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Effective Metering Data Aggregation for Smart Grid Communication Infrastructure

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***Abstract*—Advanced metering infrastructure (AMI) systems have been developed to perform automated meter reading, reduce peak loads, and use energy efficiently. Two issues exist regarding this system. The first issue is the communication and handling of consumer data concerning electricity collected by power utilities. The second issue is the management of communication network resources and scheduling of metering to avoid congestions and communication errors. The major device for addressing these two issues is a concentrator that acts as a data relay point in an AMI system. The concentrator collects data from the meter and sends them through communication networks. This study discusses the aggregation methods of the concentrator with respect to the aforementioned two issues and proposes a method to reduce network utilization and message size on a server. The method concatenates small smart metering messages sent from relevant meters. The traditional method aggregates and concatenates messages without numerical processing. The proposed method processes messages at the concentrator to reduce total message size and calculation cost on the server. Moreover, the method that combines the traditional and proposed methods was evaluated by considering a real-world case. These methods were simulated by using an ns-3 network simulator to evaluate their efficiency in sending messages concerning the volume of power consumption to the server. The results of the simulations show that the proposed methods reduce message size by as much as 98.5% in some cases and, by means of the concentrator, shorten the communication time between meters and the server. The proposed method can help to reduce loads on networks and servers.**

Keywords*—*Smart meter; AMI system; Concentrator; Data Aggregation

I. Introduction

The smart meter is a new electric power meter that possesses both communication and storage functions. Conventional power meters cumulate total energy usage and meter readers must look-see meters at monthly intervals. A smart meter captures and transmits energy use to the server of the power utility every half hour or more frequently in advanced metering infrastructure (AMI) systems [1]. AMI technologies enable smart meters to communicate with both power utilities and consumer appliances. These communication devices provide useful services such as demand response, dynamic pricing, and system monitoring. Consumers can shift the period of peak load to a low load time by means of demand response and dynamic pricing. This sometimes reduces total energy usage. Suppliers can provide a stabilization service of the grid by real-time monitoring of smart meters and power utilities. Thus, a smart meter produces many benefits to power utilities, consumers, and society in general [2].

A smart meter possesses certain problems with respect to data aggregation and data handling. Smart meters send a message of a few bytes every 15 to 60 minutes [3] [4]. In Japan, power utilities are currently planning to convert all conventional power meters, including those in households, to smart meters and install AMI systems. Twenty-seven million meters exist in the region controlled by Tokyo Electric Power Co. (TEPCO) [5]. Therefore, enormous accesses to the server of the meter data management system (MDMS) are expected to occur in a short period. However, this enormous accesses generate difficulties for conventional servers and networks [6] [7]. Moreover, communication of the AMI system requires the use of communication carrier networks such as those of telecommunication, cellular phone, and Internet providers [8]. Therefore, AMI data traffic must not block network throughput nor disturb any other network service. Reducing total message size is critical to eliminating communication fees.

This study proposes an efficient method of smart meter data aggregation to reduce the amount of data and communication cost. It also seeks to reduce server computation costs. A concentrator is positioned between smart meters and servers. It aggregates messages from smart meters and sends these messages to the server. Moreover, this study proposes a platform of AMI system simulator using ns-3 that is network simulator [9] [10] and evaluates the effectiveness of the proposed data aggregation method. The evaluation reveals that the amount and size of data on the server as well as the required time are reduced.

II. Related Works

One approach to reducing data volume is to concatenate multiple messages into a large packet. It reduces protocol overhead because packet headers are integrated and no signal gaps exist between messages. This approach can reduce the required network capacity and frequency of access to the server. However, a meter may not necessarily generate data messages frequently. Meters often require much time to aggregate sufficient data in order to reduce overheads considerably. Moreover, this process of aggregation may result in missed application deadlines. Therefore, the concentrator concatenates messages from each meter in order to meet deadlines [11].

The concentrator collects data from many smart meters and forwards them to upstream communication nodes. Data concentrators can play a crucial role in reducing required network capacity. Specifically, they can reduce protocol overhead for message concatenation algorithms that are applied to a data collection tree. Concentrators currently on the market lack the ability to reduce the volume of data and real-time aggregation capabilities. The current concentrators provide both simple integration of messages and wide area network (WAN) communications to follow the PRIME standard [12]. They also offer utilities the freedom to choose meters from various vendors as well as independence from proprietary solutions provided by a single source.

When the concentrator receives different types of messages from meters using random arrival and deadline processes, it waits and concatenates messages from meters. It then sends the processed messages to the server as one packet to meet the deadline of each message. The problems of smart metering message concatenation (SMMC) are to minimize the number of individual packets sent to the server and to meet their deadlines. In addition, SMMC is used to reduce the size of aggregated packets generated by the concentrator to below the limit size, such as the maximum transmission unit (MTU).

Babak Karimi proposed a solution to the SMMC problems: a heuristic algorithm based on earliest deadline first (EDF) scheduling. A concatenated packet is created to meet a specific threshold of a deadline of messages from meters at a concentrator. Moreover, this method adds other messages so that the packet size is as large as possible. For instance, the EDF-KN algorithm is used to choose messages from a common pool of deadlines. In addition, best-effort message selection is conducted by employing the Knapsack algorithm. The heuristic algorithms were shown to reduce overall data volume by 10 to 25% for each concentrator. This method eliminates protocol overhead without compression of the original data generated by the meters [11].

For Ad-Hoc sensor networks, Smuel Madden proposed a tiny aggregation (TAG) [13]. TAG is based on a declarative query interface and provides an aggregation service for ad-hoc networks. TAG uses an SQL-Like declarative language to express an aggregation operation over streaming sensor data and identifies the key properties of aggregation functions efficiently processed inside the network. TAG computes over the data, discards irrelevant data and combines relevant readings into more compact message. Thus, the approach reduces the bandwidth consumption. The approach of TAG is similar to the proposed method. However, it limits the operation by the subset of SQL style command, and was not integrated with ns-3, which is well-known practical network simulator of wireless network.

The structure of a smart meter network is similar to that of wireless sensor networks. A smart meter and a concentrator correspond to an end device and router of a sensor network, respectively. In a wireless sensor network, two methods are used to aggregate messages. The first is the combining method, which aggregates and combines all messages without modifying any data, then sends them to the upstream node as one large message, as shown in Fig. 1. The concentrator removes all individual headers and includes only a single header for the large aggregated message. The server, acting as a sink for all messages, can correct all meter data. The second is the manipulating method, which reveals the calculation results of messages such as average, maximum, minimum, and summation values. Thus, the manipulating message considerably reduces the total size of messages. However, the completeness of the all messages is lost because they are compressed by the calcutation. [14] [15].

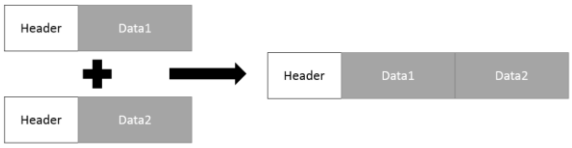

Fig. 1 Aggregation messages of the combining method

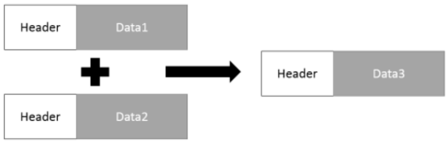

Fig. 2 Aggregation messages of the manipulating method

III. System Description

This section describes the proposed AMI network system. Fig. 3 shows the structure of the system with a concentrator.

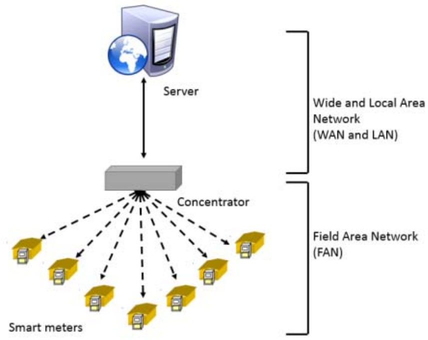

Fig. 3 Outline drawing of the AMI system

(1) WAN and local area networks (LAN): all proposed AMI systems connect to a WAN and in many cases to a LAN to send corrected data to a remote server or cloud. The internet backbone network is a part of a WAN. A high-speed mobile telephone network or passive optical network is used as a LAN. These broadband networks are effective in shortening the propagation delay of message transactions.

(2) Field area network (FAN): FAN is a network used by smart meters and concentrators. Nearly 100 smart meters can be connected to a single concentrator. The concentrator plans the message transaction schedules between the concentrator and smart meters to avoid collision and congestion. A wireless communication network is used as a FAN at the final mile to reduce the cost of laying cable.

(3) Concentrator: the concentrator plans the messaging schedule or routing for sending data related to electric power consumption to the server before a given deadline. Some existing concentrators concatenate messages by using the combining method and send the aggregated messages to a server. The concentrator retransmits the delayed message when it may

not be received at the concentrator or may be lost in the network. The concentrator can aggregate data effectively by addressing the SMMC problems, and the proposed method involves message manipulation at a concentrator. Existing concentrators that use the combining method do not possess a manipulation function, and all messages are processed on the server. Although the combining method can reduce the total message size, it cannot reduce the server processing load.

In the AMI system, the most important and frequent communication are the message transactions of automated meter reading (AMR). The data are gathered in an intermittent cycle and this cycle lasts from one second to 30 minutes. The messages are used to determine the dynamic price and stabilize the power supply in a given area. In some cases, the power utilities do not require the entire messages from all AMR devices, but rather the summation or average of all power utilities in the area. The proposed manipulating method allows messages to be aggregated from all meters and applies simple processes to the messages such as summation, average, filters, and condition warnings. The total message size of the method can be smaller than that of the existing combining method. Fig. 4 provides a flow chart of the manipulation process of this method.

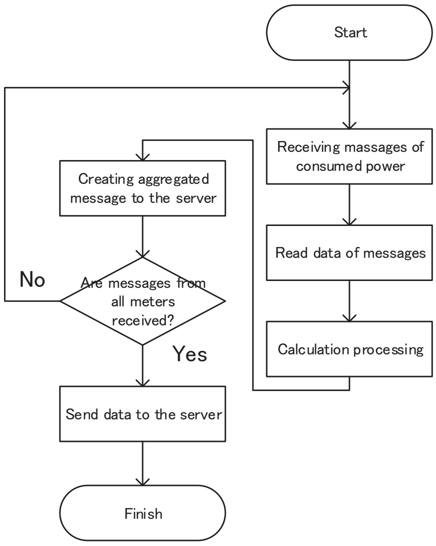

Fig. 4 Flow chart of the manipulating method

Aggregators mediate the business of negawatt, which is an amount of virtually generated power derived from saving electric power consumption. Aggregators also regulate power consumption from appliances of customers to meet target reductions. This control requires unprocessed raw data from all meters installed in customer households. By contrast, calculating the dynamic electricity price requires only the current total power consumption. In this case, the proposed manipulating method is sufficient to calculate the summation of all power consumption. The proposed concentrator can use both methods. It can aggregate messages effectively to accept different payment systems or services by using a single concentrator. The prototype concentrator is designed as a function of a Service-oriented Router (SoR) in our research laboratory [16]. The special middleware of SoR is called NEGI and the processing delay of the concentrator can be measured by using NEGI. In the following simulation, the delayed processing by means of NEGI is several milliseconds and much faster than the time of the aggregation interval and other delays.

IV. SIMULATION MODEL

A. Overview

In this study, we constructed a network simulator based ns-3 to simulate an area service. The simulator varies the set locations of nodes, number of smart meters, configuration communication network of WAN/FAN, routing protocol of FAN, aggregation interval, and method of aggregation on the concentrator. The simulator measures overall traffic volume in a network and the required time for aggregation of messages. In this simulation, smart meters send messages of electric power consumption for AMR that is the most important application and achieve additional applications in the systems by using different message correction method.

B. Smart Meter

Smart meters are used to record the amount of power consumption. The meters send messages upstream in response to metering request messages. Moreover, they exchange routing information to establish a communication path when exchanging messages with nearby meters. A smart meter stores data related to power consumption for a few days in case of transmission failures of data transfer and transfer requests from a server. In the event of a transmission failure, the smart meter retransmits messages when it receives retransmission requests from the upstream node such as another end device or concentrator.

C. Network

In the simulation, the optical line is used as the WAN whose MTU size is 8183 byte [11], and the Wi-Fi is used as the FAN. Smart meters send messages about electric power consumption of each households to the concentrator. As a routing algorithm, smart meters and the concentrator exchange routing information based on the optimized link state routing (OLSR) to avoid congestion. OLSR is a routing protocol that effectively uses network bandwidth even if few routers exist in a network or communication is congested [17]. The concentrator and smart meters send messages about both nearby nodes and communication situations in the FAN to establish a communication path before sending the message to AMR. As a transport layer protocol, the simulator uses transmission control protocol/Internet protocol (TCP/IP), which has a header of 40–60 bytes. This header is omitted in the combining method.

D. Concentrator

The concentrator manages the communication between the concentrator and smart meters. It uses three aggregation methods in this simulation.

- The first is the combining method, which is also the existing method. It is used to compare to the proposed aggregation method.
- The second is the manipulating method, which compresses a message size by calculating for all data from the meters. The manipulating method works effectively with certain services such as the dynamic pricing and visualization of total power consumption.

- The third is the grouping method, which merges the manipulating and combining methods. This grouping method works effectively when consumers under the same umbrella of a concentrator join different payment systems or services. If these systems and services are diversified in the data collection, using both methods for each system or service is more effective than using only one.

Thus, the concentrator must alternate methods according to the specification of required providing services and their different collection intervals. A payment system may employ the combining method to obtain precise information about all household power consumption. An energy supplier may use information concerning the control of electric appliances to reduce and thus save power consumption. Another energy supplier may require preprocessed data to reduce network cost in providing a dynamic pricing service, which analyzes the total amount of power consumption. Power grid stabilization requires a quick response to irregular power levels. Much time is required if a power company demands that control circuit breakers in the grid stabilize the grid after gathering and calculating all measured data. In this case, the manipulating method helps to reduce the total gathering and calculating costs. Optimizing total control performance can be more effectively accomplished by using partially manipulating and combining in the lower and higher parts of the hierarchical tree structure in an AMI system, respectively. The manipulating information includes local information, and the combining message has information about all of the smart meters. The power company can obtain the status of each local area effectively.

To address these varied requirements and provide versatilities, a concentrator must support both methods. In addition, the smart meter is not required to switch the destination in order to send the measured data to different servers dedicated to each service. Even in a case in which a customer changes to another power company, the concentrator provides the optimized data correction method independently. After the aggregation, the proposed concentrator generates the aggregated message separately and sends it to different servers.

The designed transmission protocol is as follows. The concentrator receives metering requests from servers. It then distributes these metering requests to smart meters according to a predefined schedule. After the smart meters measure amount of power consumption, the concentrator receives messages about the consumption from the meters. This process is repeated until the concentrator gathers the data of all relevant smart meters. If the concentrator does not receive a message from a meter within a certain time, the request is terminated. The concentrator then sends a request to the next scheduled meter. Fig. 5 presents a sequence diagram of the grouping method. This diagram shows the sequence of events after the concentrator receives a request from a server. TABLE 1 shows the aggregation method signed by each meter in Fig. 5. First, the concentrator aggregates messages from smart meters #1 and #3. The concentrator then manipulates the measured values. Second, it combines the data of these two meters with those of meter #2 and send this combined data to another server.

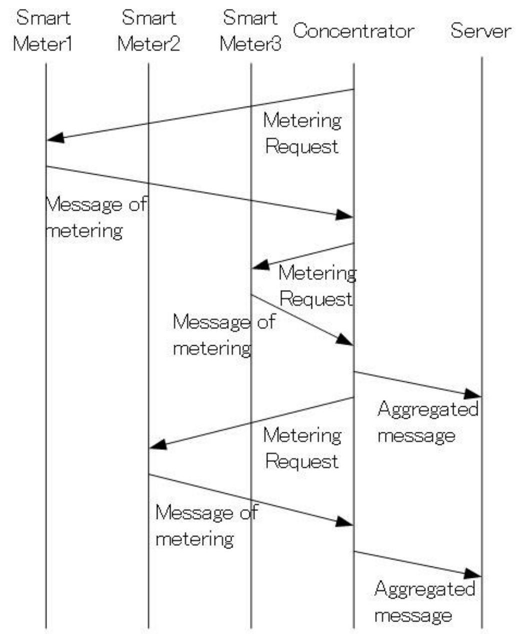

Fig. 5 the sequence diagram of the grouping method when meters send a message

TABLE 1 meters use methods

Smart meter No.	method
1	The manipulating method
2	The combining method
3	The manipulating method

E. Simulation Design

A simulation and evaluation were conducted to confirm the effectiveness of the proposed methods. We assume that the concentrator and smart meter are allocated in a block area of a residential town as shown in Fig. 6.

Fig. 6 the location of smart meters and a concentrator

The red markers indicate the positions of smart meters. A concentrator is placed at the blue marker. One hundred smart meters are placed in the area. The concentrator sets the barycenter of smart meters to equalize the distance between the concentrator and meters.

Messages send from meters to the concentrator include information related to instant or integrated power consumption. This message size is assumed to be 150 bytes at all times. For a header of the message, TCP/IP protocol is assumed and uses 50 bytes. The smart meters, concentrator, and server, that is, all nodes, have unique IP addresses. Moreover, an ID number is assigned to each smart meter. Nodes discriminate destination and source of messages by using IP addresses. Messages of routing information based on OLSR are sent every 20 minutes to the meters and concentrator. Simulation conditions and parameters are given in TABLE 2. We simulated network models using the three aggregation methods. In the simulation of the grouping method, the percentage of the mixing ratio of the combining and manipulating methods was changed per 10% for confirming its flexibility and effectiveness.

TABLE 2 simulation models

The number of servers	1
The number of concentrators	1
The number of smart meters	100
The number of hops	2-hops
The area	50m×80m
The size of meter sending message	150 byte
The interval of metering	30 min
The interval of updating route	20 min
The simulation time	2 hours
The communication protocol	TCP/IP

V. EVALUATION

This section describes the results of the simulation. The concentrator collected messages from all smart meters and the server received messages from the concentrator. Evaluations were performed regarding the reduction of data size and required time, as described in the subsections that follow.

A. Reduction of data size

This section examines the evaluation results of the data size reduction experiment. We compared the size of the received data on the server according to the performance of the three proposed methods as well as the non-aggregation method in a conventional network system. These results are shown in Fig. 7. In the grouping method, thirty meters used the combining method and seventy meters employed the manipulating method.

The combining method required sending data having the largest size. The message size when the manipulating and the non-aggregation methods were used was 150 bytes and is equal to the size of a smart meter message. With the non-aggregation method, messages from all meters were centered on the server. To store all data in a database, the operation cost of the server is high. This feature may cause serious congestion on a server when it is used in a WAN. In this situation, the proposed methods manage congestion because the methods can reduce the frequency of access to allow the existing server to accept. To validate this feature with the combining method, the total message size received by the server is 10,050 bytes, and it is smaller than that of the non-aggregation method by 33%. Although this method can reduce the total message size, it cannot reduce the processing cost of the server. However, the concentrators can process the aggregation in parallel and may reduce the total processing latency. This feature may contribute to the support of real-time applications. Moreover, the aggregation process of the concentrator has locality. This means that the aggregated data are effective for the target local area, and thus supports local applications. The central server should not provide a local service regarding data localization and efficient data transaction.

The manipulating method reduced the amount of receiving data by 98.5% compared to the combining method. Because messages were partially processed at the concentrator, the server could reduce its load. This method avoids the peak time of data communication. It proves effectivity when using a communication network for a WAN to prevent interrupting another network communication. In our simulation, the method sent the smallest packet to a server. Its message size was not the maximum packet size. Thus, when the concentrator sent a message about AMR, other messages were simultaneously concatenated in order to send a message having the maximum allowable size.

The size of data with the grouping method is greater than that with the manipulating method and smaller than that with the combining method. When 70% of all messages are aggregated by using the combining method, data size is compressed to 28%. When 10% are aggregated, it becomes 88%. The grouping method can reduce not only data size but also the computing load of the server.

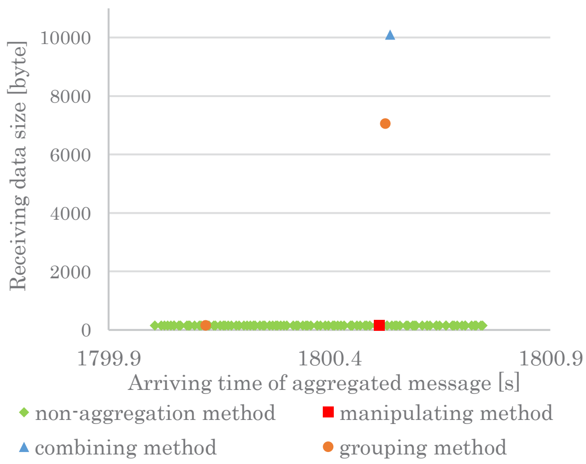

Fig. 7 Result of receiving data volume on server

B. Required time

Fig. 8 shows the required time. The bar indicating 0% means that all messages are processed by using the manipulating method. The bar indicating 100% means that all messages are processed by using the combining method. The communication time between meters and the concentrator was constant because all meters sent messages of the same size. The required time of the manipulating method was shorter than that of any other method.

As the percentage of the ratio of using the combining method became larger, the communication time between the concentrator and the server became longer. However, the required time of 100% in the usage rate the combining method was less than that of 90%. When the mixing percentage was 90%, the concentrator sent two packets as the combined message because the total size of the combined messages was 9,050 byte and bigger than the maximum transmission unit of the system. Thus, it sent three packets to the server: two packets for the combined message and one packet for the manipulated message. When the percentage was 100%, it sent only two packets by using the combining method. Based on this result, an optimization method can be proposed. Specifically, if the time of the grouping method is longer than that of another method, and another tree structure is located at the near target tree structure, a few smart meters may send messages to other neighbor concentrators in the tree structure in order to change the percent ratio, thus shortening the total required time.

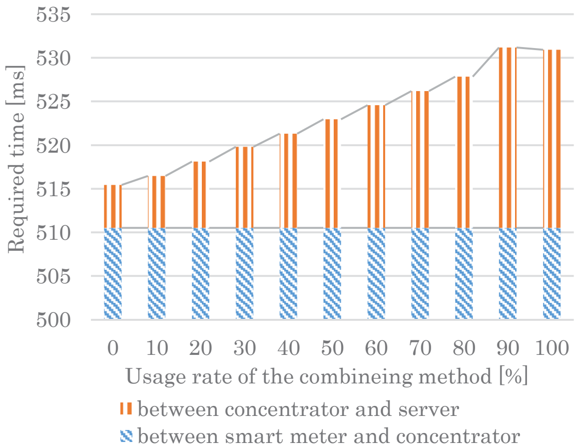

Fig. 8 Result of requited time of sending data from meters to server

VI. CONCLUSION

This study proposes the platform of simulation based on ns-3 and methods of data aggregation for an AMI system to reduce network utilization and message size on a server. The system consists of smart meters, MDMS servers, and concentrators. We propose two aggregation methods for processing the power consumption data of smart meters at both the servers and concentrator to make sure of effectivity of the simulator. Results of the network simulation show that the manipulating method reduced the total size of received messages on the server by 98.5% as compared to the performance of the traditional combining method. The grouping method allows message size to be reduced by as much as 88%. These proposed methods shorten the occupancy time at both WANs and LANs as well as at the center server.

VII. FUTURE WORK

An AMI system collects not only the messages related to electricity but also those of gas and water. It also collects data related to the temperature near the meter to reduce further loads of networks and servers. The AMI system may provide several local services. Therefore, it is necessary to extend the proposed methods and the simulator to process other messages and services.

ACKNOWLEDGMENTS

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