

DELAI D'ATTENTE MOYEN POUR  
LES FILES D'ATTENTE  $E_q/E_k/1$

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## 1. INTRODUCTION

Les applications de la théorie des files d'attente se sont diversifiées de plus en plus depuis plusieurs années. Cette théorie voulait donner ou construire des modèles générales afin de résoudre certains problèmes pratiques. On s'est vite rendu compte que les hypothèses utilisées ne correspondaient pas toujours à la réalité ou bien que le calcul des différentes quantités était beaucoup trop laborieux pour les utilisateurs.

On a donc cherché à améliorer les modèles par des approximations. Une de ces approximations consiste à approcher la loi du temps aléatoire entre deux arrivées successives de clients (clients pris au sens large) par une loi de Erlang. Il en est de même pour la loi du temps de service de clients qui sera également approchée par une loi de Erlang.

Certaines quantités que l'on ne pouvait pas obtenir par l'intermédiaire de formules analytiques ont été calculées numériquement sur ordinateur et mises en table, permettant

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ainsi aux utilisateurs de cette théorie de s'en servir sans en connaître tout les détails mathématiques de calculs. Une table ne peut-être complète, surtout si un des paramètres varie continuellement, les quantités manquantes sont généralement obtenues par interpolation linéaire.

C'est ce que nous avons voulu faire pour le calcul du délai d'attente moyen dans une file d'attente à un serveur. Il existe déjà des tables donnant certains paramètres des files d'attente, entre autre, "tables for multiple-server queueing systems involving Erlang distributions" [2], mais elles ne donnent pas directement ce délai d'attente moyen.

Le lecteur trouvera dans les pages qui suivent les explications nécessaires à l'élaboration et à l'utilisation de cette table: c'est-à-dire qu'après avoir résumé les formules analytiques connues pour certains files d'attente, nous expliquerons comment nous avons calculé numériquement, pour certaines valeurs, ce délai moyen.

En plus de donner cette table, nous avons voulu rendre accessible rapidement et sans effort son utilisation.

Pour cela, la table fût mise sur une disquette et par "accès direct" aux données, un programme d'interpolation linéaire donne directement une approximation du délai d'attente moyen pour les paramètres non-tabulés.

Cette disquette est accessible à la demande et fonctionne sur un ordinateur IBM-PC.

## 2. CALCUL DU DELAI D'ATTENTE MOYEN

Rappelons brièvement ce qu'indiquent les symboles utilisés dans une file d'attente  $E_\lambda/E_k/1$ .

$E_\lambda$  et  $E_k$  représente respectivement la loi du temps entre deux arrivées successives de clients et le temps de service.

La fonction de densité d'une variable aléatoire  $T$  du type Erlang avec paramètre  $k$ , notée  $E_k$ , est:

$$f_T(t) = \begin{cases} \frac{(k\mu)^k t^{k-1} e^{-k\mu t}}{(k-1)!} & \text{si } t \geq 0 \\ 0 & \text{si } t < 0 \end{cases}$$

Cette loi est une "Gamma" de paramètres  $k$  (entier) et  $\mu > 0$ .

La moyenne est  $1/\mu$  et la variance est  $1/k\mu^2$ . On voit immédiatement que l'on peut facilement approcher statistiquement  $k$  en prenant le quotient de la valeur moyenne au carré et de la variance.

Nous noterons par  $W(\lambda, k)$  le délai moyen d'attente dans la file. En fait, si  $T_q$  est la variable aléatoire représentant le temps d'attente passé par un client dans la file (queue)  $E_\lambda/E_k/1$ ,  $W(\lambda, k) = E[T_q]$ .

## A- Formule analytique

Nous résumons ici les résultats analytiques connus.

Lorsque  $q = 1$ , on a  $W(1,k) = (k+1)\lambda/2k\mu(\mu-\lambda)$  où  $\lambda > 0$  est le nombre moyen d'arrivées de clients et où  $1/\mu$  est le temps moyen de service. Ce résultat se retrouve dans la majorité des livres sur les files d'attente.

On peut le démontrer assez directement en déterminant la fonction génératrice de la variable  $T_q$  comme cela est fait dans le livre "Fundamentals of Queueing Theory" [1]. Nous pouvons également le démontrer en déterminant la solution spectrale de l'équation intégrale de Lindley [3]. Nous indiquons ici les étapes pour obtenir ce résultat à l'aide de cette méthode. Le choix de cette dernière s'explique facilement; c'est cette méthode que nous utiliserons pour calculer numériquement le délai.

Notons par  $A(s)$ ,  $B(s)$  et  $W(s)$  la transformée de Laplace des fonctions de densité respectives du temps entre l'arrivée successive de deux clients, du service et du délai d'attente.

Dans le cas  $E_1/E_k/1$  on a

$$A(s) = \frac{\lambda}{\lambda+s}, \quad B(s) = \left(\frac{k\mu}{k\mu+s}\right)^k$$

et on sait [3] que

$$W(s) = \frac{s(1 - \frac{\lambda}{\mu})}{\psi_+(s)}$$

où

$$\psi_+(s) = (1 - A(-s) B(s)) \psi_-(s).$$

La fonction

$$\psi_+(s) = \frac{\lambda(k\mu)^k - (\lambda-s)(s+k\mu)^k}{(s+k\mu)^k}$$

est analytique et n'a aucune racine dans le domaine du plan complexe  $\text{Re}(s) > 0$  et  $\psi_-(s) = \lambda - s$  est analytique et n'a aucune racine dans le domaine  $\text{Re}(s) < 0$ .

Ainsi

$$W(s) = \frac{s(1 - \frac{\lambda}{\mu})}{\lambda a(s) - \lambda + s}$$

avec  $a(s) = (\frac{s}{k\mu} + 1)^{-k}$ .

Le lecteur vérifiera facilement que

$$-W'(0) = W(1, k) = \frac{k+1}{2k} \frac{\lambda}{\mu(\mu-\lambda)},$$

résultat annoncé précédemment.

Le temps de passage moyen pour un client dans le système est alors  $W(1, k) + 1 = W$ . Par la formule de Little on obtient le nombre moyen de clients dans la file, noté  $L_q = \lambda W(1, k)$  et le nombre moyen de clients dans le système, noté,  $L = \lambda W$ .

Remarquons que  $W(1,k)$  est une fonction décroissante en  $k$  qui tend vers  $1/2 \lambda/\mu(\mu-\lambda)$  lorsque  $k$  tend vers l'infini; c'est-à-dire

$$W(1,1) < W(1,k) < W(1,+\infty).$$

#### B- Résultats numériques

Dans le cas où  $\rho > 1$ , pour les files d'attente  $E_k/E_k/1$ , on ne peut donner de formule analytique du délai moyen d'attente. Nous le calculerons numériquement. Nous pouvons utiliser la solution spectrale de l'équation intégrale de Lindley [3] pour obtenir  $W(s)$ , cependant, dans un article publié en 1969 [4], on a obtenu

$$W(s) = \frac{(1-\rho) s \prod_{i=1}^{k-1} (1-s/s_i)}{1 - \{A(-s)B(s)\}^{-1}}$$

où  $s_1, s_2, \dots, s_{k-1}$  sont les  $k-1$  racines avec partie réelle positive de  $A(-s)B(s) = 1$ . Les auteurs ont utilisé comme "unité de temps", le temps d'inter-arrivé de sorte que le temps moyen de service est  $\rho$ .

Le délai d'attente moyen devra donc être multiplié par le temps d'inter-arrivé si nous voulons faire disparaître cette "unité de temps".

De plus, comme le temps de service est du type  $E_k$  on a

$$W(s) = \prod_{i=k+1}^{k+l} (1-s/s_i)^{-1} \quad \text{où } s_{k+1}, s_{k+2}, \dots, s_{k+l}$$

sont les  $l$  racines avec partie réelle négative de



$A(-s)B(s) = 1$ . Dans ces conditions le délai d'attente moyen est:

$$W(\ell, k) = -W'(0) = \sum_{i=k+1}^{k+\ell} \frac{1}{s_i}$$

Ceci montre que nous devons numériquement déterminer les  $\ell$  racines, avec partie réelle négative, de l'équation  $A(-s)B(s)-1 = 0$ .

C'est ce que nous avons fait pour certaines valeurs des paramètres  $\ell, k, \lambda$  et  $\mu$ . Comme en pratique le coefficient d'utilisation  $\lambda/\mu$  doit-être plus près de un que de zéro, nous avons limité nos calculs à  $\lambda/\mu \geq 1/2$ . Nous avons donc construit une table. Les 24 dernières pages montrent une table à 8 colonnes; les colonnes 1 et 5 indiquent l'entier  $\ell$ ; les colonnes 2 et 6, l'entier  $k$ , les colonnes 3 et 7, la valeur de  $\lambda/\mu$  et finalement les colonnes 4 et 8, le résultat (en "unité de temps d'inter-arrivée") qu'il faudra diviser par  $\lambda$  pour obtenir le délai moyen d'attente.

Il est évident que cette table n'est pas complète. Les entiers  $\ell$  et  $k$  prennent les valeurs 1,2,3,4,5,6,7,8,9, 10,12,14,16,18,20 et 40 et  $\lambda/\mu$  varie entre 1/2 et 1 par saut de 0,04.

Comme nous l'avons indiqué dans l'introduction cette table fut mise sur une disquette. Un programme d'interpolation linéaire permet de calculer les quantités manquantes.

Après avoir inséré la disquette dans le lecteur et tapé "INTERPO" voici, à titre indicatif, ce que vous verrez à l'écran d'un IBM-PC.

```
interpo
  QUELLE EST LA VALEUR DE L,K,LAMBDA ET MU
  2,1,1,2

  POUR L= 2. ,LAMBDA= 1.0000

  ET POUR K= 1. ,MU= 2.0000

  LE TEMPS D'ATTENTE DANS LA FILE EST .30902

  D'AUTRES VALEURS (OUI OU NON)?
  OUI
  QUELLE EST LA VALEUR DE L,K,LAMBDA ET MU
  2 6 .5 1

  POUR L= 2. ,LAMBDA= .5000

  ET POUR K= 6. ,MU= 1.0000

  LE TEMPS D'ATTENTE DANS LA FILE EST .24560

  D'AUTRES VALEURS (OUI OU NON)?
  OUI
  QUELLE EST LA VALEUR DE L,K,LAMBDA ET MU
  1 13 12.3 14.7

  POUR L= 1. ,LAMBDA= 12.3000

  ET POUR K=13. ,MU= 14.7000

  LE TEMPS D'ATTENTE DANS LA FILE EST .19195

  D'AUTRES VALEURS (OUI OU NON)?
  NON
  Stop - Program terminated.
```

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9	1	.50	.16627	16	1	.50	.14913
9	2	.50	.06952	16	2	.50	.05576
9	3	.50	.04198	16	3	.50	.03030
9	4	.50	.02973	16	4	.50	.01946
9	5	.50	.02302	16	5	.50	.01379
9	6	.50	.01886	16	6	.50	.01042
9	7	.50	.01607	16	7	.50	.00824
9	8	.50	.01408	16	8	.50	.00675
9	9	.50	.01260	16	9	.50	.00568
9	10	.50	.01146	16	10	.50	.00488
9	12	.50	.00983	16	12	.50	.00379
9	14	.50	.00872	16	14	.50	.00309
9	16	.50	.00793	16	16	.50	.00261
9	18	.50	.00733	16	18	.50	.00226
9	20	.50	.00687	16	20	.50	.00200
9	40	.50	.00494	16	40	.50	.00104
10	1	.50	.16233	18	1	.50	.14670
10	2	.50	.06632	18	2	.50	.05386
10	3	.50	.03922	18	3	.50	.02872
10	4	.50	.02727	18	4	.50	.01812
10	5	.50	.02077	18	5	.50	.01261
10	6	.50	.01678	18	6	.50	.00937
10	7	.50	.01412	18	7	.50	.00730
10	8	.50	.01223	18	8	.50	.00589
10	9	.50	.01083	18	9	.50	.00489
10	10	.50	.00976	18	10	.50	.00414
10	12	.50	.00824	18	12	.50	.00314
10	14	.50	.00722	18	14	.50	.00250
10	16	.50	.00649	18	16	.50	.00207
10	18	.50	.00594	18	18	.50	.00177
10	20	.50	.00552	18	20	.50	.00154
10	40	.50	.00380	18	40	.50	.00072
12	1	.50	.15646	20	1	.50	.14475
12	2	.50	.06159	20	2	.50	.05235
12	3	.50	.03517	20	3	.50	.02748
12	4	.50	.02370	20	4	.50	.01706
12	5	.50	.01755	20	5	.50	.01169
12	6	.50	.01382	20	6	.50	.00856
12	7	.50	.01136	20	7	.50	.00658
12	8	.50	.00963	20	8	.50	.00523
12	9	.50	.00837	20	9	.50	.00429
12	10	.50	.00742	20	10	.50	.00359
12	12	.50	.00608	20	12	.50	.00266
12	14	.50	.00519	20	14	.50	.00208
12	16	.50	.00456	20	16	.50	.00169
12	18	.50	.00410	20	18	.50	.00142
12	20	.50	.00375	20	20	.50	.00122
12	40	.50	.00235	20	40	.50	.00052
14	1	.50	.15229	40	1	.50	.13608
14	2	.50	.05824	40	2	.50	.04565
14	3	.50	.03236	40	3	.50	.02209
14	4	.50	.02125	40	4	.50	.01260
14	5	.50	.01536	40	5	.50	.00791
14	6	.50	.01183	40	6	.50	.00531
14	7	.50	.00953	40	7	.50	.00374
14	8	.50	.00794	40	8	.50	.00274
14	9	.50	.00678	40	9	.50	.00206
14	10	.50	.00591	40	10	.50	.00159
14	12	.50	.00471	40	12	.50	.00100
14	14	.50	.00393	40	14	.50	.00068
14	16	.50	.00338	40	16	.50	.00048
14	18	.50	.00299	40	18	.50	.00035
14	20	.50	.00269	40	20	.50	.00027
14	40	.50	.00153	40	40	.50	.00005

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1	1	.54	.47544
1	2	.54	.42261
1	3	.54	.39620
1	4	.54	.38034
1	5	.54	.36978
1	6	.54	.36224
1	7	.54	.35658
1	8	.54	.35218
1	9	.54	.34866
1	10	.54	.34338
1	12	.54	.33960
1	14	.54	.33676
1	16	.54	.33457
1	18	.54	.33280
1	20	.54	.32489
1	40	.54	.40198
2	1	.54	.25555
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2	18	.54	.13024
2	20	.54	.12358
2	40	.54	.32607
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5	6	.54	.04955
5	7	.54	.04591
5	8	.54	.04314
5	9	.54	.04095
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5	18	.54	.03148
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8	20	.54	.01389
8	40	.54	.01064

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12	20	.54	.00428	20	40	.54	.00116
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14	1	.54	.08428	40	2	.54	.06797
14	2	.54	.04860	40	3	.54	.03478
14	3	.54	.03285	40	4	.54	.02086
14	4	.54	.02432	40	5	.54	.01372
14	5	.54	.01912	40	6	.54	.00960
14	6	.54	.01566	40	7	.54	.00703
14	7	.54	.01324	40	8	.54	.00532
14	8	.54	.01146	40	9	.54	.00414
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14	4	.90	1.12392	40	4	.90	.93348
14	5	.90	.93375	40	5	.90	.74550
14	6	.90	.80812	40	6	.90	.62160
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14	10	.90	.56022	40	10	.90	.37952
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14	18	.90	.39889	40	18	.90	.22471
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9	14	.94	1.20533	16	14	.94	.85354
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10	20	.94	.97540	18	20	.94	.65724
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12	4	.94	2.26392	20	4	.94	2.01566
12	5	.94	1.90819	20	5	.94	1.66141
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12	9	.94	1.28058	20	9	.94	1.03793
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12	14	.94	1.00364	20	14	.94	.76399
12	16	.94	.94180	20	16	.94	.70299
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14	20	.98	2.77964	40	20	.98	1.67980
14	40	.98	2.19332	40	40	.98	1.10049

ÉCOLE POLYTECHNIQUE DE MONTRÉAL



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