

# The M/G/1-type Markov chain with restricted transitions and its application to queues with batch arrivals

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## Abstract

We consider M/G/1-type Markov chains where a transition that decreases the value of the level triggers the phase to a small subset of the phase space. We show how this structure, referred to as restricted downward transitions, can be exploited to speed-up the computation of the stationary probability vector of the chain. To this end we define a new M/G/1-type Markov chain with a smaller block size, the  $G$  matrix of which is used to find the original chain's  $G$  matrix. This approach is then used to analyze the BMAP/PH/1 queue and the BMAP[2]/PH[2]/1 preemptive priority queue, yielding significant reductions in computation time.

## 1 Introduction

An M/G/1-type Markov chain (MC) [19] is a two-dimensional process  $\{(N_t, X_t), t \geq 0\}$  where the *level* variable  $N_t$  takes values on  $\mathbb{N}$ , while the *phase* variable  $X_t$  takes values on a finite set of size  $m_b$  or  $m$ , depending on whether the level is equal to or greater than zero. In an M/G/1-type MC the transition rates are level-independent and the level can only decrease by one during a single transition. Therefore, the generator matrix  $Q$  of an M/G/1-type MC

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is of the form

$$Q = \begin{bmatrix} B_0 & B_1 & B_2 & B_3 & \cdots \\ C_0 & A_1 & A_2 & A_3 & \cdots \\ & A_0 & A_1 & A_2 & \cdots \\ & & A_0 & A_1 & \cdots \\ 0 & & & \ddots & \ddots \end{bmatrix}, \quad (1)$$

where  $(A_i)_{i \geq 0}$  are  $m \times m$  matrices,  $B_0$  is an  $m_b \times m_b$  matrix,  $C_0$  is an  $m \times m_b$  matrix, and  $(B_i)_{i \geq 1}$  are  $m_b \times m$  matrices. All these matrices have nonnegative real entries, with the exception of the diagonal entries of  $B_0$  and  $A_1$ , which are negative and such that the matrix  $Q$  has zero row sums. There are two main steps to determine the stationary probability vector of this MC. The first step is to find the matrix  $G$ , that is, the minimal non-negative solution of the matrix equation

$$\sum_{i=0}^{\infty} A_i G^i = 0. \quad (2)$$

This equation can be solved using iterative algorithms such as (linearly-convergent) functional iterations (FI) [19, 14] or the (quadratically-convergent) cyclic reduction (CR) algorithm [4, 3]. The second step is to compute the stationary probability vector by means of Ramaswami's formula [22], which relies on the matrix  $G$ .

Although it is possible to analyze a broad range of systems using M/G/1-type MCs, they suffer from the curse of dimensionality. If  $m$  becomes large, the algorithms to find  $G$  and the stationary vector may require long computation times. For instance, FI [19] requires  $O(Nm^3)$  time per iteration, where  $N$  is the smallest integer such that  $A_i$  is (numerically) zero for  $i > N$ . However, there are cases where the solution of Equation (2) can be circumvented by exploiting the structure of the blocks  $(A_i)_{i \geq 0}$ . An example of this is when the matrix  $A_0$  has only one nonzero column. In this case it is possible to find the matrix  $G$  explicitly without resorting to iterative algorithms [14, 23]. The main contribution of this paper is to analyze and exploit the more general case where the matrix  $A_0$  has  $1 < r \ll m$  nonzero columns. This structure implies that a transition that decreases the value of the level can only trigger the phase to a small subset of the phase space. Therefore, we refer to this class of MCs as M/G/1-type MCs with restricted downward transitions. We show how this structure can be exploited to reduce the total computation time to find the stationary probability vector of the chain. For this purpose, we define a new M/G/1-type MC by observing the original chain when the phase variable is in one of the  $r$  phases corresponding to the nonzero columns of  $A_0$ . The blocks of this new MC are of size  $r$  and therefore the solution of this chain can be carried out significantly faster. In fact, computing the blocks of the censored chain takes

$O(MNrm^2)$  time, where  $M$  is the number of blocks of this chain. Then we find the matrix  $G$  of the censored chain, which requires  $O(Mr^3)$  time *per iteration*. The final step to fully determine the matrix  $G$  of the original chain is to solve a linear system, this is done in a *single step* that requires  $O((m-r)^3r + Nr^3 + N(m-r)^2r^2)$  time. Our approach therefore offers an advantage compared to general-purpose methods, which require  $O(Nm^3)$  time *per iteration*, especially when the ratio  $m/r$  is large. In addition, after finding the matrix  $G$  we exploit its structure to speed-up the computation of the stationary probability vector.

Previous work on analyzing MCs with restricted transitions has centered mainly on Quasi-Birth-and-Death (QBD) processes [18, 11, 21]. QBDs can be seen as a particular case of M/G/1-type MCs where the blocks  $\{A_i\}_{i \geq 3}$  and  $\{B_i\}_{i \geq 2}$  are equal to zero. To the best of our knowledge, M/G/1-type MCs with restricted transitions have only been treated in [5]. There the authors exploit the referred structure to speed-up the computation of  $G$  by using two specific iterative algorithms: a functional iteration and a sub-Newton method. However, in [5] an additional restriction is imposed on the chain (see Remark 2 on page 5), which reduces the applicability of their method. For instance, the MC to model the BMAP[2]/PH[2]/1 preemptive priority queue is of the M/G/1-type and has the restricted-downward-transitions property. However, this queue cannot be analyzed with the methods introduced in [5] because of the additional restrictions. The approach introduced in this paper is closely related to the one presented in [21] for QBDs. In [21] the structure of the matrix  $A_0$  is employed to speed-up the computation of the matrix  $G$ , from which the stationary probability vector can be easily obtained as it has the so-called matrix-geometric property. Here we not only extend [21] to exploit the structure of  $A_0$  to compute the matrix  $G$  of an M/G/1-type MC, but we also make use of this structure to expedite the computation of the stationary probability vector, for which the matrix-geometric property does not hold. Besides, while our focus is on M/G/1-type MCs with restricted downward transitions, the approach presented here can be applied *mutatis mutandis* to compute the matrix  $R$  of a GI/M/1-type MC with restricted upward transitions. In these MCs, an upward transition, which increases the level by at most one, can only occur if the phase variable is in a small subset of the phase space. After computing the matrix  $R$ , the stationary probability vector can be easily obtained as it also has the matrix-geometric form.

Even though at first sight the form assumed for  $A_0$  appears to be rather restrictive, this structure actually arises or can be induced in several, even well-studied, queueing models. Section 4 will show how the BMAP/PH/1 queue and the BMAP[2]/PH[2]/1 preemptive priority queue can be modeled as M/G/1-type MCs with restricted downward transitions. Moreover, these queues provide some additional structure which can be exploited in combination with our general approach to further reduce the computation time to find the stationary probability

vector. These two queueing systems will be used to illustrate numerically the substantial gain in computation time that can be obtained by using the methods introduced in this paper. In fact, for the BMAP[2]/PH[2]/1 preemptive priority queue we found that our approach is not only faster than solving the original M/G/1-type MC, but it is also faster than other methods previously proposed to find the queue-length distribution of this particular queue [25]. Although we consider these two queues in detail, there are many other systems where the restricted transitions arise, including the meteor burst packet model in [5] and the PH/MAP/1 queue with batch services.

In the next section we will show how the computation of the matrix  $G$  can be sped up by exploiting the restricted-transitions structure. After finding  $G$ , this structure can be used to accelerate the computation of the stationary probability vector, as discussed in Section 3. The performance of our approach is illustrated through the numerical results presented in Section 4. Although this paper deals with MCs in continuous time, all the results can be easily translated and applied to discrete-time MCs.

## 2 Analyzing M/G/1-type MCs with restricted transitions

In this section we focus on the the computation of the matrix  $G$ , the minimal nonnegative solution of Equation (2), for a general M/G/1-type MC with restricted downward transitions. The development here follows the lines of [21], where a similar analysis was carried out for QBD processes with restricted transitions. To start with, let us partition the phase space of the M/G/1-type MC, i.e., the set  $\{1, \dots, m\}$ , into two subsets:  $S^+ = \{1, \dots, r\}$  and  $S^- = \{r + 1, \dots, m\}$ . We can partition the matrices  $A_i$  accordingly as

$$A_i = \begin{bmatrix} A_i^{++} & A_i^{+-} \\ A_i^{-+} & A_i^{--} \end{bmatrix}, \quad i = 0, \dots, N, \quad (3)$$

where  $N$  is the smallest integer such that  $A_i = 0$  and  $B_i = 0$  for  $i > N$ , and  $A_i^{++}$  and  $A_i^{--}$  are square matrices of size  $r$  and  $m - r$ , respectively. We assume that the MC is irreducible and therefore the matrices  $A_1^{++}$  and  $A_1^{--}$  are transient generators and their inverses exist. As stated in the previous section, our focus is on the case where the block  $A_0$  has only a few nonzero columns. Here we assume, without loss of generality, that those columns are the first  $r \ll m$ , and therefore the matrix  $A_0$  can be written as

$$A_0 = \begin{bmatrix} A_0^{++} & 0 \\ A_0^{-+} & 0 \end{bmatrix}. \quad (4)$$

In general, to compute the matrix  $G$  one must rely on iterative algorithms like FI or CR [19, 14, 3]. However, if the matrix  $A_0$  has the structure in (4) and if  $r = 1$  ( $S^+$  is unitary),

the matrix  $G$  can be computed explicitly [14]. Here we assume that  $A_0$  has  $r > 1$  nonzero columns. The main consequence of this structure is that the matrix  $G$  also has  $r$  nonzero columns. To see this recall that the  $(i, j)$ -th entry of the matrix  $G$  holds the probability that, if the chain starts in state  $(k, i)$ , the first visit to level  $k - 1$  occurs by visiting state  $(k - 1, j)$ , for  $k > 1, 1 \leq i, j \leq m$  [14]. In addition, in an M/G/1-type MC, if the chain starts in level  $k$  the first visit to level  $k - 1$  must be a downward transition from level  $k$  to level  $k - 1$ , which is governed by  $A_0$ . If this matrix has the structure in (4), the first visit to level  $k - 1$ , starting from level  $k$ , must be to a state with phase in  $S^+$ . Therefore, only the first  $r$  columns of  $G$  are different from zero and this matrix can be written as

$$G = \begin{bmatrix} G_+ & 0 \\ G_0 & 0 \end{bmatrix},$$

where  $G_+$  (resp.  $G_0$ ) is an  $r \times r$  (resp.  $(m - r) \times r$ ) matrix. In the following subsections we show how the matrices  $G_+$  and  $G_0$  can be computed separately such that the total time required to compute  $G$  reduces significantly when  $r \ll m$ .

**Remark 1.** *In addition to the structure in (4), we have found M/G/1-type MCs where the blocks feature an additional structure, e.g., when modeling the batch queues introduced in Section 4. The most relevant feature is that the matrices  $(A_i^{--})_{i=2}^N$  can be written as the product of a scalar and a common matrix, i.e.,  $A_i^{--} = c_i K$ , for  $2 \leq i \leq N$ . Another observation is that the blocks  $(A_i^{+-})_{i=2}^N$  and  $(A_i^{-+})_{i=2}^N$  are actually equal to zero. This additional structure will be exploited in those places where it may provide a significant gain in the computation time to find the stationary probability vector. Apart from this, the remainder of the paper focuses mostly on the structure in (4), so that the approach proposed here can be used in other applications where only this structure arises.*

**Remark 2.** *As mentioned in the introduction, the approach in [5] also deals with M/G/1-type MCs with restricted transitions. However, this method imposes an additional restriction on the blocks of the MC. This restriction can be translated into our notation by imposing that*

$$A_i = \begin{bmatrix} A^{++} & A^{+-} \\ A^{-+} & A^{--} \end{bmatrix} \begin{bmatrix} a_i^+ I & 0 \\ 0 & a_i^- I \end{bmatrix}, \quad i \geq 0,$$

where  $(a_i^+)_{i \geq 0}$  and  $(a_i^-)_{i \geq 0}$  are nonnegative scalars and  $a_0^- = 0$ . The most restrictive implication of this assumption is that the block  $A_1$  (transitions within the same level) must have the same pattern (up to a multiplication by a scalar) than the blocks  $(A_i)_{i \geq 2}$  (transitions to upper levels). This means that, for instance, the BMAP[2]/PH[2]/1 priority queue cannot be modeled with the approach in [5] as the transitions within the same level (arrivals and service completions of high-priority customers) and those to upper levels (arrivals of low-priority customers) trigger very different transitions on the phase variable (see Appendix A).

## 2.1 Computing $G_+$

The computation of the matrix  $G$  is split in two steps: we first compute  $G_+$  by using a censoring argument and afterward we obtain  $G_0$  by solving a linear system. To compute  $G_+$  we define a new process by observing the original M/G/1-type MC only when the phase variable is in  $S^+$ . Since in the original chain any downward transition takes the chain to a state with phase in  $S^+$ , the level in the new chain can decrease by at most one in a single transition. Also, in the original chain there can be many upward transitions between two visits to states with phase in  $S^+$ . Therefore, the chain that results from observing the original MC when the phase variable is in  $S^+$  is also of the M/G/1 type. In this case however the size of the blocks is equal to  $r$ , which is assumed to be significantly smaller than  $m$ . Let the  $r \times r$  blocks  $(\bar{A}_i)_{i \geq 0}$  characterize the behavior, away from the boundary, of the new M/G/1-type MC, and let  $\bar{G}$  be the associated minimal nonnegative solution of Equation (2). As stated before, the  $(i, j)$ -th entry of  $\bar{G}$  holds the probability that, given that the chain starts in state  $(k, i)$ , the first visit to level  $k - 1$  occurs by visiting state  $(k - 1, j)$ , for  $1 \leq i, j \leq r$ . However, this is the same definition of the  $(i, j)$ -th entry of  $G_+$ , since in the original chain the first visit to level  $k - 1$ , starting from level  $k$ , can only occur to a state with phase in  $S^+$ . Therefore, to compute  $G_+$  we can compute the blocks  $(\bar{A}_i)_{i \geq 0}$  of the censored process and then solve Equation (2) to obtain  $\bar{G}$ , which is equal to  $G_+$ .

To determine the blocks  $(\bar{A}_i)_{i \geq 0}$  we define the  $(m - r) \times r$  matrices  $(W_l)_{l \geq -1}$ . The  $(i, j)$ -th entry of  $W_l$  holds the probability that, given that the chain starts in level  $k > 1$  and phase  $i \in S^-$ , the first passage to a state with phase in  $S^+$  occurs by visiting state  $(k + l, j)$ , for  $j \in S^+$  and  $l \geq -1$ . Relying on these matrices, the blocks  $(\bar{A}_i)_{i \geq 0}$  can be computed by conditioning on the first transition in the original chain. For instance, to define the matrix  $\bar{A}_0$  there are two possible sets of transitions: the chain may move directly from  $(k, i)$  to  $(k - 1, j)$  with  $i, j \in S^+$  (according to  $A_0^{++}$ ); or it may first move within the same level to a state  $(k, l)$  with  $l \in S^-$  (according to  $A_1^{+-}$ ), and then make a number of transitions that will take the chain to a state  $(k - 1, j)$  with  $j \in S^+$ , while avoiding any state with phase in  $S^+$  (according to  $W_{-1}$ ). Therefore, the matrix  $\bar{A}_0$  can be obtained as  $\bar{A}_0 = A_0^{++} + A_1^{+-}W_{-1}$ . Other paths from level  $k$  to  $k - 1$  are ruled out because they would involve either a direct transition to a state with phase in  $S^+$ , or a transition to a state with phase in  $S^-$ , but level greater than  $k$ , from which, to return to  $k - 1$ , it would be necessary to visit states in level  $k$  with phase in  $S^+$ . By proceeding in a similar manner we find that the blocks  $(\bar{A}_i)_{i \geq 0}$  are given by

$$\bar{A}_i = \begin{cases} A_i^{++} + \sum_{j=1}^{i+1} A_j^{+-}W_{i-j}, & 0 \leq i \leq N - 1, \\ A_N^{++} + \sum_{j=1}^N A_j^{+-}W_{N-j}, & i = N, \\ \sum_{j=1}^N A_j^{+-}W_{i-j}, & i \geq N + 1. \end{cases} \quad (5)$$

Recall,  $A_i = 0$  for  $i > N$ .

We now turn to the computation of the matrices  $(W_l)_{l \geq -1}$ . We start by noticing that, to go from state  $(k, i)$  to  $(k - 1, j)$ , with  $i \in S^-$  and  $j \in S^+$ , while avoiding any states with phase in  $S^+$ , the chain must make a downward transition immediately after a sojourn in the set of states  $(k, l)$  with  $l \in S^-$ . This implies that  $W_{-1}$  is given by  $W_{-1} = (-A_1^{--})^{-1} A_0^{-+}$ . In a similar manner we find that  $W_0$  is given by  $W_0 = (-A_1^{--})^{-1} (A_1^{-+} + A_2^{-} W_{-1})$ . Here the chain has the additional option of going from level  $k$  to level  $k+1$  (according to  $A_2^{-}$ ) and then returning to level  $k$  while avoiding states with phase in  $S^+$  (according to  $W_{-1}$ ). Following the same argument we find that the matrices  $(W_l)_{l \geq -1}$  can be computed recursively as

$$W_i = \begin{cases} (-A_1^{--})^{-1} \left( A_{i+1}^{-+} + \sum_{j=2}^{i+2} A_j^{-} W_{i-j+1} \right), & -1 \leq i \leq N-2 \\ (-A_1^{--})^{-1} \left( A_N^{-+} + \sum_{j=2}^N A_j^{-} W_{N-j} \right), & i = N-1 \\ (-A_1^{--})^{-1} \sum_{j=2}^N A_j^{-} W_{i-j+1}, & i \geq N \end{cases} \quad (6)$$

From Equation (5) we observe that to compute  $\bar{A}_i$  it is necessary to keep track of  $\{W_{i-N}, \dots, W_{i-1}\}$ , for  $i > N$ . Therefore, we must store  $N$  matrices of size  $(m-r) \times r$ . After obtaining  $\bar{A}_i$ , the value of  $W_i$  is computed as a function of  $\{W_{i-N+1}, \dots, W_{i-1}\}$ , for  $i \geq N$ . Then, the value of  $W_{i-N}$  can be discarded since the set  $\{W_{i-N+1}, \dots, W_i\}$  suffices to determine  $\bar{A}_{i+1}$ . This procedure continues until the matrix  $\bar{A}_M$  is computed, where  $M$  is the smallest positive integer such that  $\sum_{i=0}^M \bar{A}_i \mathbf{1} > -\epsilon \mathbf{1}$ , where  $\epsilon = 10^{-14}$  and  $\mathbf{1}$  is a column vector with all its entries equal to one. For  $i > N$ , obtaining each block  $\bar{A}_i$  requires us to compute one additional matrix  $W_i$ , which takes  $O(Nr^2(m-r))$  time. After computing  $W_i$ , the value of  $\bar{A}_i$  can be obtained in  $O(Nr(m-r)^2)$  time. Therefore, the computation of *all* the blocks  $(\bar{A}_i)_{i=0}^M$  requires  $O(M(Nr(m-r)^2) + Nr^2(m-r))$ , where, since  $r$  is assumed to be much smaller than  $m$ , the dominant term is  $O(MNrm^2)$ . Once the blocks  $(\bar{A}_i)_{i=0}^M$  are computed, we obtain  $G_+$  by solving Equation (2) with either FI [19] or CR [4]. As mentioned before, FI requires  $O(Mr^3)$  time per iteration. The cost of cyclic reduction is  $O(d'r^3 + r^2 d' \log d')$  per iteration, where  $d'$  is the numerical degree of a matrix power series that is updated at each iteration, starting with a power of 2 greater than or equal to  $M$ . Typically, the value of  $d'$  decreases rapidly in the positive-recurrent case [3].

## 2.2 Computing $G_0$

Once  $G_+$  has been computed, we can obtain  $G_0$  by solving a linear system. This can be understood by considering the partitioning in (3) and the structure in (4) to rewrite Equation

(2) as

$$-\begin{bmatrix} A_0^{++} & 0 \\ A_0^{-+} & 0 \end{bmatrix} = \sum_{i=1}^N \begin{bmatrix} A_i^{++} & A_i^{+-} \\ A_i^{-+} & A_i^{--} \end{bmatrix} \begin{bmatrix} G_+ & 0 \\ G_0 & 0 \end{bmatrix}^i = \sum_{i=1}^N \begin{bmatrix} A_i^{++} & A_i^{+-} \\ A_i^{-+} & A_i^{--} \end{bmatrix} \begin{bmatrix} G_+^i & 0 \\ G_0 G_+^{i-1} & 0 \end{bmatrix}.$$

Now, extracting the lower-left block we find

$$-\sum_{i=1}^N A_i^{--} G_0 G_+^{i-1} = A_0^{-+} + \sum_{i=1}^N A_i^{-+} G_+^i, \quad (7)$$

which is a general linear system of the form  $\sum_{i=1}^N A_i X B_i = C$ , where  $G_0$  is the only unknown term. This system has  $(m-r)r$  unknowns and equations, therefore its solution by general procedures has a time complexity of  $O((m-r)^3 r^3)$ . Hence, this system can be solved directly if  $r$  is very small. Another possibility is to use an iterative approach as proposed in [2], although these are not guaranteed to converge to the actual solution. However, the system (7) has a special characteristic: the matrices that post-multiply the unknown matrix  $G_0$  are all powers of the same matrix  $G_+$ , that is  $B_i = G_+^{i-1}$ . In Section 2.2.1 we devise a way to exploit this fact, reducing the time complexity to  $O((m-r)^3 r + Nr^3 + N(m-r)^2 r^2)$ . Also, as indicated in Section 2.2.2, there are two special cases in which the general system (7) can be reduced to a Sylvester matrix equation [10], and can therefore be solved in  $O((m-r)^3)$  time with the Hessenberg-Schur algorithm proposed in [9].

### 2.2.1 The general case

The key to solve Equation (7) is to apply a real Schur decomposition [10] to  $G_+$ , i.e., to find an orthogonal matrix  $U \in \mathbb{R}^{r \times r}$  such that  $U' G_+ U = T$ , where  $'$  denotes the transpose operator. Recall that a matrix  $U$  is called orthogonal if  $U' U = U U' = I$ . The matrix  $T \in \mathbb{R}^{r \times r}$  is upper quasi-triangular, meaning it is block upper triangular and the diagonal blocks are of size one or two [10]. We now post-multiply (7) by  $U$  to obtain

$$-\sum_{i=1}^N A_i^{--} G_0 U U' G_+^{i-1} U = \sum_{i=0}^N A_i^{-+} G_+^i U,$$

which, since  $U' G_+^j U = T^j$  for any nonnegative integer  $j$ , can be rewritten as

$$-\sum_{i=1}^N A_i^{--} G_0 U T^{i-1} = \sum_{i=0}^N A_i^{-+} G_+^i U.$$

Now let  $Y = \sum_{i=0}^N A_i^{-+} G_+^i U$ , which is a known matrix, and let  $X = G_0 U$ , to obtain

$$-\sum_{i=1}^N A_i^{--} X T^{i-1} = Y. \quad (8)$$



This system can be equivalently written in a column-wise form as

$$-\sum_{i=1}^N A_i^{--} \sum_{j=1}^r [T^{i-1}]_{j,k} X_j = Y_k, \quad (9)$$

for  $k = 1, \dots, r$ , where  $M_k$  and  $[M]_{i,j}$  are the  $k$ -th column and the  $(i, j)$ -th entry of a matrix  $M$ , respectively.

Notice that, in Equation (8), the matrices that post-multiply  $X$  are all upper quasi-triangular matrices, and all they have the same block structure as they are powers of  $T$ . Therefore it is possible to iteratively compute the columns  $X_k$ , starting with  $X_1$ . Let us assume that we have already found  $\{X_1, \dots, X_{k-1}\}$  and we want to compute  $X_k$ , for some  $1 \leq k \leq r$ . Given the upper quasi-triangular nature of  $T$  there are two possibilities. The first is that the entry  $[T]_{k+1,k}$  is zero, meaning that Equation (9) can be rewritten as

$$-\sum_{i=1}^N A_i^{--} [T^{i-1}]_{k,k} X_k = Y_k + \sum_{i=1}^N A_i^{--} \sum_{j=1}^{k-1} [T^{i-1}]_{j,k} X_j. \quad (10)$$

Therefore we can obtain the column  $X_k$  by solving a linear system of size  $m-r$ , which requires  $O((m-r)^3)$  time. The second case is when  $[T]_{k+1,k} \neq 0$ , which, due to the upper quasi-triangular structure (the diagonal blocks are at most of size two) implies that  $[T]_{k+2,k+1} = 0$ . Therefore we can find the columns  $X_k$  and  $X_{k+1}$  simultaneously by solving the system

$$-\begin{bmatrix} \sum_{i=1}^N A_i^{--} [T^{i-1}]_{k,k} & \sum_{i=1}^N A_i^{--} [T^{i-1}]_{k+1,k} \\ \sum_{i=1}^N A_i^{--} [T^{i-1}]_{k,k+1} & \sum_{i=1}^N A_i^{--} [T^{i-1}]_{k+1,k+1} \end{bmatrix} \begin{bmatrix} X_k \\ X_{k+1} \end{bmatrix} = \begin{bmatrix} \hat{Y}_k^{k-1} \\ \hat{Y}_{k+1}^{k-1} \end{bmatrix}, \quad (11)$$

where  $\hat{Y}_k^l = Y_k + \sum_{i=1}^N A_i^{--} \sum_{j=1}^l [T^{i-1}]_{j,k} X_j$ , for  $1 \leq l \leq k-1$  and  $1 \leq k \leq r$ . This is a linear system with  $2(m-r)$  unknowns that requires  $O((m-r)^3)$  time to be solved. As a result we can start by finding the first (two) column(s) of  $X$  and iteratively compute the others. After computing  $X$ ,  $G_0$  is obtained from  $G_0 = XU'$ . Obtaining the Schur decomposition of  $G_+$  and the powers of  $T$  requires  $O(Nr^3)$ . Also, setting up the right-hand side in equations (10) and (11) to find all the columns of  $X$  takes  $O(N(m-r)^2 r^2)$  time. As a result, the matrix  $G_0$  can be found in  $O((m-r)^3 r + Nr^3 + N(m-r)^2 r^2)$  time.

### 2.2.2 Two special cases

There are two special cases where an  $O((m-r)^3)$  algorithm can be used to compute  $G_0$  from  $G_+$ . In the first case it is assumed that only one of the  $(A_i^{--})_{i=2}^N$  matrices is different from zero. If  $A_k^{--}$  is the only matrix different from zero, for some  $2 \leq k \leq N$ , then Equation (7) can be written as

$$G_0 - (-A_1^{--})^{-1} A_k^{--} G_0 G_+^{k-1} = (-A_1^{--})^{-1} \left( A_0^{--} + \sum_{i=1}^N A_i^{--} G_+^i \right).$$

This is a Sylvester matrix equation [9, 8] of the type  $AXB + X = C$ , which can be solved in  $O((m - r)^3)$  time with the Hessenberg-Schur method proposed in [9].

The second case arises when the matrices  $(A_i^-)_{i=2}^N$  can be written as the product of a scalar and a common matrix, i.e.,  $A_i^- = c_i K$ , for  $2 \leq i \leq N$ . As highlighted in Remark 1, this structure arises, for instance, in the batch queues introduced in Section 4. Using this assumption we can rewrite Equation (7) as

$$G_0 - (-A_1^-)^{-1} K G_0 \sum_{i=2}^N c_i G_+^{i-1} = (-A_1^-)^{-1} \left( A_0^- + \sum_{i=1}^N A_i^- G_+^i \right). \quad (12)$$

This is also a Sylvester matrix equation of the type  $AXB + X = C$ , with  $A = (A_1^-)^{-1} K$  and  $B = \sum_{i=2}^N c_i G_+^{i-1}$ . It can therefore be solved with the Hessenberg-Schur method in [9].

In summary, our methodology to find  $G$  has three main steps: (i) compute the blocks  $(\bar{A}_i)_{i=0}^M$ , which takes  $O(MNrm^2)$  time, (ii) solve Eq. (2) to obtain  $G_+$ , which requires  $O(Mr^3)$  time per iteration, if computed with FI, and (iii) solve Eq. (7) to obtain  $G_0$ , which can be done in  $O((m - r)^3 r + Nr^3 + N(m - r)^2 r^2)$  time. On the other hand, solving the full-block-size M/G/1-type MC with FI requires  $O(Nm^3)$  time per iteration (let  $\kappa$  be the number of iterations required by FI for this chain). Therefore, the cost of step (i) is approximately  $Mr/m$  times that of a *single* iteration of FI on the full-block-size M/G/1-type MC. As a result, for the total time of this step to be similar to that of FI on the full-block-size M/G/1-type MC, the number of blocks of the censored process  $M$  would need to be on the order of  $\kappa m/r$ , which is a very large number, since  $m$  is already assumed to be large and FI may require a large number of iterations [14]. Also, the cost per iteration of step (ii) is almost negligible compared to the cost per iteration of FI applied to the full-size M/G/1-type MC. Finally, one iteration of FI on the full-size M/G/1-type MC has a time complexity comparable to the last step of our method. All in all, we expect that our method should provide a significant reduction in the time to compute  $G$ , compared to FI, especially when the ratio  $m/r$  is large, and the number of blocks  $M$  is small compared to  $\kappa m/r$ . A similar conclusion can be drawn if CR is used to solve the full-block-size M/G/1-type MC, although in this case the analysis is more involved since the time complexity per iteration is  $O(d' m^3 + m^2 d' \log d')$ , where  $d'$  varies at every iteration, as explained above [3]. In Section 4 we will show numerically how the use of our methodology leads to significant reductions in the time to compute  $G$ , compared to either CR or FI on the full-block-size M/G/1-type MC.

### 3 Computing the stationary probability vector

We have shown how the matrix  $G$  can be obtained by first computing  $G_+$  from a censored process and then solving a linear system to determine  $G_0$ . Once  $G$  has been obtained the

stationary probability vector of the original M/G/1-type MC can be computed by means of Ramaswami's formula [22], as follows. Let the matrices  $(\tilde{A}_i)_{i \geq 1}$  and  $(\tilde{B}_i)_{i \geq 0}$  be defined as

$$\tilde{A}_i = \sum_{j=i}^{\infty} A_j G^{j-i}, \quad i \geq 1, \quad \tilde{B}_i = \sum_{j=i}^{\infty} B_j G^{j-i}, \quad i \geq 1, \quad \tilde{B}_0 = B_0 + \tilde{B}_1 (-\tilde{A}_1)^{-1} C_0. \quad (13)$$

Let  $\pi$  be the stationary probability vector of the MC with generator  $Q$ , i.e., the vector such that  $\pi Q = 0$  and  $\pi \mathbf{1} = 1$ . This vector can also be partitioned according to the levels as  $\pi = [\pi_0, \pi_1, \dots]$ . Then, Ramaswami's formula states that the vectors  $\pi_i$  can be found recursively as

$$\pi_i = \left( \pi_0 \tilde{B}_i + \sum_{j=1}^{i-1} \pi_j \tilde{A}_{i-j+1} \right) (-\tilde{A}_1)^{-1}, \quad i \geq 1, \quad (14)$$

and  $\pi_0$  is such that

$$\pi_0 \tilde{B}_0 = 0, \quad \pi_0 \kappa = 1, \quad (15)$$

where  $\kappa = \mathbf{1} + \left( \sum_{j=1}^{\infty} \tilde{B}_j \right) \left( -\sum_{j=1}^{\infty} \tilde{A}_j \right)^{-1} \mathbf{1}$ . However, one may wonder whether the structure of the matrix  $A_0$  can be exploited to make the computation of  $\pi$  faster. This is the purpose of this section, where three main approaches to compute  $\pi$  are described. The first method makes use of the structure of  $A_0$  to accelerate the computation of the matrices  $(\tilde{A}_i)_{i=1}^N$  and  $(\tilde{B}_i)_{i=1}^N$ . The other two methods compute the vector  $\pi$  from the stationary probability vector of the censored process. While the first two methods apply in general to any M/G/1-type MC with restricted transitions, the last one also exploits the additional structure discussed in Remark 1.

### 3.1 Computing $\pi$ from the original process

In this section we consider the problem of exploiting the structure of  $A_0$  to compute the matrices  $(\tilde{A}_i)_{i=1}^N$  and  $(\tilde{B}_i)_{i=1}^N$ . To compute these matrices one typically starts with  $\tilde{A}_N = A_N$  and  $\tilde{B}_N = B_N$ , and computes iteratively  $\tilde{A}_i = A_i + \tilde{A}_{i+1} G$  and  $\tilde{B}_i = B_i + \tilde{B}_{i+1} G$ , for  $i = N-1, \dots, 1$ . However, if we rewrite Equation (13) in block form according to the partition in (3), we find that

$$\begin{aligned} \tilde{A}_i &= \begin{bmatrix} \tilde{A}_i^{++} & \tilde{A}_i^{+-} \\ \tilde{A}_i^{-+} & \tilde{A}_i^{--} \end{bmatrix} = \begin{bmatrix} A_i^{++} & A_i^{+-} \\ A_i^{-+} & A_i^{--} \end{bmatrix} + \sum_{j=i+1}^N \begin{bmatrix} A_j^{++} & A_j^{+-} \\ A_j^{-+} & A_j^{--} \end{bmatrix} \begin{bmatrix} G_+ & 0 \\ G_0 & 0 \end{bmatrix}^{j-i} \\ &= \begin{bmatrix} A_i^{++} & A_i^{+-} \\ A_i^{-+} & A_i^{--} \end{bmatrix} + \sum_{j=i+1}^N \begin{bmatrix} A_j^{++} G_+^{j-i} + A_j^{+-} G_0 G_+^{j-i-1} & 0 \\ A_j^{-+} G_+^{j-i} + A_j^{--} G_0 G_+^{j-i-1} & 0 \end{bmatrix}, \quad 1 \leq i \leq N. \end{aligned}$$

Therefore, the last  $m - r$  columns of the matrix  $\tilde{A}_i$  are identical to those of the matrix  $A_i$ , for  $1 \leq i \leq N$ . To compute the first  $r$  columns of these matrices we simply start with  $\tilde{A}_N^{++} = A_N^{++}$  and  $\tilde{A}_N^{-+} = A_N^{-+}$  and then iteratively compute

$$\begin{aligned}\tilde{A}_i^{++} &= A_i^{++} + \tilde{A}_{i+1}^{++}G_+ + A_{i+1}^{+-}G_0, \\ \tilde{A}_i^{-+} &= A_i^{-+} + \tilde{A}_{i+1}^{-+}G_+ + A_{i+1}^{--}G_0,\end{aligned}$$

for  $i = N - 1, \dots, 1$ . A similar observation can be made for the matrices  $(\tilde{B}_i)_{i=1}^N$  since these, as well as  $(B_i)_{i=1}^N$ , can be partitioned in two blocks depending on whether the transitions from level zero take the chain to a state with phase in  $S^+$  or  $S^-$ . Therefore, we can write

$$\tilde{B}_i = \begin{bmatrix} \tilde{B}_i^+ & \tilde{B}_i^- \end{bmatrix} = \begin{bmatrix} B_i^+ & B_i^- \end{bmatrix} + \sum_{j=i+1}^N \begin{bmatrix} B_j^+ & B_j^- \end{bmatrix} \begin{bmatrix} G_+ & 0 \\ G_0 & 0 \end{bmatrix}^{j-i}.$$

From this equation we find that  $\tilde{B}_i^- = B_i^-$ , for  $1 \leq i \leq N$ . Also,  $\tilde{B}_i^+$  can be obtained by starting with  $\tilde{B}_N^+ = B_N^+$ , and sequentially computing  $\tilde{B}_i^+ = B_i^+ + \tilde{B}_{i+1}^+G_+ + B_{i+1}^-G_0$ , for  $i = N - 1, \dots, 1$ . Once we have obtained these matrices, we can compute the vector  $\pi$  directly using Ramaswami's formula as in Equation (14). One could also rely on the fast-Fourier-transform-based implementation of Ramaswami's formula proposed by Meini [16]. With either approach, we are computing  $\pi$  by simply using the structure of  $G$  to speed up the computation of the matrices  $(\tilde{A}_i)_{i=1}^N$  and  $(\tilde{B}_i)_{i=1}^N$ . In the next section we consider a different approach in which we make use of the censored process to obtain the stationary probability vector  $\pi$ .

### 3.2 Computing $\pi$ from the censored process

In this section we show how the censored process can be used to reduce the time required to compute  $\pi$  by separately computing  $(\pi_i^+)_{i \geq 1}$  and  $(\pi_i^-)_{i \geq 1}$ , where these vectors arise by partitioning  $\pi_i$  according to  $S^+$  and  $S^-$ , i.e.,  $\pi_i = [\pi_i^+ \ \pi_i^-]$ , for  $i \geq 1$ . As stated before, we obtain the matrix  $G_+$  from a censored process of the M/G/1-type whose  $G$  matrix is actually equal to  $G_+$ . To do so, we described the censored process by means of the blocks  $(\bar{A}_i)_{i=0}^M$ , which only consider the behavior of the process away from the boundary. We now complete the description of this process by adding a boundary level, which is identical to the boundary level of the original process. This means that the new process is built by observing the original process only when it is in the subset of states  $\bigcup_{i \geq 1} \{(i, j), j \in S^+\} \cup \{(0, j), 1 \leq j \leq m_b\}$ . The boundary behavior of this process is described by the  $m_b \times m_b$  matrix  $\bar{B}_0$  (transitions within level 0), the  $m_b \times r$  matrices  $(\bar{B}_i)_{i=1}^{M_0}$  (transitions from level zero to level  $i > 1$ ) and the  $r \times m_b$  matrix  $\bar{C}_0$  (transitions from level 1 to level 0). These blocks, together with the

matrices  $(\bar{A}_i)_{i=0}^M$ , completely characterize the censored process, whose generator  $\bar{Q}$  is built from these blocks in a similar manner as the generator  $Q$  of the original process in (1).

To define the blocks  $(\bar{B}_i)_{i=0}^{M_0}$  we rely on the matrices  $(W_i)_{i \geq -1}$  as defined in (6). As stated in the previous section, we partition the original blocks  $B_i = [B_i^+ \ B_i^-]$ , where  $B_i^+$  (resp.  $B_i^-$ ) holds the transition rates that, from level zero, trigger the chain into level  $i$  and phase in  $S^+$  (resp.  $S^-$ ). Similarly, the matrix  $C_0$  can be partitioned into  $C_0^+$  and  $C_0^-$ , which hold the transition rates to level zero from states in level one and phase in  $S^+$  and  $S^-$ , respectively. Using these definitions we find that  $\bar{B}_0 = B_0 + B_1^-(-A_1^-)^{-1}C_0^-$ , which considers the two alternative paths for a transition starting and ending in level zero in the new process. This may occur directly according to  $B_0$  or by a transition to level one and a backward transition, avoiding states with phase in  $S^+$ . Carrying out a similar analysis we find that the remaining boundary blocks are given by

$$\bar{B}_i = \begin{cases} B_i^+ + \sum_{j=1}^{i+1} B_j^- W_{i-j}, & 1 \leq i \leq N-1, \\ B_N^+ + \sum_{j=1}^N B_j^- W_{N-j}, & i = N, \\ \sum_{j=1}^N B_j^- W_{i-j}, & i \geq N+1. \end{cases} \quad (16)$$

These matrices are computed sequentially from  $i = 0$  to  $M_0$ , where  $M_0$  is the smallest positive integer such that  $\sum_{i=0}^{M_0} \bar{B}_i \mathbf{1} > -\epsilon \mathbf{1}$ . Finally, we observe that the transitions from level one to level zero in the censored process are governed by  $\bar{C}_0 = C_0^+ + A_1^{+-}(-A_1^-)^{-1}C_0^-$ .

With these definitions we are ready to compute, using Ramaswami's formula, the stationary probability vector of the censored process  $\bar{\pi}$ , which can be partitioned in blocks as  $\bar{\pi} = [\bar{\pi}_0, \bar{\pi}_1, \bar{\pi}_2, \dots]$ . The importance of this vector is that it is proportional to the stationary vector  $\pi$  of the original process [13, 14], i.e.,  $\bar{\pi}_0 \propto \pi_0$  and  $\bar{\pi}_i \propto \pi_i^+$ , for  $i \geq 1$ . Actually, we would like to normalize the vector  $\bar{\pi}$  by a constant such that  $\bar{\pi}_0 = \pi_0$  and  $\bar{\pi}_i = \pi_i^+$ , for  $i \geq 1$ . This can be accomplished by computing  $\pi_0$  as in Equation (15) and assigning  $\bar{\pi}_0 = \pi_0$ . This forces  $\bar{\pi}_0$  to be normalized by the appropriate constant. The terms  $(\bar{\pi}_i)_{i \geq 1}$  can then be obtained, using Ramaswami's formula, after computing the matrices  $(\tilde{A}_i)_{i \geq 1}$  and  $(\tilde{B}_i)_{i \geq 1}$  for the censored process, as in Equation (13). Notice that, to obtain  $\pi_0$  from Equation (15), we first need to compute the matrices  $(\tilde{A}_i)_{i=1}^N$  and  $(\tilde{B}_i)_{i=1}^N$ .

Up to this point, we have computed  $\pi_0$  and  $(\pi_i^+)_{i \geq 1}$ , and we can use these to find the vectors  $(\pi_i^-)_{i \geq 1}$  in order to completely determine  $\pi$ . This can be done by rewriting Equation (14) in block form as

$$\begin{bmatrix} \pi_i^+ & \pi_i^- \end{bmatrix} \begin{bmatrix} -\tilde{A}_1^{++} & -\tilde{A}_1^{+-} \\ -\tilde{A}_1^{-+} & -\tilde{A}_1^{--} \end{bmatrix} = \pi_0 \begin{bmatrix} \tilde{B}_i^+ & \tilde{B}_i^- \end{bmatrix} + \sum_{j=1}^{i-1} \begin{bmatrix} \pi_j^+ & \pi_j^- \end{bmatrix} \begin{bmatrix} \tilde{A}_{i-j+1}^{++} & \tilde{A}_{i-j+1}^{+-} \\ \tilde{A}_{i-j+1}^{-+} & \tilde{A}_{i-j+1}^{--} \end{bmatrix}, \quad i \geq 1.$$

From this equation we can express  $\pi_i^-$  as

$$\pi_i^- = \left( \pi_0 B_i^- + \pi_i^+ A_1^{+-} + \sum_{j=1}^{i-1} \left( \pi_j^+ A_{i-j+1}^{+-} + \pi_j^- A_{i-j+1}^{--} \right) \right) (-A_1^{--})^{-1}, \quad i \geq 1. \quad (17)$$

Notice that this equation makes use of the original blocks  $\{A_i\}_{i \geq 1}$  and  $\{B_i\}_{i \geq 1}$  instead of the blocks  $\{\tilde{A}_i\}_{i \geq 1}$  and  $\{\tilde{B}_i\}_{i \geq 1}$  since their last  $m - r$  columns are identical, as shown in Section 3.1. Using this equation we can compute  $\pi_i^-$  in terms of  $\pi_0$ ,  $(\pi_j^+)_{j=1}^i$  and  $(\pi_j^-)_{j=1}^{i-1}$ , for  $i \geq 1$ , thus concluding the computation of  $\pi$ . This approach is summarized in Algorithm 1. One may consider a slight modification to this algorithm by replacing the use of Ramaswami's formula in step 7 with the Fast Ramaswami's Formula (FRF) proposed in [16], which is based on the fast Fourier transform. This may provide an important computational gain when the number of blocks  $(\bar{B}_i)_{i \geq 1}$  and  $(\bar{A}_i)_{i \geq 1}$  is large. This approach will also be considered in the numerical experiments in Section 4.

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**Algorithm 1** Computing  $\pi$  from the censored process

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**Input:** Matrices  $(\bar{A}_i)_{i \geq 1}$  and  $G$

- 1: Compute the matrices  $(\tilde{A}_i)_{i \geq 1}$  and  $(\tilde{B}_i)_{i \geq 0}$  using the iterative scheme in Section 3.1.
  - 2: Find  $\pi_0$  solving Equation (15) and set  $\bar{\pi}_0 = \pi_0$ .
  - 3: Compute the matrices  $(\bar{B}_i)_{i \geq 0}$  according to Equation (16).
  - 4: Compute the matrices  $(\tilde{\tilde{A}}_i)_{i \geq 1}$  and  $(\tilde{\tilde{B}}_i)_{i \geq 0}$  as in Equation (13).
  - 5: Set  $\sigma = \bar{\pi}_0 \mathbf{1}$  and  $i = 1$ .
  - 6: **while**  $\sigma < 1 - \epsilon$  **do**
  - 7:   Compute  $\bar{\pi}_i$  using (Fast) Ramaswami's formula.
  - 8:   Set  $\pi_i^+ = \bar{\pi}_i$  and compute  $\pi_i^-$  as in Equation (17).
  - 9:   Update  $\sigma = \sigma + \pi_i^+ \mathbf{1} + \pi_i^- \mathbf{1}$ , and  $i = i + 1$ .
  - 10: **end while**
- 

### 3.3 Computing $\pi$ from the censored process: a special case

In this section we consider how to exploit the additional structure described in Remark 1, which arises in the MCs that describe the batch queues to be introduced in Section 4. Recall that this additional structure implies that: first, the matrices  $(A_i^{--})_{i=2}^N$  can be written as the product of a scalar and a common matrix, i.e.,  $A_i^{--} = c_i K$ , for  $2 \leq i \leq N$ ; second, the blocks  $(A_i^{+-})_{i=2}^N$  and  $(A_i^{-+})_{i=2}^N$  are equal to zero. We start by noting that, due to the additional structure, Equation (17) can be written as

$$\pi_i^- = \left[ \pi_0 B_i^- + \pi_i^+ A_1^{+-} + \left( \sum_{j=1}^{i-1} c_{i-j+1} \pi_j^- \right) K \right] (-A_1^{--})^{-1}, \quad i \geq 1. \quad (18)$$

The advantage of this expression is that each term of the sum is just a vector multiplied by a scalar, while in the general case each term in the sum requires a vector-matrix multiplication. Therefore, one can simply modify step 8 in Algorithm 1 replacing the use of Equation (17) by Equation (18). However there is an additional fact that can be exploited if we make use of the FRF to compute  $(\pi_i^+)_{i \geq 1}$ . The FRF, as introduced in [16], computes not one but many vectors  $\pi_i^+$  at a time. Specifically, in each iteration the FRF computes  $\bar{M}$  terms, where  $\bar{M}$  is a power of two such that  $\bar{M} \geq M$  and  $\bar{M} \geq M_0$ . Therefore, after the first iteration we already have the terms  $(\pi_i^+)_{i=1}^{\bar{M}}$  and it suffices to compute the corresponding terms  $(\pi_i^-)_{i=1}^{\bar{M}}$ . If the MC has the structure described in Remark 1 we could do this by using Equation (18) directly. But we can also use the following observation. Let us assume that we have computed the first  $(\pi_i^-)_{i=1}^N$  by means of (18). For  $i \geq N + 1$ , we can write

$$\pi_i^- = \left( \pi_i^+ A_1^{+-} + \sum_{j=i-N+1}^{i-1} (c_{i-j+1} \pi_j^-) K \right) (-A_1^{--})^{-1},$$

as  $B_i = 0$  and  $A_i = 0$  for  $i > N$ . Now, if we focus on the computation of  $(\pi_i^-)_{i=N+1}^{2N-1}$  we can write the previous expression as

$$\pi_i^- = \pi_i^+ \hat{A}_1^{+-} + \sum_{j=i-N+1}^N (c_{i-j+1} \pi_j^-) \hat{K} + \sum_{j=N+1}^{i-1} (c_{i-j+1} \pi_j^-) \hat{K}, \quad N+1 \leq i \leq 2N-1, \quad (19)$$

where  $\hat{A}_1^{+-} = A_1^{+-} (-A_1^{--})^{-1}$  and  $\hat{K} = K (-A_1^{--})^{-1}$ . In this equation the first sum on the right-hand side only involves the terms  $(\pi_i^-)_{i=2}^N$ , while the second sum and the left-hand side involve the terms  $(\pi_i^-)_{i=N+1}^{2N-1}$ . Therefore, we can write this expression as a system of equations. To do so, let  $\bar{N} = N - 1$  and let  $\hat{\pi}_i^+$  and  $\hat{\pi}_i^-$  be

$$\hat{\pi}_i^+ = \begin{bmatrix} \pi_{1+(i-2)\bar{N}+1}^+ \\ \pi_{1+(i-2)\bar{N}+2}^+ \\ \vdots \\ \pi_{1+(i-1)\bar{N}}^+ \end{bmatrix} \quad \text{and} \quad \hat{\pi}_i^- = \begin{bmatrix} \pi_{1+(i-2)\bar{N}+1}^- \\ \pi_{1+(i-2)\bar{N}+2}^- \\ \vdots \\ \pi_{1+(i-1)\bar{N}}^- \end{bmatrix}, \quad i \geq 2.$$

Therefore, we can write the set of  $\bar{N}$  equations in (19) in matrix form as

$$\hat{\pi}_3^- = \hat{\pi}_3^+ \hat{A}_1^{+-} + R_1 \hat{\pi}_2^- \hat{K} + R_2 \hat{\pi}_3^- \hat{K},$$

where the  $\bar{N} \times \bar{N}$  matrices  $R_1$  and  $R_2$  are given by

$$R_1 = \begin{bmatrix} c_N & c_{N-1} & \dots & c_2 \\ 0 & c_N & \dots & c_3 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & c_N \end{bmatrix} \quad \text{and} \quad R_2 = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ c_2 & 0 & \dots & 0 & 0 \\ c_3 & c_2 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ c_{N-1} & c_{N-2} & \dots & c_2 & 0 \end{bmatrix}.$$

In general, we can find the vector  $\hat{\pi}_i^-$  in terms of  $\hat{\pi}_{i-1}^-$  and  $\hat{\pi}_i^+$  by solving the system

$$\hat{\pi}_i^- - R_2 \hat{\pi}_i^- \hat{K} = \hat{\pi}_i^+ \hat{A}_1^{+-} + R_1 \hat{\pi}_{i-1}^- \hat{K}, \quad i \geq 3. \quad (20)$$

This is also a Sylvester matrix equation of the type  $AXB + X = C$ , that can be solved using the Hessenberg-Schur method mentioned before [9]. Among the two decompositions that must be carried out to use this method, the Schur decomposition is the most expensive, requiring  $10b^3$  operations for a square matrix of size  $b$ . On the other hand, the Hessenberg decomposition only requires  $\frac{5}{3}b^3$  operations [9]. In this case the square matrix  $A = -R_2$  is of size  $\bar{N}$ , while the square matrix  $B = \hat{K}$  is of size  $m - r$ . Since we expect a large value for  $m - r$ , it is actually better to apply this method to the transposed system, i.e., to  $B'X'A' + X' = C'$ . In this manner we apply the Hessenberg decomposition to the larger matrix, i.e., to  $B' = -\hat{K}'$ . Additionally, since the matrix  $A' = -R_2'$  is already in real Schur form [10] (it is upper triangular), there is no need to use the QR algorithm to obtain the Schur decomposition. Therefore, after finding the Hessenberg decomposition of  $B' = -\hat{K}'$  we can find the solution to the transposed Sylvester matrix equation by solving  $\bar{N}$  Hessenberg systems of size  $m - r$ , each one requiring  $O((m - r)^2)$  time. Moreover, to find all the vectors  $(\hat{\pi}_i^-)_{i \geq 3}$  we need to solve a series of equations as in (20), but the matrices  $R_2$  and  $\hat{K}$  remain unchanged for  $i \geq 3$ . Therefore, to solve these equations we only need to apply the Hessenberg decomposition once and update the right-hand side of (20). This concludes the computation of  $\pi$ . The next section illustrates the performance of the various methods introduced in this paper by means of two queueing examples.

## 4 Examples and Numerical Experiments

The purpose of this section is to show how two different queueing systems can be modeled as M/G/1-type MCs with restricted downward transitions. The first system is a BMAP/PH/1 queue, for which the block  $A_0$  is forced to have a few nonzero columns by using a slightly larger representation of the service-time distribution. The second example is a BMAP[2]/PH[2]/1 preemptive priority queue with two types of customers where, by adequately ordering the state space, we obtain the desired structure for the block  $A_0$ . These two examples will be used to illustrate the computational gains obtained with our approach. In addition, when the batch sizes are i.i.d. random variables independent of the arrival process, the MCs used to model these queues show the additional structure described in Remark 1. Therefore, these examples will also be useful to demonstrate the gains obtained by exploiting this additional structure.

We focus on the total time required to compute the vector  $\pi$ , which includes the computation of  $G$ . As a benchmark, we compute the matrix  $G$  of the original M/G/1-type MC using



the U-based Functional Iteration [19] and Cyclic Reduction [4], for which we use the labels **FI** and **CR**, respectively. To compute  $\pi$ , after finding  $G$ , we consider Ramaswami's formula (RF) and its fast implementation (FRF). Therefore, for the total time to compute  $\pi$  we have four benchmarks: **FI-R**, **FI-F**, **CR-R** and **CR-F**. For the BMAP[2]/PH[2]/1 preemptive priority queue we also compare with the approach introduced in [25], here labeled **INF**, where both the high- and the low-priority buffers are assumed to be infinite. The methods introduced in this paper are labeled **O**, **C** and **C\***. In all the methods the censored process is used to exploit the structure of the matrix  $A_0$  to compute  $G_+$ . In the methods labeled **O** and **C** we only consider this structure, while in **C\*** we also take into account the additional structure described in Remark 1. Therefore, in the methods **O** and **C** the matrix  $G_0$  is found by solving the linear system (7) for the general case. In the method **O**, the vector  $\pi$  is found from the original process as described in Section 3.1. This can be done either with RF or FRF, therefore we have both **O-R** and **O-F**. On the other hand, for the method **C** the vector  $\pi$  is computed by means of the censored process as discussed in Section 3.2. In this case we also have both **C-R** and **C-F**. In the method labeled **C\*** we consider the additional structure in Remark 1, and therefore the matrix  $G_0$  is found by solving Equation (12). Additionally, we can compute  $\pi$  relying on the censored process and applying Equation (18). As this can be done by using either RF or FRF to compute  $(\pi_i^+)_{i \geq 1}$ , we have the two alternatives **C\*-R** and **C\*-F**. Moreover, if FRF is used to compute  $(\pi_i^+)_{i \geq 1}$ , we can also make use of Equation (20) to obtain  $(\pi_i^-)_{i \geq 1}$ . This approach will be labeled **C\*-F<sub>2</sub>**.

Since both queueing systems have similar arrival processes and service-time distributions, we devote the next section to describe these. Subsequently, we introduce both models and show how the computation of  $\pi$  can be substantially reduced by exploiting the restricted-transitions structure.

#### 4.1 The arrival process and service-time distribution

In Kendall's notation the two queues under analysis are the BMAP/PH/1 queue and the BMAP[2]/PH[2]/1 preemptive priority queue. We first define the arrival processes (BMAP and BMAP[2]) and then move on to specify the service time distributions (PH and PH[2]). The arrival process at both queues can be described by means of a Markovian Arrival Process (MAP) [15, 19]. A MAP( $m_a, D_0, D_1$ ) is a point process driven by an underlying continuous-time MC (CTMC) with  $m_a \times m_a$  generator matrix  $D = D_0 + D_1$ . The  $(i, j)$ -th entry of the matrix  $D_1$  holds the rate at which, when the underlying chain is in state  $i$ , a customer arrives and the chain makes a transition to state  $j$ , for  $1 \leq i, j \leq m_a$ . The off-diagonal entries of the matrix  $D_0$  hold the rates related to transitions without arrivals, and its (negative) diagonal entries are such that  $D\mathbf{1} = \mathbf{0}$ , where  $\mathbf{0}$  is a vector with all its entries equal to zero.

Therefore, this process results from a CTMC whose transitions are marked [12] with either of two labels: the label ‘0’ for the transitions that generate no arrivals, and the label ‘1’ for the transitions that trigger an arrival. The matrices  $D_0$  and  $D_1$  hold the rates associated with the transitions labeled ‘0’ and ‘1’, respectively. These markings can be generalized to include other information about the arriving customers. As we want to model queues with batch arrivals, the markings can be defined to include the number of customers that arrive in a single transition. In this case the arrival process is characterized by the  $m_a \times m_a$  matrices  $\{D_0, D_1, \dots, D_{\bar{L}}\}$ , where  $\bar{L}$  is the maximum batch size. The matrix  $D_j$  holds the rates related to transitions of the underlying chain that trigger a batch arrival of size  $j$ , for  $1 \leq j \leq \bar{L}$ . Since in this case the markings are related to the batch size only, this process is called a Batch Markovian Arrival Process (BMAP) [15]. This is the arrival process fed to the BMAP/PH/1 queue. In general, this process is able to model correlation between the inter-arrival times (IATs) and the batch size distribution. However, when modeling this queue as an M/G/1-type MC with restricted transitions, there is a computational gain that can be exploited by assuming that the batch sizes are i.i.d. random variables and are independent of the IATs (see Remark 1 and Section 2.2). To build a BMAP with these characteristics, let  $r_j$  be the probability that a batch is of size  $j$ , and let the batch IATs be described by a MAP( $m_a, D_0, D_+$ ). Then, the batch arrival process is a BMAP characterized by the  $m_a \times m_a$  matrices  $\{D_0, D_1, \dots, D_{\bar{L}}\}$ , where  $D_j = r_j D_+$ , for  $1 \leq j \leq \bar{L}$ .

The arrivals at the preemptive priority queue also occur in batches, but these are of two types, each one associated with a different priority level. Therefore, the markings must include not only the size of the batch, but also the type of the customers in that batch. We assume that each batch is made of customers of only one type, and the maximum size of a batch of high- (resp. low-) priority customers is  $\bar{L}_1$  (resp.  $\bar{L}_2$ ). Hence, the arrival process can be modeled as a BMAP[2] characterized by the matrices  $\{D_0, D_1^{j_1}, D_2^{j_2}, 1 \leq j_1 \leq \bar{L}_1, 1 \leq j_2 \leq \bar{L}_2\}$ , where the notation BMAP[2] reflects the fact that the markings describe both the batch size and the type of the customers in the batch (two possible types). In this case the matrix  $D_1^j$  (resp.  $D_2^j$ ) holds the transition rates associated with the arrival of a batch of  $j$  high- (resp. low-) priority customers, for  $1 \leq j \leq \bar{L}_1$  (resp.  $1 \leq j \leq \bar{L}_2$ ). As before, we can define a version of this process where the batch sizes are i.i.d. random variables and are independent of the IATs. For this purpose let  $p_i$  be the probability that a batch of high-priority customers is of size  $i$ , for  $1 \leq i \leq \bar{L}_1$ . Accordingly, let  $q_i$  be the probability that a batch of low-priority customers is of size  $i$ , for  $1 \leq i \leq \bar{L}_2$ . Also, let the batch IATs be described by a MAP with markings for each customer type, i.e., characterized by the  $m_a \times m_a$  matrices  $\{D_0, D_1, D_2\}$ , where  $D_1$  (resp.  $D_2$ ) holds the transition rates at which the underlying chain triggers the arrival of a batch of high- (resp. low-) priority customers. Combining the marked

MAP and the batch-size distributions we obtain a BMAP[2] characterized by the  $m_a \times m_a$  matrices  $\{D_0, D_1^{j_1}, D_2^{j_2}, 1 \leq j_1 \leq \bar{L}_1, 1 \leq j_2 \leq \bar{L}_2\}$ , where  $D_1^{j_1} = p_{j_1} D_1$  and  $D_2^{j_2} = q_{j_2} D_2$ , for  $1 \leq j_1 \leq \bar{L}_1$  and  $1 \leq j_2 \leq \bar{L}_2$ . Notice that, although the batch sizes are i.i.d. random variables, the IATs of both types of batch arrivals can be correlated. As with the previous queue, the independence between the IATs and the i.i.d. batch sizes can be exploited when the BMAP[2]/PH[2]/1 preemptive priority queue is modeled as an M/G/1-type MC with restricted downward transitions.

In the BMAP/PH/1 queue, the service times follow a Phase-Type (PH) distribution [14, 18] with parameters  $(m_s, \alpha, T)$ . A PH distribution describes the time until absorption in a CTMC with  $m_s$  transient states and one absorbing state. The initial probability distribution on the transient states is given by the  $1 \times m_s$  vector  $\alpha$ , and the transitions between the transient states are ruled by the  $m_s \times m_s$  transient generator  $T$ . The  $(i, j)$ -th entry of this matrix holds the non-negative rate at which a transition from state  $i$  to state  $j$  occurs, with  $i \neq j$ . The diagonal entries are negative and such that the matrix  $T$  has non-positive row sum, with at least one row having a strictly negative row-sum. The absorption rate at state  $i$  is therefore given by the  $i$ -th entry of the vector  $t = -T\mathbf{1}$ , for  $1 \leq i \leq m_s$ . The cumulative distribution function of the time until absorption is given by  $F(x) = 1 - \alpha \exp(Tx)\mathbf{1}$ , for  $x \geq 0$ . Similarly, the service times in the preemptive priority queue for both the high- and the low-priority customers are PH-distributed. For the high- (resp. low-) priority customers the parameters of the service-time distribution are  $(m_1, \alpha, T)$  (resp.  $(m_2, \beta, S)$ ). The fact that these parameters may differ for each customer type is made explicit by writing PH[2]. In the remainder of the paper the states of the MCs that underlie the arrival process and the service-time distribution are also referred to as phases.

## 4.2 The BMAP/PH/1 queue

Our first example is a single-server queue where the customers arrive according to a BMAP characterized by the  $m_a \times m_a$  matrices  $\{D_0, D_1, \dots, D_{\bar{L}}\}$ , with  $\bar{L}$  the maximum batch size. The service times follow a PH distribution with parameters  $(m_s, \alpha, T)$ . The BMAP/PH/1 queue can be modeled as an M/G/1-type MC by choosing the number of customers in the queue to be the level. This selection assures that the level decreases by at most one in a single transition, since only one service completion can occur at a time. On the other hand the level can increase by up to  $\bar{L}$  as it is triggered by a batch arrival. Let  $N(t)$  be the number of customers in the queue at time  $t$ ,  $S(t)$  the phase of the service process at time  $t$  if there is a customer in service, and  $J(t)$  the phase of the arrival process at time  $t$ . Then, the tuple  $\{N(t), S(t), J(t), t \geq 0\}$  forms a CTMC that fully describes the state of the BMAP/PH/1 queue. The state space of this MC can be described as follows: the level zero is the set of states

$\Omega_0 = \{(0, j), 1 \leq j \leq m_a\}$ , where in state  $(0, j)$  the queue is empty and the arrival process is in phase  $j$ ; the level  $k \geq 1$  is the set of states  $\Omega_k = \{(k, i, j), 1 \leq i \leq m_s, 1 \leq j \leq m_a\}$ , where in state  $(k, i, j)$  there are  $k$  customers in the queue, the service in progress is in phase  $i$  and the arrival process is in phase  $j$ . The complete state space is therefore given by  $\Omega = \bigcup_{k \geq 0} \Omega_k$ . Since this MC is of the M/G/1 type, its rate matrix has the structure in (1) with blocks given by

$$A_0 = t\alpha \otimes I_{m_a}, \quad A_1 = T \oplus D_0, \quad A_{j+1} = I_{m_s} \otimes D_j, \quad j = 1, \dots, \bar{L}, \quad (21)$$

where  $t = -T\mathbf{1}$ , and  $I_n$  is the identity matrix of size  $n$ . Here  $\otimes$  and  $\oplus$  stand for Kronecker product and sum [10], respectively. From this definition it is clear that the block size is  $m = m_s m_a$ , and that the number of nonzero columns in  $A_0$  depends on the number of nonzero elements in the vector  $\alpha$ . In fact, if  $\alpha$  has only one nonzero element, then  $A_0$  has only  $r = m_a$  nonzero columns, i.e., the block size is  $m_s$  times larger than the number of nonzero columns in  $A_0$ . This is the case if the service times are described by an Acyclic PH distribution [6]. This class of distributions (which includes the Erlang and the hyper-exponential distributions as special cases) has a canonical form introduced in [6] where all the mass of the initial probability vector is concentrated in the first phase. Therefore, in this case the vector  $\alpha$  has only one nonzero entry and the matrix  $A_0$  has  $m_a$  nonzero columns. In general, the vector  $\alpha$  may have any number of nonzero entries, but we can always find a representation of size  $m_s + 1$  such that the initial probability vector has only one nonzero entry. In fact, it is not difficult to show [20] that any continuous PH distribution with representation  $(m_s, \alpha, T)$  also has a representation  $(m_s + 1, e_1, \bar{T})$ , where  $e_1$  and  $\bar{T}$  are given by

$$e_1 = [1 \ \mathbf{0}_{m_s}] \quad \text{and} \quad \bar{T} = \begin{bmatrix} -\theta & \theta\alpha P \\ 0 & T \end{bmatrix},$$

where  $\theta$  is the diagonal entry of  $T$  of largest absolute value, i.e.,  $\theta = \max\{|T_{ii}|, 1 \leq i \leq m_s\}$ , and  $P$  is the uniformized version of the subgenerator matrix  $T$ , i.e.,  $P = \frac{1}{\theta}T + I$ . Using this result we can replace  $\alpha$  and  $T$  by  $e_1$  and  $\bar{T}$ , respectively, in Equation (21). As a consequence the block  $A_0$  has only  $m_a$  nonzero columns, and the new block size is  $(m_s + 1)m_a$ . If  $m_s$  is large, the structure of the block  $A_0$  can be exploited to speed-up the computation of the matrix  $G$  and the stationary probability vector of the chain.

To illustrate the behavior of our methods we choose the following PH distribution for the service time: we assume that the total service time is made up of a random number of i.i.d. elementary operations; each of these operations is described by a continuous PH distribution with parameters  $(\bar{m}_s, \gamma, C)$ ; the number of elementary operations that make up the total service time is described by a discrete PH distribution with parameters  $(n_s, \beta, S)$ ; as

a result [14], the total service time is a continuous PH distribution with parameters  $(m_s, \alpha, T)$  given by  $m_s = n_s \bar{m}_s$ ,  $\alpha = \gamma \otimes \beta$ , and  $T = C \otimes I + c\gamma \otimes S$ , where  $c = -Ce$ . Notice that we can easily alter the size of this representation by changing  $n_s$ , the size of the discrete PH distribution. Also, this representation is not acyclic, but we can obtain a representation of size  $m_s + 1$  where the initial probability vector has only one nonzero entry, as mentioned above.

The time to complete an elementary operation is assumed to have mean one and squared coefficient of variation (SCV) equal to two. The moments are matched with a PH distribution of size  $\bar{m}_s = 2$  using the method in [24]. Hence, the service time distribution has a representation of size  $2n_s$ , which we convert into a representation of size  $2n_s + 1$  to induce the block  $A_0$  to have  $m_a$  nonzero columns. The number of elementary service operations is assumed to be uniformly distributed between one and  $n_s$ . Therefore the mean service time is equal to  $(n_s + 1)/2$ , which is therefore fixed when  $n_s$  is specified. In addition to quantify the effect of  $n_s$  (the block size) on the computation times, we also consider the effect of the load. For this queue the load is given by  $\rho = \lambda E[L]/\mu$ , where  $\lambda$  is the mean arrival rate (inverse of the mean IAT),  $\mu$  is the mean service rate (inverse of the mean service time), and  $E[L]$  is the mean batch size. We set the batch size distribution to be uniform between one and  $\bar{L}$ , hence  $E[L] = (\bar{L} + 1)/2$ . As  $\mu$  and  $E[L]$  are fixed by specifying the values of  $n_s$  and  $\bar{L}$ , we use the rate  $\lambda$  to match a determined load  $\rho$ . The arrival process is thus assumed to have rate  $\lambda = \rho\mu/E[L]$ , SCV equal to 5, and decay rate of the autocorrelation function of the sequence of IATs equal to 0.5. These characteristics are matched with a MAP( $m_a, D_0, D_+$ ) of order  $m_a = 2$  with the method introduced in [7]. The matrices  $\{D_1, \dots, D_{\bar{L}}\}$  are obtained as  $D_j = r_j D_+$ , for  $1 \leq j \leq \bar{L}$ , where  $r_j = 1/\bar{L}$  is the probability that a batch is of size  $j$ . Since  $m_a = 2$ , the block size of the original chain is  $4n_s$  and the number of nonzero columns in  $A_0$  is only two.

In the first scenario we set both the maximum batch size  $\bar{L}$  and the maximum number of elementary service operations  $n_s$  equal to 10. The results for different values of the load are shown in Table 1. In this case the use of the FRF provides an important gain for all the methods. However, compared to the **CR-R** method, the reduction that can be achieved by using the **O-R** method is significantly larger than the one that can be obtained by using the **CR-F** method. Compared to **CR-R** we see that **O-R** provides an important gain for all the load values considered, while it provides slightly better results than **FI-R**. Also, the performance of **C-R** and **C\*-R** is actually worse than the simpler **O-R**, with a larger difference for higher loads. In fact, **O-R** is the best method among those that do not consider the structure in Remark 1. We will comment more on this later on, after presenting the results for other scenarios. The best method is **C\*-F<sub>2</sub>**, which outperforms all the other methods for

every value of the load considered, except  $\rho = 0.1$ . These results show that even for  $n_s = 10$  (the ratio  $m/r$  is  $2n_s$ ) the methods introduced in this paper are able to reduce the times to compute the vector  $\pi$ .

We now consider a scenario where the computation times become considerably larger due to an increase in the block size, as this is the case where we expect our methods to provide more important gains. For the results shown in Table 2 we take the previous scenario and simply increase the value of  $n_s$  to 50. This makes the block size equal to 200, while the number of nonzero columns in  $A_0$  remains equal to two. In this case we notice that the use of the FRF no longer provides a gain for the **CR**, **FI** nor **O** methods. This is related to the increase in the block size, since the computational cost of the FRF is more sensitive to the block size than the RF [16]. On the other hand, we see how the **O-R** method shows a dramatical reduction in computation times, especially under low and mid loads. In this case, the **C\*-R** method provides further improvements although this reduction is rather limited for high loads. Even the use of **C\*-F** does not provide a substantial reduction under high loads, compared to **C-R**. The only method that is able to show a significant reduction for  $\rho = 0.9$ , compared to **O-R**, is **C\*-F<sub>2</sub>**, which again outperforms all the other methods. Here, as well as in the previous case and for most of the load values considered, we find that the **C** approach is not able to reduce the times obtained with the **O** method. In this scenario we also observe important absolute differences: for a load of 50%, **CR-R** takes more than 3 minutes, **FI-R** requires around 15 seconds, while **O-R** performs this computation in just one second. Also, for a load of 90% the computation of  $\pi$  with **CR-R** and **FI-R** takes more than 6 and 3 minutes, respectively, while the **O-R** requires less than a minute, and the **C\*-F<sub>2</sub>** takes around 10 seconds.

As a final scenario we consider an increase in the maximum batch size, making  $\bar{L}$  equal to 20, while the other parameters are kept as in the previous scenario. The results are shown in Table 3, where the first obvious observation is that all the methods require longer computation times than in the previous scenario. Although there is a small increase in the time to compute the matrix  $G$ , the difference between these scenarios is mostly due to the significantly longer times required to compute  $\pi$ . In this case, the number of blocks  $\bar{L}$  and the number of terms  $\pi_i$  are larger, but the block size is the same as in the previous case. Therefore, the FRF-based methods, compared to their RF-based counterparts, show a relative better performance than before. However, for the **CR**, **FI** and **O** approaches the use of the FRF only provides a computational gain when the load is 0.9. On the other hand, the use of the FRF under the **C** and **C\*** approaches results in reductions for almost all the load values considered. Here again, the **O-R** method provides a significant reduction in computation time compared to either **CR-R** or **FI-R**. Also, the **C\*-F<sub>2</sub>** method is able to significantly reduce the computation

times for high loads, outperforming the other approaches once more. We also notice that, in this case, the **C-R** and the **O-R** methods show a similar performance, except when the load is very high (0.9). If we consider their FRF versions, we find that **C-F** is always better than **O-F** and, moreover, **C-F** is the best among the **O** and the **C** approaches. This is in contrast with the previous results, where **O-R** was typically the best performing among these four methods.

### 4.3 The BMAP[2]/PH[2]/1 preemptive priority queue

We now illustrate how the BMAP[2]/PH[2]/1 preemptive priority queue can be modeled as an M/G/1-type MC with restricted downward transitions. In this queue the arrivals also occur in batches and there are two types of customers, each one associated with a different priority level. We assume that each batch is made of customers of only one type, and the maximum size of a batch of high- (resp. low-) priority customers is  $\bar{L}_1$  (resp.  $\bar{L}_2$ ). Hence the arrival process can be modeled as a BMAP[2] characterized by the matrices  $\{D_0, D_1^{j_1}, D_2^{j_2}, 1 \leq j_1 \leq \bar{L}_1, 1 \leq j_2 \leq \bar{L}_2\}$ . As mentioned in Section 4.1, we can define a version of this process where the batch sizes are i.i.d. random variables and are independent of the IATs. Also, the service times for both the high- and the low-priority customers are PH-distributed. For the high- (resp. low-) priority customers the parameters of the service-time distribution are  $(m_1, \alpha, T)$  (resp.  $(m_2, \beta, S)$ ).

To model this priority queue as an M/G/1-type MC the level variable must be chosen such that during a single transition it can decrease by at most one. Therefore, one may take the level either as the number of high- or low-priority customers, since in both cases the level can only decrease by one (service completion) in a single transition, but it can increase by up to  $\bar{L}_1$  or  $\bar{L}_2$  (batch arrivals). In previous works [1, 17, 25] the number of high-priority customers has been used as the level. This choice induces a structure that can be exploited when both priority classes are assumed to have an infinite buffer. However, under BMAP arrivals, this approach requires the determination of  $\bar{L}_1$  infinite block-matrices, which is done with a linearly-convergent algorithm [25] that may require extremely long computation times. Here we opt for the second alternative, that is to take the number of *low-priority* customers as the level. We further assume that the high-priority customers have a finite buffer of size  $C$ . This approach induces a completely different structure (restricted downward transitions), which can be exploited to obtain the stationary probability vector of the MC in an efficient manner for moderate values of  $C$ , e.g., 50 or 100. The assumption of a finite high-priority queue (of moderate size) does not necessarily limit the applicability of the model since high-priority queues are typically fairly short as opposed to low-priority queues. Hence, there is little difference between having a, sufficiently large, finite or an infinite high-priority buffer.

Since the number of low-priority customers is chosen to be the level, the phase keeps track of the number of high-priority customers, and the state of the arrival and the service processes. Let  $N_1(t)$  and  $N_2(t)$  be the number of high- and low-priority customers in the system at time  $t$ , respectively. Also, let  $J(t)$  be the state of the arrival process at time  $t$ , which takes values in the set  $\{1, \dots, m_a\}$ . Let  $S_1(t)$  (resp.  $S_2(t)$ ) be the phase of the high- (resp. low-) priority service at time  $t$  when there is a customer of this class being served. When a low-priority customer is in service there is no need to keep track of  $S_1(t)$ . However, when a high-priority customer is being served,  $S_2(t)$  keeps track of the phase at which the first low-priority customer in the queue will (re-)start its service. Then, when a low-priority customer is preempted by the arrival of a high-priority one, the service phase of the preempted customer is kept in  $S_2(t)$  such that its service can be resumed from this phase. The queue is therefore described by the CTMC  $X(t) = \{(N_2(t), N_1(t), J(t), S_2(t), S_1(t)), t \geq 0\}$ . Its state space is ordered lexicographically and is described as follows. In level zero there is no need to keep track of  $S_2(t)$  since there are no low-priority customers in the system. The states in this level are subdivided in two subsets: the first considers the case where there are no high-priority customers either ( $N_1(t) = 0$ ), so it is enough to keep track of the phase of the arrival process. This case is covered by the set of states  $\Delta_{00} = \{j, 1 \leq j \leq m_a\}$ . The second subset is  $\Delta_{0+} = \{(i, j, s_1), 1 \leq i \leq C, 1 \leq j \leq m_a, 1 \leq s_1 \leq m_1\}$ , which considers the case where there are  $i > 0$  high-priority customers, i.e., the server is busy with a customer of this type, and the service phase is  $s_1$ . Therefore, the set of states corresponding to level zero is  $\Delta_0 = \Delta_{00} \cup \Delta_{0+}$ . For every level  $k \geq 1$  there are also two subsets. The first is  $\Delta_{+0} = \{(j, s_2), 1 \leq j \leq m_a, 1 \leq s_2 \leq m_2\}$ , which describes the case where there are no high-priority customers and the server is busy with a low-priority one. The second subset of level  $k \geq 1$  is  $\Delta_{++} = \{(i, j, s_2, s_1), 1 \leq i \leq C, 1 \leq j \leq m_a, 1 \leq s_2 \leq m_2, 1 \leq s_1 \leq m_1\}$ , which considers the general case with  $k \geq 1$  low-priority and  $i \geq 1$  high-priority customers, the arrival process is in phase  $j$ , the service of the high-priority customer is in phase  $s_1$ , and the next low-priority customer to be served will start (or resume) in phase  $s_2$ . The set of states in level  $k \geq 1$  is given by  $\Delta_k = (k, \Delta_{+0} \cup \Delta_{++})$  and the full state space of the MC is  $\Delta = \bigcup_{k \geq 0} \Delta_k$ .

The complete description of the blocks that characterize the M/G/1-type MC of the BMAP[2]/PH[2]/1 priority queue can be found in Appendix A. Of particular importance, however, is the block  $A_0$ , which holds the transition rates from level  $k$  to level  $k - 1$ . These transitions are triggered by the completion of a low-priority service, which can only occur in



the absence of high-priority customers. Therefore, the block  $A_0$  is given by

$$A_0 = \begin{bmatrix} I_{m_a} \otimes s\beta & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix}.$$

Only the first  $m_a m_2$  columns of this matrix are different from zero, and this number is relatively small compared to the complete block size  $m = m_a m_2 + C(m_a m_2 m_1)$ . In other words, the block size is  $(1 + C m_1)$  times larger than the number of nonzero columns in  $A_0$ . Therefore, by modeling the priority queue in this manner we induce the restricted-downward-transitions structure. In addition, if the batch-sizes are i.i.d. random variables independent of the arrival process we have that  $D_2^i = q_i D_2$ . Then, by looking at the blocks  $(A_i)_{i \geq 2}$  described in Equation (22), we find that  $A_{i+1}^- = q_i (I_C \otimes D_2 \otimes I_{m_2 m_1})$ , for  $1 \leq i \leq \bar{L}_2$ . Moreover, from Equation (22) we also find that  $(A_i^{+-})_{i=2}^{\bar{L}_2}$  and  $(A_i^{-+})_{i=2}^{\bar{L}_2}$  are zero. Therefore, these blocks have the structure defined in Remark 1, which can be exploited together with the restricted-transitions structure as described in Section 3.3.

We now consider some numerical instances of the BMAP[2]/PH[2]/1 preemptive priority queue to illustrate the performance of the methods introduced in this paper. As before, one of the main parameters of this queue is the load  $\rho$ , which in this case is given by  $\rho = \lambda_1 E[L_1]/\mu_1 + \lambda_2 E[L_2]/\mu_2$ . For customers of type  $i$ ,  $\lambda_i$  is their mean arrival rate,  $\mu_i$  is their mean service rate, and  $E[L_i]$  is their mean batch size, for  $1 \leq i \leq 2$ . Recall that high- (resp. low-) priority customers are referred to as customers of type one (resp. two). We assume that high- and low-priority customers have the same mean service rate equal to one, i.e.,  $\mu_1 = \mu_2 = 1$ . Also, both service-time distributions have SCV equal to two. We can match these two moments with a PH distribution of order 2 by using the method in [24]. The batch-size distribution is assumed to be the same for both customer types. Specifically, we set  $\bar{L}_1 = \bar{L}_2 = \bar{L}$ , and let the batch size of both types be uniformly distributed between one and  $\bar{L}$ , with mean  $E[L]$ . Here we first build a single arrival process with arrival rate  $\lambda = \lambda_1 + \lambda_2$ . With the assumptions stated above this arrival rate is given by  $\lambda = \rho/E[L]$ . We assume that the SCV of the batch IAT distribution is equal to five and the decay rate of the autocorrelation function of the sequence of batch IATs is 0.5. We use the method in [7] to match the first two moments of the IAT distribution and the decay rate of the autocorrelation function with an order-2 MAP. The resulting process is a MAP characterized by the  $2 \times 2$  matrices  $D_0$  and  $D_+$ , that describe the batch IATs irrespective of their type. The matrices  $D_1$  and  $D_2$  are obtained as  $D_j = v_j D_+$ , for  $1 \leq j \leq 2$ , where  $v_1 + v_2 = 1$ . In this scenario we also assume that both customer types have the same arrival rate ( $v_1 = v_2 = 0.5$ ). As the size

of the MAP is  $m_a = 2$  and the size of the PH representation of the service-time distributions is  $m_1 = m_2 = 2$ , the number of nonzero columns is  $r = 4$  and the block size of the original M/G/1-type MC is  $m = 4 + 8C$ .

For the results in Table 4 we set the maximum batch size equal to five and the size of the high priority buffer equal to 20. Even this buffer size causes very few losses as illustrated by the loss rate (LR) of high-priority customers included in the last column of the table. The results for the general techniques with FRF (**CR-F** and **FI-F**) are not included in this nor the following tables, because their results were always worse than their RF counterparts due to the large block size. Here we observe how the use of the censored process to compute  $\pi$  reduces the computation times significantly compared with simply solving the original M/G/1-type MC. Moreover, we see that the main gain is obtained due to the fast computation of  $G$ , and additional gains can be realized by using the censored process to compute  $\pi$ , although only when the additional structure from Remark 1 is exploited. Recall that only the **C\*** methods take advantage of this additional structure. Specifically, the use of **O-R** provides a significant reduction compared to either **CR-R** or **FI-R**. We also observe that **C-R** requires more time than **O-R**, while **C-F** shows similar times than **O-R**, and **C\*-R** performs worse than **O-R** for high loads. In fact, we have noted that in many cases, as in the previous section, the gain obtained by using **C\*-R** instead of **O-R** decreases as the load increases. The reason for this behavior is that to compute  $\pi^+$  in **C\*-R** we use Equation (14) with the blocks of the censored process, but the number of blocks increases with the load. For instance, in this scenario for loads 0.1, 0.5 and 0.9, the number of blocks  $(\bar{A}_i)_{i \geq 0}$  is 45, 199 and 552, respectively. This effect is reduced when the ratio  $m/r$  becomes large (e.g., 50), since in this case the vector-matrix multiplications of the original blocks become very expensive. Therefore, the censored process has the drawback of having many blocks, requiring many vector-matrix multiplications to compute the sum in (14). However, when the number of blocks and the number of terms in the vector  $\pi$  are large, and the block size is small, the FRF is expected to perform significantly better than the customary RF [16]. This is the case for the censored process when the load is high, and we therefore observe important gains when using **C-F** instead of **C-R**, and **C\*-F** or **C\*-F<sub>2</sub>** instead of **C\*-R**.

We now consider a simple modification on the previous scenario by increasing the buffer size from 20 to 50. This makes the block size equal to 404. For this buffer size the method **CR** fails to compute the matrix  $G$  due to lack of memory. At this point we must mention that all the times shown here were obtained using a personal computer with a 2Ghz processor and 2GB of RAM. Apart from the methods introduced in this paper, Table 5 shows the computation times for the **FI-R** method and for the approach introduced in [25]. The difference between **INF** and our methods is extremely large for moderate to large loads. It must be noted that

our methods do not scale easily with the size of the high-priority buffer  $C$ . If this parameter is large, our methods would require a large amount of memory, while the **INF** method does not suffer from this problem. However, if the buffer is not so large our methods provide huge savings in computation time. For instance, Table 5 shows that, when the load is 0.9, the **INF** approach takes more than two hours to compute  $\pi$ , **FI-R** takes more than 14 minutes, while **O-R** requires 1.2 minutes, and **C\*-F<sub>2</sub>** takes only half a minute. Additionally, the loss rate assuming a finite buffer is almost negligible, even for high loads. Among the methods that do not use the extra structure introduced in Remark 1, the best choice is **O-R**, as the methods based on the censored process require more time, partly due to the computation of the blocks of the censored process.

In the next scenario we make the maximum batch size  $\bar{L}$  equal to 15, such that both the original and the censored M/G/1-type MCs have more blocks. The computation times are shown in Table 6. Comparing with the results in Table 5, we see that all the methods require more time to compute  $\pi$ , but the increase is not proportional. Actually, the **INF** method takes more than ten times longer in the new scenario, while the **FI-R** method doubles its computation times. Among our methods, **C\*-F<sub>2</sub>** shows the best behavior for high loads, roughly doubling the computation time compared to the previous scenario. We also observe that for mid loads the difference among the **C\*** methods is negligible, but for high loads the advantage of using **C\*-F<sub>2</sub>** is large, even compared to **C\*-F**. Here again **O-R** is the best method among those that do not exploit the additional structure from Remark 1. Also, we notice that, in this and the previous scenarios, the use of the FRF provides no gain for the **O** method, as is to be expected given the large block size. For the other methods, the use of the FRF provides a significant gain for mid-to-high loads, as in this case the FRF is applied on the censored process, the size of which is by construction very small.

We conclude this section by looking at a scenario where the number of high-priority customers is a small fraction of the total number of customers. This scenario may arise, for instance, in a communication system where the high priority is assigned to a subset of the customers such that this subset will experience a better quality of service. One way to accomplish this is to assign high priority only to a small proportion of the customers. To consider this we simply set  $v_1 = 0.1$ , meaning that the high-priority customers represent only 10 percent of the customers. In Table 7 we see that under this configuration the **INF** approach has a better performance than in the previous scenario, where the proportions of high- and low-priority customers were equal. This gain is due to the fact that, in this case, the most expensive operation in all the methods is the actual computation of  $\pi$ , after obtaining  $\pi_0$  and the set of  $R$  matrices (in the **INF** approach) or the matrix  $G$  (in our approach). Since now there are relatively fewer high-priority customers in the system and the **INF** method

uses the number of these customers as the level, this method needs to compute fewer terms of the vector  $\pi$ . On the other hand, our methods use the number of low-priority customers as the level and therefore they now need to compute many more terms of  $\pi$ . In spite of this gain, under high loads the **O-R** and **C\*-F<sub>2</sub>** methods are still around 10 and 100 times faster than the **INF** approach, respectively. Compared to **FI-R**, **O-R** is between 4 and 10 times faster, while **C\*-F<sub>2</sub>** is between 5 and 400 times faster. We also observe that, for loads up to 0.7, the **O-R** method has the best performance among those that do not use the structure in Remark 1. However, for  $\rho = 0.9$  the **C-F** method is able to outperform the **O-R** approach. As in this case the proportion of high priority customers is smaller than in the previous scenario, the loss rate is also smaller and becomes negligible.

In addition to the computation times, it is relevant to consider the behavior of the approach introduced in this paper in terms of the residual error. Let the infinity norm of an  $n \times m$  matrix  $K$  be given by  $\|K\|_\infty = \max_{i=1}^n \sum_{j=1}^m K_{ij}$ . Let  $\hat{G}$  be the matrix that solves Equation (2) obtained with FI, and let  $\tilde{G}$  be the matrix found with the methods introduced in this paper. Also, let  $\hat{\pi}$  be the vector obtained by applying RF on  $\hat{G}$ , and let  $\tilde{\pi}$  be the vector obtained with any of the methods introduced here. We have computed the residual error for  $\tilde{G}$ , defined as

$$\left\| \sum_{i=0}^N A_i \tilde{G}^i \right\|_\infty,$$

which gives a measure of the goodness of  $\tilde{G}$  as a solution for Equation (2). For all the instances considered in this paper, the residual error was always below  $\epsilon = 10^{-14}$ . We also computed the differences  $\|\hat{G} - \tilde{G}\|_\infty$  and  $\|\hat{\pi} - \tilde{\pi}\|_\infty$ , obtaining a similar result. This reveals the good behavior of the approach proposed here, which is to be expected since the algorithms on which our method relies (Cyclic Reduction, the Schur decomposition and the Hessenberg-Schur method for the Sylvester equation) are numerically stable.

## 5 Conclusion

From the results in the previous section we can conclude that the methods proposed in this paper provide an important tool to evaluate the performance of the BMAP/PH/1 queue and the BMAP[2]/PH[2]/1 preemptive priority queue, since they are able to analyze rather large systems in a fraction of the time required by other methods. In general we see that, by exploiting the restricted-downward-transitions property, we are able to reduce the total time to compute  $\pi$ . The gains depend not only on the ratio  $m/r$ , but also on the parameters of the system, and how these affect the expected sojourn times in  $S^-$ , compared to those in

$S^+$ . However, we have seen in the previous examples that our methods are able to provide significant gains in computation time even for a rather small ratio  $m/r$ . Also, among the methods that only exploit the restricted-transitions structure, we have observed that typically the **O-R** method provides the best results, while the **O-F** is badly affected by the large block size. The use of the censored process, either **C-R** or **C-F**, can in some cases provide some additional gains. However, given the overhead required by the **C** methods, compared to the simpler **O-R**, the latter appears as a better option when the additional structure of Remark 1 is absent. Notwithstanding, when this additional structure is present, the use of the censored process leads to very important gains. In this case the **C\*-R** method has the best performance for low loads, while for high loads the **C\*-F<sub>2</sub>** approach is the best alternative to compute  $\pi$ .

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## A The BMAP[2]/PH[2]/1 preemptive priority queue

The purpose of this appendix is to provide the definition of the blocks that make up the generator matrix  $Q$  (Eq. (1)) of the MC that describes the BMAP[2]/PH[2]/1 priority queue. First, let the matrix  $\bar{D}_1^j$  be defined as  $\bar{D}_1^j = \sum_{k=j}^{\bar{L}_1} D_1^k$ , for  $1 \leq j \leq \bar{L}_1$ , and let  $\bar{D}_1^0 = D_0 + \bar{D}_1^1$ . The  $m_b \times m_b$  block  $B_0$  is given by

$$B_0 = \begin{bmatrix} D_0 & D_1^1 \otimes \alpha & D_1^2 \otimes \alpha & \cdots & D_1^{\bar{L}_1} \otimes \alpha & & & & & & 0 \\ I \otimes t & D_0 \oplus T & D_1^1 \otimes I & \cdots & D_1^{\bar{L}_1-1} \otimes I & \ddots & & & & & \\ & I \otimes t\alpha & D_0 \oplus T & \cdots & D_1^{\bar{L}_1-2} \otimes I & \ddots & & & & & \\ & & \ddots & \ddots & \ddots & \ddots & & & & & \\ & & & I \otimes t\alpha & D_0 \oplus T & \cdots & D_1^{\bar{L}_1-2} \otimes I & D_1^{\bar{L}_1-1} \otimes I & \bar{D}_1^{\bar{L}_1} \otimes I & & \\ & & & & \ddots & \ddots & \vdots & \vdots & \vdots & & \\ & & & & & I \otimes t\alpha & D_0 \oplus T & D_1^1 \otimes I & \bar{D}_1^2 \otimes I & & \\ & & & & & & I \otimes t\alpha & D_0 \oplus T & \bar{D}_1^1 \otimes I & & \\ 0 & & & & & & & I \otimes t\alpha & \bar{D}_1^0 \oplus T & & \end{bmatrix},$$

where  $m_b = m_a + C m_a m_1$  and  $I$  is the identity matrix of appropriate dimension. Since in level zero there are no low-priority customers, all the transitions in  $B_0$  are associated to arrivals and service completions of high-priority customers. In addition, the finiteness of the high-priority buffer is reflected in the last block column of  $B_0$ , e.g., if there are  $C - 2$  high-priority customers in the queue and 2 or more of these customers arrive in a batch ( $\bar{D}_1^2$ ), the queue will only accept 2 and the others will be dropped. The transitions from level zero to upper levels are governed by the  $m_b \times m$  blocks  $B_j$ , defined as

$$B_j = \begin{bmatrix} D_2^j \otimes \beta & 0 & \cdots & 0 \\ 0 & D_2^j \otimes \beta \otimes I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & D_2^j \otimes \beta \otimes I \end{bmatrix}, \quad j = 1, \dots, \bar{L}_1,$$

where  $m = m_a m_2 + C m_a m_2 m_1$ . Since in level zero there are no low-priority customers, if one of these arrives and finds the server idle, it starts service immediately, selecting an initial service phase according to  $\beta$ . If there is a high-priority customer in service, the incoming customer selects the phase in which it will eventually start service. The  $m \times m_b$  block  $C_0$  holds the transitions from level one to level zero and is given by

$$C_0 = \begin{bmatrix} I_{m_a} \otimes s & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix},$$

which reflects the fact that the completion of a low-priority service can only occur if there are no high priority customers in the system.

Before determining the remaining blocks we define the operator  $R(\cdot)$  applied on a matrix  $M$  as  $R(M) = I_{m_2} \otimes M$ , which will help to make the notation simpler. The  $m \times m$  block  $A_1$  is defined as

$$A_1 = \begin{bmatrix} D_0 \oplus S & D_1^1 \otimes R(\alpha) & D_1^2 \otimes R(\alpha) & \dots & D_1^{\bar{L}_1} \otimes R(\alpha) & & 0 \\ I \otimes t & D_0 \oplus R(T) & D_1^1 \otimes I & \dots & D_1^{\bar{L}_1-1} \otimes I & \ddots & \\ & I \otimes t\alpha & D_0 \oplus R(T) & \dots & D_1^{\bar{L}_1-2} \otimes I & \ddots & \\ & & \ddots & \ddots & \ddots & \ddots & \ddots \\ & & & I \otimes t\alpha & D_0 \oplus R(T) & \dots & D_1^{\bar{L}_1-1} \otimes I & \bar{D}_1^{\bar{L}_1} \otimes I \\ & & & & \ddots & \ddots & \vdots & \vdots \\ 0 & & & & & I \otimes t\alpha & D_0 \oplus R(T) & \bar{D}_1^1 \otimes I \\ & & & & & & I \otimes t\alpha & \bar{D}_1^0 \oplus R(T) \end{bmatrix}.$$

The first block row of this matrix reflects how a low-priority customer that is being attended may be preempted by the arrival of a batch of high-priority customers, and the first customer in the batch starts service in a phase selected according to  $\alpha$ . The use of  $R(\cdot)$  reflects that the system ‘remembers’ the phase in which the first low-priority customer in the queue will eventually re-start its service. The transitions to upper levels are driven by the blocks

$$A_{j+1} = \begin{bmatrix} D_2^j \otimes I & 0 & \dots & 0 \\ 0 & D_2^j \otimes I & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & D_2^j \otimes I \end{bmatrix}, \quad j = 1, \dots, \bar{L}_1, \quad (22)$$

which are related only to arrivals of low-priority customers. This concludes the description of the blocks since the block  $A_0$ , that holds the transitions from level  $k$  to level  $k - 1$ , was already described in Section 4.3.



## Tables

$\rho$	CR-R	CR-F	FI-R	FI-F	O-R	O-F	C-R	C-F	C*-R	C*-F	C*-F <sub>2</sub>
0.1	1.6	1.6	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.3	0.4
0.3	2.6	2.7	0.1	0.1	0.1	0.2	0.2	0.1	0.2	0.1	0.1
0.5	3.5	3.6	0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.2	0.1
0.7	5.3	5.4	0.8	0.9	0.5	0.9	1.4	0.8	0.9	0.3	0.3
0.9	13.7	8.6	9.3	4.1	8.4	2.7	11.6	8.2	10.6	7.2	1.7

Table 1: Computation times (sec) for  $\bar{L} = 10$ ,  $n_s = 10$

$\rho$	CR-R	CR-F	FI-R	FI-F	O-R	O-F	C-R	C-F	C*-R	C*-F	C*-F <sub>2</sub>
0.1	129.2	132.6	2.5	5.9	0.5	3.9	0.4	0.4	0.3	0.3	0.4
0.3	145.3	149.6	6.1	10.4	0.5	5.5	0.5	0.5	0.4	0.3	0.4
0.5	201.4	210.8	14.3	23.7	1.0	10.4	1.1	1.0	0.6	0.5	0.6
0.7	240.9	264.3	45.0	68.3	4.3	27.5	4.9	4.3	2.9	2.4	1.5
0.9	388.3	447.4	214.5	273.6	55.3	113.3	58.7	55.5	49.2	46.4	10.8

Table 2: Computation times (sec) for  $\bar{L} = 10$ ,  $n_s = 50$

$\rho$	CR-R	CR-F	FI-R	FI-F	O-R	O-F	C-R	C-F	C*-R	C*-F	C*-F <sub>2</sub>
0.1	196.7	203.8	5.4	12.6	1.8	9.0	1.6	1.9	0.5	0.5	0.6
0.3	251.7	261.7	11.5	21.5	3.1	12.8	3.2	2.8	0.8	0.7	0.8
0.5	291.0	311.1	27.1	47.2	8.2	23.5	7.5	7.1	1.8	1.4	1.3
0.7	393.7	424.4	104.5	135.2	34.3	62.5	35.7	34.5	11.0	9.3	3.6
0.9	740.5	717.5	561.0	538.0	285.0	252.0	210.0	200.6	182.2	172.9	28.2

Table 3: Computation times (sec) for  $\bar{L} = 20$ ,  $n_s = 50$

$\rho$	CR-R	FI-R	O-R	O-F	C-R	C-F	C*-R	C*-F	C*-F <sub>2</sub>	LR
0.1	51.0	1.1	0.3	1.2	0.5	0.4	0.4	0.4	0.4	2.09E-09
0.3	112.5	2.4	0.4	2.1	0.5	0.6	0.4	0.4	0.4	2.25E-06
0.5	164.8	5.7	0.8	4.2	1.0	0.9	0.7	0.6	0.7	5.92E-05
0.7	222.0	15.3	1.8	10.3	2.9	1.8	2.5	1.4	1.4	4.67E-04
0.9	282.8	59.1	13.2	38.7	20.1	13.5	17.8	9.7	5.0	1.93E-03

Table 4: Computation times (sec) for  $\bar{L} = 5$ ,  $C = 20$

$\rho$	INF	FI-R	O-R	O-F	C-R	C-F	C*-R	C*-F	C*-F <sub>2</sub>	LR
0.1	2	17.4	1.9	11.7	2.6	3.3	1.9	1.9	2.5	2.14E-18
0.3	343	37.4	2.7	17.2	4.3	5.6	2.7	2.8	3.8	8.10E-12
0.5	1010	84.9	5.0	32.2	7.7	10.4	4.3	4.5	6.1	1.25E-08
0.7	2427	223.1	12.7	79.2	17.9	21.7	9.5	9.7	11.3	1.41E-06
0.9	6832	846.2	71.1	308.9	95.3	81.4	59.9	45.2	31.7	3.70E-05

Table 5: Computation times (sec) for  $\bar{L} = 5$ ,  $C = 50$

$\rho$	INF	FI-R	O-R	O-F	C-R	C-F	C*-R	C*-F	C*-F <sub>2</sub>	LR
0.1	55	31.0	5.0	28.0	9.3	13.4	4.7	4.8	5.7	2.77E-10
0.3	4149	69.1	9.8	39.6	16.0	24.6	6.6	7.0	8.2	2.33E-07
0.5	10661	171.3	24.0	76.7	30.3	29.5	10.9	10.0	11.2	6.58E-06
0.7	31033	497.2	76.1	195.8	93.6	87.0	32.6	25.8	22.8	5.90E-05
0.9	82545	1832.9	398.3	699.4	475.7	426.4	240.3	187.2	64.9	2.78E-04

Table 6: Computation times (sec) for  $\bar{L} = 15$ ,  $C = 50$

$\rho$	INF	FI-R	O-R	O-F	C-R	C-F	C*-R	C*-F	C*-F <sub>2</sub>	LR
0.1	44	36.7	5.5	28.2	11.5	14.8	6.1	6.1	7.0	3.87E-14
0.3	1854	81.6	10.3	41.1	18.0	26.5	8.5	8.9	10.2	1.44E-11
0.5	2730	201.7	24.6	78.1	32.6	31.8	12.2	11.5	12.8	2.58E-10
0.7	4247	575.3	79.3	202.8	92.9	89.1	28.7	24.6	21.0	1.82E-09
0.9	6312	2570.4	700.8	1035.2	740.0	628.8	390.8	306.0	71.6	8.06E-09

Table 7: Computation times (sec) for  $\bar{L} = 15$ ,  $C = 50$ ,  $v_1 = 0.1$