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

Dusit Niyato, Lu Xiao, and Ping Wang, 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 communications in the smart grid. First, an overview of M2M communications is given. The enabling technologies and open research issues of M2M communications are also discussed. Then we address the network design issue of M2M communications for a home energy management system (HEMS) in the 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. A 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.

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 attention over the years. The idea of M2M communications is to enable M2M components to be 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, adopted communication technologies, and applications in the smart grid are presented. In addition, we address the network design issue of M2M communications for a home energy management system (HEMS) in the smart grid. The smart grid emerges as the next-generation electrical power grid with the capability of adaptive and optimal power generation, distribution, and consumption. The HEMS is part of the smart grid on the consumption side to collect data from home appliances using smart meters. This data will be used for optimizing the power supply and distribution. We introduce an 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 a 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. We present an overview of M2M communications. We introduce the M2M communications for HEMS. The network architecture and traffic concentration are discussed. Finally, we conclude the article.

OVERVIEW OF MACHINE-TO-MACHINE COMMUNICATIONS

The embryonic form of M2M communications esd 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 the and research community, mainly driven by the following factors:

- The emergence of wireless communication systems (e.g., GSM/GPRS, WiMAX, and wideband code-division multiple access [WCDMA]) in the Internet has become the premise for the advance of M2M communications. The network infrastructures of these communication systems are already in place, and can be adopted in M2M communications.
- Advanced software component enables devices to operate intelligently and autonomously. As a result, a number of

 0163-6804/11/$25.00

Different from human-to-human communications, which mainly involve voice calls, 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.

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 systems 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 from human-to-human communications, which mainly involve voice calls, 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 seamless data and control flows. Recently, a lot of efforts have been put into the standardization. For example, the European Telecommunications Standards Institute (ETSI) has launched the 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).

M2M Network Architecture

An M2M network as standardized by ETSI is composed of five key elements:
- The M2M component, usually embedded in a smart electrical device, replies to requests or transmits data.
- The M2M gateway enables connectivity between the M2M components and the communication network.
- The M2M server works as a middleware layer to pass data through various application services.
- The M2M area network provides connectivity between M2M components and M2M gateways.
- The M2M communication network provides connection between M2M gateways and M2M servers.

These five elements constitute the three domains of M2M system specified by ETSI: the M2M component working in the device domain, the M2M area network and gateway in the network domain, and the M2M server and communication network in the application domain.

Wireless M2M Communications and its Applications

The advances in wireless technologies that enable mobility and eliminate the need for cable installation for M2M components have pushed the development of wireless M2M communications. Since different M2M components vary in types and sizes, and may be located 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 toward wireless environments.

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: mobile broadband communications (e.g., WiMAX and Long Term Evolution [LTE]) and local area networking (e.g., WiFi).

In home networks, ubiquitous smart electronic devices other than traditional telephones and computers, embedded with wireless communication technologies, are outfitting. Communications among the smart electronic devices generally feature low data rate, low mobility, and low power consumption. Short-range communication technologies like Bluetooth, ultra wideband (UWB), and Infrared Data Association (IrDA) can be employed for connection between smart electronic devices (i.e., M2M components) and an M2M gateway in the home environment.

An ad hoc network provides the connectivities among multiple decentralized nodes without a pre-existing infrastructure, which is the case for most M2M components in the real world. Fast and low-cost interconnection 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 (ZigBee) and IEEE 802.11 (WiFi) can be adopted to cover the transmission range.

The cellular network is presently one of the most widely deployed wireless networks around the world, and offers a great advantage to developing 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 the cellular network supports mobility, more flexible M2M applications (e.g., intelligent transportation system) can be accommodated.

Applications of M2M Communications in the Smart Grid — The smart grid is one of the strongest 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 power generation, distribution, and consumption. Information and communication technologies (ICT) are adopted in the 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 are identified and discussed in [2].

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

Smart grid applications based on the current power grid system could be problematic since the century-old power line systems were not designed to meet modern requirements, while reconstruction of power line systems for smart grid applications would be costly and time-consuming. To address this issue, [4] incorporates cellular technologies with power line systems. 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.

OPEN RESEARCH ISSUES

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

Standardization — M2M communications will require an integration and convergence among various different communications 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 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.

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 networks 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.

Protocol Re-design — The current leading transmission protocols of the Internet, TCP/IP, are known to be inefficient for M2M traffic due to the redundant and energy-wasting overhead compared to the low data volume needing to br transmitted. Thus, transmission protocols specially designed for M2M communications need to be explored.

Spectrum Management —Due to the limited spectrum resource, wireless M2M technologies need to efficiently transmit signals over frequency channels. However, traditional static spectrum allocation may not be able to achieve optimal spectrum management, due to the inevitable shift of spectrum requirements in the supply and demand for wireless M2M services. Thus, secondary spectrum markets, which provide use of the spectrum to entities other than the original license holders, should be well functioning 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 toward well functioning secondary spectrum markets.

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.

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 while meeting QoS requirements of the traffic and applications.

M2M COMMUNICATIONS FOR HEMS IN SMART GRID

In this section, we focus on the network design issue of M2M communications for a home energy management system (HEMS) in the smart grid. Specifically, optimal traffic concentration to support HEMS in the 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.

HOME ENERGY MANAGEMENT SYSTEM (HEMS) IN SMART GRID

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

Power generation: Generation 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 competitively or cooperatively adapt the power generation strategy (e.g., price and amount of supplied power in a certain time period) to achieve the maximum profit while meeting constraints on demand, capacity, and reliability.

Power distribution: Electrical power is delivered from generators and distributed to consumers through transmission lines and distribution stations. Power distribution has to be optimized such that the loss and cost of transmission are minimized given constraints on the amount of transmitted power and transmission line capacity. The distribution can be adaptive on the power generator and consumer sides.

Power consumption: Consumption 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 quickly and accurately collect the power consumption data. This data can be used to estimate the power demand.

The HEMS focuses on the power consumer side in a smart grid in which home appliances (e.g., air conditioner, dishwasher, dryer, refrigerator, kitchen stove, and washing machine) with smart meters can be monitored and controlled by a control center to optimize the power supply

A 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.

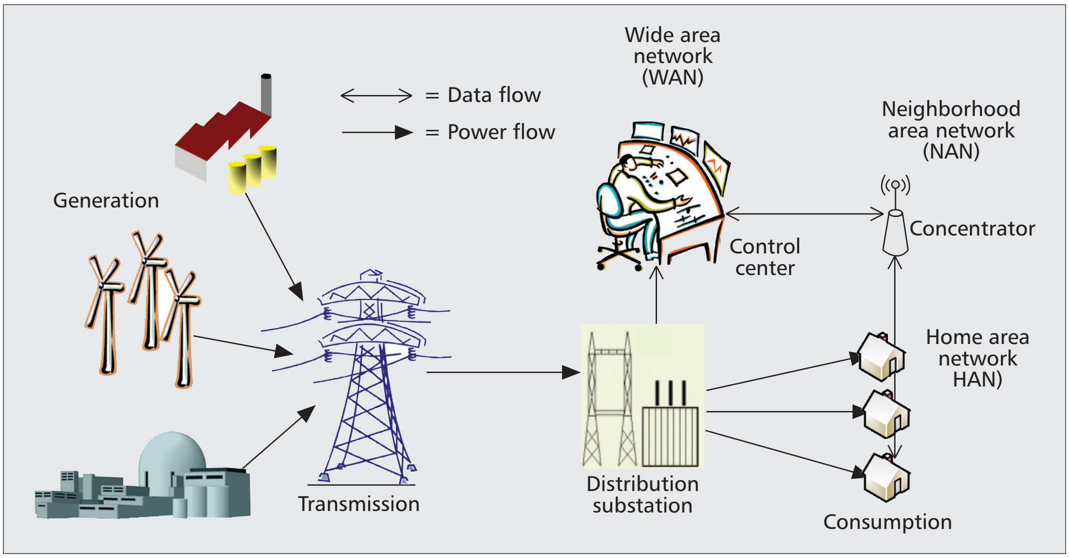

Figure 1. *A general model of the smart grid.*

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

Network Architecture for HEMS

A HEMS to collect power consumption and demand status from home appliances using smart meters is considered. The status and demand data is transferred from the smart meter of each house to the traffic concentrator or gateway (Fig. 2), which will then forward it 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). The detail of each component in the network architecture as shown in Fig. 2 is as follows.

Home appliance: A home appliance is a power consumption device in the smart grid. Home appliances in a house are connected to a smart meter, and their power consumption is measured and collected by the smart meter. Alternatively, advanced home appliances can proactively send reports to the smart meter (e.g., future power consumption demand).

Smart meter: A smart meter is a device used to collect the power consumption demand data from home appliances. A home area network (HAN) can be established among home appliances and a smart meter (e.g., using power line communication [PLC] or ZigBee).

Concentrator: A neighborhood area network (NAN) is established among smart meters of the houses in an area to support the HEMS. A 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 the concentrator. Different types of data packets with different QoS requirements can be stored in different buffers. The WAN transceiver of the concentrator retrieves a head-of-queue packet from the buffer and transmits it to a WAN base station.

WAN base station: A 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 the 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 earlier, M2M components are the home appliances and smart meters. The M2M gateway is the HEMS traffic concentrator. The M2M server is located at the control center. M2M area network is based on short-range communication technologies (e.g., WiFi), and an M2M communication network is a WAN (e.g., IEEE 802.16).

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 the 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 appli-

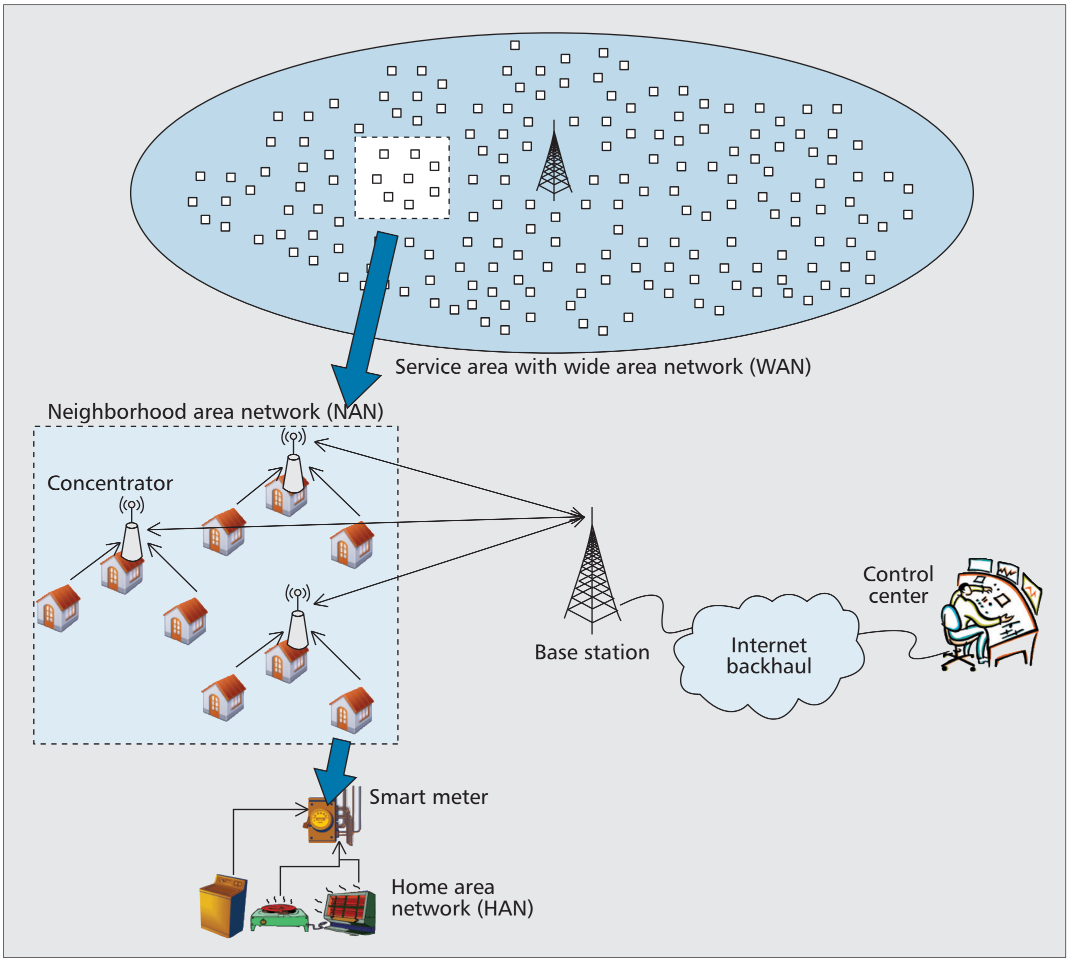

Figure 2. *M2M network architecture for the smart grid.*

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.

ances. Therefore, actual aggregated power demand (actual demand) can be different from estimated demand. If estimated demand is larger than 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 a higher price than the price in a periodic contract due to the instantaneous need, which is random and difficult to predict [7]. For example, with a periodic contract, the generator can deliver power from a cheaper source (e.g., hydroelectricity) than that of additional supply (e.g., thermal power stations).

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

Optimal Traffic Concentration

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

Cost Structure — The cost of traffic concentration is composed of the cost due to concentrator installation, C_{ins}, and the cost due to QoS degradation, C_{QoS}. Concentrator installation cost includes the physical deployment and the bandwidth used to transmit HEMS traffic to the base station. This cost is assumed to be fixed over a certain time period. For QoS degradation, cost is incurred if the HEMS traffic is not delivered to the control center quickly 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 $C_i = C_{ins} + C_{QoS} = C_{ins} + \omega_{del}D_i + \omega_{loss}L_i$, 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 S_i, and the cost can be

1 For the rest of the article, *house with a smart meter and node are used interchangeably.*

expressed as $C_i(S_i)$. The total cost of the system to be minimized is $C_{\text{tot}}(\mathbb{S}) = \Sigma_{Si \in \mathbb{S}} C_i(S_i)$, where $\mathbb{S}$ is the set of all clusters of nodes in the system.

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.

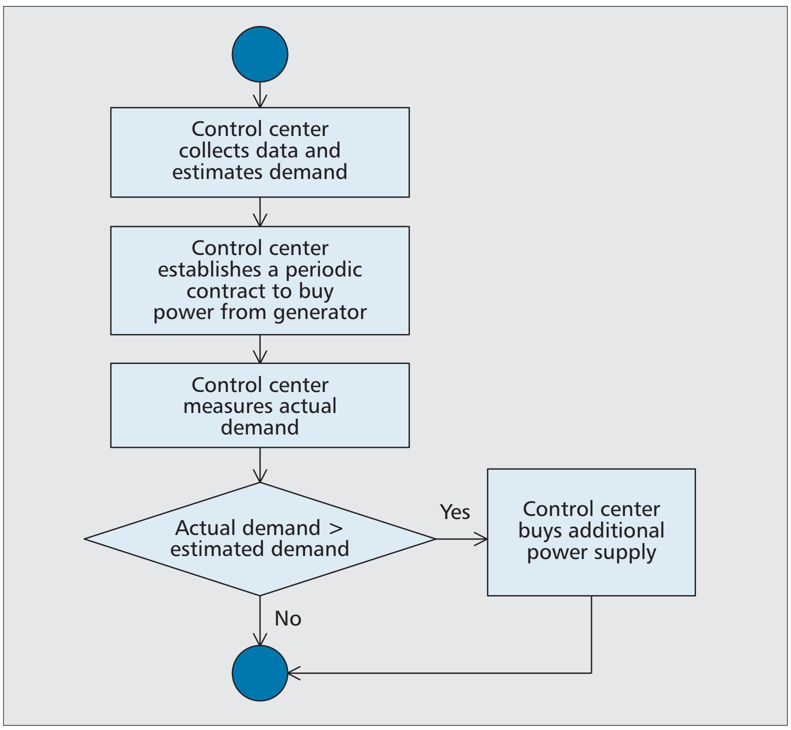

Figure 3. *Algorithm of the control center..*

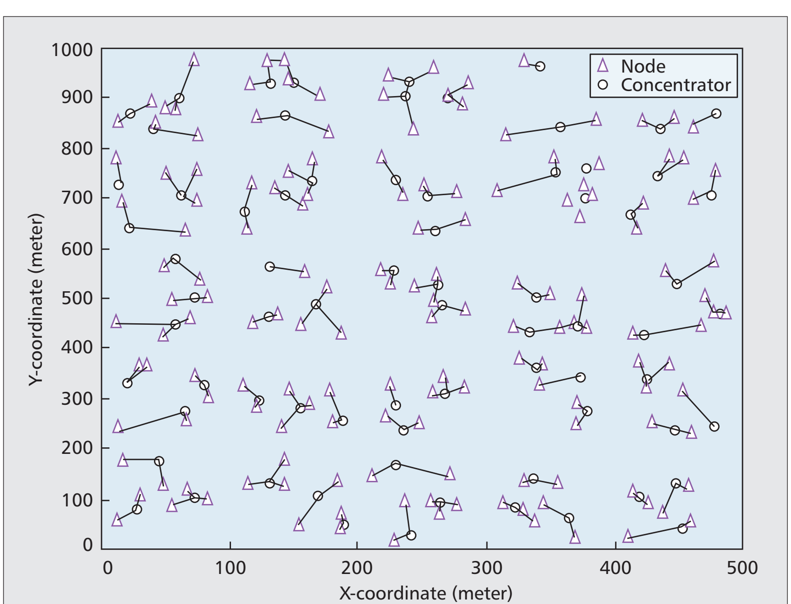

Figure 4. *Cluster formation among nodes in the HEMS.*

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 on the order of $\alpha > 2$ 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 an M/D/1/K queueing model [10] where the maximum buffer space is $K = 100$ packets.

Figure 4 shows the cluster formation among nodes. In the figure, the nodes linked with lines belong to the same cluster. We assume that the 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 a packet generation rate of 1.2 packets/min, the cluster size is mostly 3 or 4 nodes, which results in minimum total cost (Fig. 4). Figure 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 sharply due to 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.

CONCLUSION

M2M communications play an important role in data exchange of a pervasive computing regime, and can be adopted in many applications (e.g., public safety, energy management, and trans-

Set $\mathbb{S}_{old} = \{N\}$ {Initialize all nodes to be in the same cluster}
repeat
  $\mathbb{S} \leftarrow \mathbb{S}_{old}$
  for every $\mathcal{C} \in \mathbb{S}$ **do**
    $C_{new} = \min_{\mathcal{C}_1 \mathcal{C}_2} (C_{tot}(\mathbb{S} \setminus \{\mathcal{C}\} \cup \{\mathcal{C}_1, \mathcal{C}_2\}))$ 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 $C_{new} < C_{tot}(\mathbb{S})$ **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 $\mathbb{S} = \mathbb{S}_{old}$ {Algorithm terminates when splitting any cluster cannot decrease the total cost further}

Algorithm 1. *Optimal cluster formation algorithm.*

portation) with objectives to improve efficiency and reduce cost. The smart grid is one of the strongest driving forces for the advance of M2M communications. In this article, an overview of M2M communications has been given, including the motivation, network architecture, and adopted communication technologies. The work related to the application of M2M communications in the smart grid has been reviewed. The open research issues have also been discussed. M2M communications for a home energy management system (HEMS) in the 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 a HEMS can be minimized.

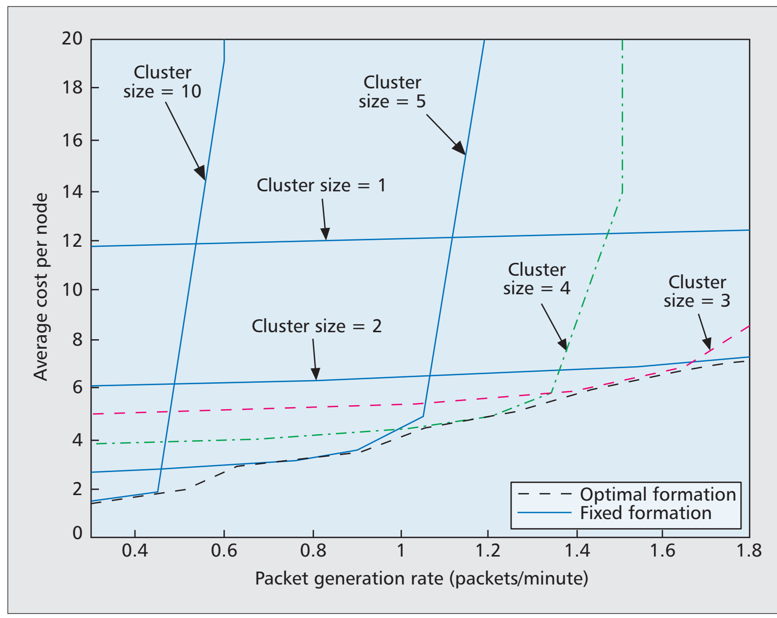

Figure 5. *Cost per node under different packet generation rates.*

Acknowledgment

This work was done in the Centre for Multimedia and Network Technology (CeMNet) of the School of Computer Engineering, Nanyang Technological University, Singapore.

References

[1] S. Krishnamurthy *et al.*, "Guide to Supervisory Control and Data Acquisition (SCADA) and Industrial Control Systems Security," NIST tech. rep, Sept. 2006.

[2] Z. Fan *et al.*, "The New Frontier of Communications Research: Smart Grid and Smart Metering," *e-Energy*, 2010, pp. 115–18.

[3] Q. D. Vo *et al.*, "Green Perspective Cognitive Radio-based M2M Communications for Smart Meters," *Int'l. Conf. Info.n and Commun. Tech. Convergence*, Jeju, Korea, Nov. 2010.

[4] M. M. Abdullah and B. Dwolatzky, "Smart Demand-Side Energy Management based on Cellular Technology — A Way Towards Smart Grid Technologies in Africa and Low Budget Economies," *Proc. IEEE AFRICON*, Sept. 2009.

[5] J. W. Mayo and S. Wallsten, "Enabling Efficient Wireless Communications: The Role of Secondary Spectrum Markets," *Info. Economics and Policy*, vol. 22, no. 1, Mar. 2010, pp. 61–72.

[6] R. Bo and F. Li, "Probabilistic LMP Forecasting Considering Load Uncertainty," *IEEE Trans. Power Systems*, vol. 24, no. 3, Aug. 2009, pp. 1279–89.

[7] P. Jirutitijaroen and C. Singh, "Reliability Constrained Multi-Area Adequacy Planning Using Stochastic Programming with Sample-Average Approximations," *IEEE Trans. Power Sys.*, vol. 23, no. 2, May 2008, pp. 504–13.

[8] H. Li and W. Zhang, "QoS Routing in Smart Grid," *Proc. IEEE GLOBECOM*, Miami, FL, 6–10 Dec. 2010.

[9] T. Rahwan and N. R. Jennings, "An Improved Dynamic Programming Algorithm for Coalition Structure Generation," *Proc. Int'l. Joint Conf. Autonomous Agents and Multiagent Sys.*, May 2008, pp. 1417–20.

[10] S. K. Bose, *An Introduction to Queuing Systems*, Springer, Dec. 2001.

Biographies

DUSIT NIYATO [M'09] is currently an assistant professor in the School of Computer Engineering, Nanyang Technological University, Singapore. He received a B.E. degree from King Mongkuts Institute of Technology Ladkrabang, Bangkok, Thailand, and a 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.

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

PING WANG [M'08] (wangping@ntu.edu.sg) received her Ph.D. degree in electrical engineering from the University of Waterloo, Canada, in 2008. She is currently an assistant professor in the School of Computer Engineering, Nanyang Technological University, Singapore. Her current research interests include QoS provisioning and resource allocation in multimedia wireless communications. She was a co-recipient of a Best Paper Award from the 2007 IEEE International Conference on Communications.