Group-Server Queues

Quan-Lin Li\textsuperscript{a}, Jing-Yu Ma\textsuperscript{a}, Mingzhou Xie\textsuperscript{b} and Li Xia\textsuperscript{b}

\textsuperscript{a}School of Economics and Management Sciences
Yanshan University, Qinhuangdao 066004 China
liquanlin@tsinghua.edu.cn

\textsuperscript{b}Center For Intelligent and Networked Systems
Department of Automation and TNList
Tsinghua University, Beijing 100084 China
xial@tsinghua.edu.cn

Abstract

By analyzing energy-efficient management of data centers, this paper proposes and develops a class of interesting Group-Server Queues, and establishes two representative group-server queues through loss networks and impatient customers, respectively. Furthermore, such two group-server queues are given model descriptions and necessary interpretation. Also, simple mathematical discussion is provided, and simulations are made to study the expected queue lengths, the expected sojourn times and the expected virtual service times. In addition, this paper also shows that this class of group-server queues are often encountered in many other practical areas including communication networks, manufacturing systems, transportation networks, financial networks and healthcare systems. Note that the group-server queues are always used to design effectively dynamic control mechanisms through regrouping and recombining such many servers in a large-scale service system by means of, for example, bilateral threshold control, and customers transfer to the buffer or server groups. This leads to the large-scale service system that is divided into several adaptive and self-organizing subsystems through scheduling of batch customers and regrouping of service resources, which make the middle layer of this service system more effectively managed and strengthened under a dynamic, real-time and even reward optimal framework. Based on this, performance of such a large-scale service system may be improved greatly in terms of introducing and analyzing such group-server queues. Therefore, not only analysis of group-server queues is regarded as a new interesting research direction, but there also exists many theoretical challenges, basic difficulties and open problems in the area of queueing networks.

Keywords: Group-server queue, data center, energy-efficient management, loss network, impatient customer.

1 Introduction

In this paper, we propose and develop a class of interesting Group-Server Queues by analyzing energy-efficient management of data centers, and establish two representative group-server queues by means of loss networks and impatient customers, respectively. Also, we show that this class of group-server queues are often encountered in many other practical areas including communication...
networks, manufacturing systems, transportation networks, financial networks and healthcare systems. Therefore, not only analysis of group-server queues is regarded as a new interesting research direction, but there also exists many theoretical challenges, basic difficulties and open problems in the area of queueing networks.

Data centers are main infrastructure platforms for various kinds of large-scale practical information systems, and always offer economies of scale for network, power, cooling, administration, security and surge capacity. So far it has been an interesting research direction to reduce the server farm energy requirements and to optimize the power efficiency which may be viewed as a ratio of performance improvement to power consumption reduction. For energy-efficient management of data centers, some authors have dealt with several key interesting issues, for example, data center network architecture by Al-Fares et al. [1], Guo et al. [20] and Pries et al. [35]; green networks and cloud by Kliazovich et al. [25], Mazzucco et al. [32], Gruber and Keller [18], Goiri et al. [13] [14] with solar energy, Li et al. [27] with wind energy, Wu et al. [41] and Zhang et al. [43]; networks of data centers by Greenberg et al. [16] [17], Gunaratne et al. [19], Shang et al. [38], Kliazovich et al. [25] and Wang et al. [39]; resiliency of data centers by Heller et al. [23] and Baldoni et al. [3]; revenues, cost and performance by Elnozahy et al. [8], Chen et al. [6], Benson et al. [4], Dyachuk and Mazzucco [7], Mazzucco et al. [31] and Aroca et al. [2]; analyzing key factors by Greenawalt [15] for hard disks, Chase et al. [5] for hosting centers (i.e., the previous one of data center), Guo et al. [21] for base station sleeping control, Guo et al. [22] for edge cloud systems, Horvath and Skadron [24] for multi-tier web server clusters, Lim et al. [30] for multi-tier data centers, Rivoire et al. [34] for a full-system power model, Sharma et al. [37] for QoS, Wierman et al. [40] for processor sharing, and Xu and Li [42] for part execution.

In analyzing energy-efficient management of data centers, queueing theory and Markov processes are two effective mathematical tools both from performance evaluation and from optimal control. Up till now, few papers have applied queueing theory, together with Markov processes, to performance analysis of data centers with energy-efficient management. Chen et al. [6] proposed a queueing model to control energy consumption of service provisioning systems subject to Service Level Agreements (SLAs). Nedevschi et al. [33] demonstrated that introducing a sleep state to power management in a data center can save much of the present energy expenditure, and even simple schemes for sleeping also offer substantial energy savings. Shang et al. [35] used network devices to routing service design, and made the idle network devices to shut down or to put into a sleep state. Gandhi et al. [9] modeled a server farms with setup cost by means of an M/M/k queueing system, where each server can be in one of the following states: work, on, idle, off, or sleep, employed the popular metric of Energy-Response time Product (ERP) to capture the energy-performance tradeoff, and gave the first theoretical result on the optimality of server farm management policies. From a similar analysis to [9], Gandhi et al. [10] used an M/M/k queueing system but each server has only three states: on, setup and off, and obtained the distributions of the response time and of the power consumption. Further, Gandhi and Harchol-Balter [11], Gandhi et al. [12] analyzed effectiveness of dynamic power management in data centers in terms of an M/M/k model, and found that the dynamic power management policies are very effective when the setup time is small, the job size is large or the size of the data center is increasing; in contrast, the dynamic power management policies are ineffective for small data centers. Schwartz et al. [36] and Gunaratne et al. [19] provided the energy-efficient mechanism with dual thresholds. Schwartz et al. [36] presented a queueing model to evaluate the trade-off between the waiting time and the energy consumption, and also developed a queueing model with thresholds to turn-on reserve servers when needed. Gunaratne et al. [19] developed a single-server queue with state-dependent
service rates and with dual thresholds for service rate transitions.

**Contributions of this paper:** The main contributions of this paper are threefold. The first one is to propose and develop a class of interesting Group-Server Queues, and establishes two representative group-server queues by means of loss networks and impatient customers, respectively, under a practical background for analyzing energy-efficient management of data centers. The second contribution is to set up a general framework for group-server queues, and to give a detailed discussion for basic issues, for instance, optimally structural division of server groups, transfer policies among server groups and/or buffers, dynamic control mechanism design, revenue management and cost control. The third contribution is to provide a simple mathematical analysis for a two-group-server loss queue, and also to design simulation experiments to evaluate the expected queue lengths, the expected sojourn times and the expected virtual service times for a three-group-server loss queue and a three-group-server queue with an infinite buffer. Note that this class of group-server queues are often encountered in many other practical areas including communication networks, manufacturing systems, transportation networks, financial networks and healthcare systems. Therefore, the methodology and results given in this paper provide highlights on a new class of queueing networks called group-server queues, and are applicable to the study of large-scale service networks in practice.

**Organization of this paper:** The structure of this paper is organized as follows. In Section 2, we propose and develop a class of new interesting queueing models: Group-Server Queues, and establish a basic framework of the group-server queues, for instance, model structure, operations mechanism, necessary notation and key factors. In Section 3, we describe a group-server loss queue from analyzing energy-efficient management of data centers, where the loss mechanism makes a finite state space so that the group-server loss queue must be stable. In Section 4, we describe a group-server queue with impatient customers and with an infinite buffer, where some key factors of this system are discussed in detail. In Section 5, we provide a simple mathematical analysis for the two-group-server loss queue, and several open problems are listed. In Section 6, we design simulation experiments for performance evaluation of the three-group-server loss queues and of the three-group-server queues with an infinite buffer, and specifically, we analyze their expected queue lengths, the expected sojourn times and the expected virtual service times. Finally, some concluding remarks are given in Section 7.

## 2 A Basic Framework of Group-Server Queues

In this section, we propose a class of new interesting queueing models: Group-Server Queues, and establish a basic framework for the group-server queues, for instance, model structure, operations mechanism, necessary notation and key factors.

We propose such group-server queues by analyzing energy-efficient management of data centers. As analyzed in the next two sections, two representative group-server queues are established according to the need of energy saving. To realize energy saving in data center networks, a sleep (or off) state introduced to some servers is a class of key techniques. Using States on, sleep, off and others, a large-scale service system with more servers is divided into several subsystems, each of which contains some servers having certain common attributes. For example, a data center has a set of all different attributes: \( E = \{ \text{work, on, sleep, off} \} \), where ‘work’ denotes that a server is ‘on’ and is also serving a customer; ‘on’ denotes that a server is idle and ready to serve; ‘sleep’ denotes that a server is at the dormancy stage with lower power consumption; and ‘off’ denotes
that a server is shut down, where a setup time may be needed if the server change its state from off to on (or sleep).

Now, we provide a concrete example how to establish the different groups of servers. Let the set of all the servers in the data center be \( \Omega = \{ \text{Server 1, Server 2, Server 3, \ldots, Server N} \} \). Then the service system of the data center can be divided into three subsystems whose server groups are given by

\[
\Omega_1 = \{ \text{Server 1, Server 2, \ldots, Server } n \}, \text{ each server is either at work or on;}
\]

\[
\Omega_2 = \{ \text{Server } n + 1, \text{Server } n + 2, \ldots, \text{Server } n + m \},
\text{ each server is either at work, on, or sleep;}
\]

\[
\Omega_3 = \{ \text{Server } n + m + 1, \text{Server } n + m + 2, \ldots, \text{Server } N \},
\text{ each server is either at work, on, sleep or off.}
\]

It is seen that the attributes of servers in \( \Omega_2 \) are more than that in \( \Omega_1 \), that is, sleep. While the sleep attribute makes \( \Omega_2 \) practically different from \( \Omega_1 \). See Fig.1 in the next section for an intuitive understanding. At the same time, to further understand the attribute role played by the energy efficient mechanism of data centers, readers may refer to the next two sections for establishing and analyzing two representative group-server queues.

In general, this class of group-server queues are often encountered in many other practical areas, for example, communication networks for green and energy saving, manufacturing systems for priority use of high-price devices, transportation networks with different crowded areas, and healthcare systems having different grade hospitals. Therefore, analyzing the group-server queues is an interesting research direction both in the queueing area and in many practical fields such as computer, communication, manufacturing, service, market, finance and so on. To our best knowledge, no pervious work has looked at and summarized the group-server queues from a theoretical or practical framework yet.

Based on the above analysis, we provide a basic framework for the group-server queues, and discuss model structure, operations mechanism, necessary notation and key factors as follows:

**Server Groups:** We assume that a large-scale service system contains many servers whose set is given by

\[ \Omega = \{ \text{Server 1, Server 2, Server 3, \ldots, Server N} \}, \]

and they also have some different attributes whose set is given by

\[ E = \{ A_1, A_2, A_3, \ldots, A_r \}, \]

where \( A_i \) is an attribute for \( 1 \leq i \leq r \). From practical need and physical behavior of a large-scale service system, the attribute set \( E \) is divided into some different subsets as follows:

\[ E = E_1 \cup E_2 \cup \cdots \cup E_s, \quad s \leq r. \]

Note that \( E_i \) and \( E_j \) may have common elements for \( 1 \leq i < j \leq s \). Applying the subsets \( E_i \) for \( 1 \leq i \leq s \) to system behavior, the server set \( \Omega \) is divided into some different groups or subsets as follows:

\[ \Omega = \Omega_1 \cup \Omega_2 \cup \cdots \cup \Omega_s, \]
where the server group $\Omega_i$ well corresponds to the attribute subset $E_i$ for $1 \leq i \leq r$. Note that the server groups $\Omega_i$ for $1 \leq i \leq s$ are disjoint. In this case, the large-scale service system is divided into $s$ subsystems, each of which contains the servers in the group $\Omega_i$ having certain common attributes in one of the subsets $E_i$ for $1 \leq i \leq s$.

In practice, the attributes $A_i$ for $1 \leq i \leq r$ have a wide range of meanings, for instance, states, properties, behaviors, control and mechanism. From such a setting, it is clear that the server grouping of a large-scale service system should not be unique.

**Arrival processes:** In the group-server queue, we assume that customer arrivals at this system are a renewal process with stationary arrival rate $\lambda$. For the customer arrivals, we shall encounter two issues: (a) Routing allocation mechanism, for example, joining the shortest queue length, and joining the shortest sojourn time. (b) Arrival rate control, for example, arrival rates depending on system states, arrival rates depending on prices, arrival rates depending on sojourn times, and arrival rates depending on threshold control.

**Service processes:** In the $i$th server group, the service times of customers are i.i.d. with general distribution function $F_i(x)$ of stationary service rate $\mu_i$ for $1 \leq i \leq N$. For the customer service processes, we shall encounter two issues: (a) service disciplines, for example, FCFS, LCFS, processor sharing, and matching service. (b) Service rate control, for example, service rates depending on system states, service rates depending on prices, service rates depending on sojourn times, and service rates depending on threshold control.

**Customers transfer among server groups:** The customers in heavy-load server groups are encouraged to transfer into light-load server groups; the customers in low-speed-service server groups are encouraged to transfer into high-speed-service server groups; the customers in high-cost-service server groups are encouraged to transfer into low-cost-service server groups; and so forth. Under customer transferring, the residual service times of non-exponential distributions always make model analysis more difficult and challenging.

**Stability is a difficult issue:** Since the group-server queue is always a large-scale complicated stochastic system, its stability and associated conditions are always very difficult to study. To easily deal with system stability, it is a simple method to introduce loss networks or impatient customers to the group-server queues, where the former is to use the finite state space, while the latter is to apply stability of the renewal processes. Therefore, this paper uses the loss networks and the impatient customers to set up some examples, which show how to simply guarantee stability of some group-server queues.

### 3 Group-Server Loss Queues

In this section, we describe a group-server loss queue from analyzing energy-efficient management of data centers. Note that the ‘Loss Mechanism’ is to set up a finite state space, whose purpose is to guarantee stability of the group-server loss queue.

In the energy-efficient management study of data center networks, it was an effective way to introduce two states: sleep and off for some servers. Based on this, we can make some different states: work, on, sleep, off and others, and the servers of the data center are grouped as $\Omega = \Omega_0 \cup \Omega_1 \cup \cdots \cup \Omega_N$. Concretely, a simple group-server loss queue is constructed under two states: work-on, and sleep. Here, work and on are assumed to have the same power consumption, hence
work and on are regarded as a state: work-on. See Fig.1, for understanding the $N+1$ server groups and even for intuitively understanding the group-server loss queue.

Now, we use the data center to describe a group-server loss queue, and set up energy efficient mechanism, system parameters and model notation as follows:

(1) **Server groups**: We assume that the data center contains $N + 1$ different server groups, each of which is a subsystem of the data center. For $j \in \{0, 1, 2, \ldots, N\}$, the $j$th server group contains $m_j$ same servers. Thus the data center contains $\sum_{j=0}^{N} m_j$ servers in total. Note that the $N+1$ different server groups can be divided into two basic categories: (a) Server group 0 is special, because its each server has only one state: work-on. Hence server group 0 with $m_0$ same servers is viewed as the base-line group in the data center. (b) Each server of the other $N$ server groups has two states: work-on and sleep.

(2) **Arrival processes**: The arrivals of customers at the data center from outside are a renewal process with stationary arrival rate $\lambda$. An arriving customer preferentially enters one idle server of the leftmost server group with idle servers. We assume that each server and the data center all have no waiting room, while each server receives and serves only one customer at a time. Hence any new arrival is lost once all the servers contain their one customer, that is, the system is full when it has at most $\sum_{j=0}^{N} m_j$ customers.

(3) **Service processes**: In the $j$th server group, the service times of customers are i.i.d. with general distribution function $F_j(x)$ of stationary service rate $\mu_j$ for $0 \leq j \leq N$.

(4) **Bilateral threshold control**: Except server group 0, each server in the other $N$ server
groups have two states: work-on and sleep. To switch between work-on and sleep, it is necessary for the $j$th server group to introduce a positive integer pair $(L_j, K_j)$ with $0 \leq L_j \leq K_j \leq m_j$, which leads to a class of bilateral threshold control applied to energy-efficient management of the data center networks.

To realize energy saving effectively, using the two states: work-on and sleep, a bilateral threshold control is introduced as follows: Once there are more than $K_j$ customers in the $j$th server group, then each server of the $j$th server group immediately enters State work-on. On the contrary, when there are less than $L_j$ customers in the $j$th server group, then each server of the $j$th server group immediately enters State sleep. Thus for the data center, we have the coupled threshold control parameters as follows:

\[ \{(L_j, K_j) : 0 \leq L_j \leq K_j \leq m_j, 1 \leq j \leq N \} . \]

(5) **Customers concentratively transfer among the server groups:** In order to make the sleep servers to enter State work-on as soon as possible, it is necessary to concentratively transfer those customers in the sleep servers of the rightmost server group with sleep servers into the idle servers (on or sleep) of the leftmost server group. Using such a way, this maximizes the number of customers in the leftmost server group with sleep servers such that the number of servers with a customer fast goes to over the integer $K_j$, which leads to that the sleep servers is started up and enters State work-on. In this case, the most sleep servers in the data center are setup at State work-on so that more and more customers are served as soon as possible.

(6) **Energy consumption:** We assume that the power consumption rates for the $1 + N$ server groups are given by $P_{W_0}, P_{W_1}, \ldots, P_{W_N}$ for State work-on; and $P_{S_0} = 0, P_{S_1}, P_{S_2}, \ldots, P_{S_N}$ for State sleep. To realize energy saving, let $0 < P_{S_j} < P_{W_j}$ for $j = 1, 2, \ldots, N$.

We assume that all the random variables in the system defined above are independent of each other.

A **basic issue:** Establishing some cost (or reward) functions is to evaluate a suitable trade-off between the sojourn time and the energy consumption. To concentratively reduce the sojourn time and to save energy, some effective methods are proposed and developed, such as, (a) the bilateral threshold control, (b) the customers at sleep servers concentratively transfer among the server groups, and (c) the residual service times are wasted or re-used. We need to analyze their performance and trade-off due to some mutual contradiction between reducing the sojourn time and saving the energy.

4 **Group-Server Queues with Impatient Customers**

In this section, we consider a group-server queue with impatient customers, which is refined and abstracted from energy-efficient management of data center networks, where the impatient customers are introduced to guarantee stability of this group-server queue with an infinite buffer.

In the data center, we still introduce two states: work-on and sleep for some servers. Based on the two different states, the servers of the data center are grouped as $\Omega = \Omega_0 \cup \Omega_1 \cup \Omega_2 \cup \cdots \cup \Omega_N$. See Fig.2 both for the $N+1$ server groups and for the group-server queue with impatient customers and with an infinite buffer.

Now, we describe a group-server queue with impatient customers and with an infinite buffer,
and also explain energy efficient mechanism, system parameters and model notation as follows:

(1) Server groups: We assume that the data center contains \( N + 1 \) different server groups, each of which is a subsystem of the data center. For a \( j \in \{0, 1, 2, \ldots, N\} \), the \( j \)th server group contains \( m_j \) same servers. Thus the data center contains at most \( \sum_{j=0}^{N} m_j \) servers. Note that the \( N + 1 \) different server groups can be divided into two basic categories: (a) Server group 0 is special, because its each server has only one state: work-on, hence server group 0 with \( m_0 \) same servers is viewed as the base-line group in the data center. (b) Each server of the other \( N \) server groups has two states: work-on and sleep.

(2) Arrival processes: The arrivals of customers at the data center from outside are a renewal process with stationary arrival rate \( \lambda \). Each arrival customer must first enter the infinite buffer, then he is assigned to the \( N + 1 \) server groups according to the following allocation rules:

(2-A1) Each server in server group 0 is always at State work-on. If server group 0 have some idle servers, then the arriving customer can immediately enter one idle server in server group 0 and then receive his service.

(2-A2) Each server in server group 1 is at State sleep. If server group 0 does not exist any idle server, then the new arrival customers have to queue and wait in the buffer. Once the number of customers waiting in the buffer is not less than \( K_1 \), then each server in server group 1 is started up to State work-on from State sleep, and all the customers in the buffer but at most \( m_1 \) customers enter server group 1 and then receive their service.

(2-A3) Each server in server group 2 is at State sleep. If server groups 0 and 1 do not exist any idle server, then the new arrival customers have to queue and wait in the buffer. Once the number

Figure 2: Physical structure of the group-server queue with impatient customers
of customers waiting in the buffer is not less than $K_2$, then each server in server group 2 is started up to State work-on from State sleep, and all the customers in the buffer but at most $m_2$ customers enter server group 2 and then receive their service.

(2-A4) Let $2 \leq l \leq N - 1$. Each server in server group $l + 1$ is at State sleep. If server groups $0, 1, 2, \ldots, l$ do not have any idle server, then the new arriving customers have to queue and wait in the buffer. Once the number of customers waiting in the buffer is not less than $K_{l+1}$, then each server in server group $l + 1$ is started up to State work-on from State sleep, all the customers in the buffer but at most $m_{l+1}$ customers enter server group $l + 1$ and then receive their service.

(2-B) If the $N + 1$ server groups do not exist any idle server, then the new arriving customers have to queue and wait in the buffer.

(2-C) In the $N + 1$ server groups, if there exists one idle server whose state is work-on, then an arriving customer in the buffer will immediately enter this server and then receive his service.

(3) Service processes: In the $j$th server group, the service times of customers are i.i.d. with general distribution function $F_j(x)$ of stationary service rate $\mu_j$ for $0 \leq j \leq N$.

(4) Customer impatient processes: Each customer in this system has an exponential patient time of impatient rate $\theta$.

(5) Bilateral threshold control: Except server group 0, each server in the other $N$ server groups have two states: work-on and sleep. To switch between work-on and sleep, it is necessary for the $j$th server group to introduce a positive integer pair $(L_j, K_j)$ with $0 \leq L_j \leq K_j \leq m_j$, which leads to a bilateral threshold control by means of energy-efficient management of the data center networks. By using the two states: work-on and sleep, a Bilateral Threshold Control is introduced as follow:

(5-1) From sleep to work-on: We assume that each server in server group $j$ is at State sleep, and an idle server does not exist in server groups $0, 1, 2, \ldots, j - 1$, for $1 \leq j \leq N$. If there are not less than $K_j$ customers in the buffer, then each server in server group $j$ is started up to State work-on from State sleep, all the customers in the buffer but at most $m_j$ customers enter server group $j$ and then receive their service.

(5-2) From work-on to sleep: We assume that each server in server group $j$ is at State work-on. If there are less than $L_j$ customers being served in server group $j$, then each server of server group $j$ immediately enters State sleep from State work-on, and those customers being served at server group $j$ are transferred to the head of the buffer. For such transferred customers, we assume that those service times obtained by the transferred customers, will become zero, and their service get start again (note that another useful case is that the received service times can be cumulative, once arriving at the total service time, the service is completed) immediately. Also, to allocate the customers in the buffer to some server groups, each customer transferred in the head of the buffer is the same as the new arriving customers. Thus we have the coupled threshold control parameters

\[ \{(L_j, K_j) : 0 \leq L_j \leq K_j \leq m_j, 1 \leq j \leq N\}. \]

(6) Customers transfer to the buffer: In order to save energy as much as possible, if there are less than $L_j$ customers being served in server group $j$, then it is necessary to transfer those customers in the server group $j$ at State work-on into the head of the buffer, and each server of server group $j$ immediately enters State sleep from State work-on.

(7) Energy consumption: We assume that the power consumption rates for the $1 + N$ server groups are given by $P_{W_0}, P_{W_1}, \ldots, P_{W_N}$ for State work-on; and $P_{S_0} = 0, P_{S_1}, P_{S_2}, \ldots, P_{S_N}$ for State
sleep. For energy saving, let \( 0 < P_{S_j} < P_{W_j} \) for \( j = 1, 2, \ldots, N \).

We assume that all the random variables in the system defined above are independent of each other.

A basic issue: Constructing some cost (or reward) functions is to evaluate a suitable trade-off between the sojourn time and the energy consumption. Note that some effective methods are proposed and developed, such as, (a) the bilateral threshold control, (b) customers in sleep servers transfer to the buffer, and (c) residual service times are wasted or re-used. We need to analyze their performance and the suitable trade-off due to some mutual contradiction between reducing the sojourn time and saving the energy.

Further discussion for stability: For the group-server queue with an infinite buffer drawn in Fig.2, it is easy to give a sufficient condition of system stability: \( \rho = \lambda/m_0 \mu_0 < 1 \), by means of a path coupling or comparison of a Markov process.

It is seen from Fig.2 that server groups 1, 2, \ldots, \( N \) provide many service resources or ability in processing the customers, and this buffer also plays a key role in concentratively transferring the customers in sleep servers to improve service ability of the whole system. Therefore, it may be an interesting open problem to set up the necessary conditions under which the system stability is, how to be influenced by the key factors or parameters, as follows: (a) the bilateral threshold control, (b) customers in sleep servers transfer to the buffer, and (c) many residual service times are wasted or re-used.

5 Mathematical Analysis and Open Problems

In this section, we provide some simple mathematical analysis for a two-group-server loss queue with server group 0 and server group 1, a whole detailed investigation of which was given in Li et al. [29]. From such mathematical analysis, it is seen that analyzing more general group-server queues is interesting, challenging and difficult, and thus several open problems are listed for the future study of group-server queues.

5.1 Some mathematical analysis

A special model: \( N = 1 \). We consider a special two-group-server loss queue with server group 0 and server group 1. See model descriptions for a more general case given in Section 3 in more details.

For convenience of readers, it is still necessary to simply re-list some assumptions and descriptions for this special case as follows: (a) Server group 0 contains \( n \) servers, each of which has only one state: work-on; while server group 1 contains \( m \) servers, each of which has two different states: work-on and sleep. (b) No waiting room is available both at each server and in the group-server queue. Once there are \( n + m \) customers in this system (i.e., one server is serving a customer), any new customer arrival will be lost due to no waiting room. (c) The arrivals of customers at this two-group-server queue are a Poisson process with arrival rate \( \lambda \). (d) The service times provided by server group 0 and by server group 1 are i.i.d. with two exponential distributions of service rate \( \mu_0 \) and \( \mu_1 \), respectively. (e) Unilateral threshold control: \( L_1 = 0 \) and \( K_1 > 0 \). In this case, if server
group 0 are full with \( n \) serving customers, and if there are not less that \( K_1 \) customers waiting at server group 1 with \( m \) sleep servers, then each server of server group 1 immediately enters State work-on, and then provides service for its customer. (f) Because of \( L_1 = 0 \), once all the customers in server group 1 have completed their service, the \( m \) servers of server group 1 immediately switch to State sleep from State work-on; if there are some idle (on) servers in server group 0, and if there are customers waiting in server group 1 in which each server is at State sleep, then the customers waiting at the sleep servers of server group 1 can transfer to those idle (on) servers of server group 0. (g) For each server in the two server groups, the power consumption rates are listed as: \( P_{W_0} \) and \( P_{W_1} \) for State work-on, and \( P_{S_1} \) for State sleep (\( P_{S_0} = 0 \) because each server in server group 0 does not have State sleep). To save energy, we assume that \( 0 < P_{S_1} < P_{W_1} \).

A QBD process: For this two-group-server loss queue, the states of the corresponding Markov process are defined as the tuples: \( (l_0, i; l_1, j) \) as shown in Fig.3, where \( l_0 = W, l_1 \in \{W, S\} \). \( W \) and \( S \) denote States work-on and sleep, respectively. Let \( i \) be the number of servers serving a customer in server group 0, and \( j \) the number of servers serving a customer in server group 1. It is seen from Fig.3 that for \( (W, i; l_1, j) \), we can set up four different sets as follows:

1. In Block 1, \( i \in \{0, 1, \ldots, n - 1, n\} \); \( l_1 = S, j = 0 \);
2. In Block 2, \( i \in \{n\} \); \( l_1 = S, j \in \{1, 2, \ldots, K - 1\} \);
3. In Block 3, \( i \in \{0, 1, \ldots, n - 1, n\} \); \( l_1 = W, j \in \{1, 2, \ldots, K - 1\} \);
4. In Block 4, \( i \in \{0, 1, \ldots, n - 1, n\} \); \( l_1 = W, j \in \{K, K + 1, \ldots, m\} \).

We denote by \( N_0 (t) \) and \( N_1 (t) \) the numbers of servers serving a customer in server group 0 and server group 1, respectively; and \( S_0 (t) \) and \( S_1 (t) \) the states of servers in server groups 0 and 1, where \( S_0 (t) = W \) and \( S_1 (t) \in \{W, S\} \). Let \( X (t) = (S_0 (t), N_0 (t); S_1 (t), N_1 (t)) \) with \( S_0 (t) = W \). Then \( \{X (t), t \geq 0\} \) is a QBD process with finitely many levels. From Fig.3, it is seen that the QBD process \( \{X (t), t \geq 0\} \) has a state space \( \Omega = \Omega_0 \cup \Omega_1 \cup \Omega_2 \cup \cdots \cup \Omega_m \), where

\[
\begin{align*}
\Omega_0 &= \{(W, 0; S, 0), (W, 1; S, 0), \ldots, (W, n - 1; S, 0), (W, n; S, 0)\}, \\
\Omega_1 &= \{(W, n; S, 1) \cup \{(W, n; W, 1), (W, n - 1; W, 1), \ldots, (W, 0; W, 1)\}, \\
\Omega_2 &= \{(W, n; S, 2) \cup \{(W, n; W, 2), (W, n - 1; W, 2), \ldots, (W, 0; W, 2)\}, \\
& \vdots \quad \vdots \\
\Omega_{K-1} &= \{(W, 0; S, K - 1) \cup \{(W, n; W, K - 1), (W, n - 1; W, K - 1), \ldots, (W, 0; W, K - 1)\}; \\
\Omega_K &= \{(W, n; W, K), (W, n - 1; W, K), \ldots, (W, 1; W, K), (W, 0; W, K)\}; \\
\Omega_{K+1} &= \{(W, n; W, K + 1), (W, n - 1; W, K + 1), \ldots, (W, 0; W, K + 1)\}; \\
& \vdots \quad \vdots \\
\Omega_m &= \{(W, n; W, m), (W, n - 1; W; m), \ldots, (W, 1; W, m), (W, 0; W, m)\}.
\end{align*}
\]

Let the subset \( \Omega_j \) be Level \( j \). Then each element in Level \( j \) or the subset \( \Omega_j \) is a phase. It is clear that the QBD process \( \{X (t), t \geq 0\} \) has the infinitesimal generator as follows:
Figure 3: State transition relations of Markov process in a two-group-server loss queue
A Markov reward process: Using the power consumption rates, we define $f(x)$ as an instantaneous reward of the QBD process $\{X(t), t \geq 0\}$ at the state $X(t) = x$. It is clear that for $x = (W, i; l_1, j)$ with $i \in \{0, 1, ..., n-1, n\}$,

$$f(W, i; l_1, j) = \begin{cases} np_{W,0} + m_{P_{S_1}}, & l_1 = S, j \in \{0, 1, ..., K-1\}, \\ np_{W,0} + m_{P_{W_1}}, & l_1 = W, j \in \{1, 2, ..., m\}. \end{cases}$$

(1)

For simplification of description, we write $f_{W,i;l_1,j} = f(W, i; l_1, j)$.

It is seen from Fig.3 and the state space $\Omega = \Omega_0 \cup \Omega_1 \cup \cdots \cup \Omega_m$ that for Level 0,

$$f_{S,0} = (f_{W,0;S,0}, f_{W,1;S,0}, \ldots, f_{W,n;S,0});$$

for Level $j$ with $1 \leq j \leq K-1$,

$$f_{S,0;S,j} = (f_{W,0;S,j}, f_{W,1;S,j}, \ldots, f_{W,n;S,j});$$

and for Level $j$ with $K \leq j \leq m$,

$$f_{W,j} = (f_{W,0,W,j}, f_{W,1,W,j}, \ldots, f_{W,n,W,j}).$$

We write

$$f_j = \begin{cases} f_{S,0}, & j = 0, \\ f_{S,0;S,j}, & 1 \leq j \leq K-1, \\ f_{W,j}, & K \leq j \leq m, \end{cases}$$

and

$$f = (f_0, f_1, \ldots, f_{K-1}, f_K, \ldots, f_m)^T.$$  

Now, for the two-group-server loss queue, we analyze some interesting performance measures: (a) The expected instantaneous power consumption rate $E[f(X(t))]$; and (b) the cumulative power consumption $\Phi(t)$ during the time interval $[0, t)$. At the same time, the probability distribution and the first passage time involved in the energy saving are also computed in detail.

The expected instantaneous power consumption rate: We note that $f(X(t))$ is the instantaneous power consumption rate of the two-group-server queue at time $t \geq 0$. If the QBD process $Q$ is stable, then

$$\lim_{t \to +\infty} E[f(X(t))] = \sum_{(W, i; l_1, j) \in \Omega} \pi_{W,i;l_1,j} f_{W,i;l_1,j} = \pi f,$$
where $\pi$ is the stationary probability vector of the QBD process $Q$, and it can be obtained through solving the system of linear equations $\pi Q = 0$ and $\pi e = 1$ by means of the $RG$-factorizations given in Li [28], where $e$ is a column vector of ones.

The cumulative power consumption $\Phi (t)$ during the time interval $[0, t)$

Based on the instantaneous power consumption rate $f (X(t))$, we define the cumulative power consumption during the time interval $[0, t)$ as

$$ \Phi (t) = \int_0^t f (X(u)) \, du. $$

(i) Computing the probability distribution: Now, we compute the probability distribution of the cumulative power consumption $\Phi (t)$ by means of a partial differential equation whose solution can explicitly be given in terms of the Laplace and Laplace-Stieltjes transforms. Let $\Theta (t, x) = P \{ \Phi (t) \leq x \}$ and

$$ H_{W;i;S,j} (t, x) = P \{ \Phi (t) \leq x, X(t) = (W, i; l_1, j) \}. $$

We write that for Level 0,

$$ H_{S,0} (t, x) = (H_{W;0,S,0} (t, x), H_{W;1,S,0} (t, x), \ldots, H_{W;n,S,0} (t, x)); $$

for Level $j$ with $1 \leq j \leq K - 1$,

$$ H_{SW,j} (t, x) = (H_{W;n,S,j} (t, x); H_{W;0,W,j} (t, x), H_{W;1,W,j} (t, x), \ldots, H_{W;n,W,j} (t, x)); $$

and for Level $j$ with $K \leq j \leq m$,

$$ H_{W,j} (t, x) = (H_{W;0,W,j} (t, x), H_{W;1,W,j} (t, x), \ldots, H_{W;n,W,j} (t, x)). $$

Based on this, we write

$$ H_j (t, x) = \begin{cases} H_{S,0} (t, x), & j = 0, \\ H_{SW,j} (t, x), & 1 \leq j \leq K - 1, \\ H_{W,j} (t, x), & K \leq j \leq m, \end{cases} $$

and

$$ H (t, x) = (H_0 (t, x), H_1 (t, x), \ldots, H_{K-1} (t, x), H_K (t, x), \ldots, H_m (t, x)). $$

It is clear that

$$ \Theta (t, x) = H (t, x) e. $$

For a column vector $a = (a_1, a_2, \ldots, a_r)$ of size $r$, we write

$$ \Delta (a) = \text{diag} (a_1, a_2, \ldots, a_r). $$

Obviously for the column vector $f$, we have

$$ \Delta = \text{diag} (\Delta (f_0), \Delta (f_1), \ldots, \Delta (f_{K-1}), \Delta (f_K), \ldots, \Delta (f_m)). $$
For the Markov reward process $\{ \Phi(t), t \geq 0 \}$, it follows from Section 10.2 of Chapter 10 in Li [25] that the vector function $H(t, x)$ is the solution to the Kolmogorov’s forward equation

$$\frac{\partial H(t, x)}{\partial t} + \frac{\partial H(t, x)}{\partial x} \Delta = H(t, x)Q,$$

with the boundary condition

$$H(t, 0) = \pi(0) \delta(t),$$

and the initial condition

$$H(0, x) = \pi(0) \delta(x),$$

$$\delta(x) = \begin{cases} 1, & x = 0, \\ 0, & x > 0. \end{cases}$$

(ii) **Computing the first passage time:** Let $\Gamma(x)$ be the first passage time of the cumulative power consumption $\Phi(t)$ arriving at a key power value $x$ as follows:

$$\Gamma(x) = \min \{ t : \Phi(t) = x \}.$$

We write

$$C(t, x) = P \{ \Gamma(x) \leq t \}.$$

It is clear that the event $\{ \Gamma(x) \leq t \}$ is equivalent to the event $\{ \Phi(t) > x \}$. Hence we get

$$C(t, x) = 1 - P \{ \Phi(t) \leq x \} = 1 - \Theta(t, x),$$

Hence, we have

$$P \{ \Gamma(x) \leq t \} = 1 - P \{ \Phi(t) \leq x \},$$

Let

$$M(r, k) = \frac{\partial^r}{\partial s^r} \left[ (Q - sI) \Delta^{-1} \right]^k \bigg|_{s = 0}, \quad r, k \geq 0.$$

Then

$$M(0, 0) = I,$$

$$M(r, 0) = 0, \quad r \geq 1,$$

$$M(0, k) = (Q\Delta^{-1})^k, \quad k \geq 1,$$

$$M(1, 1) = -\Delta^{-1},$$

$$M(r, k) = Q\Delta^{-1}M(r, k - 1) - r\Delta^{-1}M(r - 1, k - 1), \quad r, k \geq 1.$$

Therefore, we can provide expression for the $r$th moment $E[\Gamma(x)^r]$ as follows:

$$E[\Gamma(x)^r] = \left( -1 \right)^{r+1} \pi(0) \sum_{k=0}^{\infty} \frac{x^k}{k!} M(r, k) e, \quad r \geq 1,$$

where $\pi(0)$ is any initial probability vector of the QBD process $Q$. 

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5.2 Open problems

From the above analysis, it is seen that discussing more general group-server queues is interesting, challenging and difficult. Thus it may be valuable to list several open problems for the future study of group-server queues as follows:

- Setting up some suitable cost (or reward) functions, and provide and prove existence and structure of bilateral threshold control by means of Markov decision processes.
- Establishing fluid and diffusion approximations for more general group-server queues, and focus on how to deal with the residual service times of those concentratively transferred customers to the buffer or to the left-side server groups. In fact, the residual service times cause some substantial difficulties in model analysis.
- Constructing martingale problems or stochastic differential equations for more general group-server queues.
- Developing stochastic optimization and control, Markov decision processes and stochastic game theory in the study of group-server queues.

6 Simulation Experiments

In this section, we design some simulation experiments for performance evaluation of two different group-server queues: the group-server loss queues, and the group-server queues with infinite buffer. Specifically, we analyze the expected queue lengths, the expected sojourn times and the expected virtual service times for the two group-server queues.

In these following simulations, we use some common parameters for the two different group-server queues: the group-server loss queues and the group-server queues with infinite buffer, where there are three server groups in each queueing system. To that end, we take that $N = 2, m_0 = 4, m_1 = 4, m_2 = 3, \mu_0 = 5, \mu_1 = 4, \mu_2 = 3, K_1 = K_2 = 3$ and $L_1 = L_2 = 2$.

(1) The group-server loss queues

Fig.4 indicates how the expected customer number in the whole system depends on the arrival rate $\lambda \in (15, 45)$. It is seen from Fig.4 that the expected customer number in the whole system strictly increase as $\lambda$ increases.

Fig.5 shows how the expected customer number in each of three server groups depends on the arrival rate $\lambda \in (15, 45)$. It is seen from Fig.5 that the expected customer number in each of three server groups strictly increases as $\lambda$ increases.

Note that each of the two group-server queues contains three different server groups with service rates: $\mu_0, \mu_1, \mu_2$, it is easy to see that the service times of the three server groups are different from each other. In this case, for such a group-server queue, we need to introduce a virtual service time as follows: The virtual service time is defined as the average service time of any customer in the group-server queues. Thus the virtual service time describes the comprehensive service ability of a whole system through integrating the server groups with different service abilities.

Fig.6 demonstrates how the expected virtual service time and the expected sojourn time depend on the arrival rate $\lambda \in (15, 43)$, respectively. It is seen from Fig.6 that both of them strictly increase as $\lambda$ increases.
Figure 4: The expected customer number in the whole system vs. $\lambda$

Figure 5: The expected customer number in each of three server groups vs. $\lambda$
(2) The group-server queues with infinite buffer

Fig. 7 indicates how the expected customer numbers in the whole system and in the buffer depend on the arrival rate $\lambda \in (15, 40)$, respectively. It is seen from Fig. 7 that both of them strictly increase as $\lambda$ increases.

![Figure 7: The expected customer numbers in system and buffer vs. $\lambda$](image)

Fig. 8 shows how the expected customer number in each of three server groups depends on the arrival rate $\lambda \in (15, 45)$. It is seen from Fig. 8 that the expected customer number in each of three server groups strictly increases as $\lambda$ increases.

Fig. 9 demonstrates how the expected virtual service time and the expected sojourn time depend

![Figure 6: The expected virtual service time and the expected sojourn time vs. $\lambda$](image)
Figure 8: The expected customer number in each of three server groups vs. $\lambda$

Figure 9: The expected virtual service time and the expected sojourn time vs. $\lambda$
on the arrival rate $\lambda \in (15, 40)$, respectively. It is seen from Fig.9 that the expected virtual service time increases slowly as $\lambda$ increases, while the expected sojourn time increases rapidly as $\lambda$ increases.

Here, we use some simulation experiments to give valuable observation and understanding with respect to system performance, and this is a valuable help for design, operations and optimization of energy-efficient management of data centers. Therefore, such a numerical analysis will also be useful and necessary in the energy-efficient management study of data center networks in practice.

7 Concluding Remarks

In this paper, we propose and develop a class of interesting Group-Server Queues by means of analyzing energy-efficient management of data centers, and establishes two representative group-server queues through loss networks and impatient customers, respectively. Some simple mathematical discussion is provided in the study of two-group-server loss queues, and simulations are made to study the expected queue lengths, the expected sojourn times and the expected virtual service times in the three-group-server queues with infinite buffer. Furthermore, we show that this class of group-server queues are often encountered in many other practical areas including communication networks, manufacturing systems, transportation networks, financial networks and healthcare systems. Therefore, not only analysis of group-server queues is regarded as a new interesting research direction, but there also exists many theoretic challenge and basic difficulties in the area of queueing networks. We hope the methodology and results given in this paper can be applicable to analyzing more general large-scale data center networks and service systems. Along these lines, we will continue our works in following directions in the future research:

- Establishing fluid and diffusion approximations for the group-server loss queues, and also for the group-server queues with impatient customers and with infinite buffers;

- making power consumption rate and power price regulation in data center networks through the Brownian approximation methods;

- setting up and proving existence and structure of (discrete or continue) bilateral threshold control in energy-efficient management of data centers in terms of Markov decision processes; and

- developing stochastic optimization and control, Markov decision processes and stochastic game theory in analyzing energy-efficient management of data center networks.

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