems. There are three types of devices in a ZigBee network: a coordinator, routers, and end devices. A *coordinator* is responsible for establishing, maintaining, and controlling a ZigBee network. It allocates network addresses to other nodes which join the network successively. *Routers*, which are sometimes called relay nodes, take care of data transmission and have capability to extend the scope of a ZigBee network. *End devices* collect data and transmit then tor routers or coordinators.

Figure 2 shows typical ZigBee-based smart grid system architecture and the protocol stacks for each node.

B. 6LoWPAN-based smart grid system architecture

According to the comparison of ZigBee with IPv6 in Section II, we believe that the future trend is IP-based WSN, which allows engineers to manage devices over the Internet easily. Although many current smart grid systems are built using the ZigBee system architecture shown in Figure 2, in the future better system architecture like Figure 3 will make it easier for large-scale network management.

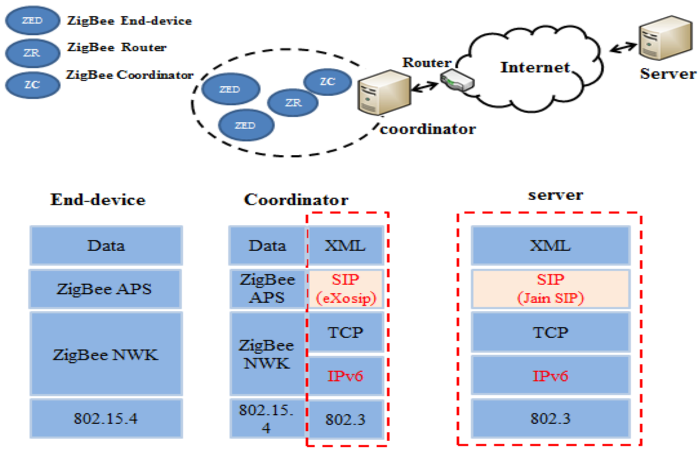

Figure 2. ZigBee-based smart grid system architecture

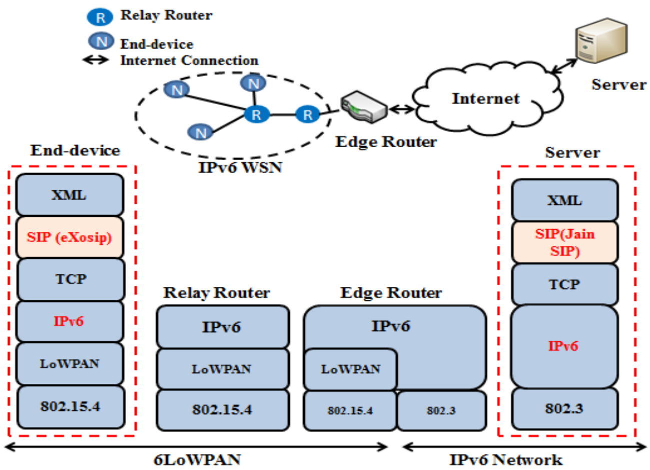

Figure 3. 6LoWPAN-based smart grid system architecture

Without amending the back-end server, this architecture can be compatible with the older system shown in Figure 2. In Figure 3, all sensor nodes are required to support 6LoWPAN. Upon IPv6, the SIP application layer protocol is used to control end devices. The gateway (edge router in Figure 3) between wired and wireless networks only needs to handle IP packets forwarding, while upper application layers do no need to do any protocol conversion. This significantly reduces the loading of this intermediate gateway.

With this improvement, both types of smart grid systems, no matter they are based on 6LoWPAN or ZigBee, can be managed with the same SIP protocol. Furthermore, 6LoWPAN devices have public IPv6 addresses, so servers can directly communicate with the end devices by their addresses, and easily discover the whole WSN topology. When any WSN device breaks down, the server can quickly notice that. Servers can collect data directly from end devices, without waiting the coordinator to handle the requests. In contrast, a ZigBee network is managed by a coordinator which must perform application-layer protocol translations and send data to servers. Therefore, this imposes heavy burdens on coordinators, and will easily cause data loss and transmission latency. Moreover, suppose a coordinator failed, the ZigBee network would be completely unable to communication with the Internet. This single point of failure (SPOF) problem is a fatal issue to ZigBee networks [19].

The advantage of the 6LoWPAN-based architecture is that, if there are legacy ZigBee-based smart grid systems, they can be easily managed by SIP. Newly deployed smart grid systems can choose 6LoWPAN protocol to enhance the communication performance, but the same SIP protocol can be used to manage devices on these two different types of networks. This greatly simplifies the management framework. Figure 4 shows a hybrid smart grid network. These two different types of networks can both be managed by SIP.

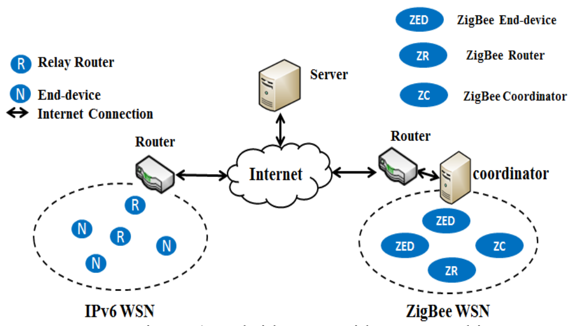

Figure 4. Hybrid smart grid system architecture

C. *SIP network management module and sysytem architecture*

One main research issue of smart grid is how to quickly transmit data and commands between servers and WSN devices. Over the past decades, SNMP and SIP are commonly used management protocols in IP networks. In addition to that, in order to integrate heterogeneous systems, International Engineering Consortium proposed IEC 61968 Common Information Model(CIM) [20], and W3C also proposed Efficient XML Interchange (EXI), which suggests using text-based XML as the standard format to transport smart grids data. Since SIP is also a text-based protocol, we chose SIP as the upper application-layer protocol to provide three functions in managing the smart grid system: subscription, notification, and instant message delivery. The software architecture of servers and end devices are shown in Figure 5.

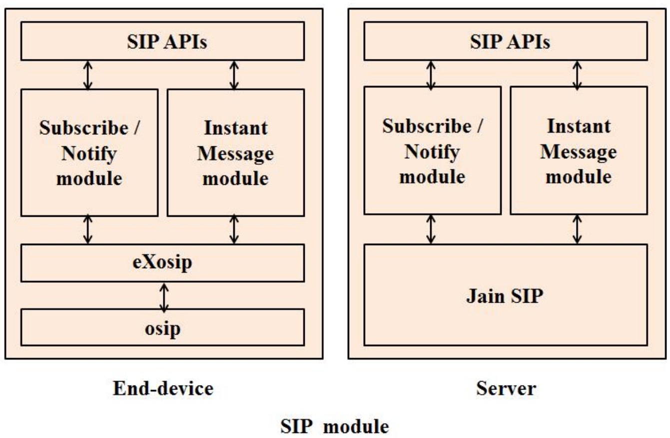

Figure 5. SIP module software architecture

1) osip 、eXosip 、Jain-SIP library:

a) End device: Using GNU osip library to implement SIP related application programs. eXosip is an extended osip library which encapsulates osip library and make it easier to develop SIP application programs.

b) Server: For administrative convenience, we use Java Server Pages (JSP) to develop a web-based management system. To integrate web programs and communication programs, Jain-SIP library is chosen to develop Java programs which communicate between servers and end devices.

2) Subscribe/Notify module: Providing subscription and notification capabilities. As shown in Figure 6, servers can subscribe data which it wants to monitor from end devices. These data may include electricity consumption, temperature of meter, and so on. The servers may also specify a condition (for example, when electricity consumption exceeds a certain threshold), and ask end devices to automatically notify servers when that happens.

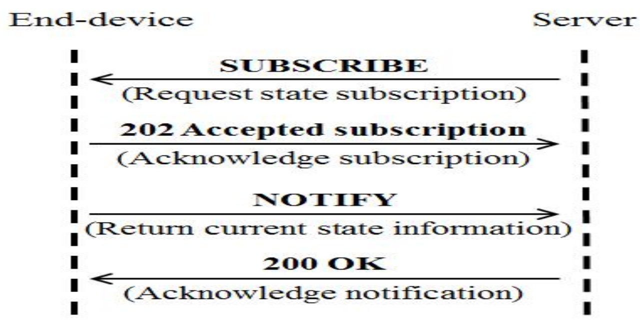

Figure 6. Signal flow of SUBSCRIBE/NOTIFY messages

3) Instant Message module: Sending messages to control end devices. In Figure 7, the server can send commands to devices, such as shutting down or starting devices, changing devices settings, and so on.

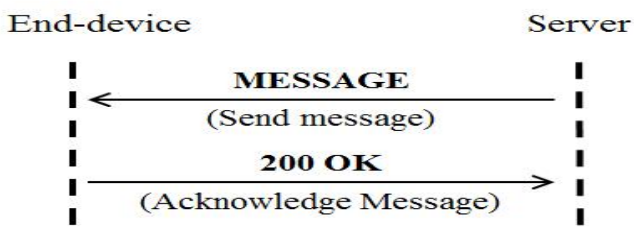

Figure 7. Signal flow of instant messages

4) SIP Application programming interface (SIP API) : Allowing the application program to call Subscribe/Notify module or Instant Message module.

D. Implementation of a SIP network management sysytem

Let us take controlling smart sockets (outlets) as an example. The signaling flow of SUBSCRIBE/NOTIFY messages in Figure 6 will be divided into the following four steps.

a) The server sends a SUBSCRIBE request to an end device, requesting power information from a smart socket. Figure 8 shows an example of the SUBSCRIBE message. The content of the Event header indicates that the server wants to get reports about the smart socket.

```
IP Header
TCP Header
Request-Line: SUBSCRIBE sip:Device@[2001:db8::2]:5000 SIP/2.0
CSeq: 1 SUBSCRIBE
From: "Server" <sip:Server@[2001:db8::1]:5070>;tag=12345
To: "Device" sip:Device@[2001:db8::2]:5000
Contact: "Server" sip:Server@[2001:db8::1]:5070;transport=tcp
Accept: application/pidf+xml
Event: socket
Content-Length: 0
                                        SIP Header
```

Figure 8. SUBSCRIBE message

b) When a device receives a SUBSCRIBE request from the server, it replies SIP response code 202, which represents that it accepts the SUBSCRIBE request.Figure 9 shows an example of the SIP response message to the SUBSCRIBE request.

```
IP Header
TCP Header
Status-Line: SIP/2.0 202 Accepted subscription
CSeq: 1 SUBSCRIBE
From: "Server" <sip:Server@[2001:db8::1]:5070>;tag=12345
To: "Device" <sip:Device@[2001:db8::2]:5000>;tag=1601623740
Contact: sip:Device@[2001:db8::2]:5000
Event: socket
Content-Length: 0
                                        SIP Header
```

Figure 9. SIP response to the SUBSCRIBE request

c) When some power usage information like voltage(volt), current(ampere), or power(watt) gets higher than the threshold specified in the subscription conditions, the smart socket will trigger a notification to the server. Figure 10 shows a SIP notification request containing text data in XML format. The sid tag value represents the socket identification number, while data tag values represent volt, ampere, and watt, respectively.

d) When the server receives those data which it subscribed, it will reply a 200 OK message to devices for acknowledgment. If devices do not receive the 200 OK message from the server, they will re-transmit, according to the rules of SIP communication protocol. Figure 11 shows a SIP response to the NOTIFY message.

Now after the server receives data from end devices, if it wants to send commands to smart sockets, it will send commands by instant messages depicted in Figure 7 .

```
IP Header
TCP Header
Request-Line: NOTIFY sip:Server@[2001:db8::1]:5070;transport=tcp
CSeq: 2 NOTIFY
From: "Device" <sip:Device@[2001:db8::2]:5000>;tag=1601623740
To: "Server" <sip:Server@[2001:db8::1]:5070>;tag=12345
Contact: sip:Device@[2001:db8::2]:5000
Content-Type: application/pidf+xml
Content-Length: 231
                                        SIP Header
<?xml version="1.0" encoding="UTF-8"?>
<ami>
<rpsocket>
  <device>1</device>
  <socket>
   <sid>0x0001</sid>
   <data>109,1.2,56</data>
  </socket>
 </rpsocket>
</ami>
                                        SIP Body
```

Figure 10. NOTIFY message

```
IP Header
TCP Header
Status-Line: SIP/2.0 200 OK             SIP Header
CSeq: 2 NOTIFY
From: "Device"
<sip:Device@[2001:db8::2]:5000>;tag=1601623740
To: "Server" <sip:Server@[2001:db8::1]:5070>;tag=12345
Contact: "Server"
<sip:Server@[2001:db8::1]:5070;transport=tcp;id=sub>
Content-Length: 0
```

Figure 11. SIP response to a NOTIFY message

e) Suppose the server sends a command to turn on a smart socket power. The type tag represents command types, while value 2 is for switch control command. The status tag represents device status, while value 1 specifies to turn it on. Figure 12 shows an example of the command.

f) When a device receives the command from the server, it replies a 200 OK response and turns on its smart socket power. Figure 13 shows the response to the SIP command.

Please note that all the aforementioned examples of SIP messages are simplified so that only fields relevant to this paper are shown.

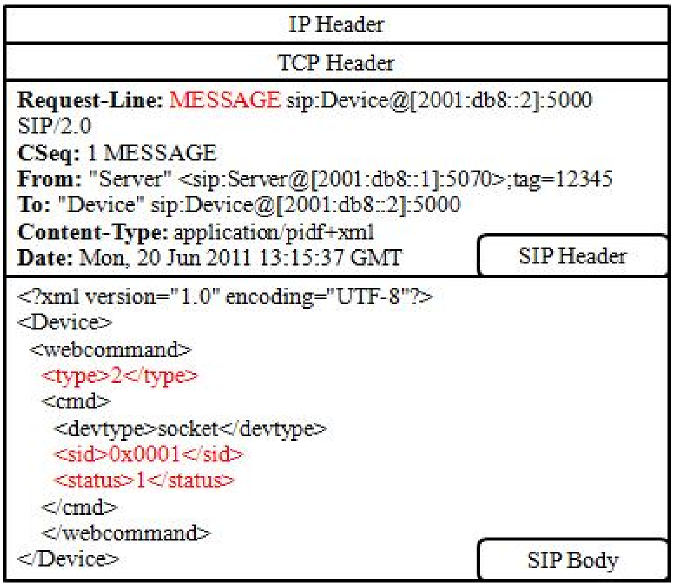

Figure 12. SIP command in an instant message

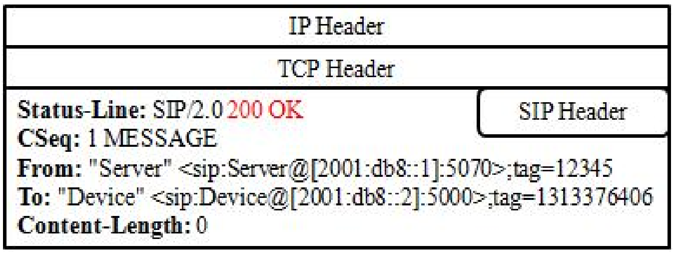

Figure 13. Response to a SIP command

IV. CONCLUSION AND FUTURE WORK

A smart grid system requires a two-way communication network. A power plant can transmit electric power and messages to clients. On the other hand, clients can also send information to the power plant. Through two-way communications, we can adjust the power utilization in a more efficient way. This paper compared the communication protocols between power plants and clients, and suggested how network management applications can be carried on these protocols.

ZigBee-based smart grids cannot directly communicate with the Internet. It needs additional conversion mechanisms and there is no standard network management tools in ZigBee. Compared with ZigBee, IPv6 is more suitable than ZigBee to support smart grids, whether in the routing protocol, address allocation, scalability and network management. Therefore, this paper illustrated how IPv6 can be introduced to smart grid systems, and used examples to illustrate how SIP network management services can be adapted to a 6LoWPAN-based smart grid system. With this architecture, servers can easily manage sensors in the smart grid through the Internet.

There are two major network management protocols: SNMP and SIP. In this paper, we use the SIP protocol as examples to manage devices in a smart grid system, where SIP is shown as a glue to manage heterogeneous smart grid systems based on ZigBee and 6LoWPAN. Some interesting future work would include comparing SNMP and SIP, especially analyzing the transmission performance and the system resources consumption on a device. This would allow administrators to manage a smart grid with the best management protocol.

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