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BMAP/G/c Queueing Model with Group Clearance Useful in Telecommunications Systems – A Simulation Approach

Srinivas R. Chakravarthy, Alexander Rumyantsev

Abstract: Queueing models in which customers or messages arrive in batches with inter-arrival times of batches possibly correlated and services rendered in batches of varying sizes play an important role in telecommunication systems. Recently queueing models of BMAP/G/1-type in which a new type of group clearance was studied using embedded Markov renewal process as well as continuous time Markov chain whose generator has a very special structure. In this paper, we generalize these models to multi-server systems through simulation approach. After validating the simulation model for the single server case, we report our simulated results for much more general situations.

Index Terms: Desktop Grid, Multiserver Systems, Group Clearance, BMAP, Simulation.

I. INTRODUCTION

Queueing models in which arrivals and services occur in batches have been studied extensively in the literature (see e.g., [6]). Recently, a queueing model in which arrivals occur according to a batch Markovian arrival process (BMAP), a versatile point process introduced by Neuts [10]. The services are offered in groups of varying sizes such that all waiting customers at the beginning of a service are taken into service, was studied by Chakravarthy, et.al., [5]. This type of group services was first studied in [5]. Such models, referred to as queueing models with group clearance in [5], have applications in modern *telecommunication* and *computing* systems, such as distributed and cloud computing, data transfer by means of wireless networks, solid-state drives and many other applications, thanks to recent developments in information technology. The authors in [5] employ matrix-analytic methods and report some interesting results both analytically and numerically by looking at the model in the context of a single server. Illustrative numerical examples are based on service times with phase type distribution. In the present paper we extend the aforementioned models to multi-server systems. While one can study the multi-server systems along the lines of [5], here we will resort to simulation to study such systems.

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Suppose that generator $Q = \sum_{k=0}^{\infty} D_k$ of dimension m is an irreducible generator of a continuous-time Markov chain (CTMC) such that D_0 governs transitions corresponding to no arrivals/events to a system, and D_k governs transitions corresponding arrivals of size k , $k \geq 1$. A BMAP is now formally characterized by the sequence of matrices $\{D_k\}$. The point process of BMAP is a semi-Markov process with transition probability matrix given by

$$\int_0^x e^{D_0 t} dt = [I - e^{D_0 x}](-D_0)^{-1} D_k, k \geq 1. \quad (1)$$

One can choose the initial probability vector, α , of the CTMC with generator Q , in a variety of ways to make the BMAP to be even more suitable for many applications in practice. Among the many choices, the most interesting one is $\alpha = \pi$, where $\pi Q = 0$, $\pi e = I$, where e is a column vector of dimension m with all entries equal to 1.

The fundamental rate, λ , is defined as $\lambda = \pi \sum_{k=1}^{\infty} k D_k e$. The quantity λ gives the rate (per unit of time) at which customers arrive to the system. The quantity $\lambda_g = \pi (-D_0) e$ gives the rate (per unit of time) at which batches arrive to the system. To have a specific value for λ_g we multiply the D_k , $k \geq 0$, by the appropriate common constant.

The motivation for Neuts to introduce BMAP as a versatile Markovian point process is the ability to model correlation, if any, of successive inter-arrival times and at the same time use matrix algebra to carry out the analysis of queueing models involving such processes. For full details on BMAP and its special cases including applications and reviews, we refer to [1–3, 8, 9, 12, 13].

Very briefly the model studied in [5] is as follows. Customers arrive according to a BMAP. If the arriving batch of customers finds the server idle, the entire batch gets into service; otherwise, the batch gets into a buffer (with unlimited capacity). The service times are generally distributed but for illustrative examples, the authors use phase type (PH-) distributions which are dense in the class of all non-negative continuous-time distributions [11]. The model is analyzed in steady-state including busy period (BP) analysis in [5]. As is

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known, the BP analysis in queueing systems, in general, is very involved and complicated. In particular, the probability density function of the BP in a relatively simple M/M/1 queueing system is obtained in terms of modified Bessel function. A detailed discussion including simulation study of BPs in the context of multi-server queueing systems can be seen in Chakravarthy [4]. One can also see a number of key references including some historical perspectives of BPs in [4].

While the BP in general is defined as the length of the time interval starting with an arrival of a customer to an empty system and ending with the departure of a customer leaving the system empty, there are two types of BPs with respect to multi-server systems. The above definition (which is the standard one and causes no confusion in the single server system) is referred to as partial BP under a multi-server queueing system. On the other hand, a full BP starts with all servers becoming busy, ending when at least one server becomes free. Note that in a single-server system the partial BP coincides with the full BP. On the contrast, stability criterion of a multi-server case does not guarantee finiteness of partial BP (i.e. system clearance) in general.

In this paper, we study the model introduced in [5] from the context of a multi-server system by using general service time distributions including heavy tailed distributions through simulation. The rest of the paper is organized as follows. In Section 2, we describe the simulated model along with listing a few key system performance measures. The validation of our simulated model (with the analytical one studied in [5]) is carried out in Section 3, and a few illustrative examples are presented in Section 4.

II. SIMULATED MODEL

We consider a *c*-server queueing system in which the arrivals occur according to a BMAP with representation $\{D_k\}$, $k \geq 0$, of dimension *m*. Let λ be the rate of customers arriving to the system and λ_g denote the rate at which the customers arrive in batches. Thus, λ/λ_g , gives the average number of customers in a batch at the time of the arrival. The service times are assumed to be generally distributed with distribution function *H*(.) having a finite mean given by $1/\mu$ so that μ gives the rate of service.

An arriving batch finding an idle server will get into service immediately; however, if all servers are busy, the arriving batch will enter into a buffer of infinite capacity and wait for a free server. Upon completion of a service, the server will become idle if the queue is empty; otherwise, the server will offer services to all those present in the queue.

While this multi-server queueing model can be analyzed, similar to the single server case done in [5], in this paper we will resort to simulation. The system performance measures (see, [5] for details on the analytic expressions needed for numerical computation and here we do not need that due to simulation) for the queueing model under study are defined as follows.

1. Probability that the server is idle, P_I .
2. Mean number of customers in the queue, μ_{Nq} .
3. Mean number of customers in service, μ_{BS} .
4. Mean number of customers in the system, μ_{NS} . Note that $\mu_S = \mu_{Nq} + \mu_{BS}$.

5. Mean sojourn time in the system of a customer, μ_{WS} .
6. Variance of waiting time of customers in the system, σ^2_{WS} .
7. Mean number of service completions during a BP, μ_{SC} .
8. Mean number of customers served during a BP, μ_{SR} . Note that $\mu_{SR} = \mu_{SC} \mu_{NS}$.

For all our cases including the validation ones, we simulated the model using ARENA [7] by using 5 replications and for 100,000 units (which in our case is minutes) for each replicate.

III. VALIDATION

It is imperative that any model developed through simulation should be validated so as to have confidence in using it for other scenarios where analytical results are not known or difficult to get. Thus, in this section we will validate our simulated model to the numerical results obtained through analytical model in [5]. Towards this end, we use Example 1 in [5] wherein the authors considered BMAP/PH/1 with five different BMAPs and three different PH- services with arrival rates, $\lambda_g = 1, 2$ and $\lambda = 3\lambda_g, 5\lambda_g$, and in all scenarios μ is fixed to be 1.

The five BMAPs and the three services considered in [5] are reproduced below. The five different BMAPs with representation $\{D_k\}$ are such that $D_k = Dp_k$, $k \geq 1$, where $\{p_k\}$ gives the batch size probability mass function. It should be pointed out that in [5] it was shown that while the steady-state probability vector depends on the batch size distribution, only a few measures depend on the mean (arrival) batch size and not on the distribution itself. However, the steady-state probability vector depends on the (arrival) batch size distribution as is to be expected.

TaP 1: **Erlang** (ErA): Here we consider an Erlang distribution of order 5 with rate $5\lambda_g$.

TaP 2: **Exponential** (ExA): This corresponds to the classical Poisson process with rate λ_g .

TaP 3: **Hyperexponential** (HeA): We look at a mixture of two exponentials with rates $1.9 \lambda_g$ and $0.19 \lambda_g$, respectively, with probabilities 0.9 and 0.1.

TaP 4: **MAP with negative correlation** (MnA):

$$D_0 = \lambda_g \begin{bmatrix} -1.00222 & 1.00222 & 0 \\ 0 & -1.00222 & 0 \\ 0 & 0 & -225.75 \end{bmatrix}$$

$$D_1 = \lambda_g \begin{bmatrix} 0 & 0 & 0 \\ 0.01002 & 0 & 0.99220 \\ 223.4925 & 0 & 2.2575 \end{bmatrix}$$

TaP 5: **MAP with positive correlation** (MpA):

$$D_0 = \lambda_g \begin{bmatrix} -1.00222 & 1.00222 & 0 \\ 0 & -1.00222 & 0 \\ 0 & 0 & -225.75 \end{bmatrix}$$

$$D_1 = \lambda_g \begin{bmatrix} 0 & 0 & 0 \\ 0.99220 & 0 & 0.01002 \\ 2.2575 & 0 & 223.4925 \end{bmatrix}$$

All of the above BMAP processes will be normalized so as to have a specified (group) arrival rate, λ_g .



Observe that these BMAPs are qualitatively different with different variance and correlation structure. It is worth mentioning that (a) the arrival processes ErA, ExA, and HeA are renewal processes and hence the correlation is 0; (b) the arrival process labeled MnA has negatively correlated arrivals, the correlation coefficient of the two successive inter-arrival times is -0.4889 and, symmetrically, the arrivals corresponding to the MpA process have positive correlation with coefficient 0.4889; (c) the ratio of the standard deviations of the inter-arrival times of these five arrival processes with respect to ErA are, respectively, 1, 2.2361, 5.0194, 3.1518, and 3.1518.

In our examples below, we consider three service time distributions. These are:

ToS 1: **Erlang (ErS)** This is Erlang of order 5 with rate 5μ in each stage.

ToS 2: **Exponential (ExS)** This is an exponential distribution with rate μ .

ToS 3: **Hyperexponential (HeS)** : Here we look at mixture of three exponentials with rates 7.30μ , 0.730μ and 0.073μ , respectively, with mixing probabilities 0.8, 0.15 and 0.05.

For the batch size distribution, we consider three different probability functions (see [5]). Note that while some system performance measures depend on the mean batch size, others do not even depend on the batch size at all. However, the steady-state probability vector of the number in queue (or number in system) does indeed depend on the batch size distribution. More on this in a later section.

BsD 1: **Poisson Batch Size** Here we assume that the arriving batch is of size k with probability given by $e^{-\theta}\theta^{k-1}/(k-1)!, k \geq 1$. Note that the mean batch size is given by $\theta + 1$.

BsD 2: **Geometric Batch Size** Here the arriving batch is of size k with probability given by $(1-p)p^{k-1}, k \geq 1$. Note that the mean batch size is given by $1/(1-p)$.

BsD 3: **Uniform Batch Size** Here it is assumed that the batch size is uniformly distributed on $\{1, 2, \dots, N\}$. Due to the finiteness of N , it is clear that we assume that $D_i = 0, i > N$. Note that the mean batch size is given by $0.5(N+1)$.

So as to compare various scenarios (where the distribution and/or mean of the batches have influence on the performance) properly, the parameters of the batch size distribution will be fixed as follows: $1+\theta = 1/(1-p) = 0.5(N+1)$ in order for the batch means to be the same.

In Tables 1 and 2 the (absolute) error percentage, which is defined as $100 |\text{analytical} - \text{simulated}|/\text{analytical}\%$ is displayed for various scenarios. By looking at the entries in these Tables 1 and 2, we outline a good agreement of the results of numerical simulation and the analytical results reported in [5]. While all the (absolute) error percentages are all very small (none exceeding 5%) with the largest one is 4.1%, a closer look at the analytical and simulated values for this measure (namely, μ_{Nq}) are, respectively, 2.14795 and 2.0601, which are close enough for all practical purposes.

Table 1. Error percentages for measures ($\lambda_g=1$).

λ	TS	BMAP	P_I	μ_{Nq}	μ_{BS}	μ_{NS}	CV	μ_{SC}	μ_{SR}
		ErA	0.4	0.0	0.0	0.0	0.1	0.0	0.0
		ExA	0.1	0.0	0.0	0.0	0.0	0.3	0.3
	ErS	HeA	0.4	0.6	0.1	0.2	0.1	0.4	0.5
		MnA	0.1	0.0	0.1	0.1	0.2	0.0	0.1
		MpA	0.1	3.8	1.8	2.1	1.1	0.0	1.8
		ErA	0.4	0.4	0.1	0.2	0.2	0.2	0.3
		ExA	0.2	0.1	0.1	0.1	0.5	0.2	0.2
3	ExS	HeA	0.0	0.5	0.4	0.4	0.1	0.2	0.6
		MnA	0.2	0.4	0.1	0.1	0.1	0.1	0.0
		MpA	0.5	1.5	0.5	0.0	0.8	0.2	0.7
		ErA	0.1	1.3	0.1	1.0	0.2	0.1	0.1
		ExA	0.3	1.4	0.4	1.2	0.1	0.1	0.4
	HeS	HeA	0.9	2.6	0.8	2.2	0.1	0.1	0.8
		MnA	0.3	1.1	0.2	0.9	0.7	0.2	0.4
		MpA	0.1	2.0	0.5	1.4	0.2	0.0	0.5
		ErA	0.4	0.1	0.0	0.0	0.1	0.0	0.0
		ExA	0.1	0.0	0.0	0.0	0.0	0.3	0.3
	ErS	HeA	0.4	0.6	0.1	0.2	0.1	0.4	0.5
		MnA	0.1	0.1	0.1	0.1	0.2	0.0	0.1
		MpA	0.1	4.1	1.8	2.2	1.0	0.0	1.9
		ErA	0.4	0.4	0.1	0.2	0.3	0.2	0.3
		ExA	0.2	0.1	0.0	0.0	0.5	0.2	0.2
5	ExS	HeA	0.0	0.6	0.4	0.4	0.1	0.2	0.6
		MnA	0.2	0.4	0.0	0.1	0.1	0.1	0.0
		MpA	0.5	1.5	0.5	0.1	0.8	0.2	0.7
		ErA	0.1	1.2	0.1	1.0	0.2	0.1	0.1
		ExA	0.3	1.4	0.5	1.2	0.0	0.1	0.4
	HeS	HeA	0.9	2.7	0.8	2.2	0.1	0.1	0.8
		MnA	0.3	1.1	0.2	0.9	0.7	0.2	0.4
		MpA	0.1	1.9	0.5	1.4	0.2	0.0	0.4

Table 2. Error percentages for measures ($\lambda_g = 2$).

λ	TS	BMAP	P_I	μ_{Nq}	μ_{BS}	μ_{NS}	CV	μ_{SC}	μ_{SR}
		ErA	1.0	0.2	0.1	0.1	0.1	0.3	0.4
		ExA	0.2	0.0	0.0	0.0	0.1	0.5	0.5
	ErS	HeA	0.2	0.1	0.0	0.0	0.1	0.1	0.1
		MnA	0.4	0.1	0.1	0.1	0.1	0.1	0.2
		MpA	0.1	0.6	0.6	0.6	0.7	0.0	0.7
		ErA	0.3	0.3	0.1	0.1	0.3	0.4	0.5
		ExA	0.0	0.0	0.1	0.0	0.1	0.1	0.2
6	ExS	HeA	0.3	0.1	0.2	0.2	0.2	0.1	0.1
		MnA	0.2	0.4	0.3	0.3	0.0	0.1	0.2
		MpA	0.1	0.9	0.3	0.5	0.3	0.2	0.5
		ErA	0.3	1.6	0.4	1.4	0.2	0.1	0.3
		ExA	0.4	0.6	0.2	0.5	0.0	0.1	0.3
	HeS	HeA	0.1	0.4	0.4	0.4	0.6	0.0	0.4
		MnA	1.4	2.7	1.1	2.4	2.0	0.1	1.2
		MpA	0.7	2.2	0.3	1.8	0.7	0.3	0.6
		ErA	1.0	0.2	0.1	0.1	0.1	0.3	0.4
		ExA	0.2	0.0	0.1	0.0	0.1	0.5	0.5
	ErS	HeA	0.2	0.1	0.0	0.0	0.1	0.1	0.1
		MnA	0.4	0.1	0.1	0.1	0.1	0.1	0.2
		MpA	0.1	0.6	0.6	0.6	0.7	0.0	0.7
		ErA	0.3	0.3	0.0	0.1	0.3	0.4	0.5
		ExA	0.0	0.1	0.1	0.0	0.1	0.1	0.2
10	ExS	HeA	0.3	0.1	0.2	0.2	0.2	0.1	0.1
		MnA	0.2	0.4	0.3	0.4	0.0	0.1	0.2
		MpA	0.1	0.9	0.3	0.5	0.3	0.2	0.5
		ErA	0.3	1.6	0.5	1.4	0.2	0.1	0.3
		ExA	0.4	0.6	0.1	0.5	0.1	0.1	0.2
	HeS	HeA	0.1	0.4	0.4	0.4	0.6	0.0	0.4
		MnA	1.4	2.7	1.1	2.4	2.0	0.1	1.2
		MpA	0.7	2.2	0.3	1.8	0.7	0.3	0.6



IV. ILLUSTRATIVE EXAMPLES

In this section we will discuss a few illustrative examples based on simulated results. In addition to the eight system performance measures listed in Section 2, we will also consider the following measures, one dealing with tail probabilities and the other with the BP. This measure will depend on the batch size distribution and will enable us to see the effect of variation/correlation in the arrival process as well as service time distribution.

9. Probability that the number in the queue exceeds a certain value, $P(N_q > n), n \geq 0$.
10. Mean BP, μ_{BP} , both partial and full ones, will be considered. Note that it will be clear from the context in the example below whether we are dealing with partial or full BP.

For the arrival processes we consider the same five BMAPs listed in Section 3. Further, we add the following two service time distributions to the ones listed in Section 3, the first, shifted exponential, belonging to the class of so-called log-concave distributions and the second, Weibull, being heavy-tailed. The probability density functions are as follows:

ToS 4: **Shifted Exponential** (SeS). The density of a SeS with a shift of magnitude 0.2 is given by

$$f(t) = 1.25e^{-1.25(t-0.2)}, t \geq 0.2.$$

ToS 5: **Weibull** (WeS). The 2-parameter Weibull considered here has the probability density function

$$f(t) = (2t)^{-0.5} e^{-\sqrt{2t}}, t \geq 0.$$

In our examples below we consider the above five BMAPs (with three batch size distributions as mentioned earlier), five service time distributions, take $\lambda_g = c$, and fix the service rate, $\mu = 1$. Note that by taking $\lambda_g = c$ we compare different multi-server queueing systems in such a way that on the average each server has a (group) arrival rate of 1.

A. Example 1

In this example, we vary $c = 1, 2, 5, 10$, and look at 300 scenarios through five types of arrivals, five services, three batch size distributions, and four values for the number of servers. We study the measures defined above, making one more convention: we define the coefficient of variation of sojourn time in the system as $CV = \sigma_{W_s} / \mu_{W_s}$.

First, we display in Table 3, the significance (at 5% level) of various measures with regard to the type of arrivals (TaP), the type of services (ToS), the number of servers (c), and the type of batch size distribution (BsD). Here an ‘‘X’’ indicates significance at 5% level and a blank space indicates insignificance at the same level.

Table 3. Significance of measures

Measure	c	TaP	ToS	BsD
$P(N_q > 1)$	X	X	X	X
$P(N_q > 2)$	X	X	X	X
$P(N_q > 4)$	X	X	X	
$P(N_q > 8)$	X	X	X	
$P(N_q > 16)$	X	X	X	
$P(N_q > 32)$	X		X	
P_l	X	X	X	
μ_{Nq}	X		X	
μ_{BS}	X	X	X	
CV	X	X	X	

An examination of the entries of Table 3 indicates the following key observations for the range of the parameter values considered.

1. Batch size distribution plays a significant role in the case of the two tail probabilities, $P(N_q > 1)$ and $P(N_q > 2)$. However, it doesn’t play a significant role in the other measures. The insignificance of the batch size distribution for the system measures (other than the tail probabilities) considered here is proved in [5].
2. For all measures considered here, the type of service times, ToS, and the number of servers (c), play a significant role indicating items such as variability in the service times, heavy tails, concavity, and the number of resources affects the system measures appreciably.
3. In almost all cases, the type of arrival process (TaP) affects significantly the system performance measures. The exceptions appear to be the mean number of customers in the queue and the tail probability, $P(N_q > 32)$.

We did a statistical analysis, including multiple comparisons, on the simulated data with regard to c , TaP, ToS, and BsD and we summarize the key observations below.

1. With regard to $P(N_q > 1)$ and $P(N_q > 2)$, we noticed:
 - a. a decreasing trend as c is increased. This is as is to be expected since a higher c (in spite of having the same (group) arrival rate of 1 per server) will help to reduce the number of customers waiting in the queue.
 - b. ErA producing a higher value for these measures; MpA producing the least value (about 25% of the ErA one). The trend of this measure decreasing with increasing variability in the interarrival times (among renewal processes) holds true.
 - c. while HeS and WeS produced two largest values, ErS yielded the smallest value in the case of both measures.
 - d. while BsD 3 yielded the largest value, BsD 1 produced the smallest value. This measure for BsD 2 is significantly different from BsD 1 but not from BsD 3.
2. With respect to $P(N_q > n), n = 4, 8, 16, 32$, we noticed similar (to $P(N_q > 1)$) observations except that there was no significant difference with respect to the type of distribution used for batch size distribution (BsD).
3. As proved in [5] the measures: $P_l, \mu_{Nq}, CV, \mu_{SC}$ are insensitive to BsD. In addition to these measures, even the μ_{BP} is insensitive to the type of distribution used for the batch size.
4. The measure, P_l , is such that
 - a. it decreases as c increases in all cases, which is as expected and coincides with observations given for $P(N_q > 1)$.
 - b. it appears that the lowest value is for ErA



arrivals and the largest is for the MpA arrivals.
c. HeS and WeS produce the largest value with ErS and SeS yielding the smallest.

5. The measure, μ_{Nq} , is such that
 - a. it decreases as c increases in all scenarios.
 - b. HeS produces the largest value while ErS yielding the smallest.
6. When we look at μ_{BS} , which stands for the mean number of customers in a service, we notice that this measure
 - a. decreases as c increases in all scenarios.
 - b. for MpA arrivals, appears to yield the largest value while ErA producing the smallest one.
 - c. for HeS and WeS arrivals, produce the largest value with the rest, namely, ErS, ExS and SeS yielding the smallest.
7. Finally, we look at the coefficient of variation, CV , of the sojourn time in the system and observe that
 - a. this increases as c increases in all cases.
 - b. the largest value appears to occur for both MpA and ErA arrivals, while the smallest one is registered for MnA arrivals.
 - c. HeS produce the largest value with ErS yielding the smallest.

The purpose of the next example is to compare partial and full BPs. We do so by looking at the mean BP, coefficient of variation of BP, and the ratio of the BP to the corresponding mean sojourn time. Note that the rest of the measures (see above) do not depend on the type of BP.

B. Example 2

This example is similar to Example 1 except that now we vary $c = 1, 2, 3, 4$ and vary the other parameters as in Example 1. Our main focus here is on the mean BPs (μ_{BP}) - both partial (PBP) and full (FBP) - as well as on the ratio of mean BP to the mean sojourn time. In Table 4 (split into many) we display these two measures under various scenarios.

Table 4. Mean BP and its ratio to mean sojourn time

ToBP	c	ToS	μ_{BP}				
			ErA	ExA	HeA	MnA	MpA
PBP	1	ErS	2.69	2.48	3.31	2.62	1.43
		ExS	1.91	1.99	2.33	2.49	1.38
		HeS	1.17	1.31	1.43	2.08	1.16
		SeS	2.08	2.20	2.76	2.54	1.40
		WeS	1.42	1.53	1.66	2.11	1.28
	2	ErS	7.47	3.74	4.05	2.90	1.79
		ExS	3.40	2.99	3.30	3.17	1.68
		HeS	2.03	2.35	2.67	3.44	1.55
		SeS	4.06	3.23	3.67	2.97	1.69
		WeS	2.44	2.52	2.79	3.25	1.61
	3	ErS	30.76	6.73	4.62	4.73	2.60
		ExS	8.10	5.49	4.64	5.38	2.32
		HeS	4.09	4.67	5.30	6.42	2.13
		SeS	11.50	5.83	4.81	4.85	2.36
		WeS	5.02	4.82	4.78	5.99	2.21
	4	ErS	160.87	13.32	5.02	8.36	4.04
		ExS	22.44	10.91	6.25	10.13	3.36
		HeS	8.52	9.47	10.72	12.90	2.99
		SeS	40.59	11.63	5.98	8.79	3.50
		WeS	11.26	9.77	7.90	11.91	3.12

ToBP	c	ToS	μ_{BP}/μ_{Ws}				
			ErA	ExA	HeA	MnA	MpA
PBP	1	ErS	2.15	1.97	2.59	1.85	1.25
		ExS	1.58	1.60	1.86	1.78	1.17
		HeS	1.10	1.17	1.21	1.75	1.04
		SeS	1.71	1.76	2.18	1.81	1.20
		WeS	1.25	1.28	1.35	1.62	1.08
	2	ErS	6.77	3.38	3.63	2.57	1.72
		ExS	3.13	2.72	2.99	2.80	1.59
		HeS	1.98	2.23	2.50	3.18	1.49
		SeS	3.72	2.93	3.31	2.63	1.61
		WeS	2.30	2.34	2.57	2.93	1.53
	3	ErS	29.06	6.34	4.32	4.39	2.56
		ExS	7.70	5.19	4.37	5.00	2.26
		HeS	3.97	4.52	5.07	6.10	2.10
		SeS	10.92	5.50	4.51	4.51	2.31
		WeS	4.85	4.62	4.56	5.63	2.16
	4	ErS	154.79	12.79	4.80	7.95	4.01
		ExS	21.68	10.52	6.01	9.64	3.32
		HeS	8.37	9.28	10.38	12.42	2.97
		SeS	39.16	11.19	5.73	8.37	3.46
		WeS	10.97	9.48	7.64	11.41	3.08

ToBP	c	ToS	μ_{BP}				
			ErA	ExA	HeA	MnA	MpA
FBP	2	ErS	1.01	1.06	1.37	1.09	0.63
		ExS	0.96	1.00	1.17	1.00	0.71
		HeS	0.68	0.72	0.75	0.80	0.65
		SeS	1.00	1.06	1.31	1.05	0.70
		WeS	0.80	0.82	0.86	0.86	0.70
	3	ErS	0.61	0.67	0.89	0.68	0.41
		ExS	0.64	0.67	0.78	0.66	0.48
		HeS	0.52	0.52	0.52	0.54	0.46
		SeS	0.65	0.69	0.85	0.70	0.46
		WeS	0.56	0.57	0.58	0.57	0.49
	4	ErS	0.44	0.50	0.66	0.50	0.31
		ExS	0.48	0.50	0.59	0.49	0.36
		HeS	0.42	0.41	0.40	0.41	0.37
		SeS	0.47	0.51	0.63	0.51	0.35
		WeS	0.44	0.43	0.44	0.43	0.38

ToBP	c	ToS	μ_{BP}/μ_{Ws}				
			ErA	ExA	HeA	MnA	MpA
FBP	2	ErS	0.91	0.96	1.23	0.97	0.60
		ExS	0.88	0.91	1.06	0.88	0.67
		HeS	0.66	0.69	0.70	0.74	0.63
		SeS	0.92	0.96	1.18	0.93	0.66
		WeS	0.75	0.76	0.79	0.77	0.66
	3	ErS	0.58	0.64	0.83	0.63	0.40
		ExS	0.61	0.63	0.74	0.62	0.47
		HeS	0.51	0.50	0.50	0.51	0.46
		SeS	0.61	0.65	0.80	0.65	0.45
		WeS	0.54	0.54	0.55	0.54	0.48
	4	ErS	0.42	0.48	0.63	0.48	0.31
		ExS	0.46	0.48	0.56	0.47	0.36
		HeS	0.41	0.40	0.39	0.40	0.36
		SeS	0.46	0.49	0.60	0.49	0.35
		WeS	0.43	0.42	0.43	0.41	0.37

A quick look at the entries in Table 4 reveals the following observations.

1. As is to be expected

$\mu_{BP} > \mu_{Ws}$ in the case when $c = 1$ for all scenarios. This is mainly due to the fact that all waiting customers at the beginning of a service will be served. It is worth comparing this to the one in the case of classical queues. In [4], it is shown that for a variety of combinations of arrival and services, $\mu_{BP} > \mu_{Ws}$ and for some others $\mu_{BP} < \mu_{Ws}$ for single as well as multiple-server cases.

2. With regard to PBP, we see $\mu_{BP} > \mu_{Ws}$ for all scenarios considered here. Again, this is not surprising and agrees with intuition due mainly to providing the type of group services considered here.
3. With regard to FBP, we notice $\mu_{BP} < \mu_{Ws}$ in all but three scenarios' (all corresponding to HeA arrivals) values are not far away from 1 and could be attributed to sampling error. It is worth pointing out that by definition the mean BP under "full" will always be less (unless $c = 1$ in which case it will be equal) than the corresponding "partial" one, and we see that in our simulated results this inequality also holds.

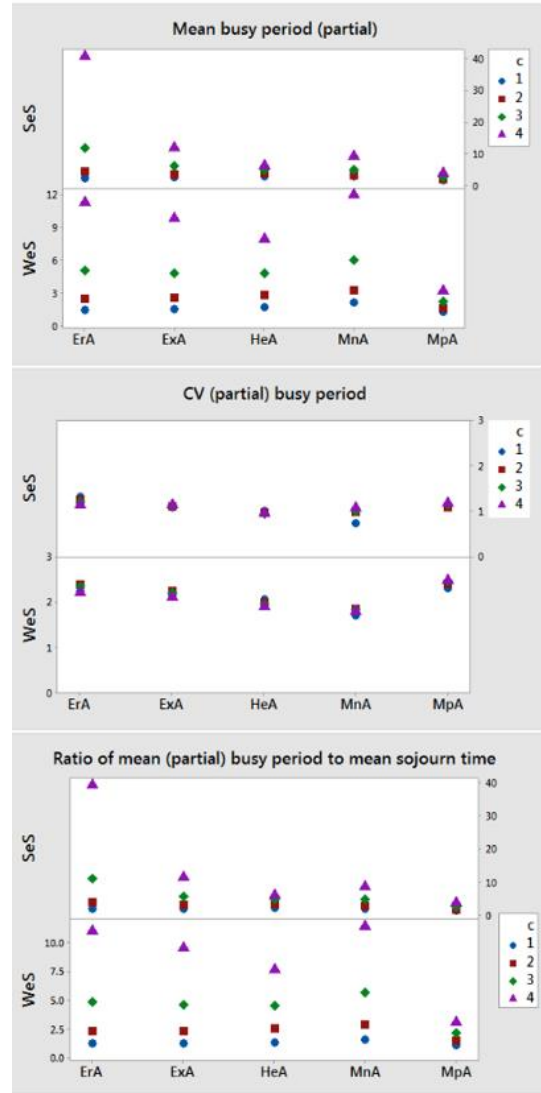
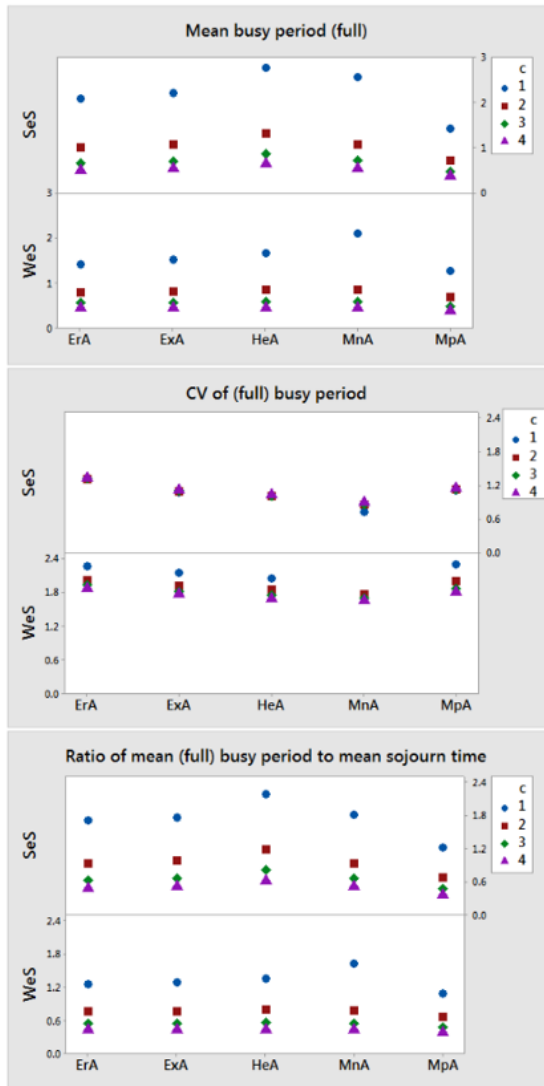


Figure 1. Selected measures under various scenarios for SeS and WeS services

Finally, we compare the two services, SeS and WeS. The plots of selected measures are given in Figure 1. Recall that WeS is a heavy tailed distribution while SeS is log-concave one. A quick look at the plots in Figure 1 reveals the distinct role of heavy tailed services with regard to the (full and partial) mean BPs, coefficient of variation of the (full and partial) BPs, and the ratio of (full and partial) mean BPs to the corresponding mean sojourn time.

V. CONCLUSION

In this paper, we considered a novel model of multiserver system with group clearance using simulation approach. This approach allowed us to significantly extend the model comparing to analytical study performed earlier, from a single-server to multi-server case, as well as to study the model under various assumptions, such as heavy-tailed or log-concave service time distribution. We illustrated the inference of correlation, variance, service time and batch size distribution on some key performance measures of the model.

Figure 1. Selected measures under various scenarios for SeS and WeS services



We also studied the partial and full busy periods, which are important characteristics of a multi-server system. These results might be of practical interest for various fields of application, including the distributed computing systems, wireless transmission systems and solid state drives.

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