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Queuing theory application in imaging service analysis for small Earth observation satellites

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Abstract

The performance of Earth observation satellites is usually analyzed by real data or system simulation, which is accurate but not systematic. Modelling satellite service systems with queueing theory and analysing the performance statistics systematically will provide a useful guide in designing satellite systems. Earth observation satellites could be regarded as a two tandem server system with a finite buffer in between, providing two-stage service: image capture and image download service. In this paper, we introduce the queueing models for different service systems: the pure image capture service system, the two-stage service system with Poisson distribution download service, the pure download service system, and the two-stage system with general download service. Formulated solutions are given and some results are shown. From this work we can see queueing theory provides a good way to analyse the performance of small earth observation satellites, which is useful for system mission analysis and optimisation in design stage.

1. Introduction

Small satellites have been widely used in many areas providing with different services such as GPS service, environmental monitoring and global telecommunications. Earth observation satellites are the satellites specifically designed to observe Earth from orbit for non-military uses such as environmental monitoring, meteorology, map making, etc. With the development of microelectronics technology, the low-cost commercial satellites become more and more popular in providing space services to the society. With a constellation of several similar low-cost small satellites, it is able to get better service and less cost than a big advanced satellite. The disaster monitoring constellation [1,14] from SSTL is such a low cost small satellite constellation. With five small earth observation satellites in the same orbit, the DMC can provide dynamic remote sensing services to any point on the globe with a daily revisit.

An analogy has been drawn between the small satellite technology and the personal computer industry in [15]. As the importance of QoS (Quality of Service) in performance evaluation of computer networks, the performance analysis of small satellites is significant when the small satellite technology is being brought into wider application, which stimulates research work on performance modelling and analysis of satellite services. System simulation and real data measurement are the current approaches for analysing the performance

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of satellite systems, which are quite accurate but cannot give a systematic analysis on the system performance, and even are computationally complex with a number of simulations to be run in the system simulation case. With a theoretical model, however, system performance measurements could be formulised and analysed in a systematic way.

Queueing theory has been widely used in the computer networks and traditional service trade. For space industry, it has been applied for performance modelling of communication satellites with great success. Because of the sun-synchronised orbit, the application of Queueing theory to the low-earth-orbit earth observation satellites is much more complex. The imaging service of a pure image capture system and the download service of a pure image download system have been modelled and analysed, respectively in the previous work from the Surrey Space Centre [3,9]. In [2], the integrated image capture service and download service is analysed with a two-dimensional Markov model, with the limited onboard storage resource considered and download service assumed Poisson pattern. In this paper, we propose to approximate the image download service with phase-type distribution, model the pure download system and the integrated service system, respectively, and give formulated solutions.

The rest of this paper is organised as follows: in Section 2, we introduce the general earth observation satellites, including system description, scheduling policy and the performance measurements of interest; in Section 3, we give the system model and results for different systems—in Sections 3.1 and 3.2 we reformulate the pure image capture service system and the integrated service system, respectively, and give the solution in a closed form; in Section 3.3 we analyse the download service system with phase-type distribution approximation and formulate the solution; in Section 3.4 the model of the integrated service system with phase-type download service is analysed and the solution is formulated; conclusions and future work are outlined at the end.

2. Observation satellite system

2.1. System description

The basic earth observation satellite system is as shown in Fig. 1, which including the following *system elements*:

- Requests: Customers come to the satellite with imaging requests. For earth observation imaging requests, the location of the interested target should be specified and encapsulated with the request information package;
- Satellite: The satellite will serve the imaging requests, scheduling the image capture operation and download operation for the request based on the orbit model. It could be further divided into three different functional elements:
  - Image capture scheduler: Based on the orbit model, the image capture opportunities could be calculated for each request. The scheduler would plan and schedule the image capture operation for all the waiting requests in sequence according to some scheduling policy;
  - Onboard storage memory: With the completion of the image capture operation, the taken image would be saved in the onboard storage memory and to be downloaded;
  - Image download scheduler: it would plan and schedule the image download operation for all the images in the memory according to some scheduling policy;
- Receiver: With the completion of the image download operation, image will be downloaded to the receiver and then delivered to the customers eventually.

As shown in Fig. 1, we can see that a successful imaging service consists of two stages: image capture service stage and image download service stage. These two service stages are in tandem manner: Requests firstly enter the image capture service stage; when the requested images are taken, they will be stored in the onboard data

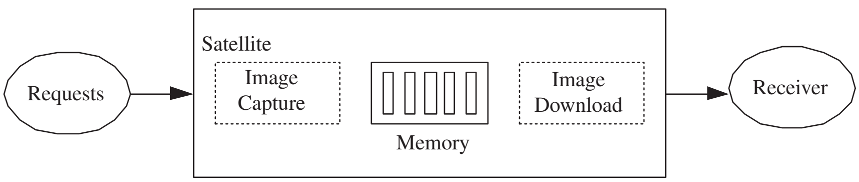

Fig. 1. Imaging service system of Earth observation satellites.

Table 1
An example of observation opportunities for Beijing in one month

Access	Start time (UTCG)	End time (UTCG)	Duration (s)
1	6 Jun 2004 01:53:18.242	6 Jun 2004 01:54:42.327	84.084
2	9 Jun 2004 02:07:59.692	9 Jun 2004 02:09:01.460	61.768
3	11 Jun 2004 01:45:23.300	11 Jun 2004 01:46:05.455	42.155
4	14 Jun 2004 01:59:29.852	14 Jun 2004 02:00:56.804	86.952
5	19 Jun 2004 01:51:17.160	19 Jun 2004 01:52:34.958	77.799
6	22 Jun 2004 02:05:49.078	22 Jun 2004 02:07:01.309	72.231
7	27 Jun 2004 01:57:23.119	27 Jun 2004 01:58:50.044	86.925
8	30 Jun 2004 02:12:32.370	30 Jun 2004 02:12:39.458	7.087

storage and considered for the download service, which indicates the end of the image service stage and the beginning of the download service stage; when the images are downloaded to the receiver and removed from the memory, the download service is completed, and also the whole imaging service. The first service stage might be blocked due to the fully occupied memory, at that time no more image capture operations could be carried out until some storage space is released by the image download operations.

2.2. Scheduling policy

There are scheduling policies associated with both service stages, defining the sequence to serve the waiting requests. There are many factors to be considered to generate a valid operation schedule, such as limited image capture opportunities, limited memory capacity, limited image download opportunities, etc. For the UK-DMC satellite which is the basic satellite model of this paper, the constraints are mainly on the limited image capture opportunities and the limited memory capacity. Table 1 shows the imaging opportunities for Beijing in one month. We can see that there are only eight access time windows to visit Beijing in one month. Therefore, different from a normal service system, the imaging service time of investigated earth observation satellites depends largely on the waiting time for a satellite overpass opportunity rather than the image capture and download operation time itself, which also inspires the need for an optimised scheduling policy for the image capture service stage.

The scheduling policy used for the image capture service stage in this paper is called *first-opportunity-first-served* (FOFS). It works in this way: all the requests that have arrived at the satellite but have not been imaged are considered and treated the same by the scheduler; with the orbit prediction software, visiting opportunity time windows for each request are calculated; the scheduler will always choose the request having the first visiting opportunity to serve first, i.e., the target the satellite passes over first will be imaged first. The scheduler works in a real-time way, so that when new requests arrive, the scheduler will adapt the schedule rapidly for the new requests queue. With this FOFS scheduling policy, the waiting time between two image capture operations will be as short as possible so that the image capture service rate and also the overall system service performance could be improved.

For the image download stage, the simplest *first-come-first-served* (FCFS) policy is used, which is because of the fact that the limited download opportunities are not the major constraint in the satellite imaging service process.

2.3. Performance measurements of interest

In ordinary networks, performance metrics usually refer to the throughput, utilization or other parameters. Since our work aims to be useful for the system design and optimisation of earth observation satellites, the *average waiting time* of an imaging request is a much more important parameter, which refers to the time span a request stays in the system before it gets the image downloaded at the ground station [2]. The total service time in this system consists of two parts: the image capture service time and the download service time. The shorter the average waiting time, the better the service performance for the system.

Another performance measurements of interests is the *blocking probability*, which refers to the block probability of the image capture service at the first stage due to the full memory occupation. This measurement shows the effects of onboard memory capacity on the system performance and indicates whether the limited memory capacity causes the system performance bottleneck.

3. System models and results

3.1. Pure image capture service system

A pure image capture service system has been studied and modelled in [3]. In this section we will present the model and analyse the service performance based on the model. The conceptual model is shown in Fig. 2. The service starts when the requests come to the satellite and join in the image capture queue, and ends when the requested image is taken. There is no queue length limit on the server and the scheduling policy for the image capture operations is FOFS. The related assumptions are as follows:

- The target location of imaging requests are uniformly distributed over the globe.
- The arrival pattern of image requests are Poisson distributed, with λ denoted the arrival rate.

As shown in Fig. 3, there is linear relationship between the request queue length and the average image capture service rate, which is reasonable because when there is more requests in the queue, the time to the next image capture opportunity is shorter.

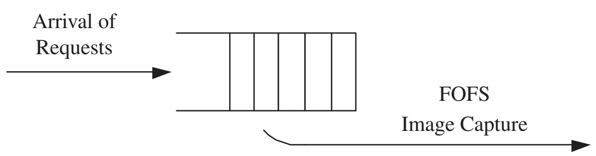

Fig. 2. The conceptual model of the pure image capture service system.

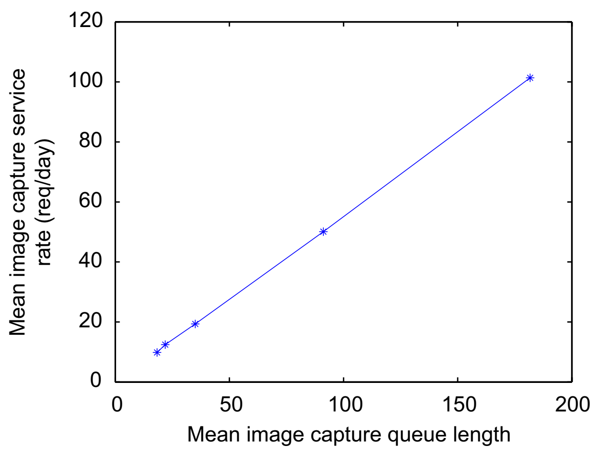

Fig. 3. The queue length vs. the mean service rate.

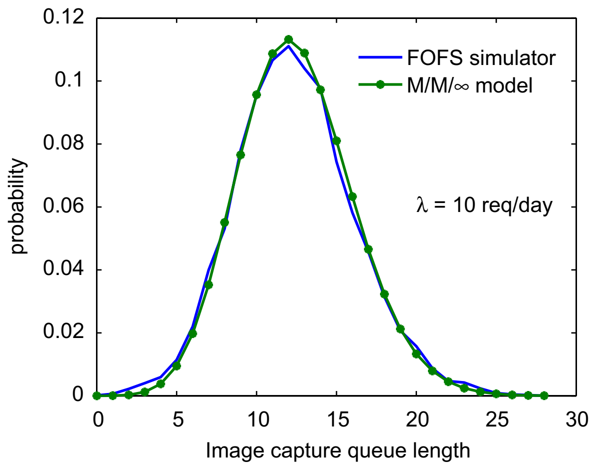

Fig. 4. The steady state queue length probabilities of the image capture queue.

With this proportional relationship between the queue length and the service rate, the pure image capture service system is modelled with the $M/M/\infty$. We define p_n as the steady state probability in the system state (n), where n is the number of requests in the image capture queue. Let us denote the basic image capture service time as exponentially distributed with mean $1/\mu_0$. Therefore the image capture service time when there are n requests in the capture queue, is exponentially distributed with mean $1/(n \cdot \mu_0)$.

From the queueing theory [4], we can obtain the system steady-state probabilities $\{p_n\}$ as

$$p_n = \frac{(\lambda/\mu_0)^n e^{-\lambda/\mu_0}}{n!} \quad (n \geqslant 0). \tag{1}$$

Fig. 4 shows there is good agreement between the simulation results with analytical results for the queue length probabilities of the image capture queue, which justifies the proposed $M/M/\infty$ model.

With the system steady-state probabilities, it is easy to obtain the other performance measurements. We can get the average image capture queue length L_i as

$$L_i = \sum_{n=0}^{\infty} n \cdot p_n = \frac{\lambda}{\mu_0} e^{\lambda/\mu_0}. \tag{2}$$

With the Little's Theorem [5], we then get the average waiting time for the image capture requests:

$$\overline{W} = \frac{L_i}{\lambda} = \frac{e^{\lambda/\mu_0}}{\mu_0}. \tag{3}$$

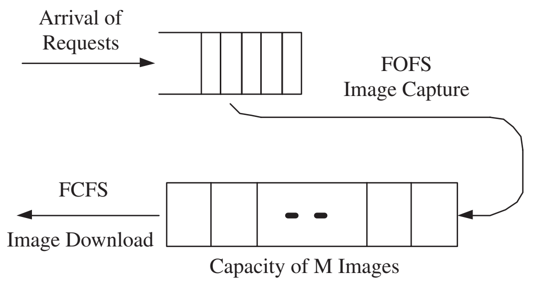

Fig. 5. The conceptual model of satellite imaging service system.

3.2. Image capture service with Poisson download service

In this section, we study the whole earth observation satellite system with the FOFS image capture service and the FCFS download service, which is assumed to be Poisson process. These two services are connected in tandem, with a buffer (onboard storage memory) in between. If the buffer is full, the first image capture service will be blocked. The conceptual model of the imaging satellite system is shown in Fig. 5. Besides the assumptions in the last section, the other related assumptions are as follows:

- The image capture queue length limit is N, i.e. there are at most N requests waiting for the image capture operation; in this paper, we just consider the case when N is large enough so similar with infinite case.
- The onboard storage capacity is M, i.e. there are at most M images stored in the memory waiting for download operation.
- For every download operation there is one and only one image downloaded.
- The download service time of a image is assumed exponentially distributed with mean $1/\mu_d$.

In [2] we have modelled the system with two-dimensional Markov model. Actually the system also belongs to the quasi-birth-and-death (QBD) process. It is a more readable and understandable model to present the system. Here we formulate the model in a QBD model manner and analyse the system performance measurements based on the model.

The QBD process was first introduced by Wallace in [6] and Evans in [7]. In general, a QBD process is a Markov chain on the state space $S = \{(n, m)|0 \leqslant n \leqslant N, 0 \leqslant m\}$, where the state space can be divided into levels and each level has N phases. In a QBD process, the possible transitions are only allowed within the same level or to the neighbouring levels. The generator matrix of a QBD process could be write in the form of

$$\mathbf{Q} = \begin{pmatrix} \mathbf{A}_0 & \mathbf{B}_0 & & & \\ \mathbf{C}_1 & \mathbf{A}_1 & \mathbf{B}_1 & & \\ & \mathbf{C}_2 & \mathbf{A}_2 & \mathbf{B}_2 & \\ & & \ddots & \ddots & \ddots \end{pmatrix},$$

where

- $\mathbf{A}_m$: purely phase transitions within a level—from state (n, m) to state (l, m) $(0 \leqslant n, l \leqslant N; n \neq l; m = 0, 1, \ldots)$.
- $\mathbf{B}_m$: one-step upward transitions from one level to the level $+1$—from state (n, m) to state $(l, m + 1)$ $(0 \leqslant n, l \leqslant N; m = 0, 1, \ldots)$.
- $\mathbf{C}_m$: one-step downward transitions from one level to the level -1—from state (n, m) to state $(l, m - 1)$ $(0 \leqslant n, l \leqslant N; m = 0, 1, \ldots)$.

For the satellite imaging service we study here, it is a finite QBD process with $M+1$ levels. With the generator matrix as

$$\mathbf{Q} = \begin{pmatrix} \mathbf{A} & \mathbf{B} & & & \\ \mathbf{C} & \mathbf{A} & \mathbf{B} & & \\ & \mathbf{C} & \mathbf{A} & \mathbf{B} & \\ & & \ddots & \ddots & \ddots \\ & & & \mathbf{C} & \mathbf{A} \end{pmatrix},$$

$$\mathbf{A} = \begin{pmatrix} * & \lambda & & & \\ & * & \lambda & & \\ & & \ddots & \ddots & \\ & & & * & \lambda \\ & & & & * \end{pmatrix},$$

$$\mathbf{B} = \begin{pmatrix} 0 & & & & \\ \mu_0 & 0 & & & \\ & 2\mu_0 & \ddots & & \\ & & \ddots & 0 & \\ & & & M\mu_0 & 0 \end{pmatrix},$$

$$\mathbf{C} = \begin{pmatrix} \mu_d & & & \\ & \mu_d & & \\ & & \ddots & \\ & & & \mu_d \end{pmatrix},$$

where $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ are all $(N + 1) \times (N + 1)$ matrix, and $\mathbf{Q}$ is $(N + 1)(M + 1) \times (N + 1)(M + 1)$ matrix. The diagonal element marked by a $*$ is the negative sum of the elements in the same row in $\mathbf{Q}$. Let $\mathbf{x}$ be the vector of the steady-state probabilities associated with $\mathbf{Q}$,

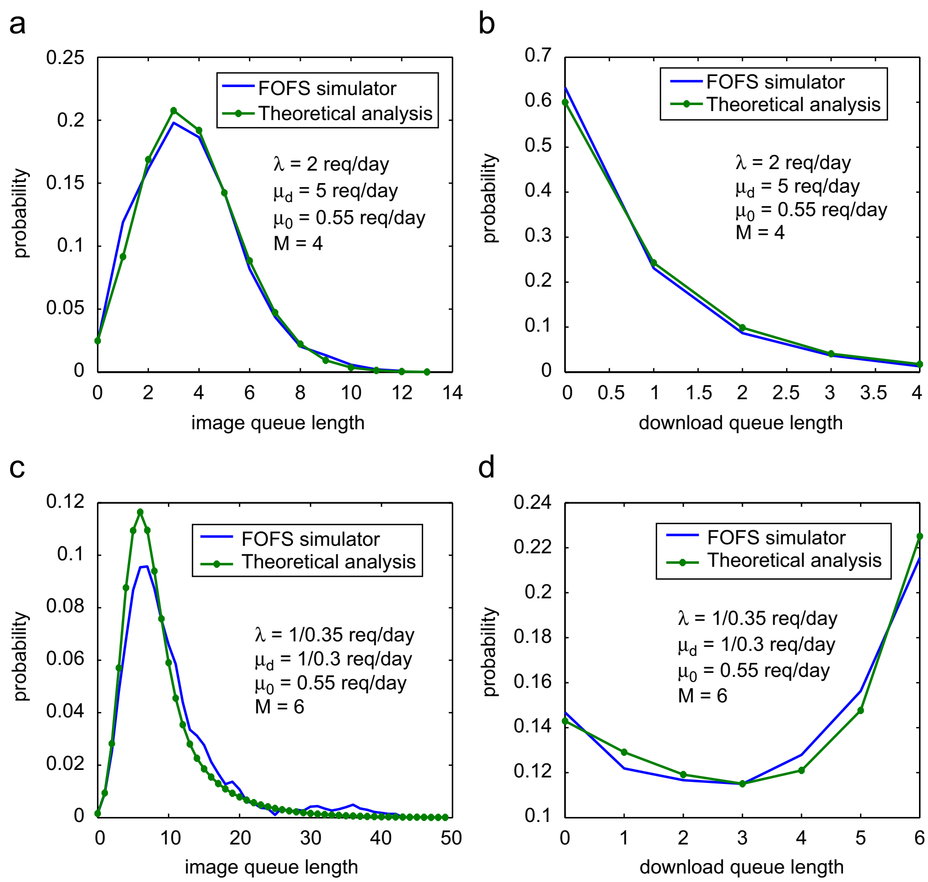

Fig. 6. Queue length probability for image capture queue and download queue, respectively.

$\mathbf{x}=(\mathbf{x}_0, \mathbf{x}_1, \ldots, \mathbf{x}_M)$ and $\mathbf{x}_m=(p_{0,m}, p_{1,m}, \ldots, p_{N,m})$, where $p_{n,m}$ is the steady state probability of the state (n, m). We have $\mathbf{xQ}=0$ and $\mathbf{xe}=1$, where $\mathbf{e}$ is a column vector of $(N+1)(M+1)$ elements each of which is equal to 1. Our task is to solve the equations and get the solution of $\mathbf{x}$. Tran and Tien [8] give a survey on computational methods developed for the steady state solution of QBD processes.

Fig. 6 shows the comparison results of simulation results with analytical results for the queue length probabilities for the image capture queue and the download queue, respectively. From the results we can see good agreement between the satellite simulation and the QBD model.

With the steady state probabilities, we are able to get the total average waiting time $\overline{W}$ by the Little's Theorem,

$$\overline{W} = \frac{\sum_{n=0}^{N}(\sum_{m=0}^{M}(n+m)\cdot p_{n,m})}{\lambda}. \tag{4}$$

And the blocking probability of the system P_b is

$$P_b = \sum_{n=0}^{N} p_{n,M}. \tag{5}$$

3.3. Pure image download service system

In the last section, the image download service is assumed a Poisson process. However, in the real earth observation satellite system, the download service time is not ideally Poisson distributed. In order to model the satellite system more precisely, let us focus on the fixed ground station image download service system in this section. The conceptual model is shown in Fig. 7. The related assumptions are as follows:

- The arrival pattern of images are Poisson distributed, with λ denoted the arrival rate.
- The onboard storage capacity is M, i.e. there are at most M images stored in the memory waiting for download operation.

- For every download operation there is one and only one image downloaded.

Fig. 8 shows the distribution of the inter image download time of a fixed ground station situated at Guildford, with latitude = 52.0 and longitude = 0.0. It appears to be discrete distribution, and has been successfully modeled with $M/G/1$ in [9]. However, it is difficult to analyse the whole imaging service of satellites with the general distributed image download service. Therefore, we propose to approximate the image download service with phase-type distribution [10,11], which is able to approximate any non-negative distributions and many well-known distributions, e.g. Gamma distribution and hyper-exponential distribution, are actually special cases of a phase-type distribution. With the download service distribution in phase-type form, the analysis of the two-tandem-queue system will be easy.

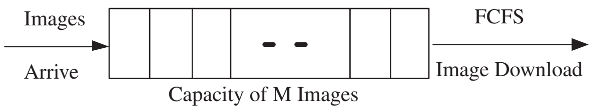

Fig. 7. The conceptual model of the pure image download service system.

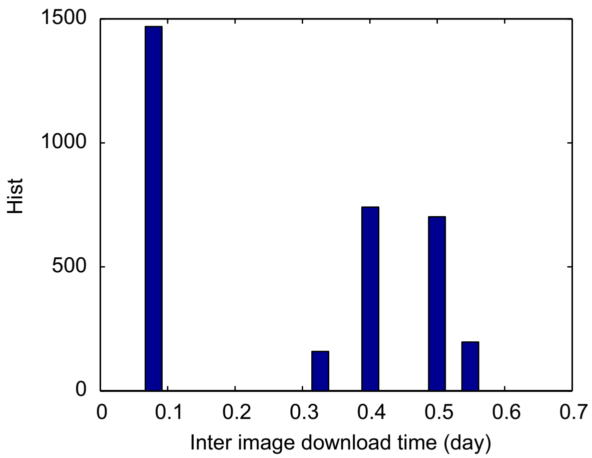

Fig. 8. The distribution of the inter image download time.

A phase-type distribution is a probability distribution that can be represented as the time to absorption in a continuous-time Markov chain with K transient states $i = 1, 2, \ldots, K$ and one absorbing state 0. Let $\alpha = (\alpha_1, \ldots, \alpha_K)$ denote the initial probabilities of starting in the transient states. We have $\alpha\mathbf{e} = 1$, where $\mathbf{e}$ is a column vector of ones. The infinitesimal generator $\mathbf{Q}$ is as follows:

$$\mathbf{Q} = \begin{pmatrix} \mathbf{T} & \mathbf{T}_0 \\ \mathbf{0} & 0 \end{pmatrix},$$

where $\mathbf{T}$ is called the phase-type generator, which is the $K \times K$ matrix of the rates of transition among the K states, and $\mathbf{T}_0$ is a $K \times 1$ vector containing all the rates of transition ou of these K states into the absorbing state 0. The diagonal elements of $\mathbf{P}$ are, respectively, the negative sum of the elements in the same row in $\mathbf{P}$. Therefore, we have $\mathbf{Te} + \mathbf{T}_0 = \mathbf{0}$. The pair $(\alpha, \mathbf{T})$ is referred to as a representation of the phase-type distribution, and K is the order of the representation.

Table 2 shows the results of fitting the image download service distribution with different order of general phase-type distribution, hyperexponential distribution and sum of exponentials. The fitting process is guilded by the EM algorithm [12]. Fig. 9 compares the Poisson process assumption and the phase-type fitting approximation with the real ground station data. We can easily see that Phase-type fitting approximation is better than the Poisson process assumption.

Now let us see the modelling of the pure image download service system with $M/Ph/1/K$ queueing model [13]. Assuming the image download service distribution is approximated by the K-order phase-type distribution $(\alpha, \mathbf{T})$. The system states are defined as $S = \{0\} \cup \{(m, k) | 1 \leqslant m \leqslant M, 1 \leqslant k \leqslant K\}$, where m is the download queue length and k is the phase status of the request in service. The rate matrix $\mathbf{Q}$ is given by

$$\mathbf{Q} = \begin{pmatrix} -\lambda & \lambda_\alpha & & & & \\ \mathbf{T}_0 & \mathbf{T} - \lambda\mathbf{I} & \lambda\mathbf{I} & & & \\ & \mathbf{T}_0\alpha & \mathbf{T} - \lambda\mathbf{T} & \lambda\mathbf{I} & & \\ & & \cdot & \cdot & \cdot & \\ & & & \mathbf{T}_0\alpha & \mathbf{T} - \lambda\mathbf{I} & \lambda\mathbf{I} \\ & & & & \mathbf{T}_0\alpha & \mathbf{T} \end{pmatrix}.$$

Let $\mathbf{x} = (x_0, \mathbf{x}1, \ldots, \mathbf{x}_M)$ be the stationary vector.

Table 2
Standard deviation of the EM phase type fitting results for the pure image download service

Order K	2	3	4	5	6	7	8
General Phase-type	0.19989	0.21263	0.22013	0.27962	0.27093	0.27312	0.2327
Hyperexponential	0.28269	0.28269	0.28269	0.28269	0.28269	0.28269	0.28269
Sum of exponentials	0.19989	0.19354	0.1912	0.23061	0.22858	0.22692	0.18829

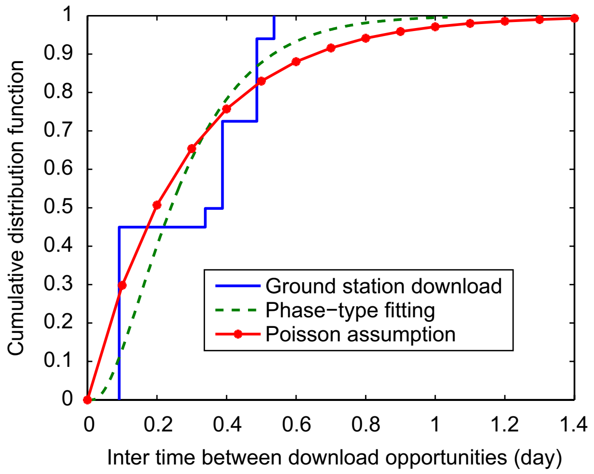

Fig. 9. The comparison results of Poisson process assumption with phase-type fitting approximation for the pure download service.

Then from $\mathbf{xQ} = \mathbf{0}$ and $\mathbf{xe} = 1$ we are able to get $\mathbf{x}$.

3.4. Image capture service with phase-type ground station download service

Now let us study the imaging service of earth observation satellites with phase-type ground station download service. The conceptual model is as in Fig. 5. The related assumptions are similar as in Section 3.2, except that the image download service is not a Poisson process, but is modelled with the K-order phase-type distribution $(\alpha, \mathbf{T})$. The system states are defined as $S = \{(n, 0)|0 \leqslant n \leqslant N\} \cup \{(n, m, k)|0 \leqslant n \leqslant N, 1 \leqslant m \leqslant M, 1 \leqslant k \leqslant K\}$, where n is the image capture queue length, m is the download queue length and k is the phase status of the request in the image download service server. The rate matrix $\mathbf{Q}$ can be obtained as follows:

$$\mathbf{Q} = \begin{pmatrix} \mathbf{A}_0 & \mathbf{B}_0 & & & \\ \mathbf{C}_1 & \mathbf{A} & \mathbf{B} & & \\ & \mathbf{C} & \mathbf{A} & \mathbf{B} & \\ & & \ddots & \ddots & \ddots \\ & & & \mathbf{C} & \mathbf{A} \end{pmatrix},$$

$$\mathbf{A}_0 = \begin{pmatrix} * & \lambda & & & \\ & * & \lambda & & \\ & & \ddots & \ddots & \\ & & & * & \lambda \\ & & & & * \end{pmatrix} (N+1) \times (N+1),$$

$$\mathbf{B}_0 = \begin{pmatrix} \mathbf{0} & & & \\ \mu_0\alpha & \ddots & & \\ & \ddots & \mathbf{0} & \\ & & M\mu_0\alpha & \mathbf{0} \end{pmatrix} (N+1) \times (N+1)K,$$

$$\mathbf{C}_1 = \begin{pmatrix} \mathbf{T}_0 & & & \\ & \mathbf{T}_0 & & \\ & & \ddots & \\ & & & \mathbf{T}_0 \end{pmatrix} (N+1)K \times (N+1),$$

$$\mathbf{A} = \begin{pmatrix} \mathbf{T} & \lambda\mathbf{I} & & \\ & \mathbf{T} & \ddots & \\ & & \ddots & \lambda\mathbf{I} \\ & & & \mathbf{T} \end{pmatrix} (N+1)K \times (N+1)K,$$

$$\mathbf{B} = \begin{pmatrix} \mathbf{0} & & & \\ \mu_0\mathbf{I} & \ddots & & \\ & \ddots & \mathbf{0} & \\ & & M\mu_0\mathbf{I} & \mathbf{0} \end{pmatrix} (N+1)K \times (N+1)K,$$

$$\mathbf{C} = \begin{pmatrix} \mathbf{T}_0\alpha & & & \\ & \mathbf{T}_0\alpha & & \\ & & \ddots & \\ & & & \mathbf{T}_0\alpha \end{pmatrix} (N+1)K \times (N+1)K.$$

Let $\mathbf{x} = (\mathbf{x}_0, \mathbf{x}_1, \ldots, \mathbf{x}_M)$ be the stationary vector. Then from $\mathbf{xQ} = \mathbf{0}$ and $\mathbf{xe} = 1$ we are able to get $\mathbf{x}$.

With the steady state solution, we are able to get the total average waiting time $\overline{W}$,

$$\overline{W} = \frac{\sum \mathbf{x}_0 + \sum_{m=1}^{M} \sum_{n=0}^{N} \sum_{k=1}^{K} (n+m) p_{n,m,k}}{\lambda}. \quad (6)$$

And the blocking probability of the system P_b is

$$P_b = \sum \mathbf{x}_M. \quad (7)$$

4. Conclusions

In this paper we apply queueing theory in performance modelling and analysis of small earth observation satellites. The pure image capture service system can be successfully modelled with $M/M/\infty$ queueing model. And the two-node tandem queue with blocking model is able to present the earth observation service system very well. We also approximate the fixed ground station download service with phase-type distribution and get the formulated solution for the download service system. The formulation of the solution for the observation service of the satellite system with general ground station download service is also obtained.

It is still at early stage to apply queueing theory in the performance modelling and analysis for the small earth observation satellites. However with queueing model, we are able to understand the service performance of the imaging satellite in a theoretical and systematical level, which helps optimisation of system configuration especially at the system design stage. In the near future we will analyse the image capture service in more details and the effects of onboard memory capacity, ground station location, having multiple ground stations and so on.

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