

Optimal gateway deployment under different queuing mechanisms in smart grid

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Abstract: By optimizing the network topology, this paper proposes a new method of queuing theory clustering algorithm based on dynamic programming in a home energy management system (HEMS). First, the total cost of the HEMS system is divided into two parts, the gateway installation cost and the data transmission cost. Secondly, through comparing two kinds of different queuing theories, the cost problem of the HEMS is converted into the problem of gateway deployment. Finally, a machine-to-machine (M2M) gateway configuration scheme is designed to minimize the cost of the system. Simulation results show that the cost of the HEMS system mainly comes from the installation cost of the gateways when the gateway buffer space is large enough. If the gateway buffer space is limited, the proposed queue algorithm can effectively achieve optimal gateway setting while maintaining the minimal cost of the HEMS at desired levels through marginal analyses and the properties of cost minimization.

Key words: smart grid; home energy management system (HEMS); queuing theory; gateway deployment

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Recently, the concept of the smart grid is proposed, which brings more intelligence into power grids by massive integration of information and communication technologies. The smart grid requires active participation of users for efficient load management, integration of renewable energy sources, smart metering, smart home or building automation^[1]. Machine-to-machine (M2M) communications are the key components for realizing the new services of smart grids.

Intelligent services usually require an intelligent device (e.g., home energy gateway (HEG)) that communicates with the grid and all local appliances inside home through wireless technologies^[2]. However, due to the high cost

of installation, the design of gateways which can bring the desired cost comes to our attention. Previous methods mainly focus on how to place or locate receiver nodes^[3-4]. Zaker et al.^[5] argued that the gateway design scheme attains low delay for high priority packets while maintaining the delay of fiber-to-the-x (FTTX) traffic and the reliability of the wireless sensor network at desired levels. Yarvis et al.^[6] proved that the more M2M gateways are deployed, the longer network lifetime becomes until the average number of hops from the home area network (HAN) node to the M2M gateway reaches 1. Liu et al.^[7] proposed a new metric, the ratio of lifetime to cost (RLC), to evaluate the efficiency of deploying gateways. In a broader scope, the deployment of smart grids is foreseen to be a key element of the energy transition from fossil fuel to renewable energy sources for the production of electricity^[8].

1 System Model

The home energy management system (HEMS) focuses on the power consumer side in the smart grid. Home appliances with smart meters can be monitored and controlled by a control center to optimize the power supply and consumption. In order to determine the optimal numbers of M2M gateways, it is essential to build an appropriate cost model of network to quantize the relationship between the number of M2M gateways and the total cost of the HEMS system.

As shown in Fig. 1, the HEMS collects power demand status from the home appliance using a smart meter. The gateway can automatically retrieve the energy consumption, diagnostic and data status from smart meters, and convey it to the utility companies using two way communication channels.

The M2M gateway retrieves a head-of-queue packet from the buffer and transmits it to backhaul network base station. However, the historical data of power demand may be incomplete and outdated due to the loss or delay of data. The HEMS traffic from smart grid in each house can be aggregated at the gateway to reduce the installation and communication cost, since fewer gateways are required and the bandwidth of the wide area network (WAN) base station can be shared. The optimal cluster formation among nodes in the HEMS is formulated so that the cost of M2M communications from the home appliance to the WAN base station can be minimized.

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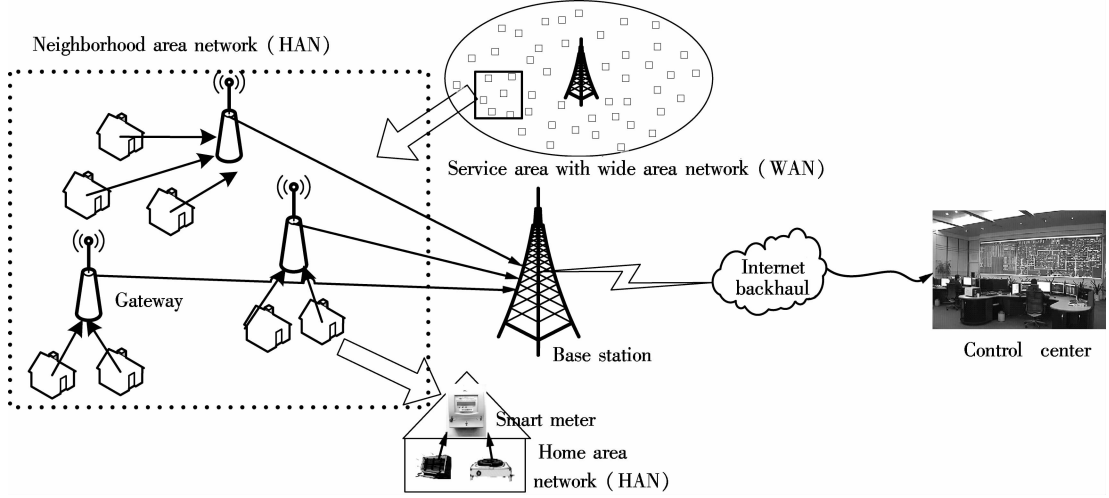


Fig. 1 M2M network architecture for smart grids

The cost of the HEMS system is divided into two parts. One is the gateway installation cost and the other is the data transmission cost. The gateway installation cost includes the physical deployment and the bandwidth used to transmit HEMS traffic to the base station^[9]. This cost is assumed to be fixed over a certain time period. The data transmission cost includes packet delay cost and packet loss cost due to lack of buffer space, and it can be obtained by the queuing theory^[10]. In this work, two typical queuing mechanisms in the smart grid are considered. The first mechanism assumes that buffer space is infinite, which means that the packets can queue in the gateway all the time. The second mechanism considers the maximum buffer space to be K packets. If the number of packets (also known as the captain) in the gateway is fewer than K , it can enter the system for queuing and receiving services; otherwise, the new packets automatically leave the system.

The minimalist illustration of a queuing model is shown in Fig. 2. The data packets generated by appliances are divided into different clusters. Each packet queuing at the gateway for service follows certain rules. The queuing system has two basic components, the input process and the queuing service.

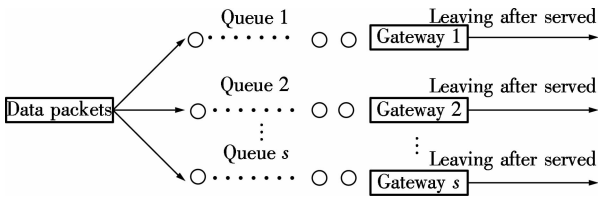


Fig. 2 Minimalist illustration of a queuing model

Assuming that the data flow obeys the Poisson distribution for parameters, the arrival distribution and service distribution are independent of each other. That is

$$p(A_t = a) = \frac{\lambda^a \exp(-\lambda)}{a!} \quad (1)$$

where A_t represents the number of data packets that arrives at time t . Since A_t is the steady state and it is independent of the queue status and service process, $E\{A_t\} = \lambda$.

The total cost of the HEMS system can be defined as

$$z = sc_s + \alpha L_{\text{delay}}(s) + \beta L_{\text{loss}}(s) \quad (2)$$

where s is the number of the gateway; c_s is the gateway installation cost; L_{delay} is the packet delay and L_{loss} is the packet loss; α and β are the cost weights of packet delay and packet loss, respectively.

Provided that the optimal number of the gateway taking the minimum z is s^* , $z(s)$ is not a continuously variable function since s can only take integer values. Using the marginal analysis method and based on the characteristics of the smallest z , we can obtain the following equation:

$$\left. \begin{aligned} z(s^*) &\leq z(s^* - 1) \\ z(s^*) &\leq z(s^* + 1) \end{aligned} \right\} \quad (3)$$

Substituting Eq. (2) into (3), we can obtain the optimal number of gateway s^* .

2 Optimal Gateway Deployment

In this section, we discuss two kinds of optimal gateway deployment under different queuing mechanisms in the smart grid networks. To minimize the total cost of the HEMS, the nodes should be divided into different clusters.

2.1 Infinite buffer space

The arrival interval of the packets is independent and subjected to a negative exponential distribution with the parameter λ . The forward time of the gateway is independent and identically distributed, and it is subjected to the negative exponential distribution with μ . The gateway buffer space is infinite, which allows the data packets to queue forever.

For a service system with s gateways, the parameters can be obtained as

$$\lambda_n = \lambda \quad (4)$$

$$\mu_n = \begin{cases} n\mu & n = 1, 2, \dots, s \\ s\mu & n = s, s+1 \end{cases} \quad (5)$$

The state transition process is described as shown in Fig. 3.

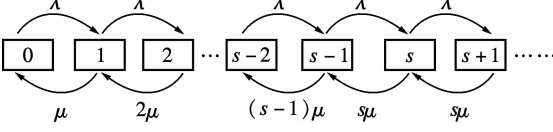


Fig. 3 M/M/s state transition process

The load level of gateway (The scale in undertaking service and the ability of meeting the needs in service desk) is given by

$$\rho = \frac{\lambda}{s\mu} \quad (6)$$

The probability of having j packets in the buffer for the gateway is $P_j = \lim_{t \rightarrow \infty} P\{N(t) = j\}$, then for all ρ , based on limit theorems for the finite state birth-death process, it is easy to prove that

$$P_n = \begin{cases} \frac{(\lambda/\mu)^n}{n!} P_0 & n = 0, 1, 2, \dots, s \\ \frac{(\lambda/\mu)^n}{s! s^{n-s}} & n = s, s+1, \dots \end{cases} \quad (7)$$

where

$$P_0 = \left[1 + \sum_{n=1}^{s-1} \frac{(\lambda/\mu)^n}{n!} + \frac{(\lambda/\mu)^s}{s!} \sum_{n=s}^{\infty} \rho^{n-s} \right]^{-1} \quad (8)$$

The number of the data packets L_q queuing at the gateway buffer is given as

$$L_q = \sum_{n=s}^{\infty} (n-s) P_n = \frac{p_0 (\lambda/\mu)^s \rho}{s! (1-\rho)^2} \quad (9)$$

The average number of the packets L_{delay} waiting at time t is expressed as

$$L_{\text{delay}} = L_q + \rho \quad (10)$$

As the gateway buffer space is unlimited, packets can queue continuously without packet losing, $L_{\text{loss}}(s) = 0$. Substituting Eq. (10) to Eqs. (2) and (3), we have

$$z = sc_s + \alpha L_{\text{delay}} \quad (11)$$

After simplifying (11), we have

$$L_{\text{delay}}(s^*) - L_{\text{delay}}(s^* + 1) \leq \frac{c_s}{\alpha} \leq L_{\text{delay}}(s^* - 1) - L_{\text{delay}}(s^*) \quad (12)$$

Calculating the value L_{delay} for $s = 1, 2, 3, \dots$, respectively, we can make the difference between two adjacent values. Since $\frac{c_s}{\alpha}$ is a known number, we can set s^* according to its value range.

2.2 Limited buffer space

Assume that a gateway buffer space can hold up to K packets and s gateways act as a service platform to work independently. When the position has been occupied by the K packets, the new packets will automatically leave. If there is empty position in the system, the new packets queue to enter the system for service. Delay occurs due to the waiting time of packets in the buffer of the gateway. Loss occurs due to the lack of buffer space and transmission error.

For the M/M/s/K, the parameter μ compared with M/M/s can be obtained as

$$\mu_n = \begin{cases} n\mu & n = 0, 1, 2, \dots, s \\ s\mu & n = s, s+1, \dots, K \\ 0 & n > K \end{cases} \quad (13)$$

The state transition process is described as shown in Fig. 4.

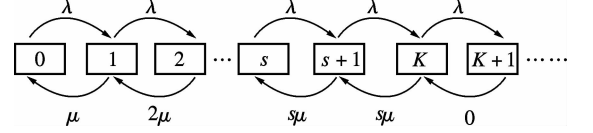


Fig. 4 M/M/s/K state transition process

According to Eqs. (6) and (13), the probability of having j packets in the buffer can be obtained as

$$P_j = \begin{cases} \frac{\rho^j}{j!} P_0 & 1 \leq j < s \\ \frac{1}{s! s^{j-s}} \rho^j P_0 & s \leq j \leq K \end{cases} \quad (14)$$

where

$$P_0 = \frac{1}{\sum_{n=0}^{s-1} \frac{\rho^n}{n!} + \sum_{n=s}^K \frac{\rho^n}{s! s^{n-s}}} \quad (15)$$

The number of data packets queuing at the gateway buffer is given as

$$L_q = \sum_{n=s+1}^N (n-s) P_n = \frac{s^s}{s!} P_0 [\rho^{s+1} - \rho^{N+1} - (N-s)(1-\rho)\rho^{N+1}] \quad (16)$$

Thus, the average number of serviced customers can be expressed as

$$\bar{L}_s = \sum_{n=0}^{s-1} n P_n + s \sum_{n=s}^K P_n = \rho(1 - P_K) \quad (17)$$

The average number of packets L_{delay} waiting at time t is expressed as

$$L_{\text{delay}} = L_q + \bar{L}_s = L_q + \rho(1 - P_K) \quad (18)$$

Since the data packets arrive at the buffer queue constantly, two aspects should be considered. First, if the surplus of arriving packets and the number of packets re-

maintaining in the queue is more than the maximum length of the buffer, the overflowed packets are dropped. Secondly, there is no overflow if the surplus of arriving packets and the number of packets remaining in the queue is less than the maximum length of the buffer.

Related mathematical expression is given as

$$S_t = \min\{K, \max\{0, S_{t-1} - \mu\} + A_t\} \quad (19)$$

So, the number of packets which is discarded at time t can be given as

$$L_{\text{loss}} = \max\{0, A_t - K + \max\{0, S_{t-1} - \mu\}\} \quad (20)$$

Substituting Eqs. (18) and (20) into Eqs. (2) and (3), after simplifying the result, we have

$$\alpha[2L_{\text{delay}}(s^*) - L_{\text{delay}}(s^* + 1) - L_{\text{delay}}(s^* - 1)] \leq c_s \leq \beta[L_{\text{loss}}(s^* - 1) + L_{\text{loss}}(s^* + 1) - 2L_{\text{loss}}(s^*)] \quad (21)$$

The optimal number of gateway s^* can be obtained because c_s is given, L_{delay} and L_{loss} can be calculated for $s = 1, 2, 3, \dots$

3 Simulation Results and Analyses

We consider a service area of 1 km^2 with one community which is composed of 100 nodes. These nodes are all served by one WAN base station. Each node generates 1.8 packets per minute on average. All the nodes are divided into several clusters and every cluster has one gateway. The optimal number of gateways can be determined by the optimal cluster size. The transmission rate of the gateway to the base station is 6 packets per minute. The gateway installation cost is assumed to be $c_s = 10$, while the cost weights of packet delay and loss are $\alpha = 0.1$ and $\beta = 1$, respectively. The maximum buffer space in M/M/s/K queuing mechanism is $K = 100$ packets.

Fig. 5 shows the average cost per node under infinite buffer space. It is observed that all the nodes are divided into several clusters. If the cluster size is small, the average cost per node is high due to the high installation costs of gateways. When the cluster size increases, the average cost decreases due to the low installation costs. However, at a certain cluster size, the system costs increase as the packet generation rates increase.

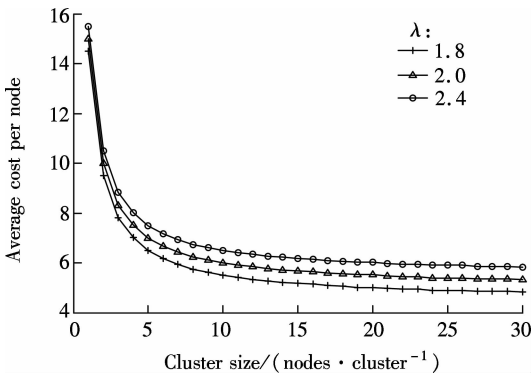


Fig. 5 Average cost per node under infinite buffer space

buffer space. When the nodes served by one gateway increase, the average cost increases after the small decline, and finally increases dramatically. It is observed that, when the data packet generation rate is 1.8 packet/min as we assumed, the optimal cluster size is 5 nodes (i.e., the gateway number is 40) which can minimize the system cost. When the packet generation rate increases, the system cost increases due to the limited buffer space.

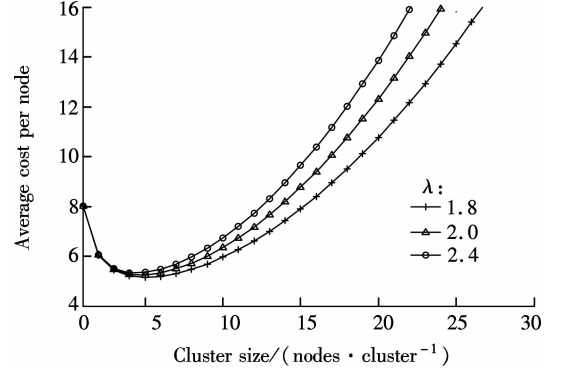


Fig. 6 Average cost per node under limited buffer space

Fig. 7 shows the average cost per node under different packet generation rates. The dotted line in the figure represents the optimal cluster information. When the packet generation rate is less than 1.8, the cluster size 5 is always close to the optimal formation. When the packet generation rate changes to more than 1.8, the corresponding optimal number of gateways is shown in Fig. 7. For the larger cluster size, the cost increases dramatically due to the limited buffer space. It is observed that the proposed cluster formation can not only determine the optimal cluster size, but also the number of nodes in each cluster, and achieves the lowest cost.

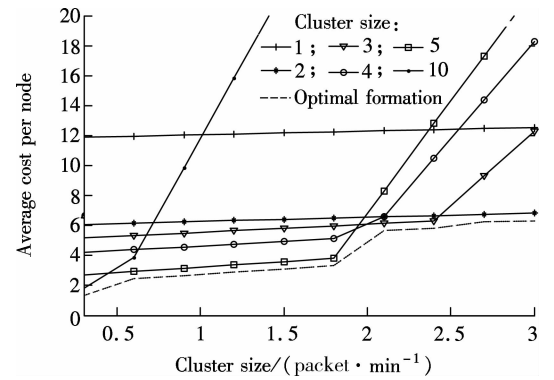


Fig. 7 Cost per node under different packet generation rates

4 Conclusion

In this paper, the optimal gateway deployment strategy in the smart grid network is proposed. The problem of minimizing HEMS cost is formulated as a gateway deployment problem. In order to solve the problem of data transmission cost, two transmission schemes under different queuing mechanisms are discussed and the optimal number of gateways is obtained in both situations. Simu-

Fig. 6 shows the average cost per node under limited

lation results show that the cost of the HEMS system mostly comes from the gateway installation if the gateway buffer space is infinite. The proposed queueing mechanism can determine the optimal number of gateways and minimize the cost of the HEMS system in the case of limited gateway buffer space.

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智能电网中不同排队机制下的最优网关配置

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摘要:通过优化网络拓扑结构,提出了一种在家庭能源管理系统(HEMS)中基于动态规划的排队论聚类算法. 首先将 HEMS 的总花费划分成网关的安装成本及数据传输成本 2 个部分,然后通过对比 2 种不同的排队论聚类算法,将家庭能源管理系统中的成本问题转化为系统网关部署问题,最后,设计了一种使系统花费最小的 M2M 网关配置方案. 仿真结果表明,当网关缓冲区间足够大时,HEMS 系统的花费主要来自网关的安装成本. 当网关缓冲区间有限时,通过边际分析方法及成本最小化特性,所提出的排队算法能够保证在最小化花费的基础上实现网关的最优分配.

关键词:智能电网;家庭能源管理系统;排队论;网关分配

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