

Performance Modelling of Imaging Service of Earth Observation Satellites with Two-dimensional Markov Chain

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ABSTRACT: Modelling satellite service systems and analysing the performance statistics systematically will provide a useful guide in designing satellite systems. A Satellite observation service consists of two stages: image capture and image download. These two stages have been modelled and analysed individually in previous studies, assuming no memory constraint onboard the satellite. It is necessary to integrate two stages in one model with the memory constraint, so that overall system performance can be analysed and the system parameters could be carefully designed to achieve a certain quality of service. In this paper, a two-dimensional Markov chain model is proposed for modelling the small LEO imaging satellite system. The queue length probabilities and a performance metric, the average total waiting time, are analysed mathematically. The effects of system parameters such as memory capacity, download rate and request arrival rate are investigated accordingly. All analytical results presented are compared with simulation results. The limitation of this model is also discussed and future model revisions are outlined. From this work we can see the queueing model can reflect the general service performance and the system parameters' effects on earth observation satellites, which is useful for system design and optimisation.

1. INTRODUCTION

Nowadays, satellites provide society with everything from environmental scientific data to global telecommunications services. Earth observation satellites are satellites specifically designed to observe Earth from orbit for non-military uses such as environmental monitoring, meteorology, map making etc. With development of microelectronics technology, the commercial satellite business with low cost systems becomes popular for the purpose of commercial utilization of space. The Disaster Monitoring Constellation^{7,8} from SSTL is such a low cost small satellite constellation providing dynamic remote sensing services to any point on the globe with a daily revisit.

With the development of small satellite technology, Quality of Service (QoS) is receiving more attention for commercial purposes and is stimulating research work on performance modelling and analysis of satellite services. Normal performance measurements include average response time, system through-put, resource utilization and so on. It is also very useful to investigate how the system components affect the system performance, the potential bottlenecks, and the software and hardware requirements of the system.

The performance analysis of a system in design stage could be carried out by system simulation or theoretical modelling. In both approaches system components and policies are modelled with their features. With system simulation, system performance could be analysed using simulation results, which are quite accurate. But the computational complexity is heavy because a number of simulations have to be run and a huge amount of data needs to be analysed. With a theoretical model, however, system performance measurements could be formulised and analysed in a systematic way.

Queueing theory has been widely used for performance modelling of communication satellites with great success. For the earth observation satellites, however, the service modelling is much more complex because of the sun-synchronised orbit. 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 Center^{1,9}. However, the important factor of an onboard storage capacity limit has not been considered. In this paper, we will add this constraint into the system and model the integrated image capture service and download service

with a queueing system.

The rest of this paper is organised as follows: in section 2, we introduce the the service process of an imaging satellite, basics of queueing theory and the pure image capture service modelling; the investigated satellite system is introduced in section 3, followed by the proposed model description and theoretical analysis; in section 4, a comparison of results from a satellite simulator with model analysis are presented, and also the effects of system parameters on the service performance; conclusions and future work are outlined at the end.

2. BACKGROUND

2.1 Satellite Observation Service System

For the low-orbit earth observation satellites investigated in this paper, the completion of a successful observation service includes following steps:

- 1) Request arrives at satellite, associated with location of target to be imaged;
- 2) Satellite schedules the image capture operation and download operation for the request, based on the orbit model;
- 3) As scheduled, an image is taken when the satellite passes over the target, with the image saved in onboard memory, waiting for download;
- 4) Image downloaded to ground station as scheduled when satellite passes over the ground station;

As shown in Figure 1, it can be observed from the above steps that the completion of an observation service could be divided into two stages: image capture service stage and image download service stage. Requests received by the satellite will be considered for the image capture service at the first stage. When the requested images are taken, they will be stored in the onboard data 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 ground station, the download service is completed, and also the whole observation service.

In each stage, requests are waiting for the service in a queueing manner. The satellite scheduler decides in what sequence the requests in the queue are served. There are many factors to be considered to generate a valid schedule for image capture and download operations without conflicts. The two major constraints in scheduling process are the limited imaging and down-

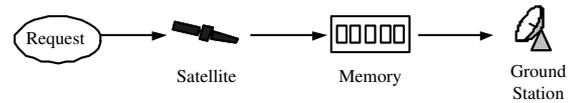


Figure 1: Service procedures of observation satellites

loading opportunities determined by the satellite orbit, and the limited resource capacity of onboard data storage. The earth observation satellites studied in this paper, unlike communication satellites which are generally in Geostationary Earth Orbit (GEO), are generally in Sun-Synchronised Low Earth Orbit (LEO). Based on their orbits, they are normally able to visit most places over the globe, but with limited visiting times. The 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, during which the imaging operation could be executed. 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.

The other major constraint in satellite operations scheduling is the limited onboard storage capacity. After the image capture operation, the image taken will be saved in the onboard memory until it is downloaded to the ground station. After the image is successfully downloaded, it will be deleted from the onboard memory. During the scheduling process, the satellite has to make sure for each image capture operation there is enough space in memory to store the new image. If the memory is fully filled, no more capture operations can take place; only downloading operations can be executed when the memory is full, which will release memory space to store new images.

2.2 Queueing Theory Basics

A typical queueing system, as shown in Figure 2, can be described in terms of three basic characteristics: the input process, the service mechanism, and the queue discipline².

- The input process: describes the sequence of requests for service.
- The service mechanism: includes characteristics like the number of servers, each server's capacity and the lengths of time that the customers use the servers.
- The queue discipline: specifies the disposition of

Access	Start Time (UTCG)	End Time (UTCG)	Duration (sec)
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

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

blocked customers.



Figure 2: A general queueing system

The Poisson process is one of the most popular stochastic processes, which means the inter-arrival times of a process are independently and exponentially distributed. To simplify the problem, in queueing system the arrival pattern of requests is often assumed as Poisson process. A Poisson process has the Markov property, i.e. the future states of a process are independent of the past states and dependent only on the present state. A Markov process with a discrete state space is referred to as a Markov chain, which is widely used for queueing modelling in many applications, such as telephone companies, bank cashier service, and so on.

There are several typical queue disciplines, such as FCFS (First-Come-First-Served), LCFS (Last-Come-First-Served), and SIRO (Service-In-Random-Order). No matter which queue discipline is applied, there is a well-known theorem holding as long as the system is stable, called the Little's Theorem³. It could be written as follows:

$$L = \lambda W \quad (1)$$

where L is the mean number of customers present, W is the mean time of the customer waiting in the system and λ is the mean arrival rate.

The Little's Theorem is a remarkable result, as it is entirely independent of any of the detailed probability distributions involved, and hence requires no assumptions about the queueing policies according to which customers arrive or are serviced, or whether they are served in the order in which they arrive.

2.3 Pure Image Capture Service Modelling

A model¹ has been proposed for the satellite system that only provides the image capture service. Therefore only the limited visiting opportunity constraint has effects on the scheduling process, no memory capacity constraint is considered. As we mentioned before, the service time of image capture is largely based on the time of waiting for a visiting opportunity. When there are several imaging requests in the system, it is very likely that the later arrival request might be visited by the satellite earlier than the first visiting opportunity of earlier request. In this case, the traditional First-Come-First-Serve scheduling discipline is inefficient, since most of the time will be wasted in just waiting for imaging opportunities.

To improve the service performance, a simple scheduling policy is proposed for the pure image capture service system, called FOFS (First-Opportunity-First-Served). 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.

The pure image capture service with FOFS scheduling policy has been studied¹, with FPASP⁴ used for orbit calculation. It is found that the average service rate is proportional to the average number of waiting requests. That is, when there are more requests waiting for the image service, the time between two successful image capture operations is shorter. The proportional relationship is reasonable because of the FOFS scheduling. A revised $M/M/1$ model is proposed for modelling the pure image capture service, where the

mean service rate is proportional to the mean queue length and the basic service time (the service time when there is only one request in the queue) is exponentially distributed. By comparison with simulation results, the model is found to be able to describe the system very well.

3. SYSTEM MODEL

3.1 Satellite System Description

In the pure image capture service modelling, only the limited visiting opportunities constraint is considered. However, in a real satellite system, the limited onboard storage capacity is an important constraint. An image capture operation can only be taken when there is enough memory to store the new image. This constraint has great effects on the satellite's overall service performance. For example, if there is no memory left to store the new image when passing over the target, the current capture operation will not be carried out and the scheduler will have to find the next earliest visiting opportunity, which will slow down the whole service process. Accordingly the proportional relationship between the average service rate and the queue length is not valid all the time.

In this paper, we will study the satellite imaging service system with the memory capacity constraint considered. The conceptual model is show in Figure 3.

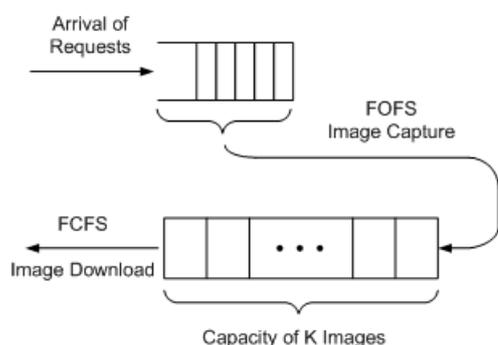


Figure 3: The conceptual model of satellite imaging service system

The system policy for the image capture queue is as follows:

- 1) The request arrives at satellite, joins the image capture requests queue, and triggers the scheduling process;
- 2) When the scheduling process is activated, the satellite scheduling system calculates the first visit opportunity for each request using the or-

bit prediction software, and schedules the earliest one as the next image capture operation;

- 3) When it is time for the scheduled observation operation, check the onboard storage, if there is enough space, go to 4); or else don't carry out this operation and go back to 2);
- 4) Carry out the image capture operation and save the image in the memory, delete the corresponding request from the image capture queue, and add it into the download queue, then go back to 2);

The idea behind this FOFS scheme is to make the waiting time between two image capture operations as short as possible so that the overall system service rate could be improved. As we can see, when the onboard storage is not full, the scheduling process for this queue is identical to the pure image capture system. Therefore the conclusions from the pure image capture service modelling are valid when the download queue is not full.

For the download queue, the queue discipline is simple First-Come-First-Served (FCFS), which works as follows:

- 1) When a request finishes the image capture service, it is moved from the capture queue to the download queue and is added to the tail of the queue;
- 2) When there is a download opportunity, the satellite serves the requests from the head of the download queue, sending the images to the ground;
- 3) Completed requests are removed from the download queue; With the FCFS policy, the image arriving in memory first would be downloaded first as well, which is reasonable for good service performance.

In this system, the related assumptions are as follows:

- The target location of imaging requests are uniformly distributed over the globe;
- The requested image sizes are all equal;
- The arrival pattern of image requests are Poisson distributed, with λ denoted the arrival rate;
- The image capture queue length limit is C , i.e. there are at most C requests waiting for the image capture operation; in this paper, we just consider the case when C is infinite;
- The onboard storage capacity is K , i.e. there are at most K images stored in the memory waiting

for download operation;

- For every download operation there is one and only one image downloaded;
- To simplify the problem, the download service time of a image is assumed exponentially distributed with mean $1/\mu_d$;

3.2 Two-dimensional Markov Chain Model

We propose a two-dimensional Markov chain model for the system described above. As we mentioned before, when the storage is not full, the first image capture queue could still be modelled by the revised $M/M/1$ model, where the basic service time is exponentially distributed and the mean service rate increases proportionally when the queue length increases. 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 $1/(n \cdot \mu_0)$. The value of μ_0 is studied in the pure image service system model¹.

Since there are two queues in the system, we need two elements to describe the status of each queue. We define (n, m) as the steady system state according to the current image capture queue condition and the onboard storage occupation status, where n is the number of requests in the first image capture queue, m is the number of images in the onboard storage, and $0 \leq n \leq C, 0 \leq m \leq K$. Based on the system description and assumptions in the above section, the system state transition diagram can be obtained, which belongs to the two-dimensional Markov chain model with the state space of $S = \{(n, m) | 0 \leq n \leq C, 0 \leq m \leq K\}$. It is shown in Figure 4.

Let $q(n_1, m_1; n_2, m_2)$ denote the probability of transition from system state (n_1, m_1) to state (n_2, m_2) , where $(n_1, m_1), (n_2, m_2) \in S$. It is easy to see that:

- $q(n, m; n + 1, m)$ is enabled by a new request arriving at the satellite;
- $q(n, m; n - 1, m + 1)$ is enabled by system's successful image capture service of a request;
- $q(n, m; n, m - 1)$ is enabled by system's successful download service of a request;

The corresponding transition rates are as follows:

$$\begin{aligned} q(n, m; n + 1, m) &= \lambda \quad (0 \leq n < C, 0 \leq m \leq K) \\ q(n, m; n - 1, m + 1) &= n \cdot \mu_0 \quad (0 \leq n \leq C, 0 \leq m < K) \\ q(n, m; n, m - 1) &= \mu_d \quad (0 \leq n \leq C, 0 \leq m \leq K) \end{aligned}$$

Let $P_{n,m}$ denote the steady state probability of the state $(n, m) \in S$. As we know, the incoming probability should be equal to the outgoing probability for any state in a stable system. With the system transition rates, the global balance state-transition equations can be obtained as follows:

$$\begin{aligned} &1) \text{ For } m = 0, \text{ then} \\ &\text{for } n = 0, \\ &\lambda \cdot P_{0,0} = \mu_d \cdot P_{0,1} \end{aligned} \quad (2)$$

$$\begin{aligned} &\text{for } 0 < n < C, \\ &(\lambda + n \cdot \mu_0) \cdot P_{n,0} = \lambda \cdot P_{n-1,0} + \mu_d \cdot P_{n,1} \end{aligned} \quad (3)$$

$$\begin{aligned} &\text{for } n = C, \\ &C \cdot \mu_0 \cdot P_{C,0} = \lambda \cdot P_{C-1,0} + \mu_d \cdot P_{C,1} \end{aligned} \quad (4)$$

$$\begin{aligned} &2) \text{ For } 0 < m < K, \text{ then} \\ &\text{for } n = 0, \\ &(\lambda + \mu_d) \cdot P_{0,m} = \mu_0 \cdot P_{1,m-1} + \mu_d \cdot P_{0,m+1} \end{aligned} \quad (5)$$

$$\begin{aligned} &\text{for } 0 < n < C, \\ &(\lambda + \mu_d + n \cdot \mu_0) \cdot P_{n,m} = \lambda \cdot P_{n-1,m} + \\ &\quad (n + 1) \cdot \mu_0 \cdot P_{n+1,m-1} + \mu_d \cdot P_{n,m+1} \end{aligned} \quad (6)$$

$$\begin{aligned} &\text{for } n = C, \\ &(\mu_d + C \cdot \mu_0) \cdot P_{C,m} = \lambda \cdot P_{C-1,m} + \mu_d \cdot P_{C,m+1} \end{aligned} \quad (7)$$

$$\begin{aligned} &3) \text{ For } m = K, \text{ then} \\ &\text{for } n = 0, \\ &(\lambda + \mu_d) \cdot P_{0,K} = \mu_0 \cdot P_{1,K-1} \end{aligned} \quad (8)$$

$$\begin{aligned} &\text{for } 0 < n < C, \\ &(\lambda + \mu_d) \cdot P_{n,K} = \lambda \cdot P_{n-1,K} + (n+1) \cdot \mu_0 \cdot P_{n+1,K-1} \end{aligned} \quad (9)$$

$$\begin{aligned} &\text{for } n = C, \\ &\mu_d \cdot P_{C,K} = \lambda \cdot P_{C-1,K} \end{aligned} \quad (10)$$

Beyond the state transition equations, we also have the normalization equation shown below:

$$\sum_{(n,m) \in S} P_{n,m} = 1 \quad (11)$$

From the normalization equation (11) and the state-transition equations (2)-(10), the steady state probabilities can be found by solving these equations according to the two-dimensional Markov chain theory. Furthermore, the state transitions in this system model belong to one special class of two-dimensional (phase and level) Markov chain: Quasi Birth-Death (QBD) process, where state transitions are only allowed between ones having adjacent levels. There are many computational methods we can take to solve the QBD

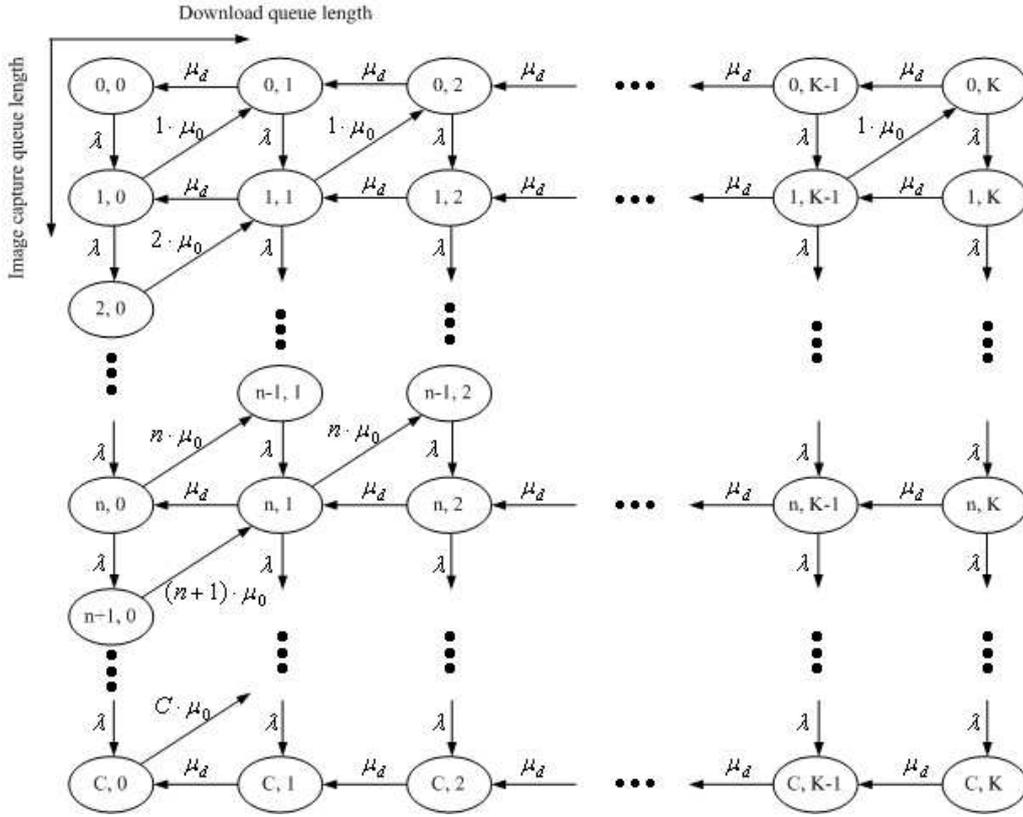


Figure 4: Transition diagram of steady states in the system

processes⁵. A recursive algorithm is a common approach to a two-dimensional Markov chain. With this computationally efficient and numerically stable method, the steady-state probabilities for any size system can be solved without problem. Based on the steady-state probabilities, system performance metrics, such as average total service time and average waiting time of imaging requests in each queue, can be derived.

3.3 Performance Measurements

In ordinary networks, performance metrics usually refer to the throughput, utilization or other parameters⁶. Since our work aims to be useful for the system design and optimisation of earth observation satellites, the average waiting time of an observation 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. The shorter the average waiting time, the better the service performance for the system.

The service time in this system consists of two parts: the image capture service time and the download ser-

vice time. With the mean queue length and the mean arrival rate, we will be able to get the average waiting time for each queue by Little's Theorem. Let \bar{T} denote the total average waiting time, \bar{T}_i denote the average image capture waiting time, and \bar{T}_d denote the average download waiting time, we have:

$$\bar{T} = \bar{T}_i + \bar{T}_d \quad (12)$$

For the image capture queue, the mean arrival rate is λ , and it is easy to get the mean queue length, denoted by L_i , as follows:

$$L_i = \sum_{n=0}^C \left(n \cdot \sum_{m=0}^K P_{n,m} \right) \quad (13)$$

The mean arrival rate for the download queue is equal with the mean service rate for the image capture queue, denoted by λ_d , can be derived as:

$$\lambda_d = \sum_{n=0}^C \left(n \cdot \mu_0 \cdot \sum_{m=0}^K P_{n,m} \right) \quad (14)$$

And the mean queue length for download queue, de-

noted by L_d , is:

$$L_d = \sum_{m=0}^K \left(m \cdot \sum_{n=0}^C P_{n,m} \right) \quad (15)$$

With the Little's Theorem (Equation (1)), it is easy to get \bar{T}_i and \bar{T}_d :

$$\bar{T}_i = \frac{L_i}{\lambda} = \frac{\sum_{n=0}^C \left(n \cdot \sum_{m=0}^K P_{n,m} \right)}{\lambda} \quad (16)$$

$$\bar{T}_d = \frac{L_d}{\lambda_d} = \frac{\sum_{m=0}^K \left(m \cdot \sum_{n=0}^C P_{n,m} \right)}{\sum_{n=0}^C \left(n \cdot \mu_0 \cdot \sum_{m=0}^K P_{n,m} \right)} \quad (17)$$

Therefore we could get the formulation for the average total waiting time as:

$$\bar{T} = \frac{\sum_{n=0}^C \left(n \cdot \sum_{m=0}^K P_{n,m} \right)}{\lambda} + \frac{\sum_{m=0}^K \left(m \cdot \sum_{n=0}^C P_{n,m} \right)}{\sum_{n=0}^C \left(n \cdot \mu_0 \cdot \sum_{m=0}^K P_{n,m} \right)} \quad (18)$$

Another way to get the total average waiting time is to regard the satellite system as a single server queueing system, service starting from request arrival and ending with images completely downloaded. Let L denote the average number of requests in the queueing system. With the Little's Theorem, we could get \bar{T} by

$$\bar{T} = \frac{L}{\lambda} = \frac{\sum_{n=0}^C \left(\sum_{m=0}^K (n+m) \cdot P_{n,m} \right)}{\lambda} \quad (19)$$

In the first approach, we know that the arrival requests of the second queue is actually the output of first queue. And also in the steady system, the average service rate is equal with the average arrival rate. Therefore, λ_d is equal with λ and equation (18) could be rewritten as

$$\begin{aligned} \bar{T} &= \frac{\sum_{n=0}^C \left(n \cdot \sum_{m=0}^K P_{n,m} \right) + \sum_{m=0}^K \left(m \cdot \sum_{n=0}^C P_{n,m} \right)}{\lambda} \\ &= \frac{\sum_{n=0}^C \left(\sum_{m=0}^K (n+m) \cdot P_{n,m} \right)}{\lambda} \end{aligned} \quad (20)$$

This is identical to equation (19) derived from the second approach.

4. RESULTS

We now investigate the imaging service of earth observation satellites with the FOFS scheduling policy, and compare the satellite simulator results with the analytical results of our two-dimensional Markov model. The orbit of the UK-DMC satellite is chosen to build the satellite simulator, which is a low Earth orbit imaging satellite that forms part of the Disaster Monitoring Constellation⁷.

There are 2000 requests with Poisson arrival in the simulation, the target locations of which are uniformly distributed over the area, the range of which is limited to latitude $[-60^\circ, 60^\circ]$ and longitude $[-150^\circ, 150^\circ]$, as shown in Figure 5.

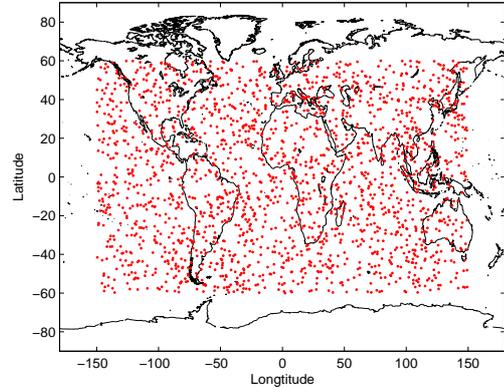


Figure 5: Distribution of targets over the globe

Figure 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 proposed two-dimensional Markov chain model.

Changing the download queue capacity, the request arrival rate and the download rate, we have another pair of comparison results as shown in Figure 7. In this scenario, because of the faster arrival rate and slower download rate, the onboard storage is more likely to be fully filled, which shows the constraint of memory capacity clearly. There is still quite good agreement between the simulation results and analytical results. In both sets of results, it is observed that there tend to be slightly more requests waiting for image capture operation in the simulation than in the theoretical model, which suggests that the proportional relationship might not be accurate between the image capture

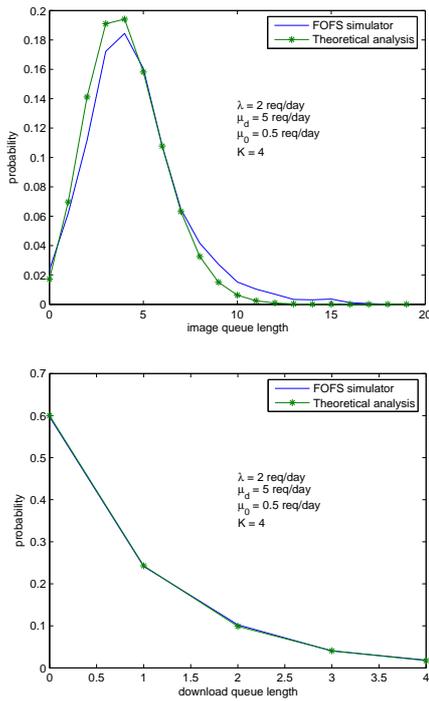


Figure 6: Queue length probability for image capture queue and download queue respectively

service rate and the capture queue length, especially for longer queues. However, the difference is small and with the good fit in both cases we are able to conclude that it is good enough for performance modelling of the satellite system.

Now let us investigate the effects of several system parameters on the key performance measurement: the average total waiting time. From Figure 8,9,10 we can see that the average total service time from the simulation is slightly longer than the result from the theoretical model, which is consistent with the results analysed above. Figure 8 shows that as the download rate increases, the average total time to wait for an imaging service decreases, which is reasonable. As we keep increasing the download rate, the average total service time reaches a plateau and does not decrease anymore, which shows that improving the download service rate can not improve the system performance when it is fast enough. Figure 9 shows that the average total service time decreases as the average arrival rate of requests decreases. But when the arrival rate is slow enough, the total waiting time for a request tends to be constant, which is also obviously reasonable.

And then we study the effects of the onboard storage capacity, i.e. the maximum download queue length.

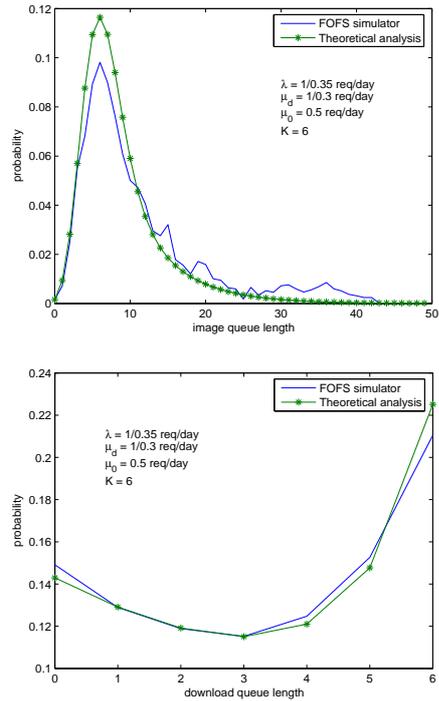


Figure 7: Queue length probability for image capture queue and download queue respectively

The onboard storage capacity does not have much influence on the performance where the download rate is fast enough for the request arrival rate, as observed from Figure 10. However, in the scenarios where the download rate is quite close to the arrival rate, the average total service time increases as the memory capacity decreases, as shown in Figure 11. This is reasonable because when the download queue is always full, the requests have to wait longer for memory space released by a download operation before the image capture operation can take place. From Figure 11, we

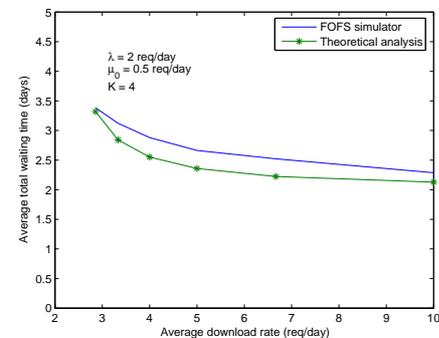


Figure 8: Effects of download rate

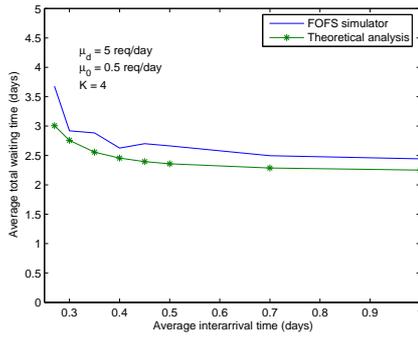


Figure 9: Effects of arrival rate

could also observe that the difference between the simulation results and the theoretical results is more obvious when K is smaller, which implies that the corresponding mean queue length of the capture queue is larger. It might also be caused by the proportional relationship assumption which becomes more obvious as the mean queue length increases. This is currently under investigation.

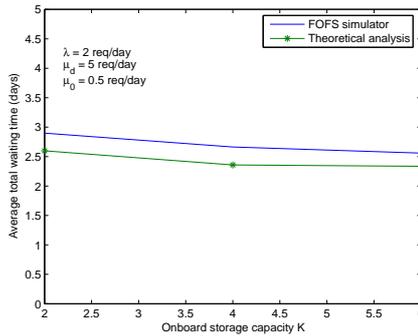


Figure 10: Effects of download queue capacity

From the analysis above we can see that all these system parameters have effects on the system performance. How to set the appropriate values to achieve system performance optimisation is an important task in the system design stage.

5. CONCLUSIONS & FUTURE WORK

In this paper we propose a two-dimensional Markov chain model to describe the image capture and download queues for an earth observation satellite, with onboard storage capacity limit considered. FOFS scheduling policy is used for the image capture queue, while FCFS is for the download queue. Comparison of satellite simulation results with model analytical results shows that the proposed two-dimensional

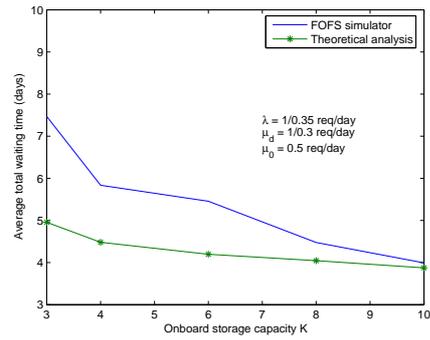


Figure 11: Effects of download queue capacity

Markov model is able to represent the imaging service process of earth observation satellite. Therefore it could be used for system optimisation in the system design stage, which is much less computationally expensive than running a large number of system simulations.

Using the model, we investigate one of the most important system performance metrics: the average imaging service time, and also analyse the effects of system parameters such as the onboard memory capacity, the download rate, and the request arrival rate. The proportional relationship between the image capture service rate and the capture queue length might not be very accurate, especially when the queue length increases. How to revise it is to be investigated in future work.

In our model analysis, to simplify the problem we have assumed the download process is a Poisson process, which is partially true due to the fact that with multiple download routes (such as mobile vehicle or inter-satellite transmission) the download event is independent and unpredictable. However, in the traditional ground station download approach, the download time windows could be predicted from the satellite orbit and the fixed ground station location. Also there could be more than one images downloaded each time. The general service time distribution is more suitable for the download queue analysis, which implies a more accurate model with more complicated mathematical derivation and points out the future work direction for the performance modelling and analysis of earth observation satellites.

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