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Machine-to-Machine Communications for Home Energy Management System in Smart Grid

Dusit Niyato, Lu Xiao, and Ping Wang

School of Computer Engineering, Nanyang Technological University, Singapore.

Abstract

Machine-to-machine (M2M) communications have emerged as a cutting edge technology for next-generation communications, and are undergoing rapid development and inspiring numerous applications. This article presents an investigation of the application of M2M communication in smart grid. First, an overview of M2M communications is given. The enabling technologies and open research issues of of M2M communications are also discussed. Then, we address the network design issue of M2M communications for home energy management system (HEMS) in smart grid. The network architecture for HEMS to collect status and power consumption demand from home appliances is introduced. Then, the optimal HEMS traffic concentration is presented and formulated as the optimal cluster formation. Dynamic programming algorithm is applied to obtain the optimal solution. The numerical results show that the proposed optimal traffic concentration can minimize the cost of HEMS.

I. Introduction

Based on the observation that there are a lot more machines, defined as things with mechanical, electrical or electric properties, than population around the world and the potential added value along with their interconnectivity, machine-to-machine (M2M) communications, allowing interconnectivity of machines, has attracted a large amount of attentions over the years. The idea of M2M communications is to enable M2M components interconnected, networked, and controllable remotely, with low-cost, scalable, and reliable technologies. M2M communications can be used in many applications (e.g., public safety, energy management, and transportation) with objectives to improve efficiency and reduce cost.

In this article, we first present an overview of M2M communications. The motivation, network architecture, the adopted communication technologies, and its applications in smart grid are presented. In addition, we address the network design issue of M2M communications for home energy management

P. Wang is the corresponding author (Email: wangping@ntu.edu.sg).

system (HEMS) in smart grid. Smart grid emerges to be the next generation electrical power grid with the capability of adaptive and optimal power generation, distribution, and consumption. HEMS is part of smart grid in consumption side to collect data from home appliances using smart meter. This data will be used for optimizing the power supply and distribution. We introduce the M2M-based network architecture for HEMS. To minimize the cost, the optimal traffic concentration is considered in which the optimal cluster formation problem is formulated and solved using dynamic programming algorithm. The numerical results show that the proposed scheme can minimize the cost of traffic concentration in HEMS.

The rest of this article is organized as follows. Section II presents an overview of M2M communications. Section III introduces the M2M communications for HEMS. The network architecture and traffic concentration are also discussed. Finally, Section IV concludes the article.

II. Overview of Machine-to-Machine (M2M) Communications

The embryonic form of M2M communications traces back to the industrial supervisory control and data acquisition (SCADA) system [1] in the 1980s. In recent years, the topic of M2M communications has attracted much attention from industry and research community, mainly driven by the following factors:

- The emergence of wireless communication systems (e.g., GSM/GPRS, WiMAX, and WCDMA) into Internet has become a premise for the advance of M2M communications. The network infrastructures of these communication systems are already in place which can be adopted in M2M communications.
- Advanced software component enables devices to operate intelligently and autonomously. As a result, a number of devices can communicate and perform a variety of functions to achieve the objective of the system. One example is the software defined radio (SDR) which can improve the flexibility of wireless communications.
- Sensors that can be used to collect information for M2M system are being widely used and increasingly adopted. The decreasing cost and increasing capability of sensors and their convenience in deployment make widespread adoption practical.

Different form human-to-human communications which mainly involve voice call, messaging, and web browsing, the objective of M2M communications is to increase the level of system automation in which the devices and systems can exchange and share data. Therefore, the protocol and data format are the major issues in M2M communications to ensure the seamless data and control flows. Recently, a lot of efforts have been put into the standardization. For example, European Telecommunications Standards Institute (ETSI) has launched M2M Technical Committee with the purpose to develop an end-to-end architecture for M2M communications. Also, to accelerate the adoption of wireless interconnectivity of different M2M components, mobile operators around the world have been active in constructing platforms to integrate M2M services with infrastructure networks, and launching M2M projects, e.g., GSM Association's Embedded Mobile Initiative.

A. M2M Network Architecture

An M2M network standardized by ETSI is composed of five key elements: 1) M2M component, usually embedded in a smart electrical device, to reply requests or transmit data, 2) M2M gateway that enables connectivity between M2M component and communication network, 3) M2M server that works as a middleware layer to pass data through various application services, 4) M2M area network that provides connectivity between M2M components and M2M gateways, and 5) M2M communication network which provides connection between M2M gateway and M2M server. These five elements constitute the three domains of M2M system specified by ETSI, i.e., M2M component working in device domain, M2M area network and gateway in network domain, and M2M server and communication network in application domain.

B. Wireless M2M Communications and Its Applications

The advances of wireless technologies which enable mobility and eliminate the need of cable installation for M2M components, have pushed the development of wireless M2M communications. Since different M2M components could be varied in types, sizes, and locate in remote areas with limited accessibility, wireless access is more cost-effective and flexible for deployment. With wireless communications technologies, M2M communications are transforming from traditional wired Ethernet towards wireless environments.

1) Enabling Wireless Technologies for M2M Communications: Advanced wireless communication technologies are the key enablers for M2M communications. To realize a unified architecture of M2M communications, M2M networks are required to bridge seamlessly with various communication systems by supporting multiple communication technologies, i.e, mobile broadband communications, e.g., WiMAX and LTE, and local area networking, e.g., WiFi.

In home networks, ubiquitous smart electronic devices other than traditional telephone and computer, embedded with wireless communication technologies, are outfitting. The communications among the smart electronic devices are generally featured by low data rate, low mobility, and low power consumption. Short-range communication technologies like Bluetooth, Ultra Wide Band (UWB) and Infrared Data Association

(IrDA) can be employed for connection between smart electronic devices (i.e., M2M component) and M2M gateway in home environment.

Ad hoc network provides the connectivities among multiple decentralized nodes without a preexisting infrastructure, which is the case for most of the M2M components in the real world. Fast and low-cost inter-connection of dispersive M2M components can be achieved by ad hoc networking. For M2M components in an ad hoc environment, medium-range communication technologies like IEEE 802.15.4 (i.e., ZigBee) and IEEE 802.11 (i.e., WiFi) can be adopted to cover the transmission range.

Cellular network is presently one of the most widely deployed wireless networks around the world, which offers an great advantage to develop M2M communications. It provides radio coverage over a wide geographic area which enables a large number of distributed remote M2M components (e.g., sensors) to communicate with each other via base stations. Also, since cellular network supports mobility, more flexible M2M applications (e.g., intelligent transportation system) can be accommodated.

2) Applications of M2M Communications in Smart Grid: Smart grid is one of the most driving forces for M2M communications. It is a new paradigm of designing and operating the electrical power system with the objective to improve efficiency, enhance service quality, and save cost in the power generation, distribution, and consumption. Information and communication technologies (ICT) are adopted in smart grid to achieve these objectives.

The communication architecture of the future smart grid systems is yet to be defined. As a result, lots of challenges and opportunities in smart grid are posed. A series of challenges in interoperability, scalable internetworking, self-organizing and security have been identified and discussed in [2].

Due to the scarcity of radio spectrum in wireless communication, [3] advocates the concept of using white space in smart grid system. As a result, an architecture of cognitive radio based M2M communications for smart grid is proposed to realize power efficiency of electricity distribution as well as spectrum efficiency.

Smart grid applications based on current power grid system could be problematic since the century-old powerline systems were not designed to meet modern requirements, while reconstruction of powerline system for smart grid applications is costly and tardy. To address this issue, [4] incorporates the cellular technologies with powerline system. Specifically, cell phones are used as an instrument to display information and allow consumers to control appliances in their homes in addition to the deployment of smart meters. Through this, smart grid applications can be realized economically and conveniently.

C. Open Research Issues

Despite the increasing M2M solutions and deployment based on current communication systems, there exist many technical challenges. In the following, we discuss several important research issues to be addressed in this field.

1) Standardization: M2M communications will require an integration and convergence among various different communication systems (e.g., local and wide area networks). However, there are very few standardizations for it. Standardization of a seamless and unified M2M architecture is highly demanded to promote a rapid development and application of M2M communications. Also, complete standardization of the enabling technologies of M2M communications, e.g., RFID, ZigBee, and UWB, needs to be specified.

2) Traffic Characterization: Characteristics of traffic exchanged among M2M components have not been well studied so far. M2M traffic will be different from that of human-based network due to the special functions (e.g., data collection and monitoring) and requirements (e.g., hard real-time traffic). Traffic characterization is the fundamental to the design and optimization of network infrastructures. M2M traffic characterization is also required to provide quality of service (QoS) support for M2M applications.

3) Protocol Re-design: The current leading transmission protocols of Internet, i.e., TCP/IP, is known to be inefficient for M2M traffic due to the redundant and energy-wasting overhead compared to low data volume required to transmit. Thus, transmission protocols specially designed for M2M communications need to be explored.

4) Spectrum Management: Due to the limited spectrum resource, wireless M2M technologies need to efficiently transmit signal over the frequency channels. However, traditional static spectrum allocation may not be able to achieve optimal spectrum management, owing to the inevitable shift of spectrum requirement in the supply and demand for wireless M2M services. Thus, for secondary spectrum markets, which provide use of the spectrum to entities other than the original license holders, they should be well-functioned to ensure that available spectrum will migrate to more efficient usage. Challenges lie in how to build up a well-behaved secondary market. Discussion with respect to M2M spectrum licenses can be found in [5] which studies the underlying principles of secondary markets and the evolving policies towards well-functioning secondary spectrum markets.

5) Optimal Network Design: As M2M communications will connect a number of devices and systems together, the optimal network design is an important issue. The network design has to minimize cost of M2M communications (e.g., hardware, maintenance, and radio resource usage) while meeting QoS requirements of the traffic and applications.

III. M2M COMMUNICATIONS FOR HEMS IN SMART GRID

In this section, we focus on the network design issue of M2M communications for home energy management system (HEMS) in smart grid. Specifically, an optimal traffic concentration to support HEMS in smart grid is presented to minimize the cost. First, a brief overview of smart grid and HEMS is presented. Then, we introduce the network architecture for HEMS. The algorithm to achieve optimal traffic concentration is proposed. Numerical results are presented to show the advantage of the proposed scheme.

A. Home Energy Management System (HEMS) in Smart Grid

Fig. 1. A general model of smart grid.

In smart grid system, three major parts, i.e., generation, distribution, and consumption (Fig. 1), have different functionalities as follows:

- *Power Generation:* Generation part is composed of different types of power generators (e.g., coal-fired, gas, wind-powered turbines, and solar power plants). A generator measures the cost, power demand, and power prices offered by other generators to adapt competitively or cooperatively the power generation strategy (e.g., price and amount of supplied power in a certain time period) to achieve the maximum profit while meeting the constraint on the demand, capacity, and reliability.
- *Power Distribution:* The electrical power is delivered from generators and distributed to consumers through the transmission lines and distribution stations. The power distribution has to be optimized such that the loss and cost of transmission are minimized given the constraints on the amount of transmitted power and transmission line capacity. The distribution can be adaptive to the power generator and consumer sides.
- *Power Consumption:* Consumption part is composed of different types of power consumers (e.g., home, industry, and government consumers). The power demand of consumers has to be determined so that the allocation of power supply and distribution can be performed optimally. To achieve such a goal, the smart meters are deployed to timely and accurately collect the power consumption data. This data can be used to estimate the power demand.

HEMS focuses on the power consumer side in smart grid in which the home appliances (e.g., air conditioner, dishwasher, dryer, refrigerator, kitchen stove, and washing machine) with smart meter can be monitored and controlled by control center to optimize the power supply and consumption. Various services of HEMS are introduced (e.g., Google Powermeter, Microsoft Hohm, and Apple Smart-Home

Energy Management) in which the consumers can track the power consumption and perform optimization to reduce the power cost. M2M Communications play a crucial role in HEMS since the information about home appliances has to be transferred to the control center for analysis and optimization. Wireless communication technologies (e.g., ZigBee and WiMAX) are the viable choices due to the low cost and flexibility of infrastructure. In the following, a network architecture of M2M communications for HEMS is discussed. Based on this architecture, the optimal traffic concentration scheme is then introduced.

B. Network Architecture for HEMS

Fig. 2. M2M network architecture for smart grid.

HEMS to collect power consumption and demand status from the home appliances using smart meter is considered. The status and demand data is transferred from smart meter of each house to the traffic concentrator or gateway (Fig. 2) which will be forwarded to the wide area network (WAN) base station (e.g., WiMAX). This WAN base station is deployed for a particular service area with a number of houses. The base station forwards HEMS traffic to the control center for data processing and storage (e.g., using Google Powermeter service). The detail of each component in the network architecture as shown in Fig. 2 is as follows:

- *Home Appliance:* Home appliance is a power consumption device in smart grid. Home appliances in the house are connected with a smart meter, and their power consumption is measured and collected by smart meter. Alternatively, advanced home appliances can proactively send report to smart meter (e.g., future power consumption demand).
- *Smart Meter:* Smart meter is a device used to collect the power consumption demand from home appliances. Home area network (HAN) can be established among home appliances and smart meter (e.g., using the power line communication (PLC) or ZigBee).
- *Concentrator:* Neighborhood area network (NAN) is established among smart meters of the houses to support HEMS. NAN has a concentrator (i.e., gateway) to collect data packets (i.e., HEMS traffic) from smart meters using short-range communication technologies (e.g., WiFi). The received packets are stored in the buffer of concentrator. Different types of data packets with different QoS requirements can be stored in different buffers. WAN transceiver of concentrator retrieves head-of-queue packet from the buffer and transmits to WAN base station.
- *WAN Base Station:* WAN base station is in charge of bandwidth allocation for the data transmission of each concentrator. After the data packets sent from concentrators are received by WAN base station,

they are then forwarded over the wired network (e.g., Internet backhaul) to the control center.

- *Control Center:* The control center receives HEMS data for processing and storage. This data is used to optimize the electrical power generation and/or distribution.

In the context of M2M communications as described in Section II-A, M2M components are the home appliances and smart meters. M2M gateway is the HEMS traffic concentrator. M2M server is located at the control center. M2M area network is based on short-range communication technologies (e.g., WiFi), and M2M communication network is WAN (e.g., IEEE 802.16).

Fig. 3. Algorithm of control center.

As the smart meter reports the power consumption status to the control center, the control center establishes a contract with the generators periodically (e.g., every hour) to buy power supply (Fig. 3). Historical data of power demand collected from the smart meters through concentrator and WAN base station is used in this contract. Given the estimated aggregated power demand (estimated demand) of all home appliances in a service area, the power price is determined by the power generator for a periodic contract (e.g., locational margin price (LMP) [6]). However, the historical data of power demand can be incomplete and outdated due to the loss and delay of data transmitted from home appliances. Therefore, the actual aggregated power demand (actual demand) can be different from estimated demand. If estimated demand is larger than the actual demand, the supplied power is wasted (i.e., over-supply). On the other hand, if actual demand is larger than the estimated demand, additional power supply is required (i.e., under-supply). For additional power supply, the power generator charges price higher than the price in a periodic contract due to the instantaneous need which is random and difficult to predict [7]. For example, with periodic contract, the generator can deliver power from cheaper source (e.g., hydroelectricity) than that of addition supply (e.g., thermal power stations).

It is clear that the packet delay and loss can result in over- and under-supply situations which incur the cost to the consumers. Therefore, the QoS requirements for HEMS traffic would be an important factor when designing network architecture for HEMS.

C. Optimal Traffic Concentration

On one hand, the HEMS traffic from smart meter in each house (i.e., node[1]) can be aggregated at the concentrator to minimize the installation and communications cost, since fewer concentrators are required and bandwidth of WAN base station can be shared. On the other hand, the deployment of concentrator

[1] For the rest of the article, "house" with smart meter and "node" are used interchangeably.

has to minimize the cost due to QoS degradation from packet delay and loss. To optimize this traffic concentration, the optimal cluster formation among nodes in HEMS to share the same concentrator is formulated so that the cost of M2M communications from home appliances to the base station can be minimized.

1) Cost Structure: Cost of traffic concentration is composed of the cost due to the concentrator installation C_{ins} and the cost due to QoS degradation C_{QoS}. Concentrator installation cost incurs due to the physical deployment and due to the bandwidth used to transmit HEMS traffic to base station. This cost is assumed to be fixed over a time period. For QoS degradation, cost incurs if the HEMS traffic is not delivered to the control center timely and reliably. The cost due to packet delay and loss can be determined as the difference between the total utility of power consumption with complete and perfect demand data and that with incomplete and imperfect demand data [8]. We assume QoS degradation cost to be a linear function of packet delay and loss. Therefore, the total cost of traffic concentration at concentrator i is denoted as $C_i = C_{\text{ins}} + C_{\text{QoS}} = C_{\text{ins}} + \omega_{\text{del}} D_i + \omega_{\text{loss}} L_i$ where D_i and L_i are packet delay and loss at concentrator i, respectively. ω_{del} and ω_{loss} are the cost weights of packet delay and loss, respectively. Let concentrator i aggregate HEMS traffic from a cluster of nodes denoted as $\mathcal{S}_i$, and the cost can be expressed as $C_i(\mathcal{S}_i)$. The total cost of the system to be minimized is denoted by $C_{\text{tot}}(\mathbb{S}) = \sum_{\mathcal{S}_i \in \mathbb{S}} C_i(\mathcal{S}_i)$ where $\mathbb{S}$ is the set of all clusters of nodes in the system.

2) Optimal Cluster Formation: Let $\mathcal{N}$ denote the set of all nodes (i.e., houses with smart meters) in a service area. To minimize the total cost C_{tot}, the nodes have to be divided into the clusters $\mathcal{S}_i \subseteq \mathcal{N}$ and concentrator i is assigned to cluster $\mathcal{S}_i$. This is an optimal cluster formation problem which can be solved by using dynamic programming algorithm [9]. The algorithm works as follows: Initially, all nodes are assumed to be in the same cluster. Then, the cluster is split into two clusters which result in the smallest total cost. If this new total cost is lower than the current total cost (i.e., with the cluster before splitting), then the algorithm updates the set of clusters. These steps are repeated until all clusters result in the lowest total cost. Algorithm 1 shows the dynamic programming-based algorithm for optimal cluster formation of the HEMS traffic concentration. The advantage of the dynamic programming based algorithm is at the guaranteed optimality solution.

Algorithm 1. Optimal cluster formation algorithm.

3) Numerical Results: We consider a service area of 1 square kilometer with 250 nodes served by one WAN base station. Each node generates 1.2 packets per minute on average. The packet includes the status and power consumption information of home appliances. The transmission rate of the concentrator to the base station is 6 packets per minute. Delay occurs due to the waiting time of packets in the buffer of concentrator. Loss occurs due to the lack of buffer space and transmission error. In this case, as the distance from the nodes to concentrator increases, the packet loss increases since the signal strength decreases in the order of $\alpha > 2$ of distance where α is the path-loss exponent (e.g., $\alpha = 3$). The concentrator installation cost is assumed to be $C_{\text{ins}} = 10$, while the cost weights of packet delay and loss are $\omega_{\text{del}} = 0.1$ and $\omega_{\text{loss}} = 1$, respectively. In the following numerical results, the packet delay and loss due to lack of buffer space is obtained from M/D/1/K queueing model [10] where the maximum buffer space is $K = 100$ packets.

Fig. 4. Cluster formation among nodes in HEMS.

Fig. 4 shows the cluster formation among nodes. In the figure, the nodes linked with lines belong to the same cluster. We assume that concentrator is located at one of the selected nodes (i.e., the center of a cluster). The formation is based on the cost of concentrator installation and QoS degradation (i.e., delay and loss). For packet generation rate of 1.2 packets per minute, the cluster size is mostly 3 or 4 nodes which results in minimum total cost (Fig. 4). Fig. 5 shows the average cost per node under different packet generation rates. The costs from fixed cluster sizes are also shown. It is observed that when the cluster size is small (e.g., 1 or 2 nodes per cluster), the total cost per node is high due to the cost of concentrator installation. For the larger cluster size (e.g., 4 or 5 nodes per cluster), at the small packet generation rate, the cost is low due to the low installation cost. However, when the packet generation rate increases (i.e., more appliances in each house), the cost increases shapely due to the QoS degradation (e.g., considerable packet delay and loss) which degrades the adaptation of the electrical power supply. The algorithm can adapt to the packet generation rate (e.g., when home appliances are added into the network). It is observed that the proposed cluster formation can determine not only the optimal cluster size, but also the members to be in each cluster to achieve the lowest cost.

Fig. 5. Cost per node under different packet generation rate.

IV. Conclusion

M2M communications play an important role in data exchange of pervasive computing regime, and can be adopted in many applications (e.g., public safety, energy management, and transportation) with objectives to improve efficiency and reduce cost. Smart grid is one of the most driving forces for the advance of M2M communications. In this article, an overview of M2M communications has been given, including the motivation, network architecture, the adopted communication technologies. The work related to the application of M2M communications in smart grid has been reviewed. The open research issues have also been discussed. Then, the M2M communications for home energy management system (HEMS) in smart grid has been introduced. The network design issue, specifically optimal HEMS traffic concentration, has been considered. The numerical results show that with the proposed optimal traffic concentration scheme, the total cost of HEMS can be minimized.

V. Acknowledgment

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Dusit Niyato (M'09) is currently an Assistant Professor in the School of Computer Engineering, Nanyang Technological University, Singapore. He received the B.E. degree from King Mongkuts Institute of Technology Ladkrabang, Bangkok, Thailand and the Ph.D. degree in electrical and computer engineering from the University of Manitoba, Winnipeg, Canada. His current research interests include design, analysis, and optimization of wireless communication, green radio communications, and mobile cloud computing.

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Lu Xiao received the B.Eng. degree in communication engineering from Beijing University of Posts and Telecommunications in 2008, and the M.Eng degree in computer engineering from Nanyang Technological University in 2010. He is current a research associate with the School of Computer Engineering, Nangyang Technological University. His current research interests focus on applications of game theory.

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Ping Wang (M'08) received her Ph.D. degree in electrical engineering from the University of Waterloo, Canada, in 2008. She is currently an Assistant Professor with the School of Computer Engineering, Nanyang Technological University, Singapore. Her current research interests include quality-of-service provisioning and resource allocation in multimedia wireless communications. Dr. Wang was a co-recipient of a Best Paper Award from the 2007 IEEE International Conference on Communications.

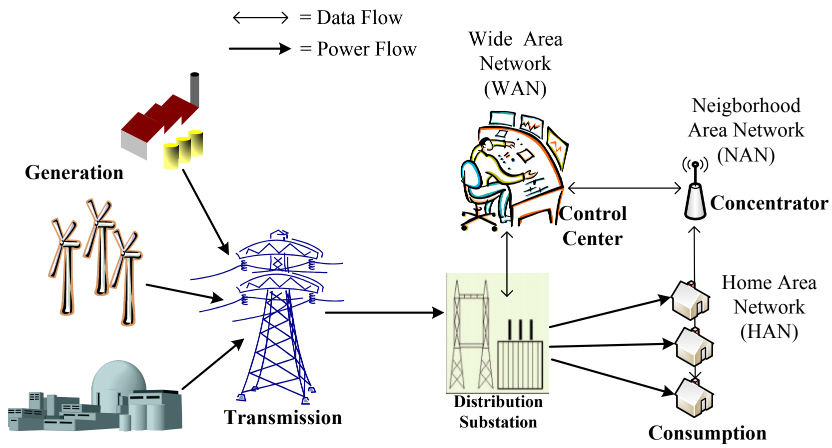

Fig. 1. A general model of smart grid.

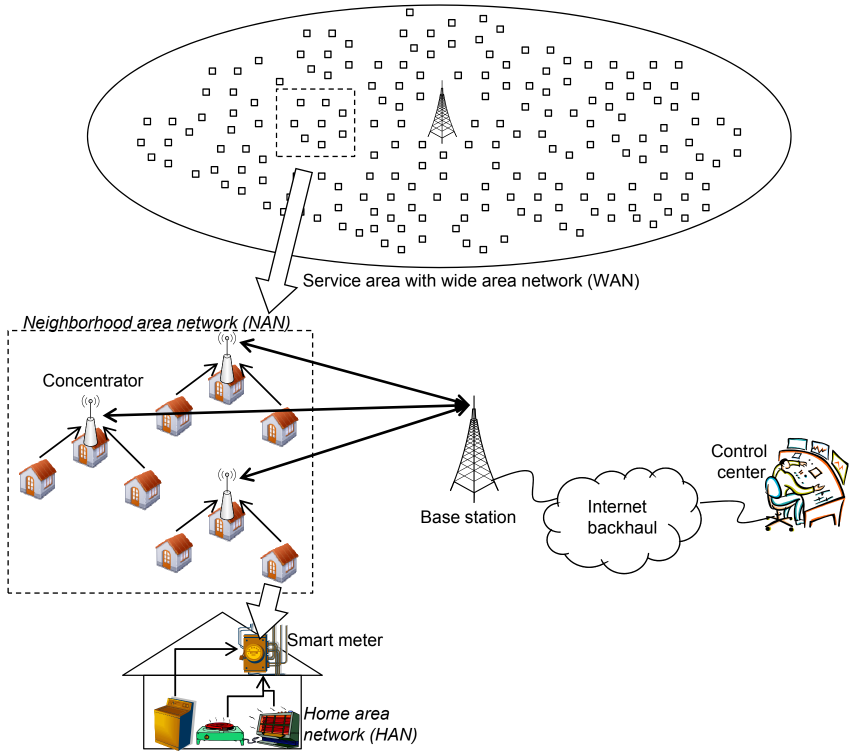

Fig. 2. M2M network architecture for smart grid.

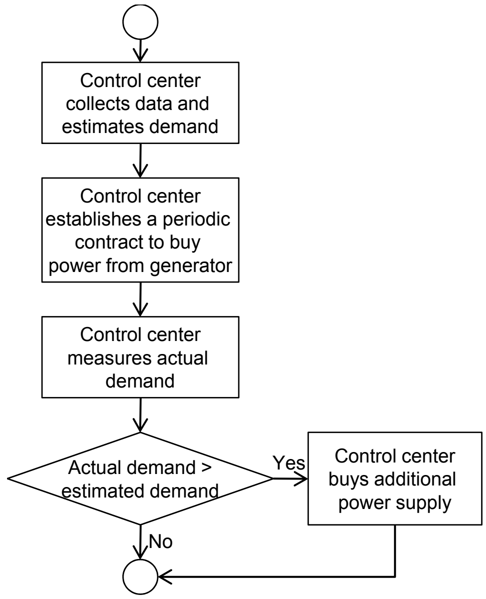

Fig. 3. Algorithm of control center.

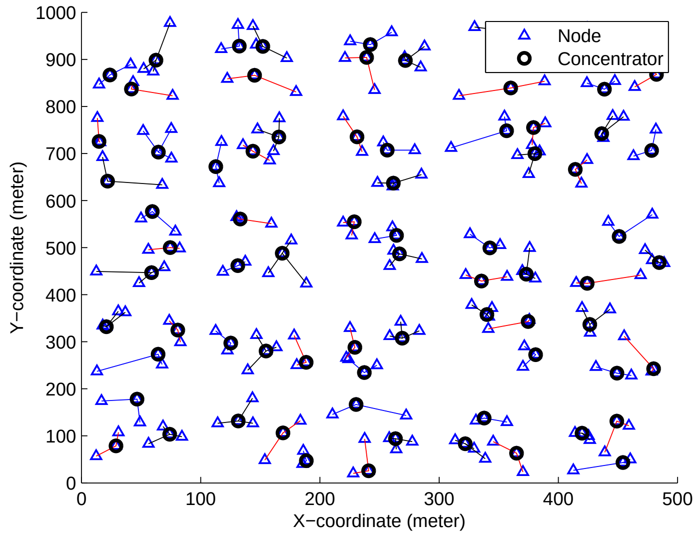

Fig. 4. Cluster formation among nodes in HEMS.

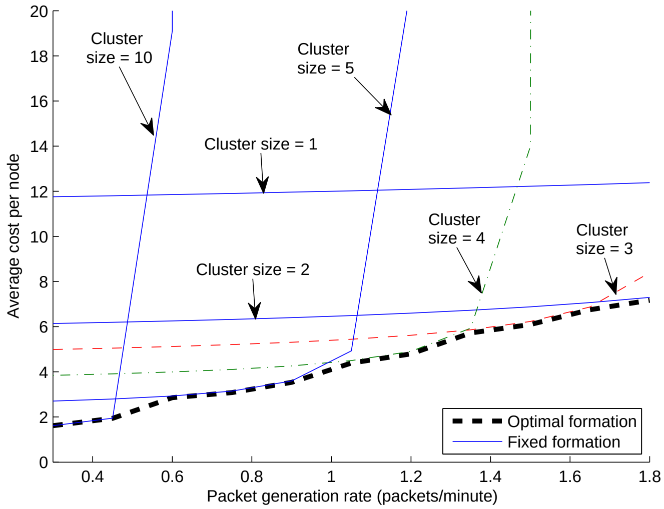

Fig. 5. Cost per node under different packet generation rate.

Algorithm 1 Optimal cluster formation algorithm.

Set $\mathbb{S}_{\text{old}} = \{\mathcal{N}\}$ { Initialize all nodes to be in the same cluster}
repeat
  $\mathbb{S} \leftarrow \mathbb{S}_{\text{old}}$
  for every $\mathcal{C} \in \mathbb{S}$ **do**
    $C_{\text{new}} = \min_{\mathcal{C}_1,\mathcal{C}_2} (C_{\text{tot}}(\mathbb{S} \setminus \{\mathcal{C}\} \cup \{\mathcal{C}_1, \mathcal{C}_2\}))$ where $\mathcal{C}_1 \cup \mathcal{C}_2 = \mathcal{C}$ { Compute the smallest total cost of new split clusters $\mathcal{C}_1$ and $\mathcal{C}_2$ from $\mathcal{C}$}
    if $C_{\text{new}} < C_{\text{tot}}(\mathbb{S})$ **then**
      $\mathbb{S} \leftarrow \mathbb{S} \setminus \{\mathcal{C}\} \cup \{\mathcal{C}_1, \mathcal{C}_2\}$ { Obtain the new set of clusters after splitting cluster $\mathcal{C}$ }
    end if
  end for
until $\mathbb{S} = \mathbb{S}_{\text{old}}$ { Algorithm terminates when splitting any cluster cannot decrease the total cost further}