

The Departure Process of a D-BMAP/Geo/1/K Queue Arising in an ATM Network

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ATM 망에서 발생하는 D-BMAP/Geo/1/K Queue의 Departure 프로세스

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We obtain the departure process of a D-BMAP/Geo/1/K queue. We also study the burstiness and correlation of the departure process. We have observed that the autocorrelation coefficients of the interdeparture time (correlogram) of the departure process may oscillated.

ATM 망의 모델링에서 발생되어 지는 D-BMAP/Geo/1/K queue의 Departure 프로세스를 구하고 그 프로세스의 bursty 정도와 correlation에 대하여 연구하였다. 또한 그 departure 프로세스의 interdeparture time의 autocorrelation 계수 (correlogram)가 oscillation을 할 수 있다는 것을 알았다.

Key words: Discrete-time queue, departure process, MMBP, correlogram, ATM

I. INTRODUCTION

In recent years there has been a lot of interest in the development of high-speed communication networks. The most promising design for high-speed networks is the Asynchronous Transfer Mode (ATM). The need for performance evaluation of ATM networks has given rise to a widespread interest for the analysis of discrete-time queueing systems. Discrete-time single server queues with or without finite capacity have been extensively

analyzed. For a review of relevant results see Pujolle and Perros¹⁾. However, little has been done for the analysis of networks of discrete-time finite capacity queues. A network of discrete-time finite capacity queues can be used to model the queueing within an ATM switch, or the queueing within a network of ATM switches. The external arrival process to the network is assumed to be bursty and correlated. Markov Modulated Poisson Processes(MMPP)^{2,3)}, and Markov Modulated Bernoulli Processes(MMBP) are

used to model a bursty arrival stream since they capture the randomly varying arrival rate. The MMPP and MMBP capture the notion of burstiness and correlation of successive interarrival times. In this paper, we assume that the arrival process to the queue is a Discrete-time Batch Markovian Arrival Process (D-BMAP) which belongs to a class of versatile point processes^{4,5}. A D-BMAP is the proposed model for a single variable bit rate source. Also, it can be used to model the superposition of several such sources⁶. The MMBP or IBP is a special case of the D-BMAP, with all arrival having a batch of size 1.

In this paper, we consider discrete-time finite capacity queues with cell loss. The service time at the queue is assumed to be geometrically distributed. The choice of the geometric distribution was motivated by ATM networks⁷. In general, a service time represents a transmission time. In an ATM networks the size of a cell is constant, and therefore, the transmission time is constant as well. However, in some ATM switch architectures a cell may be re-transmitted several times due to possible collisions with other cells. In this case, the total transmission time is typically modeled by a geometric distribution.

In general, discrete-time queueing networks as they arise in ATM do not lend themselves to an exact analysis. They can be analyzed, however, approximately using the notion of decomposition. That is, the network is decomposed into individual queues, and each queue is then analyzed separately. The most important aspect of such a decomposition is the characterization of the arrival process to an intermediate queue. In continuous-time queueing networks, typically such as the departure process is characterized approximately by a phased-type distribu-

tion, or by a general distribution defined by the mean and squared coefficient of variation. Although there has been some work regarding the departure process⁸⁻¹³, most of this work bears some limitations which seriously undermine their applicability on network-wide traffic analysis. Most of these studies only provide results on the stationary distribution of the interdeparture time. Although this is a very important piece of information, it is by no means sufficient for characterizing the non-renewal departure process: the lengths of successive interdeparture times are highly correlated and such correlation will have significant impact on downstream queueing performance. As a result, details about the dynamic behaviour of the departing stream, e.g., burstiness and correlation, have to be studied. In this paper, the departure process of the D-BMAP/Geo/1/K queue has been studied.

Blondia and Casals⁶ showed that the output process of a D-BMAP/G/1/K queue is a D-BMAP. Park and Perros¹⁴ derived the generating function of the interdeparture time distribution and correlation of the departure process of an MMBP/Geo/1/K queue. They also obtained an approximation model for characterizing the departure process by an MMBP in order to capture the correlation and burstiness of the departure process of the queue.

This paper is organized as follows. In section II, we give a brief description of the D-BMAP. The generating function of the interdeparture time of a D-BMAP/Geo/1/K queue and the correlation coefficients for the departure process are obtained in section III.

II. The Discrete-time Batch Markov Arrival Process

1. The Generating Function of the Interarrival Time of the D-BMAP

A D-BMAP can be represented by a 2-dimensional discrete-time Markov process $\{(J(k), N(k)) : k \geq 0\}$ on the state space $\{(i, j) : 1 \leq i \leq m, j \geq 0\}$, where i indicates the state of the arrival process, and j indicates the number of arrivals. The transition matrix T of the counting process has the following structure:

$$T = \begin{bmatrix} P_0 & P_1 & P_2 & P_3 & \cdots \\ & P_0 & P_1 & P_2 & \cdots \\ & & P_0 & P_1 & \cdots \end{bmatrix}$$

where $P_k, k \geq 0$, are $m \times m$ matrices. $P = \sum_{k=0}^{\infty} P_k$ be the transition matrix of the underlying Markov process. If $J(k)$ represents a phase variable and $N(k)$ a counting variable then the above Markov process defines a batch arrival process where transitions from a state (i, j) to state $(i, j+n)$, corresponding to batch arrivals of size n .

Consider a discrete-time Markov chain with transition probability matrix P . Assume the underlying Markov process is in some state $i, 1 \leq i \leq m$ at time k . At the next time instant $k+1$, the process may transit to another state or it may stay in the same state, and a batch arrival may or may not occur. Let $p_{(n,i,j)}, n \geq 0, 1 \leq i, j \leq m$, be the probability that there is a transition to state j from state i with a batch arrival of size n . Then, with probability $p_{(0,i,j)}, n \geq 1, 1 \leq i, j \leq m$, a transition to state j will take place without an arrival, and with probability $p_{(n,i,j)}, n \geq 1, 1 \leq i, j \leq m$, there will be a transition to state j with a batch arrival of size n . We have

$$\sum_{j=1}^m p_{(0,i,j)} + \sum_{n=1}^{\infty} \sum_{j=1}^m p_{(n,i,j)} = 1.$$

Using this notation, it is clear now that matrices $P_0 = [p_{(0,i,j)}]_{m \times m}$ and $P_k = [p_{(k,i,j)}]_{m \times m}$, govern transitions that correspond to no arrival and arrival of batch of size k where $k \neq 0$, respectively. A D-MAP is a special case of the D-BMAP, with all arrivals having a batch of size 1.

Through this paper, we consider an arrival process to the queue which is a D-BMAP characterized by the transition probability matrix P of the Markov process, A , $m \times m$ diagonal matrix with elements $\alpha_1, \dots, \alpha_m$ and B , defined by

$$P = \begin{bmatrix} p_{11} & p_{1m} \\ & \ddots \\ p_{m1} & p_{mm} \end{bmatrix}, \quad A = \begin{bmatrix} \alpha_1 & 0 \\ & \ddots \\ 0 & \alpha_m \end{bmatrix}, \quad \text{and } B = \begin{bmatrix} b_{11} & b_{12} & \dots \\ & \ddots & \\ b_{m1} & b_{m2} & \dots \end{bmatrix}$$

where $p_{ij}, 1 \leq i, j \leq m$ is the transition probability that the process changes from state i to state $j, \sum_{j=1}^m p_{ij} = 1, \alpha_i$ is the probability that a batch arrival occurs when the D-BMAP shifts to state i , and b_{ik} is the probability that the arriving batch size is equal to $k, k \geq 1, \sum_{n=1}^{\infty} b_{in} = 1$. The D-BMAP satisfies following equations:

$$\begin{aligned} p_{(0,i,j)} &= p_{ij}(1 - \alpha_j), \\ p_{(n,i,j)} &= p_{ij} \alpha_j^n b_{jn}, \\ p_{ij} &= \sum_{k=0}^{\infty} p_{(k,i,j)} \quad \text{for } 1 \leq i, j \leq m, \quad n \geq 1. \end{aligned}$$

This process can be also referred to as a Markov Modulated Batch Bernoulli Process (MMBBP). In general, a D-BMAP becomes an MMBP if the following relation are satisfied: For $1 \leq i, j \leq m$,

$$\begin{aligned} b_{i1} &= 1 \\ p_{ij} &= p_{(0,i,j)} + p_{(1,i,j)}, \\ p_{ij}(1 - \alpha_j) &= p_{(0,i,j)} \tag{1} \\ p_{ij} \alpha_j &= p_{(1,i,j)} \tag{2} \end{aligned}$$

A D-BMAP has been proposed as a model from single variable bit rate source

and its superposition⁶. Therefore, we assume that the batch size of a batch is bounded. Let N be the maximum batch size. Let T be the interarrival time between two successive batch arrivals. Also let $\vec{\pi} = [\pi_1, \dots, \pi_m]$ be the stationary probability vector satisfying $\vec{\pi} = \vec{\pi}P$, where $\pi_i, 1 \leq i \leq m$, is the probability that the process is in state i . The generating function of batch interarrival time $T(z)$ is

$$T(z) = \vec{p}_a \vec{T}(z) = z \vec{p}_a (I - zM)^{-1} P \vec{\lambda}$$

where

$$\begin{aligned} \vec{p}_a &= \frac{\vec{\pi}A}{\vec{\pi}\vec{\lambda}} \\ T(z) &= z(I-zM)^{-1} P \vec{\lambda} \\ M &= P(I-A) \\ \vec{\lambda} &= [\alpha_1, \dots, \alpha_m]^T. \end{aligned}$$

The average batch arrival rate ρ_b , the average cell arrival rate ρ_c , and the squared coefficient of variation of the interarrival time between two successive arrival of batch, C_b^2 are as follows:

$$\begin{aligned} \rho_b &= \vec{\pi}\vec{\lambda}, \\ \rho_c &= \sum_{i=1}^m i \vec{\pi} A \vec{b}_i, \\ C_b^2 &= \frac{T^{(2)}(1)}{T^{(1)}(1)^2} + \rho_b - 1 \end{aligned}$$

where $\vec{b}_i = [b_{1i}, \dots, b_{mi}]^T$

$$\text{and } T^{(n)}(1) = \left. \frac{d^n T(z)}{dz^n} \right|_{z=1}$$

2. The Autocorrelation of the D-BMAP

In this section, we obtain the autocorrelation of the interarrival time of batches, and the autocorrelation of the number of arrivals per slot. Let t_n be the time interval between the $(n-1)$ st and n th arrival of a batch. Also, let $t_{ij}^n, 1 \leq i, j \leq m$,

be the time interval to the moment that the D-BMAP is in state j and n th arrival occurs given that the D-BMAP is in state i , and $t_i^n, 1 \leq i \leq m$, be the time interval to the n th arrival given that the D-BMAP is in state i . Define

$$A(z) = \begin{bmatrix} A_{11}(z) & A_{1m}(z) \\ \vdots & \vdots \\ A_{m1}(z) & A_{mm}(z) \end{bmatrix} \text{ and } \vec{A}(z) = \begin{bmatrix} A_1(z) \\ \vdots \\ A_m(z) \end{bmatrix}$$

where $A_{ij}(z)$ and $A_i(z)$ are z -transforms of t_{ij}^n and t_i^n , respectively. From the definition of $A_{ij}(z)$ and $A_i(z)$ for $1 \leq i, j \leq m$, we have following equations:

$$A(z) = zPA + zMA(z) \text{ and } \vec{A}(z) = \vec{T}(z).$$

Therefore, we can obtain

$$A(z) = z(I-zM)^{-1} PA \tag{3}$$

$$\vec{A}(z) = z(I-zM)^{-1} P \vec{\lambda} \tag{4}$$

Using equations (3) and (4), we have

$$\begin{aligned} G_a(z_1, z_2) &= E \{z_1^{t_n} z_2^{t_{n+k}}\} \\ &= \vec{p}_a A(z_1) T^{k-1} \vec{p}_a(z_2) \\ &= \vec{p}_a z_1 (I-z_1M)^{-1} PA T^{k-1} \\ &\quad \times z_2 (I-z_2M)^{-1} P \vec{\lambda} \end{aligned} \tag{5}$$

where $T = [I-M]^{-1} PA$.

By differentiating equation (5) with respect to z_1 and z_2 , we have

$$\begin{aligned} E \{t_n t_{n+k}\} &= \left. \frac{\partial^2 G_a(z_1 z_2)}{\partial z_1 \partial z_2} \right|_{z_1=1, z_2=2} \\ &= \vec{p}_a (I-M)^{-1} PA T^{k-1} (I-M)^{-2} P \vec{\lambda}. \end{aligned}$$

The autocorrelation coefficient of the interarrival time of batches of a D-BMAP for lag k , $\psi_b(k)$, is given by

$$\psi_b(k) = \frac{E \{t_n t_{n+k}\} - E^2 \{t_n\}}{\text{Var} \{t_n\}} \tag{6}$$

Let X_n be the random variable representing the number of arrivals at n th slot, where $X_n = 0, 1, \dots, N$. Then, we have

$$E\{X_n\} = \rho_c,$$

$$E\{X_n^2\} = \sum_{i=1}^N i^2 \cdot \Pr\{X_n=i\} \\ = \sum_{i=1}^N i^2 \pi \mathbf{A} \mathbf{B}_i,$$

$$E\{X_n X_{n+k}\} = \sum_{i,j=1}^N ij \cdot \Pr\{X_n=i, X_{n+k}=j\} \\ = \sum_{i,j=1}^N ij \pi \mathbf{A} \mathbf{B}_i = \mathbf{P}^k \mathbf{A} \mathbf{B}_j,$$

$$\text{Var}\{X_n\} = E\{X_n^2\} - E^2\{X_n\}$$

where

$$\mathbf{B}_i = \begin{bmatrix} b_{1i} & & 0 \\ & \ddots & \\ 0 & & b_{mi} \end{bmatrix}.$$

Of interest is the autocorrelation coefficient of the number of arrival per slot of a D-BMAP for lag k , $\phi_c(k)$, given by

$$\phi_c(k) = \frac{E\{X_n X_{n+k}\} - E^2\{X_n\}}{\text{Var}\{X_n\}}. \quad (7)$$

III. The Departure Process of an D-BMAP/Geo/1/K Queue

We consider a D-BMAP/Geo/1/K queue, where the service time is defined over a slotted time axis. A service starts at the beginning of a service slot, and service completion is assumed to take place just before the end of the service slot. The arrival process is also defined over a slotted time axis with the same slot size, and it is assumed to be a D-BMAP. The parameters of the arrival process are: p_{ij}^A ,

α_i^A , and b_{ij}^A , where p_{ij}^A is the (i,j) th element of the transition probability matrix \mathbf{P} , α_i^A is the (i,i) th element of the diagonal matrix \mathbf{A} , and b_{ij}^A is the (i,j) th

element of the matrix \mathbf{B} . We define the state of the queue by the variable (s,n) . Variable s represents the state of the arrival process at the end of a slot and it takes the values: $i, 1 \leq i \leq m$, if the arrival process is in the state i . Variable n indicates the number of cells in the system at the end of a slot. We have $n=0, 1, \dots, K$, where K is the capacity of the system including the cell in service. Let \mathbf{P}_d be the transition probability matrix of the queue. Define \mathbf{P}_{wd} and \mathbf{P}_{wod} as follows:

$$\mathbf{P}_{wd} = (1-\sigma) \begin{bmatrix} 0 & 0 & 0 & 0 \\ M \mathbf{P} \mathbf{A} \mathbf{B}_1 \mathbf{P} \mathbf{A} \mathbf{B}_2 \mathbf{P} \mathbf{A} \mathbf{B}_3 \\ & M \mathbf{P} \mathbf{A} \mathbf{B}_1 \mathbf{P} \mathbf{A} \mathbf{B}_2 \\ & & M \mathbf{P} \mathbf{A} \mathbf{B}_1 \\ & & & M \mathbf{P} \mathbf{A} \mathbf{B}_1 \mathbf{P} \mathbf{A} \mathbf{B}_2 \mathbf{P} \mathbf{A} \mathbf{B}_3 & 0 \\ & & & M \mathbf{P} \mathbf{A} \mathbf{B}_1 \mathbf{P} \mathbf{A} \mathbf{B}_2 & 0 \\ & & & & M \mathbf{P} \mathbf{A} \\ & & & & & \mathbf{P} \end{bmatrix}$$

and

$$= \mathbf{P}_{wod} = \begin{bmatrix} M \mathbf{P} \mathbf{A} \mathbf{B}_1 \mathbf{P} \mathbf{A} \mathbf{B}_2 \mathbf{P} \mathbf{A} \mathbf{B}_3 \\ M \sigma \mathbf{P} \mathbf{A} \mathbf{B}_1 \sigma \mathbf{P} \mathbf{A} \mathbf{B}_2 \sigma \\ & M \sigma \mathbf{P} \mathbf{A} \mathbf{B}_1 \sigma \\ & & M \sigma \\ & & & M \sigma \mathbf{P} \mathbf{A} \mathbf{B}_1 \sigma \mathbf{P} \mathbf{A} \mathbf{B}_2 \sigma \mathbf{P} \mathbf{A} \mathbf{B}_3 & 0 \\ & & & M \sigma \mathbf{P} \mathbf{A} \mathbf{B}_1 \sigma \mathbf{P} \mathbf{A} \mathbf{B}_2 & 0 \\ & & & & M \sigma \mathbf{P} \mathbf{A} \sigma \\ & & & & & \mathbf{P} \sigma \end{bmatrix}$$

where $\bar{\mathbf{B}}_i = \sum_{n=i+1}^m \mathbf{B}_n$. We can see that the transition probability matrix, \mathbf{P}_d can be decomposed into two matrices, \mathbf{P}_{wd} and \mathbf{P}_{wod} , where \mathbf{P}_{wd} , \mathbf{P}_{wod} is a matrix that contains transitions with a departure respectively without a departure. Therefore, $\mathbf{P}_d = \mathbf{P}_{wd} + \mathbf{P}_{wod}$. We compute the generating function of the probability distribution of the interdeparture time, and then we obtain the autocorrelation of the interdeparture time

and the autocorrelation of the number departure per slot.

1. The Generating Function of the Interdeparture Time Distribution

Let t_n be the time interval between the (n-1)st and the nth departure. Also, let t_{ij}^n , $1 \leq i, j \leq L$ where $L = m(K+1)$, be the time interval to the moment that the state of the queue is j and the nth departure occurs given the queue is in state i , and t_i^n , $1 \leq i \leq L$, be the time interval to the nth departure given that the queue is in state i . Define

$$D(z) = \begin{bmatrix} D_{1,1}(z) & D_{1,L}(z) \\ \vdots & \vdots \\ D_{L,1}(z) & D_{L,L}(z) \end{bmatrix} \text{ and } \bar{D}(z) = \begin{bmatrix} D_1(z) \\ \vdots \\ D_L(z) \end{bmatrix}$$

where $D_{i,j}(z)$ and $D_i(z)$ are the z-transforms of t_{ij}^n and t_i^n , respectively. Also, let $P'(s,n)$ be the probability that immediately after a departure the system is in state (s,n). From the definition of $D_{i,j}(z)$ and $D_i(z)$, we have following equations:

$$\begin{aligned} D(z) &= zP_{wd} + zP_{wod} D(z) \\ &= z(I - zP_{wod})^{-1} P_{wd} \\ \bar{D}(z) &= zP_{wd} \bar{e} + zP_{wod} \bar{D}(z) \\ &= z(I - zP_{wod})^{-1} P_{wd} \bar{e}. \end{aligned}$$

Then, the generating function of the interdeparture time distribution $D(z)$ can be obtained from as follows:

$$D(z) = \bar{P}' \bar{D}(z) = z \bar{P}' (I - zP_{wod})^{-1} P_{wd} \bar{e}$$

where

$$\begin{aligned} \bar{P}' &= [P'(1,0), \dots, P'(m,0), \\ &P'(1,1), P'(2,1), \dots, P'(m,K)] \\ &= \frac{\bar{x} P_{wd}}{\bar{x} \lambda_d} \end{aligned}$$

From the generating function, we can obtain the moments of the time between successive departures, the squared coefficient of variation of the interdeparture time C_d^2 , and throughput ρ_d .

2. The Autocorrelation of the Departure Process

In this section, we obtain the autocorrelation of the interdeparture time, and the autocorrelation of the number of departure per slot. In order to obtain the autocorrelation of the interdeparture time, we have

$$\begin{aligned} G_d(z_1 z_2) &= E \{z_1^{t_n} z_2^{t_{n+k}}\} \\ &= \bar{P}' + D(z_1) R^{k-1} \bar{D}(z_2) \\ &= \bar{P}' + z_1 (I - z_1 P_{wod})^{-1} P_{wd} \\ &\quad \times R^{k-1} z_2 (I - z_2 P_{wod})^{-1} P_{wd} \bar{e} \end{aligned} \tag{8}$$

where $R = (I - P_{wod})^{-1} P_{wd}$.

By differentiating equation (8) with respect to z_1 and z_2 and substituting $z_1 = 1$ and $z_2 = 1$ into equation (8), we have

$$E \{t_n t_{n+k}\} = \bar{P}' (I - P_{wod})^{-2} P_{wd} R^{k-1} (I - P_{wod})^{-2} P_{wd} \bar{e}.$$

The autocorrelation coefficient of the interdeparture time of a D-BMAP/Geo/1/K queue for lag k , $\psi_d(k)$, can now be obtained using expression (6).

Let X_n be the random variable representing the number of departures in the nth slot, where $X_n = 0, 1$. We have

$$\begin{aligned} E \{X_n\} &= E \{X_n^2\} = \rho_d \\ E \{X_n X_{n-k}\} &= \bar{x} P_{wd} P_d^{k-1} \bar{\lambda}_d \end{aligned}$$

where \bar{x} is the steady state probability vector satisfying $\bar{x} P_d = \bar{x}$ and $\bar{\lambda}_d = [0, \dots, 0, 1 - \sigma, \dots, 1 - \sigma]^T$. The autocorrelation coefficient of the number departures of the queue for lag k , $\phi_d(k)$ can now be obtained from (7).

Let us consider the autocorrelation of the interdeparture time of the queue. One of the most interesting facts that we have observed is that the autocorrelation coefficients of the interdeparture time (correlogram) may fluctuate quite a lot. As an example, consider the case where

$$P = \begin{bmatrix} 0.98 & 0.01 & 0.01 \\ 0.01 & 0.98 & 0.01 \\ 0.01 & 0.01 & 0.98 \end{bmatrix} \text{ and } A = \begin{bmatrix} 0.9 & 0.0 & 0.0 \\ 0.0 & 0.5 & 0.0 \\ 0.0 & 0.0 & 0.1 \end{bmatrix}$$

The correlogram for

$$B_A = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 1.0 & 0.0 & 0.0 \\ 1.0 & 0.0 & 0.0 \end{bmatrix} \text{ and } B_B = \begin{bmatrix} 0.8 & 0.1 & 0.1 \\ 0.2 & 0.6 & 0.2 \\ 0.1 & 0.1 & 0.8 \end{bmatrix}$$

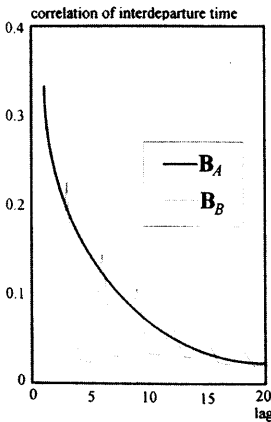


Figure 1. Correlogram of $\psi_d(i)$

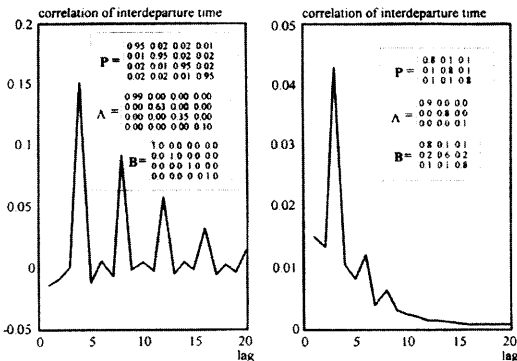


Figure 2. Correlogram of $\psi_d(i)$

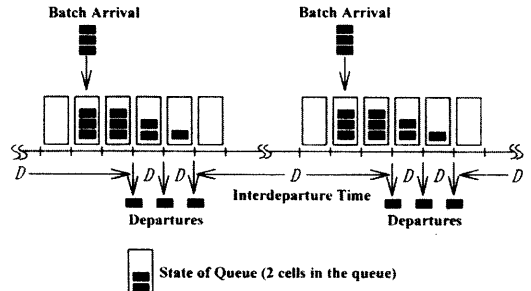


Figure 3. An example of the interdeparture time pattern

is shown in Figure 1. We note that for B_A , we have a smooth curve, whereas for B_B , we have an oscillating curve. Other examples of such oscillations are given in Figure 2. We note that this behaviour is barely seen in the departure process of an MMBP/Geo/1/K queue. This oscillation seems to be due to the variability of the number of arrivals per slot within the same state of the arrival process. Let us consider the example given in Figure 1 assuming that the batch size distributions are given by B_B . We note that when the arrival process is in state 3, the rate of arrivals α_3 is very low. Also, b_{33} is quite large in relation to b_{31} and b_{32} . In view of this the departure pattern shown in Figure 3 is possible. When the arrival process is in state 3, there may be long interarrival periods and the queue may empty out between successive batch arrivals. In this case, the pattern of the interdeparture times consists of one long interval followed by small intervals as shown in Figure 3. This pattern causes the autocorrelation of the interdeparture time to fluctuate.

IV. Conclusion

In this paper, we obtained the generating function of the interdeparture time distribution and the autocorrelation of

the departure process of a D-BMAP/Geo/1/K queue. And, we have observed that the autocorrelation coefficients of the interdeparture time (correlogram) of the departure process may oscillated. This oscillating behaviour is barely seen in the departure process of an MMBP/Geo/1/K queue.

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