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## **SENSITIVITY RESULTS IN OPEN, CLOSED, AND MIXED PRODUCT-FORM QUEUEING NETWORKS**

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**Décembre 1989**



# Résultats de Sensibilité pour les Réseaux de Files d'Attente à Forme Produit Ouverts, Fermés et Mixtes

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## Résumé

Dans cet article, nous établissons des formules générales quantifiant l'impact sur les performances d'une modification des paramètres d'un réseau BCMP [3]. Ces formules montrent que la dérivée par rapport à n'importe quelle intensité de service/arrivée de l'espérance mathématique de n'importe quelle fonction  $\Phi$  de l'état du réseau, s'exprime simplement en terme de fonctions connues de l'état du réseau. Des résultats de sensibilité portant, en particulier, sur les débits et sur les distributions des longueurs des files d'attente sont alors facilement obtenus par différents choix de la fonction  $\Phi$ .

**Mots-Clés:** Théorie des Files d'Attente; Réseaux de Files d'Attente à Forme Produit; Sensibilité; Monotonie.

# Sensitivity Results in Open, Closed, and Mixed Product-Form Queueing Networks

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## Abstract

General formulas are proposed to quantify the effects of changing the arrival and service rates in the so-called BCMP network [?]. These formulas relate the derivative of the expectation of any function  $\Phi$  of the state of the network with respect to any arrival/service rate in the network, to known functions of the state of the network. As an application, sensitivity results of interest bearing on throughputs and on the moments of queue lengths can be derived by appropriate choices of the function  $\Phi$ .

**Keywords:** Queueing Theory; Queueing Networks; Product-Form; Sensitivity; Monotonicity.

# 1 Introduction

Although the use of queueing networks in the modeling and analysis of telecommunication networks and computer systems was initiated with the work of A. K. Erlang [9] at the beginning of the century, it became widespread only after the pioneering work of Jackson [11], Gordon and Newell [10], Baskett, Chandy, Muntz, and Palacios [3], and Kelly [14] on a special class of queueing networks known as *product-form queueing networks*. The nice feature of product-form queueing networks is that for certain classes of Markovian networks, the solution of the balance equations is in the form of a product of simple factors. Afterwards, various generalizations were obtained that extend the product-form property to state-dependent routing [26], non-differentiable service time distribution functions [21], stationary dependent service times [12], and concurrent classes of customers [6], [15]. A fairly complete survey on product-form queueing networks can be found in [8].

Besides these theoretical results, efficient computational algorithms for computing the main performance measures (expected number of customers at a given node, mean waiting times, mean sojourn times, utilization factor of each node, throughputs, etc.) have been proposed by Buzen [4], Reiser and Kobayashi [18], Chandy and Sauer [5], Reiser and Lavenberg [17], and Conway and Georganas [7].

More recently, “first-order qualitative properties” of queueing networks are receiving attention in the literature. These studies aim to determine the sensitivity of various performance measures of the network with respect to particular parameters such as arrival rates, service rates, number of servers, number of customers for closed networks, etc. For closed product-form queueing networks with a single class of customers, Stewart and Stohs [25] have shown that if the service rates are load independent, then the system throughput increases when the service rate of one of the queues increases. This result has been generalized by Shanthikumar and Yao [22] to the case where the service rates are nondecreasing functions of the queue lengths. For the same network, Shanthikumar and Yao [23] have also investigated the effect of increasing the customer population on the queue lengths. Monotonicity properties in product-form queueing networks with loss of customers have been established by Nain [16] and Ross and Yao [19]. Monotonicity results have also been derived lately for non-Markovian queueing networks by Adan and Van der Wal [1], Shanthikumar and Yao [24], and Tsoucas and Walrand [27].

These properties have been obtained using stochastic comparison techniques involving different stochastic orderings, coupling and pathwise arguments. However, these probabilistic methods do not provide formulas enabling one to quantify the impact of a model parameter modification on the network behavior (e.g., rate of increase/decrease of any monotonic function of the state of the

network, etc.).

In this paper, we consider the network studied by Baskett, Chandy, Muntz, and Palacios [3], referred to as the BCMP network, and we analyze the sensitivity of an arbitrary function  $\Phi$  of the state of the network with respect to the arrival and service rates at any node. More precisely, we show that the derivative of the expectation of any function  $\Phi$  of the state of the network with respect to any arrival/service intensity, provided this quantity is well-defined, can be expressed simply in terms of known functions of the state of the network. A similar approach has been employed by Jordan and Varaiya [13] to get sensitivity results in a generalized Erlang loss system.

Our results can be used to analyse both quantitative and qualitative effects of modifying model parameters. For instance, monotonicity or nonmonotonicity properties for the moments of queue lengths at a given node, the throughput of a given class of customers at a given node, etc., can be found. In particular, some of the monotonicity properties obtained in [22] can easily be derived from this approach. Furthermore, these results can also be used for optimization purposes by appropriately choosing the “cost function”  $\Phi$ .

The paper is organized as follows. In section 2 we recall the main features of the BCMP network and introduce some definitions and notation. Section 3 contains the key results of the paper. In section 4 we present some applications.

## 2 The Model

The network considered in this paper is similar to that analyzed in [3], the only difference being in the modeling of the exogeneous arrivals (see below).

There are  $N \geq 1$  stations and  $R \geq 1$  different classes of customers. Customers travel through the network and change class according to transition probabilities. Thus a customer of class  $r$  which leaves station  $i$  upon its service completion will enter station  $j$  as a customer of class  $s$  with the probability  $p_{i,r;j,s}$ . The transition matrix  $[p_{i,r;j,s}]$  defines a Markov chain whose states are labeled by the pairs  $(i, r)$ . This Markov chain is assumed to be decomposable into  $L$  ergodic subchains. Denote by  $E_1, E_2, \dots, E_L$  the sets of states in each of these subchains. A customer of class  $r$  at station  $i$  is called a customer of type  $(i, r)$ . A customer of type  $E_l$  is a customer whose type belongs to  $E_l$ .

Customers may arrive at the network from  $NR$  external sources according to independent Poisson processes. To be more specific, define  $M_l(S)$  to be the number of customers of type  $E_l$  when the state of the network is  $S$  (to be made more precise). Then, the exogeneous arrival rate

of customers of type  $(i, r) \in E_l$  is  $\lambda_{ir}\gamma_l(M_l(S))$ , where  $\lambda_{ir} \geq 0$  and that  $\gamma_l$  is an arbitrary mapping  $\mathbb{N} \rightarrow [0, +\infty)$  that does not depend on  $\{\lambda_{ir}\}_{ir}$  (here  $\mathbb{N} := \{0, 1, 2, \dots\}$ ).

If  $\lambda_{ir} = 0$  for all  $1 \leq i \leq N$ ,  $1 \leq r \leq R$ , then the network is *closed*. If there exists a partition  $(L_A, L_B)$  of the set  $\{1, 2, \dots, L\}$ , such that

$$\forall (i, r) \in \bigcup_{l \in L_A} E_l \quad \lambda_{ir} = 0,$$

and

$$\forall l \in L_B \quad \exists (i, r) \in E_l \quad \lambda_{ir} > 0,$$

then the network is *mixed*. If for all  $1 \leq l \leq L$  there exists  $(i, r) \in E_l$  such that  $\lambda_{ir} > 0$ , then the network is *open*. We say that  $E_l$  is closed if  $\lambda_{ir} = 0$  for all  $(i, r) \in E_l$  and that  $E_l$  is open if for some  $(i, r) \in E_l$ ,  $\lambda_{ir} > 0$ .

In case  $E_l$  is open, then we assume that there exists at least one state  $(i, r) \in E_l$  such that

$$0 \leq \sum_{(j,s) \in E_l} p_{i,r;j,s} < 1. \quad (2.1)$$

Thus,  $1 - \sum_{(j,s) \in E_l} p_{i,r;j,s}$  is the probability that a customer of class  $r$  leaves the system upon its service completion at station  $i$ .

Four distinct types of service stations are considered:

*Type 1.* The service discipline is First-Come-First-Served (FCFS) and multiple servers are allowed. All customers have the same service time distribution which is a negative exponential.

*Type 2.* There is a single server and the service discipline is Processor Sharing (PS).

*Type 3.* There is an Infinite number of Servers (IS).

*Type 4.* There is a single server and the service discipline is preemptive resume Last-Come-First-Served (LCFS).

When station  $i$  is of type 1, we write  $i \in \text{FCFS}$ . The notation  $i \in \text{PS}$ ,  $i \in \text{IS}$  and  $i \in \text{LCFS}$  will have the obvious meaning.

For  $i \in \text{FCFS}$ , let  $\mu_i \alpha_i(n)$  be the service rate at station  $i$  when there are  $n > 0$  customers at this station. For stations of type 2, 3 or 4, each class of customer may have a distinct and arbitrary service time distribution (GI-servers). For  $i \in \{\text{PS}, \text{IS}, \text{LCFS}\}$ , let  $1/\mu_{ir}$  denote the mean value of the service time of a customer of class  $r$  at station  $i$ . We further assume that  $\alpha_i$  is an

arbitrary mapping  $\mathbb{N} \rightarrow [0, +\infty)$  with  $\alpha_i(0) = 0$ , which does not depend on the model parameters  $\{\lambda_{ir}, \mu_i, \mu_{ir}\}_{ir}$ .

Let  $X_{ir}$  denote the number of customers of class  $r$  at station  $i$ . The state of the network is  $S = (X_1, X_2, \dots, X_N)$  where  $X_i = (X_{i1}, X_{i2}, \dots, X_{iR})$  for  $i = 1, 2, \dots, N$ . Set  $|X_i| = \sum_{r=1}^R X_{ir}$ .

The joint equilibrium distribution of queue sizes in the network is [3], [14],

$$P(S = (x_1, x_2, \dots, x_N)) = C d(S) g_1(x_1) g_2(x_2) \cdots g_N(x_N), \quad (2.2)$$

where  $C$  is a normalizing constant and  $d(S)$  is a function of the number of customers in the system. If the network is closed then  $d(S) \equiv 1$ , otherwise

$$d(S) = \prod_{l \in L_O} \left\{ \Lambda_l^{M_l(S)} \prod_{m=0}^{M_l(S)-1} \gamma_l(m) \right\}, \quad (2.3)$$

where  $L_O := \{l \mid 1 \leq l \leq L, E_l \text{ is open}\}$  and where  $\Lambda_l := \sum_{(i,r) \in E_l} \lambda_{ir}$  for all  $l \in L_O$ .

Let  $x_i = (n_{i1}, n_{i2}, \dots, n_{iR})$  and  $n_i = \sum_{r=1}^R n_{ir}$ . Each  $g_i(x_i)$  in (2.2) is a function that depends on the type of station  $i$ :

- if station  $i$  is of type 1, then

$$g_i(x_i) = n_i! \left( \prod_{m=1}^{n_i} \frac{1}{\mu_i \alpha_i(m)} \right) \left( \prod_{r=1}^R \frac{e_{ir}^{n_{ir}}}{n_{ir}!} \right); \quad (2.4)$$

- if station  $i$  is of type 2 or 4, then

$$g_i(x_i) = n_i! \prod_{r=1}^R \left\{ \left( \frac{e_{ir}}{\mu_{ir}} \right)^{n_{ir}} \left( \frac{1}{n_{ir}!} \right) \right\}; \quad (2.5)$$

- if station  $i$  is of type 3, then

$$g_i(x_i) = \prod_{r=1}^R \left\{ \left( \frac{e_{ir}}{\mu_{ir}} \right)^{n_{ir}} \left( \frac{1}{n_{ir}!} \right) \right\}. \quad (2.6)$$

The  $e_{ir}$ 's satisfy the following set of linear equations [3]:

$$e_{ir} = q_{ir}(l) + \sum_{(j,s) \in E_l} e_{js} p_{j,s;i,r}, \quad (2.7)$$



for all  $(i, r) \in E_l$ ,  $l = 1, 2, \dots, L$ , where

$$q_{ir}(l) := \begin{cases} \frac{\lambda_{ir}}{\Lambda_l}, & \text{if } \lambda_{ir} > 0; \\ 0, & \text{if } \lambda_{ir} = 0. \end{cases} \quad (2.8)$$

### 3 Sensitivity Results

From now on we assume that the network is in equilibrium. Two types of sensitivity results are derived in this section: sensitivity results with respect to service rates (Theorem 3.1) and those with respect to exogeneous arrival rates (Theorem 3.2).

Let us introduce some notation. Let  $\Phi$  be a mapping  $(\mathbb{N}^R)^N \rightarrow [0, +\infty)$ . We say that  $\Phi$  satisfies assumption A1 (resp. A2, A3) if

1.  $\frac{\partial \Phi(x)}{\partial z}$ ,  $E \left[ \frac{\partial \Phi(S)}{\partial z} \right]$  and  $\frac{\partial E[\Phi(S)]}{\partial z}$  exist;
2.  $\frac{\partial E[\Phi(S)]}{\partial z} = \sum_{y \in \mathcal{F}} \frac{\partial \{\Phi(y)P(S=y)\}}{\partial z}$ ,

for  $z \in \{\mu_i\}_i$  (resp.  $z \in \{\mu_{ir}\}_{ir}$ ,  $z \in \{\lambda_{ir}\}_{ir}$ ), where  $\mathcal{F}$  denotes the set of all feasible states for the network under consideration (i.e., open, closed, or mixed).

We now state the first result of this section.

**Theorem 3.1** *Assume that  $\Phi$  satisfies assumption A1. Then, for  $i \in \text{FCFS}$ ,*

$$\frac{\partial E[\Phi(S)]}{\partial \mu_i} = E \left[ \frac{\partial \Phi(S)}{\partial \mu_i} \right] - \frac{\text{cov}(\Phi(S), |X_i|)}{\mu_i}. \quad (3.1)$$

*Assume that  $\Phi$  satisfies assumption A2. Then, for  $i \in \{\text{PS}, \text{IS}, \text{LCFS}\}$ ,  $1 \leq r \leq R$ ,*

$$\frac{\partial E[\Phi(S)]}{\partial \mu_{ir}} = E \left[ \frac{\partial \Phi(S)}{\partial \mu_{ir}} \right] - \frac{\text{cov}(\Phi(S), X_{ir})}{\mu_{ir}}. \quad (3.2)$$

**Proof.** Assume first that  $i \in \text{FCFS}$ . It follows from (2.2) and assumption A1 that

$$\frac{\partial E[\Phi(S)]}{\partial \mu_i} = \sum_{y \in \mathcal{F}} \frac{\partial}{\partial \mu_i} \left\{ C d(y) \Phi(y) \prod_{k=1}^N g_k(x_k) \right\},$$

$$\begin{aligned}
&= C \sum_{y \in \mathcal{F}} d(y) \left( \frac{\partial \Phi(y)}{\partial \mu_i} \right) \prod_{k=1}^N g_k(x_k) + \left( \frac{\partial C}{\partial \mu_i} \right) \sum_{y \in \mathcal{F}} d(y) \Phi(y) \prod_{k=1}^N g_k(x_k) \\
&+ C \sum_{y \in \mathcal{F}} d(y) \Phi(y) \left( \frac{\partial}{\partial \mu_i} \prod_{k=1}^N g_k(x_k) \right).
\end{aligned} \tag{3.3}$$

Using (2.4) it is easily checked that

$$\frac{\partial}{\partial \mu_i} \prod_{k=1}^N g_k(x_k) = -\frac{n_i}{\mu_i} \prod_{k=1}^N g_k(x_k). \tag{3.4}$$

Now differentiating the identity

$$C = \frac{1}{\sum_{y \in \mathcal{F}} d(y) \prod_{k=1}^N g_k(x_k)}, \tag{3.5}$$

we obtain

$$\frac{\partial C}{\partial \mu_i} = -C^2 \left( \frac{\partial}{\partial \mu_i} \sum_{y \in \mathcal{F}} d(y) \prod_{k=1}^N g_k(x_k) \right),$$

which, together with (3.4), yields

$$\frac{\partial C}{\partial \mu_i} = \frac{C}{\mu_i} E[|X_i|]. \tag{3.6}$$

Consequently, cf. (3.3), (3.4), and (3.6),

$$\begin{aligned}
\frac{\partial E[\Phi(S)]}{\partial \mu_i} &= E \left[ \frac{\partial \Phi(S)}{\partial \mu_i} \right] + \frac{E[|X_i|] E[\Phi(S)]}{\mu_i} - \frac{E[\Phi(S) |X_i|]}{\mu_i}, \\
&= E \left[ \frac{\partial \Phi(S)}{\partial \mu_i} \right] - \frac{\text{cov}(\Phi(S), |X_i|)}{\mu_i}.
\end{aligned}$$

The proof of (3.2) follows similarly by observing that from (2.5) and (2.6),

$$\frac{\partial}{\partial \mu_{ir}} \prod_{k=1}^N g_k(x_k) = -\frac{n_{ir}}{\mu_{ir}} \prod_{k=1}^N g_k(x_k).$$

This yields

$$\frac{\partial C}{\partial \mu_{ir}} = \frac{C}{\mu_{ir}} E[X_{ir}],$$

for  $i \in \{\text{PS}, \text{IS}, \text{LCFS}\}$ . ■

Let us assume that the network is either open or mixed. We now state the second result of this section that establishes sensitivity results with respect to exogenous arrival rates.

**Theorem 3.2** Assume that  $\Phi$  satisfies assumption A3. If there exists an external source of customers of type  $(i, r) \in E_l$ , then

$$\frac{\partial E[\Phi(S)]}{\partial \lambda_{ir}} = E \left[ \frac{\partial \Phi(S)}{\partial \lambda_{ir}} \right] + \frac{\text{cov}(\Phi(S), M_l(S))}{\Lambda_l} + \left( \frac{\partial e_{ir}}{\partial \lambda_{ir}} \right) \frac{\text{cov}(\Phi(S), X_{ir})}{e_{ir}}. \quad (3.7)$$

In particular, if  $E_l = \{(i, r)\}$ , then

$$\frac{\partial E[\Phi(S)]}{\partial \lambda_{ir}} = E \left[ \frac{\partial \Phi(S)}{\partial \lambda_{ir}} \right] + \frac{\text{cov}(\Phi(S), M_l(S))}{\Lambda_l}. \quad (3.8)$$

**Proof.** Assume that  $(i, r) \in E_l$ . We have, cf. (2.2) and assumption A3,

$$\begin{aligned} \frac{\partial E[\Phi(S)]}{\partial \lambda_{ir}} &= C \sum_{y \in \mathcal{F}} \left( \frac{\partial \Phi(y)}{\partial \lambda_{ir}} \right) d(y) \prod_{k=1}^N g_k(x_k) + \left( \frac{\partial C}{\partial \lambda_{ir}} \right) \sum_{y \in \mathcal{F}} \Phi(y) d(y) \prod_{k=1}^N g_k(x_k) \\ &+ C \sum_{y \in \mathcal{F}} \Phi(y) \left( \frac{\partial d(y)}{\partial \lambda_{ir}} \right) \prod_{k=1}^N g_k(x_k) + C \sum_{y \in \mathcal{F}} \Phi(y) d(y) \left( \frac{\partial}{\partial \lambda_{ir}} \prod_{k=1}^N g_k(x_k) \right). \end{aligned} \quad (3.9)$$

From (2.2), (2.4)-(2.6), it is easily seen that

$$\frac{\partial}{\partial \lambda_{ir}} \prod_{k=1}^N g_k(x_k) = \frac{n_{ir}}{e_{ir}} \left( \frac{\partial e_{ir}}{\partial \lambda_{ir}} \right) \prod_{k=1}^N g_k(x_k). \quad (3.10)$$

It follows from (2.3) that

$$\frac{\partial d(y)}{\partial \lambda_{ir}} = \frac{M_l(y)}{\Lambda_l} d(y). \quad (3.11)$$

By differentiating (3.5) with respect to  $\lambda_{ir}$  and by using (3.10) and (3.11), we obtain

$$\frac{\partial C}{\partial \lambda_{ir}} = - \left( \frac{E[M_l(S)]}{\Lambda_l} + \left( \frac{\partial e_{ir}}{\partial \lambda_{ir}} \right) \frac{E[X_{ir}]}{e_{ir}} \right) C. \quad (3.12)$$

Substituting (3.10), (3.11), and (3.12) into (3.9) yields (3.7).

It remains to check that

$$\frac{\partial e_{ir}}{\partial \lambda_{ir}} = 0$$

in (3.7) whenever  $E_l = \{(i, r)\}$ . In this case,  $q_{ir} = 1$  from (2.8), so  $e_{ir} = 1/(1 - p_{i,r;i,r})$  from (2.7), and therefore  $\partial e_{ir}/\partial \lambda_{ir} = 0$ , which completes the proof. ■

**Remark 3.1** The quantity  $\partial e_{ir}/\partial \lambda_{ir}$  involved in (3.7) can be computed by solving the linear equations, cf. (2.7),

$$\frac{\partial e_{js}}{\partial \lambda_{ir}} = \frac{\partial q_{js}(l)}{\partial \lambda_{ir}} + \sum_{(j,s) \in E_l} p_{j',s';j,s} \frac{\partial e_{j's'}}{\partial \lambda_{ir}}, \quad \forall (j,s) \in E_l, \quad (3.13)$$

where (cf. (2.8))

$$\frac{\partial q_{js}(l)}{\partial \lambda_{ir}} = \begin{cases} \frac{\Lambda_l - \lambda_{js}}{\Lambda_l^2}, & \text{if } (j,s) = (i,r); \\ -\frac{1}{\Lambda_l^2}, & \text{if } (j,s) \neq (i,r). \end{cases}$$

It follows from assumption (2.1) that  $\{\partial e_{js}/\partial \lambda_{ir}\}_{(j,s) \in E_l}$  is the unique solution of (3.13).

**Remark 3.2** As mentioned in [3], pp. 256-257, the product-form (2.2) is preserved when various forms of state-dependent service rates are incorporated in stations PS, IS and LCFS. If so, formulas (2.4)-(2.6) have to be modified accordingly but Theorems 3.1 and 3.2 remain valid provided the introduced service dependencies do not involve the model parameters  $\{\lambda_{ir}, \mu_i, \mu_{ir}\}_{ir}$ .

## 4 Applications

Many results of practical interest can be derived from Theorems 3.1 and 3.2. We point out some of them below. Recall that any point  $x$  in the domain of definition of the function  $\Phi$  can be written as  $x = (x_1, x_2, \dots, x_N)$  with  $x_i = (n_{i1}, n_{i2}, \dots, n_{iR})$ , where  $n_{ir} \in \mathbb{N}$ . Also recall that  $n_i = \sum_{r=1}^R n_{ir}$ .

### 4.1 Sensitivity of queue lengths

Let  $f$  be any nondecreasing mapping  $\mathbb{N} \rightarrow [0, +\infty)$ .

1.  $\Phi(x) = f\left(\sum_{j \in N_I} n_j\right)$ ,  $N_I \subset \{1, 2, \dots, N\}$ .

Then, for  $i \in \text{FCFS}$ , cf. (3.1),

$$\frac{\partial E \left[ f\left(\sum_{j \in N_I} |X_j|\right) \right]}{\partial \mu_i} = - \frac{\text{cov} \left( f\left(\sum_{j \in N_I} |X_j|\right), |X_i| \right)}{\mu_i}. \quad (4.1)$$

Assume that  $N_I = \{i\}$ . Then, the right-hand side of (4.1) is nonpositive since the random variable  $f(|X_i|)$  is *stochastically increasing* in  $|X_i|$ , which implies that  $\text{cov}(f(|X_i|), |X_i|) \geq 0$  (see [2], Theorem 4.7, p. 146). Therefore,

- $|X_i|$  is decreasing in  $\mu_i$  in the sense of *stochastic ordering* ([20], pp. 251-252) for all  $i \in \text{FCFS}$ .
- As a consequence,  $\sum_{j \neq i} |X_j|$  is increasing in  $\mu_i$  in the sense of stochastic ordering when the network is closed, for all  $i \in \text{FCFS}$ .

2.  $\Phi(x) = f(n_{js})$  with  $(j, s) \in E_l$ .

Then, for  $i \in \{\text{PS}, \text{IS}, \text{LCFS}\}$ , cf. (3.2),

$$\frac{\partial E[f(X_{js})]}{\partial \mu_{ir}} = -\frac{\text{cov}(f(X_{js}), X_{ir})}{\mu_{ir}}. \quad (4.2)$$

Similar to case 1 above, we deduce from (4.2) that

- $X_{ir}$  is decreasing in  $\mu_{ir}$  in the sense of stochastic ordering;
- $\sum_{(j,s) \neq (i,r)} |X_{js}|$  is increasing in  $\mu_{ir}$  in the sense of stochastic ordering when the network is closed,

for all  $i \in \{\text{PS}, \text{IS}, \text{LCFS}\}$ ,  $1 \leq r \leq R$ .

3. Assume now that  $E_l$  is open and that  $E_l = \{(j, s)\}$ . Then, cf. (3.8),

$$\frac{\partial E[f(X_{js})]}{\partial \lambda_{js}} = \frac{\text{cov}(f(X_{js}), X_{js})}{\lambda_{js}}, \quad (4.3)$$

which shows that

- $X_{js}$  is increasing in  $\lambda_{js}$  in the sense of stochastic ordering, for all  $1 \leq j \leq N$ ,  $1 \leq s \leq R$ .

The interested reader can also derive formulas for  $\partial E[f(X_{js})]/\partial \mu_i$  for  $i \in \text{FCFS}$ , and for  $\partial E[f(X_j)]/\partial \mu_{ir}$  for  $i \in \{\text{PS}, \text{IS}, \text{LCFS}\}$ .

Note that the results in applications 1 and 2 generalize earlier results of Shanthikumar and Yao (see [22], Corollary 3.1) to arbitrary state-dependent service rates (see Remark 3.2) and multi-class closed/open/mixed queueing networks.

## 4.2 Sensitivity of throughputs

1.  $\Phi(x) = \mu_{js} \frac{n_{js}}{n_j} \mathbf{1}_{\{n_{js} > 0\}}$  with  $(j, s) \in E_l$ .

Then  $E[\Phi(S)] = \mu_{js}E[(X_{js}/|X_j|)1_{\{X_{js}>0\}}]$  is the throughput of customers of class  $s$  in station  $j$  if  $j \in \text{PS}$  and if  $E_l$  is closed.

For  $i \in \text{PS}$ , we have, cf. (3.2),

$$\frac{\partial E[\Phi(S)]}{\partial \mu_{ir}} = 1_{\{(i,r)=(j,s)\}} \frac{E[\Phi(S)]}{\mu_{ir}} - \frac{\mu_{js}}{\mu_{ir}} \text{cov}\left(\frac{X_{js}}{|X_j|} 1_{\{X_{js}>0\}}; X_{ir}\right). \quad (4.4)$$

If only customers of class  $r$  may visit station  $i$  and if  $(j,s) = (i,r)$ , then (4.4) becomes

$$\frac{\partial E[\Phi(S)]}{\partial \mu_{ir}} = P(X_{ir} > 0) - E[X_{ir}]P(X_{ir} = 0).$$

2.  $\Phi(x) = \mu_{js} n_{js}$  with  $(j,s) \in E_l$ .

Then  $E[\Phi(S)] = \mu_{js}E[X_{js}]$  is the throughput of customers of class  $s$  in station  $j$  if  $j \in \text{IS}$  and if  $E_l$  is closed.

We have, for  $i \in \text{IS}$ , cf. (3.2),

$$\frac{\partial E[\Phi(S)]}{\partial \mu_{ir}} = 1_{\{(i,r)=(j,s)\}} E[X_{js}] - \frac{\mu_{js}}{\mu_{ir}} \text{cov}(X_{js}, X_{ir}). \quad (4.5)$$

If  $(i,r) = (j,s)$ , then (4.5) reduces to

$$\frac{\partial E[\Phi(S)]}{\partial \mu_{ir}} = E[X_{ir}] - \text{var}(X_{ir}).$$

3.  $\Phi(x) = \mu_j \alpha_j(n_j)$  with  $(j,s) \in E_l$ .

Recall that  $\alpha_j(0) = 0$ . Then  $E[\Phi(S)] = \mu_j E[\alpha_j(|X_j|)]$ , and  $E[\Phi(S)]$  is the throughput of station  $j$  if  $j \in \text{FCFS}$  and if  $E_l$  is closed.

We have, for  $i \in \text{FCFS}$ , cf. (3.1),

$$\frac{\partial E[\Phi(S)]}{\partial \mu_i} = 1_{\{i=j\}} E[\alpha_j(|X_j|)] - \frac{\mu_j}{\mu_i} \text{cov}(\alpha_j(|X_j|), |X_i|). \quad (4.6)$$

If  $i = j$ , then (4.6) simply becomes

$$\frac{\partial E[\Phi(S)]}{\partial \mu_i} = E[\alpha_i(|X_i|)] - \text{cov}(\alpha_i(|X_i|), |X_i|).$$

The reader is encouraged to establish cross term derivatives, e.g., the derivative of an FCFS station with respect to the service rate of an IS station.

### 4.3 Numerical approach to optimization problems

Many optimization problems in queueing networks are formulated in terms of the search for an optimal value of a system parameter so that some cost function is minimized/maximized. In general, the cost function is expressed as the mathematical expectation of a function of the system state.

One of the most direct ways of solving this kind of problem is to compute the derivative of the cost function with respect to the system parameter and to find the minima/maxima of the cost function. Unfortunately, this approach is often unfeasible because the derivative of the cost function is hard to obtain.

In product-form networks, however, owing to the Theorems 3.1 and 3.2, the determination of the derivative is reduced to the computation of the covariance of certain state variables. This provides a new approach, at least from a numerical point of view, to the solution of certain optimization problems.

As an example, let the cost function be  $E[a|X_i| + b\mu_i]$ , where  $a$  and  $b$  are nonnegative real coefficients representing holding and service costs, respectively, and where  $|X_i|$  is the queue length of an FCFS station  $i$  in a BCMP network and  $\mu_i$  is the service rate. One might want to find a value of  $\mu_i$  that minimizes this cost function. Using Theorem 3.1, one obtains

$$\frac{\partial E[aX_i + b\mu_i]}{\partial \mu_i} = b - \frac{a}{\mu_i} \text{var}(X_i). \quad (4.7)$$

Thus, the problem reduces to the computation of the roots of the right-hand side of equation (4.7).

### 4.4 Correlation between state variables

Let us choose  $\Phi(x)$  as in application 1 of section 4.1. Assume that the network is closed and that there is only one class of customers. Let  $T_i$  denote the throughput of station  $i$ ,  $1 \leq i \leq N$  (cf. section 4.2). Then,

$$\text{cov}(f(|X_j|), |X_i|) \leq 0; \quad (4.8)$$

$$\text{cov}(T_j, |X_i|) \leq 0, \quad (4.9)$$

for all  $i \neq j$ , and

$$\text{cov}\left(f\left(\sum_{j \in N_I} |X_j|\right), |X_i|\right) \geq 0, \quad (4.10)$$

for all  $i \in N_I$ , provided the service rate at each station is a nondecreasing function of the total number of customers at that station.

The proof of (4.8) and (4.10) (resp. (4.9)) follows directly from (4.1) (resp. (4.4)-(4.6)) together with the following result due to Shanthikumar and Yao ([22], Corollary 3.1). In a closed network with a single class of customers, let  $(N_A, N_B)$  denote any nontrivial partition of  $\{1, 2, \dots, N\}$ ; then

1.  $|X_j|$  ( $j \in N_A$ ) is increasing in  $\mu_i$  in the sense of stochastic ordering for all  $i \in N_B$ ;
2.  $\sum_{j \in N_B} |X_j|$  is decreasing in  $\mu_i$  in the sense of stochastic ordering for all  $i \in N_B$ ,
3.  $T_j$  is nondecreasing in  $\mu_i$  for all  $i \in N_B$ ,  $1 \leq j \leq N$ ,

provided (i) the service rate at station  $i$  is nondecreasing in  $|X_i|$  for all  $i \in N_A$ , (ii)  $\text{card } N_B = 1$  or  $\text{card } N_B \geq 2$  and the service rate at station  $i$  is nondecreasing in  $|X_i|$  for all  $i \in N_B$ .

## 5 Conclusions

In this paper, we have revisited quantitative and qualitative analysis of the BCMP network. Various formulas have been established that relate the derivative of the expectation of any function  $\Phi$  of the state of the network with respect to any arrival/service rate in the network, to known functions of the state of the network.

As an application of these results, we have shown that monotonicity/nonmonotonicity properties of the throughputs and of the queue length moments (some of which are known in the literature) can easily be derived by appropriately choosing the function  $\Phi$ . As formulas in section 4.2 suggest, in general the throughputs in mixed/closed BCMP networks are nonmonotonic in the system parameters.

It is worthwhile to note that the results obtained in the paper provide an approach to the numerical computation of the derivatives of the expectation of an arbitrary function of the system state with respect to arrival and service rates in the queueing network, and is thus of particular interest for numerical solutions of various optimization problems arising in queueing systems.

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